SECTION: Table_of_Contents_Chapter
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

CHAPTER 1. GENERAL

1.1 METEOROLOGICAL OBSERVATIONS

1.1.1 General

Meteorological (and related environmental and geophysical) observations are made for a variety of reasons. They are used for the real-time preparation of weather analyses, forecasts and severe weather warnings, for the study of climate, for local weather-dependent operations (for example, local aerodrome flying operations, construction work on land and at sea), for hydrology and agricultural meteorology, and for research in meteorology and climatology. The purpose of the *Guide to Meteorological Instruments and Methods of Observation* is to support these activities by giving advice on good practices for meteorological measurements and observations.

There are many other sources of additional advice, and users should refer to the references at the end of each chapter for a bibliography of theory and practice relating to instruments and methods of observation. The references also contain national practices, national and international standards, and specific literature. They also include reports published by the World Meteorological Organization (WMO) for the Commission for Instruments and Methods of Observation (CIMO) on technical conferences, instrumentation, and international comparisons of instruments. Many other Manuals and Guides issued by WMO refer to particular applications of meteorological observations (see especially those relating to the WMO Integrated Global Observing System (WMO, 2015, 2017), aeronautical meteorology (WMO, 2014), hydrology (WMO, 2008), agricultural meteorology (WMO, 2010*b*) and climatology (WMO, 2011*a*).

Quality assurance and maintenance are of special interest for instrument measurements. Throughout this Guide many recommendations are made in order to meet the stated performance requirements. These requirements are described in Annex 1.A. Particularly, Volume V of this Guide is dedicated to quality assurance and management of observing systems. It is recognized that quality management and training of instrument specialists is of utmost importance. Therefore, on the recommendation of CIMO,[1] regional associations of WMO have set up Regional Instrument Centres (RICs) to maintain standards and provide advice regarding meteorological measurements. These RICs play a key role for the implementation of WMO strategy for traceability assurance, which is set out in Annex 1.B. Their terms of reference are given in Annex 1.C. In addition, on the recommendation of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology[2] (WMO, 2010*a*) a network of Regional Marine Instrument Centres (RMIC) has been set up to provide for similar functions regarding marine meteorology and other related oceanographic measurements. Their terms of reference and locations are given in Volume III,

---

[1] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 19 (CIMO-IX).

[2] Recommended by the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology at its third session (2009) through Recommendation 1 (JCOMM-III).

Chapter 4, Annex 4.A[3]. Also, to undertake training in meteorology, hydrology and related sciences to meet the needs of the Region, WMO Regional Training Centres (RTC)[4] have been established.

The definitions and standards stated in this Guide (see 1.5.1) will always conform to internationally adopted standards. Basic documents to be referred to are the *International Meteorological Vocabulary* (WMO, 1992) and the *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)* (JCGM, 2012).

1.1.2 Representativeness

The representativeness of an observation is the degree to which it accurately describes the value of the variable needed for a specific purpose. Therefore, it is not a fixed quality of any observation, but results from joint appraisal of instrumentation, measurement interval and exposure against the requirements of some particular application. For instance, synoptic observations should typically be representative of an area up to 100 km around the station, but for small-scale or local applications the considered area may have dimensions of 10 km or less.

In particular, applications have their own preferred timescales and space scales for averaging, station density and resolution of phenomena — small for agricultural meteorology, large for global long-range forecasting. Forecasting scales are closely related to the timescales of the phenomena; thus, shorter-range weather forecasts require more frequent observations from a denser network over a limited area in order to detect any small-scale phenomena and their quick development. Using various sources (WMO, 2001, 2015; Orlanski, 1975), horizontal meteorological scales may be classified as follows, with a factor two uncertainty:

(a) Microscale (less than 100 m) for agricultural meteorology, for example, evaporation;

(b) Toposcale or local scale (100 m–3 km), for example, air pollution, tornadoes;

(c) Mesoscale (3–100 km), for example, thunderstorms, sea and mountain breezes;

(d) Large scale (100–3 000 km), for example, fronts, various cyclones, cloud clusters;

(e) Planetary scale (larger than 3 000 km), for example, long upper tropospheric waves.

Section 1.6 discusses the required and achievable uncertainties of instrument systems. The stated achievable uncertainties can be obtained with good instrument systems that are properly operated, but are not always obtained in practice. Good observing practices require skill, training, equipment and support, which are not always available in sufficient degree. The measurement intervals required vary by application: minutes for aviation, hours for agriculture, and days for climate description. Data storage arrangements are a compromise between available capacity and user needs.

Good exposure, which is representative on scales from a few metres to 100 km, is difficult to achieve (see 1.3). Errors of unrepresentative exposure may be much larger than those expected from the instrument system in isolation. A station in a hilly or coastal location is likely to be unrepresentative on the large scale or mesoscale. However, good homogeneity of observations in time may enable users to employ data even from unrepresentative stations for climate studies.

Annex 1.D discusses site representativeness in further detail and provides guidelines on the classification of surface observing sites on land to indicate their representativeness for the measurement of different variables. This classification has several objectives:

---

[3] Additional information on RMIC can be found at http://www.jcomm.info/index.php?option=com_content&view=article&id=335:rmics&catid=34:capacity-building

[4] For the most recent information on RTCs and their components, please visit: https://www.wmo.int/pages/prog/dra/etrp/rtcs.php

(a) To improve the selection of a site and the location of an instrument within the selected site in order to optimize representativeness by applying some objective criteria;

(b) To help in the construction of a network and the selection of its sites:

    (i) Not only for meteorological services but also, for example, for road services;

    (ii) To avoid inappropriate positioning of instruments;

(c) To document the site representativeness with an easy-to-use criterion:

    (i) It is clear that a single number is not enough to fully document the environment and representativeness of a site. Additional information is necessary such as a map, pictures or a description of the surroundings;

    (ii) Despite this numerical value, the site classification is not only a ranking system. Class 1 sites are preferred, but sites in other classes are still valuable for many applications;

(d) To help users benefit from metadata when using observations data. It is recommended that the metadata be as simple as practical, as well as appropriate for the intended use.

Annex 1.E describes a new classification scheme for initial and ongoing surface measurement quality. This, in combination with the siting classification of Annex 1.D provides a WMO recognised mechanism for classifying the overall measurement uncertainty of data from a site, and its evolution with time.

Measurement quality is extremely significant as it underpins the coordinated observing components comprising the WMO Integrated Global Observing System (WIGOS).

1.1.3 Metadata

The purpose of this Guide and related WMO publications is to ensure reliability of observations by standardization. However, local resources and circumstances may cause deviations from the agreed standards of instrumentation and exposure. A typical example is that of regions with much snowfall, where the instruments are mounted higher than usual so that they can be useful in winter as well as summer.

Users of meteorological observations often need to know the actual exposure, type and condition of the equipment and its operation; and perhaps the circumstances of the observations. This is now particularly significant in the study of climate, in which detailed station histories have to be examined. Metadata (data about data) should be kept concerning all of the station establishment and maintenance matters described in 1.3, and concerning changes which occur, including calibration and maintenance history and the changes in terms of exposure and staff (WMO, 2003). Metadata are especially important for elements which are particularly sensitive to exposure, such as precipitation, wind and temperature. One very basic form of metadata is information on the existence, availability and quality of meteorological data and of the metadata about them.

1.2 METEOROLOGICAL OBSERVING SYSTEMS

The requirements for observational data may be met using in situ measurements or remote-sensing (including space-borne) systems, according to the ability of the various sensing systems to measure the environmental elements needed. The requirements in terms of global, regional and national scales and according to the application area are described in WMO (2015). The WMO Integrated Global Observing System, designed to meet these requirements, is composed of the surface-based subsystem and the space-based subsystem. The surface-based subsystem comprises a wide variety of types of stations according to the particular application (for example, surface synoptic station, upper-air station, climatological station, and so on). The space-based subsystem comprises a number of spacecraft with on-board sounding missions and the associated ground segment for command, control and data reception. The succeeding paragraphs and chapters in this Guide deal with the surface-based system and, to a lesser extent, with the space-based subsystem. To derive certain meteorological observations by automated systems, for example, present weather, a so-called “multi-instrument” approach is necessary, where an algorithm is applied to compute the result from the outputs of several sensing instruments.

1.3 GENERAL REQUIREMENTS OF A METEOROLOGICAL STATION

The requirements for elements to be observed according to the type of station and observing network are detailed in WMO (2015). In this section, the observational requirements of a typical climatological station or a surface synoptic network station are considered.

The following elements are observed at a station making surface observations (the chapters refer to Volume I of the Guide):

Temperature (Chapter 2)
Soil temperature (Chapter 2)
Atmospheric pressure (Chapter 3)
Relative humidity (Chapter 4)
Wind direction and speed (Chapter 5)
Precipitation (Chapter 6)
Snow cover (Chapter 6)
Solar radiation and/or sunshine (Chapters 7, 8)
Visibility (Chapter 9)
Evaporation (Chapter 10)
Present weather (Chapter 14)
Past weather (Chapter 14)
Cloud amount (Chapter 15)
Cloud type (Chapter 15)
Cloud-base height (Chapter 15)

Instruments exist which can measure all of these elements, except cloud type. However, with current technology, instruments for present and past weather, cloud amount and height, and snow cover are not able to make observations of the whole range of phenomena, whereas human observers are able to do so.

Some meteorological stations take upper-air measurements (Volume I, Chapters 12 and 13), measurements of soil moisture (Volume I, Chapter 11), ozone and atmospheric composition (Volume I, Chapter 16), and some make use of special instrument systems as described in Volume III of this Guide.

Details of observing methods and appropriate instrumentation are contained in the succeeding chapters of this Guide.

1.3.1 Automatic weather stations

Most of the elements required for synoptic, climatological or aeronautical purposes can be measured by automatic instrumentation (Volume III, Chapter 1).

As the capabilities of automatic systems increase, the ratio of purely automatic weather stations to observer-staffed weather stations (with or without automatic instrumentation) increases steadily. The guidance in the following paragraphs regarding siting and exposure, changes of instrumentation, and inspection and maintenance apply equally to automatic weather stations and staffed weather stations.

1.3.2 Observers

Meteorological observers are required for a number of reasons, as follows:

(a) To make synoptic and/or climatological observations to the required uncertainty and representativeness with the aid of appropriate instruments;

(b) To maintain instruments, metadata documentation and observing sites in good condition;

(c) To code and dispatch observations (in the absence of automatic coding and communication systems);

(d) To maintain in situ recording devices, including the changing of charts when provided;

(e) To make or collate weekly and/or monthly records of climatological data where automatic systems are unavailable or inadequate;

(f) To provide supplementary or back-up observations when automatic equipment does not make observations of all required elements, or when it is out of service;

(g) To respond to public and professional enquiries.

Observers should be trained and/or certified by an authorized Meteorological Service to establish their competence to make observations to the required standards. They should have the ability to interpret instructions for the use of instrumental and manual techniques that apply to their own particular observing systems. Guidance on the instrument training requirements for observers will be given in Volume V, Chapter 5.

1.3.3 Siting and exposure

1.3.3.1 Site selection

Meteorological observing stations are designed so that representative measurements (or observations) can be taken according to the type of station involved. Thus, a station in the synoptic network should make observations to meet synoptic-scale requirements, whereas an aviation meteorological observing station should make observations that describe the conditions specific to the local (aerodrome) site. Where stations are used for several purposes, for example, aviation, synoptic and climatological purposes, the most stringent requirement will dictate the precise location of an observing site and its associated sensing instruments. A detailed study on siting and exposure is published in WMO (1993).

As an example, the following considerations apply to the selection of site and instrument exposure requirements for a typical synoptic or climatological station in a regional or national network:

(a) Outdoor instruments should be installed on a level piece of ground, preferably no smaller than 25 m x 25 m where there are many installations, but in cases where there are relatively few installations the area may be considerably smaller. The ground should be covered with short grass or a surface representative of the locality, and surrounded by open fencing or palings to exclude unauthorized persons. Within the enclosure, a bare patch of ground of about 2 m x 2 m is reserved for observations of the state of the ground and of soil temperature at depths of equal to or less than 20 cm (Volume I, Chapter 2) (soil temperatures at depths greater than 20 cm can be measured outside this bare patch of ground). An example of the layout of such a station is given in Figure 1.1;

ELEMENT 1: Floating object (Automatic)

ELEMENT 2: Picture inline fix size

Element Image: 8_I_1-1_en.eps

END ELEMENT

Figure 1.1. Layout of an observing station in the northern hemisphere showing minimum distances between installations

END ELEMENT

(b) There should be no steeply sloping ground in the vicinity, and the site should not be in a hollow. If these conditions are not met, the observations may show peculiarities of entirely local significance;

(c) The site should be well away from trees, buildings, walls or other obstructions. The distance of any such obstacle (including fencing) from the raingauge should not be less than twice the height of the object above the rim of the gauge, and preferably four times the height;

(d) The sunshine recorder, raingauge and anemometer must be exposed according to their requirements, preferably on the same site as the other instruments;

(e) It should be noted that the enclosure may not be the best place from which to estimate the wind speed and direction; another observing point, more exposed to the wind, may be desirable;

(f) Very open sites which are satisfactory for most instruments are unsuitable for raingauges. For such sites, the rainfall catch is reduced in conditions other than light winds and some degree of shelter is needed;

(g) If in the instrument enclosure surroundings, maybe at some distance, objects like trees or buildings obstruct the horizon significantly, alternative viewpoints should be selected for observations of sunshine or radiation;

(h) The position used for observing cloud and visibility should be as open as possible and command the widest possible view of the sky and the surrounding country;

(i) At coastal stations, it is desirable that the station command a view of the open sea. However, the station should not be too near the edge of a cliff because wind eddies created by the cliff will affect the wind and precipitation measurements;

(j) Night observations of cloud and visibility are best made from a site unaffected by extraneous lighting.

It is obvious that some of the above considerations are somewhat contradictory and require compromise solutions. Detailed information appropriate to specific instruments and measurements is given in the succeeding chapters.

1.3.3.2 Coordinates of the station

The position of a station referred to in the World Geodetic System 1984 (WGS-84) and its Earth Geodetic Model 1996 (EGM96) must be accurately known and recorded.[5] The coordinates of a station are (as required by WMO, 2017):

(a) The latitude in degrees, minutes and integer seconds;

(b) The longitude in degrees, minutes and integer seconds;

(c) The height of the station above mean sea level,[6] namely, the elevation of the station, in metres (up to two decimals).

These coordinates refer to the plot on which the observations are taken and may not be the same as those of the town, village or airfield after which the station is named. If a higher resolution of the coordinates is desired, the same practice applied to elevation can be followed, as explained below.

---

[5] For an explanation of the WGS-84 and recording issues, see ICAO (2002).

[6] Mean sea level (MSL) is defined in WMO (1992). The fixed reference level of MSL should be a well-defined geoid, like the WGS-84 Earth Geodetic Model 1996 (EGM96) [Geoid: the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global MSL].

The elevation of the station is defined as the height above mean sea level of the ground on which the raingauge stands or, if there is no raingauge, the ground beneath the thermometer screen. If there is neither raingauge nor screen, it is the average level of terrain in the vicinity of the station. If the station reports pressure, the elevation to which the station pressure relates must be separately specified.

If a station is located at an aerodrome, other elevations must be specified (see Volume III, Chapter 2, and WMO, 2014). Definitions of measures of height and mean sea level are given in WMO (1992).

1.3.3.3 Operating equipment in extreme environments

Continuous observations during and after extreme hydrometeorological events are extremely important, both to support recovery efforts and to prepare for future events. Mitigation strategies for common hazards are described in Annex 1.F.

1.3.4 Changes of instrumentation and homogeneity

The characteristics of an observing site will generally change over time, for example, through the growth of trees or erection of buildings on adjacent plots. Sites should be chosen to minimize these effects, if possible. Documentation of the geography of the site and its exposure should be kept and regularly updated as a component of the metadata (see Annex 1.G and WMO, 2003).

It is especially important to minimize the effects of changes of instrument and/or changes in the siting of specific instruments. Although the static characteristics of new instruments might be well understood, when they are deployed operationally they can introduce apparent changes in site climatology. In order to guard against this eventuality, observations from new instruments should be compared over an extended interval (at least one year; see the *Guide to Climatological Practices* (WMO, 2011*a*)) before the old measurement system is taken out of service. The same applies when there has been a change of site. Where this procedure is impractical at all sites, it is essential to carry out comparisons at selected representative sites to attempt to deduce changes in measurement data which might be a result of changing technology or enforced site changes.

1.3.5 Inspection and maintenance

1.3.5.1 Inspection of stations

All synoptic land stations and principal climatological stations should be inspected no less than once every two years. Agricultural meteorological and special stations should be inspected at intervals sufficiently short to ensure the maintenance of a high standard of observations and the correct functioning of instruments.

The principal objective of such inspections is to ascertain that:

(a) The siting and exposure of instruments are known, acceptable and adequately documented;

(b) Instruments are of the approved type, in good order, and regularly verified against standards, as necessary;

(c) There is uniformity in the methods of observation and the procedures for calculating derived quantities from the observations;

(d) The observers are competent to carry out their duties;

(e) The metadata information is up to date.

Further information on the standardization of instruments is given in 1.5.

1.3.5.2 Maintenance

Observing sites and instruments should be maintained regularly so that the quality of observations does not deteriorate significantly between station inspections. Routine (preventive) maintenance schedules include regular “housekeeping” at observing sites (for example, grass cutting and cleaning of exposed instrument surfaces) and manufacturers’ recommended checks on automatic instruments. Routine quality control checks carried out at the station or at a central point should be designed to detect equipment faults at the earliest possible stage. Depending on the nature of the fault and the type of station, corrective maintenance (instrument replacement or repair) should be conducted according to agreed priorities and timescales. As part of the metadata, it is especially important that a log be kept of instrument faults, exposure changes, and remedial action taken where data are used for climatological purposes.

