# Guide

# to the Applications of Marine Climatology

## WMO – No. 781

# WORLD METEOROLOGICAL ORGANIZATION

# Guide

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# to the Applications of Marine Climatology

NOTE

## TABLE FOR NOTING SUPPLEMENTS RECEIVED

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# FOREWORD

The Marine Climatological Summaries Scheme, which was first agreed by the Fourth World Meteorological Congress in 1963, has proved to be a unique and very successful set of procedures for the collection, exchange, quality control, archival and processing of marine climatological data. Complete global and regional sets of such data, dating back to at least 1960, are now available in standard formats, and with known, standardized quality, from a number of archival centres.

These marine climatological data sets, covering a large number of variables of the marine atmosphere and the sea surface, have always been extremely valuable in the provision of services to the marine user community, particularly in areas such as offshore mining and coastal construction. The data are also proving increasingly essential to many aspects of global climate studies. At the same time, these data sets are largely constructed from observations from ships of the WMO Voluntary Observing Ships scheme. Since these observing platforms are, by definition, transient in both space and time, the processing of such data requires the application of techniques which are unique and relatively sophisticated.
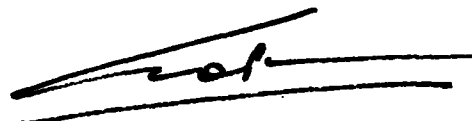
For these reasons, the WMO Commission for Marine Meteorology (CMM), at its ninth session (Geneva, October 1984), agreed on the value of preparing a publication which would provide comprehensive documentation of the knowledge and techniques already in use by a number of national Meteorological Services in the processing of marine climatological data and, at the same time, describe in detail the diverse applications of such data in the service of the marine user community. The Commission's recommendation for the preparation and publication of a *Guide to the applications of marine climatology* was subsequently approved by the thirty-seventh session of the Executive Council (Geneva, June 1985) and strongly supported by the Tenth World Meteorological Congress (Geneva, May 1987).

CMM entrusted the task of preparing this new *Guide* to its Working Group on Marine Climatology, which in turn requested one of its members, Mr Andrej Saulesleja (Canada), to become technical director and chief editor for the project. Mr Saulesleja subsequently assembled an international team of experts in the field, who all contributed directly to the preparation of the *Guide* through writing and/or editing various parts of the text. Acknowledgements to these experts are given overleaf and I would like here simply to offer the full and sincere appreciation of WMO to all contributors for their efforts.

The compilation of the complete text was effected by Mr Saulesleja, who also undertook a final revision and editing of the *Guide* following reviews submitted by a number of climatological experts in several countries. Special thanks are due to him for the considerable time and effort he has put in, on behalf both of the Commission for Marine Meteorology and of WMO in general, in preparing this new *Guide*.

While differences of opinion will inevitably exist over style and contents of a publication such as this, it is nevertheless firmly believed that the *Guide to the applications of marine climatology* provides a comprehensive, coherent and readable guide to the processing and application of marine climatological data in support of a wide variety of user interests. It should be seen as being complementary to the *Guide to climatological practices* (WMO–No. 100) and will doubtless prove a valuable source text and reference book to all Members with access to marine climatological data, and which are required to provide climate-related services to their marine user communities.

(G. O. P. Obasi)
Secretary-General

# ACKNOWLEDGEMENTS

# INTRODUCTION

## 1.1  PURPOSE OF THIS *GUIDE*

Traditionally, the growth of marine climate applications has responded to commercial and national interests in offshore regions. Over the past few hundred years these applications have been largely supportive of naval and mercantile shipping activities, and of fisheries. All of these activities were well established at the beginning of this century, and the foundations were laid as far as support from marine climate applications is concerned. Since the mid-twentieth century, the development of offshore energy resources has created new needs for climate information and new applications.

The interests of the offshore hydrocarbon industry encompass a wide range of activities: geophysical surveys, design and operation of fixed and dynamically positioned exploration and production platforms, airborne logistic support, sea-bed and overland pipelines, siting and construction of liquefaction plants and port facilities, design and routeing of marine transportation, and possible oil-spill movement, containment and clean-up. In pursuing the development of offshore energy supplies, many environmental and societal concerns must be addressed. The risks and benefits of offshore developments are perceived to have a potential impact on almost all other activities in the ocean and port areas in the vicinity. Such a range of interests means that nearly every element of climate needs to be considered in one phase or another of any offshore operation. The growth of the offshore energy industry has stimulated development in many phases of climate applications, a fact which has not been unnoticed by Members of WMO.

Ninth Congress supported the initiative of CMM and agreed that the application of marine climatological information should receive more attention than it had hitherto (reference: Abridged report of Ninth World Meteorological Congress, general summary, paragraph 3.1.6.5). Realizing that many countries were active in this field, it felt that their experience in the application of marine climatological information should be ascertained and documented for circulation to Members of WMO as guidance material. The recommendation that a *Guide* be developed was adopted by EC–XXXVII. This publication has been prepared in response to that recommendation, and summarizes the experience of many Members of WMO in applications of marine climatology. The practices outlined herein are intended to serve as a guide to others who would use climate information for similar applications. This publication is therefore meant to supplement for the marine community the information found in the WMO *Guide to Climatological Practices* (WMO–No. 100, under revision).

Marine activities, especially those associated with offshore energy production and transportation, are international in scope. Drilling equipment and transportation systems are constructed on a global scale with parts designed and built in many countries. The companies involved in construction and operation of these facilities are to a great extent multinational in nature. The systems must often be capable of functioning and surviving in a variety of environments, from the tropics to ice-infested polar regions. The equipment and operations must satisfy the safety and other regulatory requirements of many nations, but also those of classification societies and insurers, whose area of operation is global. Basic to these requirements is that climate, especially extremes, should be adequately considered.

Climate information is applied in many other ways. Fishery managers and researchers can use climate information to infer causes of changes in fish populations and to study a variety of physical, chemical and biological marine processes. Even the shipping of perishable goods may be made more expeditious by the proper use of climate information. Contingency planning in many forms makes use of information collected about climate over ocean areas. Examples of applications include the planning of responses to environmental emergencies such as oil-spills, search and rescue operations, and calculation of the cost of insurance against inclement weather for sports and other media events.

Past climate information also has applications to climate forecasting. It appears that although deterministic prediction of weather by numerical modelling is not practical for periods of more than a week in most circumstances, it may be possible to infer the characteristics of weather "averaged" over a month or a season through a foreknowledge of climatic parameters such as the distribution of water temperatures, land and sea ice or snow, and soil moisture. In some instances, the climate system remembers something of the climate weeks to years before, and is influenced by it. The El Niño-Southern Oscillation (ENSO) phenomenon is an example of such an occurrence.

### 1.1.1  The need for a *Guide to the applications of marine climatology*

The seas are in common use by all seafaring nations, but each country exerts different levels of control over the

operation of vessels in coastal waters and offshore enterprises exploring for or developing resources on the sea floor. Ownership and control are the subject of intense international negotiations.

Safety of national environmental resources and the safety of nationals operating on offshore structures are the concern of various design operation and engineering codes and practices applied throughout the world. On some of these there is agreement, but on other aspects none.

In order for the various components of the meteorological, oceanographic, engineering and regulatory community to co-operate effectively on an international scale, accepted practices must be established for the preparation and application of the marine climatological information. Because of its nature as a co-ordinating body for international meteorology, WMO can provide a lead in the establishment of accepted practices.

It is the purpose of this *Guide* to highlight and provide an unbiased assessment of current practices and databases used in marine climate applications, and to document their limitations. Moreover, it is hoped that this *Guide* could eventually develop into a basis for a common ground for the provision and incorporation of climate considerations in marine engineering design, contingency planning and regulation.

It is also recognized that improvement is always possible, and thus the methodologies described in the *Guide* should be seen as a starting point for the development of better techniques/methods for using marine climate information.

### 1.1.2 Organization of the *Guide to the applications of marine climatology*

While the applications of climatology to ocean transportation and to structures are the obvious reason for the creation of a *Guide to the applications of marine climatology*, these areas do not comprise the sum total of all such applications. There are similarities in applications, however. Fisheries, recreation and many other ocean-based activities use the same data and share many of the same techniques in the development of analysis products. Analysis and statistical techniques are shared with many other branches of science and engineering applications. There are nevertheless some geographical considerations which differentiate the relative importance of some climatic parameters.

The *Guide* naturally begins with an introduction to marine climate applications and the reasons for their importance. The chapter which follows discusses the significance of climatological elements and their relative importance to marine operations and the design of structures. The basis for all knowledge of the climate offshore is the observational record provided through conventional weather and sea-state observations [1] and other sources of data such as remote sensing and models. Chapter 3 reviews the sources of these data, their characteristics, quality and limitations. Because the data arising from ships of opportunity are a keystone for all

other data and analyses, these data are discussed in detail – in particular the history, limitations, quality-control aspects, and sources of data holdings. These observations, however, do not necessarily translate directly into the kind of information required by some applications. Many applications rely on hindcast information, which is inferred from the direct and remote-sensed observations through models. Hindcasting and the special data considerations concerning tropical storms and storm surges also appear in Chapter 3. Although it would not be possible to provide details on all aspects of marine applications, some of the more common applications are described in Chapter 4. While most of this chapter is general in nature, some of the examples provided are quite specific, and this is simply due to the fact that the *Guide* is made up of contributed materials from many Member countries. Much of the analysis, presentation and interpretation of climatological data is held in common with other climate, engineering and hydrological applications. Many of the statistics and techniques described in Chapter 5 are therefore a repeat of those materials found in other WMO sources. The effective presentation of marine climate information is also discussed in this chapter. For the marine environment, however, at least two aspects are covered in somewhat greater detail: the analysis of extremes for engineering design applications, and the analysis of persistence. Both of these are crucial for offshore design and safe, efficient operations. The last two chapters of the *Guide* discuss the geographical factors which influence climatological applications around the world, and the respective practices and relationships of Member countries *vis-à-vis* access to marine data and products. Specific examples of some analysis examples and additional techniques are found in the appendices to the *Guide*.

### 1.2 HISTORICAL PERSPECTIVE OF MARINE CLIMATOLOGICAL APPLICATIONS

The application of marine climate information has for centuries been recognized as important to the safety and economics of offshore operations. In its most primitive form, climate knowledge was simply the retained experience of the seasoned mariner, which was sometimes imparted as guidance for the apprentice shipwright or junior officer. The knowledge of what winds, weather and sea state could be expected was sometimes a carefully guarded secret among mariners in the earlier centuries of this millennium. With time, the accumulated observations found in ships' logs became a valuable commodity, especially for vessels enduring long ocean voyages. The "ritters" of Dutch sailors were particularly valuable because of their habit of frequently and dutifully recording weather wind and sea conditions in their passage over the world's oceans. Eventually, with more sophisticated navigation techniques, and because of the growing needs of such interests as shipbuilders, insurance and classification societies, the kind of information which could be handed down by ships' captains and their guilds was outgrown. The regular measurement and recording of marine

observations was adopted on a more scientific basis: wind force estimates based on the Beaufort scale became more or less universal by the 1800s, and various atlases such as that of Maury came into existence. There has always been a considerable degree of scientific and intellectual curiosity regarding conditions which occur at sea. Concerted efforts at piecing together available climate information for strategic operations occurred during war years. However, it was not until the 1960s, when offshore oil exploration intensified, that much attention from civilian authorities was brought to bear on this science. In many countries the development of marine climate applications greatly accelerated during the energy crises of the 1970s. Although world energy prices have stabilized at lower levels since then, the development of offshore hydrocarbon resources and transportation systems has continued. In order to build these systems to perform both economically and safely, governments and commercial offshore interests realized that a sound understanding of all aspects of the marine environment was needed. The development of offshore energy and frontier transportation systems hastened the study of marine climates and its engineering applications, particularly in the harsh climates of polar regions.

Simultaneously with these industrial and resource developments, there was an increased awareness in many societies of the hazards associated with these relatively new ventures, and of the fact that the developments put environmental resources at risk. Governments and the developers of energy and transportation systems responded to the public's perception of these risks by developing regulations for planning, development and operation of offshore structures, and for contingency planning in the event of spills, blowouts or other environmental emergencies.

With the shortages in world food supplies in recent decades, and through such events as the collapse of the anchovy fishery off Peru and the rise and fall of sardine and other fish stocks throughout the world, came the realization that it was necessary for governments to strive to understand and intelligently manage marine food resources. Awareness of climate variations, climate change and the importance of monitoring climate in order to understand its relationship to abundance of marine life has increased considerably. Many countries now monitor the marine climate in the hope of better understanding the relationship of climate to marine food resources, and thus managing this resource more effectively. The Second World Climate Conference [2] recognized that climate change was a common concern for all mankind, and that there was a need for a Global Climate Observing System (GCOS) and the development of a global ocean observing and data management system for improving predictions of climate change and climate monitoring.

### 1.2.1    Benefits of marine climate applications

One of the earliest documented calculations of the benefits derived from the application of marine climate

information is attributed to the use of "The Wind and Current Charts" developed by Maury, and first published in 1847. The use of these charts by mariners shortened the passage time between major trading centres by many days. Then, as now, time equalled money, and the savings to commerce were estimated at many millions of dollars in the currency of that time.*

Nowadays many nations equip their mariners with charts and sailing directions much more elaborate than the charts developed by Maury, and the knowledge of climate used by the mariner is retained through an extensive programme of formal education. Ship-routeing services in many Member countries provide climatological, forecast and real-time weather information for the benefit of the mariner.

Climate information is used in the design of ships and offshore structures. Without adequate information, these structures might have to be made unusually robust. In applying climate information for design purposes, there is a constant trade-off between economy of design and safety. It has been calculated that eliminating one metre from the height of the extreme wave used in the design of an oil exploration rig reduces the cost of building the facility by three million US dollars. The costs of underdesign are even greater. Each one of these structures costs hundreds of millions of dollars, and many lives would be lost in the event of its destruction during a storm.

### 1.3    RELATIONSHIP TO OCEANOGRAPHY

Meteorological and oceanographic sciences have developed interactively. The distinction between oceanography and meteorology becomes blurred as regards the sea surface. Both meteorologists and oceanographers have intensely studied the exchanges of energy occurring through the sea's surface. Our understanding of the nature and physics of processes taking place there is due to the combined effort of scientists from both communities, and it is recognized that close co-operation exists on an international scale also — e.g. between WMO and the Intergovernmental Oceanographic Commission (IOC). The oceans are an integral part of World Climate Programme activities. The marine climate applications described here spring from the international co-operation efforts of WMO, IOC, their Members, and scientists and engineers of the international marine community.

Just as one may consider elements such as the wind, temperature, humidity and other weather elements to distinguish the climate of the atmosphere, ocean currents, temperatures, salinity and other variables define a climate of the oceans which is intimately linked over various time scales to the atmospheric climate.

* The Earl of Harrowby, Address of the President, British Association for the Advancement of Science, Report of 24th Meeting, Liverpool, 1854 [(London, 1855) pp. lv–lxxii, esp. lx, lxii]; and Hunt's *Merchant Magazine* XXX (1854) [531–547, esp. pp. 546-547].

Essentially, this *Guide* is concerned with the climatology of the marine atmosphere and closely related oceanographic variables such as sea state and sea-surface temperatures. To a large extent the data for such a climatology are those which are internationally exchanged, archived and made available to the users under the WMO Marine Climatological Summaries Scheme (see the *Manual on Marine Meteorological Services*, WMO-No. 558). A similar data exchange and archival scheme has been established under the IOC for oceanographic data (physical, chemical and biological). This is the International Oceanographic Data and Information Exchange (IODE) system, under which all oceanographic (and some related meteorological variables) are exchanged and archived in a common format, the so-called GF-3. Further information on the organization and operation of IODE may be found in the *Manual on International Oceanographic Data and Information Exchange* [3].

## 1.4 PLANNING, DESIGN AND POST-MORTEM PHASES OF APPLICATIONS

Climatic information is used in many phases of an offshore venture, but basically its use can be categorized into three types of supporting activities — planning, development and/or post-mortem applications.

Climatic information used for planning is usually associated with the definition of the most likely and most extreme operating conditions to be endured by a system offshore. Planning information answers the questions ("what is it like?", "how strong?", and "how long?") asked by planners, engineers and regulators concerned with offshore structures and operations. Information used for planning provides estimates of feasibility and cost.

Climatic information used in development is attuned to questions concerning the conditions which can be expected to occur, the frequency with which favourable or unfavourable conditions might predominate or persist for critical phases of construction or operations.

Post-mortem applications can arise when planning and design information is incorrect, or the unexpected occurs, and in cases of inadequate planning. The penalty for inadequate design or preparation in offshore areas can be costly in terms of lives and equipment. Post-mortem applications of climate data are used to determine what went wrong, the meteorological and oceanographic conditions leading to failure and, ultimately, who is to assume liability for losses.

## 1.5 DATA FOR CLIMATOLOGICAL APPLICATIONS, SOURCES AND PROCESSING

The ultimate source of marine climate information is observations of the marine environment. Most of these still arise from measurements or estimates taken aboard ships of opportunity and a few weather ships. Increasingly, measurements are being taken from buoys, and the climate elements are remotely sensed

from satellites. Additional information is obtained when these observations undergo analysis. Objective analyses, as applied in initializing numerical models, often use a forecast field as a first-guess input field for analysis, and this procedure eventually introduces reasonably reliable information into geographical areas where no actual observations exist at the time of analysis. Similarly, the hand-produced product of the experienced analyst introduces useful prognostic information into areas where observations would otherwise be non-existent. Hindcasts, objective analyses and forecast fields are all useful in marine climate applications.

Marine weather observations are exchanged over the Global Telecommunication System (GTS), and some countries capture these data directly from the GTS. These data and the data submitted by mariners using special weather-log books comprise the primary source of climate information for climate applications offshore. The data are exchanged internationally under the WMO Marine Climatological Summaries Scheme. They are subjected to varying levels of quality control by Member countries and then archived by Responsible Members of WMO for their respective areas of responsibility. So important have these data become for applications and climate research that some Members have exchanged data through bilateral means and possess global databases of these observations. The holdings of data and data-exchange practices are discussed in more detail later in this *Guide*.

Additional data from satellite observations are held by some Members for selected ocean areas and times, but these data are more experimental in nature and are not generally exchanged or used for climate applications offshore. One major exception, however, is the use of satellite temperature and cloud information for climate monitoring applications. This is a near-real-time activity whose success and effectiveness are greatly dependent on remotely sensed information. However, in future, remotely sensed data on winds, sea states and other ocean environmental parameters will probably be routinely available in some Members' meteorological and oceanographic services, and perhaps exchanged internationally. If and when these data become available in archives, they too may find use in most marine climate applications.

Probably most useful, particularly in the design aspects of climate applications, is information synthesized from analyses and hindcasts. Wind and wave hindcasts and analyses are now used almost exclusively in designing offshore structures. The techniques used in developing accurate and consistent wind fields to be used directly in design or for driving wave models are covered in detail in subsequent chapters. The physics of the wave models which are used for hindcasting is discussed in lesser detail, as the use of wave models is the topic of another guide, but a brief discussion is included here on their properties, since they are an important source of climate data for the marine environment.

## 1.6 FACILITIES FOR CLIMATOLOGICAL DATA ARCHIVAL

Much of the raw data on which marine climate applications depend is obtained through data exchange by WMO Members under the Marine Climatological Summaries Scheme (MCSS) (see Chapter 3, Fig. 3.10). As the scheme was originally conceived, Responsible Members would archive data received from Members and prepare summary charts for each respective area of responsibility. The summary charts were intended as preparation for an ocean component of a World Climatic Atlas from which a number of applications could be satisfied. However, the capabilities of data-processing equipment have increased greatly, while the cost of data processing and data media has fallen dramatically since the MCSS was first proposed. Decadal summaries are still being produced by some Members. Moreover, Members have produced numerous atlas products, and the data exchanged have grown to be of greater value by themselves than the original atlas objective. As a result, WMO decided that it no longer needed to publish a world ocean atlas, but continues to support the data exchange objective of the MCSS because of its importance for co-ordinating the exchange of marine climate data and monitoring climate variation and change over the world's oceans.

Recently global climate research programmes such as TOGA and WOCE have collected their own special data sets for their experiments. Eventually, these will also become available for applications.

Some Members now have global databases and repertoires of software with which to access and analyse these data. At the time of writing, the databases are still large enough and the required computer resources great enough for only very large mainframe computer systems to be used for data management and analysis. However, possibly even by the time this *Guide* is published, microcomputer hardware and software capable of the scale of processing described here will be generally available. The WMO's CLICOM system [4] may have the potential to grow to be capable of this task, and would thus make the applications described here practical with very limited resources.

### References

1. World Meteorological Organization, 1991: *The accuracy of ship's meteorological observations — Results of the VSOP-NA.* WMO Marine Meteorology and Related Oceanographic Activities Report No. 26, WMO/TD-No. 455.

2. WMO/UNEP, 1990: *Climate change — The IPCC scientific assessment.* Cambridge University Press.

3. International Oceanographic Commission, 1980: *Manual on international oceanographic data and information exchange.*

4. World Meteorological Organization, 1988: *WMO World Climate Data Programme, CLICOM Reference Manual, Version 2.1.*

# CLIMATOLOGICAL ELEMENTS AND THEIR SIGNIFICANCE
# TO OPERATIONS AND DESIGN

## 2.1 GENERAL

The interests of the offshore hydrocarbon industry encompass a wide range of activities: geophysical surveys, design and operation of fixed and dynamically positioned exploration and production platforms, airborne logistic support, sea-bed and overland pipelines, siting and construction of liquefaction plants and port facilities, design and routeing of marine transportation, and possible oil-spill movement, containment and clean-up. In general, the impact which could result from a meteorological condition depends on its severity and on the sensitivity of a particular activity or operation to that condition. Similarly, meteorological phenomena can make recreational activities and the work of fishing and shipping fleets much more difficult. Some conditions, such as high winds, waves and the building up of ice from spray, constitute a serious threat to the safety of navigation and may lead to accidents and, occasionally, to the loss of lives and ships. Such a range of interests means that nearly every element of climate needs to be considered in one phase or another of any offshore operation. Nevertheless, there are certain elements which are of particular concern.

## 2.2 WIND

Wind, both direction and speed, is the most important climate element, particularly for the roles it plays with other climate and related elements. For example, wind interacts with water currents in the movement of sea ice and oil spills, with sea ice in wave generation, with air temperature in wind chill and air quality, with air and sea-surface temperature in structural icing and with cloud and visibility in determining flight limits. In itself, wind has important impacts for the design of exploration platforms with respect to the siting of flaring, cargo handling, the helideck, module access and general deck layout so that optimum relative positioning can be determined. With such a wide range of influences, it is clear that wind has an impact on every phase of offshore and related operations.

Of all atmospheric parameters, wind presents the greatest potential risk to offshore activities. Knowledge of the climatology of wind speed, direction, profile with height, and character (i.e. gustiness) is very important to an assessment of hazards to safety. The wind may exert considerable force on a structure such as a drill rig, vessel or aircraft. Since the force exerted is proportional to the square of the wind speed, extreme winds are especially critical. The wind speed alone will probably not be sufficient to affect the survivability of either rigs or vessels, but may be critical to helicopter operations, rescue procedures and personal safety on account of structural damage of components. High winds also create dangerous working conditions for personnel on exposed decks. In addition to its direct effects, the wind is also the major forcing factor in generating waves, which usually produce the predominant loads on offshore structures, and currents. It is a major factor in producing wind chill and mechanical turbulence, and in generating spray icing.

Due to its importance, wind is reported by almost all marine observing systems. Ships report wind information more frequently than any other parameter, except pressure. However, these reports are made under a variety of conditions. While many observations are visual estimates, measurements are taken using anemometers positioned in widely varying locations on ships, with associated effects of superstructures on wind flow. Dobson [1] has produced an excellent review of problems associated with wind measurement at sea.

Wind data from transient ships are of highly variable quality. Most wind reports from these ships are estimates based on the sea state. Studies show, however, that, on average, transient ship data do represent the synoptic wind field reasonably well [2, 3]. The results of the Voluntary Observing Ships Special Observing Project for the North Atlantic (VSOP-NA) [2] do suggest systematic differences between Beaufort (visually) estimated and measured winds.

Weather ships have provided the most reliable source of wind data over the ocean. Winds are measured using standard equipment by experienced observers. Instrumentation is as well sited and maintained as possible, although there are undoubtedly some effects from the ship superstructure. Weather-ship data are an accepted standard against which other data sets are compared. Unfortunately, such data are scarce. The wind data cannot be extrapolated far from the observing site, and most weather ships have now been decommissioned.

Wind data received from drill rigs are plentiful over short periods of time, but the massive superstructure may have significant effects on the airflow in their vicinity. The height at which anemometers are frequently installed on rigs to minimize interference from the superstructure (50–100 m) leads to inflated values of the wind speed relative to speeds at 10 m, on account of the decrease of frictional effects with height. Moreover, under stable atmospheres the wind may be decoupled completely from the flow at the surface.

Satellites can provide important information on the distribution of winds over the ocean. The

SEASAT-A scatterometer demonstrated the capability to estimate wind direction to within 16 degrees and wind speed to ≈1.6 m s⁻¹ [4].

Land-station wind measurements are not representative of over-water conditions, because of the increased frictional effects on the airflow caused by the rougher land surface. Diurnal changes in stability also have a great influence on surface winds over land. Studies of wind speed ratios (over water/over land) typically show mean ratios of 1.5–1.6, although considerable variability exists. At higher wind speeds ratios may be about 1.2, while for lower speeds ratios may exceed 2.0. Because of the influence of local roughness and topography at the observing site, each observing site must be calibrated individually. Moreover, the winds thus obtained should be considered representative only for distances which are relatively small compared with synoptic scales. Properly applied, wind ratios are useful for near-shore applications.

## 2.2.1    Averaging period

Most marine winds have been observed according to the WMO guidelines or their equivalent. Historically, measured marine winds were taken as one-minute mean values, but guidelines now specify that measured winds should be ten-minute mean values. The one- and ten-minute means represent the average wind speed for the one- or ten-minute period on the hour of the observation. This is widely assumed to represent the hourly mean speed. In reality, most measurements are probably made over a shorter interval, averaging the highest and lowest values.

The averaging period associated with estimated winds from ships will probably differ, depending on the method of estimation. If wind speeds are estimated from the relative measured wind, then the averaging period is assumed to represent a ten-minute mean wind (assuming that the apparent wind is averaged over ten minutes); however, if the estimates are based on the state of the sea, then the averaging period is dependent on the time required to bring the sea to its present state, and the fetch. The method of estimation is rarely known when using historical data, so the actual averaging time is always uncertain.

Hindcast winds have no averaging period associated, since they represent instantaneous values of the pressure gradient field. However, hindcast winds are usually calibrated to some "surface truth" data, such as ship or buoy observations, and in that respect should be considered to have similar averaging period characteristics. Similarly, satellite winds represent instantaneous values of a spatially-averaged wind. Dobson [1] discusses averaging periods in considerable detail.

## 2.2.2    Reference height

A commonly accepted, although not universal, reference height for winds over the ocean is 19.5 m. This is simply an assumed average height for ship anemometers.

Over land, 10 m is the standard measurement height. Relatively few wind observations are actually made at 19.5 m, other than by a few weather ships. Most ships' anemometers are located between 15 and 25 m [5], but rig measurements are made at a wide variety of elevations, ranging from about 50 to 120 m above the sea surface. Even on the same ship, the height can vary somewhat due to the loading of the ship. With rigs, the height can vary depending on whether the rig is at drilling or survival draught. Hindcast data have no associated reference height, but are empirically adjusted through boundary-layer models supposedly to represent a specific level, e.g. 19.5 m. Satellite data are similarly "calibrated" to that height. The adjustment of all these data sets is an empirical process which assumes an average vertical wind speed based on the wind speed and the stability. Individual profiles can vary greatly from the average, giving rise to a large measure of uncertainty in the wind estimates. Profiles are generally assumed to be logarithmic or to be represented by power law relationships with height. All of these formulations increase the wind profile with height, but in certain instances the surface (i.e. 19.5 m) wind may actually exceed the wind speed aloft. Dobson [1] and Shearman [6] describe vertical wind profiles and reduction techniques in detail. A critical review of techniques for reducing winds to a common reference height appears in Shearman and Zelenko [7].

## 2.2.3    Wind gusts

The wind is not steady but fluctuating. It is composed of a mean (background) component and a fluctuating (gust) component. The mean wind is generally taken to be some value obtained by averaging the wind over a period ranging from one minute to one hour. The averaging period is selected in order to generate a statistically stable mean wind speed. It is assumed that the processes generating mean flow have time scales longer than the period chosen for averaging, although this may be questionable for one-minute means or even ten-minute means under some circumstances [8]. Wind gusts represent short-duration fluctuations in wind velocity. Averaging periods for gusts are typically one second to ten seconds, since they aim to represent a peak, transient effect.

The gust factor is a simple method of comparing gust to mean wind speed. It is usually defined as the ratio between maximum gust speed (of duration $t$) over a given time interval $T$ to the mean wind speed computed over the same interval:

$$G(t/T)$$

where $t$ is the gust averaging interval, usually 1–10 seconds;

$T$ is the mean wind speed averaging interval, usually 1–60 minutes.

For example, $G_{(1\ second/60\ minutes)} = 1.2$ implies that the maximum one-second wind speed average during one

hour is 20% larger than the mean wind speed over that same hour.

Gust factors depend on mean wind speed, stability, measurement height and surface roughness, as well as on the averaging intervals $t$ and $T$.

Specific ratios of interest used by the UK Meteorological Office for the calculation of gusts over the open sea at the standard height of 10 m are [9]:

$$G_{(3 \text{ seconds/10 minutes})} = 1.30$$
$$G_{(3 \text{ seconds/60 minutes})} = 1.37$$
$$G_{(15 \text{ seconds/10 minutes})} = 1.21$$

Observed values for $G(3 \text{ seconds/60 minutes})$ at coastal stations in the UK are about 1.5.

Wind gusts are never reported in marine observations, and information on gusts is available only from land stations, moored buoys and a few limited experimental data sets from research vessels and ocean platforms. In general, however, the properties of gusts observed over land may not be applicable to the marine environment.

### 2.2.4 Wind stress

Wind stress is often of greater importance than wind speed for certain applications. Mean zonal and meridional components of the wind stress are computed from the formulae given in (2.1) and (2.2) below:

$$t_u = rC_D |u| W i \qquad (2.1)$$

$$t_v = rC_D |v| W j \qquad (2.2)$$

where $t_u$ is the zonal ($i$) wind stress vector in N m$^{-2}$;
$t_v$ is the meridional ($j$) wind stress vector in N m$^{-2}$;
$r$ is the air density in kg m$^{-3}$;
$C_D$ is the drag coefficient (typically 0.0015);
$u$ is the zonal component of the wind in m s$^{-1}$;
$v$ is the meridional component of the wind in m s$^{-1}$;
$W$ is the wind speed in m s$^{-1}$;
$i$ is the unit vector in the i (east-west) direction;
$j$ is the unit vector in the j (north-south) direction.

## 2.3 WIND WAVES AND SWELL

Wind waves (or more simply waves) are generated by the local and sustained action of winds on the water surface. Swell refers to waves which have propagated into an area from a generating area some distance away.

The fundamental design criteria for offshore drilling platforms require wave height and period information, particularly the largest wave that may be expected on average in a period of 50–100 years. There is increasing interest, however, in smaller waves which may continue over long periods of time and contribute to accelerated structural fatigue problems. Although height is of primary concern, certain structures respond more strongly to certain wave periods than others, and thus climatological information on the wave period, together with height, needs to be considered in design and

planning. The direction of wave patterns is also of concern since savings of five per cent or more of the quantity of steel used can be made by placing a suitably designed platform in the optimum direction [10]. For some purposes a complete directional spectral representation of the sea surface is required to compute response characteristics and stresses. Wave breaking is also a major cause of damage at sea. Wave generation is basically a function of wind and its duration, geography and water depth, and may be further complicated by the presence of sea ice. Ice tends to reduce the available areas of open water over which waves may be generated (fetches) and in itself acts as a damper on wave action in the vicinity of ice edges. A more complete description of the theory of waves and their effects can be found in the WMO *Guide to wave analysis and forecasting* [11].

Wind waves have significant effects on the headway vessels can make, how fast fish can be found and caught, how productive loading and unloading operations are, and on the transfer of fishing catches to factory ships and other operations. For example, the safety regulations on vessels of the former Soviet fishing fleet stipulated that when wind speeds reach 15 m s$^{-1}$ or when wave heights are over 4 m, SRT-type vessels (medium fishing trawlers) should cease to make way or should stay in port. SRTM-type vessels (medium fishing trawler-refrigerators) and BMRTs (large refrigerator fishing trawlers) have their work curtailed, and catches cannot be transferred to factory ships. When wave heights reach about 6 m (wind speeds over 17 m s$^{-1}$) processing of the catch on board factory ships ceases and SRTMs, BMRTs and RTMs (fishing trawler-refrigerators) stop fishing.

Winds over 33 m s$^{-1}$ and wave heights over 8 m are very hazardous for vessels of any tonnage, and all kinds of work cease except for safety measures.

## 2.4 TEMPERATURES OF AIR AND SEA

### 2.4.1 Air temperature

The minimum, maximum and variability of air temperature and temperature gradient are important to the selection of materials for equipment used in drill rig operations, since many materials lose much of their strength or toughness (resistance to fracturing due to a blow) in very cold or very warm conditions. Extreme temperatures, either warm or cold, can reduce the efficiency and accident-avoidance capability in workers exposed to the elements, due to incipient hypothermia or, at the other extreme, heat stroke (see section 2.6.1 on Humidex). Heating, cooling and ventilating the working and living space is important, not only for the well-being of personnel, but also for the operation of electronic control facilities. Air temperature is also a contributing factor to wind chill and spray icing.

Air temperature is usually measured by a mercury or alcohol thermometer, properly shielded from direct solar radiation by means of a louvred screen.

Remote thermistors or thermocouples may also be used. On land, air temperature measurements are taken at a height of 1.2 or 2 m above the ground. At sea, the measurements may be taken at any height, from the bridge of a ship to the deck of an oil rig. Most land-based thermometers can be properly sited to avoid the effects of heat sources; the same does not apply at sea, however. Siting is a major source of error in air temperature measurements at sea. Air temperature is not usually subject to large variations in a given area of the marine atmosphere. Therefore, a few observations, if well distributed, can describe a considerable area of ocean. Exceptions occur in the vicinity of coastlines, fronts and areas of strong surface temperature gradient, such as the Gulf Stream.

Air temperature is now recorded in degrees Celsius and tenths; however, some historical data were originally measured in degrees Fahrenheit and then converted. Moreover, some temperatures were reported only to an accuracy of whole or half degrees.

### 2.4.2 Sea-surface temperature

Minimum, maximum and variability of sea-surface temperature (SST) and temperature gradient are important in the selection of materials for equipment used in drilling operations, since many materials lose much of their strength and toughness in very cold or very warm conditions. Because of the risk of hypothermia, a sea temperature of 10°C is the critical limit for survival of personnel in the water, without adequate protection (see Figure 2.1).

For example, the survival time of a man in water of 0°C is of the order of 15 minutes [12]. The variability of sea-surface temperature is much less difficult to define than that of air temperature, since for
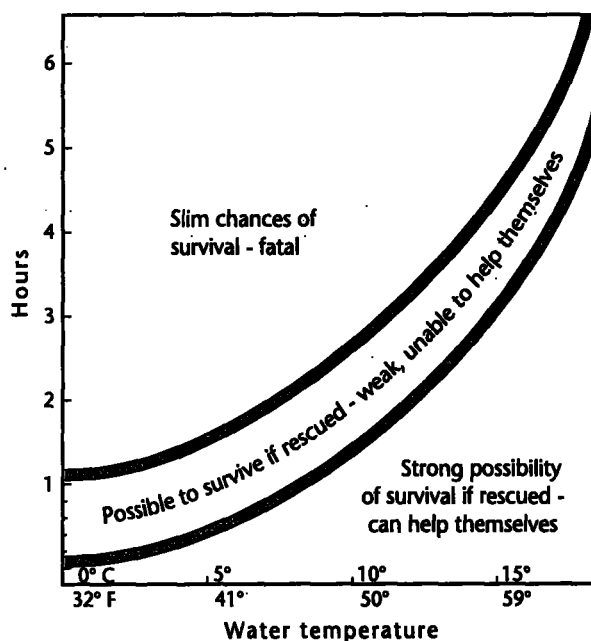


Figure 2.1 — Cold water survival chart

normal sea water the minimum value attainable is about −1.8°C, after which ice forms. Also, due to the immense heat capacity of water, the range of temperatures observed is only about 35°C. Sea-surface temperature is a minor factor in sea-spray icing. Spray icing is relatively insensitive to sea-surface temperature provided air temperatures are cold enough; however, it has been generally found that icing is less severe where sea-surface temperatures are >6.0°C.

When sea-surface temperature is measured by the bucket method, a special container is lowered over the side and immersed to obtain a sample of water. The bucket is immediately retrieved and the water temperature of the sample is then measured on deck. This is a source of variation, since it is difficult to determine to what depth the bucket has gone down. Readings may vary considerably from the surface layer to a depth of a few metres. On most ships and rigs, the sea-surface temperature is measured by a thermometer in the engine water intake or by a hull contact sensor which can be at a considerable depth below the surface. Moreover, the intake or hull contact sensor may not be at a standard, or even consistent, level because of variations in ship loading. Temperatures may also be affected by the heat from the engine room. The relative accuracy of SST measurement techniques was evaluated under the WMO/IOC VOS Special Observing Project for the North Atlantic (VSOP-NA) [2]. The VSOP-NA report concluded that hull contact measurements were to be preferred over bucket and intake measurements.

Present satellite systems are able to produce reliable estimates of sea-surface temperature at a much finer resolution. However, the sensors employed are passive infra-red radiometers, which do not have the ability to penetrate cloud. Limited data may be available from microwave radiometers, which are not much affected by cloud. Spatial resolution is much reduced, however, and the resulting averaging may cause difficulties where temperature gradients are steep, such as in the Gulf Stream. Sea-surface temperature may be subject to considerable spatial variation, particularly in the vicinity of strong current interaction zones such as the Gulf Stream/ Labrador current. The present density of observations from conventional sources is inadequate to describe the complex sea-surface temperature patterns exactly.

### 2.4.3 Wind chill

Extreme values of wind chill and frequency of wind chill above certain thresholds are very important considerations in northern locales. Wind chill is a function of wind speed and air temperature, which combine to produce excessive heat loss from everything exposed to the elements. Hypothermia and frostbite may result from wind chill in a very short time, impairing work efficiency and thus increasing accident likelihood. The heavy clothing necessary to withstand the cold also contributes to the possibility of accident. High values of wind chill will also reduce human survival time in the water.

Wind chill is defined as the rate of cooling, in watts per square metre, of any exposed surface. It is usually calculated according to the method of Siple and Passel [13]. In this method, the wind chill $H$, in watts per square metre, is given in equation (2.3) as a function of the wind speed $V$, in metres per second, and air temperature $T$, in degrees C.

$$H = ((100V)^{1/2} + 10.45 - V)(33-T)/0.86 \quad (2.3)$$

This wind chill assumes a neutral skin temperature of 33°C. The original calculations were based on the rate of cooling of water as a function of air temperature and wind speed. However, the index does offer a useful indication of the relative degree of discomfort experienced by the human body in cold weather. Wind chill values of 1500 W m$^{-2}$, typical in winter in northern locales, would result from a wind speed of 20 knots and an air temperature of −10°C. Wind-chill values greater than 1600 W m$^{-2}$ can cause exposed flesh to freeze. For estimating cooling values on ships, etc., this formula would not be appropriate.

### 2.4.4 Structural cooling

Structural cooling is an important issue in the offshore areas of the polar regions. Such cooling results from exposure of steel structural elements to low ambient temperatures, which may persist for days or even months at a time. Drilling platforms and shipping activities are equally susceptible in this regard. Certain port facilities such as cranes involved in moving cargo are also at risk. High wind chill will also stress (unless designed for) the heating plants of rigs, vessels and aircraft. The chilling of ship hulls may also have important consequences for design and selection of structural materials, as the strength and toughness of these may be reduced.

Cold temperature alone is enough to cause brittle fracture in steel which has not been manufactured to perform under such conditions. Of greater concern, however, is the effect that such cooling can have when combined with some other environmental load − for example, the possibility of encountering severe ice conditions in the form of either multi-year or heavily ridged first-year floes or icebergs is a major threat to drilling platforms or ships. Steels used in such structures and designed to withstand certain extreme ice conditions may fail in less severe ice conditions if the structure is or has for a prolonged period been exposed to low temperatures. Wind, of course, may play an important role in hastening structural cooling at a given air temperature. An example of an index that may be used to give a measure of combined wind-temperature cooling is the following, suggested by Transport Canada [14]:

$$I = -v^*T_{air} \quad \begin{array}{l} T_{air} \leq 0\ ^\circ C \\ v \geq 1\ km\ h^{-1} \end{array}$$

$$= -T_{air} \quad \begin{array}{l} T_{air} \leq 0\ ^\circ C \\ v < 1\ km\ h^{-1} \end{array}$$

$$= 0 \quad \begin{array}{l} T_{air} > 0\ ^\circ C \\ v = any\ value \end{array}$$

where   $I$  = cooling index;
     $v$  = surface hourly wind speed (km h$^{-1}$); and
     $T_{air}$ = surface air temperature (°C).

This sort of index is useful, for example, for comparing the relative magnitude of the problem posed by wind-caused cooling within two or more geographical areas.

Generally, greater strength and thickness are features of the steels used in polar marine applications. Such characteristics can be determined fairly quantitatively with regard to the sort of mechanical loads likely to be encountered in those regions. When it comes to the resistance characteristics of steel to cold temperatures, however, there is considerable variability, the inconsistent properties of the parent metal and weld being the major factors contributing to the loss of strength or toughness in a cold environment. As a result, a probabilistic approach to determining the failure criteria is necessary. Thus, costly overdesign is more likely to arise through safeguarding against a particular cold-temperature failure than through guarding against a specific ice load.

Lloyd's Register of Shipping [15] calls for a design temperature for the selection of hull steel grades for operation in low ambient temperatures to be determined as follows. Where reliable, recorded environmental data exist, the design temperature will be the lowest temperature obtained after the exclusion of all values having a probability of occurrence of less than 3 per cent. In the absence of such data, the design temperature will be calculated as the minimum recorded temperature plus 5°C. Table 2.1 lists design temperatures based on the former criterion for several areas of the Canadian Arctic.

TABLE 2.1
Design temperature (°C)

| Area | Feb. | May | Aug. | Nov. |
|------|------|-----|------|------|
| Queen Elizabeth Is. | −49 | −24 | −7 | −43 |
| Beaufort Sea | −47 | −22 | −5 | −38 |
| Lancaster Sound | −44 | −22 | −5 | −37 |
| Davis Strait | −38 | −16 | −3 | −28 |

While ship-hull design to counter cooling remains very much a matter of correct steel selection, other structures make use of different solutions. The composite steel/concrete approach offers a cost-effective alternative to steel alone that allows thinner steels to be used as well as fewer welds, the latter reducing somewhat the uncertainty in the cold-temperature aspect of the design. Other positive benefits appear to include increased resistance to brittle failure resulting from combined low temperatures and high rates of loading, as well as low natural frequency, which inhibits resonance effects with ice or wave loadings.

## 2.5　　ICING

### 2.5.1　General

Icing is the process of ice accumulation on a surface from either freezing spray, supercooled fog, freezing precipitation (rain or drizzle) or wet snow, or a combination of these phenomena. Ice build-ups from these sources can be a significant hazard for vessels, structures and aircraft operating in the marine environment. The stability of ships and drilling platforms can be adversely affected by heavy ice loads. In addition, ice accumulations can immobilize safety equipment, interfere with communications and create hazardous working conditions. Helicopter operations are extremely dangerous in icing conditions; even relatively small amounts of ice on the rotors can dramatically degrade flight performance.

There has been considerable debate as to the relative importance of the different ice-accretion mechanisms for ships and offshore structures (e.g. [16]). However, summaries of available vessel icing reports indicate that freezing spray is the most frequent and most severe cause of ice accretion offshore. Freezing precipitation events are less frequent and less severe offshore because of the warming effect of the sea as air moves over it. While atmospheric icing is less of a problem for shipping, it is of great concern for aircraft operations, e.g. search and rescue and helicopter support of offshore oil exploration activities. Open bodies of water have the potential to increase the risk of aircraft icing in the cold season through increased vertical fluxes of heat and moisture to the overlying air. In addition, the frequency of encountering freezing precipitation is often increased in coastal regions where moist onshore airflows encounter sub-freezing surfaces.

Spray icing can occur anywhere where cold air and open water coexist. These conditions are most frequently found in waters adjacent to continental land masses or sea ice, which are the source areas for outbreaks of cold air. Some examples of areas with a well-documented spray icing hazard are the waters off the east coast of Canada, Barents Sea, Bering Sea, Gulf of Alaska, Baltic Sea, Sea of Japan and Sea of Okhotsk. Spray-icing conditions are most frequently experienced in winter in mid-latitudinal waters, and in the autumn in polar waters subject to a seasonal ice cover. Atmospheric icing of vessels and structures is generally confined to coastal waters. Further information on each of the accretion mechanisms is provided below.

### 2.5.2　Freezing spray

Freezing spray is the most dangerous form of icing encountered at sea, and accounts for around 90 per cent of ship icing reports [17]. Spray ice can accrete at rates in excess of several centimetres per hour, and is difficult to remove because of its hardness and strong adhesion. Potential freezing-spray conditions occur when open water, high winds and cold air temperatures coexist.
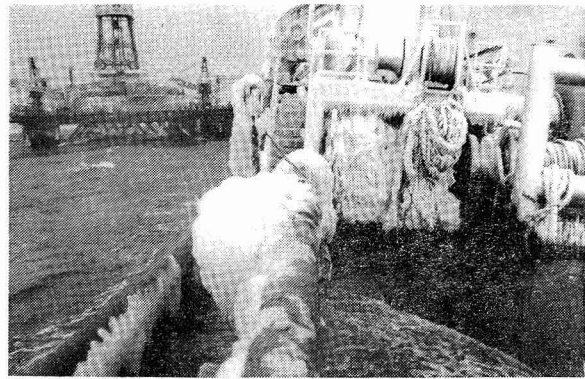


Figure 2.2 — Ice accretion on a supply vessel operating off the east coast of Canada (*Photo: Wayne Emberley*)

In these conditions, a portion of the spray intercepted by a vessel or structure will freeze to form a layer of ice. It is generally recognized that spray generated by wave impact with a vessel or structure (wave-generated spray) is the dominant source of liquid water for the freezing spray process. Nevertheless, it is possible that wind-generated spray from tearing of wave crests under high wind-speed conditions may play a significant role in the icing of stationary structures.

The rate of ice build-up from freezing spray depends on a number of complex meteorological, oceanographic and vessel parameters. These affect the two main components of the icing equation: (*a*) how much water is arriving, and (*b*) the rate of heat loss at the icing surface. The spraying process is controlled by a particular vessel's spray-making characteristics, the sea-state conditions, and vessel speed and heading. Vessels usually generate most spray when headed into the waves, and minimum spray when running with the waves. Vessel size is also an important factor in icing rates as the average liquid water content of wave-generated spray decreases exponentially with elevation. Most of the spray is confined in a 5–10 m range above sea-level, which means smaller vessels are exposed to considerably more spray than large ships or drilling platforms. There are few documented cases where spray icing has reached the deck level of drilling platforms and interfered with operations. However, under extreme environments, significant spray icing can reach elevations over 30 m above sea-level. This happened to the drilling platform "Ocean Bounty" in Lower Cook Inlet, Alaska, where over 500 tonnes of ice accumulated, requiring drilling fluids to be discharged to maintain stability [18].

The main parameters involved in the freezing process are air temperature, wind speed, sea-surface temperature, sea-surface salinity and relative humidity. The freezing process is most sensitive to variations in air temperature and wind speed, as both exert a strong influence on the heat loss from an icing surface. Wind speed also affects the amount of spray intercepted by a surface through its influence on sea

state. Significant icing usually requires air temperatures below −5°C with wind speeds above 25 knots. The strong sensitivity of spray icing to these two parameters is the main reason why simple nomograms such as that of Sawada [19] can be used to obtain reasonable estimates of spray icing potential. A discussion of the possible techniques for estimating icing potential is given in section 3.3.1.

There is conflicting evidence about the importance of sea-surface temperature. However, the most recent physical icing models confirm the conclusion of Shellard that icing is relatively insensitive to sea-surface temperature less than about +8°C. Theoretically, there is no upper sea-surface temperature limit to spray icing. However, severe superstructure icing has rarely been reported where sea-surface temperatures exceed 6–8°C. As noted by Shellard [16], sea-surface temperature has an important indirect effect on icing through the warming of air as it passes over the ocean. Salinity affects the freezing process by determining the freezing temperature of the spray (−1.8°C is a typical value for most open ocean waters), as well as by influencing the latent heat of fusion and the saturation vapour pressure. Shellard indicated that salinity was relatively unimportant. However, recent physical models suggest that salinity is the next most important variable after air temperature and wind speed. Relative humidity affects droplet and water film cooling, but has only a minor impact on icing rates.

In the northern hemisphere, the characteristic synoptic feature for spray icing is an outbreak of cold wind in the rear of a depression. The particular wind direction associated with spray icing conditions depends on the location of the source area for the cold air; e.g., off the east coast of Canada, the outbreaks usually come from the west-north-west, while in the Baltic Sea they come mainly from the east. Because the cold air is warmed as it moves out over the ocean, most cases of vessel icing occur within a few hundred nautical miles of the coast. Spray icing is not usually accompanied by atmospheric icing, especially freezing precipitation, which forms under quite different meteorological conditions. However, spray icing and evaporation fog ("sea smoke") can co-exist near the coast or ice edge during a strong, cold outbreak. Brown and Roebber [20] also noted that more than 60 per cent of vessel icing reports in Canadian waters noted snow showers or squalls during spray-icing events. These result from the thermal instability induced when cold air is moving over the much warmer sea surface, and may contribute to ice accumulations.

In reality, the icing process is infinitely more complex than the simplified picture painted above. Variations in spraying and heat loss over a vessel's superstructure lead to significant variations in ice-accumulation rates with elevation and exposure. This is one of the dangers in severe spray-icing conditions: ice accumulates more rapidly on rigging and spars, dramatically increasing a vessel's potential to capsize.

## 2.5.3 Freezing precipitation

The basic requirement for freezing precipitation is a freezing layer near or at the surface, through which droplets fall and become supercooled. These conditions are not frequently encountered over open water because of low-level heating of cold air, which reduces the risk of sub-freezing layers forming at the surface. However, freezing precipitation can be quite frequent close to the coast or pack ice during offshore flows in winter. The frequency of freezing precipitation events decreases rapidly away from the coast, and coastal stations should not be used to infer icing conditions farther offshore.

Offshore, freezing precipitation events are relatively infrequent, short-duration phenomena that are more of an operational nuisance than a major hazard, i.e., they create slippery work conditions, but are unlikely to result in heavy ice loads. From an analysis of ship icing reports, Brown and Roebber found that maximum accumulations from freezing precipitation never exceeded 5 cm. Panov [21] indicated that freezing precipitation offshore was experienced in a quite narrow temperature envelope (−5°C to −2°C) with "weak winds". However, more recent studies have shown that freezing precipitation can be experienced over a very wide range of temperatures (as low as −20°C) with wind speeds of up to 20 m s$^{-1}$.

While freezing precipitation may be only a nuisance offshore, it can be a major disruption for aircraft operations in coastal areas, particularly for helicopters. An estimate of the relative magnitude of the aircraft icing problem can be obtained by mapping the frequency of occurrence of freezing precipitation reports from ships and from airport locations used to support offshore aviation activities.

## 2.5.4 Supercooled fog

Supercooled fog can form from two mechanisms: (a) evaporation fog, also known as "sea smoke", when the air is very much colder than the sea; and (b) fog forming when a relatively warm, moist air mass moves over a water surface with a sea-surface temperature below that of the air's dew point and below 0°C (advection fog). While it has been suggested that the sea-air temperature difference must be greater than 9°C for evaporation fog or sea smoke to form, its onset is also a function of relative humidity. Hence, the sea-air difference can range from 3 to 15 depending on the relative humidity of the air. This information is presented in diagrams by Makkonen [22]. The height of the fog layer is also important as evaporation fog can range from a wispy surface layer to dense stratus cloud up to 100 m above the sea surface. Fog depth is related to mixing rates in the surface boundary layer which depend on temperature, relative humidity, stability and wind speed. A discussion of techniques for estimating fog depth is given in Makkonen. Sea smoke is more likely to be

found close to the coastline or ice edge because of the modifying effect of open water on the cold air moving over it.

Since supercooled advection fog requires the sea-surface temperature to be below 0°C, it is by definition confined to oceans with cold, saline water or over an ice pack. Conditions most conducive to the formation of supercooled advection fogs are found in areas with seasonal pack ice, just after spring break-up, and prior to freeze-up. Maps of supercooled fog frequency for the northern hemisphere presented in [23] confirm that supercooled fogs are seldom met at sea except in the vicinity of northern coastlines and ice edges. The amount of water contained in supercooled fogs is usually quite low, so a vessel needs to be exposed to these conditions for a long period to accrete appreciable amounts of ice.

### 2.5.5    Wet snow

Wet snow accretes on a structure when snowflakes covered with a thin film of water strike a surface and adhere to it. The requirement for a liquid water film means that wet-snow is usually associated with surface air temperatures in the range of 0°C to +2°C. Heavy, wet snow accretions require high snowfall intensities (typically greater than 10 mm h$^{-1}$) coupled with strong winds in the order of 10-20 m s$^{-1}$. The wind produces packing forces which accelerate snow densification and the formation of grain boundaries. Resulting accretion densities can approach glaze ice, e.g. 700-900 kg m$^{-3}$. It has been observed that large wet-snow accumulations form only on small-diameter horizontal wires and cables where the snow deposit is able to rotate and form a cylindrical accretion by sliding around the surface, or from torsional twisting of the cable. If an object is fixed, or if sliding is prevented, the accretion is more easily broken and blown away by the wind [22]. This suggests that shipping and offshore structures with generally large, fixed surfaces are unlikely to experience significant wet snow build-ups.

### 2.6    HUMIDITY

Humidity has relatively little effect on most drilling or vessel operations. There may be some discomfort however, and a resulting health hazard with high humidities accompanying high temperatures (see section 2.6.1). Also, some sensitive electronic equipment may be affected by constant high humidity. High humidity may be important in shipping for its potential damaging effect on cargo, particularly when coupled with cold sea-surface temperatures, which results in hull and cargo sweating. Painting operations may be adversely affected by high humidity, and the durability of some paint coatings reduced. High humidities are accompanied by high concentrations of airborne salt, since salt particles provide the major source of condensation nuclei in the marine atmosphere. Due to the ready moisture source, humidity is frequently very high at sea. High humidity is a major contributing factor to fog formation.

Relative humidity can either be measured directly or be computed by psychrometry from the measurement of the air temperature and wet-bulb temperature (using a thermometer from which water is evaporated until equilibrium is reached with the atmosphere). The methods and problems associated with air temperature measurement are described in the preceding section. Additional problems may occur with improper maintenance of the wet-bulb thermometer, and in deriving the dew-point temperature and relative humidity from the two measured temperatures via tables. Direct measurements, using hair hygrometers for example, are fairly reliable if the instrument is well maintained; psychrometric measurements are superior, however. Siting is important for all humidity sensors. The instruments should not be exposed to heat or moisture sources. Humidity is usually high over the ocean. However, relative humidity values can rarely be extrapolated over large areas, due to the differences in air temperatures caused by varying sea temperatures. The presence of precipitation will also cause local humidity differences. Data are not archived as humidity values, but are represented by either wet-bulb temperatures or dew-point temperatures.

The vapour pressure $e$ of the air is computed from observations of air and sea-surface temperature, and dew-point temperature. In actual fact, three vapour pressures may be computed: the actual vapour pressure of the air $e$, the saturation vapour pressure for the ambient air temperature $e_a$, and the saturation vapour pressure of air which has the same temperature as the sea surface $e_s$. One equation used to calculate the three vapour pressures is shown in equation (2.4), where the temperature $T$ (in K) is selected according to the desired vapour pressure (hPa). The ambient air temperature is used to calculate the saturation vapour pressure of the air. The dew-point temperature is used to calculate the actual vapour pressure of the air. The sea-surface temperature is used to calculate the saturation vapour pressure of air at the same temperature as the sea surface. In the following equations, $T_1 = 273.16$K, the triple point of water. The subscript w refers to saturation vapour pressure over water; the subscript i refers to saturation vapour pressure over ice. The formulae are in conformity with the WMO *Technical Regulations* (WMO-No. 49). The following equation is based on data which have been experimentally confirmed only in the range 0°C to 100°C, but the same formula can be used for saturation vapour pressure over supercooled water in the range -50°C to 0°C with, as far as is known, insignificant error.

$$\log 10\, e_w = 10.79574\,(1 - T_1/T) - 5.02800 \log 10\,(T/T_1)$$
$$+ 1.50475 \times 10^{-4}\,[1 - 10 - 8.2969\,(T/T_1 - 1)]$$
$$+ 0.42873 \times 10^{-3}\,[10^{4.76955\,(1 - T_1/T)} - 1]$$
$$+ 0.76814 \hspace{3cm} (2.4)$$

When the air temperature is less than 0°C, the saturation vapour pressure may take on one of two

values, depending on whether it is taken over water or over ice (the latter leads to supercooling of water droplets). The following equation gives the saturation vapour pressure over ice, in the range of 0°C to –100°C.

$$\log 10\ e_i = 9.09685\ (T_1/T - 1) - 3.56654\ \log 10\ (T_1/T) \\ + 0.87682\ (1 - T/T_1) + 0.78614 \qquad (2.5)$$

The relative humidity is calculated according to the formula:

$$RH = e(\text{dew point}) / e(\text{air temp}) \times 100\% \qquad (2.6)$$

The vapour pressures and humidities are usually derived parameters based on the air, sea and dew-point temperatures. Thus they are subject to the same kinds of errors in measurement.

### 2.6.1 Humidex

Warm temperatures accompanied by high humidities can produce considerable discomfort and, in the extreme, are a hazard to health. Marine operations are affected when physical exertion becomes unpleasant and frequent rest periods become necessary under high humidities and temperatures. Air-conditioning and extra ventilation systems may be necessary for some operations in excessively hot and humid regions. Additional and extensive information on discomfort indices and on climate and human health in general can be found in the WMO publication of the same name [24].

Temperatures of 27–30°C are comfortable in still air with light or no clothing when at rest. This is the neutral point. With physical exertion however, or at higher temperatures, a human body's internally generated heat will cause its temperature to rise. The body's response is to increase circulation to the skin, raising its temperature, and to cause sweating to occur so that the body may be cooled through both sensible and latent heat transfers to the air. With high humidities, the rate of evaporation of sweat is restricted and less heat may be lost from the body's surface. For the same high temperatures, therefore, one will experience greater discomfort with higher humidities. Physical exertion under high heat and humidity can result in heat exhaustion and cramps and then heat-stroke if the body is not cooled. Normally, a body cannot continue to maintain equilibrium with temperatures above 32°C and 75% relative humidity [25]. Figure 2.3 shows man's physiological response to heat and humidity.

Effective temperatures [26, 27] are a useful measure of human comfort and were used for determining air-conditioning needs, but are difficult to secure from meteorological data. Thom developed a Discomfort Index calculated as follows:

$$DI = 0.4\ (T + T_w) + 15 \qquad (2.7)$$

where $T$ = dry-bulb temperature (°F);
$T_w$ = wet-bulb temperature (°F).

The *DI* closely approximated the effective temperature scale used by the former American Society of Heating and Air Conditioning Engineers (now ASHRAE) [28].

Lally and Watson [29] also developed a formula for quantifying the discomfort associated with high temperatures and humidities, but theirs better reflects the cooling effect of skin evaporation. This "Humidex" and its application were described by Thomas [30] and Anderson [31] and later revised to incorporate metric temperatures [32]. Humidex is computed as follows:

$$H\ (\text{Humidex}) = T + h \qquad (2.8)$$

where $T$ = dry-bulb temperature (°C);
$h = 5/9\ (e - 10)$;
$e$ = vapour pressure (hPa).
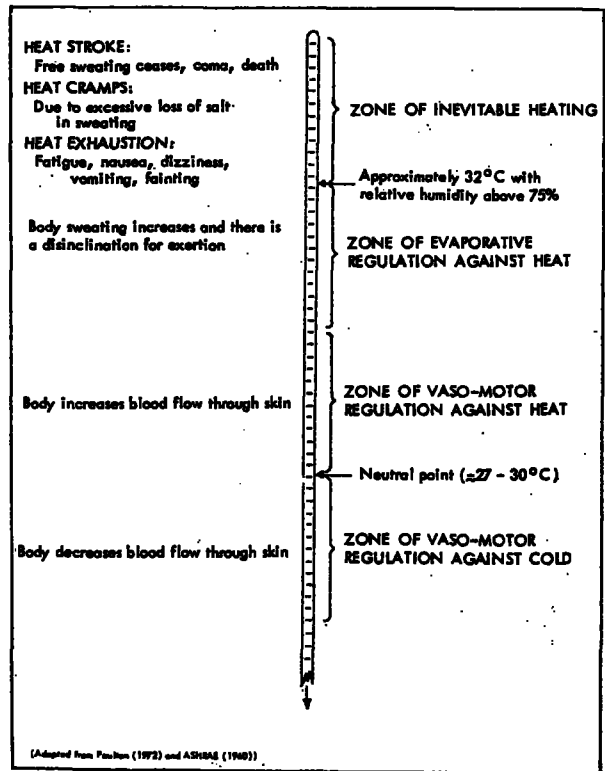


Figure 2.3 — Man's physiological responses to excessive heat and humidity

Strictly speaking, the Humidex is dimensionless, but to facilitate an understanding by the general public, °C is normally included. Table 2.2 below relates this index to human comfort.

**TABLE 2.2**
**Humidex related to comfort**

| Range of Humidex | Degree of comfort |
|---|---|
| 20–29 | Comfortable |
| 30–39 | Varying degrees of discomfort |
| 40–45 | Almost everyone uncomfortable |
| 46 and over | Most labour must be restricted |

## 2.7    VISIBILITY

Visibility may be reduced due to fog and/or precipitation, particularly snow. Other restrictions to visibility may occur; for example, in dust storms off desert coasts and less frequently in haze or smoke.

Visibility is, by definition, a visually estimated parameter. In meteorological reference the prevailing visibility is the highest visibility common to more than half the azimuthal circle. It is estimated by referring to markers at specific distances from the observing site. Because most land stations have numerous reference points, visibility information is quite reliable, although estimates at night are more difficult. There are few markers available for most ship observations, other than the ship itself; however, waves are frequently used as indicators. Estimates from large ships in low visibility are apt to be better than estimates from small ships. Only visibilities less than about one mile are important for most activities; one-half mile is critical for helicopter operations.

Observations from rigs may be more reliable due to the large size of the rig, which may also have special visibility markers attached. In low visibility a supply vessel attendant to a rig may jockey its position to the limit of visibility from the rig and report the distance indicated by the radar. Visibility estimates at night are very difficult from rigs on account of the brightness of deck and rigging lights. Instruments exist which, while they cannot measure visibility, measure the optical transmissivity of the air, which can then be related empirically to the visibility.

Transmissometers are common at airport locations, but are included in few automatic weather stations. In good weather, visibility is usually quite uniform over large areas. However, with precipitation or fog present, visibility may vary considerably with distance and over time. With precipitation, particularly snow, visibility may be reduced substantially over small areas. This is especially true in showery precipitation over the ocean. Low visibility due to precipitation does not generally persist for long periods. It can usually be expected to occur with similar frequency over a large area. However, the occurrence of fog is closely linked to the sea-surface temperature, and thus may vary considerably in space, and show preferred locations.

At sea, visibility is reported by coded values ranging from 90 to 99. The visibility ranges in kilometres corresponding to the codes are given below. The coding of visibility estimates into discrete ranges means that precise values for visibility are not available from ship observations.

Visibilities of under four kilometres, although not in themselves hazardous for shipping operations during the day, do reduce manoeuvrability. Visibilities of less than one mile, however, are hazardous for navigation and fishing. When visibility drops below a kilometre, vessels of 300 to 500 tonnes dead weight stop work, and

when it drops below 200 metres it is hazardous not only for moving vessels but also for vessels at anchor or lying to. Reduced visibility may also contribute to collisions between vessels, drill rigs and icebergs.

| Visibility code | Visibility range (km) | | |
|---|---|---|---|
| 90 | | | <0.05 |
| 91 | 0.05 | – | <0.2 |
| 92 | 0.2 | – | <0.5 |
| 93 | 0.5 | – | <1.0 |
| 94 | 1.0 | – | <2.0 |
| 95 | 2.0 | – | <4.0 |
| 96 | 4.0 | – | <10.0 |
| 97 | 10.0 | – | <20.0 |
| 98 | 20.0 | – | <50.0 |
| 99 | | | >50.0 |

The joint occurrence of visibility greater than 4 km and wind speed less than 25 knots is often referred to as "good shipping weather" in some ocean areas.

The presence of low cloud ceilings and reduced visibilities also make flying dangerous. Specific operating limits are required for take-off and landing and visual flight rules (VFR) for travel en route.

## 2.8    PRECIPITATION/THUNDERSTORMS

Rainfall, in general, is not a serious problem, although low visibility may result and decks may become slippery. Also, discomfort or hypothermia may result from wet clothing. Cloudbursts associated with thunderstorms, however, may cause equipment to be swamped if the drainage design is inadequate. Techniques for measuring and mapping precipitation at sea have been reviewed by several authors, e.g. Austin and Geotis [33], Browning [34] and Spenser [35]. In addition, the lightning associated with thunderstorms can be dangerous, since the masts and derricks tower above the water surface. Both heavy rainfall rates and lightning can cause disruption of radio transmissions. Lightning poses a serious hazard to aircraft operations, and may create problems at a drill rig if gas is being burned off at the time. Lightning would also be a serious hazard to exposed personnel in the water.

Snow and freezing precipitation are much more important. Both are of major concern in ice accretion (see section 2.5.5). Additionally, snow may reduce visibility and ceilings.

Precipitation observations at sea are mostly visual estimates, categorized as light, moderate or heavy. They are reported and archived in the "present weather" code of the marine reporting system. There is very little information on short-duration, high rainfall rates, which are likely to affect drainage and radio transmission.

Thunderstorms (and hence lightning) are reported and archived in the "present weather" code portion of the marine or land record only when thunder

is heard. Noisy, air-conditioned offices, and the noise of drilling operations, may impair the detection of thunder. Instruments are available to detect and locate lightning using the electromagnetic radiation generated by a lightning stroke. Indeed, a simple radio may serve as a lightning detector. However, detection may be impaired aboard a rig due to interference from the structure and electrical interference by motors and equipment.

Precipitation measurements are not recorded in ship-based archives. The only indication of precipitation is in the present weather codes. Based on these codes, the following definitions may be adopted:

• *Light rain/drizzle* — present weather codes 50–61, 66, 80, 91 and 68, 83, 93 if air temperature > 5°C;

• *Moderate/heavy rain* — present weather codes 62–65, 67, 81, 82, 92 and 69, 84, 94–99 if air temperature > 5°C;

• *Light snow* — present weather codes 70, 71, 76–79, 85, 87, 89 and 68, 83, 93 if air temperature < 5°C;

• *Moderate/heavy snow* — present weather codes 72–75, 86, 88, 90 and 69, 84, 94–99 if air temperature < 5°C;

• *Freezing precipitation* — present weather codes 56, 57, 66 ,67, and 50–55, 58–65, 68–69, 80–84 if air temperature < 0°C;

• *Hail* — present weather codes 89, 90, 94, 96, 99;

• *Thunder* — present weather codes 13, 17, 19, 29, 91–99.

It should be noted that hail is frequently misreported, particularly in northern latitudes, where it is confused with graupel, ice pellets and snow pellets.

## 2.9    CLOUDS

Aircraft operations may be severely curtailed due to the presence of low cloud, since certain cloud-ceiling limits must be maintained for safe take-off and landing and during VFR travel en route to avoid mid-air collisions. Low cloud ceilings frequently occur simultaneously with reduced visibilities.

Two aspects of clouds are particularly significant in marine climatology, the total cloud amount and the ceiling height (i.e. the altitude at which the total low or medium cloud opacity is at least five-eighths). The cloud amount is of minimal importance in marine activities. It is universally observed visually and, during the day-time at least, is one of the highest-quality observations. At night, cloud cover can be very difficult to detect, especially on oil rigs with the constant glare of very bright lights.

Cloud heights are more difficult to observe. Heights may be estimated, or measured by aircraft, balloon or ceilometer. Ceilometers are used at many land stations; ships and rigs are not so equipped. Balloon measurements from rigs are not always reliable, since improper filling techniques and launching procedures are frequently used.

Only low cloud ceilings are usually important, i.e. below about 500 ft. Since the top of a drill-rig derrick is usually 70–100 m (230–330 ft) above the sea surface, reasonable estimates to this height should be possible. Some automatic stations are also equipped with ceilometers.

Most cloud ceilings in good weather are uniform over a large area. Therefore, a limited amount of data spatially is not critical. Exceptions apply in the vicinity of atmospheric discontinuities such as fronts. Also, the critical low ceilings due to fog or precipitation vary considerably in space, due to the showery nature of precipitation and the dependence of fog on the underlying sea-surface temperature. Snow showers can usually be expected to occur with similar frequency over a large area. Fog, however, tends to have preferred locations.

The cloud information reported by ships consists of the total cloud amount, the amount of low cloud, the height of the lowest cloud present, and codes for the types of low, middle and high cloud present. Cloud amounts are given in eighths of the sky covered (oktas), not in tenths as often used for land observations. Sky obscured is coded as 9.

Almost all cloud heights reported by ships are estimated. Cloud heights are not reported exactly, but are given in ten discrete ranges as shown in observing guides.

