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NOTE

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of any of the participating agencies concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

THE WCDMP “GUIDELINES” SERIES

In recognizing the need for National Meteorological Services (NMSs) to improve their climate data and monitoring services, the Commission for Climatology (CCl) and the CCl Management Group placed a high priority on the distribution of guidelines for the NMSs.

Within the World Climate Data and Monitoring Programme, a meeting was held at the kind invitation of Spain (Malaga, 24-26 February 2003) in which a number of experts in the two CCl Open Programme Area Groups (OPAGs) on Climate Data and Monitoring initiated the preparation of guidelines on metadata and data homogenization, observation networks and systems, and data rescue. The participants were either members of an Expert Team of CCl, or were invited experts.

The Guidelines on Climate Observation Networks and Systems are meant to be easy to read and refer to, well illustrated, and not bulky. They provide information and assistance on how to organize and implement climate services, and present processes and technological solutions that attempt to address the special situation and needs of smaller NMSs which have limited resources.

The review of the Guidelines was the first such activity that was done within the CCl OPAG structure, so that all CCl Members were given an opportunity to review and comment, as well as to see the progress being made in the OPAGs. It was drafted by a sub-group of the CCl Expert Team on Observing Requirements and Standards for Climate, circulated for contributions and comment among the members of the CCl Expert Team, and posted to the OPAG’s web site for review and comment by the members of CCl.

It should be kept in mind that this Technical Document, like the other technical documents published under the WMO WCDMP series, is intended to provide guidance in the form of best practices that can be used by Members. Because of the diversity of NMSs with respect to size and stage of technological development along with the variability of weather types and climate, some practices may not have significant utility for specific Member. However, this document does cover a wide range of guidance that should provide some form of assistance to every Member.

Guidelines on Climate Observation Networks and Systems

Neil Plummer[1], Terry Allsopp[2], José Antonio Lopez[3]

1 Introduction

These Guidelines aim to provide climatologists with the essential information on observation networks and systems to help ensure that their outputs are adequate for the comprehensive needs of climate services, applications and research.

While climatologists are often not directly responsible for the management and operation of observational networks and systems they are nevertheless a key stakeholder group with respect to their outputs. Since the quality of climatological products and services is contingent on the availability and quality of observations then climatologists have a duty to ensure that monitoring and feedback systems are in place to help deliver data outputs according to required standards, which they themselves should help establish. They also need to ensure that managers and operators of networks and systems are fully aware of their needs and that they are part of the planning and decision-making process in the introduction of, or making changes to, observational infrastructure that may affect any aspect of their work. Operators of observation networks should take into account recommendations formulated to meet the needs of international conventions such as the United Nations Framework Convention on Climate Change (UNFCCC).

In these Guidelines, emphasis is placed on equipping climatologists with information relevant to their own operations and research needs as opposed to attempting to cover all nuances of systems and networks. This guidance will also give greater attention to infrastructure that they are more likely to encounter in their day-to-day activities (e.g. surface and upper air meteorological networks) as opposed to other networks and systems (e.g. research networks and radar systems).

It is recognised that many people who manage and administrate observational networks and systems have a wealth of knowledge on the needs of their stakeholders. However, it cannot be assumed that they understand the precise (and evolving) needs of climatologists and it is incumbent on the latter to ensure that these needs are communicated effectively and frequently.

These Guidelines will not provide detailed guidance in a number of areas that are closely associated with this topic, e.g. metadata, homogeneity, data management and quality control; they will be covered in additional Guidelines in the WCDMP series. In addition, the CCl implemented the Expert Team on National Networks and Observations in Support of Climate Activities in 2003, which may produce supplemental Guidelines to this one.

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2 Characteristics and uses of climate observations

Climate observations are important because they help satisfy important social, economic and environmental needs. They are an integral part of reducing the risk of loss of life and damage to property. Senior managers in National Meteorological and Hydrological Services (NMHSs) will need to regularly brief their governments of the reasons for recording, collecting and managing observations.

