Development of Operational Meteorology and Challenges for the Future

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Early progress

Where to begin?

Man has been interested in weather, applying whatever knowledge he has had, since time immemorial. Down through the ages weathermen have established simple pragmatic rules, observed and applied their knowledge of seasonal changes and developed elementary forecasting techniques. Although this could be termed operational meteorology, it was closer to art and folk wisdom than science. A better starting point might be the middle of the seventeenth century with the invention of measuring instruments and the establishment of small observing station networks; or perhaps the late eighteenth century when a network of 37 stations was set up in Europe followed by gradual development of the scientific basis for the study of weather. But it was not until the invention in 1832 of the electric telegraph, which was first used for the transmission of meteorological information in 1849 allowing for the preparation of weather maps based on recent data, that meteorologists were able to envisage the possibility of identifying weather systems and predicting how they might change and move.

The real beginning of international operational meteorology was probably ten years later when the first International Meteorological Conference which we are here to celebrate adopted the proposal of Lt Maury that "….*all maritime nations should cooperate and make these meteorological observations in such a manner and with such means and implements, that the system might be uniform and the observations made on board the public ship be readily referred to and compared with the observations made on board all other public ships, in whatever part of the world. And, …it becomes not only proper, but politic, that the forms of the abstract log to be used, with the description of the instruments to be employed, the things to be observed, with the manipulation of the instruments and the methods and the modes of operation should be the joint work….".* Thus was laid down the core of what should be done in a scientific approach to operational meteorology.

Over the next twenty years the concepts put forward in the maritime community were extended to the emerging national networks of observing stations and led to the First International Meteorological Congress in Vienna, in September 1873. Operational and technical issues being dealt with at that time included, among others, expansion of observing networks, instrumentation, standards for observations, codes and symbols, and telegraphic and eventually wireless communications.

These continued to develop slowly until the First World War, after which the pace of activity accelerated with new forces at work such the application of meteorology to air navigation, the use of radio broadcasts and the invention of improved instruments including the radiosonde in the early 1930s. Around this time the first mathematical model and a method for numerical weather prediction were developed but it took several months to make the necessary calculations for a six-hour forecast! From 1939 to 1945, war again interrupted orderly development but, necessity being the mother of invention, many technological advances were made in radar, in aviation, in communications, and in computers - all of which were to make significant contributions to operational meteorology.

If the impetus for the initial organized scientific approach to operational meteorology came from the requirements of mariners, the main driving force a century later was aviation. Civil aviation was undergoing rapid expansion with commercial aircraft flying longer and longer distances without refuelling. This called for not only accurate weather observations and forecasts for take off and landing, but forecasts of conditions along the routes, including over the oceans, for flight planning purposes. This required a greater degree of international cooperation in the rapid exchange of raw and processed information than had been the case until then. There was of course a counter benefit for meteorology in that aircraft flying over data sparse areas were able to make observations and measurements which were of great assistance to weather analysts.

The new era

Around this time advances were made also in meteorological science that led eventually to the development of conceptual and mathematical models to describe the behaviour of the atmosphere – the first successful numerical prediction being made by computer in 1950. Nevertheless, at this stage, predicting the weather with any degree of accuracy and consistency over a period of anything more than a day continued to defy operational meteorologists. But this state of affairs was soon to change. In the middle of the twentieth century a great technological revolution had begun that was to take the nature and scope of meteorology beyond the wildest dreams of the scientific thinkers of a hundred or even fifty years previously. The development and introduction of ever more powerful electronic computers, high-speed telecommunications and the first artificial satellites provided unprecedented opportunities for international meteorology and called for a complete reappraisal and redesign of the existing world system of gathering, processing and redistributing meteorological information.

If a date had to be assigned to the beginning of the modern era in meteorology, it would have to be 20 December 1961 when the General Assembly of the United Nations called for a new concerted approach to weather forecasting making full use of these new technologies. By this time, following the creation of the United Nations itself in 1945, the World Meteorological Convention had been adopted in 1947 and WMO established to replace the IMO in 1950 when the Convention came into force.