### 2.9.1    Flying weather

Flying weather is defined by the joint distribution of cloud ceiling and visibility classes to correspond roughly to conventional ranges for Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). Due to the method of recording visibility in ship observations, i.e. in coded ranges between 90 and 99, the exact values of visibility differ slightly from usual values. In addition, the fact that ceiling observations are not made and recorded by ships, and that cloud height estimates are reported in discrete ranges as for visibility, means that the method of determining the ceiling heights and their values is different from usual, although providing the best estimates possible for aviation operating conditions at sea. The uncertainties in visibility and cloud height estimates will probably make the differences insignificant. The following ranges of flying weather obtainable from ships' observations are suggested:

Ceiling unlimited and visibility > 2.2 n.mi;
Ceiling <1000 ft (300 m) and visibility > 2.2 n.mi;
Ceiling <1000 ft (300 m) or visibility < 2.2 n.mi;
Ceiling <600 ft (200 m) or visibility 1.1 n.mi;
Ceiling <300 ft (200 m) or visibility < 0.5 n.mi.

## 2.10    ATMOSPHERIC TURBULENCE

Low-level atmospheric turbulence is related to the wind field and the air–sea temperature difference. The frequent autumn and winter occurrence of cold air passing over relatively warm water will give rise to atmospheric instability due to convection. Also, strong gusty winds, often

with marked directional shifts on a time scale of seconds, frequently occur over the ocean, particularly associated with frontal zones or thunderstorms. These factors can create considerable mechanical turbulence, with rapidly alternating updraughts and downdraughts and highly variable wind loads. This has little or no effect on rig or merchant vessel safety but is important for sailing vessels and aircraft operations including take-off, landing and airborne rescue.

At sea, turbulence is not usually measured but can be estimated from wind speed and air–sea temperature difference measurements through empirical techniques. Otherwise, turbulence at sea is not great; however, coastlines may introduce strong local circulations and turbulence.

## 2.11  OCEAN CURRENTS

Water currents in association with surface winds play a significant role in the movement of sea ice and icebergs, the importance of which is discussed below. The currents also have an impact on the movement of powered and sailing vessels. Knowledge of this combination is also particularly vital in modelling the movement of possible oil spills and other contaminants. Currents are of strategic importance for shipping and for sailing. Bottom currents are of concern for sea-bed pipelines as they can cause sediment washouts resulting in unsupported pipelines, which consequently become overstressed.

## 2.12  SEA ICE — ICE AND ICEBERGS

The presence of floating ice in the marine environment is significant to marine operation, transportation, and design. There are three types of floating ice of different origins which may be encountered. *Sea ice* is the most common and is formed from the freezing of sea water. *River ice* is encountered in harbours and estuaries and is usually only a minor hindrance to shipping. However, ice jamming can occur, causing bridge and harbour damage and flooding. *Ice of land origin* includes both icebergs and ice islands. Icebergs are a serious hazard in regions where they are common. Ice islands are rarely encoun-tered by shipping because they are restricted to the Arctic basin and Antarctic region, and are few in number.

Ice conditions not only hamper navigation, but can occasionally lead to damage to vessels. Vessels approaching or passing through icy regions must reduce speed, which increases costs and reduces overall voyage efficiency. Icebergs are a major hazard for navigation. Collision may occur in limited visibility or in stormy weather with snowfall if an iceberg appears close to the course of the vessel. Large bergs show up on radar, but growlers (small bergs) are less likely to be identified and thus pose a risk, particularly for smaller vessels. The east coast of Canada is particularly hazardous since the main iceberg flux closely corresponds to the period and area of poorest visibility. Similarly, navigation in southern

polar regions is at risk from icebergs, but there are very little data on their distribution in this area.

### 2.12.1  Sea ice

The presence of sea ice in Arctic waters restricts ship transportation and affects ship safety. With the increased need for shipping in Arctic waters, ice avoidance strategies are not always practical. In some Member countries, elaborate entry rules now exist for various ice-infested marine zones/areas, depending on time of year and ship classifications. These rules are based on accurate knowledge of the ice climatology of each zone.

Ship classifications and hull designs are based on the amount, type and thickness of ice through which a ship can safely navigate. Stationary structures (drill rigs and platforms) which operate in ice-infested waters must also be designed to withstand ice movement and crushing forces.

The most important features of sea ice which affect marine operations are: (*a*) the amount of ice present, i.e. concentration usually measured as tenths of the sea surface covered by ice; (*b*) ice thickness, referred to as stage of development which is related to ice age; (*c*) form of ice, i.e. whether it is fast ice or pack ice, floe size, and the amount of ridging; and (*d*) ice movement. A detailed breakdown of ice terminology and further information can be obtained in the *WMO Sea-ice Nomenclature* (WMO–No. 259).

### 2.12.2  Icebergs

Almost all icebergs in the northern hemisphere are calved from glaciers in Greenland and the northern Canadian Arctic archipelago. Usually they move out into the open ocean under the influence of winds and currents and there they are progressively eroded by warmer seas and the elements. As a result of the strong current moving them southward, icebergs are generally confined to the Arctic waterways off the east and west coast of Greenland and east coast of Canada's "iceberg alley". Icebergs are classified according to size and type (i.e. shape). Their frequency and distribution are monitored by the International Ice Patrol and by various Member countries.

Because of the strong currents, Arctic bergs have high drift velocities and thus pose a major hazard for fixed offshore structures.

Most icebergs in Antarctic waters break off from the large Ross and Weddell ice sheets and then are captured to circulate in the Antarctic Circumpolar Current until they break up and melt. The majority of Antarctic icebergs are tabular in shape. These are generally much more massive than Arctic bergs.

### 2.12.3  Ice islands

Ice islands in the northern hemisphere are very large pieces of ice broken off from large ice shelves, which subsequently move into the Arctic basin from Greenland and the northern Canadian Arctic islands. These ice islands range in size from a few to tens of kilometres in diameter

and and may be from 50 to 100 m thick. The formation of ice islands is a rare event occurring once every few years. In general, ice islands are limited to the Arctic basin and as a result have almost never been encountered by commercial shipping. However, they do pose a threat to Arctic drilling rigs and artificial drilling islands.

In the southern hemisphere, ice islands —like icebergs— break off from the vast Antarctic ice shelves and again are caught in the Antarctic Circumpolar Current. They are generally larger than the ice islands occurring in the Arctic. In 1988, one such island over 6000 sq. km in size broke off the Antarctic Ice Shelf.

## 2.13    STORM SURGES

A storm surge is a short-lived change in water level associated with an intense storm system. These variations in water level are of great concern for the design of some coastal facilities, and for the operation of shipping in shallow waters. The water-level changes are caused by two factors — one being the action of the wind stress acting on an area of relatively shallow water and either piling up the water along a shore (positive surge) or dragging water away from the shoreline (negative surge), and the other being an inverse barometric effect whereby the water levels below a low-pressure area are raised. Tropical cyclones in particular are major causes of storm surges because of their strong winds and deep central pressures.

## 2.14    COMBINED EFFECTS

The joint occurrence of combinations of various meteorological and oceanographic phenomena may create hazardous conditions where their independent occurrence would not. For example, combinations of strong currents, high waves and high winds may create hazardous conditions for rigs and vessels. High winds, with associated turbulence, occurring simultaneously with low visibilities and/or icing conditions will result in increased hazards for helicopters. Very cold air temperatures and strong winds will greatly reduce the expected survival time of persons in the water based on sea temperatures alone, as will high waves. Combinations of meteorological and oceanographic factors may occur, such as high winds, high waves, strong currents, high tides and sea ice or icebergs, probably resulting in far greater risks than the occurrence of one factor alone. Some of these conditions, such as high winds, waves and water levels, are naturally linked by the systems which generate them, as in tropical cyclones.

Various combinations should be considered for critical operating ranges, and their joint frequencies computed.

## 2.15    TROPICAL CYCLONES

Despite the relatively low incidence of tropical cyclones, they are a significant hazard for navigation and other offshore operations, particularly in warm oceans. Tropical cyclones generally form over ocean water warmer than 27°C. When fully developed they are accompanied by mountainous, steep, breaking waves and winds of hurricane force. Wind speeds in tropical cyclones may exceed 160 knots, and the radius of storm winds can extend to 400 miles. Wave heights can exceed 15 m. Because of the extremely low pressures in the eye of the cyclone, water levels are raised, and, when coupled with the wind-induced water-level surge together with high seas, these systems can inflict very serious damage to coastal installations. Useful statistics on these events include their frequency of occurrence within a given area, their movement, and their intensity.

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CHAPTER 3

# SOURCES AND PREPARATION OF DATA

## 3.1 OBSERVED DATA

### 3.1.1 Historical background

For as long as mariners have been maintaining written logs they have been making entries which describe the weather they encounter. This was done for purposes of documentation, out of pure interest in weather events, and because it was felt that the information would prove beneficial for future voyages.

The first meteorological chart, an annual wind chart between 32°N and 32°S, also containing sea currents, was drawn by the English natural scientist and philosopher Halley in 1688. It was published in *Philosophical Transactions* No. 183 as an annex to Halley's essay: "An Historical Account of the trade winds Monsoons, observable in the seas between and near the tropicks, with an attempt to assign the Physical cause of the said winds".

By 1735, when George Hadley hypothesized that the trade winds (trades) are thermally driven, mariners were well aware of the effects of the trades and the doldrums (the low-latitude region of light and variable winds, the so-called horse latitudes) on their sailing capabilities. In 1770, Benjamin Franklin published his graphical Gulf Stream Chart. It provided mariners the information needed either to take advantage of, or to avoid, strong currents which could be encountered on their route. That chart was one of the earliest formal "climatic" navigational aids.

Winds have always been of particular concern to mariners. Over the decades sailors developed wind scales in descriptive terms related to the amount of sail which could be safely carried.

This process evolved into a tool which helped mariners judge their ships' performance. In 1805 Francis Beaufort, at that time a Lieutenant in the British Navy, assigned numbers to the descriptive wind scale and letters to the weather conditions in an effort to simplify the signalling of such information (see Figure 3.1 overleaf). In 1834, his signal code was adopted for general use by the British Navy. The code underwent several changes during the succeeding years. In 1874, the Conference on Maritime Meteorology was held in London and recommended that the Beaufort scale be adopted for general use in meteorological reports [1]. The Beaufort weather notation agreed upon at the 1874 Conference is given in Table 3.1.

During the sailing-ship era, the wind observations (most using the Beaufort scale) were based on the amount of wind in the sails; later, steamship observers based their wind estimates on the state of the sea. While this practice is still common today, many ships are now

### TABLE 3.1
### Beaufort weather notation of 1874

| Code | Condition | Code | Condition |
|---|---|---|---|
| b | Blue sky | p | Passing showers |
| c | Cloudy sky | q | Squally |
| | (detached clouds) | r | Rain (continuous) |
| d | Drizzling | s | Snow |
| f | Fog | t | Thunder |
| g | Gloomy | u | Ugly threatening |
| h | Hail | | sky |
| l | Lightning | v | Exceptional visibility |
| m | Mist | w | Dew |
| o | Overcast sky | z | Haze |

### TABLE 3.2
### Codes added after 1874

| Code | Condition |
|---|---|
| bc | Sky partly clouded (one-half covered) |
| e | Wet air without rain falling |
| rs | Sleet, i.e. rain and snow together |

equipped with anemometers. Winds measured in this way may be biased because of the varying height and location of the anemometers, and the effect of the ship's speed and superstructure on the airflow [2].

In 1842 an American Navy lieutenant, Matthew Fontaine Maury, who was also Superintendent of the Depot of Charts and Instruments, began an effort to produce charts based on ship observations that would aid seamen by allowing them to take advantage of the prevailing winds and currents. Maury encouraged seamen to provide their observations to the Depot and his charts, based on those observations, in return proved very beneficial to the mariners. In fact they proved so successful to the American merchant seamen that they caught the attention of other maritime nations and finally led to the 1853 First International Meteorological Conference in Brussels, Belgium. The purpose of the conference was to establish an international programme similar to the one Maury had established in the United States. The Conference agreed on the need for international co-operation and adopted a standard set of observational instructions and ship weather-log forms. In August 1872, through the efforts of some noted European meteorologists, a preparatory conference was held in Leipzig to make plans for the First International Meteorological Congress, which met in Vienna in September 1873. That

*[handwritten annotation: but WMO was only established in 1950 or 51]*

Congress laid the foundations for the International Meteorological Organization (IMO), which functioned continuously until it was replaced by the World Meteorological Organization in October 1947.

With the invention of the telegraph, it became possible for meteorologists to collect data needed to produce useful synoptic weather charts. Then, in 1896, Marconi invented the wireless telegraph, which made it possible for ships to provide near-real-time observations. By the 1920s, ships were finding wireless weather observations to be useful in constructing simple weather charts which provided information along their routes that was usually good for a day or more.

As of June 1921, the British had established a coded wireless weather report and, in the first issue of *The Marine Observer*, were referencing the reports they were receiving from a limited number of North Atlantic liners in a Provisional International Code. They specified that the 'decode' had not yet been published and, therefore, only the reporting ships in the programme could take advantage of the reports. In September 1929, IMO adopted a world-wide standard for meteorological codes. These became known as the Copenhagen Codes. The British instituted the codes as of 1 May 1930, according to *The Marine Observer*, for wireless telegraph reports from ships at sea to all ships and shore stations.

By the early twentieth century, technology was playing an important role as the collections of historical observations could now be more easily analysed using the Hollerith punched-card electrical sorting and tabulating machine (the forerunner of the electronic computer).

A number of atlases were produced from observations at sea, but Willard McDonald's (1934) was the first ocean atlas extensively to use electronic sorting machines to derive the statistics. McDonald's Atlas, as it is commonly known, was based on 5.5 million individual observations dated mainly between 1885 and 1933, but the distribution of observations was such that analyses could not be performed for the higher latitudes.

The logbooks containing marine observations are held in the archives of the maritime nations and date from about 1854, just after the Brussels Conference, although there are logbooks that date back to earlier periods. In recent years these observations have been digitized and in some cases derived from telecommunications sources to form a digital climate archive. Figure 3.2 illustrates how the digital database has generally increased over the years except during the World Wars and periods of economic depression, where the count decreases significantly.

Although the 1853 Brussels Conference adopted a standard set of observational instructions and ship log forms, most maritime nations continued to record and archive data using their own individual national practices. Exchange of archival data was greatly facilitated in mid-1963 when the International Maritime Meteorological Punch Card (IMMPC) format was introduced by WMO. For earlier years, however, a number of differing codes were used to record marine observations. Many of these differences and their attendant compatibility problems will be discussed in some detail throughout the following sections.
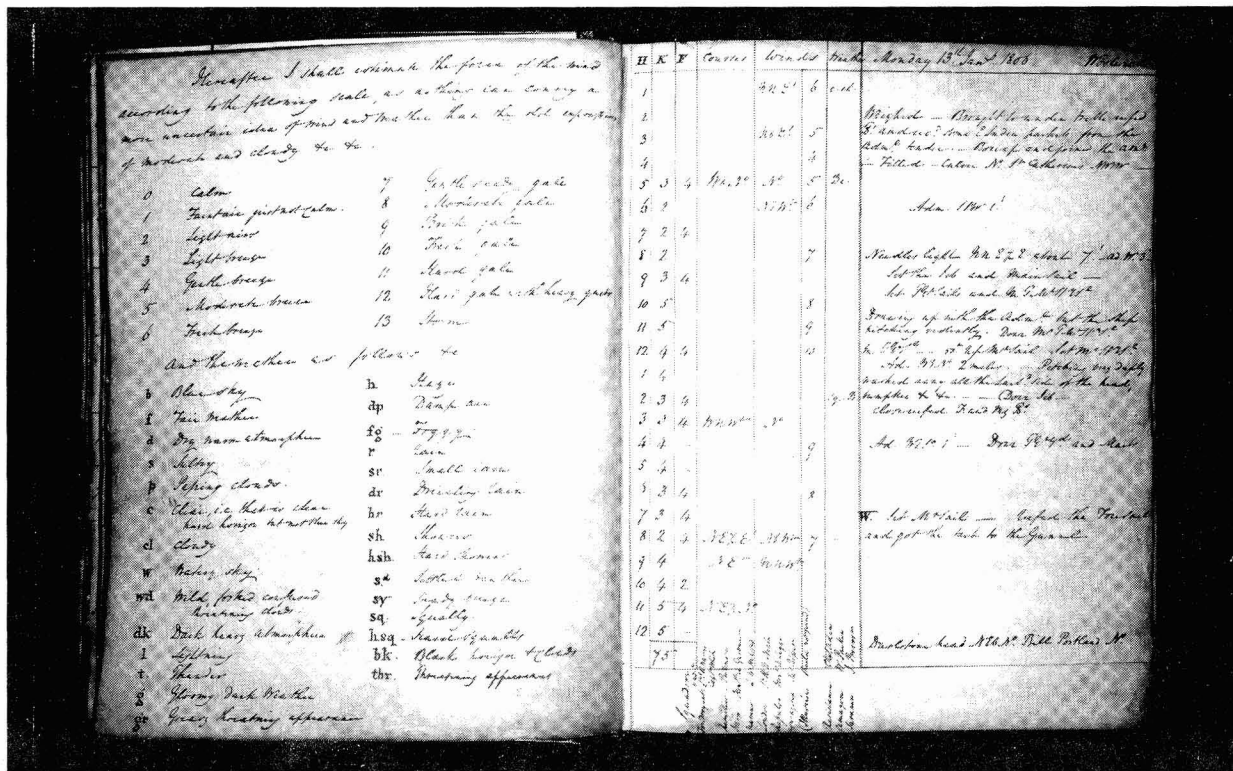


Figure 3.1 – Extract from 1806 logbook of Francis Beaufort showing original wind scale and assigned numbers
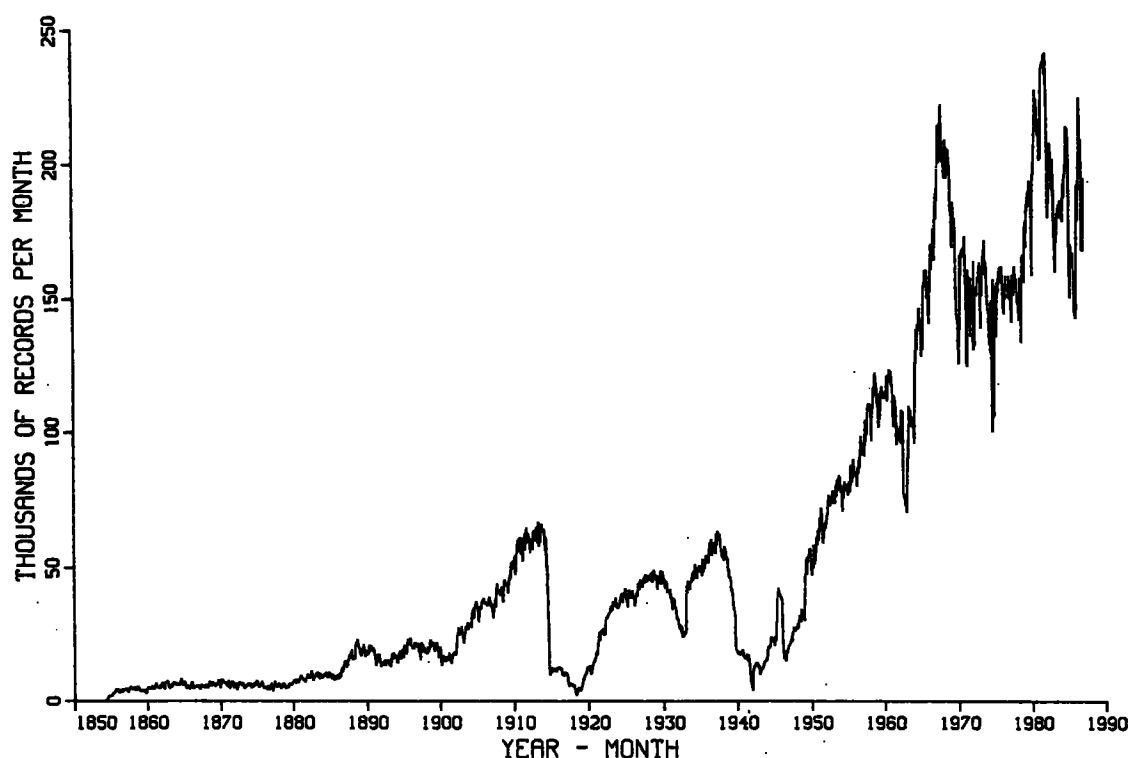
Figure 3.2 – Global marine inventory, total number of observations (from NCDC Marine Data File)

As observations are digitized from older log-books, the information is often converted to match a more recent code. Adaptations of these data to differing codes can cause biases in summaries and analyses, especially if the user is unaware of the history and transformations of the data. Prior to wide use of international codes, observations generally appear in some abbreviated form, with relatively few elements being reported. Digital records of these observations often contain only air temperature, sea-surface temperature, wind direction and speed (Beaufort force), sea-level pressure, and, less frequently, total cloud amount. A survey of about 17 historical reference manuals shows that most data were recorded using the international code in effect at the time: 1921 codes, Copenhagen 1929 codes, and the WMO 1949, 1955, and 1960 codes. With the adoption of Resolution 35 (Cg-IV) [3], there has been a common international exchange code since July 1963, significant changes being introduced in 1968, 1982, 1985, and 1987. As technology continues to change, so will the exchange media as well as the code; data exchange began with punched cards but has now shifted to magnetic tape. In 1988, about half of all available ship observations were received via the Global Telecommunication System (GTS), which became operational at the end of 1972. The GTS links all three World Meteorological Centres (Melbourne, Moscow, and Washington, DC) and the many Regional Telecommunication Hubs under the World Weather Watch Programme. It continues to expand into more geographical regions and to carry more information such as automated reporting station data (moored buoys, drifting buoys, coastal marine stations, etc.). At the present time, the international exchange agreements and the GTS complement each other in increasing the marine observation collection as well as by functioning as quality-assurance mechanisms.

3.1.2    Limitations of data

Data limitations often result from the observational code (temperatures to whole degrees, position to nearest degree, wind scale, wave-period code, etc.) in practice at the time the observation was taken. Complications arise during code changes, and when ships may not have new code books or when earlier codes are being digitized. The intrinsic structure of the collection scheme itself places limitations on both the temporal and spatial distributions of the data as a high percentage of the observations are collected by ships of opportunity. This results in most of the observations being taken along the major shipping routes and for the synoptic times (0000, 0600, 1200, and 1800Z). Radio operator work-shifts and the locations, staffing, and work schedules of land receiving stations complicate factors for real-time data receipt. The resulting data paucity is often a major limiting factor in such areas as the polar regions, most of the southern hemisphere, mid-ocean areas off the main shipping lanes, and other remote areas of the globe.
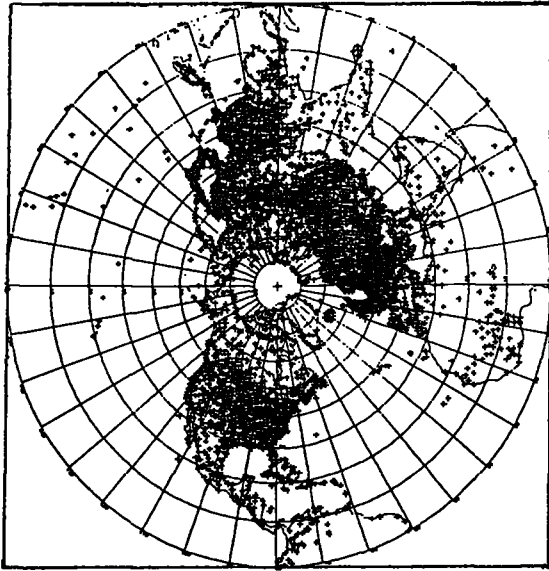
N.H. surface land observations received at NMC Washington
by 0225 UTC, 20 November 1987; observation count = 5106
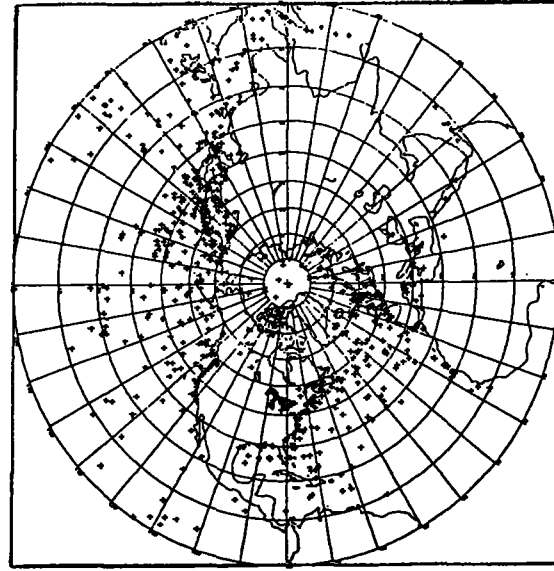
N.H. surface marine observations received at NMC Washington
by 0231 UTC, 20 November 1987; observation count = 968

Figure 3.3

Gerald [4] illustrates (Figure 3.3) typically how much less dense the observations are over oceanic areas when compared with those of land areas in the northern hemisphere. The need to increase the number of reports available in a real-time synoptic mode is important to meteorological forecast centres for their initial analyses and first-guess fields which are needed for their model runs. This information is of equal importance to the climatologist and others for various applications, including climate research. It is hoped that information derived from remote sensing will offer some additional coverage, particularly in less frequently travelled data-sparse areas.

The training and motivation of observers and other data processing staff are important factors which affect the quality of the observations and the final database. Merchant ship personnel generally do not have extensive professional training in weather observing, and that additional duty is reserved for the duty officer of the watch. Because of these circumstances, motivation to take good weather observations may not always be as good as it should be. The lack of training and motivation can sometimes be detected through correspondence and conversations with observers. Also an examination of the original ship logs will sometimes indicate the lack of training by the ways observations are encoded. In a letter published in the *Mariners Weather Log* (1987) some of the common observing practices aboard one ship were highlighted by a third mate. They include: encoding latitude and longitude a half hour or so before reporting time; using a formula to compute "cloud heights", using a wet/dry thermometer mounted on the bridge to determine the entries, instead

of the official sling psychrometer furnished by the port meteorological officer; not always observing the temperature in the shade; and using sea-surface temperature readings from the earlier watch. Practices such as these are not common, but the fact that they do occur will affect the data. Researchers must take care not to extract more information, or use a finer resolution, than that given by the recorded observations.

One must be aware of the inherent data problems to ensure the best results when using surface marine observations for any purpose. Ship data have proved to be quite reliable for climatological studies, as shown by the many successful applications and analyses based on such data. As McDonald [5] wrote in the introduction of the *Atlas of Climatic Charts of the Oceans:*

A careful study of the charts will demonstrate, however, that the observations supplied by seamen have not been careless or perfunctory; otherwise, the seasonal and geographical variations and the interrelations of the various elements would not be so consistently in evidence.

Success of the observation programme is partially the result of the benefits that the mariner and shipping companies receive from climatological and forecast products, and from search and rescue programmes based on the latest fix received via the weather observation.

Many constraints are built into the system because of the limitations of the code. These include the resolution of the observational location; for some earlier data, the ships' positions were coded only to the nearest whole degree, making those observations unfit for any statistical summaries of a finer resolution (tenths of degrees, etc). To obtain a finer spatial resolution, those

particular observations have to be eliminated in order to prevent a distribution bias. This lessens the observational count, probably shortens the period of record, and possibly produces less reliable statistics. Also, one should often consider how dependable the positions are likely to be at the time the observation was taken; this may prevent placing too much credence on too fine a resolution.

Being able to identify the ship that took an observation is useful in identifying duplicate observations, tracking voyages to improve data quality, and determining anemometer heights, ship size, and country of origin. This information-helps to improve data quality and hopefully standardize the reports. However, the radio call sign did not appear in the observational database until the late 1960s and early 1970s, and was not included in the non-real-time International Exchange Code until 1982. Throughout the years, various countries have used internal codes to keep track of a particular ship's observations during the digitizing process, but the documentation was often rather-obscure or lost altogether. Some countries started attaching call signs to digital data for internal identification in the early 1970s, making the non-real-time data compatible with telecommunicated data. However, this information was not available to other countries because of the specifications prescribed in Resolution 35 (Cg-IV) [3]. Adding to the identification problem are the generic call signs such as SHIP, BUOY, RIGG and PLAT that occasionally appear in the marine telecommunications data.

Transient ship observations are not continuous in time or space. Therefore, many statistical applications used for land-based data are not directly usable for marine data. Examples are conventional persistence and extreme-value analyses. Other data and models must be used for such analyses, or different analyses altogether must be applied to describe or estimate climatic conditions. These may include the first

and 99th percentile for a (rough) estimate of extremes, and the per cent frequency of reported precipitation instead of the mean amount of precipitation. Alternative data sources used to develop duration statistics include moored buoys and platforms. These can generally be used only in limited studies because of their relatively short period of record and restricted area coverage. In some locations buoys have been on site almost continuously since the early 1970s. If they continue in place for another decade the record will become adequate for estimating 100-year return period statistics provided the climate does not change significantly. To develop such statistics today, researchers generally turn to either the Ocean Weather Station (OWS) [6] data file or modelled data. OWS reports generally cover the period from the late 1940s until the mid-1970s, at which time they were drastically reduced in number because of their high cost. In some cases, buoy data have replaced OWS records, but they are not homogeneous sources. A few OWSs still remain in operation, but generally not at their pre-1970s location. Ocean Weather Stations have proved to be very important as bench-marks for comparing values from transient ships, modelled data, buoys and for remotely sensed data.

Observation times and the resulting temporal distribution can be a limiting factor, especially in investigating diurnal effects. Folland et al. [7], in their worldwide marine study on temperature fluctuations, separated out the statistics on day-time versus night-time observations in an effort to minimize suspected biases. Two other historical problems include: encoding the observation with only the "watch" (ship-board duty time) for an indication of time; and the biases resulting from the reporting of significantly more day-time observations than night-time ones, especially when considering specific elements such as clouds and visibility. The VSOP-NA results [8] suggest that, even though visual or Beaufort estimated winds are generally biased on the low side in
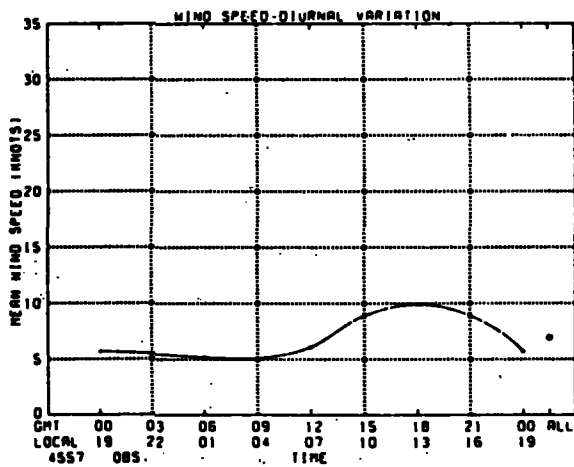


(a) – Westhampton
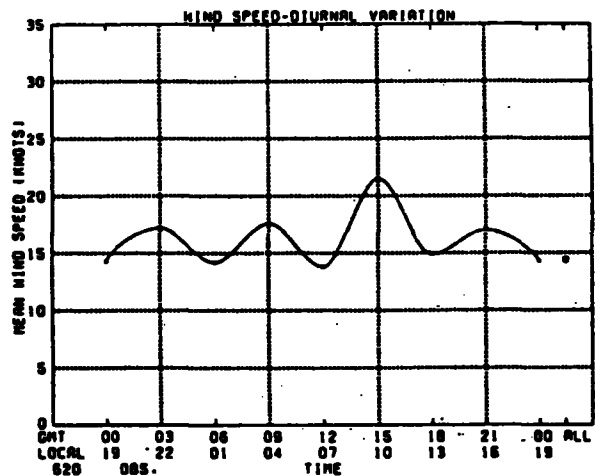
(b) – SE marine area

Figure 3.4 — Diurnal winds

comparison with anemometer measurements, this bias increases at night for winds above 15 knots. This result is attributed to observers not being able to see the roughness of the sea surface well at night.

To show how the temporal distribution of marine observation can affect the diurnal wind speed variation, graphs were selected from Lettau et al. [9]. The first example (Figure 3.4(a)) is for Westhampton, a coastal station with a continuous record of three-hourly observations.

Its diurnal wind pattern is a classical one. Wind speeds decrease during the night, reaching a minimum near sunrise (coolest temperature), and then increase with heating (mixing), reaching a maximum in the afternoon near the time of maximum heating. However, in Figure 3.4(b), where the data came from ships of opportunity passing through a pre-selected representative area, a significant amount of inter-three-hourly variability (noise) appears. This results partly from the decreased diurnal variability of the sea-surface temperature (the water acts as a "flywheel" or "damper" by absorbing heat effectively and re-radiating it more slowly than land) and the variability of observation time. Because of the observational time bias (most ship observations are taken at six-hour intervals) and the lack of continuous observations (random sampling), the resulting noise is accentuated.

Because of shipboard instrument location, motion, and sea-spray problems, transient ships are unable to take quantitative precipitation measurements. A good reference for an in-depth discussion on the subject is the WMO report Precipitation measurement at sea [10]. Some buoy systems are now being tested to see how accurately they can measure precipitation amounts. The lack of observational precipitation data limits the ability of climatologists and meteorologists to estimate precipitation amounts over the oceanic areas with standard techniques, and prevents the accurate computation of global estimates. Estimates generally have to be derived from satellite, radar, or modelled frequency data. Algorithms can be based on ship reports of present weather, the reflectivity readings from weather radars, or radiance measured from satellites. A major difficulty is the lack of "sea-truth" references. Island and coastal station data are of limited use, because they are not true indicators of oceanic climate.

Air temperature is one of the most frequently observed elements and such measurements are generally taken by means of a mercury or alcohol thermometer. Sometimes shipboard instruments are not properly ventilated, leading to a higher-than-true ambient temperature. This is more pronounced in a warm sunny climate such as the tropics. Instrument height above the water also varies significantly, depending on the size and type of ship. This difference is even greater when comparing ships with buoys. Properly locating the thermometers is often difficult because of the superstructure of the ship, or simply because the observers want to be able to read them conveniently.

Historically, air temperatures have been recorded in whole degrees Fahrenheit and to whole, half, and tenths of degrees Celsius. Some of the telecommunicated temperatures have been archived in kelvins. Such values may be misinterpreted after having been placed in a standardized format matching contemporary coding practices. Often, data users incorrectly assume that all values were originally observed to the resolution established for the database format.

Wind speeds have been recorded in Beaufort units, metres per second, knots, and kilometres per hour. The original units and accuracy of the conversions need to be kept in mind, as they may limit the use of the data for certain applications. This is also true for most other observed elements.

In converting the various units to standard units for archiving, a somewhat distorted data distribution may be created. For example, biases in frequency distributions can be introduced when Beaufort-force winds are converted to knots by choosing a central value within the range of the scale, as shown in Table 3.3.

TABLE 3.3
Beaufort to knots conversion

| Beaufort wind force | Beaufort limits in knots | Code value (knots) |
|---|---|---|
| 0 | calm | 000 |
| 1 | 1–3 | 002 |
| 2 | 4–6 | 005 |
| 3 | 7–10 | 009 |
| 4 | 11–16 | 013 |
| 5 | 17–21 | 018 |
| 6 | 22–27 | 024 |
| 7 | 28–33 | 030 |
| 8 | 34–40 | 037 |
| 9 | 41–47 | 044 |
| 10 | 48–55 | 052 |
| 11 | 56–63 | 060 |
| 12 | ≥64 | 068 |

The conversion scale from Beaufort force to knots, presented as Table 3.3, was found by comparing measurements on one of the Scilly Islands with the state of the adjacent sea. It was adopted in 1946 to become the international WMO scale and is still in use. In the opinion of many investigators [11, 12], this conversion scale is the source of another bias which gives values too low for wind forces 1 to 7 and too high for greater than Beaufort Scale 9. Some institutions would prefer the use of other visual wind equivalent scales. The VSOP-NA results also confirm that biases exist between estimated and observed winds [8].

Recent investigations into estimated winds at sea concluded that systematic biases may exist with visual or Beaufort wind estimates [13]. Isemer and Hasse found that the biases vary with wind speed,

stability and ship's heading, and that these vary with time and the observing practices. They conclude, as did Cardone et al. [14], that extreme caution should be used in adjusting visually estimated and other sources of wind data before these can be used for climate monitoring and also surface wind-stress or energy-balance calculations. It is therefore recommended that unadjusted mean values should not be used for these kinds of calculation as the results may be meaningless or —even worse— misleading in their conclusions.

        Biases can likewise occur when metre-per-second winds are converted to knots.

        Observers reporting wind speed in knots also have the tendency to make either an estimate using the Beaufort scale, which is subsequently converted to knots, or an estimate rounded to the nearest five knots. Rounded values to the nearest five knots can also come from ships equipped with anemometers, whether conversion from apparent to actual wind is automated or manual. Such biases are detectable when the historical wind data are arrayed as in the following example (Figure 3.5):

## Wind Speed Distribution
### Illustrating Beaufort and 5 knot Bias
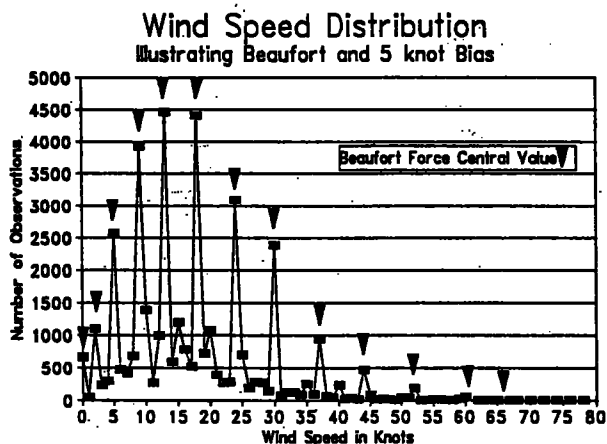


Figure 3.5 — Frequency of observation of wind speed ranges

        Wind gust information is also an important parameter, but is one not collected by ships of opportunity. Therefore, any surveys which include wind-gust data would be restricted to a few research ship data collections or moored buoy files.

        Sea-surface temperatures are sampled using two principal methods: intake (injection) thermometers and buckets. Satellites observe "skin temperature", i.e. the sea-surface temperature, via infra-red radiances. A number of studies have been conducted which show that intake temperatures average about 0.3°C to 0.7°C higher than bucket values [15]. It is not always clear, however, when examining the historical records, which sampling method was being used. Studies have revealed potential problems with both methods [15, 16]. Bucket temperatures may be influenced by colder air temperatures, especially if the bucket is uninsulated. Injection temperature will vary depending on the depth of the

intake, which depends in turn on the size of the ship and the load it is carrying at the time of the observation.

        Because of differences in instrumentation and observational methods, significant statistical differences may appear when comparing ship data with those of buoys [17, 18, 19]. For best results, the two data sets should be used, but studied independently, in deriving climatological estimates for a specific location. Lower wind speeds can be expected from buoys as compared with ships because of lower instrument heights and longer averaging times. Adjustments relative to instrument height may sometimes be desirable [19, 20]. Also, the anemometers on buoys may, with time, accumulate salt on their mechanism and could thus lose their calibration and begin to read progressively lower wind speeds than the correct values.

        Visibility is difficult to measure at sea because of the lack of reference points — other than the ship itself and the horizon. It is even more problematic at night. Coarseness of the visibility code intervals tends to minimize the problems and, in general, the observer can estimate with confidence if the visibility is poor (highly restricted) or excellent (clearly unrestricted). It is those occurrences of 2–5 n.mi. (4–10 km) visibility that are often difficult to estimate. Therefore, in the historical data file, the visibility distributions for some regions will show few or no occurrences in the middle range with no observational evidence of how the visibility made a transition from the lower to the higher categories (or vice versa).

        The cloud report in marine observations contains codes for total cloud amount, low cloud amount, low cloud type, middle cloud type, high cloud type, and height of the base of the lowest cloud seen. As regards visibility, observing clouds is particularly difficult at night. Because of the way heights are reported, aircraft-type ceilings are not available from ship observations. Ceilings can be estimated from the height of the lowest cloud when low clouds cover more than half the sky. Caution should be used when processing total and low cloud amounts since a much higher percentage of the observations contains only total cloud amounts. This artifact resulted from many of the earlier data sources which reported only total cloud amounts. For most statistical presentations which use both total and low cloud amounts, it is best to confine the input data to those observations reporting both elements. If this is not done, it is possible that the low cloud amount may appear greater than the total cloud amount. The problem can sometimes be resolved in favour of the total cloud amounts by making the frequency curves coincide as illustrated in Figure 3.6.

        Another data conversion bias results when earlier observations, which reported cloud amounts in tenths, are combined with modern observations recorded in eighths (oktas). One way this can be handled is to convert via Table 3.4.

        This conversion scheme, however, results in particularly significant biases at the two "okta" values that each contain two "tenths" values. This can be overcome to

## CLOUD AMOUNT IN EIGHTHS



## CLOUD AMOUNT IN EIGHTHS



Observation count = 669                    Observation count = 669

———— Total cloud amount ⎫   Cumulative percent frequency of indicated cloud
                         ⎬   amount equal to or less than the amount intersected
— — — — Low cloud amount ⎭   by the curve.
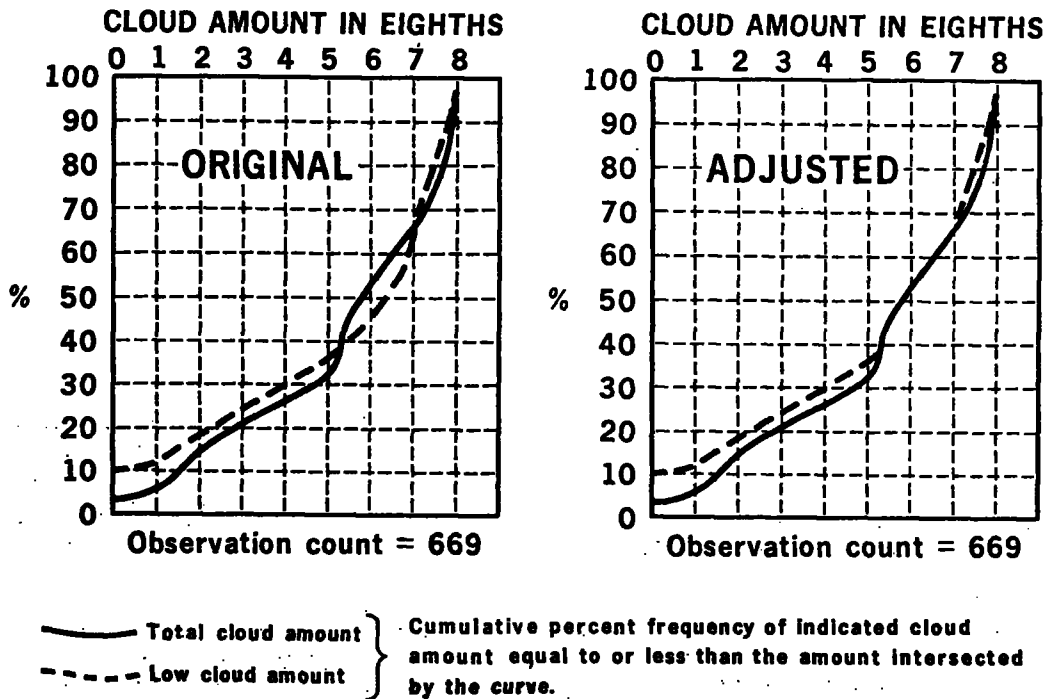
Figure 3.6 — Adjustment of cloud amounts

some extent by converting oktas to decimal values (e.g., one okta = 0.125), performing statistical analyses by fitting a cumulative distribution curve to the data, then interpolating results for desired cloud-cover values.

### TABLE 3.4
### Conversion from tenths to eighths

| Tenths | Oktas code |
|--------|------------|
| 0 | 0 |
| 1 | 1 |
| 2 or 3 | 2 |
| 4 | 3 |
| 5 | 4 |
| 6 | 5 |
| 7 or 8 | 6 |
| 9 | 7 |
| 10 | 8 |
| Obscured | 9 |

Judging cloud types can be difficult without proper training. The variable quality of the cloud types in typical ship observations has led most studies to use only the heights and amounts of clouds reported.

Wave information has been recorded in various quantitative codes since the late 1940s. There have been several major code changes that have to be considered when working with the data. From the late 1940s until July 1963, the general practice was to report only the higher of sea and swell together with the direction and period. As of July 1963, the start of the IMMPC format under Resolution 35 (Cg-IV) [3], both the sea and swell were to be recorded with the heights in half-metres,

the direction using the 36-point scale, and the period in a single-digit code. In 1968, the code for the wind-wave (sea) period was changed to reporting in seconds and the swell wave to a newly implemented single-digit code. Then, in 1982, the single-digit period code for swell was dropped in favour of reporting it in seconds. If all years of wave period record are to be utilized, then the codes have to be converted to a uniform standard. The difficulty and subjectivity inherent in wave observing makes it one of the most challenging fields of analysis. Generally speaking, wave heights are thought to be fairly accurate, climatically, but the observers' distinction between sea and swell is often poor [21]. For this reason, many studies use only the highest of reported waves, whereas others use the root mean square of sea and of swell heights. Direction observations are thought to be relatively good, but wave period observations are of questionable quality.

Although codes for ice accretion are an integral part of the WMO international ship weather report, they are seldom reported. Most icing statistics are therefore usually derived from either empirical nomograms or physical models using the main icing variables as input (see section 3.3.1).

Reporting procedures for sea-ice sightings are also included in the code, but again are seldom utilized. Most ice information is now collected through satellite imagery, with only a small portion coming from shore stations, aerial reconnaissance, or ship reports.

Because of all the limiting factors and code changes, each element should be examined closely to determine how it can best be used in any climate analyses, summarizations, or studies.
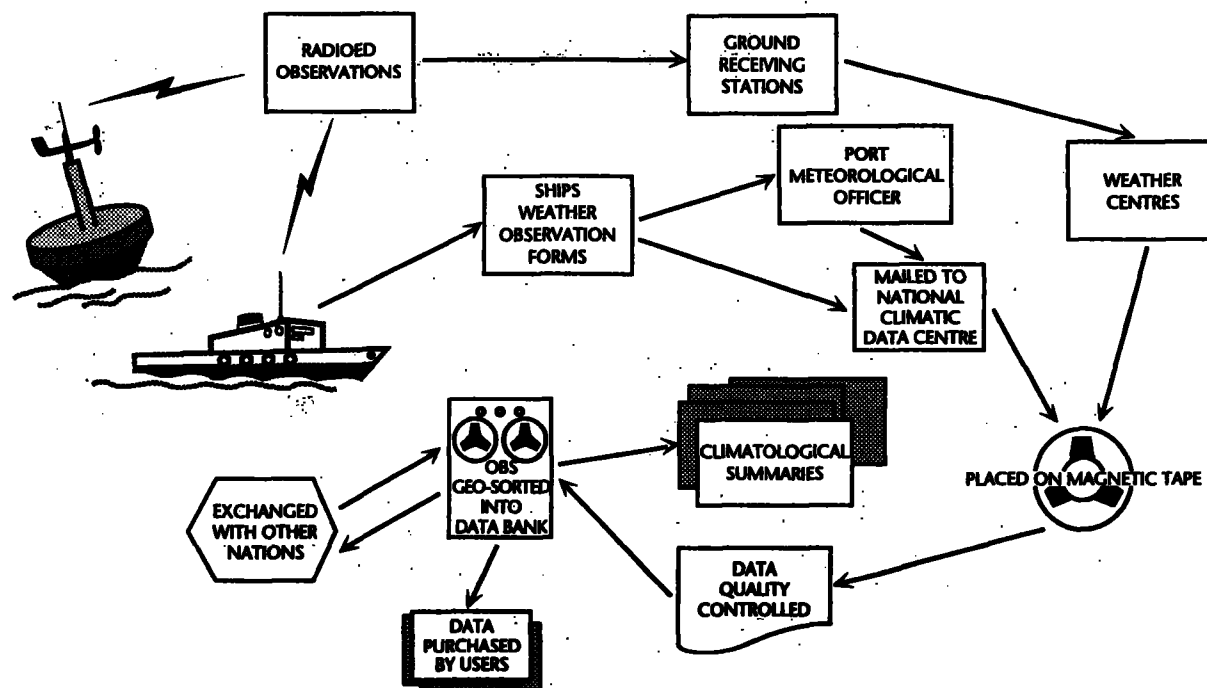
Figure 3.7 — Data flow and processing of marine observations

### 3.1.3    Sources of errors

As the reader will note, there exists a close relationship between sections 3.1.2 on limitations of data, this section on the sources of errors, and section 3.1.4 on quality control. Both systematic and random errors may limit the scope and usefulness of the data. Some errors are introduced through the observational code or archiving procedures. However, errors can be introduced during any phase of the marine observation life cycle (Figure 3.7).

An enormous number of errors can be introduced when the observation is taken and many of these may be undetectable by the time they reach the archiving stage. If any meteorological instrument is not properly calibrated, or if the observer incorrectly reads or miscodes a value, then an error has been introduced. Even when an observation has been encoded correctly, errors can be introduced at the time of transmission, receipt, digitization, or when the observation is processed (validated) and archived at the data centre. The following discussion identifies the details of many ongoing data problems.

### Ship identification

Call signs have been available since 1982 in the international exchange format and GTS reports since the late 1960s. They are the only uniform means of ship identification which can be used to identify instrument heights, type of instrumentation, type and size of ship, country of registry, and other variables. WMO–No. 47, *International list of selected, supplementary and auxiliary ships* (1986), documents this information and is available in published form and on magnetic tape for

recent years (beginning in the 1970s). Proper identification is critical in track checks (which check consecutive observations for continuity) or in the elimination of duplicate observations. If the call sign has been incorrectly entered, replaced by a generic one (e.g. SHIP, BUOY, etc.), or duplicated in error, then the quality-assurance procedure will suffer.

### Date time

If the day of the month is incorrectly entered, only a time-of-month variable would be influenced in a monthly climatological summary. Even when the date is obviously incorrect, such as 30 February, the observation would probably be deleted, still causing little effect on the final results. However, an invalid year, month, day, or hour would affect synoptic climatology and duplicate elimination. In one case study of historical data [22], duplicate observations had originated in two separate sources, but had not been identified because the dates sometimes differed by one calendar day. This occurred when original watch-number groups were incorrectly converted to local time for the midnight watch in one source (hour 2400 was converted to 0000), but the day was not advanced. Later, the times were converted to universal time, further disguising the difference problem.

### Wind speed indicator

The wind speed indicator, which tells whether wind is measured or estimated, and whether the units are knots or metres per second, can sometimes be the source of error in one of two ways. If the units indicator is in error, then the

reported wind speed will be either about double or half its actual value. Another common problem linked to the indicator is for a double conversion to occur. This can happen when the units are converted, but not the indicator. Systematic errors have also been introduced by the use of incorrect conversion factors in conversion programs.

*Position*

Miscoded quadrants (or octants) are a common cause of erroneous ship position data, often occurring when the observer forgets to change the code as the ship crosses the 0°or 180° meridian, or the Equator. These errors, and random keying or transmission errors, can sometimes be found and corrected through track checks, such as when a ship approaches a quadrant's boundary and then appears to reverse its route, or when its computed speed is unreasonable. Incorrect quadrants or octants can result in observations being located over land (landlocked), where occasionally a ship may appear to cross Africa or Australia. Landlocked marine observations can easily be found through a computer check, but those position errors that fall over water and have an invalid locator code are more difficult to identify automatically. Only when observed elements are quite different from what would be expected at their reported position are they likely to be spotted. Similar errors may also be introduced in the conversion from the reported quadrant in the ship code to an octant code required by the international exchange format.

    One illustrative example of a systematic difference in ship positions occurred when duplicate data were converted from Marsden-square, one-degree sub-square to latitude/longitude by two different national organizations [22]. One organization placed the position in the lower left corner of the one-degree square, while the other organization used the centre of the one-degree square. Because of this type of difference in data-processing techniques, combining data from different sources often leads to duplicate observations that are hard to identify because of subtle conversion differences.

    Another problem arises when latitude and longitude are taken to be in hundredths of degrees when in fact they are in degrees and minutes, or vice versa. This can be readily detected by looking for values greater than 60. If none occurs, the positions are almost certainly in minutes.

    Results can be biased when a large number of observations are collected within a short period of time. This bias can be minimized by giving weights to short time periods (e.g. months), rather than by weighting each observation equally. But even then, time biases can occur. A classic example of this appeared in one application when a large convoy of ships was concentrated in a small area for several days. The wind reports were especially unrepresentative of normal conditions, as two typhoons were active just south of the area. Using these valid, but non-representative, observations produced a biased mean wind speed that was nearly double that of the surrounding area [23].

*Present weather*

In 1982 an international code change was introduced which included a present weather indicator ($i_x$). Although the indicator, which allows for the present weather group ($7wwW_1W_2$) to be omitted when there is no significant weather to report, was included in the SHIP synoptic code FM 13-VII [24], it was not included in the international exchange codes (IMMPC[1] and IMMT[2]) until March 1985. This leaves a period of some 26 months where it was not possible to determine from IMMT records whether there was no significant present weather or whether present weather was simply not recorded. If the present weather element is not statistically adjusted during this period, the climatic aggregates may be biased towards the significant present weather codes (rain, etc.). Proper use of the ($i_x$) indicator will lessen any biases in present weather statistics. However, the introduction of ($i_x$) reduces the comprehensiveness of the weather observation, and can result in observers forgetting to record significant present or past weather.

*Clouds*

As noted earlier, marine observers generally do a good job of estimating the height of the lowest observed cloud and the amount of total and low cloud present. However, since thery are not professionally trained, the quality of cloud-type identification does not meet as high a standard and, as a rule, has not been found suitable for most climatological presentations. After ruling out cloud types, most inconsistencies in the cloud field are found among the total and low cloud amounts, cloud heights, and present weather codes. Another possible source of error in the cloud field results from the 1982 code change. If the total cloud amount (N) is coded as zero (cloudless sky) or 9 (sky obscured), then the 8 group ($8N_hC_LC_MC_H$) is not coded or transmitted. This results in the $N_h$ (low cloud amount) being left blank (1982 onward) in these instances. Thus, for studies using low cloud amounts, the total cloud amount must be checked for 0 or 9 so that the corresponding $N_h$ can be handled correctly.

    Wright [25] performed an analysis of cloudiness data over the Pacific and found an increase of cloudiness of about one okta from the 1920s to the period 1950–1969. He felt that the fluctuation was not real, but one resulting from procedure and which could possibly be ascribed to one or more of three things: (1) the 1949 WMO code change standardizing cloud amounts in eighths instead of tenths (the practice of early years and for some nations up to 1961); (2) the way in which "a trace of clouds" and "nearly overcast" were being reported; and (3) the differences between the 1921 and 1930 cloud codes.

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1. International maritime meteorological punch-card

2. International maritime meteorological tape .

## Visibility

Visibility (VV) codes (90–99) are easily checked to ensure that they fall within the allowable range. However, most detectable errors result from a disagreement between the reported visibility and present weather code. Thus observations reporting fog with good visibility (VV = 96 or 97 code) or light rain with poor visibility (VV = 91 or 92 code) are suspect. Visibility ranges should agree with specified weather types within certain limits. Another common problem occurs when three elements, such as clouds, visibility, and present weather, are not in total agreement. For example, an observation reporting a 25 nautical mile visibility with sky obscured and light rain would seem questionable. Under these circumstances, one must decide upon which elements are most probably correct and then discard the others.

Data users must also remember that the mid-range visibilities are often difficult for the observer to

estimate because of the lack of reference points at sea. This may result in the observer biasing his choices to either the lower or upper end of the visibility scale.

## Wind direction

Wind directions have not always been taken using a 36-point scale (tens of degrees true — corrected for magnetic declination). Differences in direction must be resolved when combining various systems or they will distort any directional statistics. Common directional codes, besides the 36-point scale, have been 16 of 32 points, 16 of 36 points, and a 32-point scale. Even when observed in tens of degrees observations still tend to be biased to the eight and 16 points of the compass, as shown in Figure 3.8.

To minimize biasing the data when converting to an eight-point (or similar) scale, a weighted conversion scheme such as the one outlined in Table 5.3 should be used.
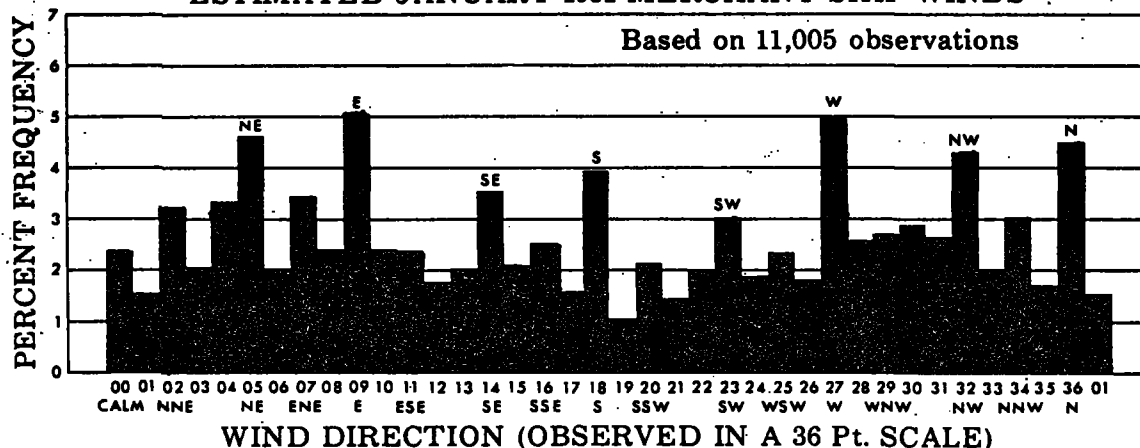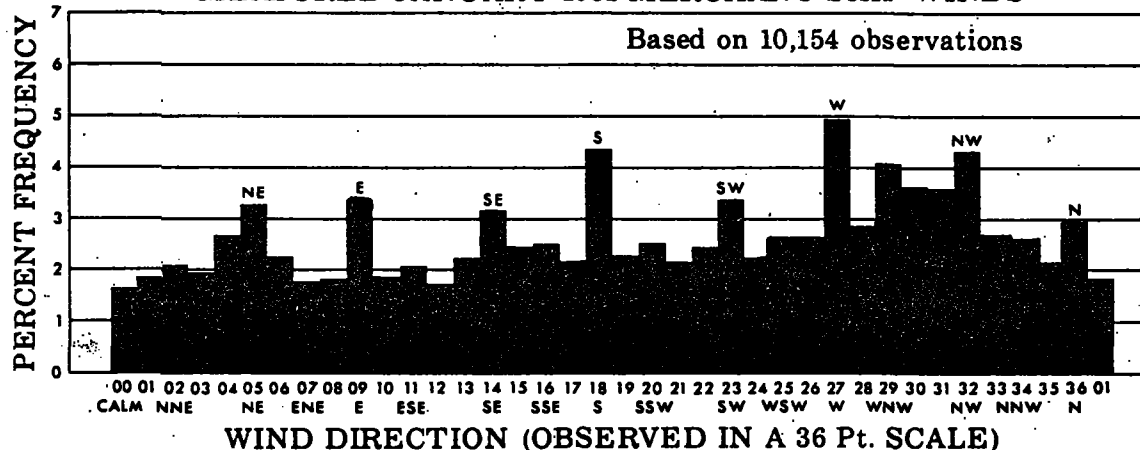


Figure 3.8 — Samples which clearly illustrate the typical wind direction observational bias

## Temperature

Temperature errors are introduced by numerous means: poor instrumentation, poor exposure, insufficient ventilation, incorrect entry, wrong conversion factors, code changes, and possibly in other ways that have not yet been detected. Clearly defined erroneous values (outliers) are easily detected and can easily be eliminated to keep them from biasing the data. It is those temperature values that were properly coded and keyed, but geographically mislocated, that are generally hardest to detect; if only a few are randomly intermingled with correct data, then not much biasing is introduced. However, if a large number have been mispositioned, then the resulting climatology could be in error. Often, when data from two or more locations are mixed, a bimodal or multimodal distribution appears, which can alert the analyst to a possible data problem. The difficult part is then separating the genuine data from the mispositioned data. Even when this is feasible, it is often impossible to relocate the misplaced data properly. The problem of identification and separation becomes very difficult if the mispositioned data appear in an area of similar climatological characteristics.

Errors can be introduced when temperature values are coded to solve storage or processing problems in the digital environment. Such schemes as overpunching the value, adding a constant, or converting to the Kelvin scale in order to eliminate the negative signs have all been used. Errors may be introduced during the conversion, often because the constant or the overpunch code was changed at some time to simplify or standardize the processing. Trying to correct errors in one element may introduce or leave an error in another. For example, whenever the air temperature is corrected, the corresponding wet-bulb and/or dew-point temperatures may also need correcting.

Prior to the code change in 1982, the dew-point temperatures from telecommunication sources were reported to the nearest whole degree Celsius, while the air (dry-bulb) temperature was reported to tenths. In instances when the atmosphere was saturated, the dew-point temperature could be reported higher than that of the dry bulb by as much as half a degree because of rounding. Care should be taken not to eliminate erroneously data based on apparent, but artificial, inconsistencies such as this.

Discrepancies also appear when the dry-bulb temperature and present weather codes are not compatible, such as in cases of occurrence of snow with warm temperatures. Other examples could be: no negative temperatures in an area where they are expected (a sign problem), or one ship or buoy always reporting the same value. This happens more frequently with automated stations when their instrumentation malfunctions or data values exceed the designed limits and is particularly prevalent with drifting buoy data.

Sea-surface temperature errors are similar to air temperature problems; i.e., most errors result from poor calibration, misreading, incorrect encoding or transmission, decoding errors, etc. Some extremely low sea-surface temperatures result from the air temperature affecting the sea-surface temperature sample. As James and Fox [26] point out, any of the following conditions could affect a bucket temperature: strong winds, extreme air/sea temperature differences, heavy precipitation, and type of bucket. Other non-climatic factors which may bias the data are: insulated bucket versus non-insulated bucket versus intake thermometer; uncalibrated equipment; code changes; non-uniform spatial distributions of data; and various types of observing platforms. Many studies have been conducted in an effort to standardize, correct and homogenize the air and sea temperatures in marine data sets [27, 25, 15,7, 28]. However, many questions still remain unanswered and few, if any, statistically based correction estimates can be applied with absolute confidence. This leaves some question as to whether the indices for global surface temperature measurement based on sea-surface temperature data are real or an artifact of the data.

## Waves

Estimating the heights and periods of the sea and swell waves can be a very difficult task even for the most experienced observer. This is especially true when more than two wave trains are present. In addition to other errors, the changing codes have introduced special problems that must be dealt with before most analyses can be performed.

Prior to July 1963, the higher of sea and swell was retained in the archived magnetic tape records. During most of this era, which generally dates back to 1949, one of the standard wave height codes had one position allocated in the format [29]. Codes 0 to 9 were equivalent to today's half-metre code, with 9 equalling 4.5 metres. A solidus (/) was included for heights that were impossible to determine. For heights greater than 4.5 metres (code 9), 50 was added to the wave direction, which was decoded by subtracting 50 from the direction and adding 10 (5 metres in the half-metre code) to the height. This made the 0 to 9 code equivalent to heights of 5 to 9.5 metres. If wave heights greater than 9.75 metres were observed, either a plain-language message was used to report the actual heights in the remarks, or an overpunch was placed in the height column (0–9) for heights in one-metre increments from 10 to 19 metres. If an invalid directional code of 51 to 86 appeared in the database, then the height would be decoded as being 5 metres too high. Most centres which archive marine data would have already converted these data to the standard half-metre code introduced in July 1963. Although the international code was changed at this time the reporting practice or coding forms were not necessarily changed. Based on a survey of Ocean Weather Stations, the practice of coding 19 half-metres as the highest reportable wave value varied from 1959 to 1968. Prior to 1968, both sea and swell periods were coded as shown in Table 3.5:

TABLE 3.5

IMMPC sea and swell period code prior to 1968.

| Code figure | | Period |
|---|---|---|
| 2 | = | 5 seconds or less |
| 3 | = | 6-7 seconds |
| 4 | = | 8-9 seconds |
| 5 | = | 10-11 seconds |
| 6 | = | 12-13 seconds |
| 7 | = | 14-15 seconds |
| 8 | = | 16-17 seconds |
| 9 | = | 18-19 seconds |
| 0 | = | 20-21 seconds |
| 1 | = | over 21 seconds |
| / | = | Calm or period unable to be determined |

In 1968, WMO introduced a code change making the sea (wind-wave) period reportable in actual seconds and the swell period reportable in the code shown in Table 3.6:

TABLE 3.6

IMMPC swell period code 1968-1982

| Code figure | | Period |
|---|---|---|
| 0 | = | 10 seconds |
| 1 | = | 11 seconds |
| 2 | = | 12 seconds |
| 3 | = | 13 seconds |
| 4 | = | 14 seconds or more |
| 5 | = | 5 seconds or less |
| 6 | = | 6 seconds |
| 7 | = | 7 seconds |
| 8 | = | 8 seconds |
| 9 | = | 9 seconds |
| / | = | Calm or period unable to be determined |

In 1982 the swell period code was also changed to actual seconds. Some archival data formats converted to an earlier code to achieve compatibility with earlier records and also retained the current code [30]. Care must be taken by users to ensure that none of the codes are misinterpreted. For example, a very common error in the pre-1968 code was miscoding of low periods as period codes 0 and 1, when they should have been 2. In the 1968 code, 0 to 4 were often erroneously used to indicate periods of calm (0) or 1 to 4 seconds, when they should have been coded 5. Reference to the wave height can give an indication of when this error was made.

Prior to 1968, the directions of the waves were determined and reported by the observer. This applied to both sea and swell after July 1963, or just to the higher of the two prior to that time. However,

beginning in 1968, the direction for the wind wave (sea) was dropped from the ship code as the wind direction was considered a representative substitute for the sea direction.

For moored buoy data the wave information (which may appear in the sea field) is based on the total energy spectrum. Therefore, the significant wave height, average (or more recently, peak) period, and direction should not be mistaken for a wind wave. National practices vary for buoy archives and are generally documented by the data centres.

*Data value*

The maritime nations and seamen of the world have provided us with a great resource in the historical marine observation file. We thus have clues to the climate over the past century and a half and to how the climate is changing. With all of its known shortcomings the file still has great potential and can provide uniquely useful information about the oceanic climate when appropriate quality-assurance and statistical analysis procedures are utilized. It is essential for the researcher and marine product developer to be keenly aware of the evolution, limitations, and proper applications of these data. It is also helpful for the user of marine products to possess some of this knowledge.

Older data sources contain many systematic errors, but they are generally of a nature that can be corrected. Today's observations imply similar problems, but with the increased automation in observing and processing, there are significantly more possibilities for errors; this is especially true of buoy and GTS data receipts.

3.1.4    **Quality control, processing and archiving of data**

Marine weather observations in national archives are from a time period spanning well over a century. Data from sailing ships, steamships, moored buoys, and drifting buoys all form a part of this global climate data resource. The lack of homogeneity among the observations within the database, even for contemporary data, means that extra care must be taken in developing and operating quality-assurance programs. The quality-control software has to be relatively sophisticated in order to be able to distinguish between types of reports, different coding practices, and possible processing-system-induced errors. One can enumerate five types of quality check that are appropriate to marine data. They can be easily recalled with the acronym LITES: L = Legality of codes; I = Internal consistency within an observation; T = Time series checks used to identify unreasonably abrupt changes (also called the Track check); E = Extreme value check, used either as absolutes for the globe or localized by area and month; S = Synoptic areal edits, where an observational element is compared with all others nearby at the same time (this is usually done via computer gridding and contour-like analysis).

The ninth session of the WMO Commission for Marine Meteorology (CMM-IX) [31] requested that the Working Group on Marine Climatology consider developing minimum standards for quality-control procedures, because a recent survey by WMO indicated that procedures employed by various Members were far from uniform. The working group, after careful review of existing quality-control procedures, established a set of minimum controls to be used by contributing Members. If desired, more sophisticated quality-control procedures can be applied later, or in conjunction with the processed data provided to other Responsible Members under the Marine Climatological Summaries Scheme (Resolution 35 (Cg-IV)). The main goal of the programme is to ensure that minimum quality-control standards are met and that doubtful data are flagged, not deleted (erased). These Minimum Quality Control Standards established by the working group [32] appear in Appendix I.

While many countries' Meteorological Services possess adequate computer resources to provide a minimum standard of quality control, some do not. The strengthening of the data management capabilities of many countries' Meteorological Services is the goal of WMO's CLICOM (CLImate COMputing) programme. Under this programme, computer systems and software have been installed in many countries. The micro-computer-based data-entry and quality-control sytems have been developed primarily for land-based applications [33], but have been adapted for marine data [34]. The marine system was found to be too slow for large volumes of data (over 20 thousand observations per month), but may have applications for the key entry and management of smaller amounts of data. The additional marine software for the CLICOM system is available from the National Climate Data Center in the USA.

Hong Kong has also developed quality-control and analysis programs for personal computers [35]. The analysis programs are used in the preparation of Marine Climatological Summary Charts under the Marine Climatological Summaries Scheme (see *Manual on Marine Meteorological Services*, WMO – No. 558, 1990). This software is available from the Royal Observatory of Hong Kong.

If earlier historical data (prior to the 1982 code change) are to be quality-controlled, then changes must be incorporated into the system to handle appropriately differences in codes, observing procedures, and digitizing procedures. A processing history of the data is important, especially if data have previously been edited and/or modified. For example, the observations before 1970 in the Comprehensive Ocean Atmosphere Data Set (COADS) [36] had been used for the US Navy Atlas Series [37] and had undergone previous editing. Some elements had been changed or eliminated during quality control, which included the creation of composite observations from apparently duplicated reports. Supplement 5 to the Comprehensive Ocean–Atmosphere Data Set, Release 1, contains a

quality-control flow chart which gives, in detail, the procedures used to quality-control COADS data. This system closely resembles current practices at the US National Climatic Data Center. Other Responsible Members can also provide interested parties with details of their quality-control procedures.

Elements that are approximately Gaussian (normally) distributed, such as temperature and pressure, can have doubtful outliers flagged by using climatological means and standard deviations. Elements that are not normally distributed and often zero-bounded, such as wind speed or wave heights, can first be checked against gross limits. Then, for a more definitive view, a monthly array of the data is useful for locating outliers. Once suspicious values are located, they can be either eliminated or checked further. To check more closely, the total observation can be reviewed, and also compared with synoptic chart data from the same time period.

A synoptic comprehensive area edit of many elements is a very useful check, but is quite complex, expensive, and time-consuming to perform. This type of check is now performed in a near-real-time operational mode, but is seldom used for climatic work. With improved technology, it may eventually prove to be more practical for climatic applications.