Climate observations are sourced from the numerous meteorological and related observational networks and systems (Fig.2.1) that underpin applications such as weather forecasting, air pollution modelling and environmental impact assessments.

Figure 2.1 Schematic showing a variety of observation systems of relevance to National Meteorological and Hydrological Services. Observation networks rely heavily on the cooperation of many individuals and organizations, many of them volunteers. (Source: Bureau of Meteorology, Australia)

However, climate observations differ in a number of important respects. Firstly, climate observations need to account for the full range of elements that describe the climate system – not just those that describe the atmosphere. Extensive observations of the ocean and terrestrial-based systems are required. Secondly, an observation at any point in time needs a reference climate against which it can be evaluated, i.e. a reference climatological period must be selected. In this regard, the observations from a station that only exists for a short period (i.e. from days to a few years) or which relocates very frequently will generally be of less value than those observations from a station whose records have been maintained to established standards over many years. Thus, in order to derive a satisfactory climatological average (or normal) for a particular climate element, a sufficient period record of homogeneous, continuous and good quality observations for that element is required. Thirdly, a climate observation should be associated – either directly or indirectly - with a set of metadata that will provide users with information, often implicitly, on how the observation should be interpreted and used. Other differences can be inferred from the sections that follow. So, while climate observations serve multiple purposes beyond specific climate needs, we must ensure that they retain, and acquire, particular characteristics that serve a range of climate needs.

The basic monthly, seasonal and annual summaries of temperature, rainfall and other climate elements provide an essential resource for planning endeavours in areas such as agriculture, water resources, emergency management, urban design, insurance, energy supply and demand management and construction. Climate data, including historical daily data, are also unlocking important relationships between climate and health, including the effects of extreme heat and cold on mortality. Millions of people each year use climatological information in planning their annual vacations. In a relatively new area of applications, high quality climate observations are being used by the weather derivatives industry, which has already traded billions of dollars US based to a large degree on climate information. Trenberth et al. (2002) provides several examples of the benefits of climate data.

The need for more accurate analysis and detection of climate change and the promise of further advances in seasonal-to-interannual prediction (SIP) have increased the value of climate data in recent decades (Fig. 2.2).

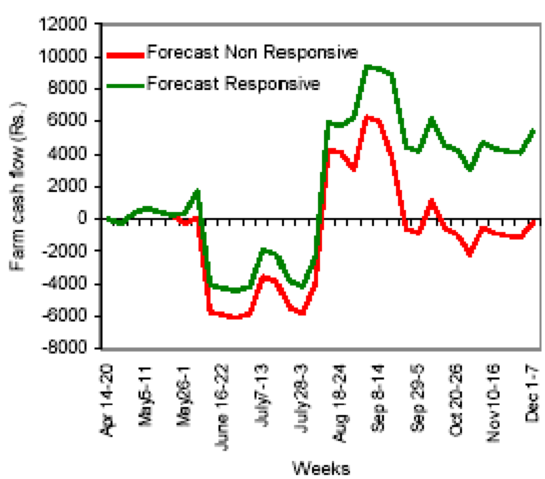

Figure 2.2. Output from a whole-farm economic model for a farm in India showing the cash flow benefits from using a management strategy which includes climate forecasts. As inputs to these models, climate observations have demonstrable economic benefits. (Source: H.Meinke, Queensland Department of Primary Industries)

Climate data are fundamental to the operation and validation of climate models, which are widely used for SIP and for generating projections of future climate. Maximising the availability of computerised historical data, including metadata, is essential for long-term climate monitoring - particularly for analysing trends in the occurrence of extreme events where data quality and longevity of record become even greater considerations (e.g. Nicholls 1995, Karl and Easterling 1999).

The more stringent requirements on observation networks and systems for recording and monitoring climate, including the detection of climate change, has led to the development of special networks at national (e.g. Reference Climate Stations), regional (e.g. Regional Basic Climatological Network) and global (e.g. the Global Climate Observing System - GCOS - Surface Network, GSN) scales.