Although there is no reference to the term "*operational meteorology*" in the WMO Convention it may be conveniently used to cover many of the activities to be promoted by WMO, including:

- *the establishment of networks of stations for the making of meteorological observations;*
- *the establishment and maintenance of meteorological centres charged with the provision of meteorological services;*
- *the establishment of systems for the rapid exchange of weather information;*
- *the standardization of meteorological observations;*
- *the application of meteorology to aviation, shipping, agriculture and other human activities.*

It was essentially these responsibilities that were re-examined in the light of the UN resolution of 1961. In response, WMO prepared an initial report discussing in broad outline a "world weather watch" comprising satellite and conventional observations, a network of world and regional weather service centres and a telecommunication system. To quote from the report, the WWW was " *intended as a co-operative global meteorological observing and* *prediction system designed to assist Meteorological Services of the world to discharge their responsibilities without each Service having to perform all the steps needed for this purpose."*

The World Weather Watch

In April 1963 the fourth WMO Congress adopted the concept of the World Weather Watch and, after a period of intense planning on both national and international levels, it became a reality four years later. The WWW in its initial design comprised three basic systems:

- the ***Global Observing System***, comprising facilities on land, at sea, in the air and in outer space for the observation and measurement of meteorological elements;

- the ***Global Telecommunication System*** for the rapid exchange of observational information as well as analyses and forecasts produced by the third component;

- the ***Global Data Processing System***, a network of computerized data processing centres around the world.

These are backed up by a variety of supporting activities including standardization of observing methods and techniques, the development of common telecommunication procedures and the presentation of both observational data and processed information in a manner understood by all regardless of language.

In addition, the first WWW Plan made reference to associated research activities and to the Global Atmospheric Research Programme in particular. This programme had also been triggered by the resolutions of the UN General Assembly and was to prove crucial to the development of the WWW and to operational meteorology. GARP, a joint venture between WMO and the non-governmental International Council of Scientific Unions, (now the International Council for Science) was one of the largest and most complex scientific projects ever launched. Its objectives, stated simply, were to extend the range, scope and accuracy of weather forecasts.

The GARP had its greatest influence through a concerted effort to develop the science and technology for application to numerical weather prediction, and through designing and mounting field experiments, focusing on specific meteorological problems, often using new and innovative observing systems. The GARP Atlantic Tropical Experiment (GATE) was fielded in 1974 with the objectives of providing the data resources to understand the effect of smaller tropical weather systems on the larger-scale circulation. Five years later in 1979 the Global Weather Experiment (FGGE) succeeded in deploying special observing capabilities that, in the aggregate, approached the global coverage dreamed of by the planners of the WWW a decade earlier. Regional programmes to study the monsoon circulation systems in Asia (MONEX) and in West Africa (WAMEX) were fielded during the same time as FGGE in order to take advantage of the intense global observational resource and, in turn, to contribute to the global effort with enhanced observations from their respective regions. Many of the systems and technologies developed and deployed during the experiments have become integral parts of the operational WWW itself.

An unusual aspect of the planning of the WWW, the importance of which cannot be overstressed, was the fundamental principle that it would be implemented and operated by Member countries themselves to the extent that their individual resources permitted and in accordance with the agreed plan. The implementation of facilities in areas outside national territories would be based on the voluntary participation of countries providing equipment and services from their own resources. To assist those with limited means and therefore less able to contribute to and benefit from the system, a voluntary assistance – now cooperation – programme was established thus ensuring that implementation was on a truly global scale.

The Global Observing System

In the years leading up to the establishment of the WWW and the GOS, a wide range of new observing technologies were at various stages of development, including automatic land stations, ocean buoys, balloon-borne systems, soundings from merchant ships and aircraft and, of course, from satellites.

The Space-based subsystem

The launch by the USSR of Sputnik I in October 1957, and Sputnik II in November 1957, followed by the launch by the USA of Explorer I in January 1958, generated tremendous interest and concern throughout the world, and a determination to ensure that this new technology would be used for peaceful purposes. The first meteorological satellite, Tiros 1,which transmitted cloud imagery, was launched by the USA in 1960. A major development was the introduction of the Automatic Picture Transmission (APT) System in the early 1960s. It provided the opportunity for all NMSs to have direct access to real time satellite imagery for analysis and forecast applications and, until high-speed communication capabilities were available, it ensured access to real time information from satellites.

The progressive development of the space-based system from the rudimentary polar orbiting satellites at the beginning of the WWW to the current operational configuration of three to four polar orbiting systems and five to six satellites in geostationary orbit has been perhaps the single greatest accomplishment in our ability to observe the global atmosphere and ocean. The satellite operators have closely co-ordinated their plans with the WWW and the provision of satellite data into the WWW system has been a model of international response to user requirements. A major recent event in this regard was the agreement last year of several research and development space agencies to participate in the GOS. This has resulted in a large expansion in the availability of data and products from the space-based sub-system.