An example of marine data arrays is given to illustrate how they can help in the quality-control process. The example is for wind speeds in Figure 3.9.

The doubtful wind-speed values appear above the dashed line. They can be checked further for validity or simply eliminated from a summary. In the second array, a few outliers have been marked for summary deletion, but the really important characteristic is the notable bimodal distribution which appears in several months. In this instance, the "lower" mode values (which are strongly evident for the winter months) were discovered to come from a tower in the Gulf of Mexico that operated for a relatively short time (several years). The interesting thing is how the bimodal distribution disappears during the summer, when the observations provided by ships of opportunity and from the tower align closely.

Data processing begins with the initial receipt of observations via manuscript log forms or through the Global Telecommunication System. If received on a log form, then a visual inspection should be conducted by trained technicians to check and correct information such as ship's call sign, date-time group, proper coding, and legible completion of observations. The next steps should include digitizing by data-entry clerks and semi-automated quality control by meteorological technicians. Digitizing errors should be corrected and the final data, with any doubtful elements flagged, should be stored in the database. During the edit, the ship's position should be checked to see that it is in navigable waters, and a track check for continuity between observations should be performed. Track
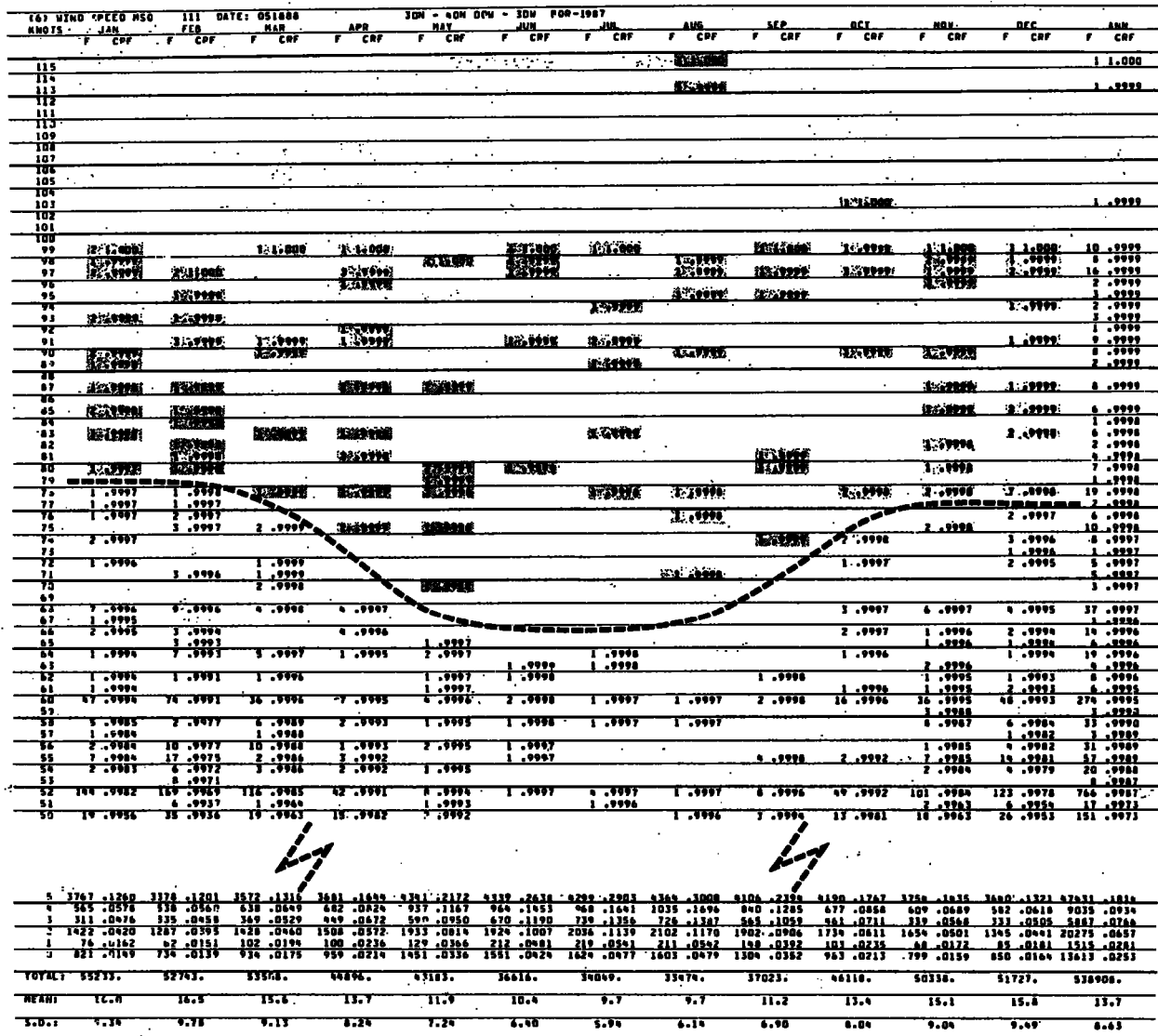
Figure 3.9 — Wind speeds arrayed by one-knot intervals for Marsden square 111 (1854–1986)

checks are particularly useful for detecting errors in position, temperature, or pressure. In most instances the errors cannot be corrected, but can be flagged as doubtful so that data users can identify them easily and decide, whether they would rather accept, reject, or attempt a correction of the data. Automatic rejection during computer processing can greatly improve the efficiency of producing large-scale climatic products.

The best approach to archiving marine data depends, to a great extent, on how the data are most often used, and on the storage capabilities of the archiving centre. Current data-management policies often dictate that only one magnetic tape file be maintained. In that case, it is not feasible to maintain separate files in geographical sequence (all data for one 10° square area together) as well as time-sort. Duplicate observations may be eliminated to save storage space and to prevent the biasing of data. Identifying duplicates is not a simple task as often they do not exactly match character by character. Schemes should be devised to check elements for matches as well as for locations and time. Caution

should be taken, however, to avoid elimination of valid discrete observations which may be in close proximity.

Without large, economical, random-access mass storage systems, the marine archive file is difficult to update. It is likely, however, that such systems will become available within a few years. If the file is maintained on a sequential read/write medium such as magnetic tape, then a synoptic time-sorted file is the easiest to update because new data can be checked for duplicates and simply appended or inserted in the proper sequence. If the archival file is of a geographical sort (e.g. Marsden Square), then the entire file has to be updated. If it is a large global file, then an annual updating may prove too expensive. In this case it is best to maintain a supplement file of all data received since the last update. The main file can be updated periodically depending upon available computer resources; at some centres periodic updating is done on a five- to ten-year basis. The organization of the archive or database, however, should be determined by its most frequent use.

### 3.1.5 Sources of data/data holdings

Retrospective surface marine climatic data archived by various nations have been compiled from numerous sources. Currently, the earliest period for most digitized marine data is the mid-1850s. Earlier manuscript data sets, such as the Maury collection (1800–1860), exist however, and resources may eventually be found to digitize much of those historical data. This will almost certainly be the case if a definitive climate-change signal is ever detected. From Figure 3.2, the drastic decline in digitized observations for the World War I and II periods can be clearly noted. One can also see the increase in digital observations beginning in the late 1940s, which is of added significance because the later observations contain more elements.

Prior to 1963 and the implementation of Resolution 35 (Cg-IV) [3], many different source formats were in existence and there was no uniform format for non-real-time international exchange. In 1968, the United States took the 17 different source "decks" (so called because they had been stored on punched cards — as in "decks of cards") that were being maintained and placed them in a common format that closely resembled the 1963 IMMPC format. Elements that could not be converted directly to the common format were retained in a supplemental field. Each observation was tagged to identify its original source. Today, because of an extensive exchange of data among participating Members, most major global archives are quite similar in content. Listed in Table 3.7 are the 17 original deck sources and their general period of record.

**TABLE 3.7**

**US surface marine data source list as of 1968**

| Deck number | Original source | Original period of record |
|---|---|---|
| 110 | US Navy Marine Observations | 1945–1951 |
| 116 | US Merchant Marine | 1949–1963 |
| 118 | Japanese Ship Observations No. 1 | 1933–1953 |
| 119 | Japanese Ship Observations No. 2 | 1963–1963 |
| 128 | International Marine Observations - Resolution 35 (Cg-IV) | 1963–1968 |
| 281 | US Navy MAR Marine Observations | 1920–1945 |
| 184 | Great Britain Marine Observations (extension) | 1953–1956 |
| 185 | USSR Marine Synoptic Observations | 1957–1958 |
| 187 | Japanese Whaling Fleet Observations | 1946–1956 |
| 188 | Norwegian Whaling Fleet Observations | 1932–1939 |
| 189 | Netherlands Marine Observations | 1939–1955 |
| 192 | Deutsche Seewarte Marine Observations | 1859–1939 |
| 193 | Netherlands Marine Observations | 1854–1938 |
| 194 | Great Britain Marine Observations | 1856–1953 |
| 195 | US Navy Ship Logs | 1942–1945 |
| 196 | Deutsche Seewarte Marine Observations (extension) | 1949–1954 |
| 197 | Danish Marine Observations (Arctic and Antarctic) | 1860–1956 |

Since then, the archive has been updated with data exchanged in accordance with Resolution 35 (Cg-IV) and data received via the GTS. Over the years, a number of special projects under the WMO Global Atmospheric Research Programme (GARP) have been conducted in an effort to collect additional data, much of which is surface marine data. The first of these projects was GATE (GARP Atlantic Tropical Experiment) from 16 June 1974 to 24 September 1974. That was followed by FGGE (First GARP Global Experiment) from 1 December 1978 to 30 November 1979 and subsequently the ten-year (1985–1995) TOGA (Tropical Ocean and Global Atmosphere Programme) observational period. The VSOP-NA created a special data set which was used to study the effect of different instrumentation and observing practice on the VOS fleet [8]. All these special projects, plus others such as the Historical Sea Surface Temperature Data Project (1861–1960), have their data archived in special formats and are available for researchers. Under Resolution 35 (Cg-IV), eight Members assumed the responsibility for archiving marine climatological data. The designated areas of responsibility are outlined in Figure 3.10, with the Responsible Member named within each area.

All countries collecting meteorological data from ships of opportunity were invited to send those data to the Member responsible for the area in which the ship was located at the time of the observation. It is then the task of the eight designated countries to maintain data archives and data services for their area of responsibility.

Those interested in acquiring marine climatological data may contact any or all of the Responsible Members to establish the periods of records, amount of quality control, and data formats most compatible with their specific needs. Addresses for the Responsible Members appear with asterisks in the following list, together with those of several other centres that archive surface marine data.

### CONTRIBUTING AND RESPONSIBLE MEMBERS

#### Africa

Weather Bureau, Private Bag 193, Pretoria, Republic of South Africa

Centre de Recherches Océanographiques, B.P. V18, Abidjan, Côte D'Ivoire

#### Asia

\* Royal Observatory, 134A Nathan Road, Kowloon, Hong Kong

\* India Meteorological Department, Lodi Road, New Delhi 110003, India

\* Japan Meteorological Agency, 1-3-4 Ote-machi, Chiyoda-ku, Tokyo 100, Japan

Japan Oceanographic Data Center, No. 3-1, Tsukiji, 5-Chome, Chuo-ku, Tokyo 104, Japan

* The Russian Federation is responsible for the compilation of a complete data set and the preparation of these summaries for these sea areas.
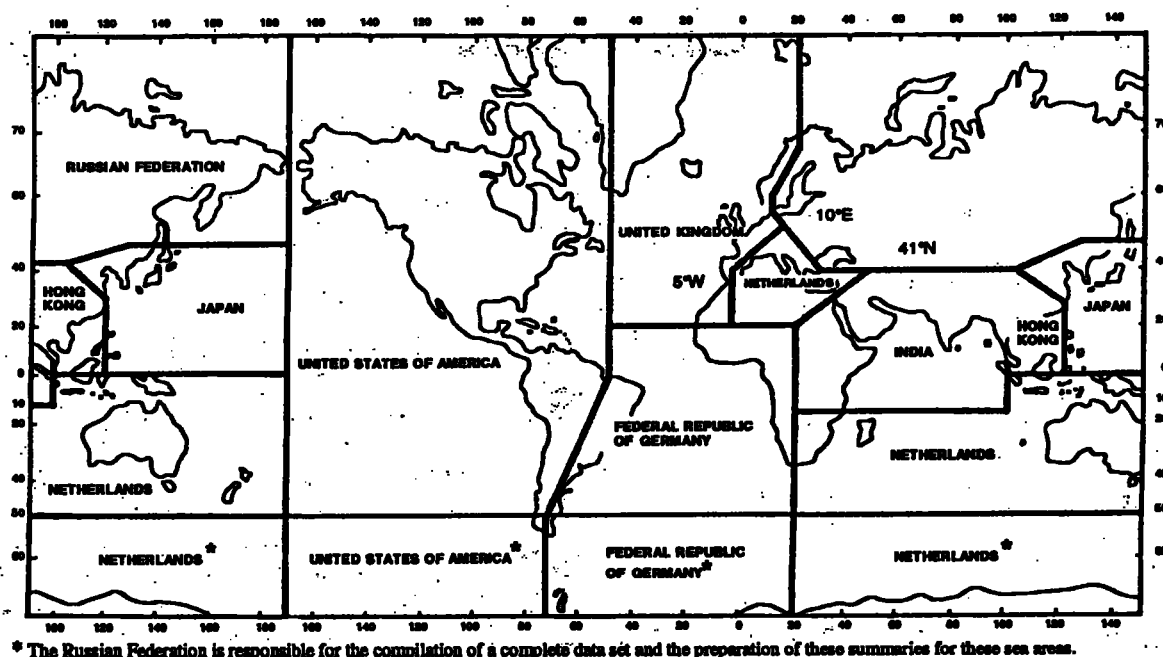
Figure 3.10 — Areas of responsibility and Responsible Members

**South America**

Centro Argentino de Datos Oceanográficos, Montes de Oca 2124, Buenos Aires 1271, Argentina (also Meteorological Service, 25 de Mayo 658, Buenos Aires 1002, Argentina).

Centro Nacional de Datos Oceanográficos, Avenida Errazuriz 232, Valparaiso, Chile

División de Meteorología, HIMAT, Carrera 10 No. 20-19, Oficina 915, Apartado Aéreo No. 20021, Bogotá, Colombia

Centro Nacional de Datos Oceanográficos (INOCAR), Casilla 5940, Guayaquil, Ecuador

Instituto Nacional de Meteorología e Hidrología (INAMHI), Shyris 1570 y Avenida Naciones Unidas, Quito, Ecuador.

Teniente Primero Armada Peruana, Gamarre 500, Chucuito – Callao; P. O. Box 80, Lima, Peru

INTEVEP, S.A., P. O. Box 76343, Caracas, Venezuela

**North and Central America**

Canadian Climate Centre, Atmospheric Environment Service, 4905 Dufferin Street, Downsview, Ontario, Canada M3H 5T4

Marine Environmental Data Service, Room 1202-200 Kent Street, Ottawa, Canada KIA 0E6

Meteorological and Geo-Astrophysical Abstracts, American Meteorological Society, 45 Beacon Street, Boston, MA 02180, USA

* National Climatic Data Center/World Data Center A — Meteorology, Federal Building, Asheville, NC 28801, USA

National Oceanographic Data Center/World Data Center A — Oceanography, Universal Building South, 1825 Connecticut Avenue, NW, Washington, DC 20009, USA

National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, USA

Satellite Data Services Division/NCDC, World Weather Building, Washington, DC 20233, USA

Scripps Institution of Oceanography, La Jolla, CA 92093, USA

Waterways Experiment Station, Coastal Engineer Research Center, Box 631, Vicksburg, MS 39180, USA

Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

**Oceania (S.W. Pacific)**

Australian Oceanographic Data Centre, P. O. Box 1332, North Sydney, New South Wales 2060, Australia (bathythermograph data)

Bureau of Meteorology, G.P.O. Box 1289K, Melbourne, Victoria 3001, Australia (surface data from ships and land)

Fiji Meteorological Service, Private Bag, Nadi Airport, Fiji

New Zealand Oceanographic Institute, P. O. Box 12346, Wellington, New Zealand

**Europe**

METEO-FRANCE, 1, quai Branly, 75340 Paris CEDEX 07, France

* Deutscher Wetterdienst — Seewetteramt/ Datenzentrum, Bernhard-Nocht-Strasse 76, Postfach 180, D-20359 Hamburg, Germany

* Koninklijk Nederlands Meteorologisch Instituut, Wilhelminalaan 10, P.O. Box 201, 3730 AE De Bilt, Netherlands

Det Norske Meteorologiske Institut, Postboks 43, Blindern, 0313 Oslo 3, Norway

Banco de Datos Oceanográficos, PO Castellana 67-28046, Laboratorio de Puertos Ramón Iribarren, Madrid, Spain

MIAS — Marine Information Advisory Service, Birkenhead, Merseyside L43 7RA, UK

* UK Meteorological Office, Marine Advisory Service, Johnson House, London Road, Bracknell, Berkshire RG12 2SY, UK

European Centre for Medium Range Weather Forecasts, Reading, Berkshire RG29 AX, UK

Ministerie van Openbare Werken, Bestuur der Waterwegen, Dienst der Kust, Vrijhavenstraat 3, B-8400 Oostende, Belgium

* Federal Service for Hydrometeorology and Environmental Monitoring, 12, Novovagankovsky Street, 123242 Moscow, Russian Federation

Pomoraki Meteoroloski Center, Prilaz VIII Korpuaa 11, P. O. Box 44, 5800 Split, Croatia

**International**
Director, WDC-A for Glaciology, National Snow and Ice Data Center CIRES, Campus Box 449, University of Colorado, Boulder, Colorado 80309, USA

Director, The Arctic and Antarctic Research Institute, 38 Bering St., 199226 St Petersburg, Russian Federation

ICES Service Hydrographique, Palaegade 2, Copenhagen K DK-1261, Denmark

Intergovernmental Oceanographic Commission/ UNESCO, 7 place de Fontenoy, 75700 Paris, France

World Meteorological Organization, C.P. No. 2300, CH-1211 Geneva 2, Switzerland

* World Data Center B, Molodezhnaya 3, Moscow 117296, Russian Federation

## 3.2    HINDCASTS — WINDS AND WAVES

A long time series of data is required in order to produce the information necessary for the design and operation of offshore facilities. For example, to produce the 50- or 100-year return period value of wave height or wind speed commonly used as input to design models, at least 20 years of data are required at each location. In most marine areas continuous time series of data for 20-year periods are rare, particularly for waves. As a result, alternative solutions have been proposed.

The primary source of design information for winds and waves in marine areas is derived from hindcasts, where historical data are re-analysed, using all available data and suitable wind and wave models.

Two techniques are used to produce design information on winds and waves. First, an entire period

of 20 years or more may be hindcast at three- or six-hour intervals, giving a continuous time series of wind and wave fields at each grid point. While this produces an ideal database for climatological statistics, it is very time-consuming and expensive. A second approach for extremes climatologies is to hindcast only the worst storms over a selected period, e.g. the worst 30 storms in 30 years. While not as flexible in terms of the range of statistics which can be derived, this approach is much more manageable and considerably less costly. Hindcasts have been made for many areas of the world, in some cases more than once. Examples include the US Navy Spectral Ocean Wave Model (SOWM) hindcast of the North Atlantic and North Pacific Oceans [37, 38], the US Army Corp of Engineers hindcast of the North Atlantic [39] and the North European Storm Study (NESS) hindcast of the North Sea [40]. These three hindcasts are all of the continuous type; many others, including proprietary hindcasts made for the oil industry for areas around the world, are the storm type.

The following paragraphs describe a wind-and-wave hindcast storm procedure. Most aspects of the hindcast procedure, other than storm selection, are the same, whether the continuous or storm approach is selected.

### 3.2.1    Hindcast approach

The application of the hindcast method includes the following main steps:
- Survey of historical meteorological data, to identify the most severe storms of the relevant types which have occurred within as long a period of history as possible;
- The specification of surface wind fields on a discrete grid for each selected historical storm;
- The numerical hindcast of the time history of the sea state on a grid of points representing the basin, for each storm;
- Calculation of the expected extreme wave heights and associated properties for each storm at each point;
- Extrapolation of the hindcast and calculated extremes through the process of extremal analysis, which provides estimates of extremes associated with specified return periods (the average interval in years between events equal to or greater than the associated extremes).

### 3.2.2    Database assembly

A comprehensive file of historical meteorological data must be assembled for the specification of surface wind fields for the production of historical storms. The data fall into basically three categories: (1) archived historical surface weather maps; (2) weather observations from ships in transit; and (3) weather observations from stationary platforms and land stations.

#### 3.2.2.1    *Historical period to be covered*

Previous experience with the historical marine meteorological databases supports selection of storms from

about the past 30 years. The database for earlier periods is much less extensive and wind fields may not be specified as accurately. Therefore, the historical period which should generally be considered extends from about the mid-'fifties to the present.

### 3.2.2.2   Data sources to be included

An extensive file of historical meteorological (and sea-state if available) data must be assembled to aid in the selection of the extreme storm set. The data sources which should be utilized in this study are listed below.

The following products (or databases) should be utilized:

- Microfilm surface weather maps;
- Ship observations (e.g. COADS);
- Drill rig observations;
- Ice charts (where appropriate);
- Buoy data;
- Satellite data (where available);
- Land observations;
- Ocean Weather Stations.

Relevant data should be obtained from Responsible Members.

Measurements from stationary platforms consist of observations from moored buoys and offshore rigs. The observations from the moored buoys, mainly the buoy network of the US National Data Buoy Office, are already contained in the ship observation collections described above, since observations from most buoys are transmitted at hourly intervals over the GTS. Similarly, most observations from the offshore rigs are also transmitted over the GTS, at least at six-hourly intervals, and these are automatically processed as ship reports in the tape files.

### 3.2.3   Storm classification and storm selection

The storm selection is accomplished in three main steps:
- Selection of potentially severe storms in the past 30 years;
- Storm verification and cross-checking between different data sources;
- Storm ranking and final selection.

The storm population is then stratified into different types capable of generating extreme waves (or winds alone, depending on the application).

### 3.2.3.1   Storm selection procedures

The top-ranked storms are selected according to their ability to generate large waves (or high winds, depending on the application). This is the most important and also the most difficult task. This task requires very careful consideration of all factors which may contribute to the identification of severe events.

In general, the storm-selection methodology consists of the following processes:

(1) Selection of potentially severe storms in the period by scanning the observed wind and wave data available from the data sources. All wind and wave records greater than or equal to an assumed threshold are extracted. The threshold is established upon examination of the wind and wave series.

(2) Data collection: For each identified storm, find the records of wind observations at coastal stations, islands, fixed platforms and meteorological buoys, etc.

(3) Discretization of wind records according to the following criteria:
   (a) By direction: standard eight sector classes (i.e. N, NE, E, SE, S, etc.) are used.
   (b) For each of the selected direction sectors, wind records are stored according to maximum wind speed, duration of wind speed above the threshold, and a severity index, which is defined as the duration (hours) of winds with speed greater than or equal to a threshold speed multiplied by the average wind speed in this period (knot × hour).

(4) For each identified storm, find in the synoptic observations the maximum pressure difference within 12 hours of the peak wave for station pairs in the study area.

(5) Microfilm scan: for the identified storms in (1) to (3) above, scan the microfilm for each map file. The microfilm scan is a tedious process in which a meteorologist inspects each six-hourly historical weather map and identifies storms against threshold criteria specifically designed to capture occurrences of high winds or sea states in the study area. For each identified storm, retrieve from each map file the following properties of the extratropical cyclones responsible for the storm event:
   (a) Central pressure (hPa) and its location;
   (b) Total pressure difference (hPa);
   (c) Maximum pressure gradient in relevant direction (hPa deg$^{-1}$);
   (d) Maximum deepening rate;
   (e) Storm velocity (and storm track);
   (f) Closest approach of storm centre to the study area centre.

(6) Seek correlations between each single parameter in (2) – (4) and the maximum observed wave height in the form of linear regression estimates or simple grading schemes based upon critical thresholds for individual parameters. Using this analysis, establish a storm detection and ranking system which is applicable to recent historical data.

(7) Apply the storm selection procedure developed and tested under (5) to the total period of record. This step will probably require a complete scan of all microfilmed surface weather maps for the total period from at least one source, computer scans of wind observations from at least one of the stations cited under (2), and a computer scan of all pressure

differences over the period of record for the station pairs cited under (3).

(8) The parameter thresholds and grading scheme will have been devised to admit a coarser storm population, which may contain 1.5 to 2 times the target population. Distil the population to the required targets through careful review of the properties (maps, station observations, ship reports, cloud track winds, etc.) of each storm on an individual basis.

The final storm-selection procedure involves basically the cross-correlation and synthesis of the several storm lists developed in this study with other previous studies.

The above procedures will yield the target population of the top storms in the target area. If the wave response is sufficiently direction-sensitive that directionality need be considered in assessment of the extreme wave climate, this target population may be found to be rather small, especially if six to seven main direction sectors ultimately need to be retained in the extremal analysis. In this case an increase in the target population will be required.

### 3.2.4 Wind field analysis

#### 3.2.4.1 Approach

The wind fields of the selected storms are produced by man-machine mix wind-field analysis, a blend of surface pressure analysis/boundary-layer model winds and kinematic analysis wind fields, based on [41]. The steps of this procedure are outlined as follows:

(1) Define the hindcast period of each storm, usually about five days. This period will consist of the following sub-periods:

(a) A period of approximately 48 hours used to spin up the wave model, in which winds prior to the period of interest build up a background sea state in the model domain;

(b) A period during which the selected storm generates seas in the study areas and including always the period within ≈12 hours of expected occurrence of peak states in each area; and

(c) The period 12–24 hours after the occurrence of peak states, during which the wind field usually no longer plays a critical role in the hindcast, but which should be modelled nevertheless so the hindcast wave series will include an adequate period of wave decay at the sites of interest.

For the spin-up and the decay periods, the approach is to specify winds from the sea-level pressure analyses (although this procedure will not work Equatorward of 20° latitude — there winds must be specified by other means, such as the hurricane model described in [42]).

(2) Select, for each storm, the historical chart series which is most complete in terms of data coverage and which appears to provide the best initial-guess

specification of the time evolution of the relevant synoptic features. On a suitable overlay to the selected chart series, plot all additional spot observations assembled for this storm.

(3) Perform a gross check on continuity and consistency of successive six-hourly pressure fields, correct gross departures from continuity and gross errors in pressure gradients.

(4) The isobaric pattern on each six-hourly analysis throughout the period to be modelled is digitized with a curve-following digitizer. Isobars intermediate to the standard 4 hPa isobars are added to the analysis and then digitized to ensure a sufficient density of pressures to allow accurate recovery of the pressure field on about a 1° latitude by 1° longitude grid. Gridded pressures are then converted to winds through a marine planetary boundary layer (MPBL) model such as that of Cardone [43]. Baroclinic forcing may be supplied at each grid point from climatological horizontal air-temperature gradients appropriate to the season. The atmospheric stability term may be specified as a function of local geostrophic wind direction, or by inclusion of gridded air-sea temperature difference values where available.

The wind field specified by the pressure analysis is checked throughout the domain for continuity as well as for errors possibly introduced in the digitization process.

The wind field specified through this procedure should by no means be a crude estimate. Such wind fields have been found to provide real-time wave hindcasts considerably more accurate than those provided by automated systems such as the US Navy's Spectral Ocean Wave Model (SOWM) [44]. However, given the availability of ship reports of relatively high density (not available in real time), a re-analysis is warranted for the critical parts of each storm period.

(5) For period (b) construct a detailed continuity chart of major features (cyclone and anticyclone centres, frontal axes, wind maxima). Plotted ship wind observations are corrected for stability, anemometer height, and Beaufort scale used. Winds from coastal and island stations are transformed to effective over-water exposure.

(6) Carry out a detailed re-analysis of the six-hourly pressure field, with pressure fields re-analysed as necessary to impose consistency between wind and pressure fields. This step is to be applied basically to a sufficient domain of period (b) fields to cover the storm region of interest. It is also applied to the domain of the model fine grid. Compute winds directly at coarse- and fine-model grid points through the MPBL.

(7) For the 24- to 36-hour period centred on the occurrence of peak winds in the study areas, carry out a kinematic analysis over the domain of the fine grid

in terms of streamlines and isotachs at six-hourly intervals. The kinematic analysis should be drawn on special map overlays, which display the wind fields specified at step 6 on the fine grid, the ship or rig (if available) reports of wind referenced to effective-neutral 20 m height, and effective over-water winds transformed from winds measured at island and coastal stations within the domain of the fine grid. The kinematic analysis should be carried out completely by hand by a skilled synoptician. Streamlines and isotachs are digitized in terms of wind speeds and directions directly on the fine-mesh grid.

(8) Display the entire sequence of six-hourly blended wind fields on the coarse and fine grids as wind barbs or vectors, and display the time history of modelled winds at a number of locations in each area where measurements are available, with measured winds superimposed if available. Edit the field to correct any errors or inconsistencies. (An example of before/after analyses appears in Figure 3.11, courtesy of the NESS project.)

(9) Interpolate the six-hourly wind fields to two-hourly wind fields for input to the wave model.

### 3.2.4.2  Grid specifications

The grid should consist of a coarse grid (e.g. spacing 1.25° latitude and 2.5° longitude), and one or more nested grids over the primary target area in which the grid spacing is half that of the coarse (i.e. 0.625° latitude by 1.25° longitude).

### 3.2.4.3  System components

#### 3.2.4.3.1  Marine planetary boundary-layer model (MPBL)

A planetary boundary-layer model is applied to the isobaric analysis to approximate the near-surface wind field (e.g. Cardone [43, 45]). Planetary boundary-layer models effectively link the external factors governing the MPBL to the near-surface wind structure. Those external factors, in a steady-state horizontally homogeneous MPBL, may be listed as follows:

- Latitude (or Coriolis parameter, $f$);
- Surface roughness parameters, $z_0$;
- Air-sea temperature difference $(T_a - T_s)$ function;
- Geostrophic wind vector, $V_g$;
- Horizontal temperature gradient, $\nabla T_a$.

The models consider the MPBL as consisting of two layers. In the lower layer, the wind and temperature variation with height is governed by the effective roughness of the surface and the heat flux across the air-sea interface. The similarity theory of Monin-Obukov is applied there to provide a framework for the description of the mean wind profile. The theory is quasi-empirical in that general expressions are formulated from dimensional considerations, and

constants that appear in the expressions are derived from experimental data. Variations in the mean wind height, $z$, in the layer are related to $u_* = (\tau/\rho)$ (surface friction velocity), $z_0$ and the Monin-Obukov length, $L$, which is a function of both $u_*$ and the heat flux.

Cardone [43] showed how a measurement of mean wind speed and direction at a single height and a measurement of air-sea temperature difference could be used with theory to calculate the wind stress along the sea surface. In the surface layer, the wind profile may be written:

$$u(z) = (u_*/k) (\log (z/z_0) - f(z/L))$$

where $k$ is von Kármán's constant (0.4) and $f$ is the so-called stability function in integrated form. Numerous measurement programmes over land surfaces, where $z_0$ is well defined, have yielded various alternative forms for $f$, but in practice the forms differ little from each other and from the particular form adopted by Cardone [43]. In Cardone [45], however, the stability functions are revised to ensure realistic solutions as the external parameters drive the solution outside the range of validity of the theory. A more troublesome aspect of marine surface layer models is the proper description of the roughness parameter, $z_0$, which for a sea surface is not strictly an external parameter, but is an effective roughness, related to the stress itself as it maintains the high-frequency wave content of the sea surface, and possibly even to the low-frequency wave properties which vary considerably with the stage of wave development. Cardone [43] used the form:

$$z_0 = A/u_* + B u_*^2 + C$$

which has been since recommended by numerous investigators (e.g. Arya [46]). A form consistent with that proposed by Large and Pond [47] is now used by some models and the following form by others:

$$z_0 = u_* m/g + \text{etc.}$$

Large and Pond suggest a formulation of the MPBL which is consistent with near-neutral stability drag coefficient CDN = 1.2 (winds below 11 m s⁻¹) or 0.49 + 0.065 U10 for higher wind speeds.

Although the above formulations for the ocean surface roughness vary considerably, particularly at low wind speeds, by choosing an appropriate set of constants, the effect of choosing one formulation over another at higher wave-generating speeds appears to be minimal. (see Smith and Banke [48], Garrett [49] and Smith [50]. Over the ranges of wind speeds which are important for wave generation, the formulae fit measured wind-profile data about equally well. The choice of one form over another appears to be a matter of choosing between simplicity and computational efficiency or a desire to fit theory more rigorously.

Cardone [43] extended the similarity theory upward through the MPBL to link the surface layer wind profile to the MPBL pressure field, while taking
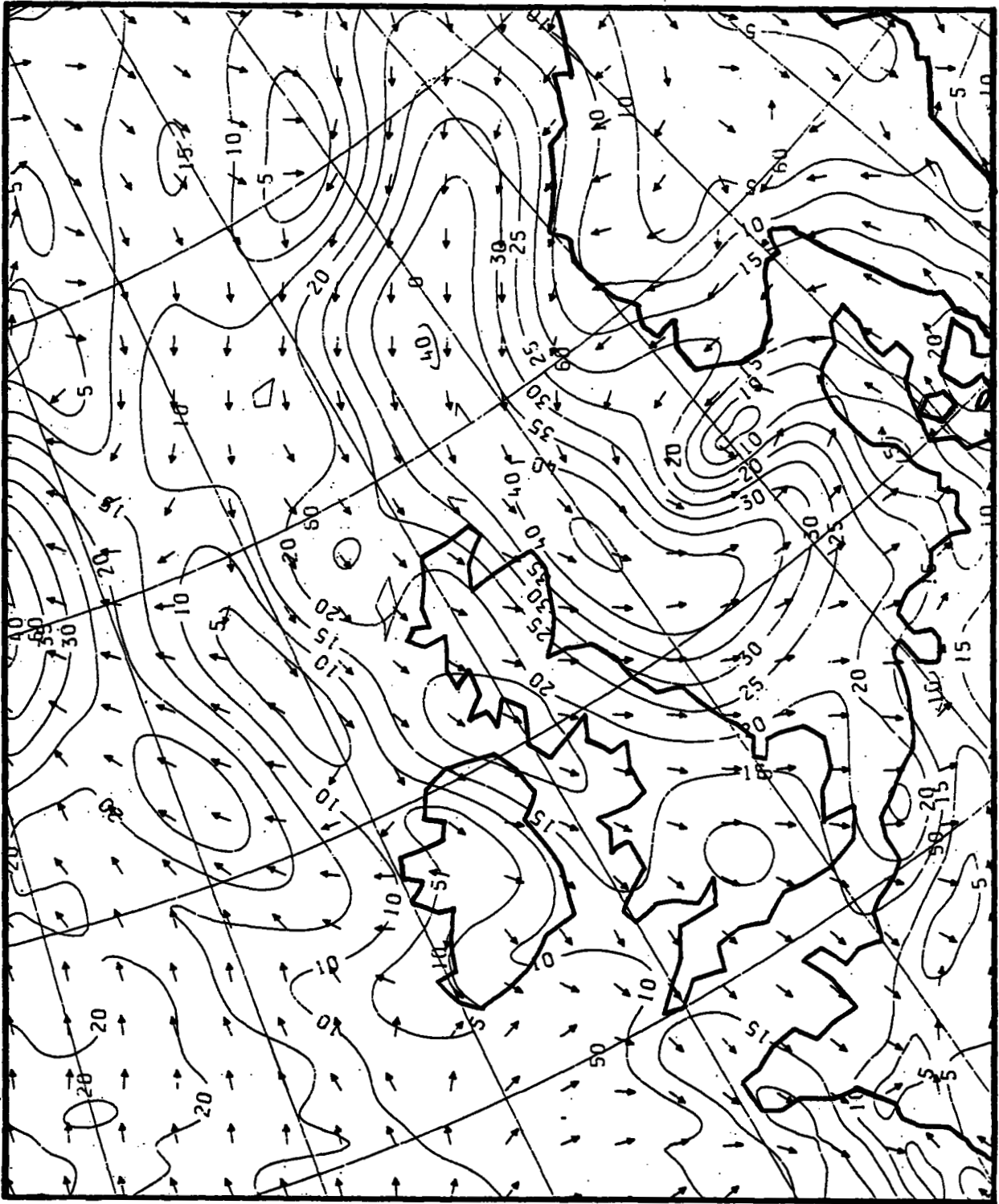
Figure 3.11 (a) -- Wind field map before manual intervention
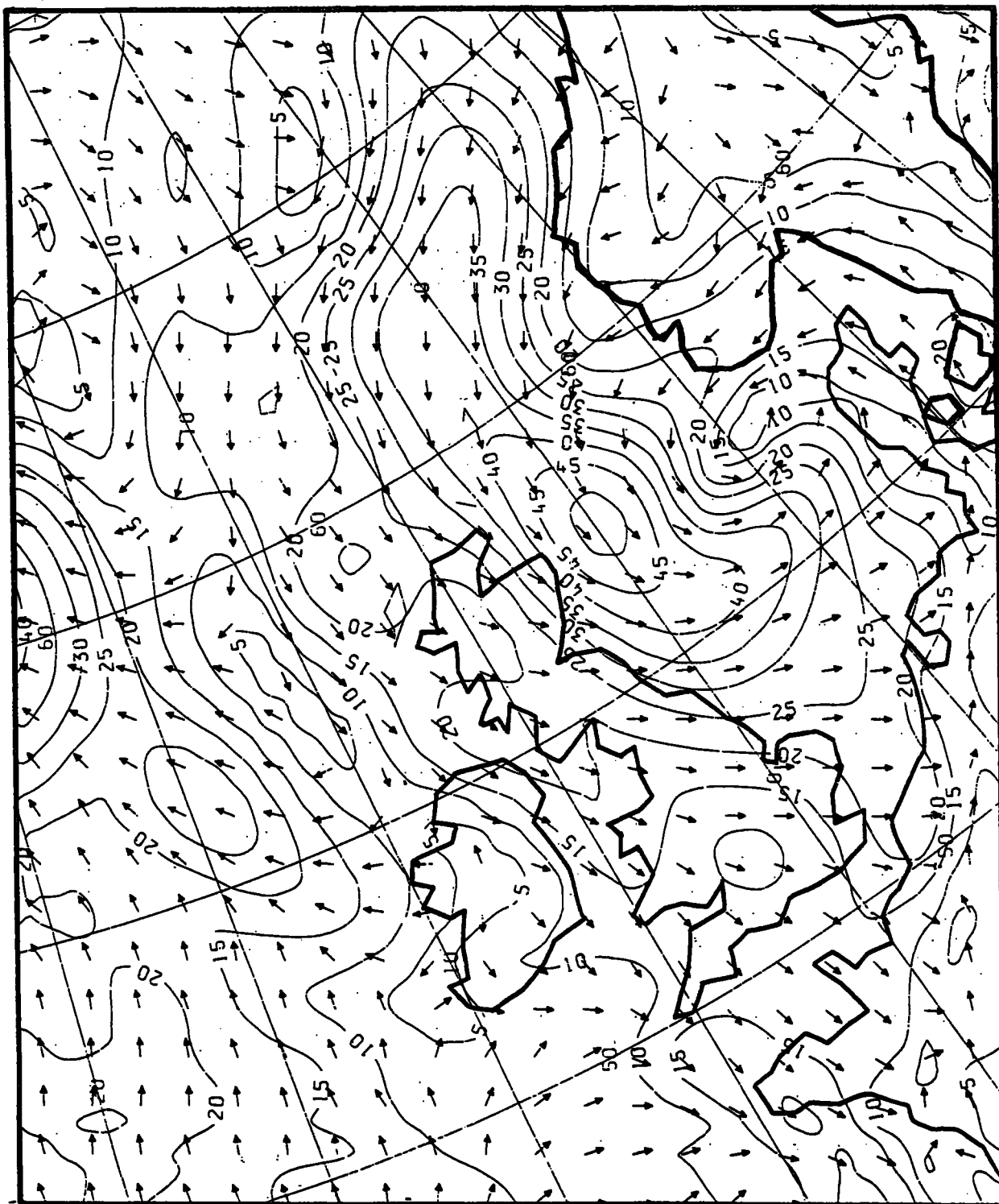
* Figure 3.11 (b) — Wind field map after manual intervention

into account atmospheric baroclinicity, which causes the pressure field itself to vary with height. The approach "patches" surface layer similarity solutions to an upper MPBL governed by classical Ekman theory, though the effects of stability, dynamic roughness and baroclinicity are combined to produce MPBL wind profiles which bear little resemblance to the Ekman-Taylor spiral. An alternative approach to describing the MPBL which has become fashionable in recent years derives from the work of Kazanski and Monin [51], who first proposed a similarity theory for the entire planetary boundary layer. The theory proposes that the geostrophic drag coefficient $u_*/|V_g|$ is a function of the surface Rossby number, $Ro = |V_g|/z_0$ and the stability parameter $\phi = - ku_*/1.L$ and a dimensional parameter describing baroclinicity such as $1/1.dV_g/dz$. The theory, of course, requires that the functions be derived from measurements, and much work [46] has been directed toward the determination of the coefficients that appear in the similarity laws proposed. Cardone's [43] MPBL is consistent with the similarity approach and produces analogous functions.

### 3.2.4.3.2 Kinematic analysis

Kinematic analysis is a tedious, time-consuming, manual process that involves the following basic steps:

- Assembly and plotting of all synoptic observations of wind speed and direction and sea-level pressure from ships and land stations at six-hourly intervals on a suitable base map projection, for the storm event (usually two to four days' duration);

- Identification and rejection of erroneous and unrepresentative reports so far as possible;

- Construction of a continuity chart which defines the movements of storm centres and fronts and other significant features of the surface wind field;

- Construction of streamlines and isotachs;

- Gridding of wind speed and direction.

Kinematic winds are extracted from the streamline/isotach analyses at the fine grid-point locations, and represent the effective one-hour average 20 m level neutral wind. The kinematic winds replace the winds derived from the pressure field in the interior of the kinematic domain, and are blended with the pressure-derived winds along the boundaries of the domain.

The kinematic winds are by far the most accurate and least biased winds, primarily because the method allows a thorough re-analysis of the evolution of the wind fields. Kinematic analysis also allows the wind fields to represent effects not well modelled by pressure-wind transformation techniques such as inertial accelerations associated with large spatial and temporal variations in surface pressure gradients and deformation in surface winds near and downstream of coasts.

### 3.2.4.3.3 Standardization of winds to effective neutral 20 m over-water winds

Wind variables supplied to a wave model at wave-model grid points should represent winds in which turbulent fluctuations of time scales less than about one hour and spatial scales less than 100 km (except near the coast) have been filtered out. The winds should also be referred to a single reference height, usually 20 m. While the possibility remains that wind gustiness or mesoscale variability plays a role in wave generation, the nature of the underlying mechanisms has not been described, and to our knowledge no contemporary spectral wave model takes rational account of these possible effects. Of more importance appears to be the effect on wave development of thermal stratification in the marine surface layer of the atmosphere.

Some modellers have adopted the simple concept of the "effective neutral" wind speed introduced by Cardone [43] to describe the effects of thermal stratification in the marine boundary layer on wave generation. The effective neutral wind speed is simply the wind which would produce the same surface stress at the sea surface in a neutrally stratified boundary layer as the wind speed in a boundary layer of a given stratification. Calculation of the effective wind at a reference elevation from measured or modelled winds and air-sea temperature differences requires a model of the marine surface boundary wind profile which incorporates a stability dependence and a surface roughness law.

The MPBL is set up to provide the effective neutral 20 m wind speed. Reports of wind speed from ships and rigs equipped with anemometers are transformed into the effective neutral 20 m values, using a file of anemometer heights of ships in the merchant fleet. For ships using estimated wind speeds, values are adjusted according to the scientific Beaufort Scale. A revised table of wind-speed equivalents is used to retrieve the 20 m wind speed and then correct for stability.

### 3.2.4.3.4 Local effects and use of land-based observations

Winds from island and coastal stations also require special treatment. The most reliable over-water/over-land wind transformations are those derived directly from paired measured data sets from closely spaced stations. The transformations, suitably stratified by wind-speed range and wind direction, would include effects associated with terrain, anemometer exposure, and local orographic effects. Time-series of winds from offshore platforms and rigs may also be used to yield transformations for other relatively nearby coastal or island stations.

### 3.2.4.3.5 Interpolation of two-hourly wind fields from six-hourly wind fields

The recommended algorithm for interpolation of winds from six hours to two hours (as required to drive the wave

model) is linear interpolation in time of zonal and meridional wind components for interpolation of wind direction, and of the fourth power of wind speed for interpolation of wind speed because wave energy scales in the same way. This scheme has been found to provide sufficient resolution in wind fields encompassing extratropical cyclones off the east coast of North America. An alternative algorithm, described below, may be adapted if errors in wave hindcasts of the validation storms are found to be attributable to excessive smoothing of winds near centres of rapidly propagating cyclones.

The alternative algorithm, which is applied first so that the standard algorithm operates only in areas remote from low centres, regards the location and radius of the principal low centres identified for a storm. High centres may also be followed, but since only moderate winds are found near highs, and errors in background winds affect wave hindcasts much less than do comparable errors in severe winds, it is not profitable to track anticyclones. In practice, the occurrence of more than two centres of increasing strength in a five-day storm is extremely rare.

In all the interpolations mentioned in this section, the quantities interpolated are $U$, $V$ and $Z = (U^2 + V^2)^2$. The wind direction is obtained by the standard goniometric formula from $U$ and $V$; the wind speed, as the fourth root of $Z$. This algorithm fails when $U$ and $V$ vanish together; in this unusual case the interpolated wind is set to zero. Experience with this algorithm suggests that the maximum wind in an interpolated field is biased low by about 0.6 m s$^{-1}$; that an isolated high wind speed in the original becomes a "cushion" of four or more moderately high speeds at contiguous points in the interpolated field; and that the wave-generating power of a gale is roughly conserved.

### 3.2.4.4    Verification of wind analysis

In order to assess the quality of wave-model predictions, it is necessary to isolate the errors (i.e. bias or any systematic errors) in the input winds which are used to drive the wave model. Graphical and statistical comparisons of the measured and modelled winds are described in this section.

### 3.2.4.4.1    Verification cases

Verification cases should be selected for each study area. These cases are selected from the events where more observed data coverage is available.

### 3.2.4.4.2    Measured wind data

Wind speed and direction (and air and surface-water temperature) records are obtained from all the rigs, buoys, etc. which were in the study area during each storm. These observations are used for the verification of the modelled winds.

All measured winds must be converted to "effective neutral" winds at 20 m above the mean sea-level similar to those used in running the wave model.

The MPBL model described previously is used to convert the measured winds at a given anemometer height into 20 m winds taking into account the thermal stratification effects.

Wind-field hindcasts are compiled for the validation storms in each of the study areas. The observed wind at a given site may be compared either directly with the hindcast wind at the nearest grid point in the model domain or after being interpolated to the measuring site.

### 3.2.4.4.3    Evaluation methods

The hindcast results at the model grid points are compared with the corresponding measured winds (after being converted to effective neutral at a common 20 m level). The three-hourly wind speeds and directions are used in this comparison. The following evaluation methods are applied.

#### Time series plots of hindcast vs. observed winds

The time series of hindcast wind speed and direction may be plotted against the corresponding observed winds at all evaluation sites for the validation storms. These plots provide excellent comparisons of the hindcast winds with the actual measurements.

#### Statistical comparison of wind hindcasts versus observations

A quantitative statistical analysis is carried out to provide an overall evaluation of the hindcast surface winds. The statistical parameters considered in this study are:

Mean error (bias) $= \Sigma(x_1 - x_2)/NPTS$;

Mean absolute error $= \Sigma |(x_1 - x_2)|/NPTS$;

Root mean square error $(RMSE) = [\Sigma(x_1 - x_2)^2/NPTS]^{1/2}$;

Scatter index $(\%) = (SD/AVE) \times 100$;

where $x_1$ is the hindcast value (i.e. model);
$x_2$ is the observed value;
$AVE$ is the mean of observed values;
$SD$ is the standard deviation;
$NPTS$ is the number of data pairs.

Targets for limiting values for these parameters should be decided in relation to the accuracy required of the forecast time series.

Linear regression analysis (and correlation) and scatter plots may also be computed.

The above parameters are calculated for each measurement site within the kinematic analysis domain for the given observations during the kinematic analysis period of each storm. In addition, overall or average values of the above parameters are calculated for all sites used in each storm. Analysis of all of these comparisons with "surface truth" data gives a measure of the reliability with which the hindcast can be used, and may highlight any problems occurring in the hindcast procedure.

### 3.2.4.5 *Archiving of wind fields*

The following hindcast gridded wind fields (given at each model grid point, on both the coarse and fine grids) should be archived:

- Wind speed in knots (effective neutral 20 m winds);
- Wind direction in degrees (meteorological notation);
- Gridded MSL pressure in hectopascals;
- Wind stress or friction velocity ($u_*$).

### 3.2.5 Wave hindcasts

A suitable wave model must be chosen to run the above selected storms. There are many worthy candidate models. For detailed description of available models the reader is referred to the WMO *Guide to analysis and wave forecasting* (WMO–No. 702).

### 3.2.5.1 *Verification of wave hindcasts*

The validation hindcasts and comparisons reveal the skill achievable in the hindcasts. The errors in the hindcast series are expected to arise primarily from wind-field errors in the source generation zone of wave energy.

### 3.2.5.1.1 *Validation cases*

Storms in each area should be selected for model validation as described in section 3.2.3.1.

### 3.2.5.1.2 *Measurements*

All available wave measurements should be obtained from automatic wave-reading systems (e.g. wave-measuring buoys, non-directional and directional, and remotely sensed wave data such as radar altimeters, SAR, HF radar, etc.). 1-D and 2-D spectral data should be obtained and used in the evaluation as described in the next section.

### 3.2.5.2 *Verification methods and graphical display*

Time series plots, error statistics and correlation should be computed as described previously in section 3.2.4.4.3.

In addition, 1-D plots of the respective observed and modelled spectra should be constructed, e.g. at peak wave height or within approximately three hours. For continuous wave measurements an appropriate moving average should be used on the recorded data (e.g. six- or seven-point moving average). The data should be represented with error bars (95 per-cent confidence).

If 2-D spectral measurements are available, they should be used to evaluate the model predicted values.

### 3.2.5.3 *Archiving of wave hindcasts*

The wave-model results for each storm should be contained in two main files:

(1) Summary of wave fields (i.e. $H_s$, $T_p$ and vector mean direction) at all coarse and fine grid points;

(2) Spectral data file which contains a header line and the 2-D spectral values (15 × 24 fields) at all grid points in the study areas. Desirable file contents are specified in the following list:

- Date: year, month, day, hour;
- Grid-point number;
- Wind speed (knots) and direction (° true);
- $u_*$ (friction velocity) or $s$ (surface wind stress);
- Significant-wave height ($H_s$) in metres and tenths of metres;
- Peak period ($T_p$) in seconds and tenths of seconds;
- Vector mean direction in degrees;
- Directional (2-D) spectral variance in m² (15 frequencies × 24 directions).

### 3.2.6 Extremal analysis

### 3.2.6.1 *Specification of extremal statistics*

From the wind/wave hindcast model, the following quantities are available at all points and at each time step:

$H_s$ significant wave height;
$T_p$ spectral peak period;
$\theta_d$ vector mean wave direction;
$W_s$ 1-hour average wind speed;
$W_d$ wind direction.

The objective of the extremal analysis is to describe extremes at all contiguous grid locations for the following variables:

- $H_s$ versus annual exceedance probability or inverse return period;
- $W_s$ versus annual exceedance probability;
- $H_m$ (maximum individual wave height) versus annual exceedance probability.

At a selected subset of grid locations, a more detailed analysis of extremes may be carried out in order to determine:

- The effective ratio of $H_m/H_s$ based upon analysis of storm build-up and decay time scales;
- Stratification of extremes on directional sector of wave approach;
- Correlation of the form $y = c_1 \times c_2$ for at least the pairs ($T_p$, $H_s$);
- Crest height, $H_c$, extremes.

One extreme-value distribution used for this purpose is the Gumbel distribution (see Appendix II for details). Extremes and confidence limits should be calculated for return periods of 2, 5, 10, 25, 50, and 100 years.

### 3.2.6.2 *Stratification of extremes*

At selected key grid points, the possible stratification of extremes on storm types should be investigated. The

hindcast population of extremes may be stratified on $\theta_d$ and separate extrapolations may be carried out on sectors (not necessarily evenly divided) containing characteristic storm types. The stratified extremes should be compared with the unidirectional statistics.

### 3.2.6.3    Extreme wave/crest-height distribution

For the points at which a detailed extreme analysis is performed, the maximum individual wave height may be estimated in each storm from the hindcast zeroth and first spectral moments following Borgman's [52] integral expression, which accounts for storm build-up and decay. The integral may be computed for two assumed maximum individual wave-height distributions: Rayleigh (as adapted by Cartwright and Longuet-Higgins [53]) and Forristall [54].

The same approach may be used to estimate the maximum crest height at a site in a storm using the empirical crest-height distribution of Haring and Heideman [55]. The median of the resulting distributions of $H_m$, $H_c$ may be taken as the characteristic maximum single values in a storm. The mean ratios of $H_m/H_s$ and $H_c/H_s$ should be calculated and used to develop a mean ratio to provide extremes of $H_m$ and $H_c$ from fields of extreme $H_s$.

### 3.2.6.4    Presentation of extremes

Fields of extremes of $H_s$, $H_m$, $W_s$ should be tabulated and displayed as field plots (contour plots if necessary) of numerical values.

Results of detailed extreme analysis at selected grid locations should be presented in tabular form for each analysed point and in graphical form. The graphical display of extrapolations shall include the fitted line, the confidence limits on the fit and the fitted points.

## 3.3    HINDCASTS OF ICING POTENTIAL

### 3.3.1    Freezing spray

Because of the lack of observed data on freezing spray (or superstrucure icing), the first step in assessing the spray-icing climate of an offshore area is to quantify the frequency and severity of potential icing conditions. Most climatologies and design studies published to date are based on hindcasts of "freezing spray potential", using one of a variety of empirical or simple physical models. These models use atmospheric and oceanographic parameters to compute an icing rate calibrated for a particular class of ship, usually small- to medium-sized fishing vessels. The term "potential" is used because these simple models are unable to take vessel parameters such as size, speed and heading into account. Exactly what the potential icing rate represents depends on the data used to develop or calibrate a particular model. Recently, more sophisticated physical models taking vessel speed and heading into account have been developed (e.g. Zakrzewski and Lozowski,

[56]). However, such models must still be calibrated for a specific class of vessel.

Freezing-spray potential is usually expressed as a single rate of ice thickness increase (e.g. cm h⁻¹). Some models use only wind speed and air temperature; others include sea-surface temperature, wave height and salinity. Because the spray-icing process is most sensitive to wind speed and air temperature, most of the available techniques provide internally consistent pictures of spatial and temporal variation in the frequency of potential spray-icing conditions under open ocean conditions. However, it is much more difficult to reach conclusions about the severity of icing from discrete icing rates, since this depends on additional factors such as vessel size, speed, and heading, and exposure time to icing conditions.

The best known simple methods for estimating icing potential include the Sawada [57] and Mertins [58] nomograms which predict icing severity classes based on empirical data, and the physically based models of Kachurin et al. [59] and Stallabrass [60] which produce icing-rate estimates. More recently, Overland et al. [61] used observed icing data and physical considerations to develop a technique for estimating icing severity categories. The main weakness of the empirical nomograms is that they are site- and vessel-specific. It is generally agreed that the Mertins' nomogram and its derivatives (e.g. Wise and Comiskey, [62]) greatly underpredict icing severity, and should no longer be used in climatological applications. The Sawada nomogram is based on icing data from Japanese fishing vessels under open-ocean, cold water conditions, and may have limited applicability.

The Kachurin et al. nomogram is recommended as a robust, physically-based method for estimating freezing-spray potential. It does not contain extensive empirical correction factors and has been found to perform well in a variety of environments. In contrast, the Stallabrass model contains empirical corrections to droplet flight time and spray liquid-water content based on calibration with vessel icing reports from the east coast of Canada, while Overland et al. incorporated trawler icing data from the Gulf of Alaska into the development of their icing algorithm.

The last quadrant of the Kachurin et al. nomogram includes a calibration factor to convert from a theoretical icing rate on a cylinder in cm h⁻¹ to a vessel icing rate in tonnes cm h⁻¹. However, since this conversion is close to unity, the nomogram output can be simply read as cm h⁻¹. Nomogram output in cm h⁻¹ has been found to agree well with observed ship-icing rates from several areas of the world. A categorical comparison of the Kachurin and Overland models with vessel icing data from Pease and Comiskey [63] showed the Kachurin nomogram to perform almost as well as the Overland algorithm. This was encouraging considering the evaluation data had been used in the development of the Overland model. In addition to its generality, a major advantage of the nomogram over the

Overland technique is that it includes wave height as an input variable. This is important for estimating icing potential in fetch-limited environments. Makkonen [64] also pointed out that the Overland model is based on a physically inappropriate predictor.

Icing severity classes are usually used to describe the spray-icing climatology of a marine area. The specification of these classes is largely subjective, and depends on the size of vessel under consideration. Overland et al. proposed three severity classes which are appropriate for the small- to medium-sized fishing vessels most at risk during icing conditions:

• Light icing < 0.7 cm h$^{-1}$;

• Moderate icing 0.7–2.0 cm h$^{-1}$;

• Heavy icing > 2.0 cm h$^{-1}$.

### 3.3.2    Aircraft icing

For marine-related aircraft operations such as search and rescue, and support of offshore oil exploration, low-level icing below about 2000 feet is a major concern. Unfortunately, most of the published aircraft-icing climatologies are for considerably higher altitudes. Ingram and Gullion [65] presented an atlas of aircraft-icing potential at 700 and 500 hPa based on air temperature and cloud cover information obtained from aircraft. Potential icing conditions were considered to exist when cloud amounts of >5/10 were encountered with air temperatures <0°C. These charts were found to overestimate actual icing frequency grossly, and were revised by Katz [66]. The lowest altitude of Katz's seasonal icing-probability maps is 5000 feet.

A major obstacle to estimating in-cloud aircraft icing potential over marine areas is a lack of data: the simplest icing potential techniques require, as an absolute minimum, profiles of air temperature and moisture. These are available at Ocean Weather Stations (OWS) and selected coastal stations. However, coverage is sparse and most of the OWS data end in the 1970s. A more recent source of data which may be applied to aircraft icing is the Naval Environmental Data Network (NEDN) data set. This contains six-hourly fields of numerical objective analyses and prognoses produced by the US Navy Fleet Numerical Oceanography Centre. Air temperature and dewpoint-depression data are available for the surface, 1000 hPa, 925 hPa, 850 hPa, 700 hPa and 500 hPa, on a 318 km grid over the northern hemisphere. An evaluation of these profiles with observed data shows generally good agreement up to the 500 hPa level; however, there is a noticeable decrease in accuracy above 850 hPa. A detailed review of available techniques and data sources for climatological estimates of fixed-wing and rotary aircraft in-cloud icing potential over marine areas is given in Roebber [67].

### 3.3.3    Atmospheric icing

Estimates of the frequency of atmospheric icing conditions can be obtained from the present weather code reported by

ships, and from coastal station synoptic reports. Freezing precipitation and rime icing are reported directly in the marine present weather code. Wet-snow accretion depends on a number of factors including snow water content, precipitation rate, air temperature, relative humidity and wind speed. However, Admirat and Sakamoto [68] indicated that the critical factor was having air temperatures in the 0°C to +2°C range. An estimate of the frequency of wet snow conditions could therefore be obtained from the joint occurrence of continuous snowfall and air temperatures in the range of 0°C to + 2°C. Makkonen [69] presented a simple technique for estimating wet-snow accretion on structures using precipitation, air temperature and humidity data. His criterion for wet-snow accretion was the joint occurrence of snow and wet-bulb temperatures >0°C.

## 3.4    HINDCASTS OF ICE ACCRETION LOADS

### 3.4.1    Freezing spray

The need for more detailed assessments of icing loads and the safety of offshore oil exploration activities in cold environments has provided the main impetus for recent developments in marine icing modelling. The current state of saline ice-accretion theory has advanced to the point where the latest models show excellent agreement with experimental ice accretions grown in wind tunnels. However, performance is not as good when predicting ice loads on ships and complex offshore structures because of a number of key knowledge gaps. These include spray-generation mechanisms and characteristics (spray frequency, duration, liquid water content, droplet-size distribution and droplet trajectories), wind-flow distortion and shadowing, transport of shed water, and uncertainties in heat transfer. The situation is further complicated in that there are no high-quality icing data sets available for model evaluation and calibration. A detailed discussion of marine ice-accretion modelling and critical knowledge gaps is given in Jessup [70].

In spite of these difficulties, there are a number of recently developed models which have shown some success at predicting ice loads on vessels and offshore structures. These include the ship spraying and icing model of Zakrzewski and Lozowski [56] and the drilling-platform icing models of Roebber and Mitten [71] and Vefsnmo et al. [72]. The application of physical icing models to provide ice-load design information requires a considerable amount of high-resolution input data. Time series of air temperature, wind speed, dew-point temperature, sea-surface temperature, wave height and wave period are required with at least a three- to six-hour resolution. Salinity information is not as critical, as this does not exhibit rapid temporal fluctuations, and representative values can be obtained from sources such as the World Ocean Atlas. In many areas of the world, ice-load hindcasting will also have to take into

account the effect of seasonal sea-ice cover on wave growth and the amount of open water.

The main data sources suitable for hindcasting ice-accretion loads are Ocean Weather Stations, lightships, drilling platforms and specialized hindcast data sets such as the NEDN described in section 3.3.2. However, most of these data sets have fairly short periods of data coverage, which is likely to pose a problem for estimating 100-year return-period design values. There is very little in the way of published icing-load climatologies because of the lack of suitable input data sets and of the computer resources required to run complex physical models. Ashcroft [73] presents one example where a platform icing model was used with 15–30 years of lightship data to calculate 50-year return-period ice loads on drilling platforms in the southern North Sea. Computer expense can be reduced by using a simple icing-rate model to screen out the most significant icing events for more detailed modelling. This approach is being used to define design ice load and anti-icing heating requirements for drilling platforms in the Barents Sea with the computationally intensive time-dependent model of Vefsnmo et al.

### 3.4.2    Atmospheric icing

Climatological models have recently been developed for estimating ice loads on transmission lines taking into account all three sources of atmospheric icing — rime, freezing precipitation and wet snow. Models such as those described by Makkonen [74] and Finstad et al. [75] can be readily applied to offshore structures without much modification provided at least three-hourly synoptic weather information is available (hourly information is preferable). The main modification required is a method to estimate precipitation intensities as these are not routinely measured at sea. Table 3.8 presents an example of the present weather code intensity assignments used in the Roebber and Mitten [71] platform icing model.

TABLE 3.8

Example of present weather code — Precipitation intensity assignments used in the offshore atmospheric icing model of Roebber and Mitten (1987)

| Code | Precipitation type | Intensity of icing $(mm\ h^{-1})$ | Droplet eff. diam. (mm) |
|------|--------------------|-----------------------------------|-------------------------|
| 56 | Slight freezing drizzle | 0.1 | 0.2 |
| 57 | Moderate-heavy freezing drizzle | 0.3 | 0.6 |
| 66 | Slight freezing rain | 1.8 | 1.0 |
| 67 | Moderate-heavy freezing rain | 4.0 | 2.0 |
| 70 | Slight, intermittent snow | 3.6 | 2.0 |
| 71 | Slight, continuous snow | 7.1 | 2.0 |
| 72 | Moderate, intermittent snow | 7.9 | 2.0 |
| 73 | Moderate, continuous snow | 15.7 | 2.0 |
| 74 | Heavy, intermittent snow | 10.2 | 2.0 |
| 75 | Heavy, continuous snow | 20.3 | 2.0 |
| 85 | Slight snow showers | 1.8 | 2.0 |
| 86 | Moderate-heavy snow showers | 4.5 | 2.0 |

As regards fog depositing rime, codes 48 and 49, there are a number of empirical techniques available for estimating liquid water. These are discussed in Kolomeychuk and Castonguay [76]. Unfortunately, most have been derived for terrestrial fogs, and may not be valid for marine areas. The equation of Kunkel [77] derived from advection fogs in Massachusetts is likely to be more appropriate for offshore areas:

$$W = (-\ln(0.02)\ /\ (vis \times 0.1447)\ )^{1.136}\ g\ m^{-3},$$

where $w$ = liquid water content and vis is horizontal visibility in metres. A median volume droplet diameter of 0.02 mm is typical for coastal advection fogs.

Makkonen [69] provided a simple expression for estimating wet snow loads from visibility data. The wet-snow criterion described in section 3.3.3 is checked first to determine if wet-snow accretion is taking place, then the rate of accretion, $I$, is estimated from visibility data by:

$$I = 2100\ V_m^{-1.29}\ g\ m^{-2}\ s^{-1}.$$

There are a greater number of uncertainties in applying atmospheric icing models offshore than at land stations, the most important being associated with the estimation of characteristic liquid water contents and droplet sizes typical of the offshore environment. However, these uncertainties are unlikely to be critical, since atmospheric icing is usually only a minor source of ice loading on vessels or offshore structures. A detailed discussion of application of atmospheric icing models to offshore structures is given in Makkonen [78].

### 3.5    STORM SURGES

A climatology of both negative and positive storm surges is required by a number of users. For example, civil engineers designing cooling water intakes for coastal power stations often need an estimate of the greatest negative surge possible over a very long time period. For a nuclear power station, a storm event which caused the cooling intake to be above water level for even a short period of time could be very dangerous. Shipping-route planners and harbour designers are also interested in negative surges because heavily laden ships navigating shallow waters often have minimum bottom clearance. A decrease in overall water level could remove that slender clearance. The design of sea defences and harbours must take positive surges into account, combining such events with the incidence of high tides and wave activity. Building construction and setbacks along coastal sites are often dictated by the climatological limits to storm-surge levels.

Where long-term water-level data are available for a particular coastal site, these can sometimes be used to estimate the risk of storm surges using the usual extreme-value analysis techniques. However, water-level data collected from one site for estimating storm surges cannot easily be used at another, as the shoreline geography and bottom topography have a

controlling influence on the surge. In most cases, climatological information together with physical models must be used to predict the likelihood of surges.

        In principle, a steady-state wind-induced change in water level is proportional to the wind stress and the length of the water body over which the wind acts, and is inversely proportional to a characteristic water depth of that water body. The transient response of the water level near shore can be considerably greater than the steady state. The non-steady response of a water body is further complicated by the effect of bottom topography and the funnelling effects of some coastlines. Because of this, the duration and evolution of extreme wind events constitute an extremely important factor. The response of continental shelves and lakes to wind and pressure forcing has been the topic of much research and modelling in recent years. The field is highly specialized. Murty [79] has published an extensive review on the subject, and the USACE Handbook [80] provides a basis for practical applications.

        Climatological applications for practical purposes are usually limited to the development of suitable climatologies of over-water extreme wind series and to the selection and developing hindcasts of extreme storm events to be used for driving a coastal circulation/surge model.

## 3.6    TROPICAL CYCLONES

In the early days of sailing ships (pre-steam power and pre-wireless) many unsuspecting ship captains suffered the ravages of a hurricane, losing their ships, crews and lives. Reports during this period, many of them made at quite a distance from the centre of the storm, have made it possible to reconstruct the most likely tracks of some of these historical tropical cyclones. Many of these tracks have been reconstructed back into the mid- to late 1800s for the six major basins. Although a number of these early tracks are doubtful, and many early storms remain totally undetected, the available tracks still provide a climatological reference for preferred paths and estimating damage (loss of ships and cargo) for that period. With the advent first of radio communication and later of aerial reconnaissance, knowledge of the positions and movements of tropical storms became much more exact. Today weather satellites make it possible to locate and track the movement of virtually all tropical storms. Thus, since the late 1960s climatological records have been of the best quality.

        Over the years various countries affected by tropical storms have published studies showing the storm tracks for a given historical period for which data were available in their regions of concern. A number of these are listed in the references and have been used in establishing digital global data sets.

        In the early 1970s the US National Climatic Data Center started compiling a global digital data file of tropical storm tracks showing 12-hourly positions and other information. These records became the database

for the *Mariners Worldwide Climatic Guide to Tropical Storms at Sea* [81]. Since the publication was printed the digital database has been updated every three to five years. The period of record for each basin is as follows:

| Basin | Earliest track information | First year of relatively good storm surge information |
|---|---|---|
| North Atlantic | 1871 | 1899 |
| Eastern North Pacific | 1949 | 1965 |
| Western North Pacific | 1884 | 1953 |
| South-east Pacific and Australia | 1897 | 1956 |
| South Indian | 1854 | 1939 |
| North Indian | 1877 | 1877 |

The concept of a standard global tropical cyclone data set was embraced by WMO in 1979 when its Eighth Congress endorsed action taken by the Commission for Atmospheric Sciences (CAS) and the Executive Committee* on the development of the WMO Programme on Research in Tropical Meteorology, as embodied in Resolution 23 (Cg-VIII). The thirty-first session of the Executive Committee met immediately after Eighth Congress and gave further consideration to the development of the implementation plan. This led to an informal meeting of experts, at Colorado State University, which recommended a uniform system of collecting global tropical cyclone data that could be archived at a place such as WDC-A for meteorology and used for tropical cyclone research and applied climatology. The Tenth World Meteorological Congress (Geneva, May 1987) agreed on the designation of Regional/Specialized Meteorological Centres (RSMCs) within the structure of the World Weather Watch (WWW), in the context of the WMO Second Long-term Plan (SLTP), in replacement of the Regional Meteorological Centres (RMCs), with a view to promoting the fulfilment of the regional requirements for geographical and/or activity specializations. At its fortieth session (Geneva, June 1988), the WMO Executive Council, in response to recommendations made by CBS at its ninth session (Geneva, January-February 1988), adopted the procedures for the designation of RSMCs and the redesignation of existing RMCs as RSMCs. At the same time, it designated the meteorological centres of Miami, New Delhi, and Tokyo as RSMCs with activity specialization in tropical cyclone analysis, tracking, and forecasting effective from 1 July 1988. Nadi, Fiji and Réunion (France) were proposed by the regional tropical cyclone bodies as RSMCs with tropical cyclone activity specialization for the South Pacific and the South-west Indian basins, respectively.