Further information on station inspection and management can be found in WMO (2015).

1.4 GENERAL REQUIREMENTS OF INSTRUMENTS

1.4.1 Desirable characteristics

The most important requirements for meteorological instruments are the following:

(a) Uncertainty, according to the stated requirement for the particular variable;

(b) Reliability and stability;

(c) Convenience of operation, calibration and maintenance;

(d) Simplicity of design which is consistent with requirements;

(e) Durability;

(f) Acceptable cost of instrument, consumables and spare parts;

(g) Safe for staff and the environment.

With regard to the first two requirements, it is important that an instrument should be able to maintain a known uncertainty over a long period. This is much better than having a high level of initial confidence (meaning low uncertainty) that cannot be retained for long under operating conditions.

Initial calibrations of instruments will, in general, reveal deviations from the ideal output, necessitating corrections to observed data during normal operations. It is important that the corrections should be retained with the instruments at the observing site and that clear guidance be given to observers for their use.

Simplicity, strength of construction, and convenience of operation and maintenance are important since most meteorological instruments are in continuous use year in, year out, and may be located far away from good repair facilities. Robust construction is especially desirable for instruments that are wholly or partially exposed to the weather. Adherence to such characteristics will often reduce the overall cost of providing good observations, outweighing the initial cost.

Appropriate safety procedures must be implemented when using instruments containing dangerous chemicals (see in particular guidance on mercury (Volume I, Chapter 3, Annex 3.A) and hazardous chemicals (Volume III, Chapter 8, 8.5 and 8.6).

In the case of radiosondes, environmental pollution should be considered when selecting radiosonde materials. Volume I, Chapter 12, Annex 12.C describes the issues and potential near-future solutions for each radiosonde component.

1.4.2 Impact of the Minamata convention

The Minamata Convention on Mercury of the United Nations Environment Programme (UNEP) came into force globally in August 2017, and bans all production, import and export of observing instruments (thermometers, barometers, etc.) containing mercury (UNEP, 2017). This agreement is a global treaty to eliminate the use of mercury to protect both human health and the environment from the adverse effects of mercury. It was agreed at the 5th session of the Intergovernmental Negotiating Committee in Geneva, in January 2013.

The Convention states that "each party shall not allow, by taking appropriate measures, the manufacture, import or export of mercury-added products listed in Part I of Annex A [of the Convention] after the phase-out date specified for those products". More specifically, this list includes the following non-electronic measuring devices except non-electronic measuring devices installed in large-scale equipment or those used for high precision measurement, where no suitable mercury-free alternative is available:

(a) barometers;

(b) hygrometers;

(c) manometers;

(d) thermometers;

(e) sphygmomanometers.

A similar regulation came into force in Europe on 10 April 2014 (Commission Regulation (EU) No. 847/2012) and a number of manufacturers in Europe are already unable to provide mercury-based instruments.

Therefore mercury based instruments are no longer recommended and it is strongly encouraged to take appropriate measures to put in place a migration strategy to move away from the use of all instruments containing mercury. Due to recent advances in electronic and digital technologies digital electronic barometers, thermometers and hygrometers are nowadays state of the art. They can provide an economical, accurate and reliable alternative to their dangerous, mercury-based precedents and offer other significant advantages in terms of data storage and real-time data display.

1.4.3 Mechanically recording instruments

In many of the mechanically recording instruments used in meteorology, the motion of the sensing element is magnified by levers that move a pen on a chart on a clock-driven drum. Such recorders should be as free as possible from friction, not only in the bearings, but also between the pen and paper. Some means of adjusting the pressure of the pen on the paper should be provided, but this pressure should be reduced to a minimum consistent with a continuous legible trace. Means should also be provided in clock-driven recorders for making time marks. In the design of recording instruments that will be used in cold climates, particular care must be taken to ensure that their performance is not adversely affected by extreme cold and moisture, and that routine procedures (time marks, and so forth) can be carried out by the observers while wearing gloves.

Recording instruments should be compared frequently with instruments of the direct-reading type.

An increasing number of instruments make use of electronic recording in magnetic media or in semiconductor microcircuits. Many of the same considerations given for bearings, friction and cold-weather servicing apply to the mechanical components of such instruments.

1.5 MEASUREMENT STANDARDS, TRACEABILITY AND UNITS

1.5.1 Definitions of standards of measurement

The term “standard” and other similar terms denote the various instruments, methods and scales used to establish the uncertainty of measurements. A nomenclature for standards of measurement is given in the *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*, which was prepared simultaneously by the International Bureau of Weights and Measures (BIPM), the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), the International Laboratory Accreditation Cooperation (ILAC), the International Organization for Standardization (ISO), the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP) and the International Organization of Legal Metrology (OIML), and issued by the Joint Committee for Guides in Metrology (JCGM). The current version is JCGM 200:2012, available at http://www.bipm.org/en/publications/guides/vim.html. Some of the definitions are as follows:

*International System of Units (SI): S*ystem of units, based on the International System of Quantities, their names and symbols, including a series of prefixes and their names and symbols, together with rules for their use, adopted by the General Conference on Weights and Measures (CGPM).

Measurement standard: Realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference.

> Example 1: 1 kg mass measurement standard with an associated standard measurement uncertainty of 3 μg

> Example 2: 100 Ω measurement standard resistor with an associated standard measurement uncertainty of 1 $\mu\Omega$

International measurement standard (international standard): Measurement standard recognized by signatories to an international agreement and intended to serve worldwide.

> Example 1: The international prototype of the kilogramme

National measurement standard (national standard): Measurement standard recognized by national authorities to serve in a State or economy as the basis for assigning quantity values to other measurement standards for the kind of quantity concerned.

Primary measurement standard (primary standard): Measurement standard established using a primary reference measurement procedure, or created as an artefact, chosen by convention.

> Example 1: Primary measurement standard of amount-of-substance concentration prepared by dissolving a known amount of substance of a chemical component to a known volume of solution

> Example 2: Primary measurement standard for pressure based on separate measurements of force and area

Secondary measurement standard (secondary standard): Measurement standard established through calibration with respect to a primary measurement standard for a quantity of the same kind.

Reference measurement standard (reference standard): Measurement standard designated for the calibration of other measurement standards for quantities of a given kind in a given organization or at a given location.

Working measurement standard (working standard): Measurement standard that is used routinely to calibrate or verify measuring instruments or measuring systems.

Notes:
1. A working measurement standard is usually calibrated with respect to a reference measurement standard.

2. In relation to verification, the terms “check standard” or “control standard” are also sometimes used.

Transfer measurement device (transfer device): Device used as an intermediary to compare measurement standards.

Note: Sometimes, measurement standards are used as transfer devices.

Travelling measurement standard (travelling standard): Measurement standard, sometimes of special construction, intended for transport between different locations.

Collective standard: A set of similar material measures or measuring instruments fulfilling, by their combined use, the role of a standard.

Example: The World Radiometric Reference

Notes:
1. A collective standard is usually intended to provide a single value of a quantity.

2. The value provided by a collective standard is an appropriate mean of the values provided by the individual instruments.

Traceability: A property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Metrological traceability: A property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

*Metrological traceability chain (traceability chain): S*equence of measurement standards and calibrations that is used to relate a measurement result to a reference.

Calibration: Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

Notes:
1. A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

2. Calibration should not be confused with adjustment of a measuring system, often mistakenly called “self-calibration”, nor with verification of calibration.

Calibration hierarchy: Sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration.

1.5.2 Traceability assurance

Measurements have a useful meaning if the results will not vary significantly with the usage of different instruments, operators or other parameters in the measurement process. This confidence is based on regulations and international agreements and quality assurance in the measurement process. It is worldwide accepted to assess the quality of measurements by a quantitative statement, which is the measurement uncertainty associated with the measurement result. The confidence in the measurement result and the stated uncertainty relies on the traceability of measurements involving an unbroken and documented chain of comparisons linking measurement result to an internationally agreed measurement standard.

Measurements should be traceable to an internationally defined and accepted reference which is in most cases the International System of Units (SI). Technical and organizational infrastructure was developed and is maintained by the "*Bureau International des Poids et Mesures*" (BIPM). Maintenance of national standards and dissemination of traceability at the national level relies on National Metrology Institutes (NMIs) or Designated Institutes (DIs). The concept of Regional Instrument Centres (RICs) has been established by Regional Associations to support NMHSs in traceability dissemination to their national meteorological standards and related environmental monitoring instruments. Terms of reference (ToR) of RICs are presented in Annex 1.C.

The responsibility for the implementation of traceability assurance on a national level lies with the NMHS, which should ensure all necessary steps to achieve the objective of the strategy. Lack of traceability assurance strongly reduces confidence in measurements and usage of measurements in local and global community.

The strategy for traceability assurance is presented in Annex 1.B.

Instruments in use face very different environmental conditions than when in a controlled laboratory environment. Factors that affect the measured quantity in-vivo (influencing quantities, drift in time, etc.) also have to be quantified and documented for each measurement. The estimated influences will add to the uncertainty value. Only then, can a measurement result be compared with any other traceable result measured in another place and/or time.

In order to promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics, sets of standard procedures and recommended practices have been developed (Volume V, Chapter 4).

1.5.3 Symbols, units and constants

1.5.3.1 Symbols and units

Instrument measurements produce numerical values. The purpose of these measurements is to obtain physical or meteorological quantities representing the state of the local atmosphere. For meteorological practices, instrument readings represent variables, such as "atmospheric pressure", "air temperature" or "wind speed". A variable with symbol a is usually represented in the form $a = \{a\}\cdot[\mathrm{a}]$, where $\{a\}$ stands for the numerical value and [a] stands for the symbol for the unit. General principles concerning quantities, units and symbols are stated in ISO (2009) and IUPAP (1987). The International System of Units should be used as the system of units for the evaluation of meteorological elements included in reports for international exchange. This system is published and updated by BIPM (2006). Guides for the use of SI are issued by the National Institute of Standards and Technology (NIST, 2008) and ISO (2009). Variables not defined as an international symbol by the International System of Quantities (ISQ), but commonly used in meteorology can be found in the *International Meteorological Tables* (WMO, 1966) and relevant chapters in this Guide.

The following units should be used for meteorological observations:

(a) Atmospheric pressure, p, in hectopascals (hPa);[7]

(b) Temperature, t, in degrees Celsius (°C) or T in kelvins (K);

---

[7] The unit "pascal" is the principal SI derived unit for the pressure quantity. The unit and symbol "bar" is a unit outside the SI system; in every document where it is used, this unit (bar) should be defined in relation to the SI. Its continued use is not encouraged. By definition, 1 mbar (millibar) = 1 hPa (hectopascal).

Note: The Celsius and kelvin temperature scales should conform to the actual definition of the International Temperature Scale (ITS-90, see BIPM, 1990).

(c) Wind speed, in both surface and upper-air observations, in metres per second (m s^{-1});

(d) Wind direction in degrees clockwise from true north or on the scale 0–36, where 36 is the wind from true north and 09 the wind from true east (°);

(e) Relative humidity, U, in per cent (%);

Note: BIPM recommends: "When any of the terms, %, ppm, etc. are used, it is important to state the dimensionless quantity whose value is being specified." For example in chapter 4 this recommendation is followed by using %rh.

(f) Precipitation (total amount) in millimetres (mm) or kilograms per square metre (kg m^{-2});[8]

(g) Precipitation intensity, R_i, in millimetres per hour (mm h^{-1}) or kilograms per square metre per second (kg m^{-2} s^{-1});[9]

(h) Snow water equivalent in kilograms per square metre (kg m^{-2});

(i) Evaporation in millimetres (mm);

(j) Visibility in metres (m);

(k) Irradiance in watts per square metre and radiant exposure in joules per square metre (W m^{-2}, J m^{-2});

(l) Duration of sunshine in hours (h);

(m) Cloud height in metres (m);

(n) Cloud amount in oktas;

(o) Geopotential, used in upper-air observations, in standard geopotential metres (m').

Note: Height, level or altitude are presented with respect to a well-defined reference. Typical references are Mean Sea Level (MSL), station altitude or the 1 013.2 hPa plane.

The standard geopotential metre is defined as 0.980 665 of the dynamic metre; for levels in the troposphere, the geopotential is close in numerical value to the height expressed in metres.

1.5.3.2 Constants

The following constants have been adopted for meteorological use:

(a) Absolute temperature of the normal ice point T_0 = 273.15 K (t = 0.00 °C);

(b) Absolute temperature of the triple point of water T = 273.16 K (t = 0.01 °C), by definition of ITS-90;

(c) Standard acceleration of gravity (g_n) = 9.806 65 m s^{-2}.

The values of other constants are given in WMO (1966, 2011*b*).

---

[8] Assuming that 1 mm equals 1 kg m^{-2} independent of temperature.

[9] Recommendation 3 (CBS-XII), Annex 1, adopted through Resolution 4 (EC-LIII).

1.6 UNCERTAINTY OF MEASUREMENTS

1.6.1 Meteorological measurements

1.6.1.1 General

This section deals with definitions that are relevant to the assessment of accuracy and the measurement of uncertainties in physical measurements, and concludes with statements of required and achievable uncertainties in meteorology. First, it discusses some issues that arise particularly in meteorological measurements.

The term *measurement* is carefully defined in 1.6.2, but in most of this Guide it is used less strictly to mean the process of measurement or its result, which may also be called an "observation". A *sample* is a single measurement, typically one of a series of spot or instantaneous readings of a sensing system, from which an average or smoothed value is derived to make an observation. For a more theoretical approach to this discussion, see Volume V, Chapters 2 and 3.

The terms *accuracy*, *error* and *uncertainty* are carefully defined in 1.6.2, which explains that accuracy is a qualitative term, the numerical expression of which is uncertainty. This is good practice and is the form followed in this Guide. Formerly, the common and less precise use of accuracy was as in "an accuracy of $\pm x$", which should read "an uncertainty of x".

1.6.1.2 Sources and estimates of error

The sources of error in the various meteorological measurements are discussed in specific detail in the following chapters of this Guide, but in general they may be seen as accumulating through the chain of traceability and the measurement conditions.

It is convenient to take air temperature as an example to discuss how errors arise, but it is not difficult to adapt the following argument to pressure, wind and other meteorological quantities. For temperature, the sources of error in an individual measurement are as follows:

(a) Errors in the international, national and working standards, and in the comparisons made between them. These may be assumed to be negligible for meteorological applications;

(b) Errors in the comparisons made between the working, travelling and/or check standards and the field instruments in the laboratory or in liquid baths in the field (if that is how the traceability is established). These are small if the practice is good (say ±0.1 K uncertainty at the 95 % confidence level, including the errors in (a) above), but may quite easily be larger, depending on the skill of the operator and the quality of the equipment;

(c) Non-linearity, drift, repeatability and reproducibility in the field thermometer and its transducer (depending on the type of thermometer element);

(d) The effectiveness of the heat transfer between the thermometer element and the air in the thermometer shelter, which should ensure that the element is at thermal equilibrium with the air (related to system time-constant or lag coefficient). In a well-designed aspirated shelter this error will be very small, but it may be large otherwise;

(e) The effectiveness of the thermometer shelter, which should ensure that the air in the shelter is at the same temperature as the air immediately surrounding it. In a well-designed case this error is small, but the difference between an effective and an ineffective shelter may be 3 °C or more in some circumstances;

(f) The exposure, which should ensure that the shelter is at a temperature which is representative of the region to be monitored. Nearby sources and heat sinks (buildings, other unrepresentative surfaces below and around the shelter) and topography (hills, land-water boundaries) may introduce large errors. The station metadata should contain a good and regularly updated description of exposure (see Annex 1.G) to inform data users about possible exposure errors.

Systematic and random errors both arise at all the above-mentioned stages. The effects of the error sources (d) to (f) can be kept small if operations are very careful and if convenient terrain for siting is available; otherwise these error sources may contribute to a very large overall error. However, they are sometimes overlooked in the discussion of errors, as though the laboratory calibration of the instruments could define the total error completely.

Establishing the true value is difficult in meteorology (Linacre, 1992). Well-designed instrument comparisons in the field may establish the characteristics of instruments to give a good estimate of uncertainty arising from stages (a) to (e) above. If station exposure has been documented adequately, the effects of imperfect exposure can be corrected systematically for some parameters (for example, wind; see WMO, 2002) and should be estimated for others.

Comparing station data against numerically analysed fields using neighbouring stations is an effective operational quality control procedure, if there are sufficient reliable stations in the region. Differences between the individual observations at the station and the values interpolated from the analysed field are due to errors in the field as well as to the performance of the station. However, over a period, the average error at each point in the analysed field may be assumed to be zero if the surrounding stations are adequate for a sound analysis. In that case, the mean and standard deviation of the differences between the station and the analysed field may be calculated, and these may be taken as the errors in the station measurement system (including effects of exposure). The uncertainty in the estimate of the mean value in the long term may, thus, be made quite small (if the circumstances at the station do not change), and this is the basis of climate change studies.

1.6.2 Definitions of measurements and measurement errors

The following terminology relating to the accuracy of measurements is based on JCGM (2012), which contains many definitions applicable to the practices of meteorological observations. Very useful and detailed practical guidance on the calculation and expression of uncertainty in measurements is given in ISO/IEC (2008) / JCGM (2008).

Measurement: The process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.

Note: The operations may be performed automatically.

Measuring instrument: device used for making measurements, alone or in conjunction with one or more supplementary devices

EXAMPLES: Platinum resistance thermometer, electronic barometer

Note: instrument is sometimes used without the adjective measuring. If the instrument includes a sensor the adjective sensing may be used.

Sensor: element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured.

EXAMPLES: Sensing coil of a platinum resistance thermometer, Bourdon tube of a pressure gauge

Note: Sometimes the term “sensing element” is used for this concept.