3 Principles of climate monitoring

Some guiding principles for long-term sustainable climate monitoring have been identified and described (e.g. Karl et al. 1995, NRC 1999). While these were primarily developed for the purposes of improving our ability to detect climate change, the principles are widely applicable to all facets of climate observations. The ten principles[4] as stated in GCOS (2003), endorsed by the Commission for Climatology (CCl) and adopted by the UNFCCC are:

3.1 The impact of new systems or changes to existing systems should be assessed prior to implementation

In this context, relevant changes are those affecting instruments, observing practices, observation locations, sampling rates, etc. The pace of change in observation networks and systems has increased during the past few decades and it is very likely that this trend will continue. Many of these changes are deliberately introduced as a result of the availability of improved technology that, for example, improves observational accuracy. Providing continuity and homogeneity of climate records can be preserved, these changes are to be encouraged by climatologists, particularly if the new technology is more reliable. However, the reasons behind some changes, e.g. purely for cost savings or to solely respond to the demands of a single stakeholder, may have less justification from a climate perspective and these should prompt climatologists to question their value. Some changes, however, are unavoidable. A key consideration in the introduction of a new system is the likelihood of the system operating, and providing continuous and homogeneous observations, over the long-term. Strategies, such as a well coordinated change management program (see section 6.10), will be required to minimise any adverse impacts from a change.

3.2 A suitable period of overlap for new and old observing systems is required

Parallel observation programs between existing observation systems and their replacements (or between new and old meteorological sites in the event of a relocation) should be part of any strategy to preserve the continuity and homogeneity of the climate record. Priority should be given to those stations that are part of special networks for climate change detection (see section 5). These programs may also include retrospective comparisons between former sites or old, retired observation systems where these

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[4] An additional ten principles have been added for satellite systems and these can be found in Appendix 2 of GCOS (2003).

locations and/or systems are still available for use. Observation managers may question the additional costs or overheads in conducting such parallel observations, particularly where many competing demands stretch their budgets. Climatologists must be prepared to show that benefits outweigh the costs and such endeavours are worth pursuing.

3.3 The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e. metadata) should be documented and treated with the same care as the data themselves

Good quality metadata are now critical to meteorological services, particularly for climate operations and research. There is a need for ready access to metadata (i.e. preferably in electronic form) for: data interpretation; quality control; network selection; network/system performance monitoring; client expectations; international obligations (e.g. for GCOS Surface Networks); and identification and adjustment of climate records for non-climatic discontinuities. As well as the station specific metadata, climatologists and data managers will need metadata on broader network issues, e.g. details on historical changes in calculating derived climate variables and information on changes in analysing weather systems (e.g. tropical cyclones). Unfortunately, metadata are often incomplete, poorly organised and inaccessible and this presents a major challenge for organisations. Metadata management through a modern database system (Fig. 3.1) is desirable although paper-based records will still need to be managed and preserved, including through conversion to electronic and/or microfilm/microfiche form if possible.