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* Now Executive Council

In March 1989 the CAS Working Group on Tropical Meteorology recommended adoption of a format devised specifically for international exchange of tropical cyclone track information based on six-hourly positions. Now all that is required is to establish the necessary mechanism so that RSMCs can transfer their annual basin tropical-cyclone information in this standard format to some central facility to be digitized and made available to WMO Members through the World Data Centres A and B. In the meantime, interested parties may contact either the National Climatic Data Center, Asheville, North Carolina 28801, to purchase a copy of its digital global database, or one of the RSMCs for regional data.

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# APPLICATION OF MARINE CLIMATOLOGICAL DATA
# IN SUPPORT OF MARINE ACTIVITIES

## 4.1 INTRODUCTION

Climatological data are generally used in support of marine operations at the planning and contractual stages, i.e. when initial decisions have to be taken so that the project can be developed or a task planned. Typically, such decisions are related to the most suitable time of year to carry out a particular task, the advantages or disadvantages of travelling along different routes between two landfalls, and potential loss of working time, or "downtime", which should be allowed for in any tender for a contract. A definitive answer is not always available on account of limitations imposed by the data, but some guidance can be given.

Ships are often chartered on the basis of maintaining a stated average speed throughout a voyage. The operator and charterer normally agree on this speed when the contract is drawn up. Some allowance is made for the probable effects of adverse weather conditions along the chosen route. Thus the charter speed for a ship engaged to ply the most direct route across the North Atlantic in winter will be lower than for the same vessel steaming on a route via the Azores. It is possible to estimate the probability of encountering adverse conditions by using climatological records from Voluntary Observing Ships (VOS). However, it must be said that this is not usually done, unless the voyage duration is particularly critical. Most operators tend to make a small but standard reduction in charter speed according to their previous experience.

There is a need, in some cases, for an assessment of the probability of entering port without delay and safely handling cargo on arrival. This may be done by examining the frequency of occurrence with which limiting conditions are exceeded at different times of year. Parameters to be considered include winds, waves, visibility, rainfall, temperature and humidity. The incidence of typhoons or thunderstorms may also be important. If the probability of encountering a delay of a specified duration is required, a suitable continuous series of observations from the port area must be accessed. Ship observations are random in space and time and do not give a satisfactory indication of duration statistics.

There are two distinct uses of climatological data in ship routeing: the first in a planning role, the second entirely operational. Often there is little choice in the general route to be taken and savings in operating costs or increased passenger comfort can be achieved by small departures from route to avoid locally unsuitable conditions. Advice regarding such departures is provided by ship routeing services using forecast information. Under certain limited circumstances, however, a major decision must be made regarding choice of general route. This is especially true for sailing boats/ships and for slow-moving vessels such as tugs with tows. While for sailing ships the distributions of wind speed and direction are main factors, wave height and direction are more important for motor vessels. In both cases sea currents should be taken into account, as well as the likelihood of adverse or dangerous conditions such as fog and storms or hurricane frequencies along the proposed routes. In this case, climatological data can be used to assess the long-term average effects of weather on vessels plying the alternative route during different seasons of the year. This analysis will not guarantee that a particular vessel sailing a chosen route on a single occasion will benefit but it will show the gain or loss of fleet operation over a number of years. Similarly, ships operating in the northern North Atlantic travel different routes at different times of the year to avoid ice.

Climatological data are also used in the day-to-day routeing of ships because conditions can be forecast numerically for several days ahead on a routine basis. Therefore, on long passages, the advised route beyond the forecast period must be calculated on the basis of climatology. This is not a particularly satisfactory solution, because the climatological average does not reflect the variations from the norm which affect the vessel.

Mineral exploration at sea usually develops in two distinct phases, the first involving seismic survey, the second sampling the more promising areas, by drilling in the case of oil or gas. Seismic survey is weather-sensitive because a vessel must make a series of transits of the area in question while towing an acoustic source and a string of hydrophones. There is an operational limit upon the wind and wave conditions which can be tolerated for both surface and deeper towing. When deciding upon the time-scale, and hence cost, of the survey, allowance must be made for the time likely to be lost due to adverse weather at the time of year concerned. The average number of hours lost can be derived from ship data, but the durations of spells of downtime can be extracted only from a continuous record from a fixed platform (or by hindcasting).

Sampling of promising areas is often carried out from a temporary or mobile structure. In the case of oil and gas this may be a drill ship, semi-submersible rig, or jack-up. Apart from likely downtime there is a requirement to assess the extreme wind and wave which the structure must withstand from the design point of view. In

many cases this design extreme will not be the all-year value, but may apply only to the more clement summer months. The extreme can be estimated by fitting an appropriate extreme-value function to the distribution of winds and waves for the season concerned.

It is extremely important to assess the effects of waste disposal at sea, whether by dumping from ships or outfalls from the coast. In the case of dumping in deep water, marine climatological data are generally relevant only when pollutants have surfaced. Deep ocean currents, however, are partially driven by global marine wind patterns. Climatological ocean currents measured by ships' drift are appropriate for objects at depths of a few metres below the surface. In some cases pollutants on the surface tend to move with the wind-induced surface current, and climatological winds may be used to assess the probability of material reaching a particular area in the long term. It is necessary to estimate the drift velocity in terms of the surface climatological wind, but this approach will not give a trajectory for any particular case. In theory it is possible to derive individual trajectories using historical wind data (or hindcasts) but the calculations are subject to fairly large errors. Sub-surface currents, however, may also play a significant role in moving pollutants. Coastal outfalls are strongly affected by tidal and rather less by wind-induced currents.

The use of the sea for recreation is steadily increasing and although the potential for capital loss is not as high as that in some marine-based industries, the hazard to life due to adverse weather can be high. The major contribution to safety is inevitably made by more accurate forecasts, but climatological data can be used in planning activities and designing equipment. Wind and wave data are used more frequently, but the range of activity is so diverse that many other parameters are required as well. Visibility, air and sea temperatures and even cloud cover may be useful in some cases.

Much of the interest is concerned with coastal regions, but there is also a need for climatological data to assist with the strategy of long-distance deep-ocean yacht races. Vessels competing in such races are often banned from receiving the services of ship routeing experts during the race. However, they are permitted to plan the routes to be taken, using climatological data to identify those areas which on average exhibit favourable winds and waves.

Climatological data can be used to assess the average downtime likely to be experienced by different components of search and rescue (SAR) service, and hence the different resources which must be committed to maintain overall SAR cover. Recent but historical data can also be used, to some extent, to estimate the trajectory of an unpowered survival craft e.g. an inflatable dinghy. However, the factors governing the motion of such craft are complex and attempts at tracking often produce results of dubious quality. A typical enquiry of this type might involve the disap-

pearance of a yacht in mid-ocean with a substantial delay before initiation of SAR action and a requirement to limit the search area.

In the sections which follow, a few descriptions of of marine climate applications are presented. In many respects, the marine area borrows techniques or applications from the wide variety of applications developed for use on land. Together, they form a body of literature and techniques, of which many are included in the WMO/WCAP Climate Applications Referral Service – CARS database.

## 4.2    FREIGHT SHIPPING

Cargo shipped by sea-going vessels to distant destinations is always subject to some degree to the effects of meteorological conditions, which often affect the quality of the cargo by causing its deterioration. The types of damage caused by unfavourable meteorological conditions are many and varied: high humidity may cause metal parts to corrode, and when coupled with high temperatures may ruin paint coatings. Specialists in the field attribute 25 per cent of the losses experienced in freight shipments each year to meteorological conditions. More than 90 per cent of the two to three million types and varieties of freight are sensitive to meteorological factors. Humidity directly contributes 10 to 20 per cent of the losses, i.e., almost one in five or ten occurrences of spoilage is due to high humidity.

Foodstuffs in particular are extremely sensitive to environmental conditions. Approximately 90–95 per cent are temperature-sensitive, and 60 to 70 per cent are sensitive to humidity. Various types of foodstuff may also suffer biological damage by mould and bacteria, which become active in high temperatures and humidities. For some cargoes the effects can also be dangerous because of the possibility of spontaneous combustion. Various microclimatic conditions arise in ships' holds, which in turn respond to conditions outside. The upper holds are directly affected by solar radiation and air temperatures, while the lower ones, which are usually below the waterline, are influenced by sea temperatures. Only refrigerated holds are protected from the effects of temperature and humidity to any significant degree.

To improve the environment in the hold, some vessels are equipped with active ventilation systems supplying the holds with outside air. However, the cargo is then directly affected by the outside air temperature and humidity. Joint research carried out by the former USSR and GDR determined the quality of fruit and vegetable cargo to be be influenced by a number of factors: air-change frequency, number and arrangement of ventilation outlets, airflow rate within the stack of freight, air parameters (temperature, humidity and dew point), direction of shipment, season and length of voyage, climatic regions en route, stowage, stacking, and materials used for packing.

Another way of reducing the harmful effects of outside conditions is through the use of hermetic

packaging. This leads to significantly higher costs, however. Finally, one may choose to alter the routes used to ship fruit, vegetables, and other loads highly sensitive to marine meteorological conditions, so that they pass through the most suitable climatic zone.

In order to ship freight with minimal losses due to outside meteorological conditions, detailed planning based on the application of comprehensive meteorological information is needed. This information must be presented in a convenient form for the user, as specially tailored climatological summaries. By means of specially prepared climatic information for sea and ocean areas, plans can be made in advance for a given type of cargo, i.e., the most probable hold microclimate, the ventilation regime and the position of the load can be projected. In fact, it may even be possible, by taking the current synoptic situation into account, to work out the most advantageous route for a specific shipment. Climatological information presented in the traditional mean monthly multi-year form, however, is not very good for this purpose. The information is best presented in the form of statistical characteristics: the probability distribution for meteorological factors on various scales, quantiles for various probabilities and bivariate probability distributions (complexes) for the meteorological elements which are most significant in terms of shipment quality. The following examples demonstrate some practical ways of applying marine meteorological data to shipping freight.

### 4.2.1 Climatic summaries of shipping routes

In summarizing marine meteorological information in the form discussed above, a series of reference guides have been compiled under the title *Characteristics of the hydrometeorological conditions along shipping routes* [1, 2, 3], containing the following information:

- Air temperature;
- Water temperature;
- Dew-point temperature;
- Absolute humidity;
- Water vapour pressure;
- Relative humidity;
- Wind speed;
- Total cloud cover;
- Air temperature — relative humidity;
- Air temperature — total cloud cover.

For these purposes, marine meteorological information is summarized for sections of the route passing through homogeneous climatic zones. Each meteorological parameter is represented by the following selection of statistical characteristics with a resolution of a month:

- Probability tables;
- Frequency tables;

- Quantile tables corresponding to proportional frequencies 0.01, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95 and 0.99;
- Mean values.

Reference guides also give information on the length of voyage segments and the average time taken to cover those segments, which makes it possible to assess the average time a vessel will spend in any particular set of meteorological conditions.

Using the information in the reference guides, the following types of problem can be solved:

- Determining the average time a vessel will spend in good (or bad) conditions;
- Determining the best month or season for shipping particular cargo;
- Determining the most probable or the extreme meteorological conditions the vessel and its load may encounter;
- Determining with a particular degree of confidence the temperature and humidity conditions the cargo and its packaging will experience;
- Determining the probability of the vessel encountering any particular meteorological conditions of interest in terms of load shipment (for example, what the probability of deck overheating is, i.e. the probability of cloudless or of only slightly cloudy weather coupled with high air temperatures).

### 4.2.2 Determination of the meteorological conditions within the hold as functions of outside conditions

Whereas references [1], [2], and [3] contain the statistical characteristics of outside climatic conditions, reference [4] permits assessment of microclimates in holds (without active ventilation systems) and containers with reference to known outside climatic conditions.

Exchange of heat and moisture with the environment through the hold walls depends on how hermetic the holds are and on the characteristics of their boundary surfaces. Temperature conditions in an empty hold follow fluctuations in outside air temperature and net radiation with some degree of inertia and phase lag. In sunny weather, maximum air temperatures in the upper regions of the hold may be from 20 to 30°C higher than the maximum outside ambient air temperatures. In large containers subject to strong heating by intense direct sunlight, the relative humidity may drop to 10 or 20 per cent. If there is a load, the thermal capacity of the hold is much higher. In a loaded hold, the type of load and its absorption and desorption coefficients affect air humidity conditions, the most extreme conditions occurring when fruit and vegetables are being transported.

Using reference [4], we can solve the following problems:

- Determination of in-hold air temperature probability distributions;
- Determination of the mean and extreme in-hold temperatures;
- Determination of in-hold air humidity probability distributions;
- Assessment of mean and extreme humidities or dew-point temperatures in the upper regions of containers;
- Assessment of extreme temperatures in containers with varying loading percentages by volume;
- Assessment of temperatures within the load on arrival after various types of change in external air temperatures (linear or periodic).

### 4.2.3 Using marine climatology to develop safe and secure techniques for transporting freight by sea

#### 4.2.3.1 Shipping fruit and vegetables in ventilated vessels

The most frequent requirement is for shipping fruit (e.g. citrus) from tropical and subtropical latitudes to ports farther north. Reference [5] presents the optimum air temperature, relative humidity and mobility parameters for ensuring safe transport of citrus fruit without refrigeration for 17 to 18 days. Reference [6] shows how external conditions affect spoilage of fruit and vegetable cargo from Cuba to the Baltic ports. It was established that the natural loss and waste depend on the initial quality of the fruit, the mass of the load, the length of the voyage, and total temperature effects, temperature being the most critical. Thus, when citrus fruit is transported in April, the total effect of temperature is 1.3 times greater than in January or February, and natural losses increase by a factor of 1.4 to 1.5. Correlation coefficients between natural fruit losses and total temperatures range from 0.84 to 0.90. On the basis of these data, it is recommended that citrus fruit be transported in January, February, or early March (from Cuba to St Petersburg).

#### 4.2.3.2 Technology of securing loads for protection against mechanical damage due to rolling and pitching

In calculating how to secure and protect the cargo, wave data and the motion of the ship must be taken into account together with the mass and position of the load [7]. This means that we must study sea and swell conditions along the route in detail, and from these parameters calculate the roll and pitch of the ship. The task is much easier where climatological wave data are available, allowing for advance planning and proper packing and securing techniques to be utilized. During the planning phase, hazardous wave conditions, i.e. events which rarely occur, must also be considered. Here, climatological data on maximum (or near-maximum) wave-height parameters are especially important. Climatological data

on wave conditions are also important in developing techniques for transporting bulk loads.

#### 4.2.3.3 Selection of optimum trans-oceanic routes for shipment of freight

The problem of selecting the correct course for a vessel on the high seas is a complex one. The main principles behind the selection are based on comparison of the following indices for the routes:

- Overall length;
- Total fuel used or fuel used per unit distance;
- Mean speed of vessel over the entire route;
- Transit time;
- Number of stormy days during the transit.

In the final analysis it comes down to the cost of the voyage proportional to the transit time. However, shipping practice shows that routes which are optimum from the point of view of conditions for navigation are sometimes not suitable because of significant load losses due to adverse conditions of temperature and humidity over all, or part, of the route. The problem of developing a method for making an economically based selection of trans-oceanic shipping routes is a rather difficult one.

One approach to solving the problem is shown in the following example: choosing a route for shipping citrus fruit from Cuba to St Petersburg. A similar approach can be used for other routes and other loads.

The optimum route for shipping fruit and vegetable loads is one where losses and quality reduction in the cargo will be at a minimum by comparison with other routes. The most important meteorological factors here are:

- Air temperature;
- Relative humidity;
- Dew-point temperature.

To take the effects of these parameters correctly into account, it must be remembered that the load of fruit and vegetables is a reservoir of heat and moisture. It accumulates these in the port where it is loaded, and maintains within the hold of the vessel the meteorological conditions of the various ports where cargo is taken on board. The temperature in the holds, and of the cargo itself, therefore changes more slowly than that of the environment outside.

First of all, the optimum meteorological conditions have to be determined in which citrus fruit deteriorate most slowly. Special research has shown that optimum conditions for oranges are 4°C and 85 per cent humidity and for grapefruit, 10°C and 85 per cent. Thus, conditionally, the new course can be set so that the vessel transporting the citrus fruit in its ventilated holds passes through the zone with the optimum climatic

conditions for cargo load as quickly as possible. Obviously, this route will run much farther north than the traditional route through the Azores. It must moreover be determined what external climatic values will correspond to optimum conditions in the hold; i.e., we must solve the problem of the transition from external climatic parameters to the microclimate in a hold cooled by the flow of outside air.

When citrus fruit is shipped from Cuba to St Petersburg, the temperature difference between outside and hold air during the shipping season is not constant (it varies between 0 and 8–9°C at various latitudes). The difference depends on the time of season and the route of shipment, the quality and the type of load, the air change frequency, the thermal characteristics of the load, the cooling (heating) rate, and the inertia of the system as a whole.

Table 4.1 shows the general difference in temperature between outside and hold air in various latitude belts in the North Atlantic, and Table 4.2 shows the external air temperatures corresponding to optimum hold conditions.

## TABLE 4.1

**Difference in temperature between outside and hold air in various latitude belts in the North Atlantic (in shipping season)**

| Latitude (°N) | 20–25 | 25–30 | 30–35 | 35–40 | 40–45 | 45–50 | 50–55 | 55–60 |
|---|---|---|---|---|---|---|---|---|
| Difference (°C) | 1.0 | 3.5 | 6.5 | 9.0 | 6.0 | 4.0 | 2.0 | 0.0 |

## TABLE 4.2

**External air temperatures corresponding to optimum hold conditions**

| Latitude (°N) | 20–25 | 25–30 | 30–35 | 35–40 | 40–45 | 45–50 | 50–55 | 55–60 |
|---|---|---|---|---|---|---|---|---|
| Type of load: | | | | | | | | |
| Oranges | 3.0 | 0.5 | -2.5 | -5.0 | -2.0 | 0.0 | 2.0 | 4.0 |
| Grapefruit | 9.0 | 6.5 | 3.5 | 1.0 | 4.0 | 6.0 | 8.0 | 10.0 |

Shipping season: Oranges (February–April); grapefruit (September–November)

The humidity characteristics of the outside air in ships with ventilation systems undergo little change when the air reaches the hold. We can therefore take the optimum value for outside air humidity as 85 per cent.

Now that we have this information, we must determine the ocean regions where it is most probable that these optimum conditions will occur together. To do this we need climatological data on the joint probability of the various combinations of temperature and relative humidity during the various months of the year.

Obviously, the course must be established so that the vessel reaches the zone with the highest probability of optimum conditions as quickly as possible. The climatic zones picked are shown in Figure 4.1, which also shows the traditional route: one can easily see that it goes right through the adverse zone where conditions for the shipment are most often far from optimum. One should bear in mind that the fruit may freeze and spoil if it encounters air temperatures below zero. This occurs when air temperatures drop below –8°C for more than five hours. The zones where conditions such as these may be observed, also determined from climatological information, are shown in Figure 4.1 by light cross-hatching; this is basically the region to the north and north-west of Newfoundland.

Figure 4.1 also characterizes the shipping seasons for two types of cargo: grapefruit (September–November) and oranges (February–April), where the shipping seasons are determined by when the fruit ripen.

However, northerly latitudes in the Atlantic can be rather hazardous for shipping in the autumn–winter period because of stormy weather. The greatest danger arises if a vessel encounters areas of tropical cyclones, high wind and wave conditions, drifting icebergs, and poor visibility. The climatological information given in reference [8] allows adjustment to the optimum routes to avoid the hazardous zones; these routes are shown in Figure 4.2 for a number of months.

Obviously, these cannot be used without taking into account the actual synoptic situation and operational weather forecasts along the route. The corrected routes are longer than the traditional ones; however, the value of the preserved cargo more than compensates for the extra fuel costs.

## 4.3    INSURANCE CLAIMS/LEGAL ASPECTS

Marine operations which encounter some form of difficulty often give rise to claims against an underwriter or one of the parties to the contract. Weather factors are always taken into account when a contract is drafted and the operation is considered to be subject to those conditions which might reasonably be expected at the time of year in the area concerned.

Points of claim and counterclaim in legal and insurance disputes are too varied to discuss in detail here, but in general the parties seek to establish:

* What actually happened, i.e. what were the prevailing weather conditions?

* How unusual were those conditions compared with the climatological mean?

* To what extent had the parties concerned allowed for "reasonable" year-to-year variation about the climatological mean?

* What meteorological information was available overall to the decision-maker and what sub-set of this information did he actually obtain?

**Boundary between good and adverse conditions**      **Area of good conditions**

**Traditional route**

**Optimum route**          **Low air temperature area**
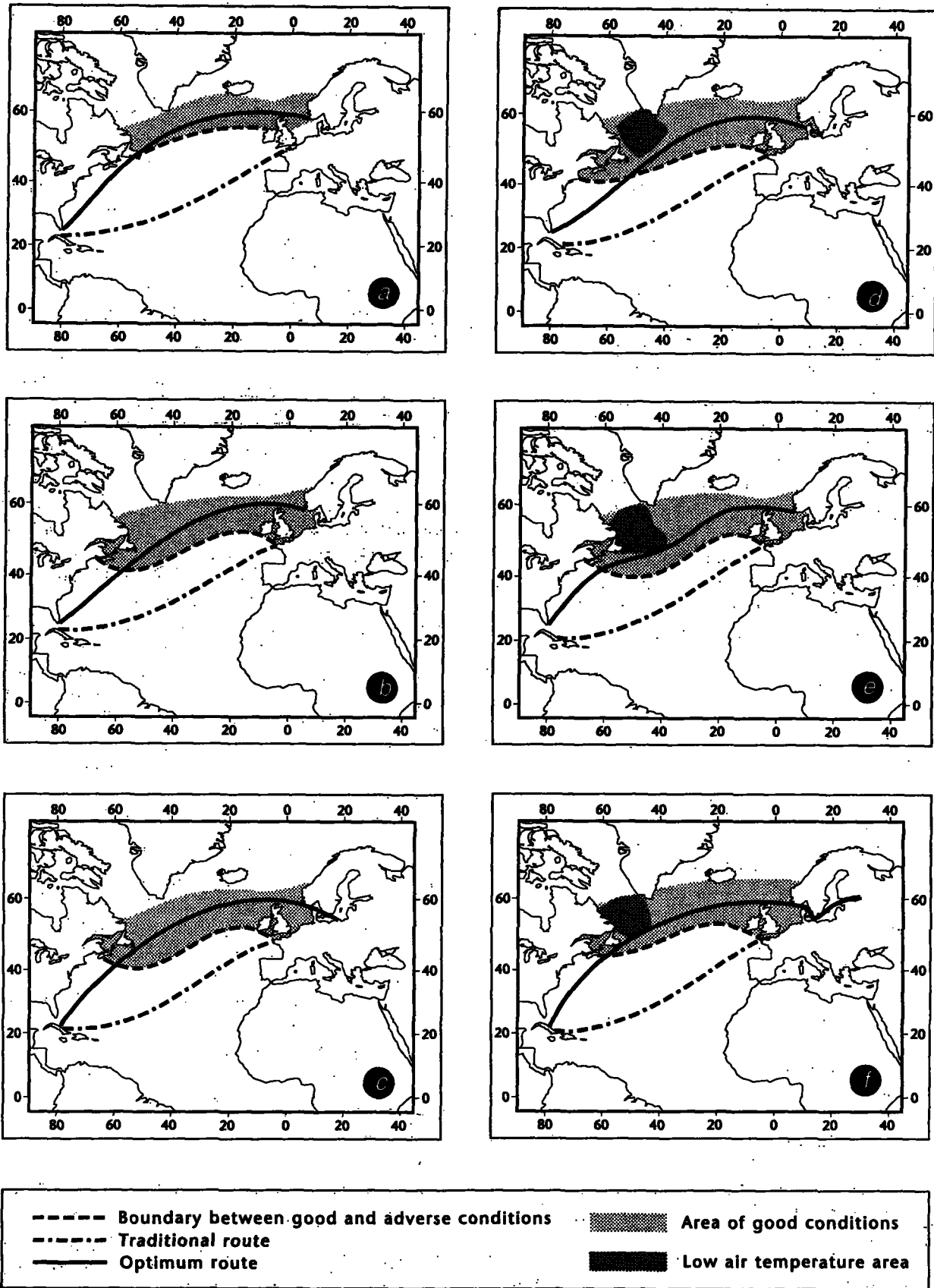
Figure 4.1 — Climatic zones selected using the criterion of optimum meteorological conditions for preserving shipments of citrus fruit.
a, b, c – September, October, November (grapefruit-shipping season); d, e, f – February, March, April (orange-shipping season)
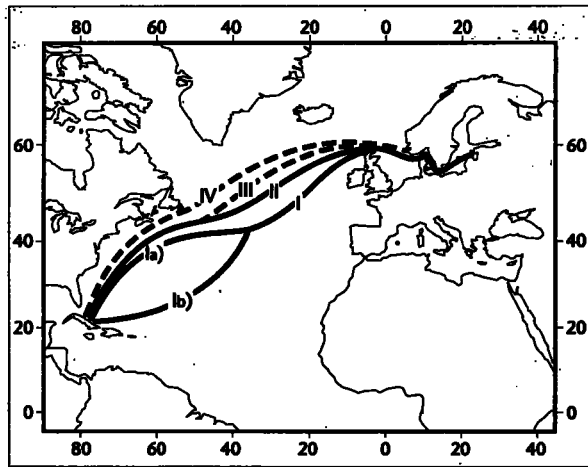
Figure 4.2 — Optimum routes for shipping citrus fruits avoiding areas with high incidence of hazardous weather phenomena. I: February–March; II: April; III: September–October; IV: November

It should be said that the wording of many contracts, while legally sound, is not sufficiently rigorous from the meteorological point of view. Many disputes could be considerably simplified, if not avoided altogether, by taking meteorological advice at the stage of drafting the contract.

### 4.3.1    Examples of disputes

One of the more common types of dispute involves slow steaming. A vessel may be chartered on the basis of an average speed maintained throughout the voyage, and failure to make that speed results in late arrival of ship and cargo. However, the average speed relates to "normal" weather conditions, and a shipper has no claim against the operator if the delay has been caused by adverse conditions. In this case the meteorologist must assess the conditions day by day along the route, using noon positions provided by the client. If positions are not given, it is possible to estimate them using a general route, but this process requires specialized knowledge of the extent to which a ship's speed is affected by adverse weather on a day-to-day basis. Under cross-examination in court few applied meteorologists could sustain a claim to have this skill and such estimation is best avoided unless the services of an analyst with nautical experience are available. It follows that applied mete- orologists without nautical experience should not comment upon the effects of the prevailing weather conditions on the vessel.

Many claims involve damage to cargo, vessel or crew and in the extreme may concern loss of life. It is still necessary to establish the prevailing conditions, particularly where effects have been very localized, e.g. thunderstorms, squalls. This is particularly so when cargo damage is cited during loading or unloading rather than in transit. However, damage during the voyage, even when established as being caused by bad weather, may still

involve a dispute regarding the amount of compensation. This arises from the extent to which the decision-maker may have contributed to the damage by failing to assess the risk of departure from average conditions and to take adequate precautions. The climatologist must state the average conditions but also give an indication of the severity and frequency of departures from the mean at the time of year concerned.

A further complication to damage claims arises when the operation has quite clearly been subject to a weather-window or other forecasting service. Questions may arise regarding the adequacy and suitability of the forecast used in view of the operation in hand. Once again, the decision-maker may be held to have compounded the loss if he did not use the most suitable and detailed source of forecast information available to him. In this case the investigating meteorologist must compile a list of generally available forecast products and indicate their suitability for the purpose in hand in terms of area, content, and period of validity. He may also make a factual comparison of the forecast and the actual conditions. Comment should not be made regarding the reasons for any discrepancies/ failures. Such comment is the pre- rogative of the forecaster who originated the forecast, and is otherwise purely speculative.

### 4.3.2    Sources of data and analysis

The basic source of data consists of observations from ships of the Voluntary Observing Fleet (VOF). However, it is unusual to be able to use observations from other ships in the close locality to establish local conditions directly. This can be done in restricted waterways and shipping lanes, but the separation between ships is generally too great in deep ocean areas. It is more usual to use surface analyses produced manually or by nu- merical weather and wave prediction models to assess conditions. These analyses must be augmented by locating ship observations which have failed to arrive via telecommunication channels by the cut-off time applied to operational work. These delayed data can be obtained from the climatological exchange of logbooks. The models are particularly useful in assessing wave conditions, given the paucity of such data. The ma- jority of cases involve high winds and waves although enquiries may also be received regarding visibility. Humidity and precipitation are sometimes requested in connection with cargo damage and can be provided for ports by using data from a local meteorological station. If there is no local observation or the ship is at sea and is not a member of the VOF, it becomes extremely difficult to answer this type of enquiry.

More localized weather conditions such as thunderstorms and associated squalls often cannot be positively identified, but use of satellite pictures and an investigation of atmospheric stability using modified radiosonde ascents in the same airstream (usually from land stations) can suggest whether such phenomena were likely to have occurred or not.

In the majority of cases the analyst will be stating an opinion regarding the weather conditions associated with the event and unlikely to be able to produce a certified copy of an observation. It is important that the limitations of the assessment are clearly stated.

Climatological means can be produced using ship data from the Marine Climatological Summaries Scheme or data from buoys, light-station vessels, OWS or other marine platforms. Experience has shown that it is better to produce a table containing the frequency of occurrence of ranges of the parameter concerned month by month or for the whole year than a single mean value. For example, the frequency of occurrence of winds in each Beaufort force may be tabulated for all Januaries from 1961 to date, to give an average "January" frequency. The process can be repeated for each month and the whole year. A sample tabulation is shown in Table 4.3.

The frequency table contains considerably more information than a climatological mean since it gives the average percentage frequency with which any chosen set of conditions is exceeded and hence some indication of how unusual the weather was at any time.

It is also necessary to examine the frequency of exceedance of the same conditions during each year to assess the inter-annual variability. Unfortunately, the density of ship traffic, and hence observations, varies quite markedly from year to year and some form of normalization is vital if the results are to be reasonably representative. Even so, there are some areas where the data are so sparse that it is impossible to reach a valid conclusion, particularly for individual months, unless there is a fixed platform in the locality. A sample tabulation for windspeed is shown in Table 4.4 for the whole year, and Table 4.5 for January only.

It is also possible to produce similar tabulations for combinations of parameters depending upon the meteorological factors believed to be relevant to the case. An investigation of delay encountered during an operation involving a weather-window may demand an analysis of the persistence of particularly adverse conditions at the time of year in question. For example, the average frequency of occurrence of a spell of winds greater than Force 8 and persisting for 36 hours may be required. The climatology of spells of conditions in a given location can be produced only from continuous records such as those from a coastal station, OWS, buoys, light-station vessels, modelled data or other fixed platform. Merchant vessels are transient in space and time and their records cannot be used for this purpose. If ship data are the only source available, it is possible to give the average number of hours when thresholds are exceeded but not the manner in which those hours are grouped into spells.

Establishing what meteorological information was available to the decision-maker is rather more difficult. A thorough examination must be made of manuals detailing coastal radio stations and their products such as the *Admiralty List of Radio Signals*, Vol. 3 [9], together with lists of national responsibilities from the WMO *Manual on marine meteorological services* [10] and *Weather reporting*, Vol. D (WMO-No. 9) [11]. There is no comprehensive guide to specialized forecasts issued by national Meteorological Services and in some areas of the world a multitude of such products are provided by commercial companies. It is probably advisable to seek advice from the national Meteorological Service in whose area the event occurred.

### 4.3.3 Communication with the client

In general, the client is most likely to be an insurance company/underwriter, marine consultant or lawyer. It is essential that a clear report be written presenting the meteorological conclusions under separate sub-headings. Since the client may be unfamiliar with meteorological terms, it is wise to minimize the use of technical terms, or to provide an adequate explanation in layman's terms. Tables and diagrams should be limited to the minimum necessary to support the arguments and should be well explained. If meteorological charts are reproduced it is usually advisable to place them in an appendix together with adequate explanation.

## 4.4    COASTAL ZONE DEVELOPMENTS

### 4.4.1    Requirements

A considerable amount of engineering activity takes place in the coastal zone. Many coastlines must be protected from erosion and flooding, and this involves major construction work. The protective sea walls and breakwaters must be designed to withstand events with relatively long return periods. The provision of such protection is rarely completed in a single project satisfying all requirements for the planned lifetime. The act of providing protection usually encourages further occupation and development of the area previously at risk from flooding. Eventually, the financial investment in the area reaches a level at which the risk of flooding built into the original design is no longer acceptable. The defences must then be strengthened, and this involves a redesign and further construction.

In addition to sea defences, harbours and marinas must be sited, designed and built. Sewage outfalls are designed and located on the sea-bed, with the actual dispersal head being completed by divers. There are also numerous subsidiary activities, such as dredging and inshore barge operations, which are weather-sensitive and benefit at the planning stage from a knowledge of the climatology and likely downtime.

Special consideration must be given to the determination of the climatological design basis for nuclear power plants. These requirements are the subject of a safety guide [12].

The generation of electrical power from winds in the coastal zone is yet another climate application for which a considerable body of knowledge exists. The *Climate Applications Referral System*

TABLE 4.3

Percentage frequency of occurrence of wind in Beaufort classes

| Wind speed Beaufort force | | | | | | Month | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
| 0 | 0.6 | 0.6 | 0.8 | 1.4 | 2.2 | 3.1 | 2.6 | 2.1 | 1.9 | 1.3 | 1.1 | 0.6 |
| 1 | 1.9 | 2.0 | 2.4 | 3.3 | 4.0 | 5.8 | 6.3 | 5.5 | 4.6 | 3.3 | 2.3 | 1.6 |
| 2 | 5.2 | 7.4 | 7.3 | 8.4 | 10.7 | 13.6 | 15.3 | 13.8 | 12.2 | 9.9 | 6.7 | 5.6 |
| 3 | 13.5 | 15.2 | 17.7 | 20.8 | 22.0 | 26.6 | 26.8 | 25.2 | 22.8 | 20.0 | 15.8 | 14.1 |
| 4 | 21.7 | 21.5 | 25.1 | 27.6 | 29.2 | 28.0 | 27.9 | 28.1 | 25.0 | 25.7 | 22.8 | 21.4 |
| 5 | 17.9 | 18.2 | 17.4 | 18.1 | 17.4 | 13.7 | 12.4 | 14.7 | 16.1 | 16.4 | 18.6 | 19.1 |
| 6 | 14.6 | 14.9 | 14.6 | 11.9 | 9.2 | 6.3 | 6.0 | 6.7 | 9.9 | 11.6 | 14.7 | 14.9 |
| 7 | 12.0 | 9.6 | 8.4 | 5.4 | 3.7 | 2.2 | 2.0 | 2.9 | 4.7 | 7.0 | 10.2 | 10.8 |
| 8 | 8.5 | 7.2 | 4.6 | 2.4 | 1.3 | 0.6 | 0.6 | 1.0 | 2.0 | 3.9 | 5.8 | 8.0 |
| 9 | 2.7 | 2.3 | 1.2 | 0.5 | 0.3 | 0.0 | 0.1 | 0.0 | 0.5 | 0.5 | 1.6 | 3.0 |
| 10 | 1.3 | 0.9 | 0.4 | 0.1 | 0.1 | – | – | 0.0 | 0.2 | 0.3 | 0.5 | 0.9 |
| 11 | 0.2 | 0.1 | 0.0 | – | – | – | – | – | 0.1 | – | 0.1 | 0.0 |
| 12 | 0.1 | 0.1 | – | – | – | – | – | – | 0.0 | – | 0.0 | 0.1 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

TABLE 4.4

Percentage frequency of occurrence of wind in Beaufort classes for each year 1961 to 1986

| Year | Wind speed Beaufort force | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1961 | 0.1 | 0.2 | 0.4 | 0.7 | 0.8 | 0.4 | 0.4 | 0.3 | 0.1 | 0.0 | 0.0 | – | – |
| 1962 | 0.0 | 0.1 | 0.3 | 0.8 | 1.0 | 0.5 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | 0.0 |
| 1963 | 0.1 | 0.1 | 0.4 | 0.7 | 0.9 | 0.6 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1964 | 0.1 | 0.2 | 0.5 | 0.8 | 1.1 | 0.6 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1965 | 0.1 | 0.1 | 0.4 | 0.9 | 1.1 | 0.8 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1966 | 0.1 | 0.1 | 0.4 | 0.9 | 1.1 | 0.8 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | – | – |
| 1967 | 0.1 | 0.2 | 0.5 | 0.8 | 1.1 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | – | – |
| 1968 | 0.1 | 0.2 | 0.5 | 0.9 | 1.1 | 0.8 | 0.6 | 0.3 | 0.2 | 0.0 | – | 0.0 | 0.0 |
| 1969 | 0.1 | 0.2 | 0.5 | 1.0 | 1.3 | 0.8 | 0.5 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1970 | 0.1 | 0.1 | 0.4 | 1.0 | 1.3 | 0.9 | 0.5 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | – |
| 1971 | 0.1 | 0.2 | 0.5 | 1.0 | 1.2 | 0.7 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1972 | 0.1 | 0.2 | 0.4 | 0.8 | 1.1 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | 0.0 | – |
| 1973 | 0.1 | 0.2 | 0.5 | 0.9 | 1.1 | 0.6 | 0.3 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1974 | 0.1 | 0.1 | 0.4 | 0.8 | 0.9 | 0.7 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | – |
| 1975 | 0.1 | 0.1 | 0.4 | 0.7 | 1.1 | 0.8 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1976 | 0.1 | 0.2 | 0.5 | 0.9 | 1.1 | 0.6 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | – | – |
| 1977 | 0.1 | 0.1 | 0.3 | 0.6 | 0.9 | 0.6 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | 0.0 | – |
| 1978 | 0.0 | 0.1 | 0.4 | 0.7 | 0.9 | 0.6 | 0.4 | 0.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1979 | 0.1 | 0.1 | 0.3 | 0.7 | 1.0 | 0.6 | 0.4 | 0.2 | 0.2 | 0.0 | 0.0 | – | – |
| 1980 | 0.0 | 0.1 | 0.3 | 0.8 | 1.0 | 0.8 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | – | – |
| 1981 | 0.0 | 0.1 | 0.2 | 0.6 | 1.1 | 0.7 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | – | 0.0 |
| 1982 | 0.0 | 0.1 | 0.3 | 0.7 | 0.8 | 0.6 | 0.4 | 0.3 | 0.2 | 0.0 | 0.0 | – | – |
| 1983 | 0.0 | 0.1 | 0.4 | 0.8 | 0.8 | 0.6 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | 0.0 | – |
| 1984 | 0.0 | 0.2 | 0.4 | 0.7 | 0.9 | 0.6 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 |
| 1985 | 0.0 | 0.1 | 0.3 | 0.6 | 1.0 | 0.6 | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | – | – |
| 1986 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Total | 1.6 | 3.6 | 9.7 | 20.1 | 25.4 | 16.6 | 11.2 | 6.5 | 3.8 | 1.0 | 0.4 | 0.0 | 0.0 |

TABLE 4.5

Percentage frequency of occurrence of wind in Beaufort classes for each January 1961 to 1986

| Year | Wind speed Beaufort force | | | | | | | | | | | | |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|      | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1961 | – | – | 0.1 | 0.3 | 0.7 | 0.4 | 0.6 | 0.4 | 0.3 | 0.1 | – | – | – |
| 1962 | – | – | 0.2 | 0.4 | 1.0 | 0.7 | 0.7 | 0.6 | 0.2 | 0.0 | 0.1 | – | – |
| 1963 | – | 0.0 | 0.2 | 0.3 | 0.5 | 0.9 | 0.4 | 0.3 | 0.2 | 0.1 | 0.0 | – | – |
| 1964 | 0.1 | 0.2 | 0.4 | 0.7 | 1.3 | 0.6 | 0.5 | 0.1 | 0.1 | – | – | – | – |
| 1965 | – | – | 0.0 | 0.3 | 0.7 | 0.9 | 0.4 | 0.7 | 0.5 | 0.2 | 0.2 | – | 0.0 |
| 1966 | – | 0.0 | 0.3 | 0.6 | 1.2 | 0.9 | 0.5 | 0.6 | 0.4 | 0.1 | 0.0 | – | – |
| 1967 | – | 0.2 | 0.2 | 0.7 | 0.9 | 1.0 | 0.7 | 0.8 | 0.2 | 0.1 | – | – | – |
| 1968 | 0.0 | 0.1 | 0.4 | 0.7 | 1.0 | 0.8 | 0.6 | 0.4 | 0.5 | 0.1 | – | – | – |
| 1969 | 0.1 | 0.0 | 0.2 | 0.6 | 1.1 | 0.8 | 0.8 | 0.7 | 0.4 | 0.1 | – | – | – |
| 1970 | – | 0.0 | 0.2 | 0.9 | 1.2 | 1.2 | 0.6 | 0.3 | 0.4 | 0.1 | 0.0 | 0.0 | – |
| 1971 | – | – | 0.3 | 0.5 | 0.8 | 0.7 | 0.7 | 0.8 | 0.5 | 0.2 | 0.1 | – | – |
| 1972 | 0.0 | 0.1 | 0.1 | 0.6 | 0.9 | 0.8 | 0.5 | 0.7 | 0.2 | 0.2 | – | – | – |
| 1973 | 0.0 | 0.1 | 0.2 | 0.7 | 1.6 | 0.8 | 0.4 | 0.2 | 0.1 | – | 0.0 | – | – |
| 1974 | – | – | 0.0 | 0.2 | 0.7 | 0.7 | 1.1 | 0.5 | 0.4 | 0.1 | 0.0 | 0.0 | – |
| 1975 | 0.1 | 0.2 | 0.2 | 0.4 | 0.9 | 0.7 | 0.4 | 0.3 | 0.3 | 0.0 | 0.1 | – | – |
| 1976 | 0.1 | 0.1 | 0.4 | 0.8 | 0.8 | 0.7 | 0.6 | 0.4 | 0.3 | 0.0 | 0.0 | – | – |
| 1977 | 0.0 | 0.0 | 0.4 | 0.7 | 0.8 | 0.5 | 0.6 | 0.4 | 0.3 | 0.1 | 0.2 | 0.0 | – |
| 1978 | 0.1 | 0.1 | 0.2 | 0.3 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | – | – |
| 1979 | 0.0 | 0.1 | 0.4 | 0.5 | 0.9 | 0.5 | 0.4 | 0.2 | 0.6 | 0.2 | 0.0 | – | – |
| 1980 | – | 0.2 | 0.1 | 0.7 | 0.6 | 0.5 | 0.7 | 0.5 | 0.2 | 0.2 | 0.0 | – | – |
| 1981 | 0.1 | 0.2 | 0.2 | 0.5 | 0.8 | 0.4 | 0.5 | 0.4 | 0.3 | 0.1 | 0.0 | – | – |
| 1982 | 0.0 | 0.1 | 0.1 | 0.7 | 0.9 | 0.7 | 0.7 | 0.5 | 0.2 | – | – | – | – |
| 1983 | – | 0.0 | 0.1 | 0.5 | 0.5 | 0.9 | 0.7 | 0.4 | 0.3 | 0.1 | 0.0 | – | – |
| 1984 | – | – | 0.1 | 0.1 | 0.4 | 0.5 | 0.7 | 0.7 | 0.6 | 0.4 | 0.2 | 0.0 | 0.0 |
| 1985 | – | 0.1 | 0.2 | 0.7 | 1.1 | 0.7 | 0.3 | 0.5 | 0.2 | 0.0 | 0.0 | – | – |
| 1986 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Total | 0.7 | 1.9 | 5.3 | 13.6 | 22.0 | 18.3 | 14.3 | 11.5 | 8.2 | 2.6 | 1.3 | 0.1 | 0.1 |

(CARS) — Energy [13] is a useful source of information in this regard.

### 4.4.2   Use of climatological data

Climatological data are an important requirement for design and planning purposes. However, the sources of data do not relate well to the inshore conditions which are of interest. Usually, data are available from coastal observing stations which report the normal meteorological parameters and sometimes wave conditions. Offshore reports from merchant ships and oil platforms provide a climatology of meteorological and wave parameters at sea. In the transition region between sea and land, in some parts of the world, there are buoys and light vessels which provide an adequate base of data. In general, however, data coverage is extremely sparse in this area along most of the world's oceans. This is the area where the majority of construction takes place.

Winds measured on land can be crudely adjusted using factors based on land and sea-surface roughnesses, and empirically derived relations, but it is difficult to do this for the transition region very close inshore. Offshore winds can be used to provide a crude climatology for inshore sites, particularly if interest is confined to winds blowing from sea to land. However,

the results may well be deficient as regards light winds, as sea-breeze and similar effects will not be well represented. A simple and operationally applicable procedure to reduce land-based or onshore wind measurements to be representative for the adjacent marine areas is not readily available.

Most wave data are obtained from offshore sources in relatively deep water. If such data are to be used for design and planning purposes in inshore waters, adjustments must be made to allow for bottom topography, beach gradient and other coastal effects. This can be done by the use of simple factors or alternatively by carrying out a complete refraction and diffraction study.

Occasionally, temperature statistics are required for machinery working offshore in hot climates. In these cases, the incidence of airflow from land to sea and the rate at which the air temperature adjusts to that of the underlying cool sea must be considered.

### 4.5   MARINE CLIMATOLOGY AND FISHERIES SCIENCE

### 4.5.1   Introduction

Fish constitute an important part of the daily diet in many countries of the world, representing nearly one
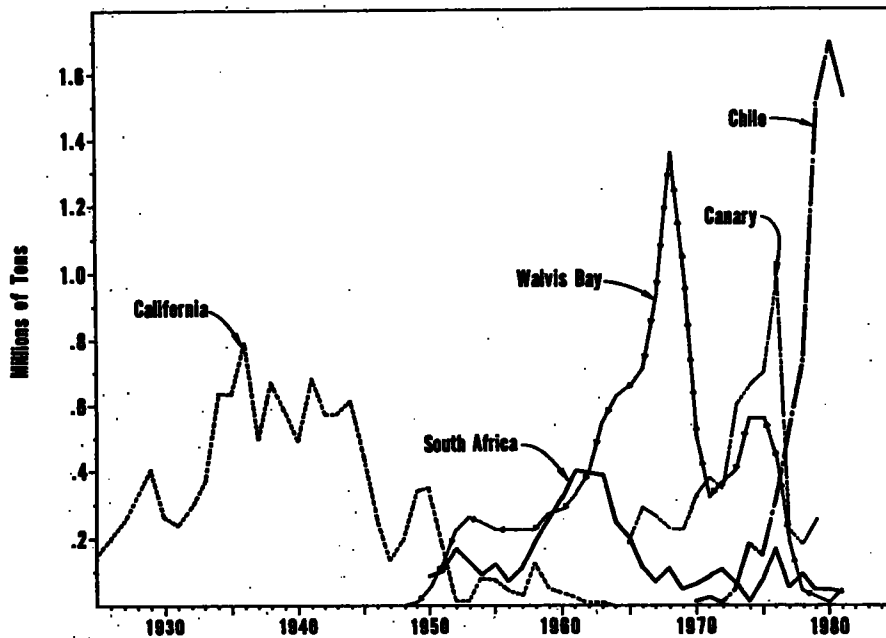
Figure 4.3 — Annual sardine landings from several eastern-boundary current stocks (*after Parrish* et al., *1983*). Walvis Bay and South Africa refer to the two major Benguela Current stocks

quarter of the global supply of animal protein [14]; fisheries and associated industries are important sources of employment, income, and foreign exchange for coastal nations. Marine fish live in a moving liquid environment which is characterized by large-amplitude variability in various conditions and processes essential to survival and successful reproduction. Their life cycles tend to be complex and to contain "weak links" wherein the organisms are particularly at the mercy of vagaries in the coupled atmosphere-ocean system [15].

Exploited fish populations are often highly variable and subject to abrupt collapses (see Figure 4.3) with attendant socio-economic consequences [16].

The conventional methods of fishery science have not been particularly effective in preventing these collapses, largely because of lack of understanding of the mechanisms regulating variability of recruitment. (The term recruitment refers to the quantity of younger fish surviving the various egg, larval, and juvenile stages, to begin to be captured in a fishery.) Inter-year

variability in recruitment is extreme, with the ratio between the number of recruits in a given year and the biomass of the parental stock which spawned them differing from year to year by factors of up to several hundred (Figure 4.4). Because of the large unexplained inter-year variance, conventional models relating recruitment to parental stock size tend to fit the data poorly (Figure 4.5).

In addition to very large variance on the inter-year time-scale, and to stock collapses and displacements occurring on the inter-decadal time-scale, important variability in fish populations is evident on even longer time-scales. For example, using analysis of fish-scale deposits in sea floor sediments as a basin, Smith [17] has pointed out indications that the total biomass of pelagic (i.e. oceanic) fish inhabiting the California Current system may have been several times larger in the early part of this century than at the present time, or even than in the late 1930s, when major fishery exploitation commenced.

Figure 4.4 — Time series of the natural logarithm of the ratio of recruit biomass to parental spawning biomass in the California Current stock of Pacific mackerel, *Scomber Japonicus* (*After Parrish and MacCall, 1978*)
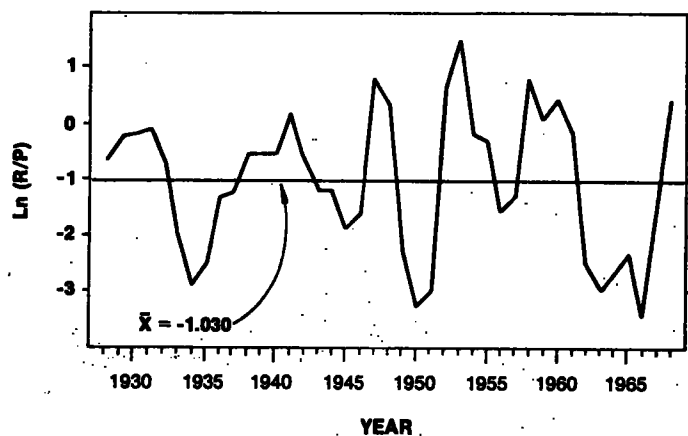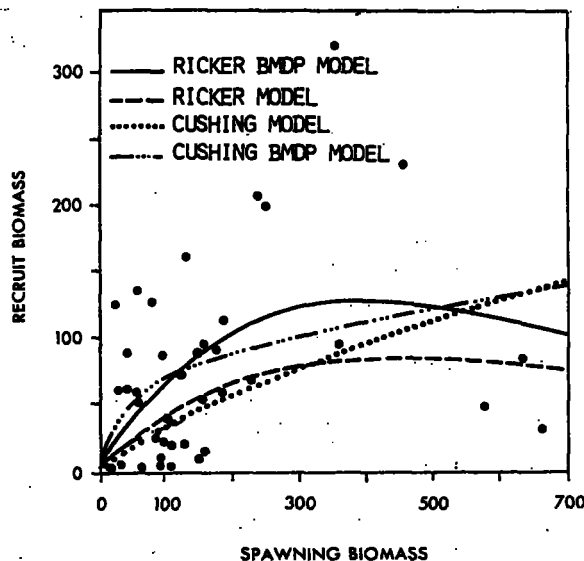
Figure 4.5 — Recruitment versus parental stock size in the California Current stock of Pacific mackerel, *Scomber Japonicus* (*after Parrish and MacCall, 1978*). Annual data points, along with several standard stock-recuitment models fitted to the data, are shown

Because of the need for scientific progress on the recruitment question in order to protect and derive maximum benefits from fishery resources around the world, an International Recruitment Programme (IREP) has been established [18]. IREP constitutes the major focus of the new Programme of Ocean Science in Relation to Living Resources (OSLR), which is co-sponsored by the Intergovernmental Oceanographic Commission (IOC) and the Food and Agriculture Organization of the United Nations (FAO). Much of the current IREP scientific programme is directed toward multilateral application of the comparative method of science [19, 20].

### 4.5.2    Comparative habitat climatology

The seasonal variation is the most regular and predictable of the longer-period components of variability in the upper ocean. As a consequence it is the one most likely to be reflected in biological adaptations. Even in the tropics, the life-cycle processes of marine organisms tend to be highly tuned to the march of the seasons. Most fishery species are sufficiently mobile as adults to exert adaptive control on the location of their feeding and spawning activities. Since net reproductive success (i.e. recruitment) is the factor controlling natural selection, it is reasonable to regard consistent patterns of correspondence of seasonal and geographical characteristics of spawning behaviour to the available climatology of environmental conditions and processes as constituting clear evidence as to the identity of the dominant mechanisms which normally control recruitment success.

For the sake of example, the following paragraphs briefly outline a particular progression of

recent studies. Key components of the progression have been applications of the comparative method of science [21] within a framework of habitat climatology. The cited studies can serve as a source of more detailed information on, and of additional citations for, the rationale pursued and the climatological methodologies employed. A point to note is that the climatological variables of importance to fish population dynamics [22] are in some cases quite different from those most often studied in the contexts of terrestrial biological systems or of surface marine commerce.

Parrish *et al.* [23] noted that coastal pelagic fish of the California Current, which feed as adults in the upwelling region centred near Cape Mendocino, migrate long distances to spawn within the Southern California Bight, where offshore surface transport near the coast is much less intense (Figure 4.6). By contrasting the climatology of conditions in the reproductive habitat and in the distant feeding grounds, and by utilizing certain other evidence, they arrived at the conclusion that avoidance of offshore transport and associated loss of larvae from the coastal habitat was a major factor controlling reproductive success (i.e. important enough to be worth the long migration). This finding has provided a basis for some successful empirical tests of recruitment against indices of offshore Ekman transport in the larval habitat; these tests are cited by Shepard *et al.* [24] as one of the few indications to date of positive progress in linking variations in fish stocks to climatic effects. More recently, Mendelssohn and Mendo [25] have extended these results to the anchoveta of the Peru Current system, where they again find an index of wind-induced offshore transport [26] to be the most important predictor of recruitment success.

A parallel inferential process has provided insight into the effect of storm-produced turbulent mixing of the water column on feeding success of newly hatched larvae. Lasker [27, 28] noted that the depth-averaged concentration of suitable food particles in the habitat off California was too low for successful feeding by newly hatched anchovy larvae, i.e., the only larvae with any chance of survival were those located within certain very limited patches of anomalously high concentrations of food particles. Lasker observed that under stormy conditions such food particle patches were destroyed by turbulent mixing of the water column. Husby and Nelson [29] assembled the climatology of an index of rate of addition of turbulent kinetic energy to the ocean by the wind (proportional to the third power of the wind speed near the sea surface) in the California Current region. They found that spawning habits indeed were such as to minimize the probability of encountering substantial wind mixing of the upper ocean. Peterman and Bradford [30] found inter-year variability in larval anchovy mortality rate off California to be strongly related to frequency of calm periods of sufficient duration for formation of fine-scale food particle strata.

Parrish *et al.* [31] combined the transport and turbulence aspects in a wider geographical context in their examination of the habitat climatologies of the four major subtropical eastern-boundary current regions of the world's oceans. They found a general pattern of avoidance of both wind-induced turbulent mixing and offshore-directed surface Ekman transport in the spawning habits of anchovies and sardines. The temperature at which spawning takes place showed a much less coherent pattern, suggesting that selection of spawning habitat on the basis of a particular optimum temperature is less important to net reproductive success than minimizing turbulent mixing (dissipation of food particle concentrations) or offshore transport (loss of larvae from the coastal habitat).

The point to be made here is that inferences drawn from comparisons of habitat climatology with characteristics of migration and timing of life-cycle events can yield important insights into the processes regulating recruitment that might well be difficult and expensive, or even impossible, to generate in other ways [32]. The process is cost-effective, largely utilizing data that are routinely available rather than entailing major outlays for special field activities and experiments.
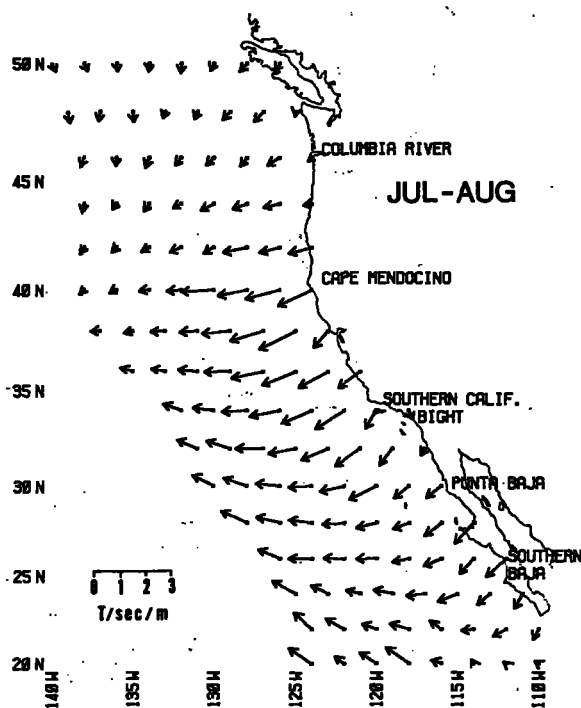


Figure 4.6 — Summer (July-August) surface Ekman transport distribution in the California Current (*after Parrish* et al., *1983*). Each vector symbol represents a vector average of estimates computed from individual surface marine weather reports. Transport is proportional to vector symbol length. A symbol length scale is provided; units are metric tons per second across each metre of horizontal width.

### 4.5.3    Marine surface data

Maritime weather reports, recorded routinely under international convention by a variety of types of ships operating at sea, continue to be a primary source of information on climatology and variability within the habitats of fish stocks. Observations of wind speed and direction, sea and air temperature, barometric pressure, humidity and cloud cover provide a basis for estimating a number of pertinent environmental variables (Figures 4.4 and 4.5) related to nutrition, transport, and physiological well-being of fish at various life cycle stages.

For example, Mendelssohn and Roy [33] used areal summaries of maritime reports, together with catch records, to demonstrate wave-like propagation of tuna distributions in the Gulf of Guinea occurring in phase with sea-temperature fluctuations conforming to a Kelvin wave [34] interpretation. Similar maritime report summaries were used by Mendelssohn and Cury [35] in a study indicating congregation of exploitable concentrations of small coastal pelagic fish in areas previously displaying surface cooling (upwelling) followed by warming (stabilization of the water column).

Environmental conditions in the ocean can vary dramatically on inter-annual time scales. Perhaps the most widely known extreme variations are the *El Niño* episodes of the south-eastern Pacific (Figure 4.7). However, major trends beyond the *El Niño* frequency band are evident in the maritime data record of that region (note in Figure 4.7 the multi-decadal increasing trends in turbulent mixing index and offshore Ekman transport which underlie the shorter *El Niño*-related variations evident at intervals of five to ten years). Apparently, such dramatic long-term variations are not restricted to the South Pacific. McLain *et al.* [36] and Shelton *et al.* [37] indicate intermittent extreme warm episodes, approaching *El Niño*-type intensity, within the Atlantic Ocean off southern Africa. Freon [38] shows decadal scale shifts in trade wind intensity off Senegal, corresponding to a dramatic change in catch per unit effort of small pelagic fish.

Belveze and Erzini [39] report a 30-year downward trend in wind speed measured at a coastal station at Essaouira, Morocco, such that the mean annual wind speeds in the late 1970s tended to be less than half those typical of the early 1950s. Because momentum is transmitted to the ocean in proportion to the square of the wind speed, such a decrease would imply a long-term decline in wind-induced coastal upwelling by a factor of four. Since the high productivity of the Canary Current system is thought to be substantially based on nutrient enrichment via coastal upwelling, such a drastic decrease, if real and widespread, could be expected to have catastrophic effects on the entire biological system. (However, it is always well to be cautious about results from any single station, and there is no report that the apparent trend at Essaouira has been corroborated by other data.) In any case, it would appear to be in the

interest of any coastal nation with fishery concerns to take advantage of available opportunities to collect and record local surface marine observations and to contribute them to the international data networks where they can be incorporated in large-scale environmental analyses, collaborative inter-regional comparative studies, etc.

Surface marine weather reports have provided the major basis for the comparative habitat climatology studies cited in the previous section. (Details on one set of suggested formulations for producing indices of Ekman transport, wind-induced turbulent mixing, and various components of atmosphere-ocean momentum and energy exchanges can be found in [40]).

### 4.5.4    Sub-surface climatology

While sub-surface measurements in the ocean are generally much less numerous than are surface data, it is often possible to assemble sub-surface climatological information with sufficient detail to be useful for fishery purposes. (IGOSS is aimed at making some of these data more readily available, and a number of countries now participate for the purpose of providing access to data.) For example, Sharp [41] summarized available oceanographic measurements to delineate areas of potentially successful exploitation of tuna in the Indian Ocean. Recently an important fishery for skipjack and yellow-fin tuna has developed in an area centred north-east of Madagascar, an area indicated in Sharp's summaries as being potentially favourable. The fishery

has grown from negligible catches to over 140 000 tonnes within six years [42].

Climatology of sub-surface structure in the upper ocean layers has been a revealing component of the comparative studies of reproductive habitats cited above [31, 32]. Brainard and McLain [43], as part of an extensive multilateral study of the ecosystem and population dynamics of the Peruvian anchoveta [44], demonstrate the possibilities for generating sub-surface climatological information in a situation where density of available data is not high.

### 4.5.5    Multilateral collaboration

At the present time, a major multinational scientific attack on the issue of recruitment variability in living marine resource populations is being mounted. The International Recruitment Programme (IREP), within the IOC-FAO Programme of Ocean Science in Relation to Living Resources (OSLR), has been mentioned above. (IGOSS and the International Commission on North Atlantic Fisheries are active in this area.) The International Council for the Exploration of the Sea (ICES) has constituted an IREP Steering Group to promote collaborative action. Active development of regional IREP programmes is under way within several of the regional bodies of IOC and FAO, and within certain other associated intergovernmental bodies (e.g. the Permanent Commission for the South Pacific (CPPS)). The Scientific Committee on Oceanic Research (SCOR), of the International Council of
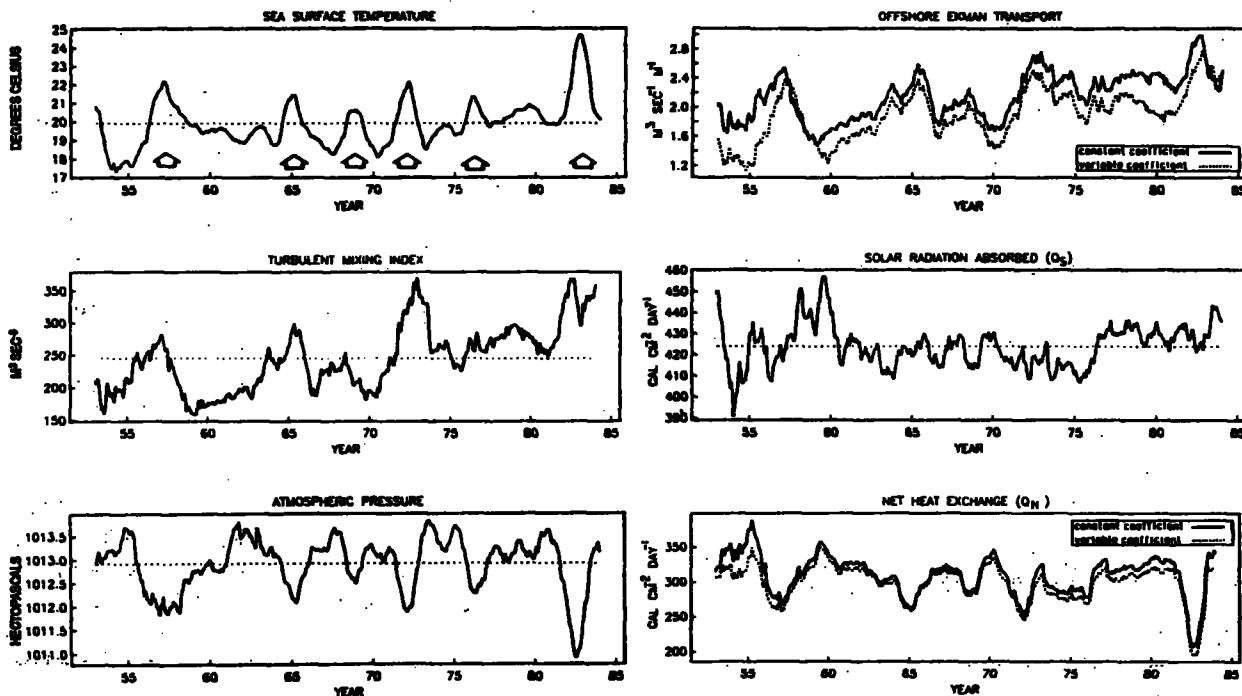


Figure 4:7 — Low-frequency non-seasonal variations in the habitat of the Peruvian anchoveta; 12-month running means of monthly averages of estimates computed from individual surface marine weather reports (after Bakun, 1987).
Major El Niño events are indicated by arrows drawn below the sea surface temperature graph.

Scientific Unions (ICSU), is collaborating actively. France has established a *Programme National sur le Déterminisme du Recrutement* (PNDR). The US National Marine Fisheries Service is in the process of reorienting to a "Global Ecosystem" focus for research and management activities. A variety of other international and national scientific efforts bearing on the general problem area could be added to this list (e.g. the Joint Global Ocean Flux Study (JGOFS) within the International Geosphere-Biosphere Programme (IGBP)).

The idea that such a global collaborative commitment can serve to support and progressively advance a framework of comparative scientific insight is attractive in a situation where crucial resource issues have proved very resistant to solution in the isolated contexts of individual fish stocks and habitats [19]. Basic to such a framework will be comparably formulated climatological information on conditions and processes within the ocean habitat. We have an impressive recent example of co-operative assembly and integrative analysis of climatological and other types of data in the recent multilateral study of the ecosystem of the Peruvian anchoveta [44]. Similar efforts in other areas around the world would serve to encourage and facilitate broad application of the comparative method. By so offering its experience and results for incorporation in a wider comparative context, each local effort could expect to realize enhanced scientific utility in terms of its own local fishery concerns, while in turn expanding the available suite of potential comparative analogues and thereby contributing to the general scientific benefit of all of the associated regional efforts.

## 4.6      CLIMATIC MONITORING AND CLIMATE CHANGE

Events of the last few decades in a number of regions of the globe have attracted the attention of the world to problems of climatic change. Among these events were the droughts in northern Africa, the unreliable monsoon in India, the anomalously dry summer in the former USSR in 1972, the unusually cold winter of 1978/79 in North America and so on. Were these isolated, random events in the development of climate or were they precursors of radically new processes causing the climate to change? Many economic measures depend on the answer to this question, particularly where planning the world's food supply is concerned. This fact led to the establishment in 1979 of the World Climate Programme, when the Eighth World Meteorological Congress, having approved the draft plan and basis of the WCP, determined that one of the principal tasks of the WCP would be monitoring (diagnosis) of changes and fluctuations in climate. The three warmest years on record of global mean combined land-air and sea-surface temperatures occurred in the 1980s. The Second World Climate Conference [45] recognized that climate change was a common concern for all mankind, and the need for a Global Climate Observing System (GCOS) and

the development of a global ocean observing and data management system for improving predictions of climate change and climate monitoring.

Climatic monitoring is the process following the state of the climatic system, determining how anomalous it is and elucidating possible reasons for such anomalies, and the scale of probable changes. The purpose of monitoring is to provide regularly updated information on changes in the climate system and the effects of climatic fluctuations. Operational climatology might be defined as near-real-time climatology where it forms the basis for the understanding of recent climate anomalies and their implications or impacts on socio-economic and natural ecosystems. It also forms the basis for climate forecasting. These topics are very broad, however, and will be only briefly touched upon here as they are addressed in a wide range of literature and a number of WMO, IOC and UNEP programmes.

It has been established, taking expert appraisals by leading scientists as a basis [46], that, amongst the factors determining climatic variations with short periods, the foremost are variability in physical parameters such as sea-surface temperature, heat content of the active layer of the ocean, the ocean water depth characteristics temperature ($T$) and salinity ($S$) (including salinity near the surface), ocean currents, sea level and sea ice.

### 4.6.1      Climatic change

For exploration activities which at any particular site or area might have a lifetime of perhaps half a dozen years at the most, the importance of climatic change and how it might invalidate design information based on the existing database is not too great. For production activity which might be expected to last 20 to 30 years or longer, however, consideration of possible future climatic change becomes appropriate.

While both warming and cooling relative to existing conditions are possible, warming (mainly induced by increased atmospheric $CO_2$ and other "greenhouse gases") is considered more likely. Global circulation models based on $CO_2$ doubling indicate that such a warming trend could amount to an increase of 2 to 4°C in the mean annual temperature of the northern hemisphere by the mid-21st century or soon thereafter. This modelled warming is not expected to be uniform across the whole hemisphere; for example, the Arctic may experience a much greater surface temperature increase (perhaps 10°C) than other latitudes. This larger increase is related to the general thermal stability of the lower levels of the Arctic atmosphere and to the retreat of the highly reflective ice and snow surfaces. Thus most models indicate that warming in polar regions will be concentrated close to the surface rather than distributed throughout the troposphere. In the Atlantic and Pacific areas between 40 and 55°N, surface warming is expected to be comparable to the hemispheric mean value.

Similarly, general circulation model results show a seasonal variability in the amount of warming. In the Arctic, the magnitude of the warming in the summer is much less than that in the winter. Modelled summer sea ice is thin or absent in many areas, the surface albedo is reduced significantly and net incoming solar radiation increased. The additional solar radiation is used either for melting the sea-ice upper surface or for warming the ice-free mixed layer, which has a large heat capacity. Thus the summer warming of the surface air turns out to be relatively small [47]. At the latitudes of the Atlantic and Pacific offshore areas, warming is expected to be fairly uniform throughout the year.

A pronounced Arctic warming may have a number of implications for climatic and related elements which bear on Arctic offshore routeing and siting decisions. The increased warming relative to equatorial areas would alter the temperature difference between the Pole and Equator, which helps to drive storm systems around the globe. It appears there would be a more uniform gradient of air flow between Pole and Equator so that circulation may slacken in the mid-latitudes but possibly intensify at high latitudes. Thus storm activity embedded in that flow could be more prevalent in the Arctic. At the other climatological extreme, some scientists have speculated that increased tropical ocean temperatures could give rise to more frequent or intense tropical storm activity, but some argue for a decrease because of enhanced atmospheric stability.