Result of a measurement: A set of quantity values being attributed to a measurand together with any other available relevant information.

Notes:

1. When a result is given, it should be made clear whether it refers to the indication, the uncorrected result or the corrected result, and whether several values are averaged.

2. A complete statement of the result of a measurement includes information about the uncertainty of the measurement.

Corrected result: The result of a measurement after correction for systematic error.

Value (of a quantity): A number and reference (unit) together expressing the magnitude of a quantity.

Example: Length of a rod: 5.34 m

True value (of a quantity): The quantity value consistent with the definition of a quantity.

Notes:

1. This is a value that would be obtained by a perfect measurement.

2. True values are by nature indeterminate.

Accuracy (of a measurement): A qualitative term referring to the closeness of agreement between a measured quantity value and a true quantity value of a measurand. The accuracy of a measurement is sometimes understood as the closeness of agreement between measured quantity values that are being attributed to the measurand. It is possible to refer to an instrument or a measurement as having a high accuracy, but the quantitative measure of the accuracy is expressed in terms of uncertainty.

Uncertainty: A non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Repeatability: The closeness of agreement between indications or measured quantity values obtained on the same or similar objects under a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements over a short period of time.

Note: Relevant statistical terms are given in ISO (1994*a*) and ISO (1994*b*).

Reproducibility: The closeness of agreement between indications or measured quantity values obtained on the same or similar objects under a set of conditions that includes different locations, operators and measuring systems, and replicate measurements.

Error (of measurement): Measured quantity value minus a reference quantity value.

Instrumental bias: Average of replicate indications minus a reference quantity value.

Random error: The component of measurement error that in replicate measurements varies in an unpredictable manner.

Notes:

1. Random measurement error equals measurement error minus systematic measurement error.

2. A reference quantity value for a random measurement error is the average that would ensue from an infinite number of replicate measurements of the same measurand.

Systematic error: The component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

Notes:

1. Systematic measurement error equals measurement error minus random measurement error.

2. Like true value, systematic error and its causes cannot be completely known.

Correction: Compensation for an estimated systematic effect.

Some definitions are also repeated in Volume V, Chapter 4 for convenience.

1.6.3 Characteristics of instruments

Some other properties of instruments which must be understood when considering their uncertainty are taken from JCGM (2012).

Sensitivity: Quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured.

Note: The sensitivity of a measuring system can depend on the value of the quantity being measured.

Discrimination threshold: The largest change in a value of a quantity being measured that causes no detectable change in the corresponding indication.

Resolution: The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

Hysteresis: The property of a measuring instrument whereby its response to a given stimulus depends on the sequence of preceding stimuli.

Stability (of an instrument): The property of a measuring instrument whereby its metrological properties remain constant in time.

Drift: A continuous or incremental change over time in indication due to changes in metrological properties of a measuring instrument.

Step response time: The duration between the instant when an input quantity value of a measuring instrument or measuring system is subjected to an abrupt change between two specified constant quantity values and the instant when a corresponding indication settles within specified limits around its final steady value.

The following other definitions are used frequently in meteorology:

Statements of response time: The time for 90 % of the step change is often given. The time for 50 % of the step change is sometimes referred to as the half-time.

Calculation of response time: In most simple systems, the response to a step change is:

$$Y = A\left(1 - e^{-t/\tau}\right) \tag{1.1}$$

where Y is the change after elapsed time t; A is the amplitude of the step change applied; t is the elapsed time from the step change; and τ is a characteristic variable of the system having the dimension of time.

The variable τ is referred to as the time constant or the lag coefficient. It is the time taken, after a step change, for the instrument to reach $1/e$ of the final steady reading.

In other systems, the response is more complicated and will not be considered here (see also Volume V, Chapter 2).

Lag error: The error that a set of measurements may possess due to the finite response time of the observing instrument.

1.6.4 The measurement uncertainties of a single instrument

ISO/IEC (2008) / JCGM (2008) should be used for the expression and calculation of uncertainties. It gives a detailed practical account of definitions and methods of reporting, and a comprehensive description of suitable statistical methods, with many illustrative examples.

1.6.4.1 The statistical distributions of observations

To determine the uncertainty of any individual measurement, a statistical approach is to be considered in the first place. For this purpose, the following definitions are stated (ISO/IEC (2008) / JCGM (2008); JCGM, 2012):

(a) Standard uncertainty;

(b) Expanded uncertainty;

(c) Variance, standard deviation;

(d) Statistical coverage interval.

If n comparisons of an operational instrument are made with the measured variable and all other significant variables held constant, if the best estimate of the true value is established by use of a reference standard, and if the measured variable has a Gaussian distribution,[10] the results may be displayed as in Figure 1.2.

ELEMENT 3: Floating object (Automatic)
ELEMENT 4: Picture inline fix size
Element Image: 8_I_1-2_en.eps
END ELEMENT

Figure 1.2. The distribution of data in an instrument comparison

END ELEMENT

In this figure, T is the true value, $\bar{O}$ is the mean of the n values O observed with one instrument, and σ is the standard deviation of the observed values with respect to their mean values.

In this situation, the following characteristics can be identified:

(a) The systematic error, often termed bias, given by the algebraic difference $\bar{O} - T$. Systematic errors cannot be eliminated but may often be reduced. A correction factor can be applied to compensate for the systematic effect. Typically, appropriate calibrations and adjustments should be performed to eliminate the systematic errors of a measuring instrument. Systematic errors due to environmental or siting effects can only be reduced;

(b) The random error, which arises from unpredictable or stochastic temporal and spatial variations. The measure of this random effect can be expressed by the standard deviation σ determined after n measurements, where n should be large enough. In principle, σ is a measure for the uncertainty of $\bar{O}$;

(c) The accuracy of measurement, which is the closeness of the agreement between the result of a measurement and a true value of the measurand. The accuracy of a measuring instrument is the ability to give responses close to a true value. Note that "accuracy" is a qualitative concept;

(d) The uncertainty of measurement, which represents a parameter associated with the result of a measurement, that characterizes the dispersion of the values that could be reasonably attributed to the measurand. The uncertainties associated with the random and systematic effects that give rise to the error can be evaluated to express the uncertainty of measurement.

---

[10] However, note that several meteorological variables do not follow a Gaussian distribution. See 1.6.4.2.3.

1.6.4.2 Estimating the true value

In normal practice, observations are used to make an estimate of the true value. If a systematic error does not exist or has been removed from the data, the true value can be approximated by taking the mean of a very large number of carefully executed independent measurements. When fewer measurements are available, their mean has a distribution of its own and only certain limits within which the true value can be expected to lie can be indicated. In order to do this, it is necessary to choose a statistical probability (level of confidence) for the limits, and the error distribution of the means must be known.

A very useful and clear explanation of this notion and related subjects is given by Natrella (1966). Further discussion is given by Eisenhart (1963).

1.6.4.2.1 Estimating the true value – n large

When the number of n observations is large, the distribution of the means of samples is Gaussian, even when the observational errors themselves are not. In this situation, or when the distribution of the means of samples is known to be Gaussian for other reasons, the limits between which the true value of the mean can be expected to lie are obtained from:

Upper limit: $$L_U = \bar{X} + k \cdot \frac{\sigma}{\sqrt{n}} \qquad (1.2)$$

Lower limit: $$L_L = \bar{X} - k \cdot \frac{\sigma}{\sqrt{n}} \qquad (1.3)$$

where $\bar{X}$ is the average of the observations $\bar{O}$ corrected for systematic error; σ is the standard deviation of the whole population; and k is a factor, according to the chosen level of confidence, which can be calculated using the normal distribution function.

Some values of k are as follows:

TABLE: Table horizontal lines

Level of confidence	*90 %*	*95 %*	*99 %*
k	1.645	1.960	2.575

The level of confidence used in the table above is for the condition that the true value will not be outside the one particular limit (upper or lower) to be computed. When stating the level of confidence that the true value will lie between both limits, both the upper and lower outside zones have to be considered. With this in mind, it can be seen that k takes the value 1.96 for a 95 % probability, and that the true value of the mean lies between the limits L_U and L_L.

1.6.4.2.2 Estimating the true value – n small

When n is small, the means of samples conform to Student's t distribution provided that the observational errors have a Gaussian or near-Gaussian distribution. In this situation, and for a chosen level of confidence, the upper and lower limits can be obtained from:

Upper limit: $$L_U \approx \bar{X} + t \cdot \frac{\hat{\sigma}}{\sqrt{n}} \qquad (1.4)$$

Lower limit: $$L_L \approx \bar{X} - t \cdot \frac{\hat{\sigma}}{\sqrt{n}} \qquad (1.5)$$

where t is a factor (Student's t) which depends upon the chosen level of confidence and the number n of measurements; and $\hat{\sigma}$ is the estimate of the standard deviation of the whole population, made from the measurements obtained, using:

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2}{n-1} = \frac{n}{n-1}\cdot\sigma_0^2 \qquad (1.6)$$

where X_i is an individual value O_i corrected for systematic error.

Some values of t are as follows:

TABLE: Table horizontal lines

Level of confidence	*90 %*	*95 %*	*99 %*
df			
1	6.314	12.706	63.657
4	2.132	2.776	4.604
8	1.860	2.306	3.355
60	1.671	2.000	2.660

where df is the degrees of freedom related to the number of measurements by $df = n - 1$. The level of confidence used in this table is for the condition that the true value will not be outside the one particular limit (upper or lower) to be computed. When stating the level of confidence that the true value will lie between the two limits, allowance has to be made for the case in which n is large. With this in mind, it can be seen that t takes the value 2.306 for a 95 % probability that the true value lies between the limits L_U and L_L, when the estimate is made from nine measurements (df = 8).

The values of t approach the values of k as n becomes large, and it can be seen that the values of k are very nearly equalled by the values of t when df equals 60. For this reason, tables of k (rather than tables of t) are quite often used when the number of measurements of a mean value is greater than 60 or so.

1.6.4.2.3 Estimating the true value – additional remarks

Investigators should consider whether or not the distribution of errors is likely to be Gaussian. The distribution of some variables themselves, such as sunshine, visibility, humidity and ceiling, is not Gaussian and their mathematical treatment must, therefore, be made according to rules valid for each particular distribution (Brooks and Carruthers, 1953).

In practice, observations contain both random and systematic errors. In every case, the observed mean value has to be corrected for the systematic error insofar as it is known. When doing this, the estimate of the true value remains inaccurate because of the random errors as indicated by the expressions and because of any unknown component of the systematic error. Limits should be set to the uncertainty of the systematic error and should be added to those for random errors to obtain the overall uncertainty. However, unless the uncertainty of the systematic error can be expressed in probability terms and combined suitably with the random error, the level of confidence is not known. It is desirable, therefore, that the systematic error be fully determined.

1.6.4.3 Expressing the uncertainty

If random and systematic effects are recognized, but reduction or corrections are not possible or not applied, the resulting uncertainty of the measurement should be estimated. This uncertainty is determined after an estimation of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects. It is common practice to express the uncertainty as “expanded uncertainty” in relation to the “statistical coverage interval”. To be consistent with common practice in metrology, the 95 % confidence level, or k = 2, should be used for all types of measurements, namely:

$$< expanded\ uncertainty >= k \cdot \sigma = 2 \cdot \sigma \qquad (1.7)$$

As a result, the true value, defined in 1.6.2, will be expressed as:

$$< true\ value >=< measured\ value > \pm < expanded\ uncertainty >=< measured\ value > \pm 2\sigma$$

1.6.4.4 Measurements of discrete values

While the state of the atmosphere may be described well by physical variables or quantities, a number of meteorological phenomena are expressed in terms of discrete values. Typical examples of such values are the detection of sunshine, precipitation or lightning and freezing precipitation. All these parameters can only be expressed by "yes" or "no". For a number of parameters, all of which are members of the group of present weather phenomena, more than two possibilities exist. For instance, discrimination between drizzle, rain, snow, hail and their combinations is required when reporting present weather. For these practices, uncertainty calculations like those stated above are not applicable. Some of these parameters are related to a numerical threshold value (for example, sunshine detection using direct radiation intensity), and the determination of the uncertainty of any derived variable (for example, sunshine duration) can be calculated from the estimated uncertainty of the source variable (for example, direct radiation intensity). However, this method is applicable only for derived parameters, and not for the typical present weather phenomena. Although a simple numerical approach cannot be presented, a number of statistical techniques are available to determine the quality of such observations. Such techniques are based on comparisons of two datasets, with one set defined as a reference. Such a comparison results in a contingency matrix, representing the cross-related frequencies of the mutual phenomena. In its most simple form, when a variable is Boolean ("yes" or "no"), such a matrix is a two by two matrix with the number of equal occurrences in the elements of the diagonal axis and the "missing hits" and "false alarms" in the other elements. Such a matrix makes it possible to derive verification scores or indices to be representative for the quality of the observation. This technique is described by Murphy and Katz (1985). An overview is given by Kok (2000).

1.6.5 Accuracy requirements

1.6.5.1 General

The uncertainty with which a meteorological variable should be measured varies with the specific purpose for which the measurement is required. In general, the limits of performance of a measuring device or system will be determined by the variability of the element to be measured on the spatial and temporal scales appropriate to the application.

Any measurement can be regarded as made up of two parts: the signal and the noise. The signal constitutes the quantity which is to be determined, and the noise is the part which is irrelevant. The noise may arise in several ways: from observational error, because the observation is not made at the right time and place, or because short-period or small-scale irregularities occur in the observed quantity which are irrelevant to the observations and need to be smoothed out. Assuming that the observational error could be reduced at will, the noise arising from other causes would set a limit to the accuracy. Further refinement in the observing technique would improve the measurement of the noise but would not give much better results for the signal.

At the other extreme, an instrument – the error of which is greater than the amplitude of the signal itself – can give little or no information about the signal. Thus, for various purposes, the amplitudes of the noise and the signal serve, respectively, to determine:

(a) The limits of performance beyond which improvement is unnecessary;

(b) The limits of performance below which the data obtained would be of negligible value.

This argument, defining and determining limits (a) and (b) above, was developed extensively for upper-air data by WMO (1970). However, statements of requirements are usually derived not from such reasoning but from perceptions of practically attainable performance, on the one hand, and the needs of the data users, on the other.

1.6.5.2 Required and achievable performance

The performance of a measuring system includes its reliability, capital, recurrent and lifetime cost, and spatial resolution, but the performance under discussion here is confined to uncertainty (including scale resolution) and resolution in time.

Various statements of requirements have been made, and both needs and capability change with time. The statements given in Annex 1.A are the most authoritative at the time of writing, and may be taken as useful guides for development, but they are not fully definitive.

The requirements for the variables most commonly used in synoptic, aviation and marine meteorology, and in climatology are summarized in Annex 1.A.[11] It gives requirements only for surface measurements that are exchanged internationally. Details on the observational data requirements for Global Data-processing and Forecasting System Centres for global and regional exchange are given in WMO (2010*c*). The uncertainty requirement for wind measurements is given separately for speed and direction because that is how wind is reported.

The ability of individual sensing instruments or observing systems to meet the stated requirements is changing constantly as instrumentation and observing technology advance. The characteristics of typical instruments or systems currently available are given in Annex 1.A.[12] It should be noted that the achievable operational uncertainty in many cases does not meet the stated requirements. For some of the quantities, these uncertainties are achievable only with the highest quality equipment and procedures.

Uncertainty requirements for upper-air measurements are dealt with in Volume I, Chapter 12.

---

[11] Established by the CBS Expert Team on Requirements for Data from Automatic Weather Stations (2004) and approved by the president of CIMO for inclusion in this Guide after consultation with the presidents of the other technical commissions.

[12] Established by the CIMO Expert Team on Surface Technology and Measurement Techniques (2004) and confirmed for inclusion in this Guide by the president of CIMO.

SECTION: Landscape chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

ANNEX 1.A. OPERATIONAL MEASUREMENT UNCERTAINTY REQUIREMENTS AND INSTRUMENT PERFORMANCE REQUIREMENTS

(See explanatory notes at the end of the table; numbers in the top row indicate column numbers.)