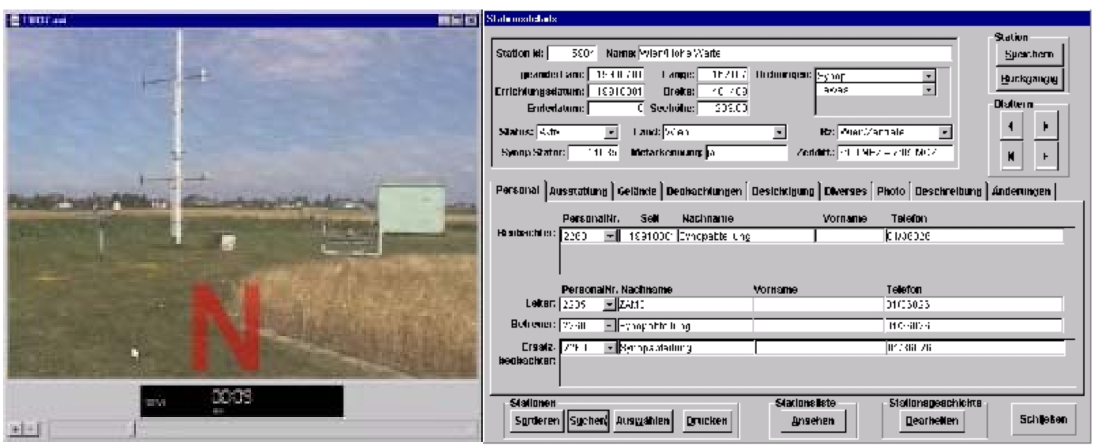


Figure 3.1. Modern databases are providing efficient access to important station metadata, including photographs, site plans and other useful documents. (Source: Central Institute of Meteorology and Geodynamics ZAMG, Austria)

Recording of information in spreadsheets may be a useful interim way of ensuring that metadata are maintained. Management of metadata should fit with the broader information policy of an organisation and must ensure that private (e.g. observer addresses), personal (e.g. performance information) and any commercial-in-confidence information are not distributed without approval or consent.

Detailed Guidelines on Climate Metadata and Homogenization are covered in WMO TD No. 1186 (WCDMP 2).

3.4 The quality and homogeneity of data should be regularly assessed as a part of routine operations

It is important that the responsibilities for ensuring the quality of climate data are distributed throughout the organisation and are not considered the sole responsibility of climate data managers. Meteorological services should endeavour to develop a Data Management policy with strategies that involve a strong focus on data quality, and including laboratory and testing facilities, quality assurance processes, real-time monitoring and correction, quality control procedures and data archiving. Some organisations may extend this philosophy to a quality policy for the organisation (e.g. Knez et al. 2003). The monitoring principles 3.1 to 3.3 discuss ways of minimising the impacts of inhomogeneities. Organisations should also endeavour to have systems in place to alert to inhomogeneities in near real-time so that early corrective action can be taken. So far, delayed-mode detection of inhomogeneities has most commonly been applied to temperature and precipitation data. Adjusting for inhomogeneities has proven more problematic for some climate elements (e.g. dew point, wind speed and direction).

3.5 Consideration of the needs for environmental and climate-monitoring products and assessments, such as assessments from the Intergovernmental Panel on Climate Change (IPCC), should be integrated into national, regional and global observing priorities

Climatologists need to identify the observational priorities for their countries based on the capabilities of existing networks and systems to satisfy a range of climate needs. As well as quality requirements, climatologists should ensure that networks provide adequate spatial and temporal sampling so that areas that exhibit large spatial variations in climate are adequately sampled and that areas that experience (or which may be expected to in the future) large temporal or spatial climatic variations are also well sampled. In addition to the recommendations from reports of the IPCC, the adequacy of observation networks and systems at large regional and global levels are assessed by the GCOS adequacy reports for the UNFCCC (GCOS 1998, GCOS 2003) and their recommendations should be integrated into national priorities. Many countries prepare national reports on their systematic climate observations as a result of requests from the UNFCCC Conference of the Parties (COP) and these too should be utilised. Another important aspect of this monitoring principle is to anticipate the use of observations in the development of environmental impact assessments. In this respect, co-location of priority climate stations with sensors monitoring wider atmospheric parameters (e.g. the Global Atmospheric Watch Network monitoring atmospheric constituents, see Fig.3.2) should be given strong consideration.

Figure 3.2. The Cape Grim Baseline Air Pollution Station on the remote north-western tip of Tasmania (Australia) samples air flowing from the Southern Ocean, largely free from athropogenic pollutants. (Source: Bureau of Meteorology, Australia)

3.6 Operation of historically-uninterrupted stations and observing systems should be maintained

This principle is another that is fundamental to the production of homogeneous and continuous climate records. Countries have been encouraged to identify stations in a number of special networks established for long-term climate monitoring (see section 5), which will help satisfy this goal. However, the desire for continuous operation should permeate throughout all meteorological and related station networks that provide climatological data. Since changes in observing systems are inevitable, it is critical that NMHSs have change management programs in place, which include parallel observation programs. Much effort is being channelled into ensuring the long-term continuation of sites critical to climate (Fig. 3.3). Countries should recognise that their stations with long historical time series of climatological elements constitute national, regional and global heritage to their nations.