Increased temperature and increased storm activity may lead to increases in the values of such design elements as extreme wind speeds, wave action and structural icing potential – all of major significance to offshore activity. For example, increased wave action would result in greater design wave heights and possibly longer durations of critical wave-period conditions, contributing to fatigue problems. Changes in structural icing potential would be reflected in both intensity and duration. The season might be shifted and its duration could increase in more ice-free polar regions. The geographical extent of the icing-prone area might also increase and be shifted northward. Warming of ocean surface waters would lead to gradual sea-level rises, with consequent adverse impacts on low-lying coastal areas and on existing or planned infrastructure in the coastal zone.

Considerable uncertainty remains as regards the magnitude of greenhouse-gas-induced changes of climate parameters. However, it now appears prudent to factor in the possibility of such changes in associated designs, policies, strategies and legal frameworks covering marine interests. Unfortunately, the methodology for factoring in such uncertain changes remains unavailable for the most part.

In view of the importance of sea ice and icebergs with respect to offshore routeing and siting, their response to future warming is highlighted in the following section.

### 4.6.1.1 Implications of warming for sea ice and icebergs

In the present climate, first-year ridging of ice or multi-year floes and hummocks poses major problems for tankers trying to make headway through it, and similarly for fixed or dynamically positioned platforms, which must either be designed to withstand the ice or be prepared to move off-station to avoid it. There is also some problem due to scour by ridges and hummocks in some of the shallower waters, which could affect sea-bed pipelines. In these cases, strict design criteria must be met, involving large financial outlays, which add significantly to the cost of marketing any future reserves. This is a particular problem for the Arctic, mainly in the Parry Channel, Beaufort Sea and Queen Elizabeth Island areas.

The advent of warmer climate conditions would lead to a decrease both in the overall extent of sea ice and in the thickness of that ice which continues to exist. At the same time, however, the lesser concentrations of ice generally would probably allow more multi-year floes, a great deal of which are at present restricted to the polar basin and among the high Arctic islands, to penetrate into more southerly waterways where, for example, Beaufort-related production activity is expected to occur. In the long term, such movement of old ice would disappear, but it would probably be a problem at least for the lifetime of any production activity at present foreseen. Another concern might be increased wave/structural icing potential as increased storm activity affects waters that are no longer damped by sea-ice cover.

The threat of icebergs is mainly restricted to the eastern Arctic and the waters east of Labrador and Newfoundland. Problems relate both to collision with platforms or tankers and to sea-bed scour, which could destroy even embedded pipelines used to connect production platforms to coastal markets or collection points.

A future warmer environment, at least in the short term, could result in increased calving from Arctic glaciers so that concentrations of icebergs in Arctic waters would be increased. On the other hand, melting of the icebergs would probably accelerate, so that fewer, or at least smaller ones, would be likely to survive to affect the southern offshore areas.

Given that the problem of selecting and adjusting the most appropriate data is resolved, the question of climate change becomes an important concern. Any statistics which are developed on the basis of existing climate data or gridded fields with the intent of applying them to the design of production expected to have a 20- to 30-year lifetime could be invalidated by a trend in climate during that time. Resulting under- or over-design could mean significant capital losses or environmental damage.

The question of climatic change is far from simple. The possibility of warming or cooling must first

be resolved, followed by determination of the manner in which such a change would be reflected on a regional basis such as for the Arctic or Pacific or Atlantic. How would such change further affect other climatic elements, and then what would be the impact of these on offshore activities themselves? There is such a chain of connecting assumptions to be made that room for error is large, given our current state of knowledge. Nevertheless, qualitative assessments can be usefully attempted now and hopefully refinements in them will be possible in the near future as we become able to study past and present climate patterns and their relationships with offshore activity in more detail.

### 4.6.2 Calculation of the surface heat balance for climate monitoring and medium- and long-range weather forecasting

The exchanges of heat, water and momentum at the air-sea interface play a crucial role in the dynamics of the atmospheric and oceanic disturbances on time-scales longer than a few weeks. In this subsection we discuss issues related to calculating the heat fluxes across the air–sea interface for the purpose of monitoring the climatic state and for initializing long-range weather- and climate-prediction models.

The net downward heat flux at the ocean surface, $F_N$, may be written in terms of four components as follows:

$$F_N = F_S(1-a_w) - F_I - F_{LE} - F_H, \qquad (4.1)$$

where $F_S$ is the incoming solar radiation just above the surface, which is then reduced by the ocean surface albedo $a_w$; $F_I$ is the net upward long-wave radiative flux; $F_{LE}$ the upward latent heat flux; and $F_H$ the upward sensible heat flux. Over most of the global oceans, the dominant components on the right-hand side of equation (4.1) are the solar radiation and latent heat-flux components.

It will not be feasible in the near future to measure the heat-flux components directly on a global basis. Indirect methods are necessary to parameterize the components in terms of easily observable quantities, such as the standard parameters measured by participants in the Voluntary Observing Ship (VOS) network. However, conventional data are not available on a routine basis over large areas of the Pacific, Indian and South Atlantic Oceans. Furthermore, the flux estimates from the bulk formulae do not satisfy the 5–10 $Wm^{-2}$ accuracy requirements of most applications [48, 49]. Deployment of instrumented buoys and research vessels can overcome some of these difficulties, but humidity and radiation fields are difficult to measure even under the best of environmental conditions, when trained technicians are maintaining the instruments on a daily basis.

It is clear that there are only two feasible options for obtaining the surface heat fluxes on a routine, global basis in the near future: (1) static analyses that combine satellite and *in situ* data, and (2) dynamic

analyses that assimilate all sources of data in space and time. By static analysis, we mean producing continuous fields of the heat-flux components at a given time without the use of a dynamic prediction model. The dynamic analyses are an extension of the data-assimilation schemes used by the world's major operational centres such as the US National Meteorological Centre (NMC). Statistical/dynamic analysis schemes are a hybrid of static and dynamic analysis methods.

At the present time there are several climatologies of the surface heat balance over the global oceans that are readily available for use in model development and climate studies. These include the atlas by Esbensen and Kushnir [50] based on a climatology of VOS data provided by the US National Climate Data Center (NCDC), the estimates by Hsiung [51] based on the consolidated data set assembled by the US Navy Fleet Numerical Weather Central, and the atlas of Oberhuber [52] based on the Comprehensive Ocean-Atmosphere Data Set (COADS). These climatologies were calculated by substituting monthly averaged data into the bulk formulae for the components of the surface heat balance shown in equation (4.1) and can be regarded as updates and improvement of the pioneering work by Budyko and his colleagues [53]. Regional climatologies include those of Hastenrath and Lamb [54, 55] for the Indian, tropical Atlantic and Eastern Pacific Oceans, Weare et al. [56] for the tropical Pacific Ocean, and Isemer and Hasse [57] for the North Atlantic Ocean.

Climatologies are useful in the sense that they show the large-scale patterns of the heat-balance components. But more subtle features, such as the position of the zero isoline of the net downward heat-flux field, cannot be determined with certainty. There is considerable room for improvement by correcting systematic errors in the historical data and developing better methods and formulae for calculating the heat-flux components.

Progress is possible on several fronts. First, improved estimates of the climatological heat-flux components are possible by more fully exploiting data from the maritime nations of the world and archived under the MCSS scheme. Second, as satellite estimates of cloud cover, near-surface moisture, surface wind vectors, and other relevant parameters become available in the near future, improvements will be possible in static analyses of the surface heat fluxes by combining conventional data with satellite data. Since satellites directly measure radiation from the Earth-atmosphere system, the greatest potential for improvement is in the estimation of $F_S(1-a_w)$ and $F_I$. Improvements in the estimates of $F_H$ and $F_{LE}$ are likely to come primarily from a reduction in spatial and temporal sampling errors. The improved estimates of the surface heat fluxes from static analyses can play an important role in the understanding of air-sea interaction phenomena and in the development of the data assimilation schemes that will probably replace the static analysis in the future.

An important issue for the development of climatologies extending over a century or longer will be how to remove systematic errors due to changing technology and analysis techniques. This is a problem for historical data archives. The problem is likely to become more severe with the introduction of satellite data and constantly changing dynamical models into the analysis loop. For this reason, it is extremely important that all observed data be archived so that information on the source and characteristics of the data are readily available for the purposes of intercomparisons and reanalysis.

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# CHAPTER 5

# ANALYSIS, PRESENTATION AND INTERPRETATION

The analysis, presentation and interpretation of marine climatological information for applications take on many forms, and combine the use of various statistical techniques. At a very basic level, marine applications serve a need to answer the question, "what is it like out there?" For this purpose, very basic statistics such as means, medians and per cent frequency of occurrence are useful, for the need is often not specific but subjective and sometimes aimed at obtaining a basis of comparison for further and more detailed queries later.

Information used in planning and design of marine operations and structures ultimately depends on an input of numbers describing some limitation obtained from an objective assessment of environmental factors from observed or derived data. Although not exclusively dealing with extreme conditions, these applications address the loads and limitations the marine environment imposes — the "how strong?", "how often?" and "how long?" questions which are included in almost every climate application, marine or otherwise. At this level, information requirements have grown and climate information must be objective, as well as expressible in the form of hard numbers or facts.

Inherent in any set of observations, samples or measurements are errors in measurement and statistical uncertainties due to the sampling process. Moreover, the requirements of climate applications are often such that an extrapolation is required from a limited set of information. Statistical techniques must be applied to marine climate data to estimate the likelihood of error or uncertainty and to fit the information to suitable distribution patterns. This chapter, parts of Chapter 5 of the WMO *Guide to Climatological Practices* (WMO–No. 100) and information found through bibliographies contained therein should provide an adequate, albeit incomplete, introduction to the application of statistics in climate.

In addition to a discussion of various statistical representations used in applications, a number of ways of presenting and interpreting marine climatological information are described in this *Guide*. There are numerous ways in which analyses can be performed and the information displayed. It is very important that the presentation should be clear, easily usable and not subject to misinterpretation. Form is frequently considered to be less important than the information contained; however, the form often determines whether or not the material even gets looked at before a decision is made — thus the presentation is very important. A number of ways of presenting marine climate information are shown. The intent here is not to provide an exhaustive list of examples, but to suggest some techniques which may be adapted.

## 5.1 STATISTICAL TECHNIQUES IN MARINE CLIMATOLOGY

### 5.1.1 Statistical distributions and applications

Chapter 5 of the WMO *Guide to Climatological Practices*, in particular paragraph 5.2.5, discusses a number of common distributions used in climate applications, their statistical properties and statistical tests. With a few exceptions, this material is not reproduced in this *Guide*, and the reader is advised to refer to the former for background material common to all climatological applications.

#### 5.1.1.1 *Statistical distributions in marine climatology*

The most commonly occurring statistical distributions in marine climate applications are those used in the estimation of design extremes, which are described towards the end of this section.

In general, traditional means and standard deviations are less useful than a frequency distribution to engineers engaged in planning and design. For example, in some cases, for instance wind loading, the use of mean values is likely to be misleading and could result in underdesign.

However, there are cases where statistical distributions can be used to parameterize the data. For example, the relation between wind and wave climatologies can be expressed in the form of a gamma function and three associated parameters. Similarly, power calculations for wind turbines can be made in terms of the two constants from a two-parameter Weibull fitted to the data, rather than than the entire distribution.

Similar parameterization has been carried out to give the climatology of the persistence of conditions. However, such techniques can be misleading, because the parameters are neither universally applicable nor portable. Usually, a substantial local record is required to establish the values of the parameters.

In a few cases, vector means can be useful. Examples are the probable (long-term) drift of wind-driven or ocean-current-driven pollutants. However, in the case of ocean currents, the predominant or prevailing current is also required, together with an estimate of variability or constancy.

#### 5.1.1.2 *Frequency analysis*

In working with very large data sets, a good overall picture and sufficient information for many applications

can often be conveyed by arranging the data into groups or classes of a frequency distribution. This is a very useful way of displaying relative frequency, or probability, information. The relative frequency approaches the true probability as the number of observations increases, assuming the past and future data sets are stationary and have no trend.

### 5.1.1.2.1 Univariate frequency analysis

Constructing a univariate frequency distribution essentially consists of choosing the classes, sorting the data into them, then counting the number of items in each class. The number of classes chosen is generally no fewer than five nor more than 15, although the choice depends mostly on the number of observations. As a rough guide the number of classes should not exceed five times the decimal logarithm of the number of observations. Thus, for 100 observations or more, there should be a maximum of ten classes.

Class intervals should not overlap and, if possible, should be equal. The latter condition cannot always be met, especially if data are qualitative (e.g. the number of days with rain), or if the frequencies fall off very rapidly over part of the range. In such cases, class frequencies must be chosen so as to fit the data and to serve the practical application for which the frequency table has been designed.

The class interval is obtained by determining the range between the highest and lowest values and dividing this by the number of classes and then rounding off to obtain a convenient class-interval size. By accumulating the frequency of occurrence the cumulative frequency is obtained, which may be divided by the total number of data points to obtain the relative cumulative frequency in each class interval. The latter is often referred to as percent exceedance.

In practical applications, more useful results can be obtained by constructing a cumulative frequency distribution in which the estimated probability that a certain value will be exceeded is calculated. The data are ranked in order of magnitude and each variable is assigned a probability $F = m/(n + 1)$, where $m$ is the rank in the climatological series and $n$ is the total number of data points. $F$ is the estimated probability of occurrence of the variable less than that shown.

The same features of the frequency distribution may be brought out graphically in a histogram. The cumulative percentage frequency distribution may also be graphed as an ogive by plotting the upper value of each class interval on the abscissa scale against the cumulative percentage frequency for that class interval on the ordinate scale and drawing either straight lines between the points or a smooth line amongst them as an approximation.

Univariate frequency analyses are important representations for many parameters, including precipitation, icing, cloud amount, visibility, wind chill, air temperature, sea temperature, wind speed, wave height and wave period.

While some of the parameters listed above are functions of more than one variable, they are single-valued functions, and thus qualify as univariate frequency distributions (e.g. wind chill).

For most parameters it is sufficient to produce the frequency distributions on a monthly, or in some cases seasonal, basis.

An example of a frequency analysis for wind speed is shown in Figure 5.1 and Table 5.1.



WIND SPEED FREQUENCIES
DEC-FEB
1864 TO 1987
N=1969

WATERS OF THE TURKS AND CAICOS

WIND SPEED (KTS)



WIND SPEED
EXCEEDANCE
DEC-FEB
1864 TO 1987
N=1969

WATERS OF THE TURKS AND CAICOS
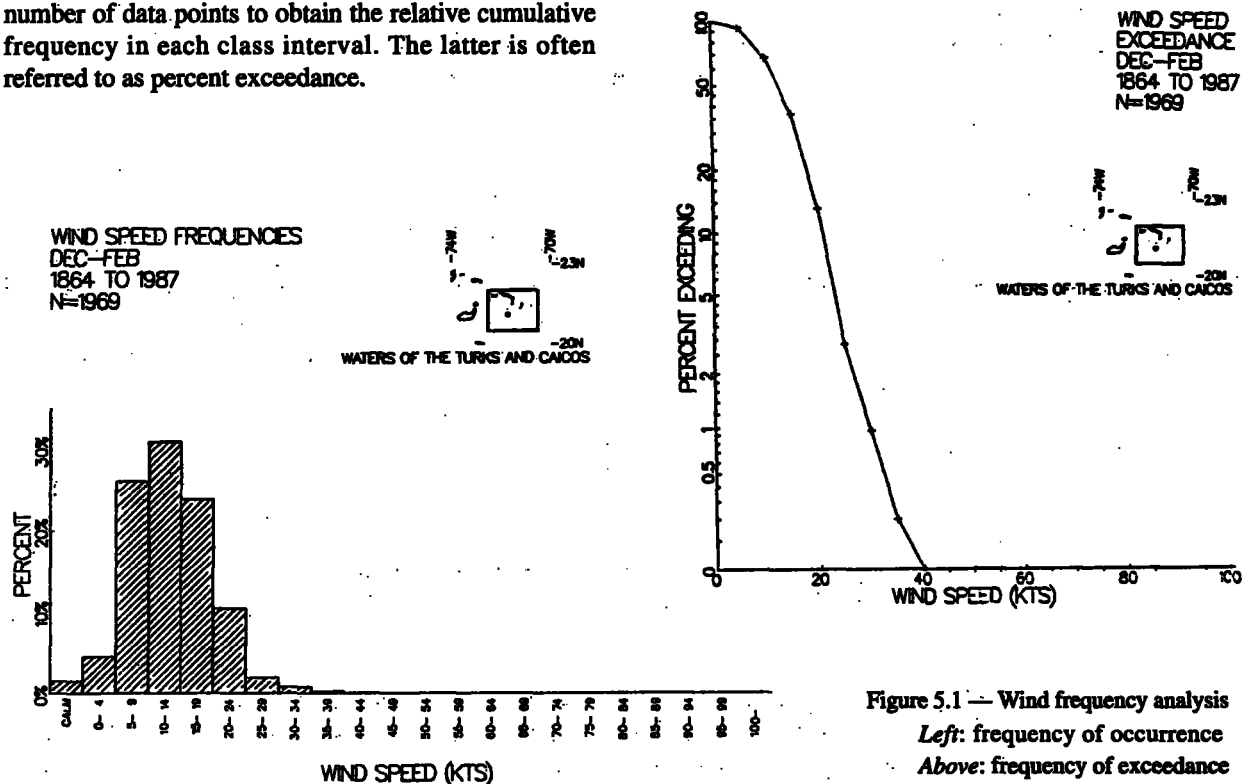
WIND SPEED (KTS)

Figure 5.1 — Wind frequency analysis
*Left*: frequency of occurrence
*Above*: frequency of exceedance

### TABLE 5.1
### Percentage frequency of wind speed by direction

| Location: Waters of the Turks and Caicos | Dec.–Feb. 1864–1987 | |
|---|---|---|
| Wind speed (knots) | Total frequency | Exceedance frequency |
| 0–4 | 6.4 | 100.0 |
| 5–9 | 25.9 | 93.6 |
| 10–14 | 30.7 | 67.6 |
| 15–19 | 23.7 | 36.9 |
| 20–24 | 10.3 | 13.1 |
| 25–29 | 1.9 | 2.8 |
| 30–34 | .8 | 1.0 |
| 35–39 | .2 | .2 |
| 40–100 | | |
| TOTAL | 100.0 | |

Total number of observations: 1969
Mean latitude of observations: 21.1N
Mean longitude of observations: 71.7W

#### 5.1.1.2.2 Multivariate analysis

Analysis of the joint occurrence of two or more variables may be made in one of several ways.

Scatter diagrams, where the arrangement of the data values in the plot indicates nature of the joint distribution of the two variables, are frequently used. Information on which statistical model should be used, whether the relationship is linear or curvilinear, whether transformations would be beneficial, whether some data are outliers or are too extreme and require further investigation, or whether any useful relationship exists at all, can be determined from a scatter plot prior to more detailed statistical analysis such as correlation or regression analysis. These techniques are described in detail in WMO–No. 100.

Bivariate frequency analyses are often produced from the joint frequency of two variates, e.g. wind speed and direction, in a contingency table. Such tables can be produced for any combination of parameters; however, some combinations are much more common than others. Especially useful are wind speed by direction, wave height by direction, wave height by wave period, and ceiling versus visibility. The last of these may be calculated in two ways: either ceiling and visibility, or ceiling or visibility. Simple frequencies and cumulative frequencies may be calculated. Examples of a contingency table and graphical bivariate frequency analyses are shown in Table 5.2 and Figure 5.2.

### TABLE 5.2
### Percentage frequency of combined wave height by period

| Location: Waters of the Turks and Caicos | | | | | | | | | June–Aug. 1864–1987 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wave height (metres) | ≤5 (sec) | 6–7 (sec) | 8–9 (sec) | 10–11 (sec) | 12–13 (sec) | 14–15 (sec) | >15 (sec) | Calm. | Total frequency | Exceedance frequency |
| 0.0–0.9 | 14.7 | 1.1 | .7 | .2 | | | | 3.2 | 19.9 | 100.0 |
| 1.0–1.9 | 35.1 | 13.8 | 4.0 | .5 | 1.0 | .2 | | | 54.6 | 80.1 |
| 2.0–2.9 | 8.0 | 9.0 | 2.4 | .7 | .9 | .3 | | | 21.2 | 25.6 |
| 3.0–3.9 | 1.4 | 1.1 | .6 | .2 | .1 | .1 | | | 3.4 | 4.3 |
| 4.0–4.9 | .3 | .1 | .2 | | | | | | .6 | .9 |
| 5.0–5.9 | | .1 | | | | | | | .1 | .3 |
| 6.0–6.9 | | | .1 | | | | | | .1 | .3 |
| 7.0–7.9 | | | | | | | | | | .2 |
| 8.0–8.9 | | | | | | | | | | .2 |
| 9.0–9.9 | | | | | | | | | | .2 |
| 10.0–10.9 | | | | | | | | | | .2 |
| 11.0–11.9 | | | | | | | | | | .2 |
| 12.0–12.9 | | | | | | | | | | .2 |
| 13.0–13.9 | | | | | | .1 | | | .1 | .2 |
| 14.0–14.9 | | | | | | | | | | .1 |
| 15.0– | | | | .1 | | | | | .1 | .1 |
| TOTAL | 59.1 | 25.1 | 7.9 | 1.6 | 1.9 | .7 | | 3.2 | 100.0 | |

Total number of observations: 1182; mean latitude of observations: 21.2N; mean longitude of observations: 71.7W

COMBINED WAVE HEIGHT/
PERIOD FREQUENCIES
JUN—AUG
1864 TO 1987
N=1182
(3.2% CALM)                    WATERS OF THE TURKS AND CAICOS
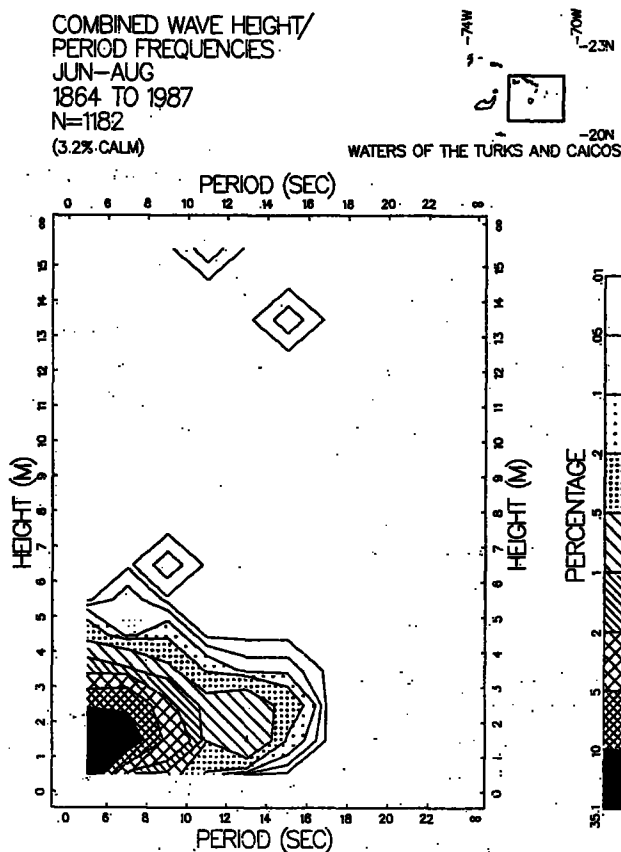


Figure 5.2—Bivariate frequency analysis

## 5.1.2    Basic statistics

Basic statistics such as the mean, median, mode, standard deviation, minimum, maximum, and fractiles may be calculated for each collective month or season for most parameters. The location and number of valid observations from which the statistics were calculated should also be shown. In any instance where there are insufficient data to compute a statistic, asterisks or some other indicator should fill the output tables.

### 5.1.2.1    Mean

The mean is calculated from the formula:

$$\bar{X} = \left(\sum_{i=1}^{N} X_i\right) / N \qquad (5.1)$$

where $X_i$ is the parameter value and $N$ is the number of observations. Annual means may be calculated by averaging the monthly or seasonal means (not weighted), since to average all data would introduce biases on account of unequal numbers of observations in the different months. If one or more months have no data, the annual means may be calculated on fewer monthly values, or by using longer time periods such as seasons.

### 5.1.2.2    Standard deviation

The population standard deviation may be computed according to the formula:

$$\sigma = \left\{\left[N\left(\sum_{i=1}^{N} X_i^2\right) - \left(\sum_{i=1}^{N} X_i\right)^2\right] / N(N-1)\right\}^{\frac{1}{2}} \qquad (5.2)$$

where $X_i$ is the parameter value and $N$ is the number of observations.

### 5.1.2.3    Coefficient of variation

For comparing values of the standard deviation between different places, the influence of the actual magnitude of the mean can easily be eliminated by expressing $\sigma$ as a percentage of the mean, i.e. as a dimensionless quantity called the coefficient of variation:

$$C_v = \left(\sigma / \bar{X}\right) \cdot 100 \qquad (5.3)$$

This statistic is used to provide a measure of relative variability.

### 5.1.2.4    Median

The median of the observations is computed by sorting the observations into ascending order, taking the central observation, and counting through the sorted data set to that point. The value at that point then represents the median. If there are an even number of observations, there will be two central points. In this case the average of the two values is the median.

### 5.1.2.5    Fractiles (or percentiles)

Many applications use fractile values, e.g. the highest 10 per cent or lowest 20 per cent values in a data series. The methodology for computation is similar to that for the median (the median is a fractile).

To compute a percentile, the data are sorted in ascending order. For a series of $N$ ranked values, the position of the $K$th percentile is the $K(N+1)/100$ value. When the $K$th percentile is not a whole number, interpolation is required.

### 5.1.2.6    Mode

The mode is the most probable or most frequent value in any array. For climatological observations such as the number of days with fog or the most prevalent wind direction, the modal value is often the most representative. An important feature of the mode is that it is an actual value in a climatological series; this may not be true for the arithmetic mean, when the variable is discrete. However, the mode has only a limited utility since it cannot be used for further analysis except in describing the average. Some series have more than one modal value.

### 5.1.2.7    Maximum, minimum

The maximum/minimum value is the highest/lowest valid value in the data set. In the case of observations from transient ships, the maximum value is often suspect. A more stable estimate of high values may be obtained from a suitable fractile.

### 5.1.2.8 Other wind statistics

Several additional statistics may be computed for the wind field, including vector mean speed and direction, the zonal and meridional mean speeds and standard deviations, the steadiness and the zonal to meridional correlation. The following paragraphs describe their computation.

#### 5.1.2.8.1 Vector mean speed and direction

The vector mean speed and direction are computed from the mean $u$ (eastward) and $v$ (northward) components of the wind. These mean values are then converted to direction from and speed by the standard goniometric formula below. The annual mean values may be similarly computed from the annual means of the $u$ and $v$ components.

In the following equations $w$ is the wind speed, $u$ is the component of the wind speed in the east-west direction, positive towards the east, and $v$ is the component of the wind speed in the north-south direction, positive towards the north.

$$w = \left(\bar{u}^2 + \bar{v}^2\right)^{\frac{1}{2}}$$

$$h = \arctan \bar{v} / \bar{u} \tag{5.4}$$

If $\bar{u}, \bar{v}$ both positive, $180° < h < 270°$

$\bar{u}, \bar{v}$ both negative, $0° < h < 90°$

$\bar{u}$ negative, $\bar{v}$ positive, $90° < h < 180°$

$\bar{u}$ positive, $\bar{v}$ negative, $270° < h < 360°$

#### 5.1.2.8.2 Steadiness

The steadiness parameter is the ratio of the vector mean speed to the scalar mean speed. This gives an indication of the persistence of the wind from a particular direction. For example, if the wind were to blow from one direction for an entire period, the steadiness value would be 1.0. Conversely, if the wind were to blow equally from all directions at the same speed, the steadiness (and the vector mean) would be zero. Annual steadiness is annual vector mean speed divided by annual scalar mean speed. This value is lower in general than the mean of the 12 monthly steadiness values, and can be equal only if all 12 monthly vector mean directions are equal.

#### 5.1.2.8.3 Zonal to meridional correlation

This computation is given by the formula:

$$r(u,v) = ((\Sigma_i u_i * v_i) - (n*u*v)) / ((n-1)\,(\sigma(u)*\sigma(v))) \tag{5.5}$$

where $r$ is the zonal to meridional correlation;

　　$u_i$ is the individual value of the $u$ component of wind speed;

　　$v_i$ is the individual value of the $v$ component of wind speed;

　　$n$ is the number of wind observations;

　　$u$ is the mean zonal wind speed for the month;

　　$v$ is the mean meridional wind speed for the month;

$\sigma(u)$ is the standard deviation of the zonal wind speed;

$\sigma(v)$ is the standard deviation of the meridional wind speed.

The annual values of the means and standard deviations are computed from the unweighted averages of the monthly or seasonal values. The tabulated values of zonal to meridional correlation, together with computed mean velocity components and standard deviations, could be used to reconstitute a wind rose for a marine area not having a sufficient number of observations otherwise [1]. They are also useful in quantitatively describing variations in the wind regime in space and time.

## 5.2 PRESENTATION OF CLIMATOLOGICAL ANALYSIS

Results of climatological analysis may be presented in a number of different ways, including tabulations, graphs and contoured maps. Although the information content and analysis are paramount, the layout and certain documentation features add greatly to the usefulness and effectiveness of the presentations.

In general, in order to be effective, a presentation should include information locating the product in time and space, indicate the quality, source and/or numbers of observations used, and when and by whom the analysis or presentation was performed. The most important information should be made to predominate if possible.

The following sections describe many possible marine climatological presentations and provide numerous examples.

### 5.2.1 Tabulations

All tables should contain the following information: location and/or name given to the area, the time span of the data (the time the first observation is encountered for the specific area to the year the last observation is encountered), and the number of observations used to calculate the statistics. Tables can be displayed as number counts, or percentage frequency. When there are not enough data to produce proper statistics, the field is filled with asterisks or some other indication of this fact. As a general rule, if there are not at least 40 valid and well-distributed observations for each analysis time period, then no tables of any kind should be produced. It must be emphasized that well-distributed observations are a key ingredient as biases can be introduced if a large quantity of the data are collected over a short timeframe. This often happens when buoy or platform data are mixed with ship observations.

#### 5.2.1.1 Temporal and spatial variability

A listing of the number of observations by climatological variable for each month and year for the period of interest is a very useful tool in assessing homogeneity of the

database. This is of considerable importance in climatological analysis, due to the inherent biases in marine data composed mainly of observations of transient ships. Similarly, the number of observations per unit geographic area may be mapped to assess biases. Biases arise due to spatial variability of observations (shipping lanes, drilling areas, etc.) and temporal variability — year to year, seasonally and monthly. It is impossible to assess statistics for a given area adequately without consideration of the temporal and spatial distribution of the observations on which the analyses are based.

### 5.2.1.2    Basic statistical tables

These tables summarize standard statistics such as mean, median, standard deviation, percentiles, and maximum/minimum values observed for each month. This type of analysis is normally produced for the following climatological variables:

> Air temperature;
> Sea surface temperature;
> Air-sea temperature difference;
> Dew-point temperature;
> Dew-point depression;
> Relative humidity;
> Vapour pressure;
> Wind speed;
> Vector mean wind;
> Sea-level pressure;
> Wave height;
> Wave period;
> Swell height;
> Swell period;
> Combined (or resultant) wave height;
> Combined (or resultant) wave period;
> Wind stress;
> Heat flux;
> Evaporation rate.

The calculation of these statistics has been described in section 5.1.1 above.

### 5.2.1.3    Univariate frequency tabulations

The frequency of any parameter may be tabulated for any given time period (e.g. month, season). Values for the class limits should be defined by the needs of the user, except that certain measured parameters are coded for data transmission and archiving. In this case the possible class limits are restricted by the values of the codes. As noted above, class limits may be strictly numeric, e.g. 50–60 knots; by coded values, e.g. visibility codes 90–92 (corresponding to visibilities of less than 50 m to 500 m); or in descriptive terms, such as heavy snow, moderate icing, etc. Examples are provided below.

### 5.2.1.4    Bivariate frequency tabulations

Joint frequency analyses of two variables may be produced for many combinations of parameters. The frequency of occurrence of concurrent conditions of the two variables is given in each cell of a table. Such tabulations should also include sums of each univariate condition for both variables.

An important bivariate analysis summary is the frequency of wind speed by direction class. Direction classes can be either 8, 12, 16 or more points of the compass, but the analyst should approach the use of more than eight direction classes with caution because of a reporting bias among some observers to these directions. Unfortunately there are similar reporting biases for wind speeds and other variables. Classes may also be provided for calm and variable winds. The table can include both simple and exceedance frequencies (see Table 5.1).

The computation of the frequencies in each direction class should be modified to take account of the fact that the observations may be taken in three different ways, and reported in four different ways, and that there are different numbers of observation "bins" in each class. As a result, observations may be split in such a way that one part of an observation goes into one class, and another goes into another class. Tables 5.3(b)–(d) show the proportion of each observation which is assigned to each direction class. This step is somewhat arbitrary, but is necessary to avoid biasing the statistics to certain compass points. It should be noted that "variable" directions are possible only in 36-point compass observations. The code option does not exist for other reporting practices. Therefore, the percentage of observations with variable wind direction is calculable only from the sample of 36-point wind observations.

TABLE 5.3(a)

**Definitions for wind and wave direction classes**

| 8 point | | 12 point | | 16 point | |
|---|---|---|---|---|---|
| N | 337.5–022.5 | 360 | 345–015 | N | 348.75–011.25 |
| | | 30 | 015–045 | NNE | 011.25–033.75 |
| NE | 022.5–067.5 | 60 | 045–075 | NE | 033.75–056.25 |
| | | | | ENE | 056.25–078.75 |
| E | 067.5–112.5 | 90 | 075–105 | E | 078.75–101.25 |
| | | 120 | 105–135 | ESE | 101.25–123.75 |
| SE | 112.5–157.5 | 150 | 135–165 | SE | 123.75–146.25 |
| | | | | SSE | 146.25–168.75 |
| S | 157.5–202.5 | 180 | 165–195 | S | 168.75–191.25 |
| | | 210 | 195–225 | SSW | 191.25–213.75 |
| SW | 202.5–247.5 | 240 | 225–255 | SW | 213.75–236.25 |
| | | | | WSW | 236.25–258.75 |
| W | 247.5–292.5 | 270 | 255–285 | W | 258.75–281.25 |
| | | 300 | 285–315 | WNW | 281.25–303.75 |
| NW | 292.5–337.5 | 330 | 315–345 | NW | 303.75–326.25 |
| | | | | NNW | 326.25–348.75 |

**TABLE 5.3(b)**

**Assignments to direction classes for input on 36-point scale**

| Input 36 point | Inferred range of input | 8-point scale | 12 point | 16 point |
|---|---|---|---|---|
| 1 | 5–15 | N | 360 | 5/8N,3/8NNE |
| 2 | 15–25 | 3/4N,1/4NE | 30 | NNE |
| 3 | 25–35 | NE | 30 | 7/8NNE,1/8NE |
| 4 | 35–45 | NE | 30 | NE |
| 5 | 45–55 | NE | 60 | NE |
| 6 | 55–65 | NE | 60 | 1/8NE,7/8ENE |
| 7 | 65–75 | 1/4NE,3/4E | 60 | ENE |
| 8 | 75–85 | E | 90 | 3/8ENE,5/8E |
| 9 | 85–95 | E | 90 | E |
| 10 | 95–105 | E | 90 | 5/8E,3/8ESE |
| 11 | 105–115 | 3/4E,1/4SE | 120 | ESE |
| 12 | 115–125 | SE | 120 | 7/8ESE,1/8SE |
| 13 | 125–135 | SE | 120 | SE |
| 14 | 135–145 | SE | 150 | SE |
| 15 | 145–155 | SE | 150 | 1/8SE,7/8SSE |
| 16 | 155–165 | 1/4SE,3/4S | 150 | SSE |
| 17 | 165–175 | S | 180 | 3/8SSE,5/8S |
| 18 | 175–185 | S | 180 | S |
| 19 | 185–195 | S | 180 | 5/8S,3/8SSW |
| 20 | 195–205 | 3/4S,1/4SW | 210 | SSW |
| 21 | 205–215 | SW | 210 | 7/8SSW,1/8SW |
| 22 | 215–225 | SW | 210 | SW |
| 23 | 225–235 | SW | 240 | SW |
| 24 | 235–245 | SW | 240 | 1/8SW,7/8WSW |
| 25 | 245–255 | 1/4SW,3/4W | 240 | WSW |
| 26 | 255–265 | W | 270 | 3/8WSW,5/8W |
| 27 | 265–275 | W | 270 | W |
| 28 | 275–285 | W | 270 | 5/8W,3/8WNW |
| 29 | 285–295 | 3/4W,1/4NW | 300 | WNW |
| 30 | 295–305 | NW | 300 | 7/8WNW,1/8NW |
| 31 | 305–315 | NW | 300 | NW |
| 32 | 315–325 | NW | 330 | NW |
| 33 | 325–335 | NW | 330 | 1/8NW,7/8NNW |
| 34 | 335–345 | 1/4NW,3/4N | 330 | NNW |
| 35 | 345–355 | N | 360 | 3/8NNW'5/8N |
| 36 | 355–005 | N | 360 | N |

**TABLE 5.3(c)**

**Assignments for direction input on 32-point scale**

| Input 32 point | Inferred range of input | 8-point scale | 12 point | 16 point |
|---|---|---|---|---|
| 1 | 5.625–16.875 | N | 5/6 360,1/6 30 | 1/2N,1/2NNE |
| 2 | 16.875–28.125 | 1/2N,1/2NE | 30 | NNE |
| 3 | 28.125–39.375 | 30 | 1/2NNE,1/2NE | |
| 4 | 39.375–50.625 | NE | 1/2 30,1/2 60 | NE |
| 5 | 50.625–61.875 | NE | 60 | 1/2NE,1/2ENE |
| 6 | 61.875–73.125 | 1/2NE,1/2E | 60 | ENE |
| 7 | 73.125–84.375 | E | 1/6 60,5/6 90 | 1/2ENE,1/2E |
| 8 | 84.375–95.625 | E | 90 | E |
| 9 | 95.625–106.875 | E | 5/6 90,1/6 120 | 1/2E,1/2ESE |
| 10 | 106.875–118.125 | 1/2E,1/2SE | 120 | ESE |
| 11 | 118.125–129.375 | SE | 120 | 1/2ESE,1/2SE |
| 12 | 129.375–140.625 | SE | 1/2 120,1/2 | 150    SE |
| 13 | 140.625–151.875 | SE | 150 | 1/2SE,1/2SSE |
| 14 | 151.875–163.125 | 1/2SE,1/2S | 150 | SSE |
| 15 | 163.125–174.375 | S | 1/6 150,5/6 180 | 1/2SSE,1/2S |
| 16 | 174.375–185.625 | S | 180 | S |
| 17 | 185.625–196.875 | S | 5/6 180,1/6 210 | 1/2S,1/2SSW |
| 18 | 196.875–208.125 | 1/2S,1/2SW | 210 | SSW |
| 19 | 208.125–219.375 | SW | 210 | 1/2SSW,1/2SW |
| 20 | 219.375–230.625 | SW | 1/2 210,1/2 240 | SW |
| 21 | 230.625–241.875 | SW | 240 | 1/2SW,1/2WSW |
| 22 | 241.875–253.125 | 1/2SW,1/2W | 240 | WSW |
| 23 | 253.125–264.375 | W | 1/6 240,5/6 270 | 1/2WSW,1/2W |
| 24 | 264.375–275.625 | W | 270 | W |
| 25 | 275.625–286.875 | W | 5/6 270,1/6 300 | 1/2W,1/2WNW |
| 26 | 286.875–298.125 | 1/2W,1/2NW | 300 | WNW |
| 27 | 298.125–309.375 | NW | 300 | 1/2WNW,1/2NW |
| 28 | 309.375–320.625 | NW | 1/2 300,1/2 330 | NW |
| 29 | 320.625–331.875 | NW | 330 | 1/2NW,1/2NNW |
| 30 | 331.875–343.125 | 1/2NW,1/2N | 330 | NNW |
| 31 | 343.125–354.375 | N | 1/6 330,5/6 360 | 1/2NNW,1/2N |
| 32 | 354.375–5.625 | N | 360 | N |

**TABLE 5.3(d)**

**Assignments for directions in 16 of 36- or 16 of 32-point scale**

| Input 36 point | Input 32 point | Inferred range of input | 8-point scale | 12 point | 16 point |
|---|---|---|---|---|---|
| 2 | 2 | 1125–33.75 | 1/2N,1/2NE | 1/6 360,5/6 30 | NNE |
| 5 | 4 | 33.75–56.25 | NE | 1/2 30,1/2 60 | NE |
| 7 | 6 | 56.25–78.75 | 1/2NE,1/2E | 5/6 60,1/6 90 | ENE |
| 9 | 8 | 78.75–101.25 | E | 90 | E |
| 11 | 10 | 101.25–123.75 | 1/2E,1/2SE | 1/6 90,5/6 120 | ESE |
| 14 | 12 | 123.75–146.25 | SE | 1/2 120,1/2 150 | SE |
| 16 | 14 | 146.25–168.75 | 1/2SE,1/2S | 5/6 150,1/6 180 | SSE |
| 18 | 16 | 168.75–191.25 | S | 180 | S |
| 20 | 18 | 191.25–213.75 | 1/2S,1/2SW | 1/6 180,5/6 210 | SSW |
| 23 | 20 | 213.75–236.25 | SW | 1/2 210,1/2 240 | SW |
| 25 | 22 | 236.25–258.75 | 1/2SW,1/2W | 5/6 240,1/6 270 | WSW |
| 27 | 24 | 258.75–281.25 | W | 270 | W |
| 29 | 26 | 281.25–303.75 | 1/2W,1/2NW | 1/6 270,5/6 300 | WNW |
| 32 | 28 | 303.75–326.25 | NW | 1/2 300,1/2 330 | NW |
| 34 | 30 | 326.25–348.75 | 1/2NW,1/2N | 5/6 330,1/6 360 | NNW |
| 36 | 32 | 348.75–11.25 | N | 360 | N |

Directional frequency tables of waves may be produced in the same way as for winds.

Another very important joint frequency analysis is that of ceiling versus visibility. This may be obtained in two different ways. Two sets of tables may be produced: (1) the visibility class and the ceiling class must be satisfied, i.e. both constraints to the class must be satisfied; (2) the visibility class or the ceiling class must be met, i.e. either of the class requirements is satisfied. The latter is of particular importance for flying activities, in that if either the visibility is reduced, or low cloud ceilings exist, flying is restricted. As noted above, the selection of classes is limited by the class ranges in the reporting codes of visibility and cloud height.

## 5.2.1.5    Exceedance listings

Exceedance listings of observations for values greater (or less) than a specified threshold may be produced (i.e. observations where wind speed is greater than 50 knots are listed) or, alternatively, only the top ten (or so) values may be listed. Such listings are useful where the correctness of observed extremes is to be examined, or in the selection of extreme events in the past for hindcasting purposes or further analysis.

## 5.2.2    Graphics

For all graphs, the location name given to the area, the time span of the data (from the time the first observation is encountered for the specific area to the year the last observation is encountered), and the number of observations used to calculate the statistics should be shown with the graph or in an accompanying table or text. Again, as a general rule, if there are not at least 40 valid observations for each analysis time period, then a graphic plot should not be produced, and some indication given that an insufficient number of observations were available for this portion of the graph.

Although not shown in these examples, the date the graph was produced, and the author or agency producing the graph, should also be indicated. This is extremely important for computer-produced graphics and databases because these are continuously changing or being expanded. There is also the recurring possibility of error.

## 5.2.2.1    Graphs of basic statistics

These graphs summarize standard statistics such as mean, median, standard deviation, percentiles, and maximum/

minimum values observed for each observing period (e.g. month). An example is provided in Figure 5.3.

In this example solid or dashed lines connect the median and percentile values for each month. The maximum and minimum values observed are indicated by arrows and the standard deviation is indicated by an error bar for each month. The mean values are at the centre of each error bar.

An alternative to the above is provided in Figure 5.4 [2]. In this example, much the same information as in Figure 5.3 is provided in the form of bars of varying width.

## 5.2.2.2    Univariate frequency graphs

All univariate frequency graphs may be displayed as bar or line graphs. Frequency graphs may be produced for any of the tabulations listed in section 5.2.1. Selection of suitable shading for classes helps to convey the information quickly to the user, as shown in the earlier examples.

## 5.2.2.3    Bivariate frequency graphs

Bivariate frequency graphs may be produced for any combination of two parameters. These graphs, which have the frequency of one parameter on the abscissa, and the frequency of the second parameter on the ordinate, appear as two-dimensional contour diagrams (Figure 5.2). If contours are not drawn, and the raw number frequencies are plotted, these graphs reduce to scatter diagrams as in the example given in Figure 5.5.

## 5.2.2.4    Frequency roses

Frequency roses may be produced for wind speed, wave height and the various other fields by direction. Usually
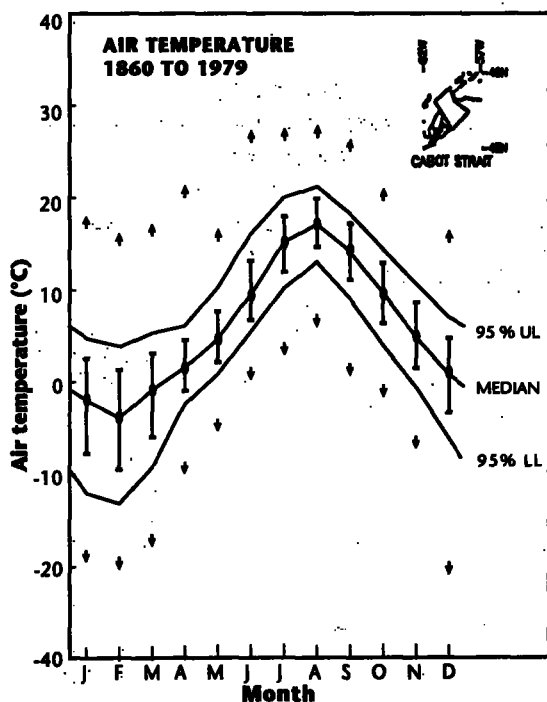
Figure 5.3 — Air temperatures in the Cabot Strait
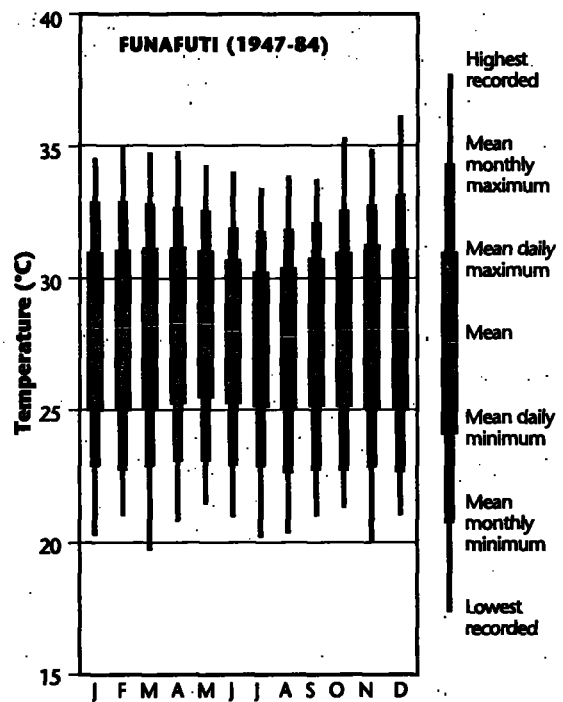
Figure 5.4 — Air temperature variability at Tuvalu (Funafuti)

STATION 65
TORONTO
MARCH 1972 TO 1973
NUMBER OF OBSERVATIONS 276
OCCURRENCES OF CALM 24
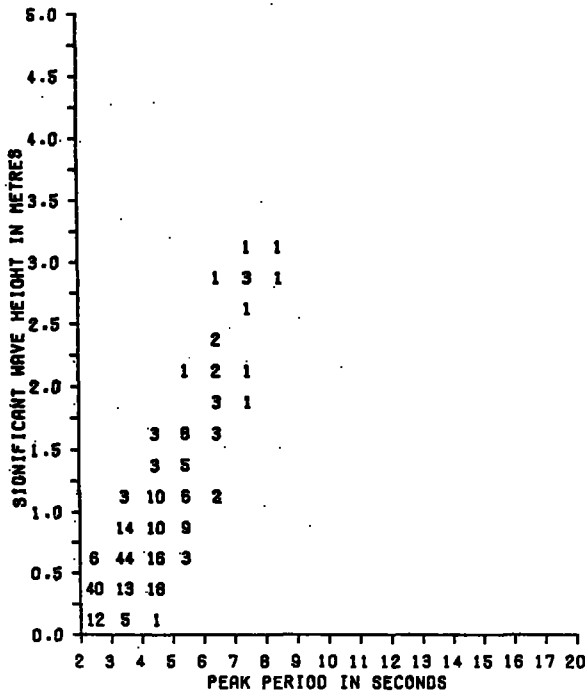


Figure 5.5 — Wave height/period

FREQUENCY OF
WIND SPEED
BY DIRECTION
DEC–FEB
1864 TO 1987
N=1969

WATERS OF THE TURKS AND CAICOS
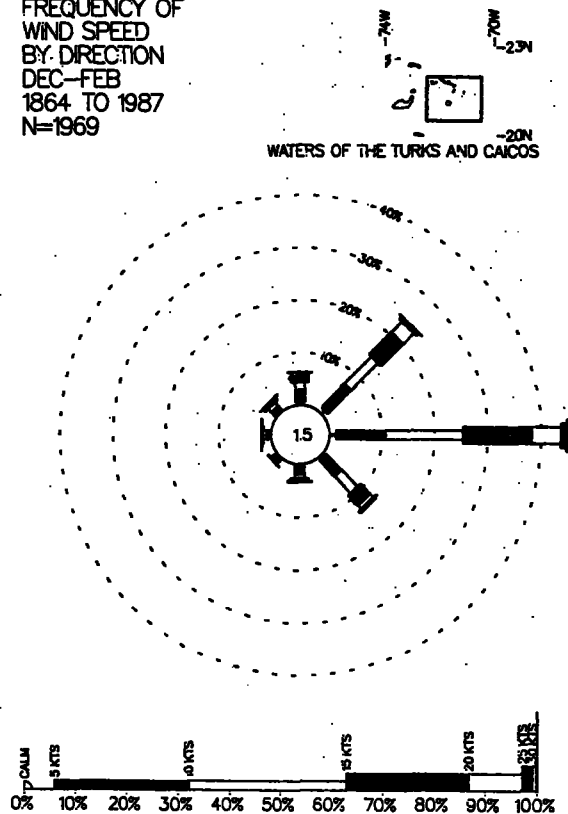


Figure 5.6 — Wind speed/direction rose

direction classes corresponding to 8, 12 or 16 points of the compass are selected. These correspond to direction range sizes of 45, 30 and 22.5 degrees respectively. The ranges are shown in Table 5.3. The length of the bars on the rose in Figure 5.6 correspond to the frequency of the class.

In their simplest form, when all wind speeds are put into one class, the frequency rose degenerates to a wind direction rose. In some cases, the mean wind speed associated with winds from a particular direction is also printed with this rose.

Joint frequency analyses of any other parameter and wind or wave direction may also be produced. Thus, analyses of air temperature by wind direction, wave height by swell direction or freezing spray by combined wave direction can be produced. Again the roses may have either 8, 12 or 16 points. The length of the bars on the rose correspond to the frequency of the class (Figure 5.6).

In an alternative form of wind rose, selected exceedance thresholds are plotted against wind speed for a particular wind direction. The advantages of this presentation are that the frequency of occurrence of the highest wind speed is given prominence.

Similar rose graphs to the examples above may be produced for other combinations of climatological variables.

### 5.2.3    Climatological charts

Maps are an effective and efficient means of summarizing and communicating a great deal of data and information while at the same time stimulating interest in the climatic

elements displayed. Climatic maps are in many cases either more suitable than tables, or at least very valuable supplements to them. Their formats generally depend on the elements being considered, the amount of data available, and the purpose to be served by the data.

Climatic maps have become increasingly important in applications to a wide range of social, economic and environmental activities. They range from comparatively simple maps, such as those showing basic statistics on single climatic parameters, to more complex charts, such as the duration of consecutive occurrences, return periods of extreme events, or co-incident frequencies of two or more parameters.

Many of the maps are prepared for general planning purposes. However, the majority are tailored for a particular user or theme which involves the design, development and construction of a project or facility and the day-to-day operating procedures at the site or operations area. The climatic elements and parameters are widely variable but should be oriented towards the application with pertinent information easily extracted.

A list of climatic maps for several applied activities appears below. It is by no means a complete list but is included in order to illustrate the scope and variety of the applied maps which have been produced.

### 5.2.3.1    *Climatic maps for applied purposes*

For each of the important elements described in Chapter 2 a selection of climatic maps may be prepared. All of the maps listed below will not be relevant for all

applications; there may also be analyses useful for specific applications which are not included in the following list. Some examples are provided.

### Wind speed and direction

Monthly (or seasonal) and annual maps of scalar mean wind may be produced. Also, maps of monthly vector mean wind velocity should be produced in the form of scaled arrows rather than contours. Prevailing wind direction (mode) may also be produced in the form of arrows and may be displayed on the scalar mean speed contour plot (Figure 5.7).

Maps of percentage frequency of wind speeds above or below certain critical thresholds are also useful for certain applications. Typical threshold values would

be 34 and 48 knots indicating gale- and storm-force wind frequencies. Maps of durations of wind speeds above or below critical thresholds are also important for time-dependent applications such as towing barges or re-supply (Figure 5.8).

Maps of the 50- or 100-year return period wind speed may also be produced for design considerations. The use of hindcast winds is recommended for this application. The contouring of the maximum wind speed is not recommended, especially from the transient ship data, in view of data-quality considerations. In any event, the maximum value is not a stable field and its use may lead to spurious contours. Running the data through extreme-value analysis smooths out much of the variability due to errors in analysis and observation, and

# WIND DIRECTION AND SPEED
## OCTOBER
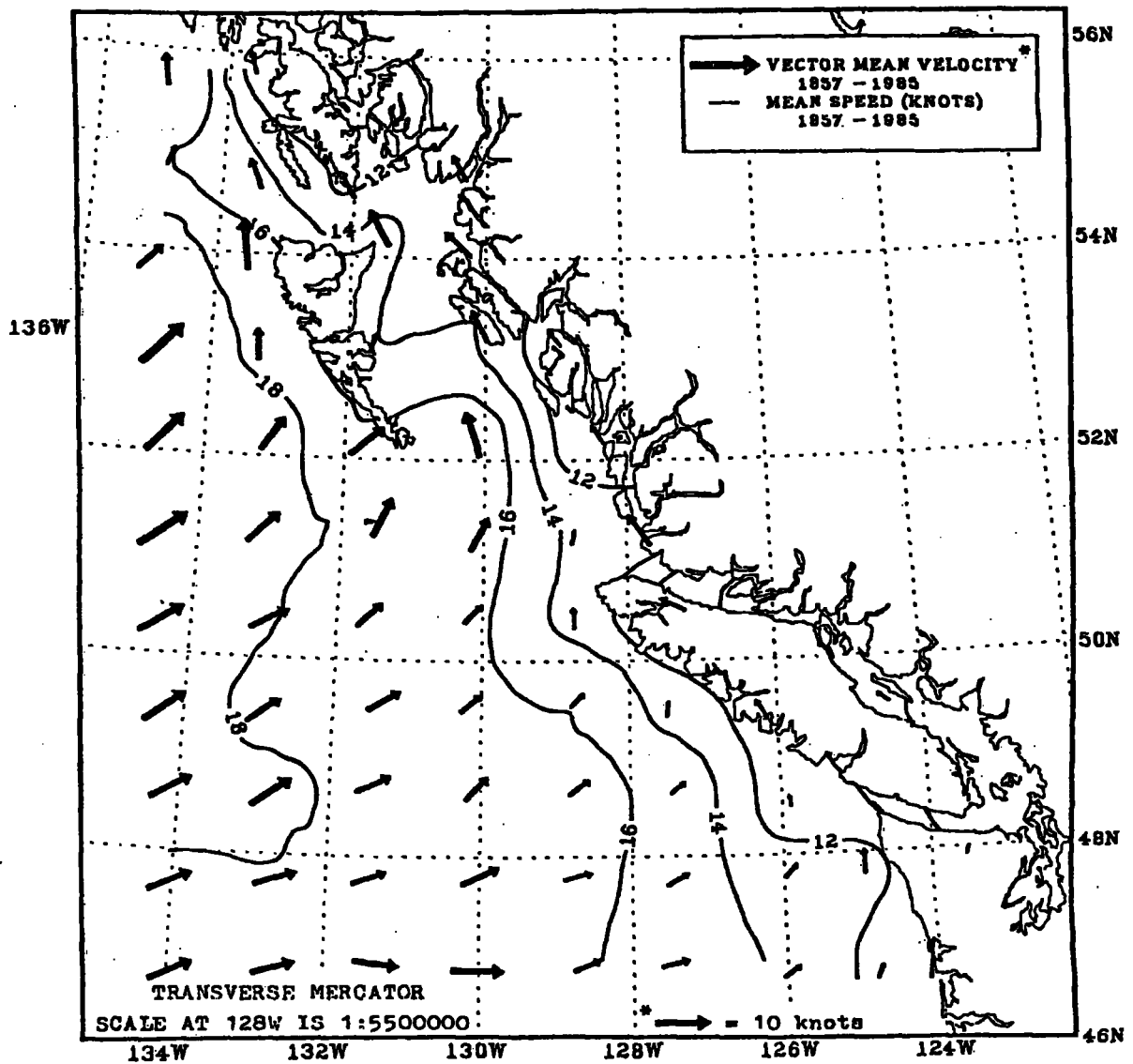


Figure 5.7 — Wind direction and speed

provides a more useful product as well. Extreme-value analysis using transient ship data is not recommended on account of the spatial and temporal variability in data coverage, the wide range of observing practices used, and numerous errors in the data.

### Air/sea temperature

Maps may be produced for each month of mean air/sea temperature. In temperate latitudes contours should be produced at intervals of 5°C, with intervals of 2.5°C where necessary. Contours of 10- to 100-year return period values of high and low temperatures may also be produced if suitable data exist. The maps may be useful in selecting structural materials. Contours of minimum and maximum air/sea temperatures should be avoided when data from

transient ships are used, for data quality considerations; the 95–99th percentile values of the charts are a much more stable statistic for indicating high and low values.

### Wave height, period and direction

Monthly and annual maps of mean significant (combined or resultant) wave-height (sea plus swell) may be produced. Prevailing wind wave direction (mode) may also be produced in the form of arrows and may be displayed on the mean wave height contour plot.

Maps of percentage frequency of significant wave heights above or below certain critical thresholds are also useful for some applications. Typical threshold values would be 4 and 8 m. Maps of durations of wave heights above or below critical thresholds are also important for
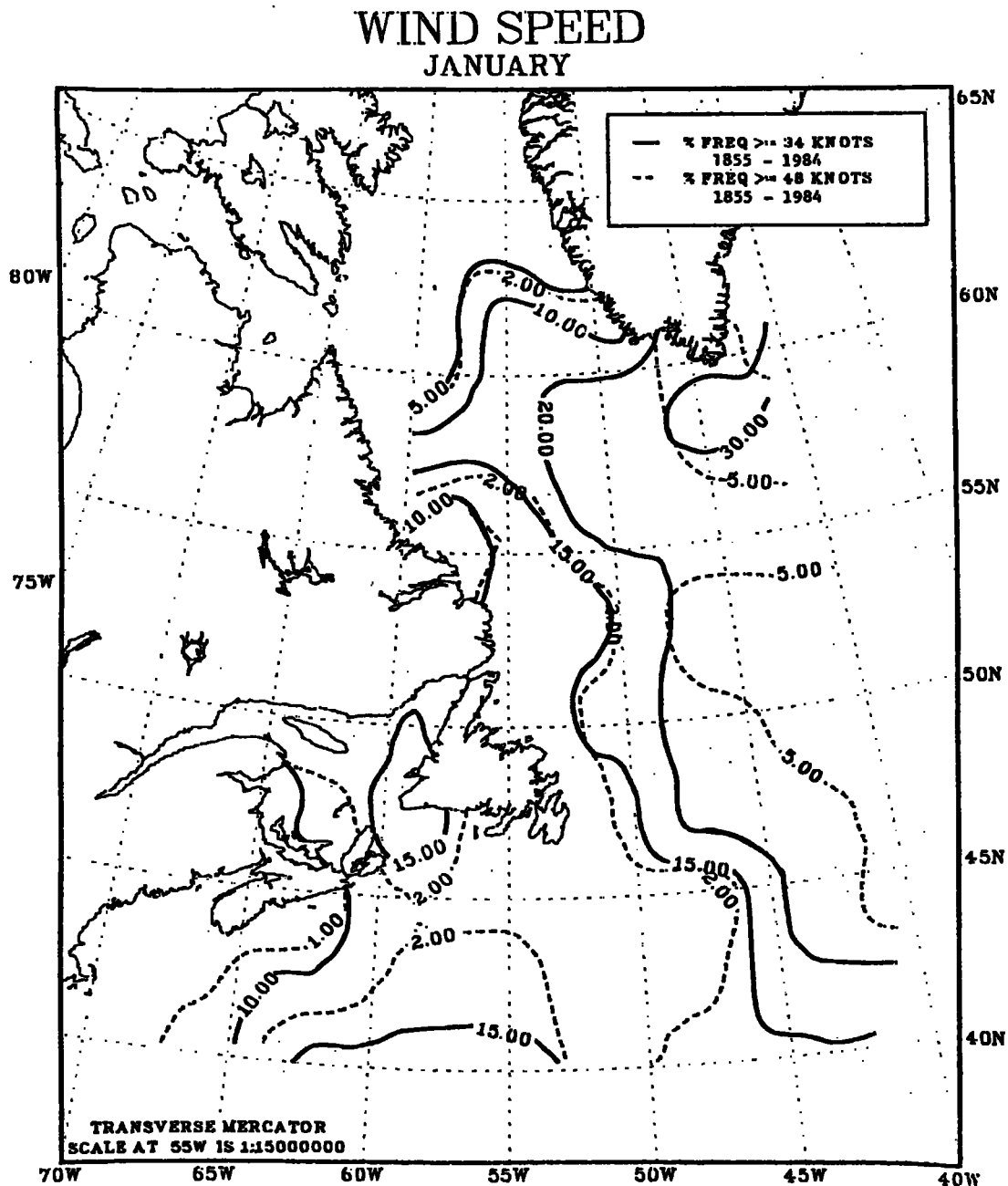


Figure 5.8 — Wind speed

time-dependent applications such as the resupply of towing barges, contingency planning, and search and rescue preparations.

Maps of the 50- or 100-year return period significant wave height may be produced for design considerations. The contouring of the maximum reported wave height is not recommended for the same reasons as given for wind data.

Maps of mean or median wave period may be produced for each month. In addition, the percentage frequency of wave period greater or less than some threshold value may be required for certain applications.

### Ice cover

Monthly and/or seasonal maps showing median, percentile or extreme ice cover are useful for planning purposes. An example of such a chart appears in Figure 6.4. This chart has been compiled from satellite-sensed data. In addition to ice cover, however, statistics on the frequency of occurrence of icebergs, the frequency and thickness of ice ridges in pack ice, and ice strength would be useful for design and planning in the offshore. Unfortunately, information on the latter is scarce at this time. It is hoped that with time and improved remote sensing from satellite and aircraft, and the development of a capability to archive and analyse these data, the required information will eventually become available.

### Vapour pressure/relative humidity

Maps of mean vapour pressure and relative humidity may be produced for each month. For vapour pressure, isolines should be at 2 hPa increments from two to twenty hectopascals and at 4 hPa increments thereafter. For relative humidity, isolines should be at five or ten per cent intervals.

### Icing rate and thickness

Maps of percentage frequency of classes of icing rate may be produced for each month when icing is likely to occur. Hindcasts or observations may be used for the application. Given good, complete time series of data, maps of duration of icing events and total ice accretion thickness for events may also be produced. Transient ship data are not suitable for this type of analysis, since they do not consist of continuous time series of observations at a point. Drilling vessels and hindcasts may be used to produce appropriate data.

### Cloud amount and height

Maps of percentage frequency of clear, scattered, broken, overcast and obscured conditions may be produced. Percentage frequency of cloud height for certain critical levels for aviation may also be produced; in particular, frequency of occurrence of ceilings of less than 50 m, 50–300 m and greater than 300 m could be useful.

### Visibility

Maps of percentage frequency of prevailing visibility in certain critical classes may be produced, in particular less than 0.5 n.m., 0.5–2.2 n.m., and greater than 2.2 n.m.

### Flying weather (ceiling plus visibility)

Maps of joint frequency of visibility and ceiling height may be produced in the form of percentage exceedance of combinations of the critical ranges given individually above. The combined range of ceiling and visibility should conform as closely as possible to aircraft operating categories (ie. VFR, IFR) to ensure their utility.

### Wind chill/cooling rate

Maps of percentage frequency of wind chill exceeding certain critical ranges may be produced, e.g. for conditions when work must be halted because exposed flesh might freeze. Similarly, a cooling index map might be produced to delineate the frequency of ship hull cooling rates which exceed some critical threshold. High (e.g. 99%) percentile value may be mapped to give extremal estimates for operations planning and selection of structural materials. If ship observations are summarized, the use of minimum values is not recommended on account of the data-quality problems as identified earlier.

### Precipitation

Since most marine data sources do not contain quantitative precipitation measurements, the type of analysis possible is restricted to percentage frequency analysis of the type of precipitation, e.g. rain, heavy rain, heavy snow, freezing precipitation, etc.

### MSL pressure

Maps of mean MSL pressure may be produced for each month, with contour intervals of 4 hPa, with an interval of 2 hPa where necessary. Because of the irregularity of data coverage, great care should be exercised in using ship data. A better alternative is to contour pressure derived from gridded objective analysis fields.

### 5.2.3.2    Examples of charts

Examples of various charts of the kind described above appear on the following pages. The layout and features depicted on such charts are generally a function of their ease of use or utility, but such factors as aesthetics, availability of existing analyses or computer software and, most importantly, cost of production often determine the nature of the final product. In view of the nature of this publication, only a selection of those charts reproducible in black and white have been included. For a good example of a full colour marine atlas, the reader is invited to consult the *Atlases of the World's Oceans* published by the former USSR.

Although computer programs have been used in extracting data and analysis in the above, the original charts have still been drafted or hand-analysed. The following charts are from fully computerized analyses.
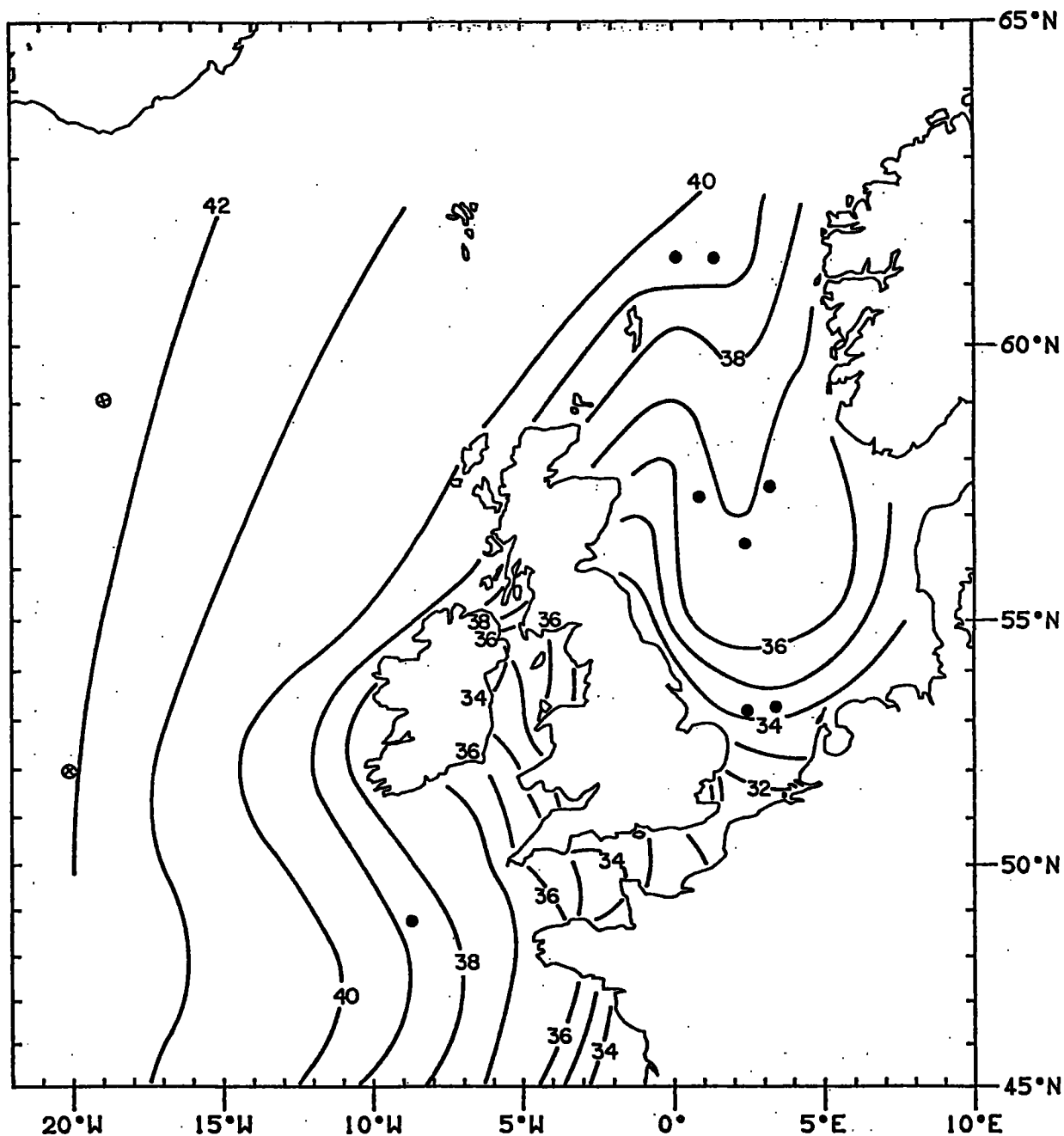
Estimates of 50-year return omnidirectional hourly-mean wind speeds at 10 m above still water level

Contours are in m s$^{-1}$; estimated maximum error is ± 2 m s$^{-1}$. Ocean Weather Stations, where wind speeds have been measured for many years at fixed locations, are shown ⊗. Sites used for verification purposes are shown ●.