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
1. Temperature								
1.1 Air temperature	−80 – +60 °C	0.1 K	I	0.3 K for ≤ −40 °C 0.1 K for > −40 °C and ≤ +40 °C 0.3 K for > +40 °C	20 s	1 min	0.2 K	Achievable uncertainty and effective time-constant may be affected by the design of the thermometer solar radiation screen Time constant depends on the airflow over the sensing element
1.2 Extremes of air temperature	−80 – +60 °C	0.1 K	I	0.5 K for ≤ −40 °C 0.3 K for > −40 °C and ≤ +40 °C 0.5 K for > +40 °C	20 s	1 min	0.2 K	
1.3 Sea-surface temperature	−2 – +40 °C	0.1 K	I	0.1 K	20 s	1 min	0.2 K	
1.4 Soil temperature	−50 – +50 °C	0.1 K	I		20 s	1 min	0.2 K	

SECTION: Landscape page with header_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
2. Humidity								
2.1 Dewpoint temperature	−80 – +35 °C	0.1 K	I	0.1 K	20 s	1 min	0.25 K	Measurement uncertainty depends on the deviation from air temperature
						Wet-bulb temperature (psychrometer)		
2.2 Relative humidity	0 – 100 %	1 %	I	1 %	20 s	1 min	0.2 K	If measured directly and in combination with air temperature (dry bulb) Large errors are possible due to aspiration and cleanliness problems (see also note 11) Threshold of 0 °C to be noticed for wet bulb
					{			
							Solid state and others	
					40 s	1 min	3 %	Time constant and achievable uncertainty of solid-state sensing instruments may show significant temperature and humidity dependence

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
3. Atmospheric pressure								
3.1 Pressure	500 – 1 080 hPa	0.1 hPa	I	0.1 hPa	2 s	1 min	0.15 hPa	Both station pressure and MSL pressure Measurement uncertainty is seriously affected by dynamic pressure due to wind if no precautions are taken Inadequate temperature compensation of the transducer may affect the measurement uncertainty significantly MSL pressure is affected by the uncertainty in altitude of the barometer for measurements onboard ships
3.2 Tendency	Not specified	0.1 hPa	I	0.2 hPa			0.2 hPa	Difference between instantaneous values

SECTION: Landscape page with header_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
4. Clouds								
4.1 Cloud amount	0/8 – 8/8	1/8	I	1/8	n/a		2/8	Period clustering algorithms may be used to estimate low cloud amount automatically
4.2 Height of cloud base	0 m – 30 km	10 m	I	10 m for ≤ 100 m 10 % for > 100 m	n/a		~10 m	Achievable measurement uncertainty can be determined with a hard target. No clear definition exists for instrumentally measured cloud-base height (e.g. based on penetration depth or significant discontinuity in the extinction profile) Significant bias during precipitation
4.3 Height of cloud top	Not available							

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*

5. Wind								
5.1 Speed	0 – 75 m s^{-1}	0.5 m s^{-1}	A	0.5 m s^{-1} for ≤ 5 m s^{-1} 10 % for > 5 m s^{-1}	Distance constant 2 – 5 m	2 and/or 10 min	0.5 m s^{-1} for ≤ 5 m s^{-1} 10 % for > 5 m s^{-1}	Average over 2 and/or 10 min Non-linear devices. Care needed in design of averaging process Distance constant is usually expressed as response length Averages computed over Cartesian components (see Volume V, Chapter 3, 3.6 of this Guide) When using ultrasonic anemometers, no distance constant or time constant is needed. For moving mobile stations, the movement of the station needs to be taken into account, inclusive of its uncertainty.
5.2 Direction	0 – 360°	1°	A	5°	Damping ratio > 0.3	2 and/or 10 min	5°	
5.3 Gusts	0.1 – 150 m s^{-1}	0.1 m s^{-1}	A	10 %		3 s	0.5 m s^{-1} for ≤ 5 m s^{-1} 10 % for > 5 m s^{-1}	Highest 3 s average should be recorded

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
6. Precipitation								
6.1 Amount (daily)	0 – 500 mm	0.1 mm	T	0.1 mm for ≤ 5 mm 2 % for > 5 mm	n/a	n/a	The larger of 5 % or 0.1 mm	Quantity based on daily amounts Measurement uncertainty

								depends on aerodynamic collection efficiency of gauges and evaporation losses in heated gauges
6.2 Depth of snow	0 – 25 m	1 cm	I	1 cm for ≤ 20 cm 5 % for > 20 cm	< 10 s	1 min	1 cm	Average depth over an area representative of the observing site
6.3 Thickness of ice accretion on ships	Not specified	1 cm	I	1 cm for ≤ 10 cm 10 % for > 10 cm				
6.4 Precipitation intensity	0.02 mm h^{-1} – 2 000 mm h^{-1}	0.1 mm h^{-1}	I	(trace): n/a for 0.02 – 0.2 mm h^{-1} 0.1 mm h^{-1} for 0.2 – 2 mm h^{-1} 5 % for > 2 mm h^{-1}	< 30 s	1 min	Under constant flow conditions in laboratory, 5 % above 2 mm h^{-1}, 2 % above 10 mm h^{-1} In field, 5 mm h^{-1} and 5 % above 100 mm h^{-1}	Uncertainty values for liquid precipitation only Uncertainty is seriously affected by wind Instruments may show significant non-linear behaviour For < 0.2 mm h^{-1}: detection only (yes/no) instrument time-constant is significantly affected during solid precipitation using catchment type of gauges
6.5 Precipitation duration (daily)	0 – 24 h	60 s	T	n/a	60 s			Threshold value of 0.02 mm h^{-1}

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*

7. Radiation								
7.1 Sunshine duration (daily)	0 – 24 h	60 s	T	0.1 h	20 s	n/a	The larger of 0.1 h or 2 %	
7.2 Net radiation, radiant exposure (daily)	Not specified	1 J m^{-2}	T	0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} 5 % for > 8 MJ m^{-2}	20 s	n/a	15 %	Radiant exposure expressed as daily sums (amount) of (net) radiation Best achievable operational uncertainty is obtained by combining the measurements of two pyranometers and two pyrgeometers
7.3 Global downward/upward solar radiation	Not specified	1 J m^{-2}	T	2 %	20 s	n/a	5 % (daily) 8 % (hourly)	Daily total exposure
7.4 Downward/upward long-wave radiation at Earth surface	Not specified	1 J m^{-2}	T	5 %	20 s	n/a	10 %	

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
8. Visibility								
8.1 Meteorological optical range	10 m – 100 km	1 m	I	50 m for ≤ 600 m 10 % for > 600 m –	< 30 s	1 and 10 min	The larger of	Achievable measurement uncertainty may depend on

(MOR)				≤ 1 500 m 20 % for > 1 500 m			20 m or 20 %	the cause of obscuration Quantity to be averaged: extinction coefficient (see Volume V, Chapter 3, 3.6 of this Guide). Preference for averaging logarithmic values
8.2 Runway visual range (RVR)	10 m – 2 000 m	1 m	A	10 m for ≤ 400 m 25 m for > 400 m – ≤ 800 m 10 % for > 800 m	< 30 s	1 and 10 min	The larger of 20 m or 20 %	In accordance with WMO-No. 49, Volume II, Attachment A (2004 ed.) and ICAO Doc 9328-AN/908 (second ed., 2000) New versions of these documents may exist, specifying other values.
8.3 Background luminance	0 – 40 000 cd m^{-2}	1 cd m^{-2}	I		30 s	1 min	10 %	Related to 8.2 RVR

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table horizontal lines

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Variable	*Range*	*Reported resolution*	*Mode of measurement/observation*	*Required measurement uncertainty*	*Instrument time-constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
9. Waves								
9.1 Significant wave height	0 – 50 m	0.1 m	A	0.5 m for ≤ 5 m 10 % for > 5 m	0.5 s	20 min	0.5 m for ≤ 5 m 10 % for > 5 m	Average over 20 min for instrumental measurements
9.2 Wave period	0 – 100 s	1 s	A	0.5 s	0.5 s	20 min	0.5 s	Average over 20 min for instrumental measurements

9.3 Wave direction	0 – 360°	1°	A	10°	0.5 s	20 min	20°	Average over 20 min for instrumental measurements
10. Evaporation								
10.1 Amount of pan evaporation	0 – 100 mm	0.1 mm	T	0.1 mm for ≤ 5 mm 2 % for > 5 mm	n/a			

Notes:

1. Column 1 gives the basic variable.
2. Column 2 gives the common range for most variables; limits depend on local climatological conditions.
3. Column 3 gives the most stringent resolution as determined by the *Manual on Codes* (WMO-No. 306).
4. In column 4:

   I = Instantaneous: In order to exclude the natural small-scale variability and the noise, an average value over a period of 1 min is considered as a minimum and most suitable; averages over periods of up to 10 min are acceptable.

   A = Averaging: Average values over a fixed period, as specified by the coding requirements.

   T = Totals: Totals over a fixed period, as specified by coding requirements.

5. Column 5 gives the recommended measurement uncertainty requirements for general operational use, i.e. of Level II data according to FM 12, 13, 14, 15 and its BUFR equivalents. They have been adopted by all eight technical commissions and are applicable for synoptic, aeronautical, agricultural and marine meteorology, hydrology, climatology, etc. These requirements are applicable for both manned and automatic weather stations as defined in the *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160). Individual applications may have less stringent requirements. The stated value of required measurement uncertainty represents the uncertainty of the reported value with respect to the true value and indicates the interval in which the true value lies with a stated probability. The recommended probability level is 95 % ($k = 2$), which corresponds to the 2 σ level for a normal (Gaussian) distribution of the variable. The assumption that all known corrections are taken into account implies that the errors in reported values will have a mean value (or bias) close to zero. Any residual bias should be small compared with the stated measurement uncertainty requirement. The true value is the value which, under operational conditions, perfectly characterizes the variable to be measured/observed over the representative time interval, area and/or volume required, taking into account siting and exposure.

SECTION: Landscape page with header_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

TABLE: Table no lines

Notes *(cont.)*

6. Columns 2 to 5 refer to the requirements established by the CBS Expert Team on Requirements for Data from Automatic Weather Stations in 2004.

7. Columns 6 to 8 refer to the typical operational performance established by the CIMO Expert Team on Surface Technology and Measurement Techniques in 2004.

8. Achievable measurement uncertainty (column 8) is based on instrument performance under nominal and recommended exposure that can be achieved in operational practice. It should be regarded as a practical aid to users in defining achievable and affordable requirements.

9. n/a = not applicable.

10. The term *uncertainty* has preference over *accuracy* (i.e. uncertainty is in accordance with ISO/IEC/JCGM standards on the uncertainty of measurements (ISO/IEC (2008) / JCGM (2008)).

11. Dewpoint temperature, relative humidity and air temperature are linked, and thus their uncertainties are linked. When averaging, preference is given to absolute humidity as the principal variable.

SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

ANNEX 1.B: STRATEGY FOR TRACEABILITY ASSURANCE

1. INTRODUCTION

Traceability of measurement and calibration results plays a key role for many application areas, ranging obviously from the assessment of climate variability and changes, but also to aspects that may have strong economic and legal impacts in the context of issuance of warnings for severe weather to protect lives and livelihood.

Ensuring metrological traceability enables full confidence in the validity of measurement results, which leads to confidence in the implications of the measurement data: in the forecasts and warnings derived from the measurements; in climate analyses and trends derived from the measurements. And this in turn leads to improvements in disaster risk reduction, climate change mitigation, advice for policy developers, human health and safety, and property protection.

On the other hand, the lack of traceability of measurement results was recognized as major concern by Commission for Instruments and Methods of Observation (CIMO) because the full potential of WMO Integrated Global Observing System (WIGOS) would be brought into question without regular traceability. Therefore, CIMO stressed the need to sensitize NMHSs to the necessity of regular instrument calibrations, in addition to preventive maintenance and periodical instrument checks, as an essential tool to ensure the required traceability and quality of measurement results.

Numerous developing country Members have no calibration laboratory at all to ensure the traceability of their instruments. Some Members are also facing challenges with the calibration of their network instruments and are replacing a comprehensive calibration strategy with a policy of carrying out field verification checks to identify instruments which are out of the required uncertainties and to perform complete laboratory calibrations only of those instruments which were identified as not meeting the expected uncertainties during the field verification check. Field verification check is related to on-site regular calibration and should be distinguished from the field inspection which can be considered as a “one-point calibration”.

The strategy presented in this Annex seeks to build upon best available practices to strengthen calibration services and improve traceability assurance across WMO Members. It focuses on providing widely acceptable guidelines in order to increase confidence in measurement results.

2. OBJECTIVE OF THE STRATEGY

The main objective of the calibration strategy for traceability assurance is to ensure the proper traceability of measurement and calibration results to the International System of Units (SI), through an unbroken chain of calibrations, each contributing to the measurement uncertainty.

This strategy applies to meteorological measurements for which a traceability chain to SI is well established.

The strategy aims to provide guidance on how to effectively and efficiently achieve this objective.

3. RESPONSIBILITY FOR IMPLEMENTING THE STRATEGY

The responsibility for traceability assurance lies with WMO Members, which should enable all the required calibrations as well as other necessary steps to achieve the objective of the strategy.

It is up to each NMHS to choose the most suitable approach for their traceability assurance, but ensuring the metrological traceability of all measurement results is strongly recommended.

4. WAYS OF TRACEABILITY ASSURANCE

Simplifying the ISO/JCGM definition, metrological traceability could be described as a direct link between a result of a measurement made in the field and a result obtained by the calibration process in a calibration laboratory. It ensures that different measurement methods and instruments used in different countries at different times produce reliable, repeatable, reproducible, compatible and comparable measurement results. When a measurement result is metrologically traceable, it can be confidently linked to the internationally-accepted measurement references.

At the top of the metrological traceability chain there is an internationally defined and accepted reference, in most cases the International System of Units (SI), whose technical and organizational infrastructure has been developed and maintained by the *Bureau International des Poids et Mesures* – BIPM (www.bipm.org).

The framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue is called the CIPM Mutual Recognition Arrangement (CIPM MRA). The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available from the CIPM MRA Key Comparison Database (KCDB), (http://kcdb.bipm.org/).

NMIs are responsible for maintenance of national standards and dissemination of traceability on the national level, either by themselves or by Designated Institutes (DIs). DIs are well experienced institutes, operating at the top of the national metrology system, but are not part of formal NMI structure. They are designated to be responsible for certain national standards and associated services that are not covered by the regular activities of NMIs.

Further dissemination of traceability relies on accredited calibration laboratories whose implemented quality management system is accredited by national accreditation body. National accreditation bodies are usually signatories of International Laboratory Accreditation Cooperation Mutual Recognition Arrangement (ILAC MRA) which ensures the acceptance of and confidence in calibration certificates across national borders.

Whenever possible, all the measurements within any particular country have to be traceable to SI.

Taking into account all aforementioned, as well as WMO Members’ capabilities and needs, the following ways of traceability assurance can be identified:

4.1 Fully assured traceability – target, high confidence level in measurements.

4.2 Assured traceability (without accreditation) – good confidence level but some risks, improvement recommended.

4.3 Partially assured traceability – poor confidence and high risk, improvement required.

4.4 Lack of traceability – level of confidence cannot be assessed, urgent need for improvement.

4.1 Fully assured traceability – target, high confidence level in measurements

This way of traceability assurance (Figure 1.B.1) ensures fully traceable meteorological measurement results provided by particular NMHS’s service, to the international standards. The whole traceability chain is covered by accreditation according to ISO/IEC 17025 and /or by CIPM MRA.

NMHS’s field instruments have to be calibrated in the accredited calibration laboratory regularly, ensuring the highest achievable measurement uncertainties.

In case that calibration laboratory is also accredited for on-site calibrations that cover the whole range of meteorological parameters, those calibrations can be performed, but particular care on the required and achievable uncertainties must be taken into account.

If on-site calibrations are not covered by accreditation they must not be used for regular traceability assurance, but as field verification checks only. Field checks are not part of traceability assurance. They can only be used as an additional quality control aiming to identify instruments out of required uncertainties.

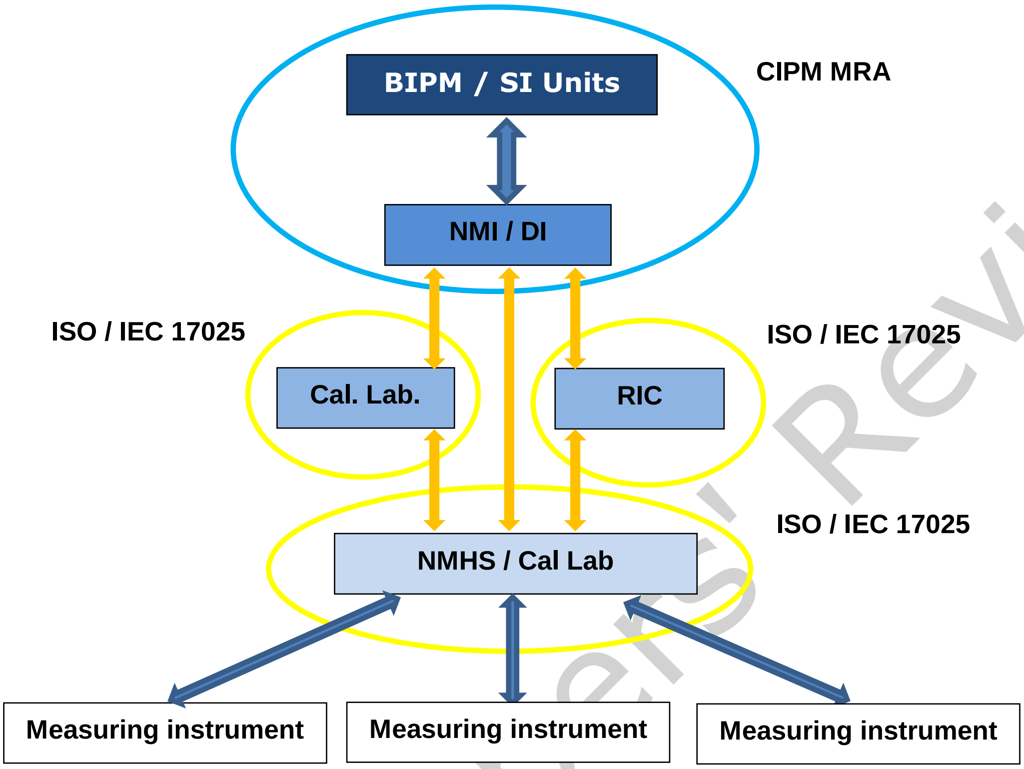

Figure 1.B.1: Fully assured traceability - target, high confidence level in measurements

The following preconditions must be met to achieve this status:

- NMHS has a calibration laboratory.
- Laboratory personnel are well trained and competent to properly operate laboratory standards and equipment.
- Calibration standards and equipment meet the target uncertainties required for calibrations of meteorological instruments.
- Calibration standards and equipment are regularly calibrated and maintained.
- Quality management system, including all the calibration procedures, working instructions and forms, is well documented and applied in laboratory work.
- Calibration laboratory is accredited according to ISO/IEC 17025.
- Calibration laboratory participates in interlaboratory comparisons.

A determined engagement of NMHS’s management board to support continuous strengthening of their calibration laboratory should be stated. This should be followed by a clear policy on the needs for regular calibrations of meteorological instruments for which standards exist, under the responsibility of NMHS, including the defined calibration intervals, as well as policy on implementation of calibration results.