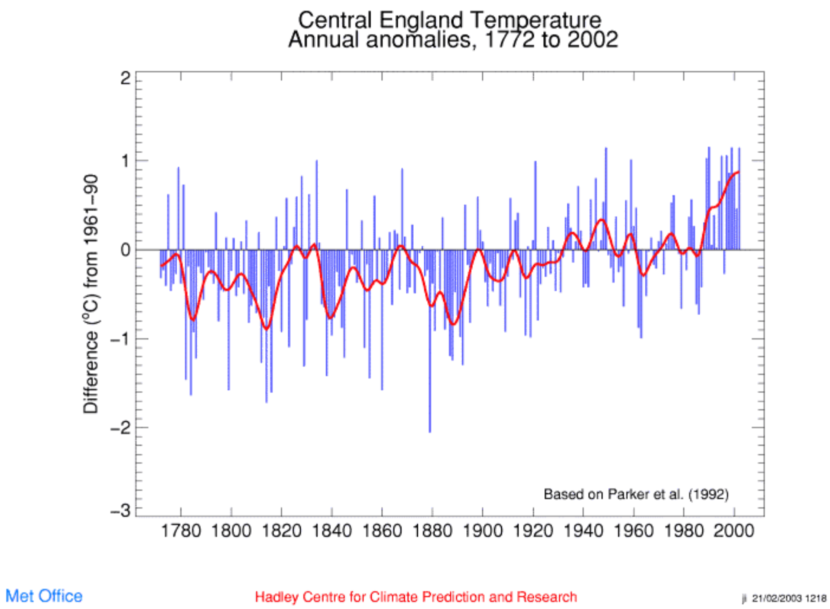


Figure 3.3. An example of a long and valuable climate data series. The Central England Temperature (CET) is representative of a roughly triangular area of the United Kingdom enclosed by Bristol, Manchester and London. The monthly series began in 1659, and to date is the longest available instrumental record of temperature in the world. Since 1974 the data have been adjusted by 1-2 tenths °C to allow for urban warming. (Source: The Hadley Centre, United Kingdom Meteorological Office)

3.7 High priority for additional observations should be focussed on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution

National, regional and global network adequacy assessments are pertinent here. The development of improved observational technologies should focus on those observations and regions for which capturing quality observations have proven problematic (e.g. precipitation in cold climates). Often these regions are associated with ecosystems that are sensitive to climate change and so the observations have additional importance for climate impacts assessments and adaptation studies. Priorities should also be linked to the social, economic and environmental fabric of the country and this may, for example, strengthen the case for supporting the observational needs for specific climate applications. The GCOS and Reference Climate Station (RCS) networks may have inadequate spatial resolution for monitoring some critical climate elements at the national scale (e.g. precipitation) so that some additional national networks, which adhere to these climate monitoring principles, will need to be identified.

3.8 Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation

Sustainable climate monitoring can only be achieved through a shared understanding, and considerable liaison, between observation network and system managers, data managers and climatologists. The latter will need to represent the very broad needs of end-users. There are close parallels here with the first principle identified, particularly regarding the need for a change management program. There are some good examples of countries who have attempted to seek all stakeholder needs, including climatological needs, prior to designing new networks (e.g. Frei 2003). Climatologists should be ready to respond to demands for this information by attempting to provide details of national observation needs for a range of key climatological applications (e.g. analysis of climate variability, climate prediction) and, with respect to individual climate elements, requirements for quality, spatial density and sampling frequency. Comprehensive statements of requirements should be prepared (see section 4 and Appendices 1 and 2), which include accuracy requirements.