*(Source: Analysis of VOF and instrumental data)*

Chart 5.1

# DURATION WIND SPEED >= 48 KNOTS
## MARCH
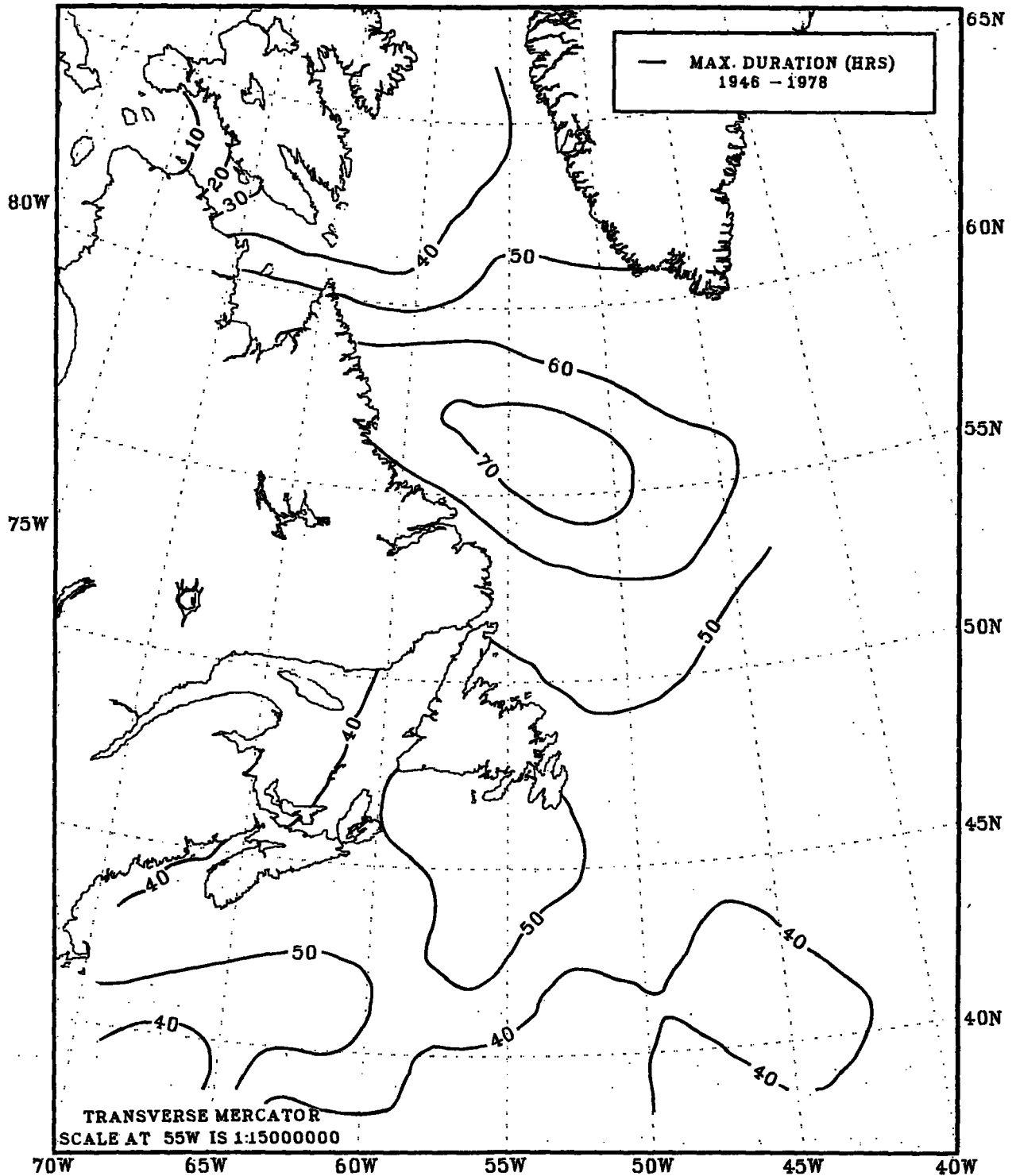


Chart 5.2

# SHIPPING WEATHER
## JULY
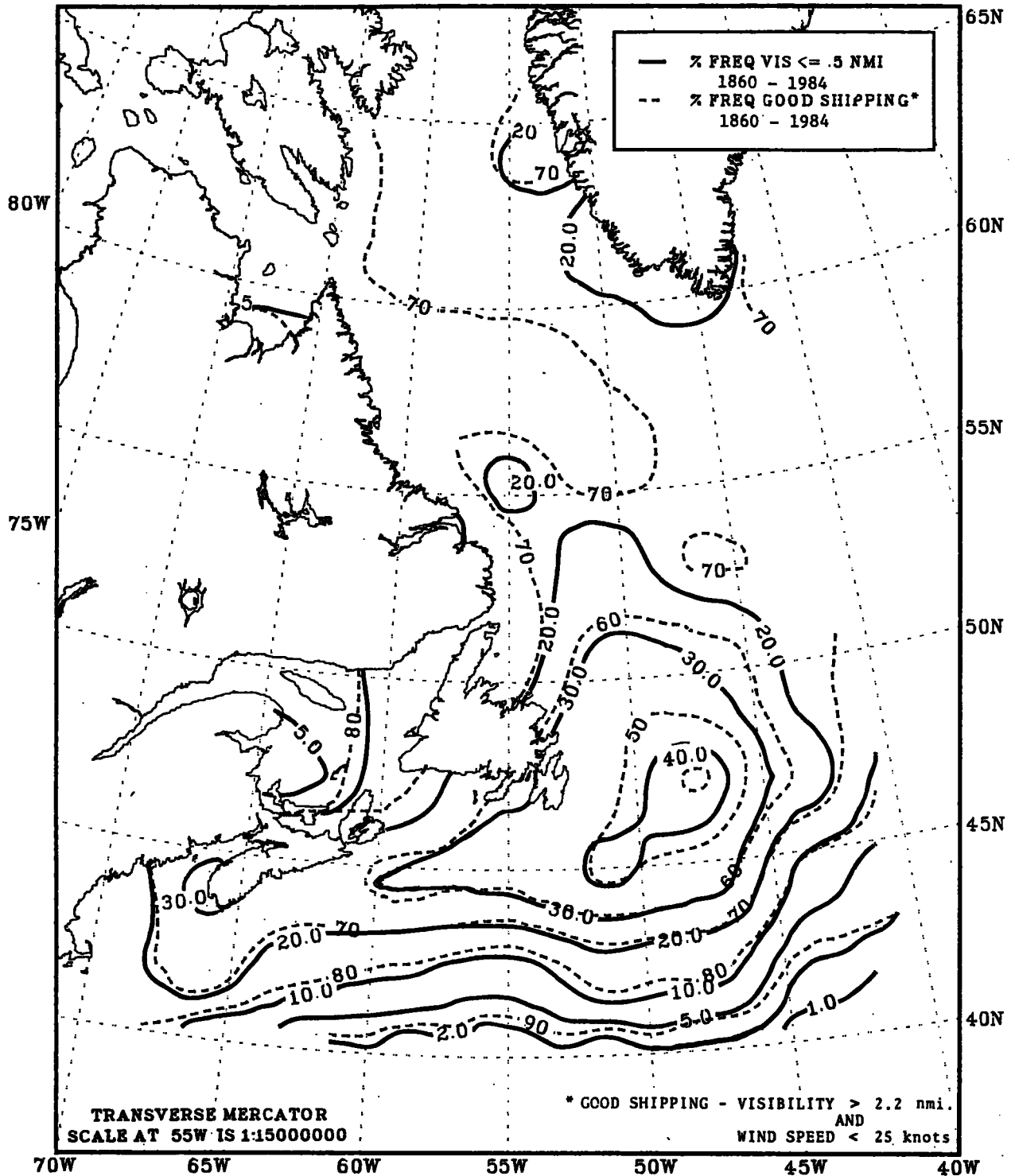


Chart 5.3
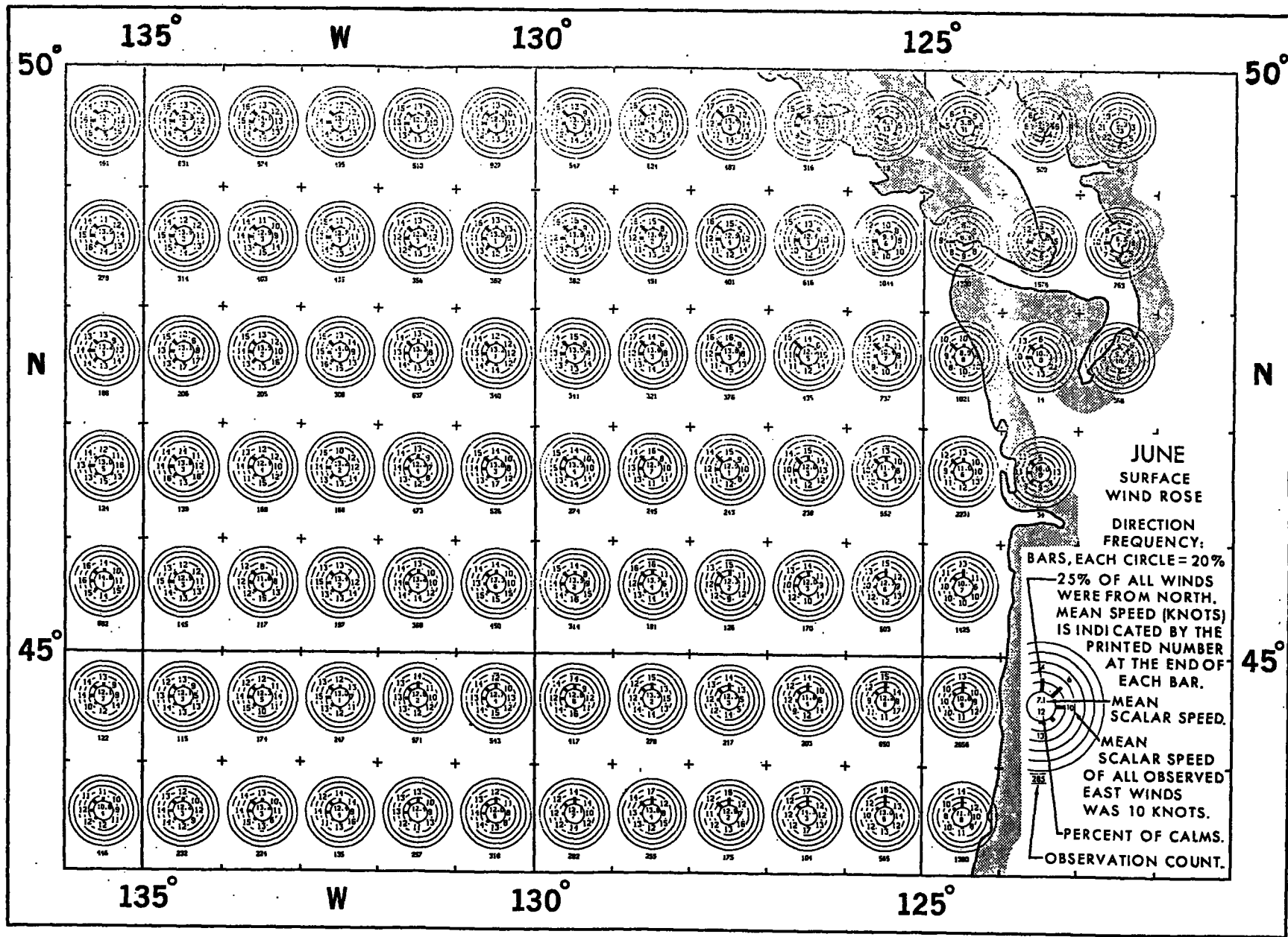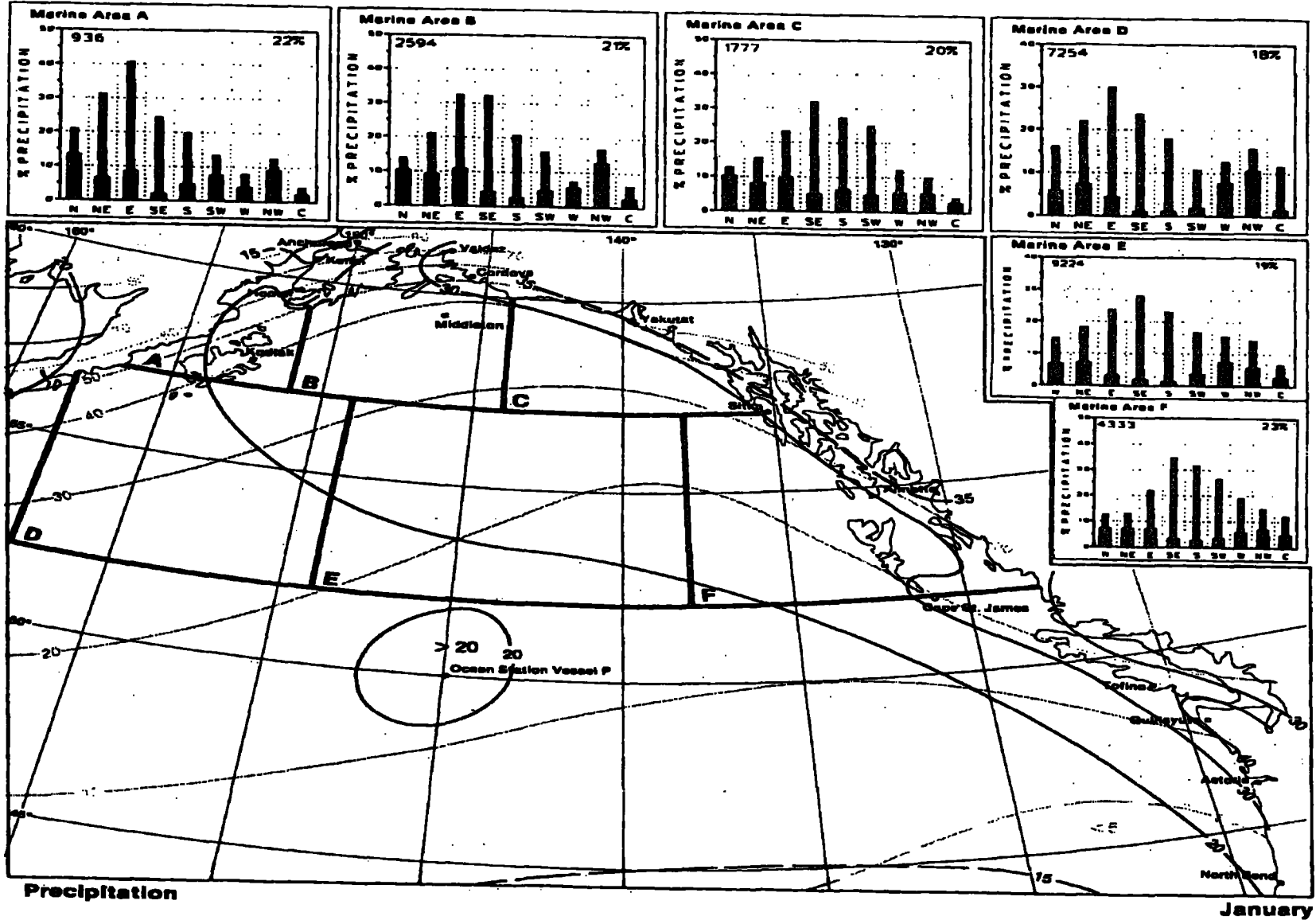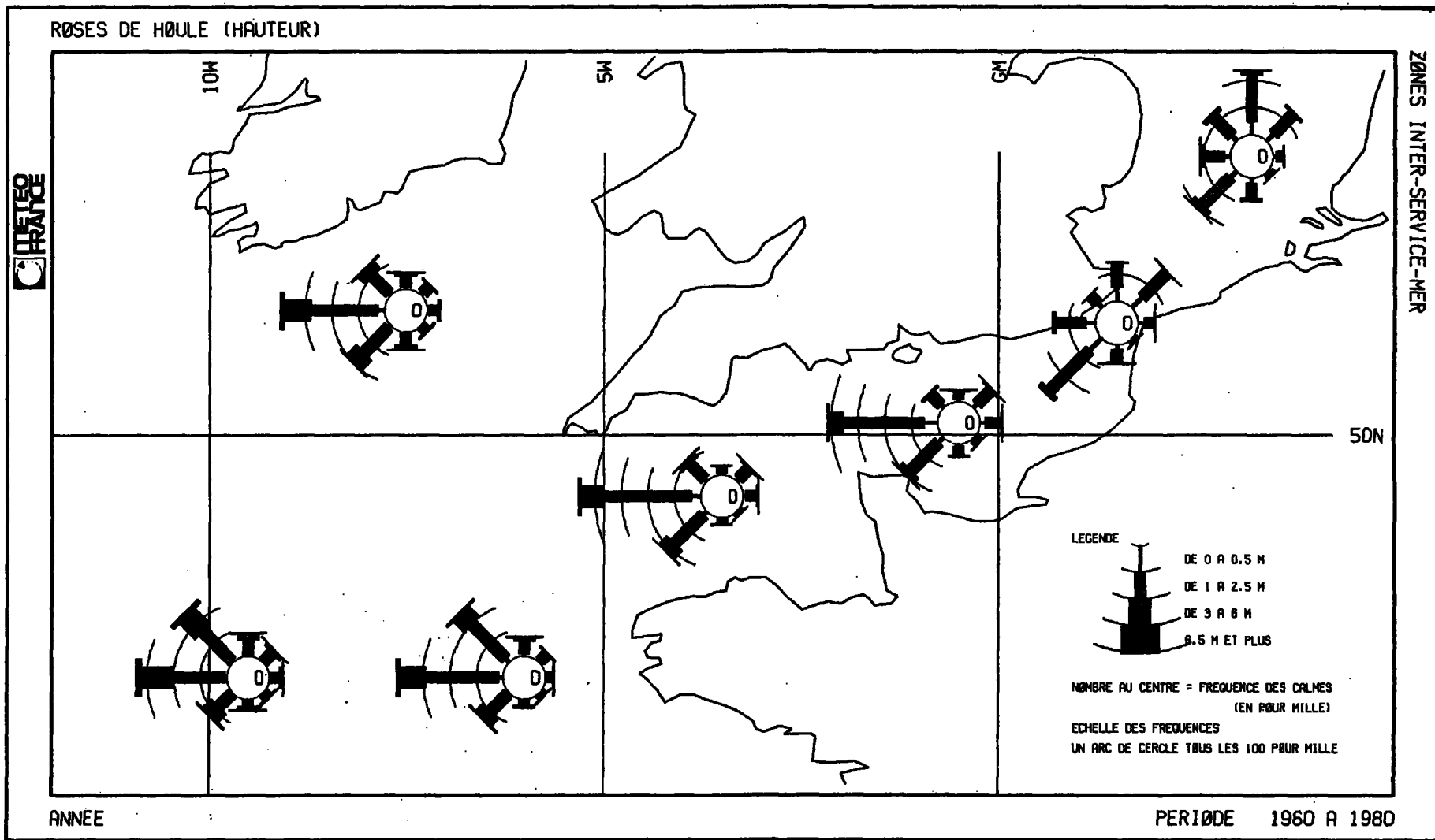
JUNE
SURFACE
WIND ROSE

DIRECTION
FREQUENCY:
BARS, EACH CIRCLE = 20%

25% OF ALL WINDS
WERE FROM NORTH.
MEAN SPEED (KNOTS)
IS INDICATED BY THE
PRINTED NUMBER
AT THE END OF
EACH BAR.

MEAN
SCALAR SPEED.

MEAN
SCALAR SPEED
OF ALL OBSERVED
EAST WINDS
WAS 10 KNOTS.

PERCENT OF CALMS.

OBSERVATION COUNT.

Chart 5.4

**Precipitation**

**January**

Chart 5.5

ROSES DE HOULE (HAUTEUR)

ZONES INTER-SERVICE-MER

50N

LEGENDE

DE 0 A 0.5 M

DE 1 A 2.5 M

DE 3 A 6 M

6.5 M ET PLUS

NOMBRE AU CENTRE = FREQUENCE DES CALMES
(EN POUR MILLE)

ECHELLE DES FREQUENCES
UN ARC DE CERCLE TOUS LES 100 POUR MILLE

ANNEE

PERIODE    1960 A 1980
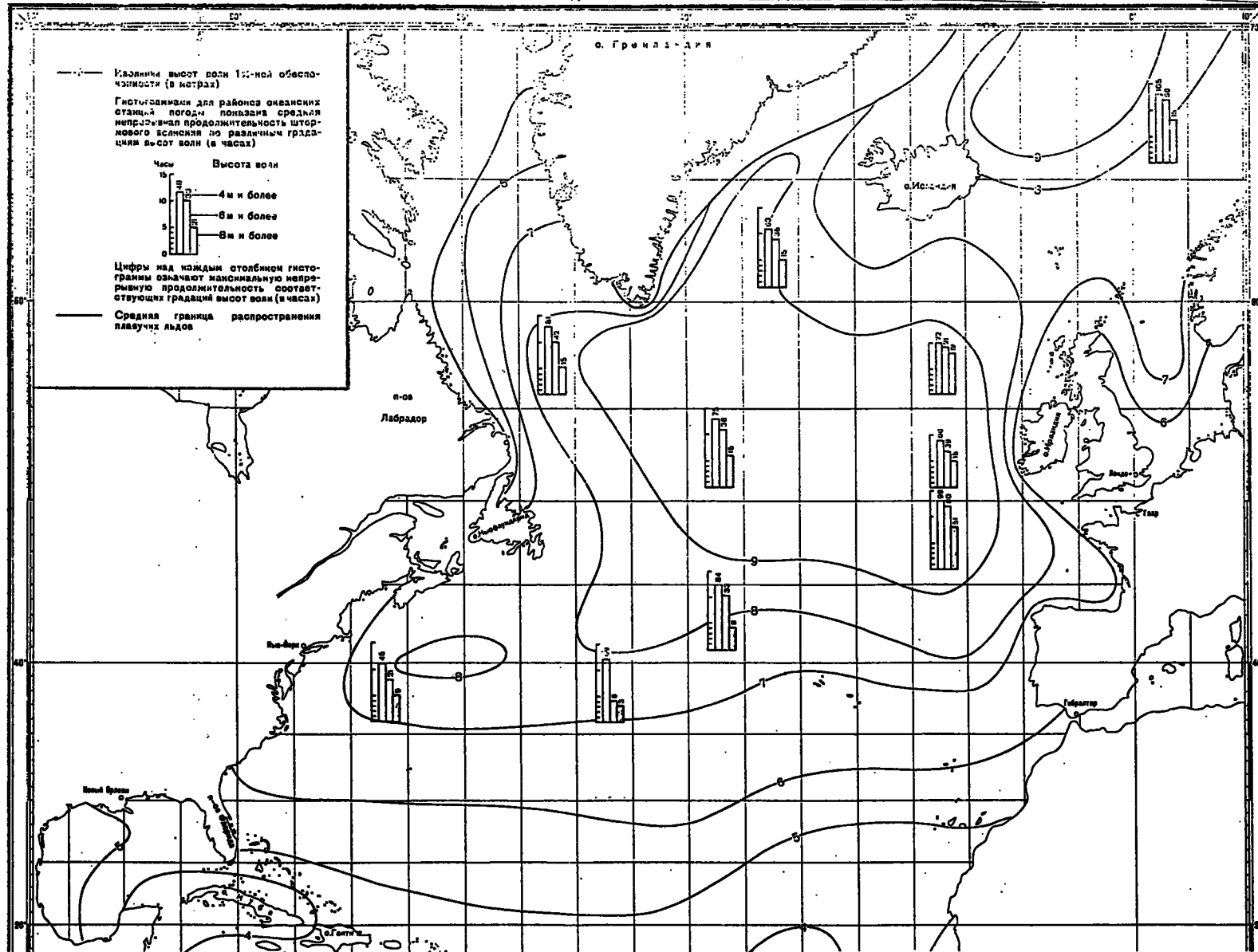
Chart 5.6

Chart 5.7

## 5.3      DURATION (PERSISTENCE) ANALYSIS

*Statistics on the durations of meteorological events are useful in a variety of applications, including event planning, site selection, engineering and climatological research. The duration of an event can be defined as a continuous period of time during which a specified set of criteria are met. Intervals can then be defined as the periods that occur between events. Figure 5.9 illustrates the simple binary nature of the problem. Either an event is in progress or it is not. Some of the complexities that confound practical application are also apparent in Figure 5.9, i.e. when events and intervals begin and end. The following questions naturally arise:*

• What threshold criteria define an event?

• What departures from the criteria will be allowed before the duration is considered to be terminated?

• If the application is seasonal, how are events defined when they straddle the beginning/ending of the season?

• What form of interpolation is allowed for missing data?

• When dealing with probabilities, are events to be weighted equally or according to their duration?

• Can the average duration of events adequately convey information to a decision-maker?

• What kinds of statistical model are available for duration-interval estimation?

• Why use empirically derived duration statistics instead of model output duration statistics?

Some possible approaches to these problems are discussed and examples of output from computer programs utilizing conventional meteorological data are presented.

### 5.3.1      Limitations of data

Data from transient ships (ships of opportunity), by their very nature, are unsuitable for duration statistics. They are not continuous in time nor are their locations fixed. The dozen or so Ocean Weather Stations (OWS) give the only ship observations which meet the criteria for persistence analyses. The OWS period of record of continuous or nearly continuous on-station records is generally between 20 and 25 years. The paucity of sites is the major limiting factor for most persistence studies, especially in the southern hemisphere, where only one OWS operated for approximately five years. Moored buoys and oil-drilling platforms can supplement the OWS data, but their periods of record are generally too short except for limited statistics, and they again are relatively few in number with very limited geographical coverage. This leaves only modelled data for wide geographical coverage and a continuous period of record. When discussing modelled duration data we can mean two things: (a) the element under consideration is derived for some period of time using a computer model and then conventional duration analysis is applied; or, (b) conventional, readily available data are used and persistence statistics are model-generated. In either case these data also have limitations such as those resulting from the quality and power of the model (e.g. some are
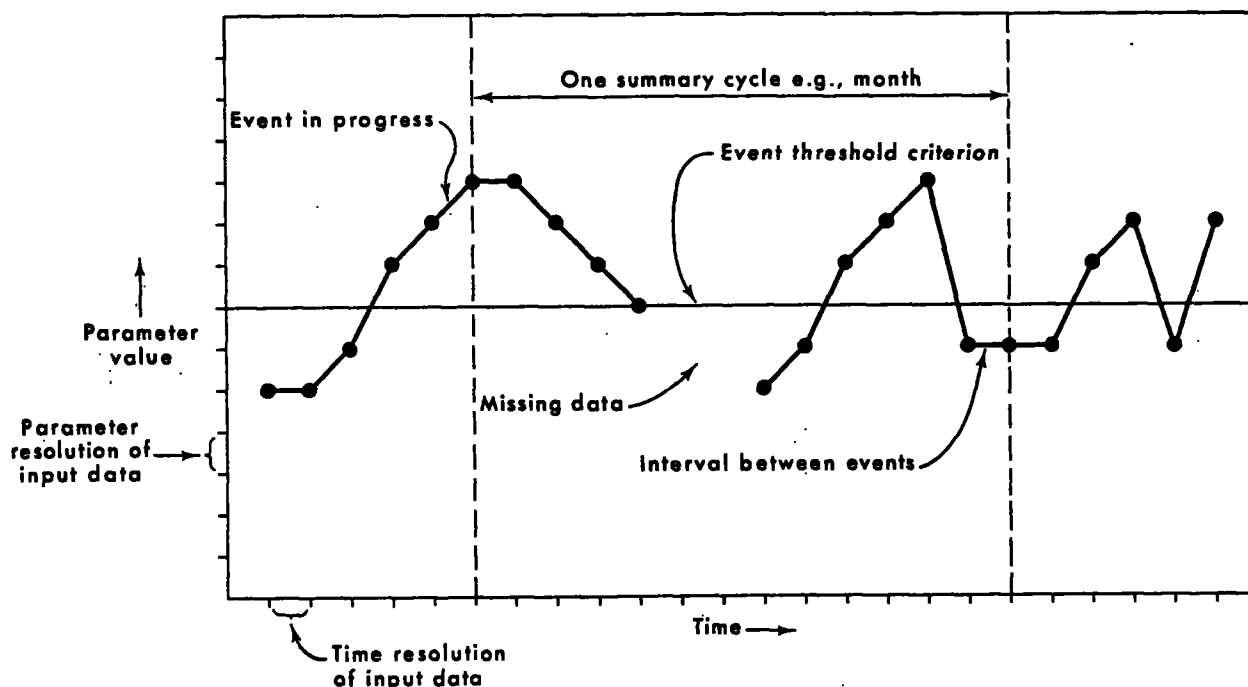


Figure 5.9 — Schematic of a time series

restricted to deep water, some have boundary problems near land or the Equator, etc.). Not all elements can be model-generated, and geographical coverage is often restricted to the northern hemisphere for long-term data. Other limiting factors, in general terms and not in reference to marine data only, are further described in the following sections.

### 5.3.2    Analysis criteria selection

Critical thresholds (which can be multivariate) should be defined via inequalities in such a way that data occurring at the threshold value can be classified. Assumptions regarding time resolution must also be established. For example, in one application a three-hourly observation was assumed representative of one-and-a-half hours before and after the observation. This assumption was tested for gale frequencies (winds greater than or equal to 34 knots) at Ocean Weather Stations, and was found to be very reasonable [3]. More elegant procedures, such as the fitting of spline interpolation functions to define beginning and ending times, can also be employed.

### 5.3.3    Handling brief breaks in an event

For some applications (e.g. wind-induced water level rise or surge), brief excursions from defined thresholds may not warrant termination of an event or interval between events. To this end, minimum allowable excursions can be specified in absolute time units (e.g. three hours) or as a fraction of the total event duration that would be obtained if a brief break were ignored. As an example, one may wish to allow a single three-hour interval to break a 12-hour duration, but not a potential multi-day duration.

### 5.3.4    Durations that straddle summary periods

A question arises regarding what to do with durations that are ongoing when the period of record begins or ends. When duration statistics are not intended to be representative of year-round conditions, the most common approach is to stratify data by period, usually a month or season. In these instances, the decision regarding what to do with durations that are under way when the period begins or ends is fairly important. If, for example, a duration that occurs at the beginning of a month is not used in the statistics for that monthly summary, data in that month are lost. If a duration that extends beyond the end of the month is automatically terminated at the end of that month, an artificially short duration occurs. The problem becomes more serious for durations that tend to persist for long periods of time since they are liable to be missed altogether if we insist that they begin and end within a month or season. The solution depends upon the application. Two possible alternatives are suggested, assuming that long-term climatological analyses are desired:

(a)       If the purpose of the analysis is related to geographically fixed structures, monthly or seasonal

summaries will probably not be required, since the structure will be exposed to a year-round environment. In these instances, durations that are under way at the beginning and end of a long period of record should not be included in the calculations. Little data are lost by simply omitting these events from the analyses, as they usually make up only a small fraction of the data set. Since one cannot know the exact length of time these events persist, it is better not to bias the calculations with estimates.

(b)       If the application aims for a mobile structure or for relatively short-term operations that are scheduled to begin at a specific time, it may be best to consider durations under way at the beginning of the month as beginning on the first day of the month. The artificially short durations at the beginning of the month could be considered as the statistical equivalents of the artificially short durations that would be encountered if one were arbitrarily to commence or terminate some operation. Events that extend past the end of the month could be carried into subsequent months, even though part of the occurrence was not in the month in question. To retain the integrity of the stratification period, however, durations should not be allowed to continue too long. As a general rule, once the event has persisted for the equivalent length of a month or season (the summary unit), then it should be artificially terminated. One result of this procedure is that the same event can be counted in more than one month (or season). Because of this, monthly or seasonal summaries cannot be readily combined into annual statistics. Therefore, annual statistics should be computed independently and not summarized later.

### 5.3.5    Interpolation procedures

Data gaps occur in most climatological time series. The simplest solution to this problem is to omit any duration which does not have complete data. For many applications this may be acceptable, but it can tend to eliminate extremely long durations from the statistics. This is because the longer the duration of the event, the more likely it is to contain data gaps. Linear interpolation or some higher-order process can be used to fill in missing data. However, some reasonable upper limit of missing data must be established, beyond which the duration is rejected from computations.

### 5.3.6    Duration weighting

Depending upon the type of question to be answered, one may be interested in (a) the probability of an event regardless of its duration (equally weighted events) and/or (b) the total proportion of time encompassed by events of specified duration (where events are weighted by their proportion of time exceeding the threshold).

(a)       Equally weighted events can be used for certain types of event planning. This procedure answers questions such as "Once an event has begun, what is the

probability it will last *x* hours or more?" A common example is the operation that must await favourable conditions to begin and requires those conditions to persist for *x* hours for successful completion. In this case, durations longer than *x* hours are all weighted equally, since the *x* hour selected is the important criterion. Likewise, durations of less than *x* hours can all be considered misses and weighted equally. In this case, the denominator of an empirical probability computation is the total number of events and the numerator is the number of events that persisted *x* hours or more.

(*b*)        In the alternative case, where events are weighted by their durations (unequally weighted events), the important consideration is "What percentage of the time can events of duration greater than *x* hours be expected to occur?" The same question can be phrased to include a range of hours, i.e. duration greater than *x* but less than or equal to *y*, to coincide with a work shift, for example. In this case, the denominator of the probability equation is the total number of hours in the data sample and the numerator is the total duration of the events (in hours).

### 5.3.7        Average duration of events

The average duration of an event is defined by *t*, where $t = T/N$, *T* is the total time for all events defined by a given threshold and *N* is the number of events. This average value can be used to parameterize event durations. It is most useful when activities are planned to take place when environmental conditions are within operating limits. For example, offshore engineering operations can proceed whenever wind speed and wave height are below some specified threshold values. If the time associated with start-up and shut-down procedures constitutes a significant portion of the operating time, then information on the per cent frequency of exceeding the threshold value is not sufficient for a good estimate of productive operating time. In these instances the average duration of an event together with the probability or relative frequency of exceeding the threshold value of the event can be used to determine the clock time necessary to obtain *x* hours of productive operational time [4]. These calculations can be made for months or seasons of severe, near-normal, or mild weather.

On the other hand, when equipment is designed or plans are made for a single event, such as frost protection, test flights, sporting events, etc., the average duration of a damaging event may not be sufficient. In these instances the expected range of the durations and intervals between events is often required.

### 5.3.8        Statistical models for duration statistics

When the time series for a variable is not sufficiently long or there are frequent gaps in the time series, the calculation of empirical probabilities for durations and intervals may not be satisfactory. In these instances

statistical models can sometimes be used to calculate probabilities of event durations and intervals. Lund and Tsipouras [5], Sigl *et al.* [6], Gringorten [7], Lund and Grantham [8], Graham [4] and Kuwashima and Hogben [9], among others, have developed such models. Graham used a Weibull distribution to parameterize the average duration of significant wave heights and wind speeds in the North Sea. His model requires an estimation of the probability of occurrence of values above or below the threshold. Similarly, Kuwashima and Hogben estimated wind and wave persistence via cumulative probabilities. Sigl *et al.* used a power-exponential distribution to estimate wind speed durations and intervals between events in the United States for user-specified threshold values. That model requires an estimate or calculation of mean wind speeds at a specific level above the ground.

Gringorten used a Markov chain technique to estimate the duration of various categories of weather. Lund and Grantham proposed a model to estimate the duration of four categories of precipitation in the eastern United States. Both of those models require input of hour-to-hour correlations for each weather category and the climatological frequency of occurrence of the categories of interest. For the eastern United States, Lund and Tsipouras developed an empirical model to obtain event duration probabilities for two-category weather events, using various climate variables such as precipitation, temperature, sky cover, and ceiling. The model requires an estimate of the climatological per cent frequency of the event being modelled, such as winds exceeding 10 knots or less than 4 knots, precipitation or no precipitation, etc.

In general, statistical models used to estimate durations of events require an estimate of one or more of the following: (1) the mean of the variable of interest; (2) an estimate of its serial correlation coefficient; and/or (3) the probability of occurrence of values above or below the threshold value of an event. The models are almost always empirically derived, usually for specific geographical locations. As such, modelled results are not necessarily better or worse than pure empirical calculations.

### 5.3.9        Empirically derived duration and interval probabilities

Examples of empirically derived duration and interval statistics are shown in Tables 5.4 to 5.9. Statistics for Tables 5.4 to 5.7 were derived from 20 years of hindcast wave height data with output every six hours. Table 5.8 is based on 35 years of three-hourly land-station observations and Table 5.9 on three-hourly buoy observations. Definitions of the column identifiers in the duration and interval tables are as follows:

MAX:   The maximum duration (or interval) followed by the number of times an episode of that length occurred. The abbreviation MO in the monthly

tables represents episodes that lasted a month or longer.

TE: The number of events satisfying the stated criteria. An event begins with the element value increasing to the given threshold.

TI: The number of intervals. These are episodes not satisfying the stated criteria. An interval begins with the element value falling below the given threshold.

T: The total number of data points included in TE or TI.

T*: The total number of data points that met the stated criteria. This is more than T if missing

data made the duration or interval impossible to determine. It can be used to determine the likelihood of encountering the conditions (specified by computing T*/TH).

TH: The total number of data points examined.

Since Tables 5.4 to 5.7 provide total counts of events for each cell (rather than totals or percentages of data points), they are useful primarily for calculations involving event frequencies. Tables 5.8 and 5.9 were prepared to illustrate methods for deriving additional information such as total time within given events. Tables 5.8 and 5.9 also illustrate methods for handling missing data.

## TABLE 5.4
### Wave height durations – monthly



4 Events with wave heights ≥6 ft. (1.8m) persisted 12 hours; 22 events persisted ≥96 hours.

The longest event with wave heights ≥3 ft. (0.9m) persisted 1 month or more and it occurred 8 times.
The longest event with wave heights ≥40 ft. (12.2m) persisted for 6 hours and it occurred 1 time.

22 Events had wave heights ≥3 ft. (0.9m) which comprised a total of 1,524 hindcasts.

1,649 Hindcasts were examined, and 1,626 had wave heights ≥3 ft. (0.9m).

Durations for a particular month extend from the time the event begins (or the first of the month if already in progress), and terminate when the event ends. Events become undefined if missing data is encountered. Durations lasting a month or more are categorized together. Durations may persist into the next month(s).

## TABLE 5.5
### Wave height intervals – monthly



There were 13 12-hour intervals between events of wave heights ≥9 ft. (2.7m); 4 intervals persisted 96 hours or more.

The longest interval between events of wave heights ≥6 ft. (1.8m) was 132 hours and it occurred 1 time.
The longest interval between events of wave heights ≥64 ft. (19.5m) was 1 month or more and it occurred 9 times.

There were 13 intervals between events of wave heights ≥3 ft. (0.9m) which comprised a total of 23 hindcasts.

1,235 Hindcasts were examined, and 23 had wave heights <3 ft. (0.9m).

Intervals for a particular month extend from the time the event ends (or the first of the month if the event is not in progress), and terminate when the event begins. Intervals become undefined if missing data is encountered. Intervals lasting a month or more are categorized together. Intervals may persist into the next month(s).

## TABLE 5.6
### Wave height durations – all days



33 Events with wave heights ≥3 ft. (0.9m) persisted 0.5 day; 68 events persisted >1 day but ≤2 days.

The longest event with wave heights ≥28 ft. (8.5m) persisted 2 days and occurred 2 times.
The longest event with wave heights ≥24 ft. (7.3m) persisted 2.5 days and occurred 1 time.

393 Events had wave heights ≥3 ft. (0.9m) which comprised a total of 10,094 hindcasts.

13,606 Hindcasts were examined, and 10,398 had wave heights ≥3 ft. (0.9m).

Durations extend from the time the event begins and terminate when the event ends. Events become undefined if missing data is encountered.

## TABLE 5.7
### Wave height intervals – all days



1 Interval between events of wave heights ≥34 ft. (10.4m) persisted 0.5 day; 2 intervals persisted >1 day but ≤2 days.

The longest interval between events of wave heights ≥3 ft. (0.9m) was 18.25 days and it occurred 2 times.
The longest interval between events of wave heights ≥40 ft. was 308.25 days and it occurred 1 time.

There were 401 intervals between events of wave heights ≥3 ft. (0.9m) which comprised a total of 3,133 hindcasts.

13,606 Hindcasts were examined, and 3,208 had wave heights <3 ft. (0.9m).

Intervals extend from the time the event ends and terminate when the event begins. Intervals become undefined if missing data is encountered.

(Examples from US Navy, 1983)

The column headings in Tables 5.8 and 5.9 are basically the same as the column trailers in Tables 5.4 to 5.7, but additionally:

TO: The total number of observations examined.

P: The percentage of data points meeting a criterion [(T*/TO) × 100]. Note that the marginal percent frequencies P for the same threshold in the duration and interval tables will not always add to exactly 10 per cent. This is caused by missing data, and by events running into the following month.

I: The number of linear interpolations used to estimate values when missing data were encountered. In this example three-hourly data were used and interpolations were made for up to two consecutive missing observations.

Tables 5.8 and 5.9 provide information on both weighted and unweighted durations and intervals. In Table 5.9 there are four lines of output per threshold value. In sequence (top to bottom) the first line consists of the cumulative per cent frequency of events, or intervals between events, for the given threshold (equally weighted events, see section 5.3.6(a)). The second line is the number of data points making up the events which meet the specified criteria (including interpolated observations). The third line contains the accumulated percentage of time within each category, considering only those observations meeting the threshold criteria as totalling 100 per cent (cumulative sum of data points from line 2 divided by the total sum (T) × 100). The fourth line gives an estimate of the cumulative percentage of time within each category (unequally weighted events, see section 5.3.6(b)) considering all data as totalling 100% (the values in line 3 × 0.01 × P). The number of interpolated estimates is given for each event threshold. Despite these interpolations, a number of missing values still remain as indicated by the comparison of the columns T and T*. For this reason, the values in line 4 are estimates, since the value of P is calculated from all available data, and the event durations and intervals are often based on less than all the data. Note the various ways of looking at the problem: observations versus events; distributions of data that total 100% within a criterion versus totals of 100% for all criteria; cumulative versus class-interval data; and finally percentages versus raw frequencies.

Some examples of the types of questions that can be answered using the Tables 5.4 to 5.9 are:

## TABLE 5.8

### Wind persistence tables

*(Examples from Paskausky et al. (1984))*



The percentage of all events that had durations of X hours or less. In this example, events of wind speeds of greater than 5 knots lasted for 18 hours or less in 56.7 percent of the cases. Therefore 43.3 percent of the events with a threshold of greater than 5 knots lasted more than 18 hours.

Maximum Duration: The maximum duration in hours followed by the number of times an event of that duration occurred.

Total Events: The number of events satisfying the criterion stated. An event is an episode which begins and ends with the wind speed crossing a given threshold.

The total number of observations that met the criterion. This may be more than T because some observations may have met the criterion, but missing data either before or after the observation made the duration impossible to determine.

Total Intervals: The number of intervals satisfying the criterion stated. An interval is an episode between events which begins and ends with the wind speed crossing a given threshold.

The total number of 3 hourly observations that were included under Total Episodes.

The number of linear interpolations in time performed to estimate values when missing data were encountered. See "Construction of Duration-Interval Tables" for more details.

The total number of individual 3 hourly observations examined.

The interval tables show the probability of occurrence of a specified time interval between certain wind events. In this example 88.0 percent of the intervals between events of wind speeds greater than 5 knots last 9 hours or less. This simply refers to periods where wind speeds are ≤ 5 knots. Therefore winds of ≤ .5 knots only occur in 12.0 percent of the occurrences for more than 9 hours.

The percentage of occurrences [(T*/TO) × 100] of the criterion. Note that the marginal percent frequencies "P" for the same threshold in the duration and interval tables will not always add to exactly 100%. This is caused by missing data, and by events running into the following seasons.

## TABLE 5.9

BUOY NUMBER 46003      LATITUDE 52.0N   LONGITUDE 156.0W
MAR

DURATION (HOURS) OF WAVE HEIGHT (METERS) EVENTS GREATER THAN THE GIVEN CATEGORIES

| WAVE HGT (M) | HOURS DURATION OF EVENTS (UPPER BOUNDS) | | | | | | | | | | | | | MAX | TE | T | T* | TO | P | I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 6 | 9 | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 108+ | | | | | | |
| > 1.0 | .0 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 16.7 | 100.0 | 744-01 | 6 | 1049 | 1049 | 1057 | 99.2 | 17 |
| > 1.0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1047 | | | | | | |
| > 1.0 | .0 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | 100.0 | AVERAGE LENGTH OF DURATIONS= 524.5 | | | | | |
| > 1.0 | .0 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | 99.2 | | | | | | |
| > 1.5 | .0 | .0 | 8.3 | 8.3 | 8.3 | 16.7 | 16.7 | 25.0 | 25.0 | 25.0 | 25.0 | 33.3 | 41.7 | 100.0 | 543-01 | 12 | 901 | 901 | 946 | 95.2 | 25 |
| > 1.5 | 0 | 0 | 3 | 0 | 0 | 7 | 0 | 14 | 0 | 0 | 0 | 30 | 36 | 811 | | | | | | |
| > 1.5 | .0 | .0 | .3 | .3 | .3 | 1.1 | 1.1 | 2.7 | 2.7 | 2.7 | 2.7 | 6.0 | 10.0 | 100.0 | AVERAGE LENGTH OF DURATIONS= 225.3 | | | | | |
| > 1.5 | .0 | .0 | .3 | .3 | .3 | 1.1 | 1.1 | 2.5 | 2.5 | 2.5 | 2.5 | 5.7 | 9.5 | 95.2 | | | | | | |
| > 2.0 | 4.8 | 14.3 | 19.0 | 23.8 | 23.8 | 23.8 | 33.3 | 47.6 | 52.4 | 57.1 | 66.7 | 76.2 | 76.2 | 100.0 | 417-01 | 21 | 658 | 658 | 771 | 85.3 | 17 |
| > 2.0 | 1 | 4 | 3 | 4 | 0 | 0 | 21 | 43 | 20 | 23 | 54 | 58 | 0 | 427 | | | | | | |
| > 2.0 | .2 | .8 | 1.2 | 1.3 | 1.3 | 1.8 | 5.0 | 11.6 | 14.6 | 18.1 | 26.3 | 35.1 | 35.1 | 100.0 | AVERAGE LENGTH OF DURATIONS= 94.0 | | | | | |
| > 2.0 | .1 | .6 | 1.0 | 1.6 | 1.6 | 1.6 | 4.3 | 9.9 | 12.5 | 15.4 | 22.4 | 30.0 | 30.0 | 85.3 | | | | | | |
| > 2.5 | 17.6 | 32.4 | 38.2 | 44.1 | 44.1 | 44.1 | 52.9 | 61.8 | 79.4 | 85.3 | 85.3 | 88.2 | 88.2 | 100.0 | 222-01 | 34 | 531 | 531 | 766 | 69.3 | 17 |
| > 2.5 | 6 | 10 | 6 | 8 | 0 | 0 | 33 | 42 | 108 | 44 | 0 | 32 | 0 | 242 | | | | | | |
| > 2.5 | 1.1 | 3.0 | 4.1 | 5.6 | 5.6 | 5.6 | 11.9 | 19.8 | 40.1 | 48.4 | 48.4 | 54.4 | 54.4 | 100.0 | AVERAGE LENGTH OF DURATIONS= 46.9. | | | | | |
| > 2.5 | .8 | 2.1 | 2.9 | 3.9 | 3.9 | 3.9 | 8.2 | 13.7 | 27.8 | 33.6 | 33.6 | 37.7 | 37.7 | 69.3 | | | | | | |
| > 3.0 | 30.3 | 36.4 | 39.4 | 42.4 | 48.5 | 54.5 | 60.6 | 72.7 | 81.8 | 84.8 | 90.9 | 90.9 | 90.9 | 100.0 | 219-01 | 33 | 410 | 410 | 745 | 55.0 | 14 |
| > 3.0 | 10 | 4 | 3 | 4 | 12 | 14 | 20 | 60 | 53 | 21 | 53 | 0 | 0 | 156 | | | | | | |
| > 3.0 | 2.4 | 3.4 | 4.1 | 5.1 | 8.0 | 11.5 | 16.3 | 31.0 | 43.9 | 49.0 | 62.0 | 62.0 | 62.0 | 100.0 | AVERAGE LENGTH OF DURATIONS= 37.3 | | | | | |
| > 3.0 | 1.3 | 1.9 | 2.3 | 2.8 | 4.4 | 6.3 | 9.0 | 17.0 | 24.2 | 27.0 | 34.1 | 34.1 | 34.1 | 55.0 | | | | | | |
| > 5.0 | 26.3 | 31.6 | 47.4 | 63.2 | 68.4 | 68.4 | 94.7 | 94.7 | 94.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 63-01 | 19 | 102 | 102 | 744 | 13.7 | 4 |
| > 5.0 | 5 | 2 | 9 | 12 | 5 | 0 | 48 | 0 | 0 | 21 | 0 | 0 | 0 | 0 | | | | | | |
| > 5.0 | 4.9 | 6.9 | 15.7 | 27.5 | 32.4 | 32.4 | 79.4 | 79.4 | 79.4 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | AVERAGE LENGTH OF DURATIONS= 16.1 | | | | | |
| > 5.0 | .7 | .9 | 2.2 | 3.8 | 4.4 | 4.4 | 10.9 | 10.9 | 10.9 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | | | | | | |

TOTAL NUMBER OF MISSING OBSERVATIONS THAT WERE REPLACED BY ESTIMATES AND USED IN THE T* FREQUENCIES=016

BUOY NUMBER 46003      LATITUDE 52.0N   LONGITUDE 156.0W
MAR

INTERVAL (HOURS) BETWEEN WAVE HEIGHT (METERS) EVENTS GREATER THAN THE GIVEN CATEGORIES

| WAVE HGT (M) | HOURS INTERVAL BETWEEN EVENTS (UPPER BOUNDS) | | | | | | | | | | | | | MAX | TI | T | T* | TO | P | I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 | 6 | 9 | 12 | 18 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | 108+ | | | | | | |
| > 1.0 | 33.3 | 33.3 | 66.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 12-01 | 3 | 8 | 8 | 744 | 1.1 | 0 |
| > 1.0 | 1 | 0 | 3 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| > 1.0 | 12.5 | 12.5 | 50.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | AVERAGE LENGTH OF INTERVALS= 24.0 | | | | | |
| > 1.0 | .1 | .1 | .5 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | | | | | | |
| > 1.5 | 22.2 | 22.2 | 55.6 | 55.6 | 88.9 | 88.9 | 88.9 | 88.9 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 54-01 | 9 | 45 | 45 | 744 | 6.0 | 0 |
| > 1.5 | 2 | 0 | 9 | 0 | 16 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| > 1.5 | 4.4 | 4.4 | 24.4 | 24.4 | 60.0 | 60.0 | 60.0 | 60.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | AVERAGE LENGTH OF INTERVALS= 135.0 | | | | | |
| > 1.5 | .3 | .3 | 1.5 | 1.5 | 3.6 | 3.6 | 3.6 | 3.6 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | | | | | | |
| > 2.0 | 15.8 | 31.6 | 42.1 | 52.6 | 68.4 | 68.4 | 89.5 | 94.7 | 94.7 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 63-01 | 19 | 113 | 113 | 744 | 15.2 | 1 |
| > 2.0 | 3 | 6 | 8 | 15 | 0 | 41 | 13 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| > 2.0 | 2.7 | 8.0 | 13.3 | 20.4 | 33.6 | 33.6 | 69.9 | 81.4 | 81.4 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | AVERAGE LENGTH OF INTERVALS= 339.0 | | | | | |
| > 2.0 | .4 | 1.2 | 2.0 | 3.1 | 5.1 | 5.1 | 10.6 | 12.4 | 12.4 | 15.2 | 15.2 | 15.2 | 15.2 | 15.2 | | | | | | |
| > 2.5 | 33.3 | 45.5 | 51.5 | 60.6 | 63.6 | 72.7 | 75.8 | 84.8 | 87.9 | 97.0 | 100.0 | 100.0 | 100.0 | 100.0 | 84-01 | 33 | 236 | 236 | 745 | 31.7 | 1 |
| > 2.5 | 11 | 8 | 6 | 12 | 5 | 22 | 12 | 43 | 19 | 70 | 28 | 0 | 0 | 0 | | | | | | |
| > 2.5 | 4.7 | 8.1 | 10.6 | 15.7 | 17.8 | 27.1 | 32.2 | 50.4 | 58.5 | 88.1 | 100.0 | 100.0 | 100.0 | 100.0 | AVERAGE LENGTH OF INTERVALS= 708.0 | | | | | |
| > 2.5 | 1.3 | 2.6 | 3.4 | 5.0 | 5.6 | 8.6 | 10.2 | 16.0 | 18.5 | 27.9 | 31.7 | 31.7 | 31.7 | 31.7 | | | | | | |
| > 3.0 | 12.1 | 33.3 | 45.5 | 48.5 | 63.6 | 69.7 | 72.7 | 75.8 | 81.8 | 81.8 | 90.9 | 90.9 | 93.9 | 100.0 | 126-01 | 33 | 336 | 336 | 745 | 45.1 | 2 |
| > 3.0 | 4 | 14 | 12 | 4 | 28 | 14 | 9 | 13 | 39 | 0 | 82 | 0 | 36 | 81 | | | | | | |
| > 3.0 | 1.2 | 5.4 | 8.9 | 10.1 | 18.5 | 22.6 | 25.3 | 29.2 | 40.8 | 40.8 | 65.2 | 65.2 | 75.9 | 100.0 | AVERAGE LENGTH OF INTERVALS=1008.0 | | | | | |
| > 3.0 | .5 | 2.4 | 4.0 | 4.6 | 8.3 | 10.2 | 11.4 | 13.2 | 18.4 | 18.4 | 29.4 | 29.4 | 34.2 | 45.1 | | | | | | |
| > 5.0 | 18.2 | 22.7 | 27.3 | 27.3 | 27.3 | 36.4 | 45.5 | 50.0 | 54.5 | 54.5 | 63.6 | 68.2 | 72.7 | 100.0 | 744-01 | 22 | 891 | 891 | 993 | 89.7 | 29 |
| > 5.0 | 4 | 2 | 3 | 0 | 0 | 16 | 20 | 15 | 18 | 0 | 55 | 31 | 34 | 693 | | | | | | |
| > 5.0 | .4 | .7 | 1.0 | 1.0 | 1.0 | 2.3 | 5.1 | 6.7 | 8.8 | 8.8 | 14.9 | 18.4 | 22.2 | 100.0 | AVERAGE LENGTH OF INTERVALS=2673.0 | | | | | |
| > 5.0 | .4 | .6 | .9 | .9 | .9 | 2.5 | 4.5 | 6.0 | 7.9 | 7.9 | 13.4 | 16.5 | 19.9 | 89.7 | | | | | | |

TOTAL NUMBER OF MISSING OBSERVATIONS THAT WERE REPLACED BY ESTIMATES AND USED IN THE T* FREQUENCIES=016

* See text for a description of the line entries.

- For a given criterion, what percentage of all the events had durations of x days or less?

- For a given criterion, what percentage of the time can events be expected to persist longer than x hours?

- Considering all the intervals between specified events, what percentage persisted more than x hours?

- What percentage of the time can events less than a given threshold be expected to persist longer than x days?

### 5.3.10   The need for empirically derived duration-interval statistics

A legitimate question that can be raised concerns whether it is worth the time and effort to produce empirically derived duration and interval statistics, as opposed to using a duration model which can generate these statistics from easily derived quantities. Results suggest that the empirically derived duration and interval statistics are often necessary.

Depending upon its application, an important characteristic of a model can be its generality or transportability. One application was tested using a wave height and wind speed duration model [4]. In Graham's model, like many other duration models, a relationship was established between some readily available or easily calculated statistic and some empirically derived duration frequency statistics. In the development of the Graham model, a relationship

In the *US Navy Spectral Ocean Wave Model Hindcast Climatology: North Atlantic Ocean* [10], empirical duration statistics were calculated for 63 grid points across the North Atlantic Ocean. Those statistics were computed in a format identical to Tables 5.4 to 5.7. These data provide ample opportunity to test the transportability of Graham's model. The generality of this model for representing data from across the North Atlantic Ocean was tested using the following hypothesis: If two different grid points, or even the same grid point for different months or seasons, have a given threshold (say 20 m s$^{-1}$) associated with similar quantiles (say the 75th percentile plus or minus one percentile), then the duration statistics for the given threshold value are from the same population. The Kolmogorov-Smirnov (K.S.) statistic was used to test this null hypothesis. (The K.S. test is an extremely powerful non-parametric test [11].) An example of its application for two grid points in the North Atlantic is depicted in Table 5.10, where the hypothesis is rejected at the 5 per cent level. Figures 5.10 and 5.11 depict the results of the K.S. tests using a significance level of 0.05. The results of the K.S. tests are plotted and analysed based on comparisons of the duration frequency statistics at the grid point represented by an asterisk and all other grid points depicted by discrete dots on each map. Isopleths have been drawn using the percentage of K.S. tests accepting the hypothesis between the key grid point (asterisk) and all other plotted grid points. At least five tests (across seasons, within seasons and varying thresholds) were required, with the restriction of similar quantiles of the threshold value, to include a large sample of grid points in the analysis.

For wind speed, Figure 5.10 indicates that only for a limited spatial extent can the hypothesis be accepted. Sometimes the size of this area is relatively large, varying in area depending upon the location of the key grid point. This suggests that there are subtle climatic character-

istics affecting duration statistics, i.e. preferred areas of cyclogenesis, frontolysis, etc., which are not captured when considering only the quantiles associated with a given threshold value of wind speed. A similar analysis may be performed for the significant wave height.

Hence, Graham's model would not be applicable (i.e. it is not transportable) for the representation of this data set in generality, but it could be quite useful if applied in the appropriate area. However, one must be judicious in the use of models and, whenever feasible, empirically derived duration statistics should also be calculated.

### 5.3.11 Duration-interval analysis checklist

A checklist is provided below for users who require duration-interval calculations.

(1) Select threshold criteria.
   (a) Establish parameter thresholds.
   (b) Establish time domain resolution and assumptions regarding the temporal data.

(2) Define minimum allowable break in an event.

(3) For periodic summaries (i.e., those that are not intended to represent year-round conditions), establish the method for treating durations that straddle the beginning and ending of the period.
   (a) Decide how to use durations that overlap both ends of the period.
   (b) Determine whether to consider events under way at the beginning of the period to begin on the first day of the period. Define the longest allowable duration of an event which extends past the end of the summary period.

(4) Define interpolation procedures.
   (a) Establish the number of missing data that will be allowed.
   (b) Define the interpolation process, if any.

(5) Establish duration weighting for probability computations.
   (a) Weight durations equally?
   (b) Weight durations according to their length?

(6) Make it very clear to the recipient what is being done and what the output means.

### 5.4 EXTREME-VALUE ANALYSIS

### 5.4.1 Introduction

The *Guide to climatological practices* (WMO–No. 100) explains the requirement for extreme-value analysis thus:

Extreme values have always been of interest not only to professionals concerned with engineering-design problems, but also to laymen curious about the magnitudes of unusual or rare natural phenomena. Instead of learning what is the greatest one-day rainfall or what is the strongest wind speed, users sometimes prefer to know how often the extreme events occur.

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**TABLE 5.10**

**Hypothesis: Duration statistics of the two grid points are from the same population**

GRID POINT 11                              LAT. 58.3 N. LON. 12.3 W.
23% of hindcasts were ≥12 ft (threshold value)

| ≥12 ft | 10 | 18 | 22 | 23 | 23 | 24 | 25 | 28 | 30 | 31 | 36 | 37 | 41 | 41 | 45 | 100 | Cumulative % of events |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ≥12 ft | 8 | 7 | 3 | 1 | 0 | 1 | 1 | 1 | 2 | 2 | 1 | 4 | 1 | 3 | 0 | 3 | 46 Number of events |

6  12  18  24  30  36  42  48  54  60  66  72  78  84. 90 96+
HOURS DURATION OF EVENTS
Total number of events (N$_{11}$) = 84

GRID POINT 18                              LAT. 51.5 N. LON. 42.7 W.
21% of hindcasts were ≥12 ft (threshold value)

| ≥12 ft | 11 | 28 | 35 | 50 | 58 | 69 | 73 | 78 | 79 | 86 | 89 | 93 | 94 | 94 | 94 | 100 | Cumulative % of events |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ≥12 ft | 9 | 13 | 6 | 12 | 6 | 9 | 3 | 4 | 1 | 6 | 2 | 3 | 1 | 0 | 0 | 5 | Number of events |

6  12  18  24  30  36  42  48  54  60  66  72  78  84  90 96+
HOURS DURATION OF EVENTS
Total number of events (N$_{18}$) = 80

| ≥12 ft | 2 | 9 | 13 | 27 | 35 | 45 | 47 | 50 | 49 | 55 | 53 | 55 | 53 | 53 | 49 | 0 | Differences of cumula- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

6  12  18  24  30  36  42  48  54  60  66  72  78  84  90 96+    tive % of
HOURS DURATION OF EVENTS                                           events

Result: α = .05 Reject hypothesis when any categorical difference exceeds
21% for N$_{11}$ = 84 and N$_{18}$ = 80.

PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WIND SPEED

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Figure 5.10

PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WAVE HEIGHT
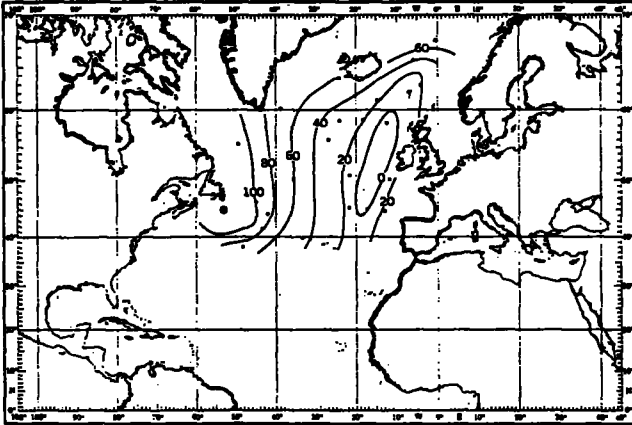
PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WAVE HEIGHT
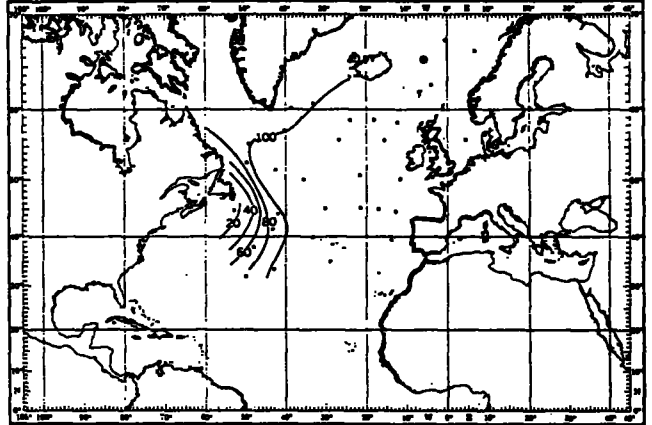
PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WAVE HEIGHT
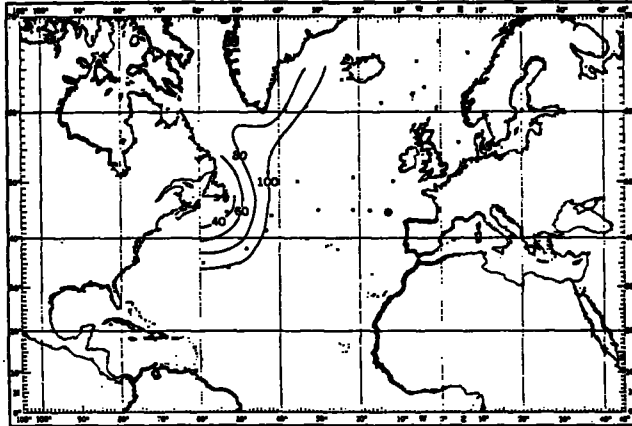
PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WAVE HEIGHT
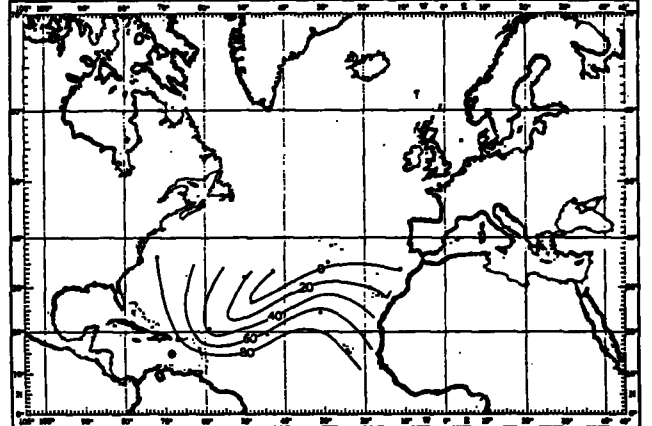
PERCENT OF K. S. TESTS ACCEPTING HYPOTHESIS FOR WAVE HEIGHT
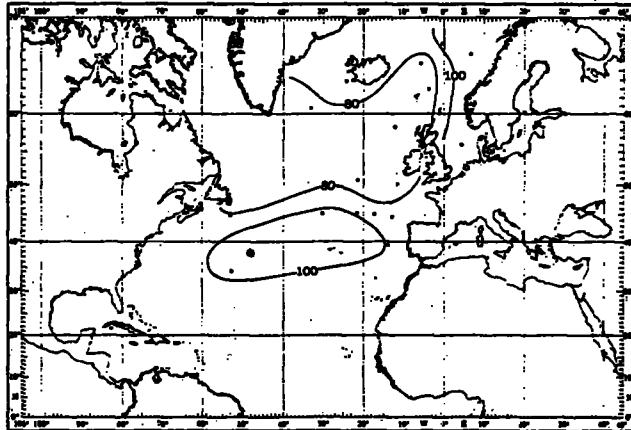
Figure 5.11

The theory of extreme values has been successfully used in climatology to determine the recurrence interval of annual extremes of wind speed, precipitation, atmospheric pressure, temperature, and more widely, in hydrology, to compute the magnitude of rare floods and duration of droughts.

In analysing extreme values from historical series there are two main questions: the first is whether the value is real or whether it is an observational error, and the second is whether values which are even more extreme are possible. To answer these questions, a special branch of mathematical statistics was developed: the theory of limit distributions. Poisson, who established the law of rare events, can be considered its founder. The problem of analysing extreme values is fundamentally one of establishing the distribution function of the extremes, enabling us to answer both of the above questions.

The major difficulties encountered in deriving extreme values relate to the choice of a representative sub-set of data, and to deciding which form of probability distribution to use. Theoretically, the distributions apply and should be fitted only to the rarer events, i.e. those occurring less frequently, which are to be found in the "tail" of any frequency distribution. Given this limitation, efforts are often made to limit the sub-set of data to the rarer events. Thus, the maximum wind speed in each year or month may be extracted from a long record, and the mathematical function fitted in the expectation that the sub-set of data will lie almost entirely in the tail of the general frequency distribution. An alternative approach consists in fitting a general function to the entire distribution of data and extrapolating to rare events. To some extent, this technique is based upon the belief that the extremes are part of the general distribution and therefore one mathematical function should fit throughout and be capable of meaningful extrapolation. Unfortunately, this may not be true.

The following sections describe some of the theory, graphical and numerical procedures and techniques for working out solutions in extreme-value analysis. A detailed treatment of the underlying theory of extreme-value analysis and options with respect to selecting statistical distributions and fitting techniques is also found in the WMO *Guide to climatological Practices* and in Sevruk and Geiger [12]. Recently, Farago and Katz [13] produced an excellent review of the application of extreme-value theory in climate applications.

## 5.4.2    Return period — The concept

An event which has occurred $m$ times in a long series of $n$ independent trials, one per year say, has an estimated probability $p = m/n$; conversely, the average interval between recurrences of the event during a long period would be $n/m$; this is defined as the return period $T$ where: $T = 1/p$.

For example, the 0.01 probability level of an event occurring in any one year corresponds to a 100-year return period for that event. This does not imply that such an event would occur at regular 100-year intervals, or would not recur until 100 years afterwards. Rather, it is more likely that over a long period, say 500 years, five events of equal or greater magnitude would have occurred.

Engineers concerned with design of structures frequently request estimates of meteorological parameters having, on average, a long period of time between occurrences (return period), i.e., they are rare events. Return periods of once in 100 and once in 50 years are commonly requested by the offshore construction industry. The magnitude of the estimate is very important because the structure will be designed to withstand the specified event while avoiding overdesign. Construction costs are closely linked to the magnitude of the "design" extreme.

The marine climatologist must estimate these rare events from a time series of data usually covering a relatively short period and which is therefore unlikely to contain any of the rarer extremes. The technique employed depends upon fitting a mathematical function to a chosen sub-set of the data. The fitting process results in a probability distribution which can be extrapolated to give the magnitude of the rarer events.

### 5.4.2.1    Risk analysis

It may happen that, during a definite period of $t$ years, an event of magnitude $X > XT$ does not occur at all, or that it occurs several times. The probability that, during a given period of $t$ years, a respective phenomenon will occur $m$ times, is given by:

$$P_{m/t} = \left(\frac{t}{m}\right) p^m (1-p)^{t-m}$$

where $\left(\dfrac{t}{m}\right) = \dfrac{t!}{m!(t-m)!}$ and where $p = 1/T$.

Assuming, for example, that $t = 100$ years, then we determine the following probabilities for various values of $m$:

| $m = 0$ | $P_{m/100} = 0.366$ |
|---|---|
| 1 | 0.370 |
| 2 | 0.185 |
| 3 | 0.061 |
| 4 | 0.014 |
| 5 | 0.003 |

## 5.4.3    Mathematical functions for extremes

The most commonly used* theoretical distributions for extreme values are the Fisher-Tippett types I, II and III

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* "Commonly used" here refers to classification societies, insurance and commercial interests, architects and engineers. Some examples of similar approaches used in the Russian Federation are included further on in the *Guide*.

[14]). The type I distribution is unbounded, whereas type II has a lower limit but is unbounded above, and type III has an upper limit. The type I is often known as the double exponential or Gumbel (after Gumbel [15]) distribution and is the more commonly used of these types. Fisher-Tippett type II is known as the Frechet distribution and has been used for estimation of floods and extreme rainfalls [16,17]. The type III distribution gives rise to the Weibull extreme-value distribution [18] which has also been widely used for estimating extreme wind speeds and temperatures [17, 19]. Other distributions have been used, such as the gamma [20] and the log normal [21]. The form of some of these distributions appears in Table 5.11.