Both polar-orbiting and geostationary satellites provide visible and infrared cloud images which have become an invaluable tool in the identification and monitoring the change and movement of weather systems, which is of special importance over the tropics and ocean areas. Temperature and humidity profiles are available from polar-orbiters and water vapour images along with indications of wind structure can be obtained from geostationary satellites. It must be said, however, that other than in the application of visible and infrared imagery on weather analysis, the actual impact of satellite data on global, regional and local-scale numerical analyses has been slow to materialise due partly to the need for calibration and corresponding "*ground truth*" in situ measurements. In the decade of the 1990s the major numerical prediction centres developed ways to assimilate satellite observed radiance values into their analysis schemes and this has begun to bring the value of satellite data up to the level that has long been anticipated.

Surface-based sub-system

To meet all the requirements for observational data, the GOS was designed at the outset as a composite system made up of a number of different types of observing tools, both surface based and space based, with sufficient flexibility to allow the choice and mix of observing elements to be adjusted to advances in technology and changing requirements. Despite the advances in satellite observing technology, the backbone of the system continues to be around 10,000 stations on land – an increase from 8,000 in 1963 - making observations at or near the Earth's surface at least every three hours, but often hourly, of a number of parameters. Some 4,000 of these stations make up the Regional Basic Synoptic Networks drawn up by the six Regional Associations to meet the collective needs of its Members and from which observational reports are exchanged globally in real time. These numbers have changed little over the last 40 years but the number of RBSN stations making all eight observations per day has risen from 60% to nearly 80% in that period. An important development over the past twenty years has been the introduction of automatic weather observing technologies that have permitted more efficient use of personnel and allowed for observations to be made in and transmitted from more remote locations

This has had considerable impact over the oceans where large numbers of drifting and moored buoys have been deployed which report automatically measurements of sea and air temperatures, atmospheric pressure and wind speed and direction. There are at the moment some 800 drifting buoys providing 6,000 reports per day. This has not, however lessened the requirement for observations from ships recruited under the WMO Voluntary Ship programme. These measure much the same variables as stations on land with the important additions of sea surface temperature and wave height and period. The number of ships operating in the scheme has remained fairly static at around 7,000 of which 40% are at sea at any given time. The introduction of satellite based telecommunication systems has been of major benefit in the transmission and collection of reports.

Another major element of the surface-based component of the GOS is the network of upper-air stations from which balloon-borne radiosondes make measurements of atmospheric pressure, wind velocity temperature and humidity from just above ground level to heights of up to 30 km. The establishment and maintenance of the desired network of some 1000 stations worldwide has however remained an intractable problem. From a base of just over 500 stations in 1963, the number of working stations increased to nearly 650 in the earl 1990s but has since dropped to below 600. While the evolution of the systems from those based on radar to those based on navigational-aid radio beacons and to the current utilisation of the Global Positioning System has resulted in a continuing improvement in data quality and ease of operation, the high cost of equipment and expendables has made it impossible to attain the global network envisaged. Some compensation has however been achieved through the utilization of vertically pointing radar systems (profilers) and especially through the use of modern avionics on commercial aircraft which provide detailed information on ascent and descent as well as at in-flight cruise levels. Another significant development in recent years has been the introduction of Automated Shipboard Aerological Systems which has provided a welcome increase in the upper-air data over the oceans; but again, high costs have rendered the rate of implementation rather slow; with around half at sea at any given time, only some 21 ships, most of them plying the north Atlantic are suitably equipped.

It is, of course essential that all meteorological measurements and observations are as accurate and reliable as instruments will allow. To ensure that the highest standards are maintained, the quality of all observational data is continuously monitored through a system of global and regional centres. These apply common criteria in the identification of "suspect" stations which are then notified to those responsible for their operation so that corrective measure can be taken.

The Global Telecommunication System

If the life-blood of operational meteorology is observational data and processed information, then the GTS is its arteries, heart and veins. In the days just prior to the creation of the WWW, observational data were collected nationally and subregionally mainly by telegraph or telephone, or occasionally over landlines, and broadcast using relatively unreliable high frequency radio transmissions to regional centres. With very few point-to-point circuits the arrangements were slow, cumbersome, and unreliable. The GTS was designed to operate at three levels: (1) The Main Telecommunications Network - a high-speed circuit that connected three World Centres and branched to 21 (now 25) regional hubs so that the regions were effectively connected to the global system; (2) Regional Meteorological Telecommunications Networks; and (3) National Meteorological Telecommunication Networks. Of the 247 circuits called for in the original plan, 222 are currently in operation.