Traceability of the laboratory standards and equipment has to be assured, by the means of calibrations at NMI or DI, accredited WMO Regional Instrument Centre (RIC), or other accredited calibration laboratory, aiming at meeting the requirements of the Members in terms of target uncertainty.

The NMHS's calibration laboratory should also, jointly with other relevant departments, develop procedures aiming to avoid gaps in field measurements due to calibration activities. This should be achieved by a small reserve of calibrated instruments that can be used as a replacement set for the instruments in the network. Those recovered should be calibrated in the laboratory forming, as a consequence, a new set of replacement and so on, to cover the whole network.

Additional quality control could be assured by performing non-accredited on-site calibrations or field verification checks, but only to identify instruments out of uncertainty specifications. Those identified instruments must be calibrated according to the accredited calibration methods.

A set of travelling standards and / or portable calibration devices used for non-accredited on-site calibrations or field checks has to be regularly calibrated in the accredited calibration laboratory, and checked before and after field use.

4.2 Assured traceability (without accreditation) – good confidence level but some risks, improvement recommended

This way of traceability assurance (Figure 1.B.2) is still appropriate and acceptable, but does not ensure fully traceable meteorological measurement results. It is applicable to those NMHSs with calibration facilities, but without accreditation according to ISO/IEC 17025. Although those calibration laboratories are not accredited, their calibration standards have to be calibrated by accredited calibration laboratories, accredited RICs, or by laboratories that are signatories of CIPM MRA. The least appropriate way, but still acceptable, could be a calibration done by non-accredited RIC, but that RIC must demonstrate fully assured traceability of its calibration standards.

NMHS's field instruments have to be calibrated either in the calibration laboratory (if it exists), or on site by portable calibration devices that are calibrated at accredited laboratories and that cover the whole range of meteorological parameters. All calibrations have to be performed regularly ensuring the highest achievable measurement uncertainty.

Field verification checks can be used only as an additional quality control, aiming to identify instruments out of required uncertainties, but not for the traceability assurance.

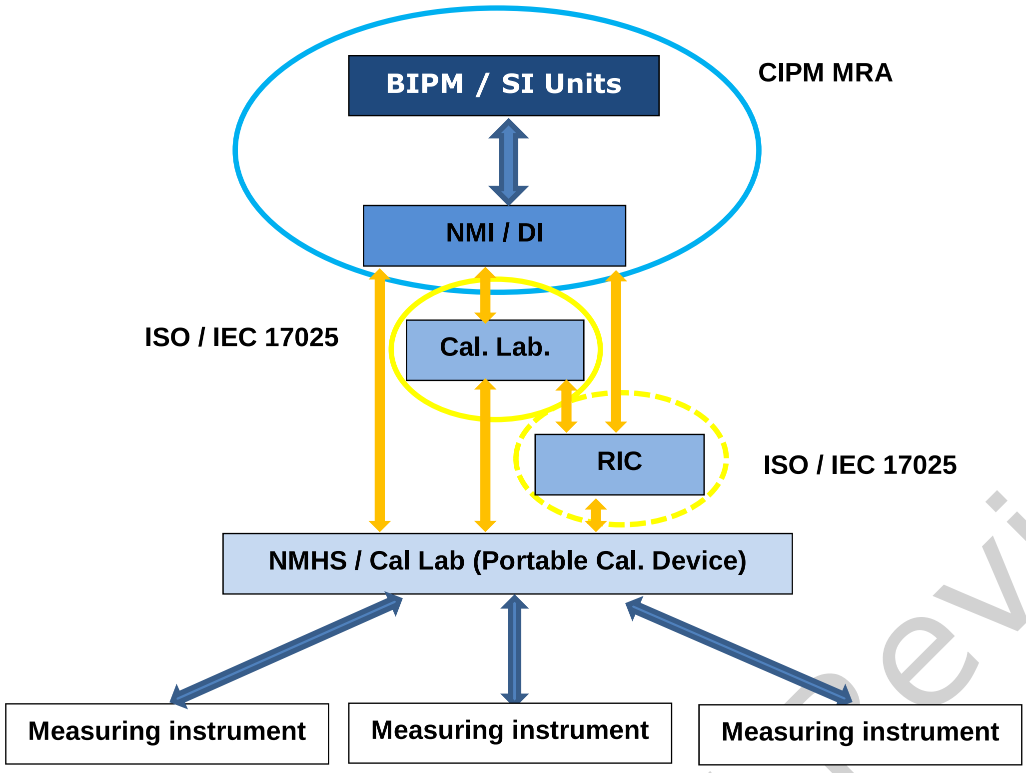

Figure 1.B.2: Assured traceability (without accreditation) – good confidence level but some risks, improvement recommended

The following preconditions must be met to achieve this status:

- NMHS has a calibration laboratory, or at least portable calibration devices covering the whole ranges of measured meteorological parameters.
- Laboratory personnel are well trained and competent to properly operate calibration standards and equipment.
- Calibration standards and equipment meet the target uncertainties required for calibrations of meteorological instruments.
- Calibration standards and equipment are regularly calibrated and maintained.

In addition, following is highly recommended:

- Quality management system, including all the calibration procedures, working instructions and forms, should be documented and applied in laboratory work.
- Although not accredited, calibration facilities should follow the requirements of ISO/IEC 17025.
- Participation in the interlaboratory comparisons is of a great benefit.

Traceability of the laboratory standards and equipment has to be assured by the means of calibrations at NMI or DI, or RIC, or other accredited calibration laboratory. Non-accredited RICs must demonstrate traceability of their standards to SI through an accredited laboratory or NMI/DI.

A determined engagement of NMHS's management board to support continuous strengthening of their calibration facilities is desired. It should be followed by a defined policy on the needs for regular calibrations of all meteorological instruments under the responsibility of NMHS, including the calibration intervals, as well as policy on implementation of calibration results.

The procedures aiming to avoid gaps in field measurements due to calibration activities should be developed. Possible solution is that NMHS has, at its disposal, a small reserve of calibrated instruments that can be used as a replacement set for the instruments in the network. Those recovered should be calibrated regularly forming, as a consequence, a new set of replacement and so on, to cover the whole network.

Additional quality control could be assured by performing field verification checks, but only to identify instruments out of uncertainty specifications. A set of travelling standards or portable calibration devices used for field checks has to be regularly calibrated in the calibration laboratory, and checked before and after field use.

4.3 Partially assured traceability – poor confidence and high risk, improvement required

This way of traceability assurance (Figure 1.B.3) is the least appropriate, and should be followed only when the two aforementioned ways are not applicable. It is applicable to NMHSs without calibration laboratory and portable calibration devices, but with a field inspection kit.

The field inspection kit must be regularly calibrated by accredited calibration laboratories, accredited RICs, calibration laboratories that are signatories of CIPM MRA, or at worst case by non-accredited RIC or calibration laboratory. The latter should be used in the absence of all the aforementioned options and only when those laboratories can demonstrate fully assured traceability of their calibration standards.

A field inspection is not equivalent to a regular laboratory calibration or a field verification check, but could be an acceptable means of ensuring the network observations quality. The field inspection can be considered as a "one-point calibration".

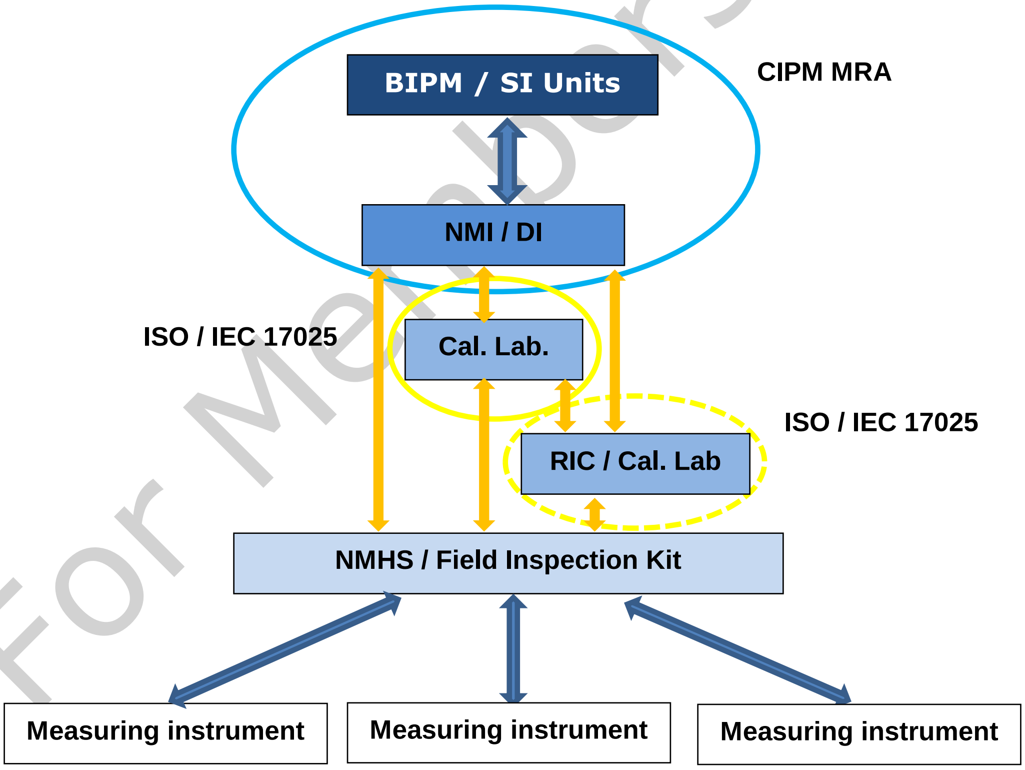

Figure 1.B.3: Partially assured traceability – poor confidence and high risk, improvement required

Enabling at least partially assured traceability, Members are encouraged to achieve the following:

- Field inspection kit should be acquired, with the required metrological characteristics regarding field instruments and with a calibration certificate issued by accredited calibration laboratory.

- The cost effective field inspection kit should include travelling instruments for field inspection of, at least, instruments for measurement of pressure, temperature, humidity and rainfall.

- The field inspection kit should be regularly calibrated by accredited calibration laboratory, by accredited RIC or by NMI or DI. In the case when accredited calibration services are not available, chosen calibration laboratory must demonstrate fully assured traceability.

- The field inspection kit should be checked/cross-checked before and after field use, whenever more than one kit exists.

- Personnel designated to operate the field inspection kit should be well-trained and competent to perform field inspections.

- Technical procedures for operating the field inspection kit should be documented.

- Field inspections should be performed on a regular time base.

- The results of field inspections must be documented.

4.4 Lack of traceability – not appropriate

Lack of metrological traceability leads to a lack of reliability of meteorological measurements, and consequently, highly reduces confidence in the implications of measurement data such as weather forecasts, warnings, and climate analyses. Ultimately, this brings into question the usefulness of meteorological measurements for the global community. So the consequences of untraceable measurement results are severe.

Therefore, measurement traceability is essential and WMO Members are urged to assure traceability of all the measurements under their responsibility.

SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

ANNEX 1.C. REGIONAL INSTRUMENT CENTRES[13]

1. Considering the need for the regular calibration and maintenance of meteorological instruments to meet the increasing needs for high-quality meteorological and hydrological data, the need for building the hierarchy of the traceability of measurements to the International System of Units (SI) standards, Members' requirements for the standardization of meteorological and related environmental instruments, the need for international instrument comparisons and evaluations in support of worldwide data compatibility and homogeneity, the need for training

---

[13] Information on RICs capabilities and activities is available at: https://www.wmo.int/pages/prog/www/IMOP/instrument-reg-centres.html

instrument experts and the role played by Regional Instrument Centres (RICs) in the Global Earth Observing System of Systems, the Natural Disaster Prevention and Mitigation Programme and other WMO cross-cutting programmes, it has been recommended that:[14]

A. **Regional Instrument Centres with full capabilities and functions** should have the following capabilities to carry out their corresponding functions:

Capabilities:

(a) A RIC must have, or have access to, the necessary facilities and laboratory equipment to perform the functions necessary for the calibration of meteorological and related environmental instruments;

(b) A RIC must maintain a set of meteorological standard instruments and establish the traceability of its own measurement standards and measuring instruments to the SI;

(c) A RIC must have qualified managerial and technical staff with the necessary experience to fulfil its functions;

(d) A RIC must develop its individual technical procedures for the calibration of meteorological and related environmental instruments using calibration equipment employed by the RIC;

(e) A RIC must develop its individual quality assurance procedures;

(f) A RIC must participate in, or organize, inter-laboratory comparisons of standard calibration instruments and methods;

(g) A RIC must, when appropriate, utilize the resources and capabilities of the Region according to the Region's best interests;

(h) A RIC must, as far as possible, apply international standards applicable for calibration laboratories, such as ISO/IEC 17025;

(i) A recognized authority must assess a RIC, at least every five years, to verify its capabilities and performance;

Corresponding functions:

(j) A RIC must assist Members of the Region in calibrating their national meteorological standards and related environmental monitoring instruments;

(k) A RIC must participate in, or organize, WMO and/or regional instrument intercomparisons, following relevant CIMO recommendations;

(l) According to relevant recommendations on the WMO Quality Management Framework, a RIC must make a positive contribution to Members regarding the quality of measurements;

(m) A RIC must advise Members on enquiries regarding instrument performance, maintenance and the availability of relevant guidance materials;

(n) A RIC must actively participate, or assist, in the organization of regional workshops on meteorological and related environmental instruments;

(o) The RIC must cooperate with other RICs in the standardization of meteorological and related environmental measurements;

---

[14] Recommended by the Commission for Instruments and Methods of Observation at its fourteenth session, held in 2006.

(p) A RIC must regularly inform Members and report,[15] on an annual basis, to the president of the regional association and to the WMO Secretariat on the services offered to Members and activities carried out.

B. **Regional Instrument Centres with basic capabilities and functions** should have the following capabilities to carry out their corresponding functions:

Capabilities:

(a) A RIC must have, or have access to, the necessary facilities and laboratory equipment to perform the functions necessary for the calibration of meteorological and related environmental instruments;

(b) A RIC must maintain a set of meteorological standard instruments[16] and establish the traceability of its own measurement standards and measuring instruments to the SI;

(c) A RIC must have qualified managerial and technical staff with the necessary experience to fulfil its functions;

(d) A RIC must develop its individual technical procedures for the calibration of meteorological and related environmental instruments using calibration equipment employed by the RIC;

(e) A RIC must develop its individual quality assurance procedures;

(f) A RIC must participate in, or organize, inter-laboratory comparisons of standard calibration instruments and methods;

(g) A RIC must, when appropriate, utilize the resources and capabilities of the Region according to the Region’s best interests;

(h) A RIC must, as far as possible, apply international standards applicable for calibration laboratories, such as ISO/IEC 17025;

(i) A recognized authority must assess a RIC, at least every five years, to verify its capabilities and performance;

Corresponding functions:

(j) A RIC must assist Members of the Region in calibrating their national standard meteorological and related environmental monitoring instruments according to **Capabilities** (b);

(k) According to relevant recommendations on the WMO Quality Management Framework, a RIC must make a positive contribution to Members regarding the quality of measurements;

(l) A RIC must advise Members on enquiries regarding instrument performance, maintenance and the availability of relevant guidance materials;

(m) The RIC must cooperate with other RICs in the standardization of meteorological and related environmental instruments;

(n) A RIC must regularly inform Members and report,[17] on an annual basis, to the president of the regional association and to the WMO Secretariat on the services offered to Members and activities carried out.

---

[15] A Web-based approach is recommended.

[16] For calibrating one or more of the following variables: temperature, humidity, pressure or others specified by the Region.

SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

ANNEX 1.D. SITING CLASSIFICATIONS FOR SURFACE OBSERVING STATIONS ON LAND

(The text of the common ISO/WMO standard 19289:2014(E))[18]

INTRODUCTION

The environmental conditions of a site[19] may influence measurement results. These conditions must be carefully analysed, in addition to assessing characteristics of the instrument itself, so as to avoid distorting the measurement results and affecting their representativeness, particularly when a site is supposed to be representative of a large area (i.e. 100 to 1 000 km^2).

1. SCOPE

This annex[20] indicates exposure rules for various sensors. But what should be done when these conditions are not fulfilled?

There are sites that do not respect the recommended exposure rules. Consequently, a classification has been established to help determine the given site's representativeness on a small scale (impact of the surrounding environment). Hence, a class 1 site can be considered as a reference site. A class 5 site is a site where nearby obstacles create an inappropriate environment for a meteorological measurement that is intended to be representative of a wide area (at least tens of km^2). The smaller the siting class, the higher the representativeness of the measurement for a wide area. In a perfect world, all sites would be in class 1, but the real world is not perfect and some compromises are necessary. A site with a poor class number (large number) can still be valuable for a specific application needing a measurement in this particular site, including its local obstacles.

The classification process helps the actors and managers of a network to better take into consideration the exposure rules, and thus it often improves the siting. At least, the siting environment is known and documented in the metadata. It is obviously possible and recommended to fully document the site, but the risk is that a fully documented site may increase the complexity of the metadata, which would often restrict their operational use. That is why this siting classification is defined to condense the information and facilitate the operational use of this metadata information.

A site as a whole has no single classification number. Each parameter being measured at a site has its own class, and is sometimes different from the others. If a global classification of a site is required, the maximum value of the parameters' classes can be used.

---

[17] A Web-based approach is recommended.

[18] In this Annex the word "sensor" is not used in the way as it is defined in 1.6.2 of this chapter. According to this definition it should be replaced with the word "instrument". As this Annex is just referencing the text of the ISO standard this has not been changed.

[19] A "site" is defined as the place where the instrument is installed.

[20] Whereas this is referred to as an annex in the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8), it is referred to as a standard in the ISO document.

The rating of each site should be reviewed periodically as environmental circumstances can change over a period of time. A systematic yearly visual check is recommended: if some aspects of the environment have changed, a new classification process is necessary.

A complete update of the site classes should be done at least every five years.