For most environmental data the Gumbel distribution, fitted by the method of moments, has been accepted as appropriate for (representing) the probability distribution for extremes. This distribution is a double exponential distribution. More detailed discussion of double exponential and other extreme value distributions can be found in [22] and [12].

In the theory of extremes, the double-exponential (Gumbel) distribution is accorded an important place for its universal nature and the ease with which practical problems can be solved. A number of works have established that the extremes of many meteorological elements follow this distribution, e.g. temperatures, wind speeds, precipitation and atmos-

TABLE 5.11
**Common statistical distributions**
*(Baird et al., 1986; AES, 1986)*

| Continuous distribution | Probability density function |
|---|---|
| Normal | $f(x) = \dfrac{1}{\sigma\sqrt{2\pi}} \exp\left[ -(x-\mu)^2 / 2\sigma^2 \right]$ |
| Lognormal $(y - \ln x)$ | $f(x) = \dfrac{1}{x\sigma_y\sqrt{2\pi}} \exp\left[ -\left(\ln x - \mu_y\right)^2 / 2\sigma_y^2 \right]$ |
| 3-parameter lognormal $(y - \ln(x - \varepsilon))$ | $f(x) = \dfrac{1}{(x-\varepsilon)\sigma_y\sqrt{2\pi}} \exp\left[ -\left(\ln(x-\varepsilon) - \mu_y\right)^2 / 2\sigma_y^2 \right]$ |
| Exponential | $f(x) = \dfrac{1}{\beta} \exp\left[ -\dfrac{x-\varepsilon}{\beta} \right]$ |
| 2-parameter gamma | $f(x) = \left[ \,\lvert\beta\rvert \,\Gamma(\gamma) \right]^{-1} \left( \dfrac{x}{\beta} \right)^{\gamma-1} \exp\left[ -\dfrac{x}{\beta} \right]$ |
| 3-parameter gamma (Pearson type 3) | $f(x) = \left[ \,\lvert\beta\rvert \,\Gamma(\gamma) \right]^{-1} \left( \dfrac{x-\varepsilon}{\beta} \right)^{\gamma-1} \exp\left[ -\dfrac{x-\varepsilon}{\beta} \right]$ |
| Log Pearson type 3 | $f(x) = \left[ \,\lvert\beta\rvert \,\Gamma(\gamma) \right]^{-1} \left( \dfrac{\ln x-\varepsilon}{\beta} \right)^{\gamma-1} \exp\left[ -\dfrac{\ln x-\varepsilon}{\beta} \right]$ |
| Type I (Gumbel) | $f(x) = \alpha \exp\left[ -\alpha(x-u) - e^{-a(x-u)} \right]$ |
| Type II (Frechet) | $f(x) = \dfrac{k}{v-\varepsilon} \left( \dfrac{v-\varepsilon}{x-\varepsilon} \right)^{k+1} \exp\left[ -\left( \dfrac{v-\varepsilon}{x-\varepsilon} \right)^k \right]$ |
| Type III (largest value) | $f(x) = \dfrac{k}{\omega-v} \left( \dfrac{\omega-x}{x-v} \right)^{k-1} \exp\left[ -\left( \dfrac{\omega-x}{x-v} \right)^k \right]$ |
| EV 3 (Weibull) (smallest value) | $f(x) = \dfrac{k}{v-\varepsilon} \left( \dfrac{x-\varepsilon}{v-\varepsilon} \right)^{k-1} \exp\left[ -\left( \dfrac{x-\varepsilon}{v-\varepsilon} \right)^k \right]$ |
| GEV | $f(x) = \dfrac{1}{\alpha_f} \left( 1 - \dfrac{(x-u)k_f}{\alpha_f} \right)^{k_f^{-1}-1} \exp\left[ -\left( 1 - \dfrac{(x-u)k_f}{\alpha_f} \right)^{k_f^{-1}} \right]$ |

pheric pressures. The information requirement in these cases is eased somewhat. Thus, the usual mathematical statistics requirement for observations to be independent is not so strict; Watson [23] shows that if a random value is unbounded, the limit distributions of the dependent and the independent values are identical. It is also unnecessary for discreteness in time of the data from which the extremes are taken to be equal.

Two-parameter distributions (such as the Gumbel) are favoured by some analysts over three- or more parameter distributions. For most environmental data, especially in marine areas, data series are short — of the order of 20–50 years or less. Three-parameter distributions, it is argued, tend to overfit the variations in the data, giving misleading results. The fit, and thus the results, tends to change each time a new data point is added, which is undesirable.

In practice, the choice of function may not be decided by its theoretical attributes but rather as a result of goodness of fit to the available data and the physical meaningfulness of the extreme value produced. Several distributions may be fitted, or alternatively one may be preferred as a consequence of long experience of its applicability to the parameter and data source used.

### 5.4.4    Forensic extreme-value analysis

The term forensic extreme-value analysis is used here to refer to the case in which the objective of the analysis is to estimate the return period of an event of specified magnitude. This event may be an actual observed event which was particularly severe and may have led to property damage or loss of life. It may also be an event that has been simulated using a deterministic model.

This type of analysis is different from typical extreme-value analysis in which the objective is to estimate the magnitude of a particular event, given a specific return period. Although many of the considerations are similar, the analysis can be very complex. In any event, the consequences of being wrong (or of appearing to to be wrong) in the case of forensic analysis are such that this type of problem is often referred to an expert.

### 5.4.5    Multivariate extreme-value analysis

In some situations it may be desirable to define the extreme values of a specific process defined by more than one variable. The models described thus far are all univariate models; however, these models may be used in this type of application but only if the joint effect of multiple variables is quantified through the use of a response index or model.

If the variables are mutually independent, quantiles can be estimated from the product of the individual exceedance probabilities from a univariate model. Similarly, if they are totally dependent they can be defined by the exceedance probabilities of one of the variables. If the variables are only partially dependent, a multivariate extreme-value model is required.

Multivariate models for extreme-value analysis have been developed recently and are described in [24].

Many of the multivariate models are relatively new and further development is required for practical applications. A multivariate extreme-value analysis should be undertaken only with the assistance of appropriate expertise.

### 5.4.6    Selection of extreme events

Two methods are commonly used to select a proper data set: the annual exceedance method, and the peak-over-threshold method. It has been demonstrated that both series tend to merge at return periods greater than ten years. These procedures are described below.

### 5.4.6.1    Annual maximum series (AMAX)

The most common method of selection is to choose one maximum of a particular event from each year of the period of record. This is called the annual maximum series which, by definition, yields $n$ values in $n$ years. It is used more often for reasons of convenience. The major drawback to the annual maximum series is that it ignores the second, third, etc. largest events within a year, even though they may be more extreme than the annual maximum from other years. When at least 25 years of record are available, experience has indicated that the AMAX model provides sufficiently reliable estimates of (50–100-year) extreme values, provided that:

* Appropriate data preparation and checking procedures are successfully completed;

* Appropriate distributions are selected and their parameters are estimated correctly.

### 5.4.6.2    Peak-over-threshold series (POT)

An alternative method to the annual maximum series is to select all the values above a specific threshold value regardless of their year of occurrence. This is commonly referred to as the peak-over-threshold (POT) method, or partial duration series. Typically, approximately $n$ storms are chosen over $n$ years. However, more or fewer storms may be chosen depending on the circumstances. The number of storms selected is constrained by two factors: too few storms means that the statistics are based on a very limited sample, therefore the confidence limits will be large, and the return periods unstable, varying widely depending on the inclusion or exclusion of certain storms, or with the addition of new storms; if too many storms are chosen, some may not be true extreme events. As a result the sample will not be homogeneous, and the sample will be biased, giving misleading results.

In areas with a mixed population of extremes, e.g. a monsoon climate subject to tropical storms, the POT technique is the only one really viable. In temperate latitudes POT usually results in the extraction of storm maxima. Nevertheless, POT has the weakness that choice of the threshold has a marked

effect on the design extreme eventually produced and there is no objective way of setting that threshold.

The same constraints on data and on selection of distributions apply to the POT model as to AMAX, but it has been found that the POT model generally gives better results when significantly fewer than 25 years of data are available [25]. The POT model estimates tend to be unbiased provided that the number of years of record is greater than 15. When the number of years of record $n$ is less than 15, the estimates may be only slightly biased high or low if at least $2n$ events are selected. Experience indicates that reasonable estimates of extremes can be produced with as few as five to ten years of data using the POT approach. The number of events selected must be at least 20, and a regional analysis of available data should be undertaken where possible to provide support for the estimate. As the number of years of record approaches 25 both the AMAX and the POT models give unbiased estimates, but the standard error of estimate is smaller for the POT model. The POT approach is therefore recommended. A recommended methodology are given in section 5.4.8. Examples of POT are given in Appendix II.

When fewer than five years of data are available, neither the POT nor the AMAX approaches should be attempted.

## 5.4.7    Data limitations

The derivation of extremes demands as long a record as possible. This is an immediate source of difficulty with marine data, because long continuous records of meteorological parameters are relatively scarce at sea. Reliable series of observations from oceanographic buoys and offshore platforms, while continuous, are often relatively short, e.g. one to five years in duration. Such records can be used, but must be put into climatological context by using a longer neighbouring record. The difficulty is usually in identifying a neighbouring record which, while too far away to be used for extreme value estimation, is close enough and sufficiently representative of overall climatology to be used to adjust the record in question.

The main source of marine meteorological data remains the observations from merchant ships of the Voluntary Observing Fleet. Unfortunately these data are random in space and time, so that it is usually not possible to use annual maxima. Although POT methods can be attempted, some analysts prefer fitting a function to the whole distribution of data, often using Weibull (not the Weibull extreme-value distribution in this case). However, the fit, and hence the extrapolation to long return periods, is very sensitive to the data sample. The extent to which the sample represents the true distribution is variable when VOS data are used. The method is not considered highly reliable by some analysts because of the nature of the data.

### 5.4.7.1    Screening of data

There are several important conditions which the data must satisfy before extreme-value analysis may be

applied. Firstly, the data must be numerous and consistent. A minimum of 15 years of data is usually recommended. Trends in the data must be absent since conditions are assumed to persist into the future. It is recommended that a test of randomness be applied to the time series. Secondly, it is assumed that data are independent, i.e. the occurrence of one extreme is not coupled to the next. Annual extremes generally satisfy this condition, unless successive values are recorded at the end of December and the beginning of January.

Statistical frequency analysis assumes that the sample to be analysed is a reliable set of measurements of independent random events from a homogeneous population. The validity of this assumption can be verified using statistical significance tests. Non-parametric tests are most commonly used. Graphical displays can also be used to good advantage to assess these assumptions. Brief descriptions for each test are given below; fuller descriptions are given by the National Environment Research Council [26] and Siegel [11] and in section II.3 — Statistical tests — of Appendix II.

#### 5.4.7.1.1    Trend

If successive measurements of members of a time series have been made during gradually changing conditions, then there will be a more or less noticeable trend in the magnitude of the members of the series when arranged in chronological order. For example, urban build-up in the vicinity of airports frequently causes changes in the wind regime there. A very simple test for the presence of trend and its statistical significance can be made on the Spearman rank-order correlation coefficient. The co-efficient is computed from pairs consisting of the chronological order of an event and its associated rank (see section II.3 of Appendix II).

#### 5.4.7.1.2    Independence

Two events can be considered independent only if the probability of occurrence of either is unaffected by the occurrence of the other. This definition can be extended to a sample size of $N$. Practically, in a time series, independence can be measured by the significance of the correlation coefficient between $N-1$ pairs of the $i$th and $(i+1)$th members of the series and if the correlation coefficient is not significantly different from zero, then independence is assumed. It is noted here that, in a strict mathematical sense, this does not necessarily define independence.

#### 5.4.7.1.3    Homogeneity and jump

If some more or less abrupt change occurred during the sampling period, then some difference could be expected between the means of the sub-samples before and after the change. An example of this would be the relocating of an anemometer, or a change in exposure due to cutting down a forest. Assuming a normal distribution and that the two sub-samples have the same variance, then the difference in the sub-sample means can be tested for significance

using Student's $t$ distribution. These assumptions are not generally met in the environment so the Mann-Whitney non-parametric test is used instead. If two sub-samples of approximately the same size are chosen, it would be expected that if there were no changes in conditions, then the sums of the ranks of the two sub-samples would not differ by too much. The Mann-Whitney $U$ statistic is a function of the sub-sample sizes and the sums of their ranks. The distribution of $U$ is known and critical values at various significance levels have been tabulated. A decision can be made on whether the means of the sub-samples differ significantly.

### 5.4.7.1.4 *Randomness*

A simple non-parametric test is used to determine whether the data in the extreme value series are random. Data are ranked in chronological order, and the median is determined. The number of runs of observations above and equal to or below and equal to the median are counted. Theoretically, the number of runs could be as high as the total number of observations, indicating an extreme short-term cyclic pattern, or as low as 2, indicating an abrupt change half-way through the period over which the sample was collected. The median is used for this test, since the probability of exceeding the median is always 0.5, regardless of the probability distribution from which the sample was drawn, thus making the test non-parametric or distribution-free. The distribution of runs above and below the median is known, and upper and lower critical values have been tabulated, thus enabling a decision to be made on whether the data are random.

### 5.4.8    Recommended methodology

An outline of a recommended aproach for estimating extreme values appears in the block diagram reproduced as Figure 5.12. This figure summarizes preceding sections on extremes into a recomended methodology. A typical application of this methodology appears in section II.1 of Appendix II, which illustrates the use of this methodology with the Gumbel distribution. Further examples of approaches to extreme-value analysis are also provided in the appendix. A selection of these are presented to illustrate a body of knowledge, viewpoint and literature on this topic which developed in the former Soviet Union.

Farago [27] has reviewed the theoretical aspects of extreme-value analysis and its practical application to meteorological variables. Farago and Katz [13] have written a WMO/WCAP monograph which discusses extremes and design values in climatology. Simple and easy-to-use software on floppy disk for applying extreme-value analysis of annual extremes as described in this publication is available through the Hungarian Meteorological Service.

The process of designing an offshore structure is a complex one. Climatic extremes define some of the loads for which a structure must be designed, but these are but one consideration in a process which must satisfy regulatory boards or agencies in many countries and insurers or underwriters in most. In some cases, the latter may influence the approach used in producing a design extreme. The methodology and practice followed could therefore vary from country to country.
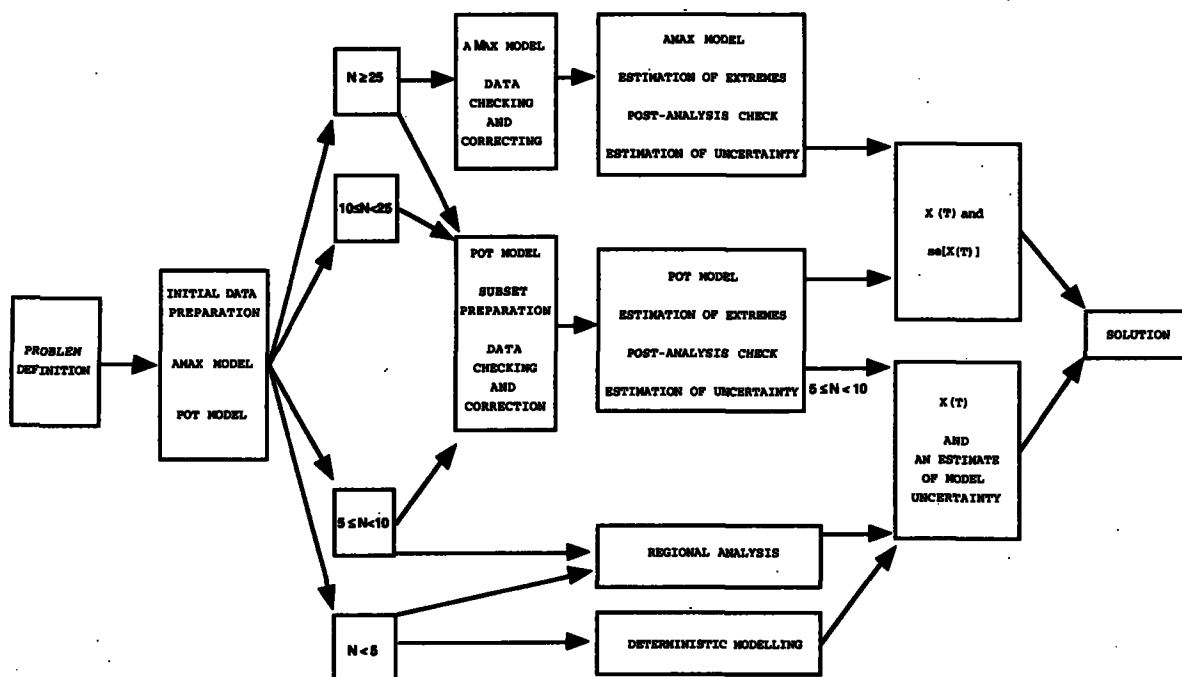


Figure 5.12 — Data preparation and checking

## 5.4.8.1    *Data preparation and checking*

The following steps should be undertaken for the preparation of data for a POT extreme-value analysis:

• Obtain the initial data directly from the appropriate data collection agency;

• Obtain the data station description and history. Details which should be requested and included with a station report include:

   – A description of the geographical setting of the station including instrument location;

   – Instrument type and installation details (height above ground, clearance from nearby obstacles, etc.);

   – Details of calibration history and maintenance cycle;

   – Details of any post-processing and data-quality checks which might have been undertaken by the data collection or archiving agency;

• Check the data record for completeness. A data series is often incomplete, usually for one of four reasons:

   – Data collection may possibly have been discontinued for a period because of financial or manpower constraints;

   – Data may be missing because recording was affected by the phenomena of interest (for example, the anemometer is destroyed!);

   – Data may be missing because of the archiving procedure used by the data collection agency;

   – Data may appear to be missing because of the presence of zeros.

In the first case the recommended solution is to repair and then concatenate the record as illustrated in Figure 5.13, so that the period of record becomes equal to the total duration of available data. Discrimination should be exercised where the missing data period might reasonably be expected to include a period with a significant extreme.

Repair (or filling in) of the data may be undertaken with the assistance of appropriate expertise where a knowledge of the applicable process suggests that events of interest (extremes) were not missed during the repaired gaps. Repair ensures that the record length is as long as can legitimately be inferred for the data set.

In the second case, e.g. where the magnitude of the process of interest was greater than the capability of instruments to record it, the responsible data agencies may be contacted to assist in estimating the missing data.

In the third case, data may be missing or incorrect on account of errors in quality-control and conversion procedures or errors in handling or merging of the data by the data-collecting agency. In some countries, data have been recorded in one set of units and subsequently converted. Data values may have been rounded in the process. Due to metrification, it is possible for conversion and rounding of the archived data to have occurred twice. Improperly applied conversion may result in the occurrence of artificially produced impossible data values which may subsequently have been rejected in some quality-control
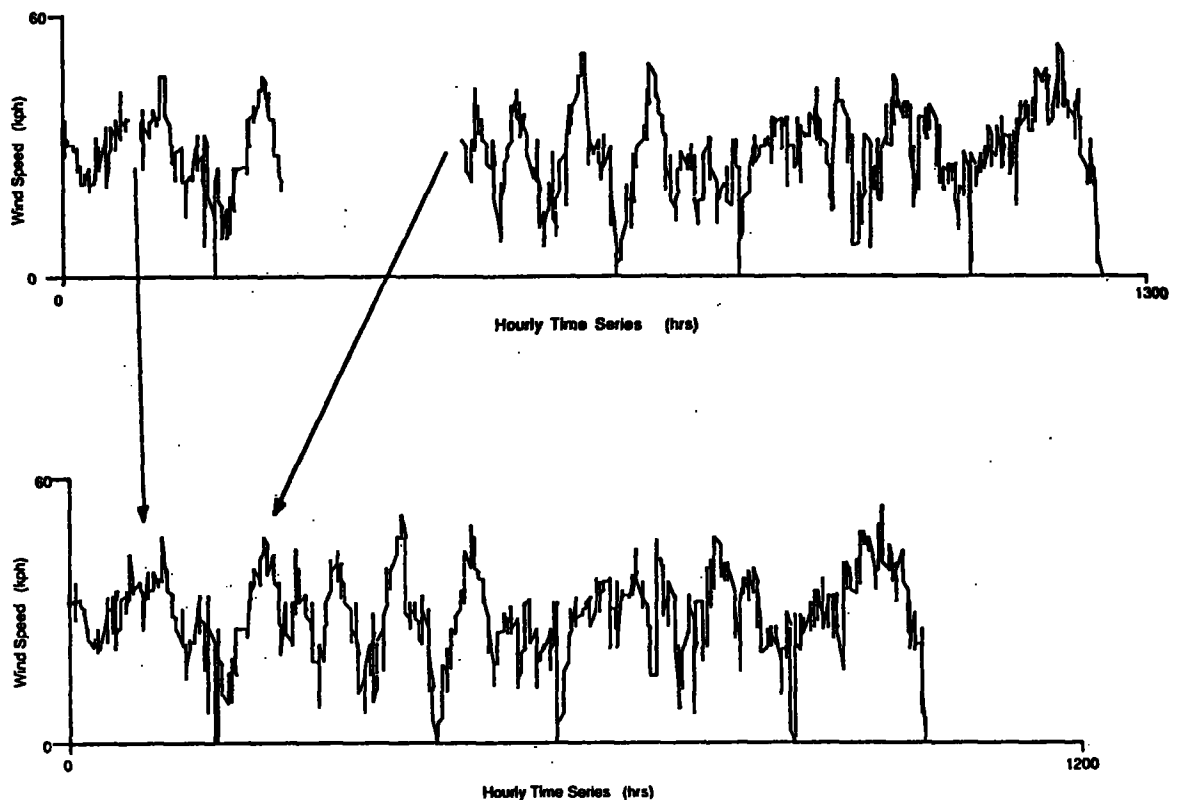


Figure 5.13 — Concatenated hourly time series

procedures. Caution and comparison with corroborating evidence recommended for data having undergone conversion of units.

　　　　In the fourth case, most data agencies differentiate between zeros and missing data by coding the different reasons. If this is not so, the reasons must be determined and if the data are missing, then the record can be concatenated as shown in Figure 5.13. If the missing data are true zeros, only the conditional probability, given that the process of interest occurs, can be determined.

• The data should be corrected as necessary as described above, and where sufficient information exists, they should also be corrected for any trend or jump caused by changes documented in the station history.

• A decision must be taken whether to use the AMAX or POT approach. (In the procedure which follows, it has been assumed that POT has been chosen — the methodology for AMAX is similar.)

• The parent POT series should be selected in chronological order to satisfy the criteria defined below:
　　– The threshold must be above the mode of the parent distribution;
　　– At least 20 events must be selected. It is advisable, provided that the threshold is greater than the mode, to select between five and ten times $N$ to define the initial parent POT series;
　　– There must be at least two events per year.

The data should be screened in order to ensure that a minimum inter-event time is exceeded. The minimum inter-event time is required to ensure that selected events are independent of each other in a manner which is consistent with the knowledge of the geophysical process of interest. Selection of an inter-

event time should be undertaken with the assistance of appropriate expertise.

• The resulting observations should be arranged in order of decreasing magnitude and a rank $m$ assigned ($m = 1$ for the largest value).

### 5.4.8.2　Pre-analysis examination

As the first step in the pre-analysis examination, the selected POT series should be plotted as a time series as shown in Figure 5.14. This type of plot may indicate that trend, jump or lack of independence or homogeneity is present in the data set. The existence of any of these characteristics should be verified using the statistical tests outlined in Table 5.12.

TABLE 5.12
Statistical tests for pre-analysis examination
(See section II.3 of Appendix II)

| Charac- teristics | Data set | Test |
|---|---|---|
| Trend | Complete time series | • Spearman rank order correlation coefficient |
| Jump | Two time series: • Before jump • After jump | • Wald-Wolfowitz • Mann Whitney test for jump |
| Indepen- dence | Complete time series | • Autocorrelation function • Spearman rank order serial correlation coefficient |
| Homogen- eity | Two sub-series: • Process A • Process B | • Wald-Wolfowitz • Mann Whitney test for homogeneity |
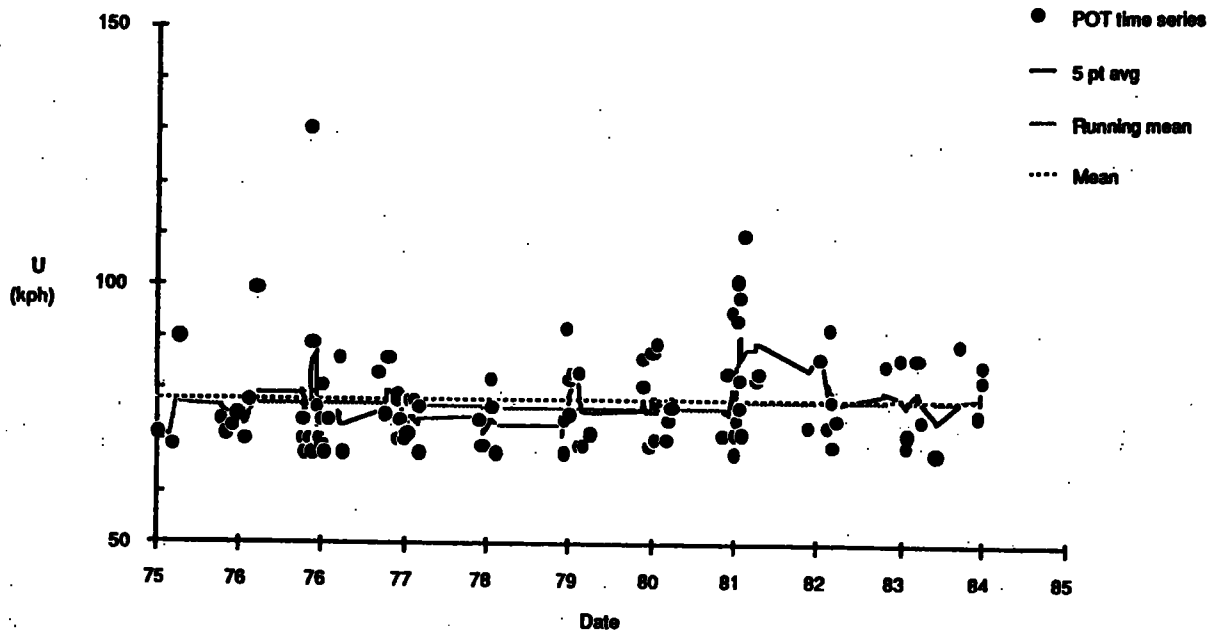


Figure 5.14 — Data trend; POT time series

Where these tests provide a strong indication of trend, jump, lack of independence or non-homogeneity, further analysis is warranted. Corrective action may ultimately be required.

### 5.4.8.3    Estimation of extremes

#### 5.4.8.3.1    Calculation of sample moments

From a sample of size $M$, corresponding to $M$ observations with $x_i$ ($i = 1$ to $M$) above a threshold $x_0$, compute the sample mean $x$, the sample standard deviation $s_x$, and the sample coefficient of skewness $g_x$.

$$\bar{x}\left(\sum_{i=x}^{M} x_i\right) / M$$

$$s_x = \left\{\sum_{i=x}^{M}(x_i - \bar{x})^2 / (M-1)^{\frac{1}{2}}\right\}$$

$$g_x = \frac{M}{(M-1)(M-2)}\sum_{i=1}^{M}(\bar{x} - x)^3 / (s_x)^3$$

#### 5.4.8.3.2    Definition of the POT parameters

Because the threshold is selected arbitrarily, and its choice affects both the resulting sample size (which can be large) and the values of the POT parameters, the relationship between the threshold and the resulting parameters must be checked in an iterative manner to ensure that the assumptions of the POT model are satisfied (i.e. a Poisson process and an exponential distribution of peaks).

The recommended procedure, therefore, is to select a threshold, estimate the parameters, check the POT model and repeat until either the POT model assumptions are satisfied, or the model is shown to be unsuitable for the application at hand. After this point, the data can be checked graphically again for trend, jump, independence and homogeneity. The elements of this procedure are described below:

- The threshold $x_0$ is defined in the selection of the POT data series as described earlier.

- The Poisson distribution parameter $k$ is estimated by moments as

$$\lambda = M/N$$

where $M$ is the number of events and $N$ is the record length in years.

- The two exponential distribution parameters are the threshold $x_0$ and the scale parameter $b$. The scale parameter is estimated by the method of moments as

$$\beta = \bar{x} - x_0.$$

Where the distribution of peaks is distorted because of gaps (i.e. by recorder bias) and where one of these gaps corresponds to the threshold, $b$ should be estimated from the second moment using

$$\beta = s_x.$$

There are two main assumptions underlying the POT model described above:

- For a Poisson process, the ratio of the mean to the variance of the number of events per year is unity;

- For an exponential distribution of magnitudes, the population coefficient of skewness is two.

Experience has shown that the results of a POT model are not sensitive to the Poisson process and therefore the second requirement is more important than the first. The validity of the POT model can be assessed by comparing the sample values to the two criteria. If they differ significantly, the threshold should be increased, and moments and parameters recalculated, until both criteria are satisfied and at least the sample skewness approaches two or the sample size $M$ reaches a minimum allowable value of $2N$ (or at least 20).

An additional useful test for the Poisson process is that the inter-event durations should be exponentially distributed.

#### 5.4.8.3.3    Quantile estimates

Quantiles are estimated using the following expression:

$$x_T = x_0 + \beta \ln\lambda + \beta_{yT}$$

where the reduced variate $yT = -\ln \ln (T/(T-1))$. Values of $yT$ are given in Table 5.13 for common return periods.

#### TABLE 5.13
#### Reduced variate for POT quantiles

| Return period, $T$ | 2 | 5 | 10 | 20 | 25 | 50 | 100 |
|---|---|---|---|---|---|---|---|
| Reduced variate, $yT$ | -0.367 | 1.500 | 2.250 | 2.970 | 3.199 | 3.902 | 4.600 |

#### 5.4.8.3.4    Graphical presentation

For each $x_i$, compute a plotting position using the Gringorten formula (as an approximation of the exponential probability distribution plotting position)

$$P_m = \lambda (m - 0.44)/(M + 1.12)$$

and the corresponding "empirical return period"

$$T_m = 1/P_m.$$

Plot each $x_i$ at its corresponding plotting position on exponential probability paper. If exponential probability paper is not available the data can be plotted on linear graph paper using the linear reduced variate, $Rv$, for the exponential distribution, defined as:

$$Rv = -\ln (P_m).$$

On the same exponential probability paper, the quantile estimates for a range of return periods as construction points should also be plotted.

### 5.4.8.4   Post-analysis checking

In many cases, the existence of an apparent outlier may be suspected after the extreme-value analysis is completed. An outlier may be suspected because one or more data points depart significantly from the trend of either the data or the fitted distribution, plotted as described above. An outlier may exist for one of several reasons:

- It may deviate from other observations because it was generated by some other process;

- It may be a rare event from the same population distribution;

- It may be an observational error which was not detected in pre-analysis examination;

- The statistical model may be wrong.

The extent to which an outlier may represent a problem is a function of the type of distribution, the sample size and the presence of corroborative regional information. It should be noted that:

- Three-parameter distributions are more sensitive to outliers than two-parameter distributions;

- The influence of an outlier on the moments of a distribution are larger for a small sample than for a large sample;

- If the date of the outlier is known, raw or other data records can be reviewed for corroborative evidence which might support or explain the presence of the outlier.

The following procedures are recommended depending on whether the suspected outlier is reasonable.

#### 5.4.8.4.1   High outliers

If the apparent outlier is a high outlier, i.e., it has a low probability of occurrence, the following procedures should be undertaken:

- Determine if the data point is correct by checking the source or basis of the data for errors associated with either measurement or recording or archiving methodology, especially where the data were derived using numerical models;

- Verify the physical processes which are the underlying cause of the observation, and determine if it is consistent with the other observations.

If the outlier is the result of a non-homogeneous process it should be removed and consideration should be given to quantifying and combining the probabilities of two processes. If the apparent outlier is a homogeneous observation, the calculations should be rechecked. If they are correct, then:

- The observation may be a rare event; or

- The model may be wrong, and consideration should be given to using another extreme-value model.

If the model is not wrong or there is no other suitable extreme-value model, then the best that one can do is to repeat the analysis without the outlier and define an envelope of likely return periods for the observation.

In the special case of forensic analysis, a more detailed understanding of the outlier and its statistical significance is required.

#### 5.4.8.4.2   Low outliers

The occurrence of low outliers is an often-overlooked phenomenon, but the user should review any analysis for the presence of such outliers. In particular, low outliers can significantly distort sample skewness and the user will be inclined to use distributions which are consistent with low skewness (i.e. a three-parameter distribution which can have an upper limit). The danger of low outliers is that an artificial case may be created where the estimated upper limit is less than the largest extremes being estimated.

If a low outlier is suspected, the following procedures should be undertaken:

- Contact the original data-collection agency to determine that the data points are correct or whether they may have been exceeded (winds, for example, are sometimes measured using instrumentation which is limited in its operating or recording range);

- Verify the physical processes which are the underlying cause of the observation and determine if it is consistent with the other observations;

- If the outlier is the result of a non-homogeneous process, it should be removed and consideration should be given to how the probabilities of two processes should be quantified and combined;

- If the apparent outlier is consistent with the remainder of the sample, the calculations should be rechecked and if they are correct, the model may be wrong. Consideration should then be given to using another extreme-value model. If a three-parameter distribution was used for the conditional probability distribution, the estimated upper band should be checked to ensure that it is consistent with the observed data.

#### 5.4.8.4.3   Uncertainty of extremes estimates

The uncertainty due to sample size alone of extremes estimates can be approximated using the sampling standard error, $se$ $(x_T)$. The sampling standard error can be combined with the normal distribution to estimate confidence limits about any estimate of a quantile, $x_T$.

When the threshold is fixed, and parameters are estimated by moments for the Poisson/exponential POT model, the sampling standard error $se$ $(x_T)$ can be computed from

$$se\ (x_T) = [1+(\ln \lambda + y_T)^2]^{1/2} \beta/(\ln k).$$

### 5.4.9   Tropical cyclones and storm surges — Special considerations

Planning to minimize the effects of tropical cyclones requires properly designed and located buildings. To express the risk in terms of a common description, engineers are usually required by local law to design for the

worst event which would be expected to occur in 50 or 100 years (n-year events). These types of law discourage expensive construction in more vulnerable areas. The design climatological information most often used is the maximum wind and flood expected to occur within a period of n years. This is often referred to as the n-year wind speed or n-year flood level. Hurricanes contribute both high winds and flood waters from storm surge and heavy rainfall. An alternative approach is to develop a design, or worst-possible, storm. This is analogous to the concept of probable maximum precipitation estimates used for planning and design considerations with storm rainfall. Indeed, the accumulated risk of flooding from rainfall and storm surge must be combined with wind and wave extremes in an area prone to the ravages of tropical cyclones.

*Methodology*: The generic methodology in determining an n-year event falls in two categories: direct climatology or climatological simulation. If reliable records of wind speed or flood levels exist for a period of two to three times n (in years), the n-year event can be estimated directly from an analysis of the data. For a variety of reasons, this is almost never the case and hence a climatological simulation is usually required. In the case of tropical cyclones, one may use actual historical tropical cyclones and estimate, by the use of a model, the resulting winds or flood levels that occurred. An n-year event can then be derived from these estimates. If a sufficient history of tracks is not available, these also can be simulated by fitting the various parameters to proper statistical distributions and then selecting, at random, from these distributions (Monte-Carlo methods), allowing for inter-correlations between the various parameters.

*Data requirements*: Required data include:

- Historical records of tropical cyclones with maximum winds, minimum sea-level pressure and radius of maximum winds (or other measure of cyclone size);

- Historical record of winds at the points of interest;

- Historical record of floods at the points of interest.

The historical storm record is absolutely essential and although it is never complete in wind and pressure measurements, such records are generally available throughout the world. Rarely is there an adequate record of actual winds observed at (or near) points of interest, fundamentally because observing sites are widely separated. In a statistical sense, winds can be simulated and verified against available observations. Reasonable return periods for winds of a certain level can then be derived.

Storm surge, in principle, can be handled in the same way. Storm-surge modelling, however, is a much more complex problem than wind modelling in that it also requires input such as radius of maximum winds, storm translational speed and heading, in addition to central pressure on wind fields. Also required is a detailed description of the offshore bathymetry.

A risk analysis programme used by the US National Hurricane Center is described by Neumann [28] while some of the factors involved in storm-surge modelling are described by Jarvinen *et al.* [29]. A complete description of climatological information requirements and procedures to be used with respect to nuclear power plants at coastal sites is described in the International Atomic Energy Agency Guide [30].

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## GEOGRAPHICAL CONSIDERATIONS

Geography plays an important role in determining which climatic parameters are of most concern, hence what analysis techniques to apply and what applications to consider. In this section, some of these features are discussed for selected geographical areas. This chapter describes some of the more notable or peculiar features associated with major geographical areas, and which have some importance for marine climatological applications; it is not meant to be a climatology nor to describe more than a few selected examples. The chapter concludes with a selected general climatological bibliography.

### 6.1    ARCTIC POLAR OCEANS

#### 6.1.1    Arctic and polar oceans off North America

Sea ice is an ever-present concern for offshore activity in northern polar regions. Even in those areas which may be clear of ice only during the July-to-October period of the year, there is frequently a threat of ice floes moving into them owing to changing wind conditions. A number of aspects of sea ice must be considered. Thickness is a major concern, whether due simply to normal growth during the winter or to ridging caused by the interaction of adjacent ice masses. Age is also very important because when ice floes survive through several winters they become increasingly strong, as the brine in them is replaced by fresh water which refreezes. Such "old ice" poses the greatest problems for marine transportation. Concentration (percentage of the water surface covered with ice), extent, and the mobility of the ice are also of importance. Forces on structures are imposed by a combination of wind and currents acting on the ice. Information on the subject and measurements are usually scarce. Often, engineering data must be inferred from remote sensing and models. This continues to be an area of active research.

Significant concentrations of icebergs characterize eastern Canadian waters and areas offshore of Greenland, where in many instances they are embedded in sea-ice cover. Their size and strength make them formidable enemies for any offshore activity. During the open-water season, their mobility is increased when they are freed of surrounding sea ice. Scouring tendencies of icebergs (and of heavily ridged sea ice) are important in considering any sea-bed pipelines. The size of bergs, their number and characteristic movements are of considerable interest for designers and planners. Adequate information is often unavailable, but modelling activities are in the research stage.

Visibility is a consideration for both marine and airborne activities. While modern detection systems have somewhat reduced the problem for vessels on the high seas, the efficient operation of port facilities and offshore structures subject to the impact of ice features can still be dependent upon good visibility conditions. Logistic support in the form of aircraft, particularly helicopters, is also susceptible to reduced visibility and, further, to poor flight conditions involving low ceilings and in-cloud icing generally.

Water currents in association with surface winds play a significant role in the movement of sea ice and icebergs, the importance of which has been discussed above. Knowledge of this combination is also particularly vital in modelling the movement of possible oil spills. Bottom currents are of concern for sea-bed pipelines as they can cause sediment washouts resulting in unsupported pipelines, which consequently become overstressed. Co-operation of meteorological and oceanographic services in this area is essential.

#### 6.1.1.1    North-west Atlantic

Climatologically, a common characteristic is the presence of moving pack ice during winter and early spring over the Labrador Sea and Grand Banks. Icebergs calved from glaciers in Baffin Bay to the north drift southward through the autumn and winter to menace shipping and drilling in these waters in spring and summer.

Storms frequently traverse the southern parts of the Labrador Sea, Grand Banks and Scotian Shelf. The wind and wave climate on the Grand Banks is probably the most demanding anywhere in Canadian waters. Juxtaposition of warm/cold air and water currents south of Nova Scotia and Newfoundland creates the ingredients necessary for the development of extremely deep and extensive lows with strong winds and high seas.

The proximity of the Gulf Stream as a source of relatively warm, moist air results in frequent persisting cloud and fog when the winds are favourable. Along the continental margin on the east coast, the battle between cold and warm air masses gives rise to conditions which make freezing precipitation a frequent occurrence.

It is a bitter irony that one of the most promising areas for oil exploration, the Hibernia area on the Grand Banks, is also one of the most hazardous as regards climate. 100-year return maximum winds are estimated to be of the order of 110 to 115 knots with the 100-year extreme maximum wave just under 35 metres. Strong winds and currents make icebergs a problem for pipelines and sub-sea well facilities, because these bergs scour the bottom at times and would tear out anything unprotected or even firmly attached.

Climatic information on multi-dimensional weather windows will clearly be a very real constraint on feasible design and construction of offshore facilities in the North-western Atlantic.

### 6.1.1.2    *Pacific, N.E.*

The Pacific Ocean areas off the North American west coast seem at first to be a generally benign environment for offshore activities. Temperatures are relatively mild, tempered by a fairly long over-sea trajectory. Freezing spray is not frequent and there are no pack ice or icebergs to speak of except near Alaska. The Pacific, however, is a very large ocean and although the generating potential for strong winds in synoptic-scale systems may not appear to be as great as for the Atlantic, the weather systems on the Pacific side are frequently of a fully-developed nature. Waves in the Pacific have ample opportunity to grow to their full potential. Swells of long period propagate from great distances to mingle with locally generated seas.

The wind regime immediately offshore of Canada and the United States is complicated by the nearby mountains and their rough topography, thus it is not readily modelled using coarse-resolution pressure-field data, as has been attempted for other offshore areas. Mesoscale modelling may be necessary to produce usable hindcasts of wind over drilling areas. A further problem characteristic of the Canadian West Coast and Alaska is outflow winds or the "squamish". This refers to the streaming outward of cold Arctic air (which has previously invaded the interior) through fiords along the coast at considerable speed. This condition can result in some very severe sea-spray icing near the mouth of these fiords. The same atmospheric precursors produce strong outflow winds at some locations along the coastline of the United States. The dynamics are similar to those responsible for the mistral in the Mediterranean Sea.

An extreme wave of the order of 30 metres was observed during exploratory drilling off Vancouver Island in the mid-'seventies. This was before a moratorium on exploratory drilling came into effect in that part of Canada to resolve environmental concern regarding risks from spills. The environmental concern remains. The narrow width of the continental shelf means that drilling will be carried out close to the shore and supply routes to the mainland could be minimized. Oil has been produced at offshore facilities along the California coast for decades. The coastline of western North America is aesthetically pleasing and highly vulnerable to pollution from spills. Winds and currents are such that, if spills occur, it is certain that large areas will be at hazard.

### 6.2    MID-LATITUDES (NORTH)

Some of the heaviest ship traffic operates in the mid-latitudes of the northern hemisphere, thereby providing some of the world's best coverage of marine observations for the mid-latitudes of the Pacific and south-west Atlantic Oceans. Even in those regions, most of the traffic moves along the major shipping routes, and all the data errors and limitations discussed in Chapter 3 also apply here.

Although the analyst generally has more information for the northern mid-latitudes, there are a multitude of ways in which erroneous data can bias the results. A continuous vigil must be kept to minimize any false conclusions which derive from the limitations of the data set.

### 6.3    TROPICS

In all practical definitions the tropics are a region which encompasses the equatorial zone. The tropics include such diverse climatic regions as the deserts of the Sudan and western Australia, and the monsoon climates of central Africa and southern Asia. The bulk of the tropical region, however, is covered by ocean.

One of the most significant geographical impacts on the climate of the tropics is the diminished effect of the Coriolis force on geophysical dynamics in the equatorial zone. The mid-latitude geostrophic wind law has little validity in regions within 15° latitude of the Equator. Little tropical cyclone activity is found within 10° latitude of the Equator, and rarely is any found within 5°. Pressure gradients in this region are often weak, and streamline analyses on synoptic charts are often required in order to detect potentially significant weather systems. Because of the difference in circulation patterns between the hemispheres, the Equator is often used as a boundary in numerical models, in much the same way as a land mass is used to bound ocean circulations. Generally displaced from the geographical Equator lies a line of convergence at which the north-easterly and south-easterly trades meet; this line is known as the Intertropical Convergence Zone (ITCZ). This convergence zone is sometimes referred to as the meteorological Equator which, because of its relationship to the progression of the Sun, constantly undergoes changes in intensity and position within the equatorial zone.

Tropical cyclones and the monsoons are the most noted weather phenomena in much of the tropics (see Figure 6.1). While the monsoon effects are basically reflected in the data from ships of opportunity, the effects of tropical cyclones are generally not seen in the data because ships try to avoid storm encounters. Also, the relative placement of the continents on the globe (e.g. the proximity of South America to Africa), the size and location of the major pressure features (e.g. the subtropical highs) and temperature patterns (i.e. cooler temperatures in the tropics of the eastern South Pacific and South Atlantic) are strongly correlated with the development of tropical cyclones. It is noteworthy that there is little tropical cyclone development in the eastern South Pacific Basin, and no occurrence in the South Atlantic Ocean has ever been detected. For climate applications the tropical cyclones must be treated separately from other wind systems. Design wind loadings in the tropics are often based on the sole

**Western North Pacific**
Main Season: April–December
with significant occurrences
in all months

**North Indian Ocean**
Main Season: May–July
and September–December
with significant occurrences
in April and August

**Eastern North Pacific**
Main Season: June–October
with significant occurrences
in May and November

**North Atlantic**
Main Season: August–October
with significant occurrences
in June, July and November

**South Indian Ocean**
Main Season: December–March
with significant occurrences in
April, October and November

**Southwest Pacific and Australian Area**
Main Season: December–April
with significant occurrences
in May, June and November

The figures represent the average
number of tropical cyclones per
5–degree square per year. The origi-
nal chart was prepared by the
National Climatic Data Center.

The World of Tropical Cyclones

Figure 6.1 — The world of tropical cyclones

consideration of winds produced by these events, thus simplifying the problem somewhat. Although data are scarce for specific sites or areas, the characteristics of these systems, and hence their winds, are often transferable from one location to another.

An obvious parameter distinguishing the tropical climate from any other is temperature. Tropical seas are warm and so is the air over them (generally 24–29°C). Ventilation, air-conditioning and refrigeration systems must be adapted to the climate of the waters over which they must operate. Some regions are especially extreme. The Red Sea and Persian Gulf achieve air and sea temperatures in the thirties in summer and humidity is high. Humidex (an index of heat stress described in Chapter 2) in the Gulf often exceeds 45 (see Figure 6.2).

This is a level at which most people can no longer function without some form of cooling. For many individuals, illness from heat becomes inevitable under these conditions. Humidex or a similar index should be useful for planning operations requiring manual labour in areas of hot and humid climates.

Topographic effects are important in the tropics. For example, topographic channelling of winds through the de Tehuantepec Isthmus, over the Caribbean Sea, and through the Mona Passage and Formosa Strait produces persistently strong winds. Features like those, and others such as the geographically induced differential heating over south-west Asia, all affect the climate. Differential heating establishes summer monsoons and the East African low-level "Somali Jet."
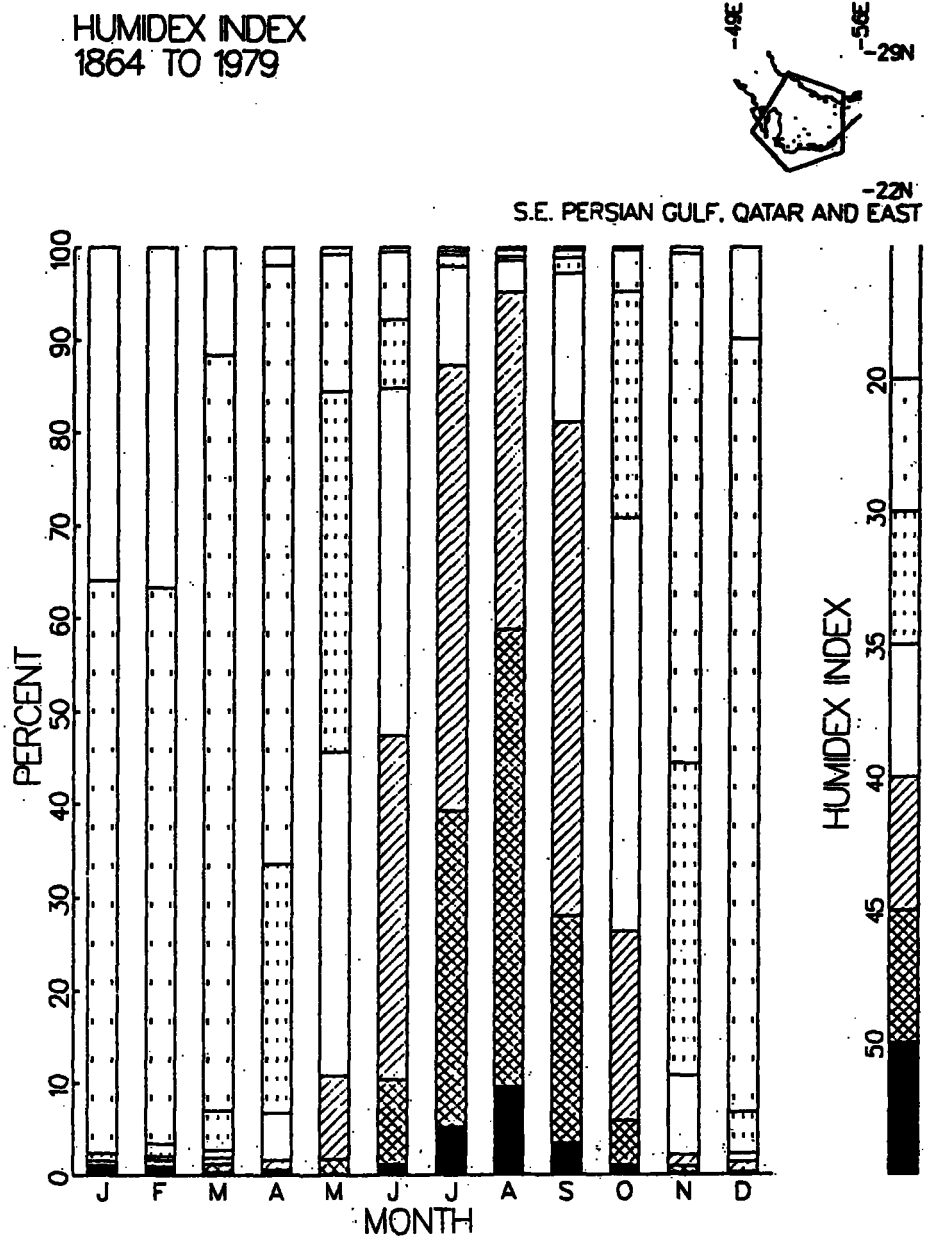


Figure 6.2 — Humidex index

Wind stress associated with the Somali Jet produces oceanic upwelling, further affecting the humidity and temperature in that region.

The most significant recurring climatic phenomenon, although at uneven intervals, is the *El Niño/ Southern Oscillation* (ENSO). A change in the definitions of the *El Niño* and Southern Oscillation has evolved in recent years to the point where today they are generally thought of as being synonymous. The large-scale ocean-atmosphere anomaly (fluctuation) is responsible for both the reduction in strength of the easterly trades and the pressure gradient across the region. *El Niño* years (warm events) have warm water near the Equator and along the Peru coast with high precipitation from the date line to the South American coast. In this region normally upwelling with low water temperatures and dry conditions prevail.

With such special interest in the ENSO and the added collection of observations during those events, care must be taken when calculating long-term means and other climate statistics to ensure that the climatological data are not biased towards the ENSO years.

### 6.3.1    Wind systems of the South Atlantic

Relatively strong south hemispheric westerlies occur between the subtropical anticyclone and the circumpolar Antarctic trough at 65 to 70°S.

### 6.3.2    Coastlines of the tropical and South Atlantic

The Atlantic coastlines of South America and Africa extend over several climatic zones. The interaction between continental and marine influences leads to special effects such as coastal upwelling, land/sea breezes and other local specialities of wind and sea climate which will be described below.

### 6.3.3    Land/sea breeze, coastal wind systems

In tropical and subtropical regions where the land/sea breeze is relatively strongly developed, it cannot be investigated using marine data. Wind observations of well-situated coastal sites are best suited for such local wind evaluations. In moist climates, thunderstorms may be adjoined to the sea breeze; in dry climates, the sea breeze brings a marked decrease of temperature and an increase of moisture. The sea breeze is especially strong in the upwelling areas.

The land breeze during the night is normally not as strong as the sea breeze. If the coastline is heavily indented as in southern Brazil, the speed and direction of the land/sea breeze change considerably from place to place. During the summer, at the Rio de la Plata area and along the northern coast of Argentina, land and sea breezes are well developed. During the winter-time and farther to the south this thermal wind system is confined to fair, sunny days.

Along the north-western coast of Africa, the sea and land breezes are well developed, especially at those times when the trades or monsoons are weak. In coastal regions with high cliffs, additional squally downslope winds occur.

### 6.3.3.1    The mistral and other orographically influenced wind systems

Coastal mountain ranges, especially those possessing large or moderately sized interior drainage basins, are often sites of anomalously strong winds. Funnelling and intensification of winds can occur where there is a restriction to flow at a coastal outlet. The mistral, described below, is an example of such a wind system, but similar wind systems with other local names can be found at times along the western coast of North America and the eastern coast of Asia. Katabatic winds draining cold air from glaciers and valleys are a prominent feature of certain areas along the coasts of Greenland, Baffin Island and Antarctica.

The mistral, in the north-westerly part of the Mediterranean Sea, provides an example of a cold wind strongly influenced by orography. There are two main mountain ranges, the Pyrenees in the west and the Alps in the east, with a gap of about 200 km in between. In the centre of this gap another mountain range, the Cévennes, is situated. Thus the cold air has only two main outlets in the Mediterranean, the Rhone valley in the north and the Garonne-Carcassone valley in the west-north-west. These are the two main wind directions for stormy cold air outbreaks. They are supported by a trough or a low which frequently forms in the lee of the Alps over the Gulf of Genoa. A stormy mistral (> 8 Beaufort) appears when the pressure difference between the eastern edge of the Pyrenees and the Ligurian Sea exceeds 15 hPa.

Figure 6.3 shows the frequencies (in per cent) of stormy mistral situations of each month and the year for the area 42–44°N, 3–5°E (Golfe du Lion). Full columns denote wind forces 10–12 Beaufort, and open ones forces of 8–9 Beaufort. At least in cases of severe storms, the squalls reach hurricane force.

February is the main month for mistral occurrences; then in the western part of the Golfe du Lion a storm frequency of 40 per cent is reached, which is one of the highest in the world for a single month. In August the lowest frequency of mistral occurrences is observed. Nearly all storms in the Golfe du Lion are mistral events. In the annual mean, only 0.6 per cent of storms are not connected with cold air outbreaks.

Strong mistrals may reach the African coast and the Straits of Sicily. While the air is dry and often cloudless in the Golfe du Lion, it gathers moisture by evaporation during its displacement, so that clouds and showers are formed in the central part of the western Mediterranean. Showers may become thundery in the vicinity of Africa.

Along the coasts, there are great differences in wind forces with mistral conditions due to shelter by mountains (in Toulon the yearly storm frequency reaches 0.7 per cent, in Nice only 0.1 per cent) or the formation
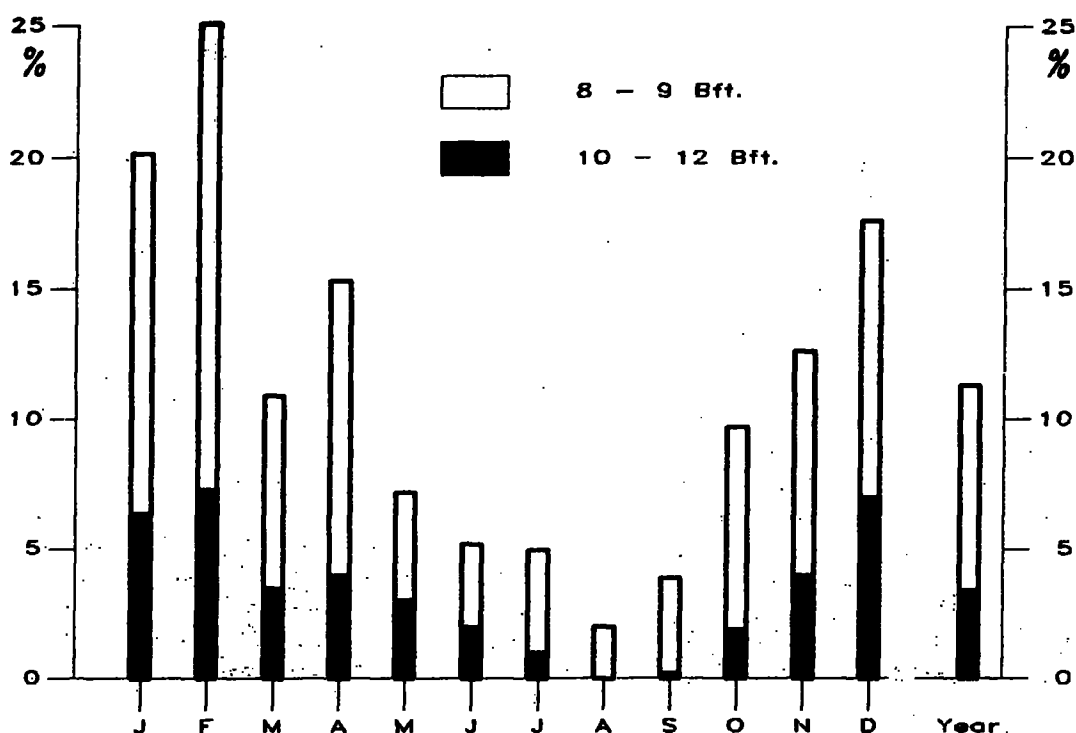
Figure 6.3 — Frequencies of the mistral (> = 8 Beaufort) in the Golfe du Lion (42–44° north, 3–5° east)

of low-level jets in front of valleys and between islands, e.g. in the Strait of Bonifacio between Corsica and Sardinia (9.6 per cent annual storm frequency at Cap Pertusato). Also Cap Béar at the southern border of France has a very high storm frequency, with an annual mean of 11.5 per cent.

Stormy and sheltered coastal strips are well known by shipping and have to be taken into account for planning routes and schedules in mistral situations.

### 6.3.4 Coastal upwelling

Upwelling is a forced, upward-directed motion of sea water occurring where the surface water is transported away by steady surface winds.

Due to their relatively low water temperatures, coastal upwelling areas are important for freight shipping (see section 4.2). In those areas there is the danger of ship sweat, especially when air and cargo in the ship hold are warm and moist.

The surface current is deflected from the wind direction by approximately 45°, in the northern hemisphere to the right and in the southern hemisphere to the left. This means that even coastal parallel winds, such as the trades near north-western and south-western Africa, produce upwelling. As the water temperature at a depth of 150 to 200 metres is about 15°C, this value is also found at the sea surface in upwelling areas.

The meteorological consequence of the cold upwelling water in the subtropics is a high relative humidity with a significant tendency to fog formation, a great frequency of low stratus clouds, sometimes with

drizzle, but otherwise extreme aridity, since the cooling of air masses at the sea surface prevents convection.

More information on upwelling may be gained from marine climatologies (e.g. [1] or [2] for the Atlantic) or from sea pilots (e.g. [3] for the African west coast).

### 6.3.5 South American coast

Near mountains, downsloping gusts may reach the sea and become dangerous to boats. Especially rough conditions with strong winds are found near the southern tip of South America. Very dangerous squalls occur in the mountainous passages of Tierra del Fuego (Fireland) and in the western part of the Magellan Strait during storm situations. Each squall may approach from a different direction and attain hurricane force.

South of Cape Horn wave heights of 20 metres are occasionally exceeded; single "extreme" waves may reach 40 metres.

### 6.3.6 African coast

Along the western coast of Morocco, Atlantic depressions in winter bring clouds and rain with winds (gharbi) from south to west. They are followed by strong winds, and sometimes gales, from north-west, with cool weather and showers.

During spring or autumn, north of Cape Verde hot and dry winds occasionally blow from easterly directions (harmattan, chergui, irifi) carrying dust and sand to the coast and the sea, with a consequent strong reduction of visibility. Sometimes in northern winter the harmattan even reaches the Gulf of Guinea. In the summer, when

the African south-west monsoon is well developed, no harmattan can exist in that region.

High waves with very deep valleys are called "freak waves" because they are dangerous to shipping. They are caused when waves move against a sea current. A main zone of freak waves is situated in the Agulhas Current south-east of Africa which extends into the South Atlantic. They occur during west or south-west storm conditions and may attain a height of 20 metres.

## 6.4    SOUTH HEMISPHERIC WEST-WIND REGION

In the south hemispheric west-wind zone, data are rare on account of the lack of shipping there. Ice coverage observations south of 60°S are scarce in winter. Observations of as many years as possible should be taken between latitudes 40 and 70°S. Months should be combined as necessary and the size of selected areas (for which all data are put together) must become larger than along the main shipping routes. Because of the steep north-south gradients, the areal extent of these selected areas should be greater in longitude than in latitude, e.g. 20° of longitude by 5° of latitude. The difficult task is the selection of the optimum box size for summarization giving a proper balance between noise elimination and climatological detail, in order to define the climate accurately.

## 6.5    SOUTH ATLANTIC AND PACIFIC

The pressure difference between the subtropical anti-cyclone and the sub-polar trough is much greater in the southern than in the northern hemisphere, resulting in stronger winds. Because wind speeds are greatest in the latitudes 40–50°S, this zone is named the "Roaring Forties".

Due to the relatively strong winds, waves are high in the south hemispheric westerlies; in most areas mean significant waves exceed 2.5 m nearly every month.

Because of the paucity of data in these regions, it is often better for the analyst if data are summarized for larger rather than smaller geographical areas; this helps to smooth out some of the variability introduced by having only a few randomly sampled data values.

## 6.6    ANTARCTIC

Most of the year there is little open water poleward of the Antarctic Circle. The southern tip of South America and the Antarctic Peninsula narrow the waterway forming the Drake Passage, which tends to channel and strengthen the wind and wave regimes. This is also an area of ocean current convergence, as warm Pacific and cold Weddell Sea waters meet (Deacon [4] – see Figure 6.4). Relatively few observations are collected, and those that are may be biased towards warmer periods.
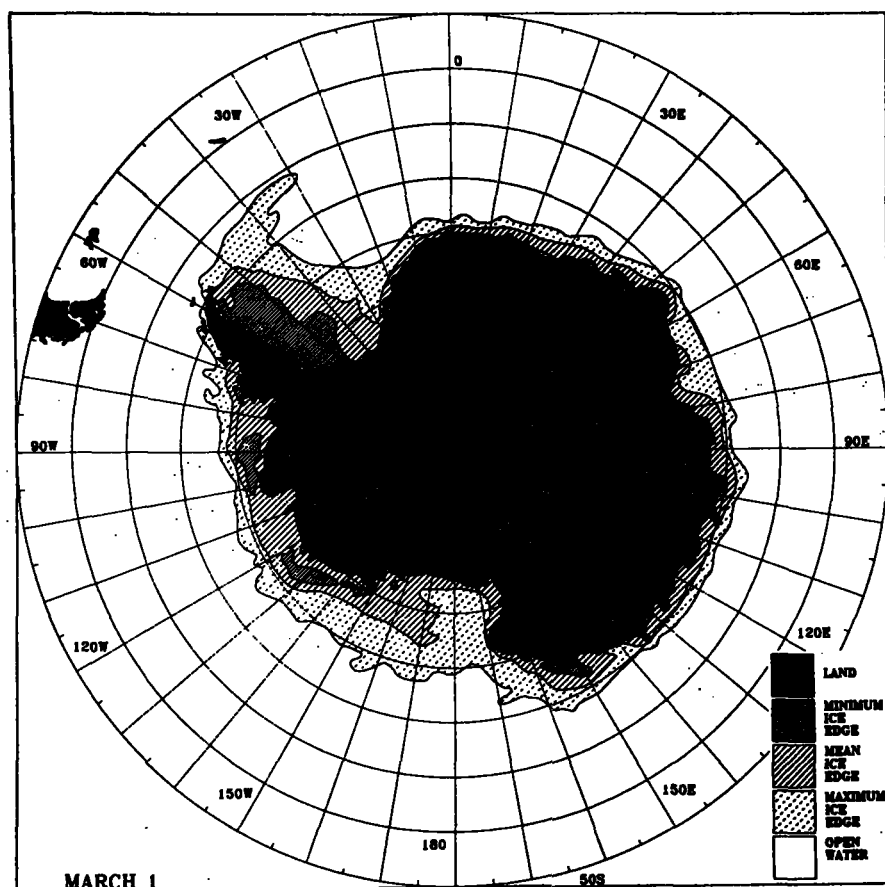


(From Commander, Naval Oceanography Command, 1985)

Figure 6.4 — Maximum – mean – minimum ice edges
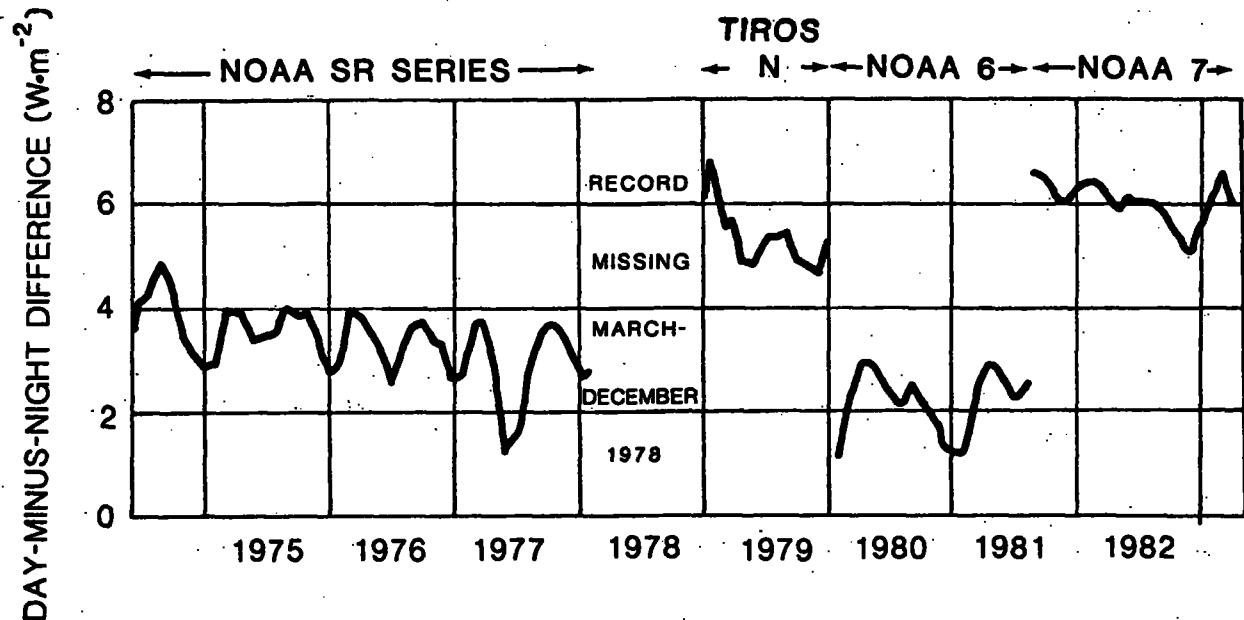
Figure 6.5 — Time series of the day-minus-night difference for global monthly average outgoing long-wave radiation (emittance) (*from Gruber and Krueger, 1984*)

· Important advances in space and buoy technology have contributed to improving our understanding of the polar regions. However, these automated sensing systems have their own unique problems. For example, weather conditions might exceed the buoy design limits, a sensor might stick and report identical values for months on end, or the transmitter might simply stop operating. One major problem with satellites is illustrated by Gruber and Krüeger [5] with their time series of the day-time minus night-time difference of global monthly average outgoing long-wave radiation. A discontinuity in the time series occurs each time a new satellite and sensor are launched (see Figure 6.5). Satellites also have sensor degradation problems, the amount and rate of deterioration being most difficult to establish.

Satellite-sensed data of sea ice and other elements can help the analyst improve the final product. Accurate detection of the ice edge can establish the position of the lower sea-surface temperature limit (approximately −1.8 °C). This contributes to the wave-height analysis because pack ice quickly dampens the amplitude of waves, and neutralizes wave energy as waves progress into the areas of higher ice concentration. Satellite sea-surface temperatures, although not totally in agreement with those from ships or buoys, do establish relatively reliable temperature gradients which can help to enhance the analysis in data-sparse regions.

Since the late 1940s, the Wordie Ice Shelf on the south-western side of the Antarctic Peninsula has seemingly undergone a major retreat. This conclusion was based on two successive LANDSAT images of the shelf acquired in 1974 and 1979 (Doake [6]). He estimated that the ice front retreated some 7 km during this period, which reduced the shelf area by some 250 km². If this or other

perceived changes in the Antarctic environment (such as the recently detected depletion of the ozone layer over the Antarctic) proves to be the result of climatic change and not simply of anomalies in the normal climate cycle, then it is crucial that more timely, accurate data be gathered for the region. In fact, an increase of quality benchmark information will undoubtedly be required before any definitive statements can be made about climatic trends.

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# PRACTICES OF MEMBER COUNTRIES

The practices of Member countries vary considerably in the provision of data and analyses to other Members. A survey of Members has been conducted regarding the availability of data and services to Members of both WMO and other organizations as well as the fee levied. Forty-two Member countries responded to the survey questionnaire, their answers forming the basis of the text below.

## 7.1 RELATIONSHIP WITH OTHER MEMBERS

### 7.1.1 Data

The Marine Climatological Summaries Scheme is based upon the free exchange of data from merchant ships. The Members recruiting the vessels send the data to one or more of eight Responsible Members (RM). Each RM archives and processes data from a designated ocean area. The cost of keying the data and transmitting them to the RM falls to the individual Members. Each RM bears the considerable cost of archiving and quality control of all the data collected for its own area.

Data from these archives are available to any Member on request. However, in recognition of the resources committed to maintaining the regional archives, the RMs are permitted to charge the cost of extracting and transmitting the data. In some cases, these charges are waived in recognition of equivalent services provided, i.e. an exchange will be negotiated.

Ten Members of the forty-two replying to the survey indicated that they charged cost of extraction, while fifteen either made no charge or were involved in exchange agreements. The remaining Members did not provide or receive data. A more detailed list of Members is given in Table 7.1.