Over the years the GTS has progressed from the original “store-and-forward” system with its mix of automatic and manned facilities requiring an intense management effort, and which was subject to outages and failures especially at the regional level, to a system which might be described as a “mixed” system with some national and regional components utilising “two-way point-to-multi-point” satellite based systems, while others operate in the traditional mode. All MTN centres are equipped with computer-based message switching and data communication systems and the migration to Transmission Control Protocol/Internet Protocol (TCP/IP) is continuing apace. The great strength of the WWW GTS is that it allows the telecommunication connections between countries and within and between Regions to be determined by those countries concerned as long as international exchange commitments and protocols, as set down in the WMO Technical Regulations, are met. The GTS is constantly under review and planning for upgrading the global system to take advantage of state-of-the-art technology, while ensuring every Member receives the meteorological information it requires, is a high priority.

Global Data Processing System (GDPS)

The ultimate responsibility for operational meteorology in each country rests with the National Weather Service. The purpose of the WWW Global Data Processing system- now called the Global Data Processing and Forecast System - is to make available to the NMSs weather analyses and forecasts to enable them to meet their national responsibilities. The original WWW Plan focused on the establishment of three World Meteorological Centres (WMCs) and anticipated a number of Regional Centres (RMCs) to eventually emerge. The operational concept was for the WMC to undertake the task of assembling data, information such as output fields from global numerical prediction models, and their interpretation for use by the various RMCs which in turn would add a level of more detail in order to support the National Meteorological Centres (NMCs) in their service provision responsibilities. Over the years the research contributions from major field programmes and the development of major modelling centres such as ECMWF in Europe, and GFDL and NCAR in the USA, as well as research programmes at academic and research institutions around the world, has done much to expand the definition and role of the GDPS. Numerical weather prediction on the continental and sub-regional to meso-scales has become a routine part of operational meteorology.

The structure of the GDPS has evolved and currently there are some twenty-five what are now termed Regional Specialised Meteorological Centres (RSMCs) with geographic specialisation. These centres run a suite of models and analyses particularly designed and tuned to provide forecast guidance for a particular topographical or ocean area often using data sources of a local or regional nature e.g. radar data. In addition there are six RSMCs with tropical cyclone prediction responsibility, and eight RSMCs with transport modelling responsibilities. The latter category has regional responsibility to provide atmospheric transport model products for environmental emergency response in the case of a nuclear accident, volcanic eruption or other emergency. In addition, several designated RSMCs provide medium range weather forecasts, drought monitoring and prediction and extended and long-range forecasts. Some 32 additional NMCs possess some level of numerical prediction capability, ranging from full global models to limited area models to more high-resolution meso-scale models.

Remarkable advances in techniques for the assimilation into models of new tyoes of data, from, for example, satellites and ground-based remote sensing systems, and in the procedures for processing model output, such as ensemble prediction schemes, that allow one to objectively attain the best possible forecast outcome, continue to increase the accuracy and usefulness of numerical prediction products.

The continued improvement of both accuracy and lead-time of weather forecasts attests to the progress made in operational meteorology as a whole as well as in the development of the atmospheric sciences in general and numerical prediction in particular. Five-day forecasts today have better accuracy than two-day forecasts did in the 1970s and he prediction of extreme events such as the occurrence, intensity and track of tropical cyclones has also shown marked improvement. … CLIVAR….

Applications of operational meteorology

Before looking briefly at the future we should remind ourselves that the applications of operational meteorology, although outside the scope of this paper, are of course, its “raison d’etre “ and have been the main driving force in its development. Each country of the world – large or small, developed or developing, whatever its geographical location – shares a concern for weather and climate. Through the World Weather Watch, the global programme in operational meteorology, countries can adapt their activities to make the best use of the weather and minimise its harmful effects. The most obvious benefits are in the protection of life and property through, for example, the detection, tracking and prediction of tropical storms and other severe weather conditions, but many economic and social activities are heavily influenced by weather. The requirements of shipping, marine fisheries and offshore oil exploration and exploitation continue to warrant dedicated meteorological services, as does civil aviation which is perhaps the major single consumer of operational weather information. Apart from safety aspects, huge savings in time and fuel costs can be achieved through weather related route planning in both shipping and aviation. In agriculture also, where the production, collection, transport, storage and distribution of produce are all greatly weather sensitive, losses due to excessive rain, hail, frost and snow can be substantially reduced by taking advantage of weather information and warnings. Myriad other activities – the construction industry, tourism, water resources development, land transport – can and do benefit from specialised services and as these activities become more advanced the demands for improved and more varied weather advice continue to expand.