In the following text, the classification is (occasionally) completed with an estimated uncertainty due to siting, which has to be added in the uncertainty budget of the measurement. This estimation is coming from bibliographic studies and/or some comparative tests.

The primary objective of this classification is to document the presence of obstacles close to the measurement site. Therefore, natural relief of the landscape may not be taken into account, if far away (i.e. > 1 km). A method to judge if the relief is representative of the surrounding area is the following: does a move of the station by 500 m change the class obtained? If the answer is no, the relief is a natural characteristic of the area and is not taken into account.

Complex terrain or urban areas generally lead to high class numbers. In such cases, an additional flag “S” can be added to class numbers 4 or 5 to indicate specific environment or application (i.e. 4S).

2. AIR TEMPERATURE AND HUMIDITY

2.1 General

Sensors situated inside a screen should be mounted at a height determined by the meteorological service (within 1.25 to 2 m as indicated in the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8)). The height should never be less than 1.25 m. The respect of the higher limit is less stringent, as the temperature gradient versus height is decreasing with height. For example, the difference in temperature for sensors located between 1.5 and 2 m is less than 0.2 °C.

The main discrepancies are caused by unnatural surfaces and shading:

(a) Obstacles around the screen influence the irradiative balance of the screen. A screen close to a vertical obstacle may be shaded from the solar radiation or “protected” against the night radiative cooling of the air, by receiving the warmer infrared radiation from this obstacle or influenced by reflected radiation;

(b) Neighbouring artificial surfaces may heat the air and should be avoided. The extent of their influence depends on the wind conditions, as wind affects the extent of air exchange. Unnatural or artificial surfaces to take into account are heat sources, reflective surfaces (for example buildings, concrete surfaces, car parks) and water or moisture sources (for example, ponds, lakes, irrigated areas).

Shading by nearby obstacles should be avoided. Shading due to natural relief is not taken into account for the classification (see above).

The indicated vegetation growth height represents the height of the vegetation maintained in a “routine” manner. A distinction is made between structural vegetation height (per type of vegetation present on the site) and height resulting from poor maintenance. Classification of the given site is therefore made on the assumption of regular maintenance (unless such maintenance is not practicable).

2.2 Class 1

(a) Flat, horizontal land, surrounded by an open space, slope less than ⅓ (19°);

(b) Ground covered with natural and low vegetation (< 10 cm) representative of the region;

(c) Measurement point situated:

(i) At more than 100 m from heat sources or reflective surfaces (buildings, concrete surfaces, car parks, etc.);

(ii) At more than 100 m from an expanse of water (unless significant of the region);

(iii) Away from all projected shade when the sun is higher than 5°.

A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 % of the surface within a circular radius of 100 m surrounding the screen, makes up 5 % of an annulus of 10–30 m, or covers 1 % of a 10 m radius area.

ELEMENT 5: Picture inline fixed size NO space
Element Image: 8_I_1B1_en.eps
END ELEMENT

Figure 1.D.1. Criteria for air temperature and humidity for class 1 sites

2.3 Class 2

(a) Flat, horizontal land, surrounded by an open space, slope inclination less than ⅓ (19°);

(b) Ground covered with natural and low vegetation (< 10 cm) representative of the region;

(c) Measurement point situated:

(i) At more than 30 m from artificial heat sources or reflective surfaces (buildings, concrete surfaces, car parks, etc.);

(ii) At more than 30 m from an expanse of water (unless significant of the region);

(iii) Away from all projected shade when the sun is higher than 7°.

A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 % of the surface within a radius of 30 m surrounding the screen, makes up 5 % of an annulus of 5–10 m, or covers 1 % of a 5 m radius area.

ELEMENT 6: Picture inline fixed size NO space
Element Image: 8_I_1B2_en.eps
END ELEMENT

Figure 1.D.2. Criteria for air temperature and humidity for class 2 sites

2.4 Class 3 (additional estimated uncertainty added by siting up to 1 °C)

(a) Ground covered with natural and low vegetation (< 25 cm) representative of the region;

(b) Measurement point situated:

(i) At more than 10 m from artificial heat sources and reflective surfaces (buildings, concrete surfaces, car parks, etc.);

(ii) At more than 10 m from an expanse of water (unless significant of the region);

(iii) Away from all projected shade when the sun is higher than 7°.

A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 % of the surface within a radius of 10 m surrounding the screen or makes up 5 % of a 5 m radius area.

ELEMENT 7: Picture inline fixed size NO space

Element Image: 8_I_1B3_en.eps
END ELEMENT

Figure 1.D.3. Criteria for air temperature and humidity for class 3 sites

2.5 Class 4 (additional estimated uncertainty added by siting up to 2 °C)

(a) Close, artificial heat sources and reflective surfaces (buildings, concrete surfaces, car parks, etc.) or expanse of water (unless significant of the region), occupying:

   (i) Less than 50 % of the surface within a 10 m radius around the screen;

   (ii) Less than 30 % of the surface within a 3 m radius around the screen;

(b) Away from all projected shade when the sun is higher than 20°.

ELEMENT 8: Picture inline fixed size NO space
Element Image: 8_I_1B4_en.eps
END ELEMENT

Figure 1.D.4. Criteria for air temperature and humidity for class 4 sites

2.6 Class 5 (additional estimated uncertainty added by siting up to 5 °C)

Site not meeting the requirements of class 4.

3. PRECIPITATION

3.1 General

Wind is the greatest source of disturbance in precipitation measurements, due to the effect of the instrument on the airflow. Unless raingauges are artificially protected against wind, for instance by a wind shield, the best sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or where other objects act as an effective windbreak for winds from all directions. Ideal conditions for the installation are those where equipment is set up in an area surrounded uniformly by obstacles of uniform height. An obstacle is an object with an effective angular width of 10° or more.

The choice of such a site is not compatible with constraints in respect of the height of other measuring equipment. Such conditions are practically unrealistic. If obstacles are not uniform, they are prone to generate turbulence, which distorts measurements; this effect is more pronounced for solid precipitation. This is the reason why more realistic rules of elevation impose a certain distance from any obstacles. The orientation of such obstacles with respect to prevailing wind direction is deliberately not taken into account. Indeed, heavy precipitation is often associated with convective factors, whereby the wind direction is not necessarily that of the prevailing wind. Obstacles are considered of uniform height if the ratio between the highest and lowest height is less than 2.

Reference for the heights of obstacles is the catchment’s height of the raingauge.

3.2 Class 1

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). The raingauge shall be surrounded by low obstacles of uniform height, that is subtending elevation angles between 14° and 26° (obstacles at a distance between 2 and 4 times their height);

(b) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). For a raingauge artificially protected against wind, the instrument does not necessarily need to be protected by obstacles of uniform height. In this case, any other obstacles must be situated at a distance of at least 4 times their height.

ELEMENT 9: Picture inline fixed size NO space
Element Image: 8_I_1B5a_en.eps
END ELEMENT

or:

ELEMENT 10: Picture inline fixed size NO space
Element Image: 8_I_1B5b_en.eps
END ELEMENT

Figure 1.D.5. Criteria for precipitation for class 1 sites

3.3 Class 2 (additional estimated uncertainty added by siting up to 5 %)

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°);

(b) Possible obstacles must be situated at a distance at least twice the height of the obstacle (with respect to the catchment's height of the raingauge).

ELEMENT 11: Picture inline fixed size NO space
Element Image: 8_I_1B6_en.eps
END ELEMENT

Figure 1.D.6. Criteria for precipitation for class 2 sites

3.4 Class 3 (additional estimated uncertainty added by siting up to 15 %)

(a) Land is surrounded by an open area, slope less than ½ (≤ 30°);

(b) Possible obstacles must be situated at a distance greater than the height of the obstacle.

ELEMENT 12: Picture inline fixed size NO space
Element Image: 8_I_1B7_en.eps
END ELEMENT

Figure 1.D.7. Criteria for precipitation for class 3 sites

3.5 Class 4 (additional estimated uncertainty added by siting up to 25 %)

(a) Steeply sloping land (> 30°);

(b) Possible obstacles must be situated at a distance greater than one half (½) the height of the obstacle.

ELEMENT 13: Picture inline fixed size NO space
Element Image: 8_I_1B8_en.eps
END ELEMENT

Figure 1.D.8. Criteria for precipitation for class 4 sites

3.6 Class 5 (additional estimated uncertainty added by siting up to 100 %)

Obstacles situated closer than one half (½) their height (tree, roof, wall, etc.).

ELEMENT 14: Picture inline fix size
Element Image: 8_I_1B9_en .eps
END ELEMENT

Figure 1.D.9. Criteria for precipitation for class 5 sites

4. SURFACE WIND

4.1 General

Conventional elevation rules stipulate that sensors should be placed 10 m above ground surface level and on open ground. Open ground here represents a surface where obstacles are situated at a minimum distance equal to at least 10 times their height.

4.2 Roughness

Wind measurements are disturbed not only by surrounding obstacles; terrain roughness also plays a role. WMO defines wind blowing at a geometrical height of 10 m and with a roughness length of 0.03 m as the surface wind for land stations.

This is regarded as a reference wind for which exact conditions are known (10 m height and roughness length of 0.03 m).

Therefore, roughness around the measuring site has to be documented. Roughness should be used to convert the measuring wind to the reference wind, but this procedure can be applied only when the obstacles are not too close. Roughness-related matters and correction procedure are described in the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8), Volume I, Chapter 5.

The roughness classification, reproduced from the annex in the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8), Volume I, Chapter 5, is recalled here:

Terrain classification from Davenport (1960) adapted by Wieringa (1980*b*) in terms of aerodynamic roughness length z_0

TABLE: Table horizontal lines

Class index	*Short terrain description*	*z_0 (m)*
1	Open sea, fetch at least 5 km	0.000 2
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, $x/H > 20$	0.10
5	High crops; scattered obstacles, $15 < x/H < 20$	0.25
6	Parkland, bushes; numerous obstacles, $x/H \approx 10$	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City centre with high- and low-rise buildings	≥ 2

Note: Here x is a typical upwind obstacle distance and H is the height of the corresponding major obstacles. For more detailed and updated terrain class descriptions see Davenport et al. (2000).

4.3 Environment classification

The presence of obstacles, including vegetation, (almost invariably) means a reduction in average wind readings, but less significantly affects wind gusts.

The following classification assumes measurement at 10 m, which is the standard elevation for meteorological measurement.

When measurements are carried out at lower height (such as measurements carried out at 2 m, as is sometimes the case for agroclimatological purposes), a class 4 or 5 (see below) is to be used, with flag S (Specific situation).

Where numerous obstacles higher than 2 m are present, it is recommended that sensors be placed 10 m above the average height of the obstacles. This method allows the influence of the adjacent obstacles to be minimized. This method represents a permanent solution for partly eliminating the influence of certain obstacles. It inconveniently imposes the necessity for higher masts that are not standard and consequently are more expensive. It must be considered for certain sites and where used, the height of obstacles to be taken into account is that above the level situated 10 m below the sensors (e.g. for an anemometer installed at a 13 m height, the reference "ground" level of the obstacles is at a 3 m height; an obstacle of 7 m is considered to have an effective height of 4 m).

In the following, an object is considered to be an obstacle if its effective angular width is over 10°. Tall, thin obstacles, that is with an effective angular width less than 10° and a height greater than 8 m, also need to be taken into account when considering class 1 to 3, as mentioned below. Under some circumstances, a cluster of tall, thin obstacles will have a similar effect to a single wider obstacle and will need to be considered as such.

Changes of altitude (positive or negative) in the landscape which are not representative of the landscape are considered as obstacles.

4.4 Class 1

(a) The mast should be located at a distance equal to at least 30 times the height of surrounding obstacles;

(b) Sensors should be situated at a minimum distance of 15 times the width of thin obstacles (mast, thin tree) higher than 8 m;

Single obstacles lower than 4 m can be ignored.

Roughness class index is less than or equal to 4 (roughness length ≤ 0.1 m).

ELEMENT 15: Picture inline fixed size NO space
Element Image: 8_I_1B10_en.eps
END ELEMENT

Figure 1.D.10. Criteria for surface wind for class 1 sites

4.5 Class 2 (additional estimated uncertainty added by siting up to 30 %, possibility to apply correction)

(a) The mast should be located at a distance of at least 10 times the height of the surrounding obstacles;

(b) Sensors should be situated at a minimum distance of 15 times the width of thin obstacles (mast, thin tree) over 8 m high;

Single obstacles lower than 4 m can be ignored.

Roughness class index is less than or equal to 5 (roughness length ≤ 0.25 m).

ELEMENT 16: Picture inline fixed size NO space
Element Image: 8_I_1B11_en.eps
END ELEMENT

Figure 1.D.11. Criteria for surface wind for class 2 sites

Note: When the mast is located at a distance of at least 20 times the height of the surrounding obstacles, a correction (see the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8), Volume I, Chapter 5) can be applied. For nearer obstacles, a correction may be applied in some situations.

4.6 Class 3 (additional estimated uncertainty added by siting up to 50 %, correction cannot be applied)

(a) The mast should be located at a distance of at least 5 times the height of surrounding obstacles;

(b) Sensors should be situated at a minimum distance of 10 times the width of thin obstacles (mast, thin tree) higher than 8 m.

Single obstacles lower than 5 m can be ignored.

ELEMENT 17: Picture inline fixed size NO space
Element Image: 8_I_1B12_en.eps
END ELEMENT

Figure 1.D.12. Criteria for surface wind for class 3 sites

4.7 Class 4 (additional estimated uncertainty added by siting greater than 50 %)

(a) The mast should be located at a distance of at least 2.5 times the height of surrounding obstacles;

(b) No obstacle with an angular width larger than 60° and a height greater than 10 m, within a 40 m distance.

Single obstacles lower than 6 m can be ignored, only for measurements at 10 m or above.

ELEMENT 18: Picture inline fixed size NO space
Element Image: 8_I_1B13_en.eps
END ELEMENT

Figure 1.D.13. Criteria for surface wind for class 4 sites

4.8 Class 5 (additional estimated uncertainty cannot be defined)

Site not meeting the requirements of class 4.

5. GLOBAL AND DIFFUSE RADIATION

5.1 General

Close obstacles have to be avoided. Shading due to the natural relief is not taken into account for the classification. Non-reflecting obstacles below the visible horizon can be neglected.

An obstacle is considered as reflecting if its albedo is greater than 0.5.

The reference position for elevation angles is the sensitive element of the instrument.

5.2 Class 1

(a) No shade projected onto the sensor when the sun is at an angular height of over 5°. For regions with latitude ≥ 60°, this limit is decreased to 3°;

(b) No non-shading reflecting obstacles with an angular height above 5° and a total angular width above 10°.

ELEMENT 19: Picture inline fixed size NO space
Element Image: 8_I_1B14_en.eps
END ELEMENT

Figure 1.D.14. Criteria for global and diffuse radiation for class 1 sites

5.3 Class 2

(a) No shade projected onto the sensor when the sun is at an angular height of over 7°. For regions with latitude ≥ 60°, this limit is decreased to 5°;

(b) No non-shading reflecting obstacles with an angular height above 7° and a total angular width above 20°.

ELEMENT 20: Picture inline fixed size NO space
Element Image: 8_I_1B15_en.eps
END ELEMENT

Figure 1.D.15. Criteria for global and diffuse radiation for class 2 sites

5.4 Class 3

(a) No shade projected onto the sensor when the sun is at an angular height of over 10°. For regions with latitude ≥ 60°, this limit is decreased to 7°;

(b) No non-shading reflecting obstacles with an angular height above 15° and a total angular width above 45°.

ELEMENT 21: Picture inline fixed size NO space
Element Image: 8_I_1B16_en.eps
END ELEMENT

Figure 1.D.16. Criteria for global and diffuse radiation for class 3 sites

5.5 Class 4

No shade projected during more than 30 % of the daytime, for any day of the year.

ELEMENT 22: Picture inline fixed size NO space
Element Image: 8_I_1B17_en.eps
END ELEMENT

Figure 1.D.17. Criteria for global and diffuse radiation for class 4 sites

5.6 Class 5

Shade projected during more than 30 % of the daytime, for at least one day of the year.

6. DIRECT RADIATION AND SUNSHINE DURATION

6.1 General

Close obstacles have to be avoided. Shading due to the natural relief is not taken into account for the classification. Obstacles below the visible horizon can be neglected.

The reference position for angles is the sensitive element of the instrument.

6.2 Class 1

No shade projected onto the sensor when the sun is at an angular height of over 3°.

ELEMENT 23: Picture inline fixed size NO space
Element Image: 8_I_1B18_en.eps
END ELEMENT

Figure 1.D.18. Criteria for direct radiation and sunshine duration for class 1 sites

6.3 Class 2

No shade projected onto the sensor when the sun is at an angular height of over 5°.

ELEMENT 24: Picture inline fixed size NO space
Element Image: 8_I_1B19_en.eps
END ELEMENT

Figure 1.D.19. Criteria for direct radiation and sunshine duration for class 2 sites

6.4 Class 3

No shade projected onto the sensor when the sun is at an angular height of over 7°.

ELEMENT 25: Picture inline fixed size NO space
Element Image: 8_I_1B20_en.eps
END ELEMENT

Figure 1.D.20. Criteria for direct radiation and sunshine duration for class 3 sites

6.5 Class 4

No shade projected during more than 30 % of the daytime, for any day of the year.

ELEMENT 26: Picture inline fixed size NO space
Element Image: 8_I_1B21_en.eps
END ELEMENT

Figure 1.D.21. Criteria for direct radiation and sunshine duration for class 4 sites

6.6 Class 5

Shade projected during more than 30 % of the daytime, for at least one day of the year.

ANNEX 1.E. CLASSIFICATION OF INITIAL AND ONGOING SURFACE MEASUREMENT QUALITY

Annex 1.E will be included following approval by CIMO-17 session.