TABLE 7.1
Provision of data to other Members – status 1988

| Basis of provision |
| --- |
| *Cost of extraction:*<br>Australia, Canada[1], Finland, Germany (Fed. Rep.), Hong Kong[1], India, Japan, the Netherlands[1], Norway[1], Saudi Arabia, United Kingdom |
| *Free of charge:*<br>Bangladesh, Benin, Brunei Darussalam, France, Greece, Iceland[2], Israel, Italy[2], Kuwait, Mauritius, New Zealand, Turkey, United Arab Emirates, Uruguay, Yugoslavia |
| *None provided:*<br>Chile, Colombia, Denmark, Egypt, Ethiopia, Ireland, Kenya, Korea, Malaysia, Morocco, Pakistan, Sao Tome, Singapore, Sudan, Thailand, Tunisia |

[1] Will negotiate exchange where possible.
[2] Available as part of exchange only.

### 7.1.2 Climatological analyses and services including climate summaries

Many of the Members who provide data on demand are also able to produce climatological summaries or analyses. The complexity of the analyses varies considerably, but eighteen out of forty-two Members declared some expertise, and several others indicated that they were in the process of developing such capability. Nine of the eighteen Members providing services indicated that other Member countries would be charged a fee. In one case, the charge depended on the use for which the data were intended, otherwise it was determined by the direct cost of provision of the service. Six of the nine Members indicated that they were willing to reduce or entirely remove the fee in consideration of reciprocal services or exchange agreements.

A more detailed list of Members and their practices is given in Table 7.2.

TABLE 7.2
Provision of analyses, services and summaries
to Members – status 1988

| Basis of provision |
| --- |
| *Cost of provision:*<br>Australia, Canada, Hong Kong[1], Iceland[1], India[1], Japan[1], New Zealand[2], Norway[1], United Kingdom[1] |
| *Free of charge:*<br>France, Germany (Fed. Rep.)[3], Italy, Kuwait, Malaysia, Mauritius, the Netherlands[3], Saudi Arabia, Yugoslavia |
| *None provided:*<br>Bangladesh, Benin, Brunei Darussalam, Chile, Colombia, Denmark, Egypt, Ethiopia, Finland, Greece, Ireland, Israel, Kenya, Korea, Morocco, Pakistan, Sao Tome, Singapore, Sudan, Thailand, Tunisia, Turkey, United Arab Emirates, Uruguay |

[1] Variable scale of charges depending upon use of data.
[2] Charge may be offset by value of services provided in exchange.
[3] Climatological summaries only.

## 7.2 RELATIONSHIP WITH COMMERCIAL ORGANIZATIONS

As the weather-awareness of industries and other commercial organizations has increased, Meteorological Services have experienced a growth in the number of requests for information. Twenty-seven out of forty-two Member countries confirmed that specialized advice was provided to clients on demand. The sophistication of services varied considerably from standard summaries of data to consultancy reports specifically tailored to the customer's requirements.

Only four Member countries provided free advice, whereas sixteen charged a fee related to the cost of providing the service. Seven Members based their fees upon commercial considerations; however, the methods of setting the fee varied depending upon local policy as discussed in section 7.4 below. A more detailed list of Member countries and the practices governing supply of information to commercial organizations is given in Table 7.3.

### TABLE 7.3
### Provision of services to commercial organizations – status 1988

| Basis of provision |
| --- |
| **Full commercial fee:**<br>Brunei Darussalam; France[1], Germany (Fed. Rep.)[1], India[2], Ireland, the Netherlands[1], United Kingdom[1] |
| **Cost of provision:**<br>Australia, Canada[3], Finland, Hong Kong, Iceland, Israel, Kenya[4], Malaysia[4], Mauritius, New Zealand, Norway, Sudan, Tunisia, United Arab Emirates[5], Yugoslavia[5] |
| **Free of charge:**<br>Bangladesh, Korea, Saudi Arabia, Singapore |

[1] Scale of charges includes commercial and non-commercial use.
[2] Subject to minimum fee for commercial organization.
[3] Plus an overhead depending on organization concerned.
[4] Nominal fee charged.
[5] Charge depends on identity of inquirer, may be zero.

## 7.3 RELATIONSHIP BETWEEN PUBLIC SECTOR AND COMMERCIAL METEOROLOGICAL SERVICES

As the demand for weather information has increased, Commercial meteorological services have developed in parallel with national Services. Twelve Member countries identified such commercial services existing in their national area. It is interesting to note that in all but one case the State Service was providing specialized services, in three cases totally free of charge. The exception was Japan, where a special legal relationship exists between public and commercial sectors, with the State Service supervising the provision of meteorological advice.

The relationship between the two types of organization varied from total isolation to commercial competition. In some cases there was active co-operation. Further brief details are given in Table 7.4. It is possible that commercial meteorological services fulfil an important role in many countries by providing extra capacity for consultancy work where demand exceeds the limited resources available from State Services.

### TABLE 7.4
### Relationship between public sector and commercial meteorological services – status 1988

| Commercial met. service exists in: | Basis of interaction |
| --- | --- |
| Australia | As for other commercial organizations |
| Canada | Fee charged but co-operative rather than competitive |
| France | Special terms |
| Japan | Supervised by JMA, which provides data and products |
| Korea | No interaction |
| Malaysia | Limited interaction |
| New Zealand | Competitive basis without prejudice |
| Saudi Arabia | Data exchanged for services |
| Singapore | Provided with climate information |
| United Arab Emirates | Data exchanged; no direct support |
| United Kingdom | Competitive basis without prejudice |
| Netherlands | Competitive and collaborative |
| Norway | Competitive and collaborative |

## 7.4 RELEVANT INTERNAL POLICIES

In most cases, the decision to levy a fee, or to provide data or consultancy free of charge, is made at governmental level, and not within the Meteorological Service. Many State Services are under increasing pressure to contribute to their running costs by carrying out commercial work. However, some national governments have enacted legislation specifically banning the State Meteorological Service from providing commercial meteorological services and limiting any fee to recovery of the cost of extracting data from their archival medium and sending them to the inquirer.

In complete contrast, however, there are State Meteorological Services which refuse all access to their data or attach very high prices so that commercial organizations cannot purchase and remain viable. This action is prompted by concern that meteorological standards may fall unless provision of advice is limited to the centre of national expertise. Further, there is concern that commercial meteorological services should contribute to the meteorological infrastructure supporting collection, processing and archiving of data and the provision of forecasts.

The majority of national Meteorological Services reach a compromise in which they charge

commercial fees for work done on behalf of organiz-
ations deriving a special advantage thereby, but protect
clients such as universities which are engaged upon pure
research, and individual members of the general public.

The relationship with commercial meteoro-
logical services is also usually dictated by government
policy. In some cases the national Service acts as a
supplier of raw materials from which the commercial
service fashions a product with added value, which it can
sell to a range of customers. Where demand for services in
a particular area outstrips the national Service's ability to
cope individually with the customers, an agreement may
be reached to provide a range of automated or higher-
quality products to the commercial meteorological service
in return for a licensing fee. In some cases staff from the
public sector may by hired at commercial rates by the
commercial sector.

Where commercial competition exists, the State
Service usually provides basic data, or the raw material, at
a fee which reflects its own internal costs in providing the
infrastructure needed to secure the data or product initially.
Essentially this means that the fee is not being used to
prevent competition, but equally the commercial service is
not being subsidized and hence assisted to undercut the fees
charged by the national Service.

Mechanisms and formulae used to set fees are
as varied as the national policies governing the Meteoro-
logical Services. At the most fundamental level a nominal
amount may be charged which has no relation to the cost
of providing the product or indeed to its value to the
customer.

The assessment of the direct cost of providing
a particular product is normally quite straightforward.
Usually it is possible to quantify the cost associated with
staff time and computer usage as well as any other
consumables used in providing the service. Staff costs are
rarely equated with salary, but include the extra expenses
associated with employing staff and providing the
immediate working environment.

However, many national agencies are required
to charge a fee which not only includes direct or marginal
costs, but also makes a contribution towards the total
running costs of the organization. The magnitude of the
contribution required is a matter of national policy, and
varies quite widely. It is also possible to set fees by
including an element reflecting the value to the customer
i.e. in proportion to the possible advantage gained by
taking the advice, or the possible financial risk run by
neglecting it. There is no evidence that this practice has
been used by Meteorological Services although the mag-
nitude of fees levied for professional consultancies in other
disciplines has been used.

It is important to realize that the most that
can be achieved by national Meteorological Services is
to secure a contribution towards their total operating
costs. The capital investment and day-to-day costs of the
national meteorological infrastructure are such that a
"profit" in the commercial sense cannot, by definition,
ever occur.

Unfortunately, the wide variations in policy do
cause difficulties in the area of marine climatology. The
data exchange system is very efficient, and it is relatively
easy, given the necessary computing resources, for an
individual Member to obtain marine data for large parts
of the oceans. Large commercial organizations, and
particularly commercial meteorological services, can seek
out those Members with policies which do not demand
a contribution to the meteorological infrastructure and
purchase data and analyses at an unrealistically low rate.
This practice deprives other Members, whose policies are
more aligned with the commercial, of the revenue they
require to maintain their standards. Concern regarding this
situation was reflected in paragraph 5.4.7 of the general
summary of the ninth session of the Commission for
Climatology in the following statement:

> Some Members may request that special climate
> data sets that they provide should not be further
> distributed, especially for commercial purposes.
> Members receiving these data sets should respect
> the providing Member's request in these cases.

## 7.5    PUBLICATIONS SERVICES FOR MARINE CLIMATOLOGICAL APPLICATIONS

Twenty-three of the forty-two Members surveyed pro-
vided climatological summaries or analyses. The media
used varied, paper being the most common, followed by
magnetic tape. However, many Members are able to
provide microfiche or floppy disks. Details of products
and media are given in Table 7.5 overleaf.

In addition to specialized summaries and
analyses, some Members produce marine "house maga-
zines" containing some climatological information.
Usually, these publications have a dual role of inform-
ing the marine community of developments and also
encouraging the observers of the Voluntary Observing
Fleet, who provide much of the data used for climato-
logical purposes.

### Reference

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on Marine Meteorological Services*. WMO-TD No. 348,
WMO, Geneva.

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*          *

## TABLE 7.5
## Publications and analyses available from Members – status 1988

| Members | Products | Media |
|---------|----------|-------|
| Australia | Single station analyses, coastal stations, monthly means at sea | Magnetic tape, microfiche, paper |
| Bangladesh | Climate analyses | Paper |
| Brunei Darussalam | Summary tabulations | Floppy disks, paper |
| Canada | Climate summaries and full-range analyses | Magnetic tape, floppy disk, microfiche, paper |
| Denmark | Light-vessel statistics | Books |
| France | Climate analyses | Magnetic tape, floppy disk, paper |
| Germany, Fed. Rep. of | Summaries and routeing climatology | Paper, books |
| Hong Kong | Climate summaries | Magnetic tape, floppy disk, paper |
| Iceland | Climate summaries | Paper |
| India | Climate summaries | Magnetic tape, paper |
| Ireland | Climate summaries | Paper |
| Italy | Coastal stations | Magnetic tape, paper |
| Kenya | Coastal rainfall distribution, wind speed and direction | Paper |
| Malaysia | Monthly summaries | Paper |
| Mauritius | SST, daily and monthly sea levels | Paper |
| Netherlands | Summaries, bulletins | Magnetic tape, microfiche, paper |
| Norway | Climate analyses, hindcasts | Magnetic tape, paper |
| New Zealand | SST, wave climate, tropical cyclones | Paper |
| Turkey | Daily and monthly SST | Paper |
| United Arab Emirates | Wind and wave data | Floppy disk, paper |
| United Kingdom | Marine climate summaries and analyses (global) | Magnetic tape, floppy disk, microfiche, paper |
| Yugoslavia | Scientific marine climate publications | Magnetic tape, paper |

# APPENDIX I

## MINIMUM QUALITY-CONTROL STANDARDS

### *(Appendix to paragraph 3.1.4)*

NOTE: See specification for quality-control indicators $Q_1$ to $Q_{18}$ at the end of this appendix. $\Delta$ = space (ASCCI 32).

| Element | Error | Action |
|---|---|---|
| 1 | $i_T \neq 0\text{--}5$ | Correct manually |
| 2 | $AA \neq$ valid year | Correct manually, otherwise reject |
| 3 | $MM \neq 01\text{--}12$ | Correct manually, otherwise reject |
| 4 | $YY \neq$ valid day of month | Correct manually, otherwise reject |
| 5 | $GG \neq 00\text{--}23$ | Correct manually, otherwise reject |
| 6 | $i_w \neq 0, 1, 3, 4$ | Correct manually, otherwise $Q_5 = 4$ |
| 7 | $Q \neq 0\text{--}3, 5\text{--}8$ | Correct manually, otherwise reject |
| 8 | $L_aL_aL_a \neq 000\text{--}900$ | Correct manually, otherwise reject |
| 9 | $L_oL_oL_o \neq 000\text{--}800, 900\text{--}999$ when $Q = 1, 2, 6, 7$ $\neq 000\text{--}900$ when $Q = 0, 3, 5, 8$ | Correct manually, otherwise reject |

### *Time sequence checks*

| | | |
|---|---|---|
| | Change in latitude $> 0.7°$/hour | Correct manually, otherwise reject |
| | Change in longitude $> 0.7°$/hour when latitude 00–39.9 | Correct manually, otherwise reject |
| | Change in longitude $> 1.0°$/hour when latitude 40–49.9 | Correct manually, otherwise reject |
| | Change in longitude $> 1.4°$/hour when latitude 50–59.9 | Correct manually, otherwise reject |
| | Change in longitude $> 2.0°$/hour when latitude 60–69.9 | Correct manually, otherwise reject |
| | Change in longitude $> 2.7°$/hour when latitude 70–79.9 | Correct manually, otherwise reject |
| 10 | | No checking |
| 11 | $h \neq 0\text{--}9, \Delta$ $h = \Delta$ | Correct manually and $Q_1 = 5$, otherwise $Q_1 = 4$ $Q_1 = 9$ |
| 12 | $VV \neq 90\text{--}99, \Delta\Delta$ $VV = \Delta\Delta$ | Correct manually and $Q_2 = 5$, otherwise $Q_2 = 4$ $Q_2 = 9$ |
| 13 | $N \neq 0\text{--}9, \Delta, /$ $N < N_h$ | Correct manually and $Q_3 = 5$, otherwise $Q_3 = 4$ Correct manually and $Q_3 = 5$, otherwise $Q_3 = 2$ |
| 14 | $dd \neq 00\text{--}36, 99, \Delta\Delta$ $dd = \Delta\Delta$ | Correct manually and $Q_4 = 5$, otherwise $Q_4 = 4$ $Q_4 = 9$ |
| | <u>dd versus ff</u> $dd = 00, ff \neq 00$ | Correct manually and $Q_4$ or $Q_5 = 5$, otherwise $Q_4 = Q_5 = 2$ |
| | $dd \neq 00, ff = 00$ | Correct manually and $Q_4$ or $Q_5 = 5$, otherwise $Q_4 = Q_5 = 2$ |

| Element | Error | Action |
|---|---|---|
| 15 | $ff > 80$ knots | Correct manually and $Q_5 = 5$, otherwise $Q_5 = 3$ |
| 16 | $s_n \neq 0, 1$ | Correct manually, otherwise $Q_6 = 4$ |
| 17 | $TTT = \Delta$ <br> $-25 > TTT > 40$ | $Q_6 = 9$ <br> Control manually and $Q_6 = 1, 3$ or $4$ and if corrected $Q_6 = 5$ |

### TTT versus humidity parameters

| | | |
|---|---|---|
| | $TTT < WB$ (wet bulb) | Correct manually and $Q_6 = Q_7 = 5$, otherwise $Q_6 = Q_7 = 2$ |
| | $TTT < DP$ (dew point) | Correct manually and $Q_6 = Q_7 = 5$, otherwise $Q_6 = Q_7 = 2$ |
| 18 | $s_n \neq 0, 1, 5, 6, 7, 9$ | Correct manually, otherwise $Q_7 = 4$ |
| 19 | $WB <= DP$ <br> $WB = DP = \Delta\Delta$ | Correct manually and $Q_7 = 5$, otherwise $Q_7 = 2$ <br> $Q_7 = 9$ |
| 20 | $930 > PPPP > 1050$ hPa <br><br> $870 > PPPP > 1070$ hPa <br> $PPPP = \Delta\Delta\Delta\Delta$ | Control manually and $Q_8 = 1, 3$ and if corrected $Q_8 = 5$ <br> Correct manually and $Q_8 = 5$, otherwise $Q_8 = 4$ <br> $Q_8 = 9$ |
| 21 | $ww = 22$–$24, 26, 36$–$39, 48, 49, 56, 57,$ <br> $66$–$79, 83$–$88, 93, 94$ and latitude $< 20°$ | Correct manually and $Q_9 = 5$, otherwise $Q_9 = 4$ |
| 22, 23 | $W_1 = W_2 = 7$ and latitude $< 20°$ <br> $W1 < W2$ | Correct manually and $Q_9 = 5$, otherwise $Q_9 = 4$ <br> Correct manually and $Q_9 = 5$, otherwise $Q_9 = 2$ |
| 24, 25, | | |
| 26, 27 | $N = 0, \Delta, 9$ and $N_h C_L C_M C_H \neq \Delta$ | Correct manually and $Q_3 = 5$, otherwise $Q_3 = 4$ |
| 28 | $s_n \neq 0, 1$ | Correct manually, otherwise $Q_{10} = 4$ |
| 29 | $T_w T_w T_w = \Delta\Delta\Delta$ <br> $-2.0\ T_w T_w T_w > 37.0$ | $Q_{10} = 9$ <br> Control manually and $Q_{10} = 1, 3$ or $4$ and if corrected $Q_{10} = 5$ |
| 30 | Indicator $\neq 0$–$7, \Delta$ | Correct manually, make it $\Delta$ if not correctable |
| 31 | Indicator $\neq 0$–$9, \Delta$ | Correct manually, make it $\Delta$ if not correctable |
| 32 | $20 < P_w P_w < 30$ <br> $P_w P_w > 30 \neq 99$ <br> $P_w P_w \neq \Delta\Delta, /$ | $Q_{11} = 3$ <br> $Q_{11} = 4$ <br> $Q_{11} = 9$ |
| 33 | $35 < H_w H_w < 50$ <br> $H_w H_w => 50$ <br> $H_w H_w = \Delta\Delta, //$ | $Q_{12} = 3$ <br> $Q_{12} = 4$ <br> $Q_{12} = 9$ |
| 34 | $d_{w1} d_{w1} \neq 00$–$36, 99, \Delta\Delta$ <br> $swell_1 = swell_2 = \Delta$ | Correct manually and $Q_{13} = 5$, otherwise $Q_{13} = 4$ <br> $Q_{13} = 9$ |
| 35 | $25 < P_{w1} P_{w1} < 30$ <br> $P_{w1} P_{w1} > 30$ and $\neq 99$ | $Q_{13} = 3$ <br> $Q_{13} = 4$ |
| 36 | $35 < H_{w1} H_{w1} < 50$ <br> $H_{w1} H_{w1} => 50$ | $Q_{13} = 3$ <br> $Q_{13} = 4$ |
| 37 | $I_s \neq 1$–$5, \Delta$ | Correct manually, otherwise $\Delta$ |
| 38 | $E_s E_s \neq 00$–$99, \Delta\Delta$ | Correct manually, otherwise $\Delta\Delta$ |
| 39 | $R_s \neq 0$–$4, \Delta$ | Correct manually, otherwise $\Delta$ |
| 40 | Source $\neq 0$–$6$ | Correct manually |
| 41 | Platform $\neq 0$–$9$ | Correct manually |

| Element | Error | Action |
|---|---|---|
| 42 | No call sign | Insert manually |
| 43 | No country code | Insert manually |
| 44 | $Q \neq 0{-}6, 9$ | Correct manually |
| 45, 46 | | No quality control |
| 47 | $i_R \neq 1{-}4$<br>$i_R = 4$ and $RRR = \Delta\Delta\Delta,///$<br>$i_R = 3$ and $RRR \neq \Delta\Delta\Delta$ | Correct manually and $Q_{14} = 5$, otherwise $Q_{14} = 4$<br>$Q_{14} = 9$<br>Correct manually and $Q_{14} = 5$, otherwise $Q_{14} = 2$ |
| 48 | $RRR \neq 001{-}999$ and $i_R = 1,2$ | Correct manually and $Q_{14} = 5$, otherwise $Q_{14} = 2$ |
| 49 | $t_R \neq 0{-}9$ | Correct manually and $Q_{14} = 5$, otherwise $Q_{14} = 4$ |
| 50 | $s_n \neq 0, 1, 5, 6, 7, 9$ | Correct manually, otherwise $Q_7 = 4$ |
| 51 | $W_B = > TTT$ or $DP > TTT$ | See element 17 |
| 52 | $a \neq 0{-}8, \Delta$<br>$a = 4$ and $ppp \neq 000$<br><br>$a = \Delta$ | Correct manually and $Q_{15} = 5$, otherwise $Q_{15} = 4$<br>Correct manually and $Q_{15} = 5$, otherwise<br>$Q_{15} = Q_{16} = 2$<br>$Q_{15} = 9$ |
| 53 | $ppp > 150$<br><br>$ppp > 250$<br>$ppp = \Delta\Delta\Delta$ | Correct manually and $Q_{16} = 1,3$ and if corrected<br>$Q_{16} = 5$<br>Correct manually and $Q_{16} = 5$, otherwise $Q_{16} = 4$<br>$Q_{16} = 9$ |
| 54 | $D_s \neq 0{-}9, \Delta$<br>$D_s = \Delta, /$ | Correct manually and $Q_{17} = 5$, otherwise $Q_{17} = 4$<br>$Q_{17} = 9$ |
| 55 | $V_s \neq 0{-}9, \Delta$<br>$V_s = \Delta, /$ | Correct manually and $Q_{18} = 5$, otherwise $Q_{18} = 4$<br>$Q_{18} = 9$ |
| 56 | $d_{w2}d_{w2} \neq 00{-}36, 99$ | Correct manually and $Q_{13} = 5$, otherwise $Q_{13} = 4$ |
| 57 | $25 < P_{w2}P_{w2} < 30$<br>$P_{w2}P_{w2} > 30$ and $\neq 99$ | $Q_{13} = 3$<br>$Q_{13} = 4$ |
| 58 | $35 < H_{w2}H_{w2} < 50$<br>$H_{w2}H_{w2} = > 50$ | $Q_{13} = 3$<br>$Q_{13} = 4$ |
| 59 | $c_i \neq 0{-}9, \Delta$ | Correct manually, otherwise $\Delta$ |
| 60 | $S_i \neq 0{-}9, \Delta$ | Correct manually, otherwise $\Delta$ |
| 61 | $b_i \neq 0{-}9, \Delta$ | Correct manually, otherwise $\Delta$ |
| 62 | $D_i \neq 0{-}9, \Delta$ | Correct manually, otherwise $\Delta$ |
| 63 | $z_i \neq 0{-}9, \Delta$ | Correct manually, otherwise $\Delta$ |

### Specifications for quality-control indicators $Q_1$ to $Q_{18}$

| | |
|---|---|
| 0 | No quality control (QC) has been performed on this element |
| 1 | QC has been performed; element appears to be correct |
| 2 | QC has been performed; element appears to be inconsistent with other elements |
| 3 | QC has been performed; element appears to be doubtful |
| 4 | QC has been performed; element appears to be erroneous |
| 5 | The value has been changed as a result of QC |
| 6-8 | Reserve |
| 9 | The value of the element is missing |

## MATHEMATICAL APPENDIX: ADDITIONAL STATISTICAL PROCEDURES

### II.1 EXTREME-VALUE ANALYSIS — RECOMMENDED METHODOLOGY: GUMBEL POT EXAMPLE

#### II.1.1 Data preparation

A parent POT series corresponding to all hourly wind speeds over a threshold of 50 km h$^{-1}$ has been provided by a data-collection agency. The length of record is ten years (1975–1984). The series was screened to yield an "independent" parent series with a minimum inter-event time of 24 hours. The total number of remaining events is 331. The mode of the parent population is 25 km h$^{-1}$.

A second threshold of 68 km h$^{-1}$ was selected yielding a sample size ($M$) of 102. These data are summarized in Table A.II.1 overleaf. Note that a larger threshold (and correspondingly smaller $M$) could have been selected. In this case, a threshold value was selected arbitrarily such that it produced on average approximately ten storms per year.

#### II.1.2 Pre-analysis examination

The time series of the peak over threshold events is shown in Figure 5.14 (Chapter 5) and it does not indicate any jump or trend so the tests outlined in Table 5.12 are not required. There also does not appear to be any dependence in the data with the exception of a tendency to cluster in the late autumn and winter months of each year. Because these are wind data and the winds are strongest in the autumn and winter months, this clustering does not indicate any statistical correlation.

#### II.1.3 Estimation of extremes

##### II.1.3.1 Calculation of sample moments

The sample moments of the data in Table A.II.1 are:

$$\bar{x} = 78 \text{ km h}^{-1}$$
$$s_x = 10.1 \text{ km h}^{-1}$$
$$g_x = 2.1$$

##### II.1.3.2 Definition of the POT parameters

The number years of data, $N$, = 10.
The number of selected events, $M$, for a threshold of 68 km h$^{-1}$ = 102.
Therefore the average number of events per year, $\lambda = 102/10 = 10.2$.
The scale parameter $\beta = 78 - 68 = 10$.

For these parameters, the ratio of the mean to the variance for the number of events/year is 1.13. This supports the use of the Poisson distribution. The sample skewness of 2.1 is close to 2, which supports the use of the exponential distribution. Therefore, the POT model is assumed to be valid and quantiles can be estimated.

For the purpose of illustrating the effect of the threshold on the parameters of the POT model, the threshold is increased incrementally with the results indicated in Table A.II.2.

**TABLE A.II.2**
**Evaluation of POT model**

| $x_0$ (km h$^{-1}$) | $x$ (km h$^{-1}$) | $g_x$ | $\lambda$ | $\beta$ | $\lambda$ var $\lambda$ |
|---|---|---|---|---|---|
| 68 | 78 | 2.1 | 10.2 | 10 | 1.1 |
| 72 | 82.5 | 2.3 | 6.6 | 10.5 | 1.3 |
| 80 | 89.1 | 2.7 | 3.4 | 9.1 | 0.8 |
| 85 | 93.7 | 2.4 | 2.0 | 8.7 | 1.3 |

The results indicate that the POT model is valid for all values of the threshold and the arbitrary choice of any threshold would have produced acceptable results within the limitations of statistical uncertainty.

#### II.1.3.3 Quantile estimates

Based on section 5.4.8.3.3, the quantiles for the POT distribution are estimated using the following formula:

$$x_T = x_0 + \beta \ln\lambda + \beta_{yT}$$

For example:

$$x_{100} = 68 + 10 \ln (10.2) + 10(4.60) = 137 \text{ km h}^{-1}$$

A range of quantile estimates for various return periods is provided in Table A.II.3 for the threshold of 68 km h$^{-1}$.

**TABLE A.II.3**
**Pot quantile estimates and standard errors**

| Return period $T$ (years) | Wind speed $x_T$ (km h$^{-1}$) | Standard error $se$ ($x_T$) (km h$^{-1}$) |
|---|---|---|
| 1.005 | 75 | 1.2 |
| 2 | 95 | 2.8 |
| 5 | 106 | 3.9 |
| 10 | 114 | 4.6 |
| 20 | 121 | 5.3 |
| 50 | 130 | 6.2 |
| 100 | 137 | 6.9 |

## TABLE A.II.1
### Observed data over threshold in chronological and ranked form

| Chronological | | Ordered | | | |
| --- | --- | --- | --- | --- | --- |
| Year | Wind speed (km h⁻¹) | Wind speed (km h⁻¹) | Rank | Probability | Return period (years) |
| 75 | 71.7 | 130.50 | 1 | .01 | 17.88 |
| 75 | 69.30 | 109.80 | 2 | .02 | 6.42 |
| 75 | 90.40 | 101.30 | 3 | .03 | 3.91 |
| 75 | 74.10 | 99.70 | 4 | .03 | 2.81 |
| 75 | 71.70 | 98.10 | 5 | .04 | 2.20 |
| 75 | 72.90 | 95.00 | 6 | .05 | 1.80 |
| 75 | 75.40 | 93.40 | 7 | .06 | 1.53 |
| 76 | 70.50 | 91.90 | 8 | .07 | 1.32 |
| 76 | 77.90 | 91.90 | 9 | .08 | 1.17 |
| 76 | 99.70 | 90.40 | 10 | .09 | 1.05 |
| 76 | 74.10 | 89.00 | 11 | .10 | .95 |
| 76 | 70.50 | 89.00 | 12 | .11 | .87 |
| 76 | 68.10 | 89.00 | 13 | .12 | .80 |
| 76 | 70.50 | 87.50 | 14 | .13 | .74 |
| 76 | 130.50 | 86.10 | 15 | .14 | .69 |
| 76 | 89.00 | 86.10 | 16 | .15 | .64 |
| 76 | 68.10 | 86.10 | 17 | .16 | .60 |
| 76 | 76.70 | 86.10 | 18 | .17 | .57 |
| 76 | 76.70 | 86.10 | 19 | .18 | .54 |
| 76 | 70.50 | 86.10 | 20 | .19 | .51 |
| 76 | 70.50 | 84.70 | 21 | .20 | .49 |
| 76 | 74.10 | 84.70 | 22 | .21 | .46 |
| 76 | 74.10 | 83.30 | 23 | .22 | .44 |
| 77 | 80.60 | 83.30 | 24 | .23 | .42 |
| 77 | 69.30 | 83.30 | 25 | .24 | .41 |
| 77 | 68.10 | 83.30 | 26 | .25 | .39 |
| 77 | 74.10 | 83.30 | 27 | .26 | .38 |
| 77 | 86.10 | 81.90 | 28 | .27 | .36 |
| 77 | 68.10 | 81.90 | 29 | .28 | .35 |
| 77 | 83.30 | 81.90 | 30 | .29 | .34 |
| 77 | 75.40 | 81.90 | 31 | .30 | .33 |
| 77 | 86.10 | 81.90 | 32 | .31 | .32 |
| 77 | 77.90 | 80.60 | 33 | .32 | .31 |
| 77 | 70.50 | 80.60 | 34 | .33 | .30 |
| 77 | 79.30 | 79.30 | 35 | .34 | .29 |
| 77 | 74.10 | 77.90 | 36 | .35 | .28 |
| 78 | 70.50 | 77.90 | 37 | .36 | .27 |
| 78 | 71.70 | 77.90 | 38 | .37 | .27 |
| 78 | 77.90 | 77.90 | 39 | .38 | .26 |
| 78 | 77.90 | 77.90 | 40 | .39 | .25 |
| 78 | 68.10 | 76.70 | 41 | .40 | .25 |
| 78 | 76.70 | 76.70 | 42 | .41 | .24 |
| 78 | 74.10 | 76.70 | 43 | .42 | .24 |
| 78 | 69.30 | 76.70 | 44 | .43 | .23 |
| 78 | 69.30 | 76.70 | 45 | .44 | .22 |
| 79 | 81.90 | 76.70 | 46 | .45 | .22 |
| 79 | 76.70 | 75.40 | 47 | .46 | .22 |
| 79 | 68.10 | 75.40 | 48 | .47 | .21 |
| 79 | 68.10 | 75.40 | 49 | .48 | .21 |
| 79 | 74.10 | 75.40 | 50 | .49 | .20 |
| 79 | 91.90 | 74.10 | 51 | .50 | .20 |

Table A.II.1 *(contd.)*

| Chronological | | Ordered | | | |
|---|---|---|---|---|---|
| Year | Wind speed (km h⁻¹) | Wind speed (km h⁻¹) | Rank | Probability | Return period (years) |
| 80 | 81.90 | 74.10 | 52 | .50 | .19 |
| 80 | 75.40 | 74.10 | 53 | .51 | .19 |
| 80 | 83.30 | 74.10 | 54 | .52 | .19 |
| 80 | 69.30 | 74.10 | 55 | .53 | .18 |
| 80 | 83.30 | 74.10 | 56 | .54 | .18 |
| 80 | 69.30 | 74.10 | 57 | .55 | .18 |
| 80 | 71.70 | 74.10 | 58 | .56 | .17 |
| 80 | 86.10 | 74.10 | 59 | .57 | .17 |
| 80 | 80.60 | 74.10 | 60 | .58 | .17 |
| 80 | 69.30 | 74.10 | 61 | .59 | .17 |
| 80 | 69.30 | 74.10 | 62 | .60 | .16 |
| 81 | 87.50 | 74.10 | 63 | .61 | .16 |
| 81 | 70.50 | 72.90 | 64 | .62 | .16 |
| 81 | 89.00 | 72.90 | 65 | .63 | .16 |
| 81 | 70.50 | 72.90 | 66 | .64 | .15 |
| 81 | 74.10 | 71.70 | 67 | .65 | .15 |
| 81 | 76.70 | 71.70 | 68 | .66 | .15 |
| 81 | 71.70 | 71.70 | 69 | .67 | .15 |
| 81 | 83.30 | 71.70 | 70 | .68 | .14 |
| 81 | 71.70 | 71.70 | 71 | .69 | .14 |
| 81 | 95.00 | 71.70 | 71 | .69 | .14 |
| 81 | 68.10 | 71.70 | 72 | .70 | .14 |
| 81 | 71.70 | 71.70 | 73 | .71 | .14 |
| 81 | 74.10 | 71.70 | 74 | .72 | .14 |
| 82 | 74.10 | 70.50 | 75 | .73 | .13 |
| 82 | 93.40 | 70.50 | 76 | .74 | .13 |
| 82 | 101.30 | 70.50 | 77 | .75 | .13 |
| 82 | 81.90 | 70.50 | 78 | .76 | .13 |
| 82 | 76.70 | 70.50 | 79 | .77 | .13 |
| 82 | 98.10 | 70.50 | 80 | .78 | .13 |
| 82 | 71.70 | 70.50 | 81 | .79 | .12 |
| 82 | 109.80 | 70.50 | 82 | .80 | .12 |
| 82 | 81.90 | 70.50 | 83 | .81 | .12 |
| 82 | 83.30 | 69.30 | 84 | .82 | .12 |
| 82 | 72.90 | 69.30 | 85 | .83 | .12 |
| 83 | 86.10 | 69.30 | 86 | .84 | .12 |
| 83 | 72.90 | 69.30 | 87 | .85 | .12 |
| 83 | 91.90 | 69.30 | 88 | .86 | .11 |
| 83 | 77.90 | 69.30 | 89 | .87 | .11 |
| 83 | 69.30 | 69.30 | 90 | .88 | .11 |
| 83 | 74.10 | 69.30 | 91 | .89 | .11 |
| 83 | 84.70 | 69.30 | 92 | .90 | .11 |
| 83 | 86.10 | 69.30 | 93 | .91 | .11 |
| 84 | 69.30 | 68.10 | 94 | .92 | .11 |
| 84 | 71.70 | 68.10 | 95 | .93 | .11 |
| 84 | 86.10 | 68.10 | 96 | .94 | .10 |
| 84 | 74.10 | 68.10 | 97 | .95 | .10 |
| 84 | 68.10 | 68.10 | 98 | .96 | .10 |
| 84 | 89.90 | 68.10 | 99 | .97 | .10 |
| 84 | 75.40 | 68.10 | 100 | .97 | .10 |
| 84 | 81.90 | 68.10 | 101 | .98 | .10 |
| 84 | 84.70 | 68.10 | 102 | .99 | .10 |

## II.1.4    Post-analysis checking

### II.1.4.1    *Sampling standard error — POT approach*

The uncertainty due to sampling of the quantiles summarized above can be estimated using the following expression:

$$se\left(x_T\right) = \frac{B}{\sqrt{N}}\left[1+\left(\ln \lambda = y_T\right)^2\right]^{\frac{1}{2}}$$

$$= \frac{10}{\sqrt{10}}\left[1+\left(\ln 10.2 + y_T\right)^2\right]^{\frac{1}{2}}$$

The standard error of estimate is provided in Table A.II.4 for a range of return periods.

### TABLE A.II.4
### Standard error factors for EVI distribution

| T(years) | 2 | 5 | 10 | 20 | 25 | 50 | 100 |
|---|---|---|---|---|---|---|---|
| $\delta_T$ | 0.918 | 1.546 | 1.951 | 2.638 | 2.815 | 3.368 | 4.025 |

### II.1.4.2    *Sampling standard error — GEV distribution*

When parameters are estimated by moments, the sampling error $se(x_T)$ can be computed from

$$se(x_T) = (s_x / \sqrt{N})\delta_{T,g}$$

There is no simple formula for $\delta_{T,g}$ and tables do not exist. As an approximation, the variation with skewness could be ignored and values given in Table A.II.4 for the EVI distribution (i.e. $g_x = 1.14$) could be used. The actual standard error will exceed this value because of the sampling error for the coefficient of skewness $(g_x)$.

## II.1.5    Examples of extreme-value analyses

The numerical and graphical methods of fitting data to an extreme-value distribution are illustrated using peak-over-threshold data from Table A.II.5 which contains 20 ranked extreme hourly maximum wind speeds for 20 years of record from OWS PAPA.

### II.1.5.1    *Numerical solution*

The Gumbel distribution fitted to the extreme-value series, whether annual maximum series or peak-over-threshold, by the method of moments is simply represented by the following equation:

$$X_T = \mu + K(T)\sigma$$

where $X_T$ is the value of the variable equalled or exceeded once in the return period $T$; $\mu$ and $\sigma$ are the mean and standard deviation, respectively, of the observed series of extremes; $K(T)$ is a frequency factor dependent on the return period, obtained from the following equation:

$$K(T) = -(\sqrt{6}/\pi)\{0.5772 + \ln \ln [T/(T-1)]\}$$

It should be noted that this $K$ factor differs from that originally proposed by Gumbel, which was based on return period and sample size $n$. For fitting by the method of moments that factor was found to be biased, and a revised factor $K(T)$ introduced.

$$x = 63.3 \qquad s = 7.34$$

Then:

$$X_T = x + K(T) \cdot s$$
$$X_{100} = 63.3 + 3.137 \,(7.34)$$
$$X_{100} = 86.3 \text{ knots}$$

For a return period of 50 years, where $K(T) = 2.592$, $X_{50}$ is 82.3 knots. In other words, given a sufficiently long record, the hourly wind speed at OWS PAPA equals or exceeds 82.3 knots once every 50 years. The probability of this happening in any given year is 0.02.

### TABLE A.II.5
### Extreme hourly maximum wind speeds - OWS PAPA

| Rank (m) | $X_m$ | $T = (n+0.12)/(m-0.44)$ |
|---|---|---|
| 1 | 80 | 35.9 |
| 2 | 78 | 12.9 |
| 3 | 78 | 7.9 |
| 4 | 69 | 5.7 |
| 5 | 66 | 4.4 |
| 6 | 64 | 3.6 |
| 7 | 62 | 3.1 |
| 8 | 61 | 2.7 |
| 9 | 61 | 2.4 |
| 10 | 61 | 2.1 |
| 11 | 61 | 1.9 |
| 12 | 60 | 1.7 |
| 13 | 60 | 1.6 |
| 14 | 60 | 1.5 |
| 15 | 60 | 1.4 |
| 16 | 59 | 1.3 |
| 17 | 58 | 1.2 |
| 18 | 56 | 1.15 |
| 1 | 56 | 1.1 |
| 20 | 56 | 1.0 |

### II.1.5.2    *Graphical solution*

Graphical analysis is often preferred because of the ease of extrapolating the data and of dealing flexibly with outlying observations. Extreme-value probability paper is used on which frequencies are plotted as abscissae (double logarithmic scale) and extreme values as ordinates (linear scale). Extreme values are first ranked in increasing order (maxima) or decreasing order (minima). Each value has a plotting position corresponding to its probability. For extreme-value paper scaled in terms of return periods, the plotting probability of each extreme is $(n + 0.12)/ (m - 0.44)$, where $m$ is the order number of the items arranged in descending magnitude and $n$ is the total number of items in the sample. This defines the return period $T$, usually expressed in years. For paper using a percentage frequency scale as abscissa the plotting probability for

each extreme is $1.0 - (m - 0.44) / (n + 0.12)$. On some types of extreme-probability paper a line marked "mean" is given on which the arithmetic average of the sample can be used to guide construction of the best-fit straight line.

Care must be exercised in extrapolating or extending the line much beyond the period of record because of the considerable inherent sampling error. In any event, confidence limits should be computed so that the user may see the danger resulting from unreasonable extrapolation beyond the period of record.

Using the data from Table A.II.5, for plotting on graph paper scaled in return periods (Figure A.II.2), an appropriate wind speed interval is chosen to include about three-quarters of the ordinate axis and then plot the extremes against their corresponding probabilities expressed as return periods. The mean (63.3) of the sample is plotted as one point on the best-fit line. The straight line is extrapolated to the 100-year return period for illustration. Reading from the graph, 50- and 100-year return period events would be equal to or exceed 82 and 86 knots respectively.

## II.1.5.3  Confidence limits

Because of the errors involved in estimating climatological extremes with a given return period, it is necessary to assign limits between which the calculated value can be said to lie with a certain probability.

The confidence interval is given by the range:

$$X_T - t(\alpha) S_e \text{ to } X_T + t(\alpha) S_e$$

where:

$$S_e = B . s/n^{1/2}$$
$$B = (1 + 1.14 K_T + 1.1 K_T^2)^{1/2}$$

and $t(\alpha)$ is given below for various values of $\alpha$, the confidence level:

$\alpha = 95\%$  $t(\alpha) = 1.960$
$\alpha = 90\%$  $t(\alpha) = 1.645$
$\alpha = 80\%$  $t(\alpha) = 1.282$
$\alpha = 68\%$  $t(\alpha) = 1.000$

It should be noted that these confidence limits address only statistical confidence, and not instrument or observing errors or sampling variability.

The confidence limits may be computed and displayed on the graph from the following formulae:

$$X_T - t(\alpha) S_e; \; X_T + t(\alpha) S_e$$
$$S_e = B . s/n^{1/2}$$
$$B = (1 + 1.14 K(T) + 1.1 K(T)^2)^{1/2}$$
$$B = (1 + 1.14 (3.137) + 1.1 (3.137)^2)^{1/2}$$
$$B = 3.924$$
$$S_e = 3.924 (7.34) / (20)^{1/2}$$
$$S_e = 6.44$$

For 95 per cent confidence level, $t(\alpha) = 1.96$; therefore, the range for the confidence intervals at the 100-year return period is from $86.3 - 1.96 (6.44)$ to $86.3 + 1.96 (6.44)$, or 73.7 to 98.9 knots. For a 50-year return period, the range would be $82.3 - 1.96 (5.53)$ to $82.3 + 1.96 (5.53)$, or 71.5 to 93.1 knots.
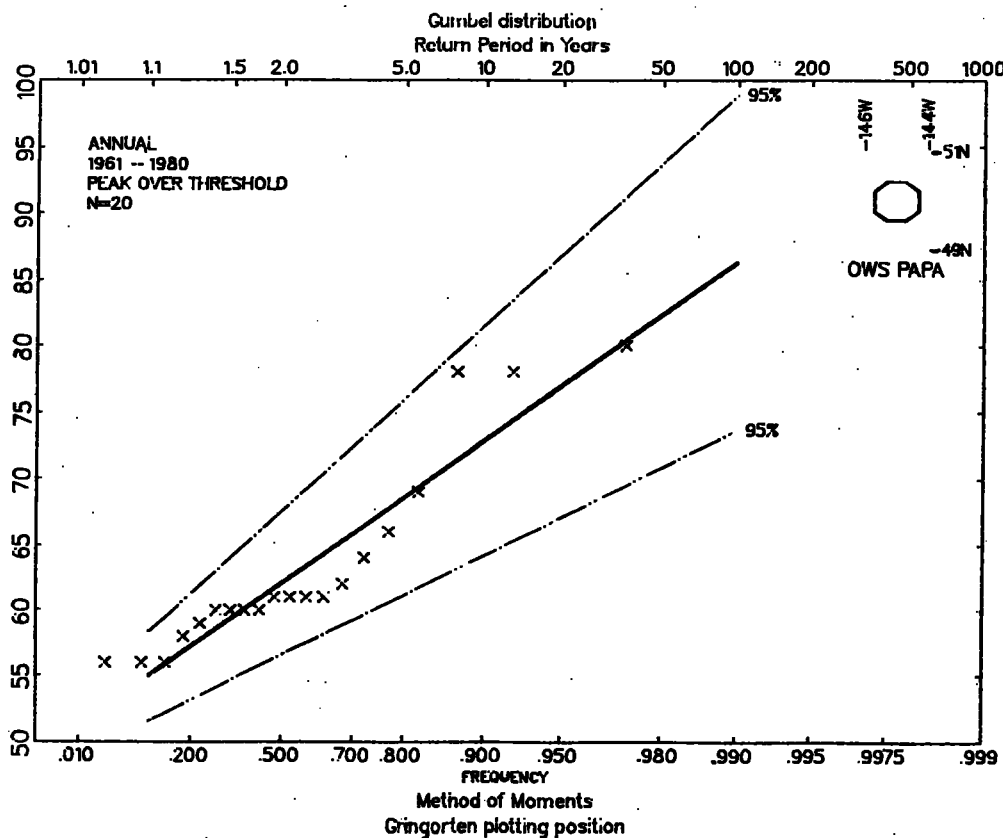


Figure A.II.2 — Extreme value analysis for OWS P

## II.2    FURTHER EXAMPLES – RUSSIAN FEDERATION

Additional examples are provided here of extreme-value analyses and techniques. In particular, it should be noted that these examples document the practical application of extreme-value analysis techniques in the Russian Federation. The references and bibliography at the end of this appendix introduce a body of work which is considerable. For the sake of brevity, the methodology is not completely described.

### II.2.1    Extreme temperatures

An example is given below of how the double exponential distribution (Gumbel) is applied in analysing extreme mean pentadal air temperatures using North Atlantic ocean station data covering 16 years. In this example, the extremes are sampled by season; in this way, 48 extremes are obtained for four seasons for each of nine stations.

The observed extremes are traced on extreme-probability paper, on which we also show the straight line determined from fitting the theoretical distribution. The degree of fit between the theoretical and the observed distributions is assessed by constructing confidence intervals with a probability of 68 per cent, the figure of 68 per cent being chosen because with 95 per cent probability the interval becomes so wide as to be practically meaningless when applied to a particular event. In this situation it is impossible to use the normal criteria of mathematical statistics as there is no grouping of the data by gradations.

Figure A.II.3 shows the distribution of extreme air temperatures in the area of station D in winter. As we can see, most of the points fall within the confidence limits, which indicates that there is good agreement between the theoretical and the observed distributions. At the same time, we can see that the points in the far left part of the graph, which correspond to the most extreme events, are outside the confidence limits, particularly the minima. We can deduce from this that these farthest points follow some other distribution.

The 68 per cent probability level is nonetheless low enough, so we introduce the following variable for a further check on the fit of the functions:

$$S\left\{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - x^*\right)^2\right\}^{\frac{1}{2}} \qquad \text{(A.II.1)}$$

where $x_i$ is the observed extreme, and $x^*$ is the theoretical extreme.

$S$ is an analogue of the standard deviation. It is accepted that if this measure of divergence is commensurable with the temperature-measurement accuracy, the observed distribution is in agreement with the theoretical, and that otherwise it is not. $S$ is calculated for all the distribution curves. It turns out that
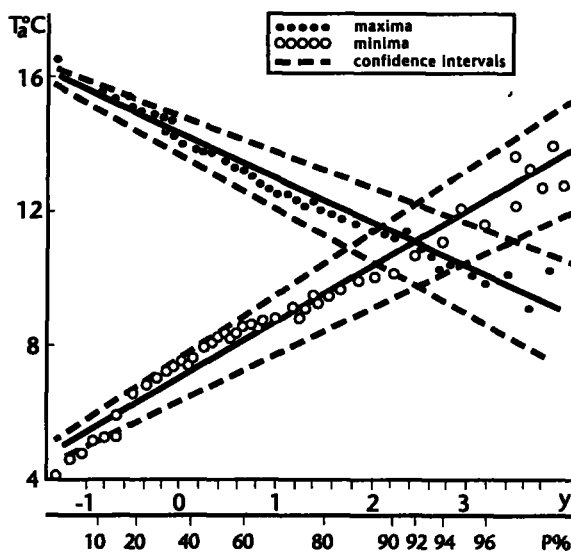


Figure A.II.3 – Extreme winter air temperatures at OWS D

$S$ is not large, and that its maximum value is 0.5°C, which is of the same order as the accuracy of observation. We can therefore take the view that the extreme values of the mean pentadal air temperatures follow a double exponential distribution.

Also, by extending the line until it intersects the ordinate axis, we can obtain the furthest extreme values, which it is obviously impossible to exceed [or at least in theory!].

### II.2.2    Extreme wind speeds

In analysing extreme wind speeds, a somewhat different approach is more often used; it relies on three methods, which we shall examine in turn.

The first method is based on approximating the probabilities of the distribution of maximum wind speeds using a function of the following form:

$$P(V) = e^{-\left(\frac{x}{\beta}\right)^{\gamma}} \qquad \text{(A.II.2)}$$

where $P(V)$ is the probability of exceeding wind velocity $V$, and $\beta$ and $\gamma$ are the parameters of the distribution.

This expression is a special case of Gudrich's distribution. Parameters $g$ and $b$ have a fully defined physical significance, i.e., $g$ is a measure of the variability of random values, while $b$ is assimilated to the mean. They can be determined from observed data using the formulae:

$$\gamma = \frac{\sum_{i=1}^{n}\ln\ln\frac{1}{P_i(V)} - \frac{1}{n}\sum_{i=1}^{n}\ln\ln\frac{1}{P_i(V)}\sum_{i=1}^{n}\ln V_i}{\sum_{i=1}^{n}(\ln V_1)^2 - \frac{1}{n}\left(\sum_{i=1}^{n}\ln V_i\right)^2} \qquad \text{(A.II.3)}$$

$$\beta = \exp\left\{-\frac{1}{\gamma^n}\sum_{i=1}^{n}\left[\ln\ln\frac{1}{P_i(V)} - \gamma\ln V_i\right]\right\} \qquad \text{(A.II.4)}$$

where $V_i$ is storm wind velocity; $P_i(V)$ is the wind speed frequency (wind speed distribution function); and $n$ is the number of class intervals for the data.

Function (A.II.2) is often used in a modified form to obtain calculated wind speed parameters. The modified form is different in that the random variable argument is normalized to its mean or median value. This is the second approximation method. Here, the distribution function has the form

$$P(V) = \bar{e}^{\,\beta'\left(\frac{V}{\bar{V}}\right)^{\gamma}} \qquad (A.II.5)$$

where $P(V)$ is the probability of exceeding wind velocity $V$, $\gamma$ and $\beta'$ are the parameters of the distribution, and $\bar{V}$ is mean wind speed.

Climatological applications practice has shown that the above observed distribution is independent of the time of year and the region, and depends only on $V$, i.e., it is a one-parameter distribution. The dependence between the mean of the random variable and the nature of the probability distribution is based on the physical nature of the random variable as a generalized characteristic, combining within itself all possible values of the random variable.

The physical significance of the $\beta$ parameter defines the variability of the random variable as it did in the first method. The $\beta$ parameter is a single-valued function of $\gamma$. Both parameters are dimensionless.

All the methods assume that a rectifying grid is used for simplifying the presentation of the calculations described. The bilogarithm of the frequency is shown against one scale, and the logarithm of the wind speed against the other. The accuracy with which the exponential functions approximate the distribution curves is tested by their degree of rectilinearity (fit) to the observations plotted on this bilogarithmic grid. If the observed distribution falls on a single line in the grid, the choice of approximating function is taken to have been correct. If the observed points deviate significantly from the line, we draw the opposite conclusion.

A distribution of type (A.II.2) was used to assess wind strengths representing a hazard to shipping in the northern Atlantic and Pacific in winter. Data were used from nine ocean stations in the North Atlantic and three in the northern Pacific. The recurrence of winds of storm force, using the requirements for information of this kind issued by the marine authorities, is given for the velocity gradations >14, >17, >21, >25, >29, >33, >40 and >50 m s⁻¹. The recurrences were shown on a Gudrich distribution grid (see Figure A.II.4).

Presenting the data in the form of a graph shows that, in accordance with the Gudrich distribution, the main bulk of the points cluster closely around the line and we note that usually no more than two or three points, corresponding to extremely rare storms, deviate from it.

Having established this fact, we can analyse storm wind speeds which may appear once in a certain
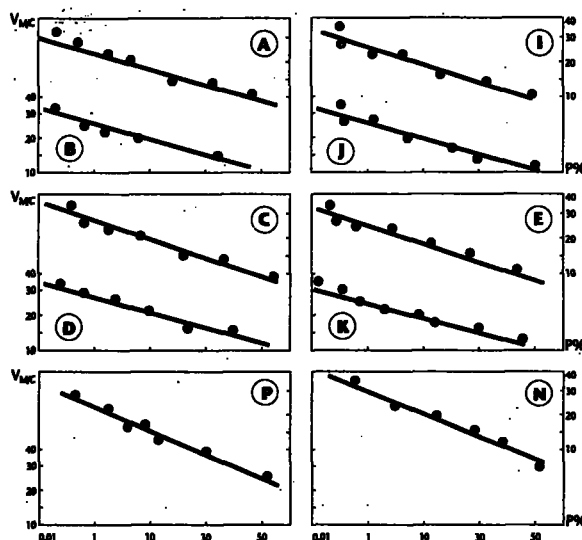


Figure A.II.4 — Distribution of storm winds for some ocean stations in the northern Atlantic and Pacific

number of years, for example, 5, 10, 20 or 50 years. We can do this using either a Gudrich distribution grid (by extrapolating the line into the area of low frequency and reading off the wind speeds corresponding to the frequencies given by the return period), or analytically, using the expression

$$V_\rho = \exp\left\{\frac{\ln \ln \bar{N}_\rho + \gamma \ln \beta}{\gamma}\right\} \qquad (A.II.6)$$

where $\bar{N}_\rho$ is the mean number of storms of a given force per month; and $V_\rho$ is the maximum wind speed over a period of $\rho$ years.

TABLE A.II.6

Storm force winds (m⁻¹) possible once in a certain number of years (winter)

| Ocean station | $\gamma$ | $\beta$ | Period (years) | | | |
|---|---|---|---|---|---|---|
| | | | 5 | 10 | 20 | 50 |
| A | 2.2 | 12.6 | 31 | 32 | 33 | 35 |
| B | 2.2 | 14.2 | 34 | 35 | 37 | 39 |
| C | 2.3 | 14.4 | 33 | 35 | 36 | 38 |
| D | 2.3 | 14.7 | 34 | 35 | 36 | 37 |
| E | 2.1 | 12.1 | 30 | 32 | 33 | 34 |
| I | 2.4 | 13.9 | 32 | 33 | 34 | 36 |
| J | 2.4 | 14.1 | 32 | 33 | 34 | 36 |
| K | 2.4 | 12.8 | 29 | 30 | 31 | 32 |
| M | 2.3 | 12.3 | 28 | 29 | 31 | 33 |
| P | 2.2 | 13.7 | 35 | 36 | 37 | 39 |
| V | 2.1 | 11.9 | 31 | 32 | 33 | 35 |
| N | 1.8 | 7.9 | 25 | 26 | 27 | 28 |

Experience has shown that both these methods give almost identical results. Table A.II.6 gives data on the maximum wind speeds in the North Atlantic and northern

Pacific which may occur once in a certain number of years, taken from the Gudrich distribution grid. The table shows that the stormiest conditions occur in the regions of ocean stations B and C in the North Atlantic and station P in the Pacific. Also, there is no great difference between the storm winds which may occur once in five years and those which may occur once in fifty years, which are 3–4 m s⁻¹ stronger as a rule.

## II.3    STATISTICAL TESTS

### II.3.1    Spearman rank order correlation coefficient test for trend

The significance of any trend can be tested using the Spearman rank order correlation coefficient, $r_s$ [1]. The test statistic $r_s$ is a function of the difference in rank, $d_i$, between adjacent items in two series, $X_1 ... X_n$, and $Y_1 ... Y_n$. Here $d_i$ denotes the difference in rank between a series arranged in order of decreasing magnitude and a series arranged in chronological order. If two or more observations in a series are equal, the mean rank is assigned to each tied observation. If the proportion of ties is not large, their effect on $r_s$ is negligible, and the test statistic can be computed as:

$$r_s = 1 - (6\Sigma d_i^2) / (N^3 - N)$$

For sample size $N$ of 10 or larger, the statistic, $r_s$, is distributed by Student's $t$ distribution with $N-2$ degrees of freedom. Therefore:

$$t = r_s[(n - 2) / (1 - r_s^2)]^{1/2}$$

A two-tailed test is used and the null hypothesis is that there is no trend.

If a significant number of tied ranks exist, a correction factor must be incorporated in the computation of $r_s$.

The correction factor for tied ranks is given by:

$$S = \Sigma(t_m^3 - t_m)12$$

where $t_m$ is the number of observations tied at a given rank. If $R_x$ refers to the ranks of the series $X_1, X_2...X_N$ and $R_y$ to the time series represented by $Y_1, Y_2...Y_N$, then the test statistic is given by:

$$r_s = (\Sigma R_x^2 + \Sigma R_y^2 - \Sigma d_i^2) / [2\sqrt{(\Sigma R_x^2 \Sigma R_y^2)}]$$

where:

$$\Sigma R_x^2 = [(N - 1)^3 - (N - 1)]/12 - S_x,$$
$$\Sigma R_y^2 = [(N - 1)^3 - (N - 1)]/12 - S_y.$$

$S_x$ and $S_y$ are the correction factors for ties for $R_x$ and $R_y$ respectively.

### II.3.2    Wald-Wolfowitz test for jump

The Wald-Wolfowitz split sample test [1] can be used to determine whether two samples have significantly different means, variances, skewness or kurtosis. The test statistic is the number of runs, $R_{ww}$, for either subseries, in the rank series for the combined and ranked sample series. For sample sizes $n_1 > 4$ and $n_2 > 20$, the

sampling distribution tends to normality with $z$ a standard normal variate.

### II.3.3    Mann-Whitney test for jump

$$z = \frac{R_{ww} - [(2n_1n_2) / (n_1n_2) = 1] - 0.5}{[2n_1n_2(2n_1n_2 - n_1)] / [(n_1 = n_2)^2 (n_1 + n_2 - 1)]^{\frac{1}{2}}}$$

The Mann-Whitney test statistic for jump is the same as that for homogeneity except that the sub-samples are collected before and after the suspected jump. The Mann-Whitney statistic, $U$, is used to determine whether the sub-samples have significantly different means.

### II.3.4    Autocorrelation coefficient test for independence

Even if a variable is random and stationary, it may not be independent. For streamflow, large natural storage such as lakes or groundwater reservoirs may cause large flows to be followed by further large flows, while in meteorology, large-scale features of the Earth's atmospheric circulation may cause a succession of severe storms.

Such persistence can be reflected by the autocorrelation function $Q_k$ which, for a sample of size $N$, is estimated by its sample value, $r_k$.

For large samples, the function is approximately normally distributed with variance $1/N$ and hence a confidence band of 0 plus or minus $2/\sqrt{N}$ would include all estimates within two standard errors of the expected value of zero for an uncorrelated time series.

### II.3.5    Spearman rank order serial correlation coefficient test for independence

The Spearman rank order serial correlation coefficient can also be used to test for independence.

The test statistic $r_s$ is the same as for the Spearman test for trend except that $R_x$ refers to ranks of the series $X_1, X_2,....,X_{N-1}$, and $R_y$ to ranks of the series $X_2, X_3,....,X_N$. If two or more observations have equal values, the same correction factor must be applied.

If the proportion of ties is not large, their effect on $r_s$ is negligible, that is, $S << [(N-1)^3-(N-1)]/12$, and $r_s$ can be computed using:

$$r_s = 1 - (6\Sigma d_i^2) / [(N-1)]^3 - (N-1)]$$

The quantity

$$t = r_s [(N-3) / (1-r_s^2)]^{\frac{1}{2}}$$

is distributed as Student's $t$ with $N-3$ degrees of freedom when $N > 11$.

Recent developments indicate that in many cases it is not essential that data series be independent and that the classical extreme-value theory also applies to stationary dependent series. Some of the results for the dependent case may also be extended to non-stationary situations.

## II.3.6 Mann-Whitney test for homogeneity

The Mann and Whitney test [1] is used to determine whether two samples have significantly different means. The Mann-Whitney test statistic, $U$, is a function of the sum of the ranks and is defined by the smaller of

$$U_1 = n_1 n_2 + n_1(n_1+1)/2 - R_1$$

or

$$U_2 = n_1 n_2 - U_1$$

Here $R_1$ denotes the sum of the ranks in sub-sample 1.

For $n_1 > 4$ and $n_2 > 20$, the sampling distribution of $U$ tends rapidly to normality with

$$U_2 = n_1 n_2 - U_1$$

$$z = \frac{U - n_1(n_2/2)}{\left\{ \left[ \frac{n_1 n_2}{N(N-1)} \right]\left[ \frac{N^3 - N}{12} - S \right] \right\}^{\frac{1}{2}}}$$

where $\qquad S = \Sigma(t_m^3 - t_m)/12$

where $t_m$ is the number of observations tied at a given rank.

The samples can be said to have a significant difference of means if:

$$z < -1.645 \text{ for significance level } \alpha = 0.05$$

or

$$s < -2.326 \text{ for } \alpha = 0.01.$$

For $n_2$ up to 20, the critical values of $U$ for significance levels A = 0.05 and A = 0.01 may be computed. If the computed value of $U$ is less than or equal to the computed values, the samples are said to have significant difference of means at the level indicated.

## II.3.7 Wald-Wolfowitz test for homogeneity

The Wald-Wolfowitz test statistic for homogeneity is the same as that used for jump except that the sub-samples are sorted to conform to the suspected processes. The Wald-Wolfowitz statistic $R_{ww}$ is used to determine when the sub-samples have significantly different means.

## II.4 TESTING FOR AN APPROPRIATE DISTRIBUTION

### II.4.1 Comparison of sample coefficients of skewness with assumed population distribution

For samples of moderate size, an indication of the possible appropriateness of some two-parameter distributions can be obtained by comparing the sample value of the coefficient of skewness with the value for the assumed population distribution (see Table A.II.7).

Three qualifications should be noted. First, even for large samples, this check should be performed in conjunction with visual-evaluation and goodness of fit tests. Otherwise, a sample could be identified as being drawn from a normal distribution because sample skewness $g$ is approximately zero. But, in fact, the zero skewness only indicates symmetry. Secondly, the sampling error of the coefficient of skewness is large even for sample sizes that are moderately large in geophysical terms. For example, for the normal distribution, the sampling variance of the coefficient of skewness, to order $N$, is [2]:

$$\text{var}(g) = \frac{6N(N-1)}{(N-2)(N+1)(N+3)}$$

For sample sizes of 10, 25 and 50 this expression yields values for the standard error of 0.687, 0.464 and 0.337.

TABLE A.II.7
Coefficients of skewness for common distributions

| Distribution | Coefficient of skewness |
|---|---|
| Normal | $\gamma_{1,x} = 0$ |
| Lognormal | $\gamma_{1,\ln x} = 0$ |
| Exponential | $\gamma_{1,x} = 2$ |
| Type I | $\gamma_{1,x} = 1.14$ |

Finally, for skewed distribution such as the Type I, the expected value of sample skewness approaches the population value asymptotically. In a recent Monte Carlo simulation of extreme rainfall depths, Watt and Nozdryn-Plotnicki [3] found that a correction factor suggested by Hazen [4], when applied to sample skewness, $g$, provided a better estimate of the population value of skewness, $\gamma_1$.

$$\gamma_1 = (1 + 8.5/N)g$$

Therefore, for sample sizes of 10, 25 and 50, the expected sample value, $g$, would be 0.616, 0.851 and 0.974.

### II.4.2 Goodness of fit

The following guidance is provided as an aid in evaluating the goodness of fit of extreme-value distributions:

#### II.4.2.1 Graphical evaluation

Visual evaluation of goodness of fit on appropriate probability paper is the most common approach to evaluating the adequacy of a distribution. A plotting position is selected and the observed data series is plotted on appropriate probability paper, i.e. normal, lognormal, Type I probability paper. A linear trend on a particular probability paper is usually taken to indicate that the sample was drawn from the distribution for which that paper applies. This procedure is acceptable for large samples, but for small samples, a plot which appears to fit one distribution could do so solely as the result of sampling variability and could in fact belong to another distribution.

If the trend of the observed data series is not linear, a common assumption is that a two-parameter distribution with fixed skewness is not adequate and a three-parameter distribution (e.g. Type II, Type III or LP3) should be used. ·

A fitted probability distribution function is usually plotted on the same graph as the observed series (a possibility plot) and then, in addition to determining whether or not a three-parameter distribution is appropriate, visual evaluation is used to assess the goodness of fit of the distribution selected. As well as assessing the overall "scatter", attention is directed to the extremes (both high and low) of the data series. Sometimes concern is expressed about deviations of the extreme points from the fit line, and indeed these points may be outliers. However, such deviation should not be used to reject a distribution that otherwise provides an acceptable fit.

Visual inspection of a probability plot also prompts consideration of inappropriate asymptotic behaviour, such as negative values for quantile estimates in the case of the Type I and normal distributions and unreasonably low upper bounds in the case of the three-parameter lognormal and log Pearson Type 3 distributions.

### II.4.2.2    Goodness-of-fit tests – general comments

Goodness-of-fit tests are often used to determine which distribution among several is the most appropriate statistical model of the geophysical process.

These tests may be classified as tests which are available from theoretical statistics and tests based on the probability (x–y) plot. In either case, the test involves an index which expresses the agreement between an observed sample maximum and some theoretically specified population. The latter may be specified without any reference to the sample data or it may result from fitting a distribution to the sample. In the case of tests available from theoretical statistics, the index is a sample statistic having a distribution. If the observed index value lies in the tail of its sampling distribution it throws doubt on the hypothesis that the sample came from the specified distribution.

These tests include:

(a)    The chi-square test;

(b)    The Kolmogorov-Smirnov (KS) test and

(c)    The Cramer-Von Mises (CVM) test;

(d)    Special tests for specific distributions (Table A.II.8).

### II.4.2.3    Chi-square test

The chi-square test is one of the most frequently applied tests for engineering data. It is not, however, generally suitable for small sample sizes, i.e. less than 30 to 50 observations.

The data in a chi-square test must also be grouped in arbitrary intervals and the results of the test can depend on how the data are grouped, especially for small samples.

### II.4.2.4    Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test is described in Lawless (1982). In this test, the statistic

$$D = \max_{k=1}^{N} \left| \frac{k}{n} - F_i\left(x_k|\theta_i\right), \left|F_i\left(x_k|\mu_i\right) - \frac{k-1}{N}\right| \right|$$

is computed, in which $N$ = sample size; $F_i(x_k \mid \theta_i)$ = distribution being tested with parameters $\theta_i$; and $x_k = k$th ordered data value. A KS test of distribution fit at an arbitrary per cent significance level compares the statistic $D$ with a tabulated acceptance criteria value $D_m$.

When parameters in the distribution being tested have been estimated from the data, it is important to use tables which take this into account: standard tables for the KS statistic do not do this. Table A.II.8 gives references to tables for the EVI, Weibull, normal, lognormal and expotential distributions. Unfortunately the necessary tables do not yet exist for other distributions used in extreme-values analysis.

### II.4.2.5    Cramer-Von Mises test

The Cramer-Von Mises test is described in [5]. In this test, the statistic

$$W^2 = \sum_k \left[F_i\left(x_k|\theta_i\right) - \frac{k-0.5}{N}\right]^2 + (12N)^{-1}$$

can also be used in a similar fashion as a non-parametric test of goodness.

The CVM test considers the average squared deviation of the data from the distribution and is similar to the MPPCC test (see next section). ·

When parameters in the distribution being tested have been estimated from the data, it is important to use tables which take this into account; standard tables for the CVM statistic do not do this. A.II.8 gives references to tables for the EVI, Weibull, normal, lognormal and expotential distributions. Unfortunately the necessary tables do not yet exist for other distributions used in extreme-values analysis. .

TABLE A.II.8

Distribution specific goodness-of-fit tests

(Lawless, 1982)

| Distribution | Comments |
|---|---|
| Normal or 2-parameter lognormal | KS, CVM and others |
| Type I (Gumbel) or . | KS |
| 2-parameter Weibull | CVM |
| | Test of K = 0 in GEV |
| | KS, CVM and others |
| Exponential | KS, CVM |
| | KS, CVM and other tests |

## II.4.2.6 Goodness-of-fit indices based on probability (x–y) plot

A number of goodness-of-fit indices based on the probability (x–y) plot have been devised by hydrologists. These indices are based on the deviations between the ordered observed values and ordered fitted values, i.e.

$$d_i = x_i - \hat{x}_i.$$

A number of different indices result, depending on the following three factors:

(a) The plotting position formula used to define $\hat{x}$;

(b) Whether or not the direction, $d_i$, is expressed in dimensionless form (i.e. divided by $\bar{x}$); and

(c) The method of adding the deviations (normally either mean absolute value or root mean square).

In the comprehensive studies of floods referred to earlier, it was found that this approach was unsatisfactory because the outcome is sensitive to the three factors listed above.

Recent studies [6, 7] have also suggested that a suitable test statistic can be obtained using the maximum probability plot correlation coefficient (MPPCC). The MPPCC test results in similar conclusions as the classical tests but it does not require a detailed theoretical knowledge of statistics or tables of acceptance values for a range of significance levels and sample sizes. The MPPCC test is described in [8].

In the MPPCC test the ranged median plotting positions of the data are fitted to a straight line on the appropriate probability paper using the least-squares method. If the distribution models the data, the plot will be linear, and the MPPCC will be nearly equal to 1. The "best" distribution is that for which the MPPCC is closest to 1.

Ellingwood [7] suggested that the MPPCC test is a useful practical test to be used to choose among distributions which satisfy a classical goodness-of-fit test.

## II.4.2.7 Summary

Besides the general tests described above, special tests have been derived for certain distributions used in extreme-value distributions as described in Table A.II.7.

In general, goodness-of-fit tests are suitable for indicating acceptance or rejection of a given distribution. They are not suitable for choosing among several distributions. For example, two distributions which both satisfy a goodness-of-fit test may still provide widely different estimates for a given return period without indicating which is the more appropriate.

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