Challenges for the Future

Economic and social factors

As we have seen, operational meteorology has continued to develop steadily over the past 150 years or so and will no doubt continue to do so. Advances in science and especially technology have made it possible to provide more and more sophisticated services and placed even greater requirements on the operational system in terms of the quantity and quality of information and the speed with which it is produced. Although some activities may become less weather dependant others may become more so and the financial savings greater. However, the cost of providing these services, making full use of the available scientific and technological knowledge, has been increasing and in the current global economic climate, the necessary financial resources are not always forthcoming. On the contrary, in most countries National Meteorological Services are under pressure to reduce costs and, in many cases, encouraged to charge the user for services provided. The main challenge for the meteorological community is to improve the efficiency of existing systems introducing new technology as appropriate, and to devise less expensive modes of operation and methods of delivering services, all without any deterioration in the quality of these services. It will be necessary too, to make concerted efforts to optimise the potential of Meterological Services to contribute to economic and social activities through creating a greater awareness of the advantages and economic benefits that can be realized by the application of current and forecast weather information

As the provision of user-oriented applications and services have become more and more dependent on highly advanced technology, the cost of which is beyond the reach of many countries, there is evidence of a growing gap between developed and developing countries in the ability to provide these services. In addition, the globalisation of observing, computing and telecommunication systems tends lead to funding and technical leadership being chiefly in the hands of the more developed countries. Consequently, one of the main challenges that WMO faces is to redress the current trend and ensure that all developing countries are in a position to provide the services necessary for their sustainable development and towards the reduction of poverty. The WMO Congress, its governing body, has already adopted a strategy to address this issue and although most aspects are outside the scope of operational meteorology, significant contributions can be made in enhancing the capability of the less developed WWW centres to assimilate and analyse information from major centres and to generate value-added products so as to improve further their capacity, for example, to forecast potentially catastrophic weather phenomena such as cyclones and floods, and to improve and expand applications to agriculture.

Scientific and technical issues

A start has already been made in addressing the cost effectiveness of producing observational data with a major effort being undertaken to re-examine and redesign the GOS particularly in the light of the expanding space-based component. User requirements and individual observing system capabilities have been charted in ten application areas; candidate observing systems – space-based and surface-based – for the coming decade have been examined; Observing System Experiments have and will be carried out to test possible configurations of the GOS; recommendations for the evolution of the GOS to meet the most pressing needs in the near term and in the next 10 to 15 years have been developed. As an example, a solution to the inadequacies of the current upper-air sounding systems over the tropics and ocean areas may be found in greater use of wind-profilers (radar) and of aircraft measuring systems during ascent and descent, in improved use of satellite data and in targeted observations. In this connection another –perhaps smaller, but vitally important - challenge arises, namely the allocation and protection of radio frequencies required for the operation of the many in situ and remote observing systems. The competition for these is expected to become even more intense as the frequency bands needed for meteorology fill up and those remaining become more highly coveted by other user communities.

The future GOS will have to be a truly composite system employing the best mix or integration of observing techniques, in terms of cost-efficiency, and scientific accuracy, and able to capitalize on existing and new technologies not presently incorporated or not fully utilized. The impact of changes in the GOS in the next decade or so are expected to be so great that a completely new approach to data gathering and handling and to product development, distribution and utilization will have to be developed. This coincides with the need for a thorough review and up dating of information exchange and data management to make greater use of the huge potential offered by the Internet and satellites. Work has already begun on the “Future WMO Information System” as an integrated approach to meeting both real- and non-real-time requirements for all WMO Programmes; it is intended to build upon successful existing components in an evolutionary process. Because of the rapidly evolving information technology, the FWIS will utilize industry standards for protocols, hardware and software which will reduce costs and allow greater exploitation of the Internet and web services.

The expected continuation of the exponential increase in computing power will allow higher resolution models with a more accurate representation of atmospheric processes. The introduction of Ensemble Prediction Systems has the potential to greatly improve forecasting services in all geographical areas and to expand applications to many new economic activities by providing seasonal forecasts and probability forecasts for specific environmental variables dependant on atmospheric drivers. This will assist also in meeting one of the biggest challenges facing the meteorologist, namely, the prediction of climate variability with time scales from a season to a century. As this could be the subject of a paper in itself, it will suffice to mention as an illustration familiar to us all – the El Nino effect. Because sea surface temperature in the tropical Pacific ocean influences rainfall and temperature in adjacent regions, which in turn influence the same parameters in selected regions in middle latitudes, the present capability to forecast SST, using coupled atmosphere/ocean models up to a year in advance, can contribute to forecasting climate conditions in these areas. To understand and predict climate processes and events is the goal of the WMO Climate Research Programme but the operational meteorologist has also a major role to play as he does in almost every social, economic and scientific activity which is influenced by the weather.

To meet these challenges even stronger international cooperation and coordination is called for at various levels and in various domains, which in turn calls for an even stronger WMO.