ANNEX 1.F. OPERATING EQUIPMENT IN EXTREME ENVIRONMENTS

Extreme weather events and harsh climatic environments have direct impacts on observing networks leading to interruption of the core functions of National Meteorological and Hydrological Services (NMHSs). The damage to real time observing and monitoring systems during a weather event can severely limit the effectiveness of forecasting and warning services. The loss of delayed mode observations affects the capacity to plan for extreme events and understand their climatology.

The WMO DRR country-level survey (2006)[21] identified droughts, flash and river floods, extreme winds, severe storms, tropical cyclones, storm surges, forest and wildfires, heat waves, landslides and aviation hazards as the top ten hazards of concern to all Members. Maintenance of high-quality observational records (historical and real-time) is critical for DRR applications. These observations are critical to:

(a) risk identification;

(b) risk reduction through the provision of early warnings to support emergency preparedness and response as well as climate services for medium- and long-term sectoral planning; and

(c) risk transfer through insurance and other financial tools. Thus, interruptions in monitoring caused by damages to instruments and observing networks as a result of natural hazards hamper NMHSs capacities in delivering effective services not only during and following a disaster but also in the long-term, if these systems are not rebuilt.

In this regard, the Commission stressed that it is critical to ensure that instrumentation and observing networks are designed per standards that would withstand the impact of extreme weather events.

There are a number of factors that influence the robustness of equipment, both infrastructure and sensors in the field. The most straightforward and most efficient way of ensuring the availability of a system is to design robustness into the system from the beginning. Factors to be considered are:

---

[21] http://www.wmo.int/pages/prog/drr/natRegCap_en.html

Data availability - one of the first factors to consider is the requirement for data availability. Are there other similar sources of information nearby? Is this the only information available to the forecasters and therefore critical in extreme events? If so, more effort will be needed in the design and planning of the station to ensure availability of data. What type of outages can you tolerate? Does it matter that the data is not available on a regular basis for five minutes? Does it matter if it is not available for a day? All these questions inform the way the system is designed for robustness and how the system is supported.

Threats - What are the extreme weather events that will impact the weather station at a particular location? In an ideal world, all parameters would be monitored to the highest standard. However, funding realities generally mean that this is not possible. Identify the critical parameters and concentrate on ensuring their availability.

Environmental impacts - every location presents its own challenges. Review topography to ensure any ground work will not be subject to water erosion. Include in your consideration soil type, local pollution sources, proximity to the sea and salt corrosion, vandalism risk, etc. These threats impact both the design and the maintenance requirements.

Once the need for the observation is appreciated, and the strengths and weaknesses of the location have been assessed, then a range of mitigation strategies can be considered to maximise the availability of observations and minimise operational cost. These approaches fall into one of several categories listed in Table 1 below.

Table 1.F.1 General approaches for mitigating the impact of extreme environment on observation instrumentation and infrastructure.

Approach	Method	Strength	Weakness
Site redundancy	Increase the density of measurement locations and equipment in critical areas	Increased density of measurements reduces the impact of the loss of information from a single site	Increase in capital costs and maintenance efforts.
		Potential to use lower cost solutions	Risk of overall lower quality data and reliability
		Allows network quality control, potentially reducing maintenance costs and predicting system failures	
Instrument redundancy	Duplicate sensitive or vulnerable instruments at a particular site	Increased availability of data	Increase in capital costs
		Greater flexibility to manage outages and maintenance	
Use of	Choose materials that are designed to	Depending on usage, these materials will	Tend to be more expensive both as raw

environmentally appropriate infrastructure materials	survive in extreme environments (e.g. Marine and high-grade steel, UV resistant plastics, high oil containing timbers)	last longer and be stronger	materials and in construction
		Reduces maintenance burden	
	Use appropriately rated enclosures and glands	Reduces the risk of damage to equipment caused by water ingress or dust	Short term costs can be slightly higher
Design	Use of structural engineers for design of infrastructure such as masts	Ensures the infrastructure will withstand extreme weather conditions	In the short term can be slightly more costly
		Lengthens the life of infrastructure by minimising the stress caused by environmental impacts	
		Reduces over engineering and associated costs	

Specific examples of event types and the threat they pose to infrastructure and instruments in the immediate and longer term are given in Table 2. Methods of mitigation of these threats are also provided. These mitigations are in line with the four approaches of Table 1. While extensive, the mitigations are not exhaustive; they are a compilation of general knowledge and experience of a variety of National Meteorological organisations. In applying any of these methods, the user will need to consider the impact on measurements in their situation. While mitigation may work for a particular problem, it may also cause issues for other parameters. The user needs to consider their specific environment before employing any of these solutions.

Table 2.F.2 Extreme weather hazards, examples of their associated infrastructure and sensor vulnerabilities, and mitigating actions.

Event Type	***Hail***
Cause	Characteristic of weather systems such as thunderstorms
Considerations	What size and intensity of hail would the system need to cope with? * Generally hail less than 2.5 cm diameter is not considered to be significant hail, while > 4.5 cm hail will create a significant dent in a car, and > 7 cm will smash a windscreen.

	* Less than 5 % of hail is greater than 2.5 cm diameter	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Impact	* damage to: radomes - dints and holes; observer shelters - breakage of louvers; electronics enclosures - dints and holes; masts - dints, nicks or snapping	* use high strength materials (including steel, carbon fibre) for the outer skin materials of enclosures etc. and that the structures are strong and well supported * use component-designed radomes, shelters, enclosures etc. that allow for panel changes
	* deterioration of coated surfaces	* use high strength materials that do not require painting or other coating methods
	* damage to solar panels	* install removable high strength, stiff and structurally supported covers
	* deterioration of painted surfaces	* use high strength and corrosion resistant materials that do not require painting or other coating methods
	Vulnerability or Impact to Sensors	***Mitigation***
Impact	* mechanical anemometers, damage to cups in particular. Small and light weight plastic cups are particularly vulnerable.	* use heavy-duty instruments constructed from strong materials. Depending on the use, specialized materials such as carbon fibre may be considered.
	* ultrasonic anemometers, damage to arms and detectors causing misalignment.	* use heavy-duty instruments mounts and arms constructed from strong materials. Depending on the use, specialized materials such as carbon fibre may be considered.
	* radiation instruments, damage to their domes.	* use alternate technologies such as pitot tube anemometers that rely on aerodynamic design and have minimally exposed components
Event Type	***Flood***	

Cause	Result of significant weather systems, including thunderstorms, cyclones etc. Flooding may occur well down stream of the weather event.	
Considerations	Is the system expected to resume function post immersion? What maximum rainfall amount and rate would be expected? Is the site vulnerable to up stream flooding?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Water Ingress	* ground mounted equipment undermined or washed away	* use mounting systems that stabilise the surrounding soil by spreading the load. There are commercial solutions that use a submerged "tripod" arrangement that minimises soil disturbance while spreading the load * design and align foundations parallel to any expected surface flow to minimise hydrostatic pressure.
Corrosion	* equipment damaged by exposure/immersion in water	* use materials such as marine grade stainless steel, galvanised iron or steel, appropriate plastics; avoid the use of aluminium * ensure all connectors are wrapped in water proofing tape to prevent corrosion * use preventative coatings and impregnating materials e.g. fish oil, paint * in marine environments, use sacrificial anodes
Contamination	* corrosion of metal components, particularly connectors, welds, joints	* perform regular data monitoring and regular inspections and maintenance of infrastructure and equipment in vulnerable environments to manage maintenance regime * coat welds, joints and nuts with grease e.g. silicon, even butter
Power surge	* loss of data due to power or communications failure	* include redundant communications via an alternate supplier
Debris	* damage from large debris in stream flow impacting towers and	* reinforce lower sections of towers to expected flood height

	screens	
	* damage to protective coatings	* ensure all powder or other coating is pit and chip free

Dominant Hazard	Vulnerability or Impact to Instruments	Mitigation
Water Ingress	* any non-submersible sensor	* mount the data acquisition system enclosure as high as practical to avoid being submerged (water stage station for example) * design and align foundations parallel to any expected surface flow to minimise hydrostatic pressure * use appropriately "IP" (Ingress Protection or International Protection) rated seals and enclosures for equipment, typically IP67 and above for waves and splash
	* equipment in close proximity to high water flow (direct contact or erosion) becomes submerged	* use appropriately "IP" rated seals and enclosures for equipment, typically IP67 and above for waves and splash
Corrosion	* equipment damaged by exposure/immersion in water, particularly connectors, welds, joints	* use appropriately "IP" rated seals and enclosures for equipment, typically IP67 and above for waves and splash * avoid metals that do not passivate or are susceptible to corrosion for example low grade steel * inspect equipment regularly to ensure all paint and coated surfaces are pit and chip free * protect connectors and clamps using grease/oil impregnated tape or similar * carefully select metal types at joints or use of isolating separators and lubricants (high viscosity grease) to ensure that electrolysis is minimized
Contamination	* foreign chemical or dirt build-up on sensing elements, such as relative humidity sensing elements	* perform regular inspections and data monitoring to manage maintenance regime
Debris	* damage from large debris in stream flow impacting towers and	* in flood prone areas, elevate instruments and enclosures above flood

	screens	level
Event Type	***Land/ Mudslide***	
Cause	Result of rainfall in combination with unstable ground conditions	
Considerations	* What is the slope of the land? * Is the area subject to a long period of moderate rainfall?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Water Ingress	* ground mounted equipment undermined or washed away	* use mounting systems that stabilise the surrounding soil by spreading the load. There are commercial solutions that use a submerged "tripod" arrangement that minimises soil disturbance while spreading the load * use appropriately "IP" rated seals and enclosures for equipment, typically IP67 and above for waves and splash * mount data acquisition system enclosure as high as practical when the sensor can be submerged (water stage station for example)
Water Current	* ground mounted equipment undermined or washed away	* use mounting systems that stabilise the surrounding soil by spreading the load. There are commercial solutions that use a submerged "tripod" arrangement that minimises soil disturbance while spreading the load * design and align foundations parallel to any expected surface follow to minimise hydrostatic pressure.
Mud	* nearly all, total destruction	*site equipment on local mounds, or sculpture land to redirect mud and water around equipment
Debris	* nearly all, total destruction	* reinforce lower sections of towers to expected land/mud slide height
	See also "Flood"	
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***

Water Ingress	* failure of any non-submersible sensor	* mount data acquisition system enclosure as high as practical when the sensor can be submerged (water stage station for example) * use appropriately "IP" rated sensor enclosures and seals, typically IP67 and above for waves and splash * mount instruments at height greater than expected 20 to 50 year event * perform regular inspections and data monitoring to manage maintenance regime
Water Current	* instruments break away or are submerged in mud	
Mud	* nearly all, total destruction	
Event Type	***High Winds***	
Cause	Extreme weather systems such as cyclone, thunderstorm etc. with winds over 100 km h^{-1} (approx. 27.8 m s^{-1})	
Considerations	* What maximum average wind and maximum instantaneous wind would a system need to withstand? * Is there much material that could become flying debris during an event	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Wind	* damage to: radomes - dints and holes; observer shelters - breakage of louvers; electronics enclosures - dints and holes; masts - dints, nicks or snapping * major structural damage due to debris * structural damage due to drag and wind pressure	* use high strength materials (including steel, carbon fibre) for the outer skin materials of enclosures etc. and ensure the structures are strong and well supported * use component-designed radomes, shelters, enclosures etc. that allow for panel changes * use guy wires on tower/tripod mast to minimise damage from vibration, attached to suitable anchors, e.g. concrete or physical anchors * ensure all compartments / doors close securely; consider inclusion of door-open warning alarms. * where practical, design infrastructure to reduce wind load using curved and low profile surfaces

		* consider the aerodynamics of the design to minimise drag and to stabilise the construction
	* undermining of infrastructure supports through erosion and wind stress	* perform regular inspections, particularly after major events, to ensure the structural integrity of foundations and mounts
	* creation of micro-fractures, degradation of welded joints and loosening of clamps, etc., due to wind vibration	* perform regular inspections, particularly after major events, to ensure the structural integrity of foundations and mounts
		* provide additional support for major infrastructure such as guy wires for masts to limit flexing during high winds
Debris	* towers severely damaged	* use towers/tripods with appropriate wind load rating
		* attach masts to suitable anchors, e.g. concrete or physical anchors

Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Wind	* damage to instruments due to wind force and small debris	* use heavy-duty instruments
		* use wind instruments with few moving parts, such as "pitot tube" instruments which use pressure difference, and ultrasonic wind instruments, to eliminate vulnerabilities associated with moving parts; however, these may still be damaged by flying debris
		* inspect and ensure instruments are appropriately and securely mounted prior to the event, and that rain gauges and screens are appropriately bolted down
		* tie down or remove any loose objects or material that could act as flying debris during a storm. Inspect surroundings for trees or bushes with branches that are likely to break or fall during a high wind event; arrange for their removal
		* use high strength rope or wire to support anemometer arm
		* ensure cabling is well secured and supported

Debris	* damage to instruments due to flying debris	* consider the aerodynamics of the design to minimise drag and to stabilise the construction * clean up the area around the equipment and remove any material that could become a projectile
Event Type	***Thunderstorms***	
Cause	Strong winds, lightning and rainfall from larger storms	
Considerations	* Are the systems expected to operate after a lightning strike?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
lightning	* electrical surge	* use electrical surge protection on the power circuit and individual surge protection on each monitored channel (e.g. temperature, wind) * use appropriate earthing of infrastructure through a collector (e.g. Franklin Rod or Spline Ball), to a conductor for dissipation to ground. Note: all connections must maintain high conductivity and bends should be no greater than 45 degrees
Water	* corrosion See also "Flood" See also "High Wind"	* use suitable materials such as stainless steel, galvanized steel and appropriate plastics * use preventative coatings and impregnating materials, e.g. fish oil, paint * in marine environments use sacrificial anodes * perform regular inspection and maintenance of infrastructure and equipment in vulnerable environments
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***

lightning	* instruments with exposure and no tolerance for direct or indirect lightning strikes	* use grounding rod/plate, finial, etc. on weather station tower/tripod * use surge suppression devices between instruments and data acquisition system to protect the data acquisition system
	* induced noise	* avoid long unshielded cables
Water	* corrosion of connectors, etc.	* protect connectors and clamps using grease/oil impregnated tape or similar * carefully select metal types at joints or use isolating separators and lubricants (high viscosity grease) to ensure that electrolysis is minimized
	* foreign chemical build-up on sensing elements, such as relative humidity sensing elements	* perform regular inspection and data monitoring to manage maintenance regime
	See also "Flood" See also "High Wind"	
Event Type	***Tropical Cyclone***	
Cause	Characteristic of a weather system	
Considerations	* Does rotating winds present any additional risk?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Wind	* rotating winds	* for infrastructure that may rotate in high winds, design mounts and cables so that it does not drive or turn cables beyond limits * tie down or remove any loose objects or material that could act as flying debris during a storm. Inspect surroundings for trees or bushes with branches that are likely to break or fall during a high wind event; arrange for their removal.
	See also "High Wind"	

Debris	See also "High Wind"	
Event Type	***Tornado***	
Cause	A weather sub-system characterized by high winds and blowing debris	
Considerations	* Does rotating winds present any additional risk?	
Dominant Hazard	***Impact to Infrastructure examples***	***Mitigation***
Wind	* rotating winds See also "High Wind"	* for infrastructure that may rotate in high winds, design mounts and cables so that it does not drive or turn cables beyond limits
Debris	See also "High Wind"	
Event Type	***Storm Surge***	
Cause	Results of cyclones and Severe weather	
Considerations	***Constraints***	
Current	See also "Tsunami"	
Water	See also "Flood"	
Debris	See also "Flood"	
Event Type	***Tsunami***	
Cause	Independent of meteorological factors, resulting from geological movement, underwater land slip or meteor	
Considerations		

Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Current	* erosion or loss of footings	* ensure tower and screen footings are reinforced to deal with the force of water travelling between 2 to 20 m s^{-1}. Note the run-up for a tsunami is significantly greater than the height of the wave. * secure masts and large infrastructure to nearby structures with additional ropes * tie down or remove any loose objects or material that could act as flying debris during a storm. Inspect surroundings for trees or bushes with branches that are likely to break or fall during a high wind event; arrange for their removal.
Water	See also "Flood"	
Debris	See also "Flood"	
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Current	* nearly all, total destruction	* in tsunami prone areas, mount instruments above likely tsunami run-up height
	See also "Flood"	
	See also "Flood"	
Event Type	***Snow/ Blizzard /Icing***	
Cause	Extreme cold weather systems, and associated with prolonged cold and windy weather	
Considerations	* Are systems expect to operate after freeze / thaw situations? * Are instruments or infrastructure specified to cope with sustained depressed temperatures?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Cold and ice	* deterioration of shelters, masts, etc., due to the weight of	* investigate the use of ice phobic coatings and materials

accretion	ice/snow	
	* weakening of screens and enclosures caused by the expansion of freezing water in joints, cracks and crevices	* ensure screens and enclosures are well maintained; use materials that are tolerant to expansion stress and less prone to rot such as non-brittle plastics
	* towers/masts	* use towers/masts that are slightly flexible and/or that will vibrate slightly to loosen snow and ice
	* snow/Ice cover on solar panels resulting in eventual loss of power	* tilt solar panels as close to vertical as possible to prevent snow/ice accretion
Wind	* failure of infrastructure (e.g. mast) in high wind due to ice accretion	* choose materials that maintain elasticity below expected minimum temperature
		* de-ice on a regular schedule

Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Cold and ice accretion	* ice build up on instruments, e.g. mechanical anemometers, ultrasonic sensors, rain sensors and gauges	* use heated instruments (e.g. anemometers) and heat cycling instruments (e.g. humidity) if practical. Ensure the heater does not interfere with other instruments * use a continuous flow of air (ideally dry air) to prevent water or snow to settle, or ice to form * apply heat tape directly to surfaces (electrical resistance elements embedded in a flexible sheet or nichrome wire); most effective on sensors without moving parts * use instruments that have ice phobic surfaces or coatings * spray a low freezing-point fluid (such as glycol or ethanol) on sensors during icing events; not suitable for humidity sensors * mount wind sensor on slightly flexible mast (e.g. "wind surfer" mast) * in heavy icing conditions none of these methods are effective

	* snow/ice cover on pyranometers/radiation sensors * snow/ice accretion on infrastructure impacting the measurement environment, e.g. snow/ice cover on temperature sensors and screens causes incorrect data (due to a much higher time constant), and causes turbulence around anemometers	* use a continuous flow of air (ideally dry air) to prevent water or snow to settle, or ice to form * prevent icing or de-ice on a regular basis using methods above such as ice phobic materials, low freezing point fluids * minimise the surface area of the infrastructure
Event Type	***Avalanche***	
Cause	Result of snowfall build-up in combination with certain ground and atmospheric conditions	
Considerations	* What is the slope of the terrain near the site?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Mass and Debris	* destruction of infrastructure in path of avalanche * snow/ice cover on solar panels resulting in eventual loss of power See also "Land/ Mudslide"	* site station higher on mountain sides * construct tower with multiple solar cells at various height * include back up batteries and alarms for loss of voltage and current supply
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Mass and Debris	* nearly all * snow/ice cover on optical sensors * snow/ice cover on pyranometers/radiation sensors * snow/ice cover on temperature sensors and screens causes incorrect data (due to a much higher time constant)	* construct tower with multiple sensor suites at various heights * for light coverage consider automated cleaning * prevent icing or de-ice on a regular basis using methods above such as ice phobic materials, low freezing point fluids

	See also "Snow/ Blizzard /Icing" See also "Land/ Mudslide"	
Event Type	***Dust Storm***	
Cause	Result of high winds in combination with certain ground conditions	
Considerations	How long do we expect systems to operate unattended or maintained? What IP rating would we expect?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Oblation	* equipment that can be damaged by sandblasting or burying.	* avoid the use of coated materials; choose polished metal
	* failure or deterioration of protective coatings that may lead to pitting or overall corrosion	* inspect painted, plastic or powder coasted surfaces for chips, crazing or cracking
Dirt	* build-up of dust / sand in enclosures	* use enclosures with an IP6X or higher
		* design mounts and frames to minimise the build-up of sand and dirt
	* clogging of aspirated screen	* perform regular inspections and clearing
	* loss of power or communications	* include back up batteries and alarms for loss of voltage and current supply
		* include redundant communications via an alternate supplier
Dominant Hazard	***Vulnerability or Impact to Sensors***	***Mitigation***
Oblation	* aspirated equipment drawing dust	* stop aspiration when wind or particle count is above a set point
Dirt	* clogging of non-aspirated equipment	* increase inspection frequency of equipment to remove dust build up
		* use well-sealed (high IP rated) enclosures for data acquisition system, e.g. IP68

		* increase replacement frequency of filter in dusty environments
		* design sensors to minimise the surface area and presence of crevices and pockets where dirt can build up
	* optical and solar radiation equipment	* for light coverage, consider daily automated cleaning
Event Type	***Fire***	
Cause	Result of hot weather, lightning or vandalism	
Considerations	* How hot is a typical fire likely to burn? * How long is a fire likely to keep burning?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Heat and Combustion	* deformation of metal and plastic components	* avoid plastics with low melting temperature and lightweight metals
	* failure of electronics in extreme heat	* use enclosures that provide some insulation such as a double skin. * ensure electronics are correctly rated for use in the climate they are being deployed in, e.g. 20 to 30 °C above the climatic maximum temperature
	* damage reducing IP rating	* inspect and replace seals
	* destruction of any combustible materials	* construct with non-combustible materials such as metal and concrete * avoid cracks and crevices in the design of housings etc. where embers and sparks can lodge. Openings should be screened or sealed where practical
	* failure of structural integrity of masts and other infrastructure following the event	* perform regular inspections for stress fractures, fatigue and grain growth in metal components
	* failure or deterioration of protective coatings that may lead to pitting or overall corrosion	* inspect painted, plastic or powder coated surfaces for chips, crazing or cracking

Debris	* damage from falling debris	* site equipment in fire prone areas with appropriate clearance from potential falling structures and trees
Dust	See also "Dust Storm"	

Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Heat and Combustion	* deformation of casings/enclosures and failure of electronics	* avoid plastics with low melting temperature and lightweight metals * use enclosures that provide some insulation such as a double skin but avoid combustible insulation materials
	* damage reducing IP rating	* inspect and replace seals
	* destruction of any combustible materials	* construct with non-combustible materials such as metal and concrete
	* sensors damaged by heat effects (sensing elements or housings)	* ensure sensors are correctly rated for use in the climate they are being deployed in. e.g. 20 to 30 °C above the climatic maximum for electronics and 5 to 10 °C above for the measurement range
	* failure of structural integrity of masts and other infrastructure following the event	* perform regular inspections for stress fractures, fatigue and grain growth in metal components
	* failure or deterioration of protective coatings that may lead to pitting or overall corrosion	* inspect painted, plastic or powder coated surfaces for chips, crazing or cracking
Debris	* damage from falling debris	* site equipment in fire prone areas with appropriate clearance from potential falling structures and trees
Dust	See also "Dust Storm"	

Event Type	***Drought***
Cause	Result of prolonged periods of low or no rain
Considerations	Do footings need to accommodate dynamic soils?

Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Dust Erosion	* degradation of equipment foundations in clay soils (cracking, erosion) See also "Dust Storm"	* use mounting systems that stabilise the surrounding soil such as a physical anchor which causes minimal soil disturbance while spreading the load
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Dust Erosion	* failure of electronics * clogged filters	* check for dry joints in electronics * perform more frequent filter changes in dusty conditions
Event Type	***Heat Wave / Solar radiation***	
Cause	Prolonged periods of elevated temperatures and/or intense sunlight	
Considerations	Can instruments or infrastructure cope with sustained elevated temperatures?	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Heat	* few, unless exterior surfaces have low temperature tolerance * failure of electronics due to overheating	* avoid plastics with low melting temperature and lightweight metals * use canvas or similar to shade electronics and reduce thermal stress on systems * where practical, bury the electronics box; Note: ensure that no water ingress can occur * use passive cooling such as with a vent and chimney design; Note: ensure the risk of water ingress is not increased, by placing the vent above expected water levels; use filters / screens to prevent dust and animals from gaining access * use active cooling such as with fans (note cautions above regarding

Irradiation	* ageing of welds and joints * structural deterioration due to UV exposure * discolouration and ageing of plastic components	water, dust and animal ingress) * use active coolers such as Peltier coolers or air-conditioning * perform more frequent inspections for metal fatigue and deterioration * use UV resistant materials such as metals, hardwood or UV stabilised plastics * perform more frequent inspections to detect distortion and deterioration of enclosures and screens in particular * use canvas or similar to shade electronics and reduce thermal stress on systems
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Heat	* sensors damaged by heat effects (sensing elements or housings)	* ensure instruments are correctly rated for use in the climate they are being deployed in. e.g. 20 to 30 °C above the climatic maximum temperature for electronics and 5 to 10 °C above for the measurement range
	* failure of instruments due to overheating	* where measurements will not be compromised, use Peltier coolers or airflow (passive and active)
Irradiation	* structural deterioration due to UV exposure	* use UV resistant materials such as metals, hardwood or UV stabilised plastics
Event Type	***Earthquake/ Volcano***	
Cause ***Considerations***	Independent of meteorological factors	
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***

Eruption	* volcano: burying by fallout; destruction from direct contact with flow	* maximise use of fire resistant materials
Land movement	* earthquake: most infrastructure	* use mounting systems that stabilise the surrounding soil such as a physical anchor which causes minimal soil disturbance while spreading the load
	* ash cover on solar panels: eventual loss of power	* include back up batteries and alarms for loss of voltage and current supply
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Eruption	* volcano: dust contamination	* see dust above
Land movement	* earthquake: weighing gauges, loosely mounted instruments, e.g. tipping bucket rain gauge	
	* ash cover on optical sensors	* for light coverage consider automated cleaning
	* ash cover on pyranometers/radiation sensors	* for light coverage consider automated cleaning
Event Type	***Security***	
Cause	Vandalism	
Considerations		
Dominant Hazard	***Vulnerability or Impact to Infrastructure***	***Mitigation***
Vandalism	* theft or wanton damage	* use fencing * use non-removable fittings for high value items such as solar panels * in remote areas, encourage engagement from the local community regarding the value of the service provided by the equipment
Wildlife	* chewing of cables	* use strong conduit or armoured cables
	* crushing of infrastructure by animals rubbing against the	* use appropriate livestock fencing

	equipment	
Dominant Hazard	***Vulnerability or Impact to Instruments***	***Mitigation***
Vandalism	* theft or wanton damage	* use fencing * in remote areas, encourage engagement from the local community regarding the value of the service provided by the equipment
Wildlife	* bird attacks on ultrasonic sensors	* use bird spikes on the edges of roosting points
	* contamination and corrosion by bird droppings	* use bird spikes on the edges of roosting points
	* crushing or misalignment of sensors by animals rubbing against the equipment	* use appropriate livestock fencing

SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. GENERAL
Chapter_ID: 8_I_1_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

ANNEX 1.G. STATION EXPOSURE DESCRIPTION

The accuracy with which an observation describes the state of a selected part of the atmosphere is not the same as the uncertainty of the instrument, because the value of the observation also depends on the instrument's exposure to the atmosphere. This is not a technical matter, so its description is the responsibility of the station observer or attendant. In practice, an ideal site with perfect exposure is seldom available and, unless the actual exposure is adequately documented, the reliability of observations cannot be determined (WMO, 2002).

Station metadata should contain the following aspects of instrument exposure:

(a) Height of the instruments above the surface (or below it, for soil temperature);

(b) Type of sheltering and degree of ventilation for temperature and humidity;

(c) Degree of interference from other instruments or objects (masts, ventilators);

(d) Microscale and toposcale surroundings of the instrument, in particular:

  (i) The state of the enclosure's surface, influencing temperature and humidity; nearby major obstacles (buildings, fences, trees) and their size;

  (ii) The degree of horizon obstruction for sunshine and radiation observations;

  (iii) Surrounding terrain roughness and major vegetation, influencing the wind;

  (iv) All toposcale terrain features such as small slopes, pavements, water surfaces;

  (v) Major mesoscale terrain features, such as coasts, mountains or urbanization.

Most of these matters will be semi-permanent, but any significant changes (growth of vegetation, new buildings) should be recorded in the station logbook, and dated.

For documenting the toposcale exposure, a map with a scale not larger than 1:25 000 showing contours of ≈ 1 m elevation differences is desirable. On this map the locations of buildings and trees (with height), surface cover and installed instruments should be marked. At map edges, major distant terrain features (for example, built-up areas, woods, open water, hills) should be indicated. Photographs are useful if they are not merely close-ups of the instrument or shelter, but are taken at sufficient distance to show the instrument and its terrain background. Such photographs should be taken from all cardinal directions.

The necessary minimum metadata for instrument exposure can be provided by filling in the template given on the next page for every station in a network (see the figure below). An example of how to do this is shown in WMO (2003). The classes used here for describing terrain roughness are given in Volume I, Chapter 5, of the Guide. A more extensive description of metadata matters is given in WMO (2017).

ELEMENT 27: Picture inline fix size
Element Image: 8_I_1C_en.eps
END ELEMENT

Figure 1.G. General template for station exposure metadata

SECTION: Chapter_book

Chapter title in running head: CHAPTER 1. GENERAL

Chapter_ID: 8_I_1_en

Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

REFERENCES AND FURTHER READING

Brooks, C.E.P. and N. Carruthers, 1953: *Handbook of Statistical Methods in Meteorology*. MO 538, Meteorological Office, London.

Bureau International des Poids et Mesures, 2006: *The International System of Units (SI)*. BIPM, Sèvres/Paris.

Bureau International des Poids et Mesures/Comité Consultatif de Thermométrie, 1990: The International Temperature Scale of 1990 (ITS-90) (H. Preston Thomas). *Metrologia*, 27:3–10.

Davenport, A.G., 1960: Rationale for determining design wind velocities. *Journal of the Structural Division*, American Society of Civil Engineers, 86:39–68.

Davenport, A.G., C.S.B. Grimmond, T.R. Oke and J. Wieringa, 2000: Estimating the roughness of cities and sheltered country. *Preprints of the Twelfth American Meteorological Society Conference on Applied Climatology* (Asheville, NC, United States), pp. 96–99.

Eisenhart, C., 1963: Realistic evaluation of the precision and accuracy of instrument calibration systems. National Bureau of Standards–C, Engineering and Instrumentation, *Journal of Research*, 67C(2).

International Civil Aviation Organization, 2002: *World Geodetic System – 1984 (WGS-84) Manual*. ICAO Doc 9674–AN/946, Quebec.

International Organization for Standardization, 1994*a*: *Accuracy (Trueness and Precision) of Measurement Methods and Results – Part 1: General Principles and Definitions*, ISO 5725-1:1994/Cor.1:1998. Geneva.

———, 1994*b*: *Accuracy (Trueness and Precision) of Measurement Methods and Results – Part 2: Basic Method for the Determination of Repeatability and Reproducibility of a Standard Measurement Method*, ISO 5725-2:1994/Cor.1:2002. Geneva.

———, 2009: *Quantities and Units – Part 1: General*, ISO 80000-1:2009. Geneva.

International Organization for Standardization/International Electrotechnical Commission, 2008: *Uncertainty of Measurement – Part 3: Guide to the Expression of Uncertainty in Measurement*, ISO/IEC Guide 98-3:2008, Incl. Suppl. 1:2008/Cor 1:2009, Suppl. 1:2008, Suppl. 2:2011. Geneva. (equivalent to: Joint Committee for Guides in Metrology, 2008: *Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement*, JCGM 100:2008, Corrected in 2010).

International Union of Pure and Applied Physics, 1987: *Symbols, Units, Nomenclature and Fundamental Constants in Physics*. SUNAMCO Document IUPAP-25 (E.R. Cohen and P. Giacomo), reprinted from Physica 146A, pp. 1–68.

Joint Committee for Guides in Metrology, 2012: *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*. JCGM 200:2012.

Kok, C.J., 2000: *On the Behaviour of a Few Popular Verification Scores in Yes/No Forecasting*. Scientific Report. WR-2000-04. KNMI, De Bilt.

Linacre, E., 1992: *Climate Data and Resources – A Reference and Guide*. Routledge, London.

Murphy, A.H. and R.W. Katz (eds.), 1985: *Probability, Statistics and Decision Making in the Atmospheric Sciences*. Westview Press, Boulder.

National Institute of Standards and Technology, 2008: *Guide for the Use of the International System of Units (SI)* (A. Thompson and B.N. Taylor). NIST Special Publication No. 811, Gaithersburg, United States of America.

Natrella, M.G., 1966: *Experimental Statistics*. National Bureau of Standards Handbook 91, Washington DC.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bulletin of the American Meteorological Society*, 56:527–530.

United Nations Environment Programme, 2017: Minamata Convention on Mercury http://www.mercuryconvention.org/Portals/11/documents/Booklets/COP1%20version/Minamata-Convention-booklet-eng-full.pdf

Wieringa, J., 1980*b*: Representativeness of wind observations at airports. *Bulletin of the American Meteorological Society*, 61:962–971.

World Meteorological Organization, 1966: *International Meteorological Tables* (S. Letestu, ed.) (1973 amendment). (WMO-No. 188, TP. 94). Geneva.

———, 1970: *Performance Requirements of Aerological Instruments: an Assessment Based on Atmospheric Variability* (C.L. Hawson). Technical Note No. 112 (WMO-No. 267, TP. 151). Geneva.

———, 1992: *International Meteorological Vocabulary* (WMO-No. 182). Geneva.

———, 1993: *Siting and Exposure of Meteorological Instruments* (J. Ehinger). Instruments and Observing Methods Report No. 55 (WMO/TD-No. 589). Geneva.

———, 2001: *Lecture Notes for Training Agricultural Meteorological Personnel* (J. Wieringa and J. Lomas) (WMO-No. 551). Geneva.

———, 2002: Station exposure metadata needed for judging and improving the quality of observations of wind, temperature and other parameters (J. Wieringa and E. Rudel). *Papers Presented at the WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2002)* Instruments and Observing Methods Report No. 75 (WMO/TD-No. 1123). Geneva.

———, 2003: *Guidelines on Climate Metadata and Homogenization* (P. Llansó, ed.). World Climate Data and Monitoring Programme (WCDMP) Series Report No. 53 (WMO/TD-No. 1186). Geneva.

———, 2008: *Guide to Hydrological Practices* (WMO-No. 168), Volume I. Geneva.

———, 2010*a*: *Abridged Final Report with Resolutions and Recommendations of the Third Session of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology* (WMO-No. 1049). Geneva.

———, 2010*b*: *Guide to Agricultural Meteorological Practices* (WMO-No. 134). Geneva.

———, 2010*c*: *Manual on the Global Data-processing and Forecasting System* (WMO-No. 485), Volume I, Appendix II-2. Geneva.

———, 2011*a*: *Guide to Climatological Practices* (WMO-No. 100). Geneva.

———, 2011*b*: *Technical Regulations* (WMO-No. 49), Volume I, Appendix A. Geneva.

———, 2014: *Guide to Meteorological Observing and Information Distribution Systems for Aviation Weather Services* (WMO-No. 731). Geneva.

———, 2015 *(Updated in 2017)*: *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160), Volume I. Geneva.

———, 2017: *Guide to the WMO Integrated Global Observing System* (WMO-No. 1165). Geneva.