3.9 The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted

The needs of climate imply a long-term commitment to observing systems is required. For those systems that have potential for climate monitoring, there needs to be a clear transition plan (from research to operations) developed. Some of the best examples of observation networks and systems that have made the transition are the Tropical Atmosphere Ocean (TAO) array established as part of the Tropical Ocean Global Atmosphere (TOGA) experiment for monitoring the El Nino-Southern Oscillation phenomenon. Any transition will require the development of infrastructure supporting the broader requirements of climate as described elsewhere in this section (e.g. metadata, robust data management systems, regular maintenance/inspection of stations, life-cycle management of equipment and sensors).

3.10 Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems

One of the major differences between the observational requirements of climate and weather concerns the treatment of observations beyond a few hours of their collection. While the operational value of observations to weather forecasters usually rapidly depreciates, it does not for climatologists. Climate data management systems generally sit between the observation systems and the delivery and production of climate products and services (Fig. 3.4).

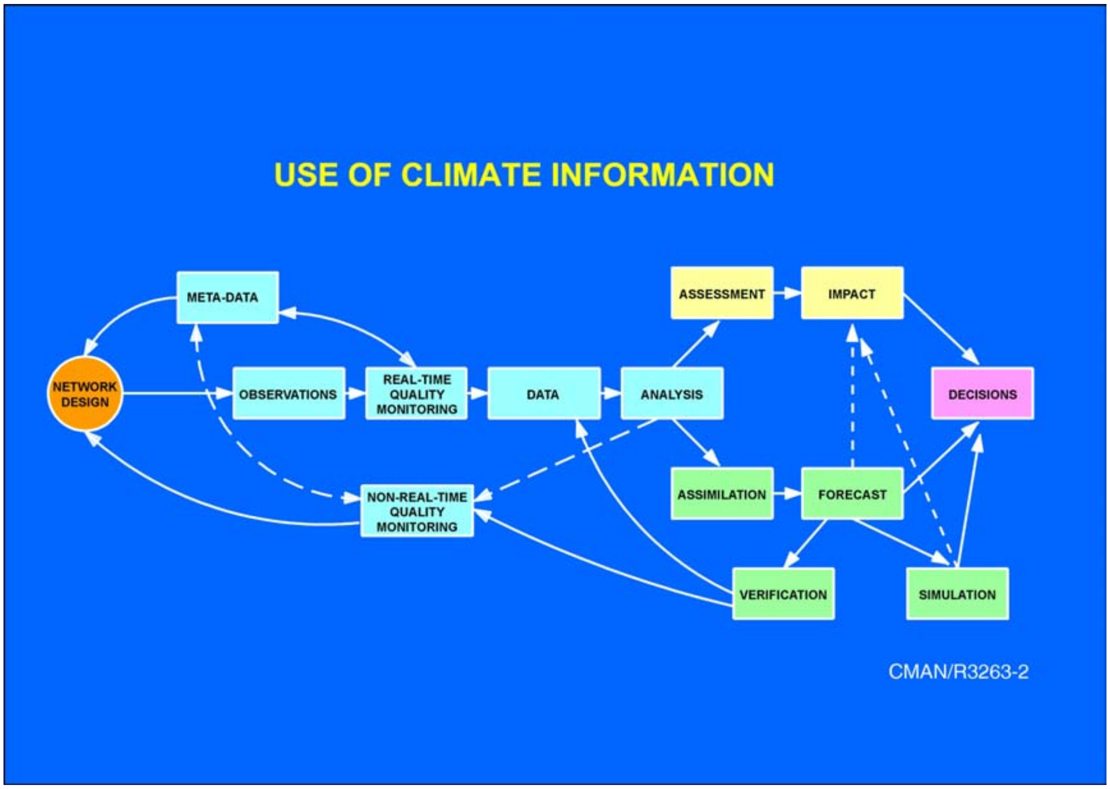


Figure 3.4. The fundamental role of observations, networks, climate data management systems and metadata in providing climate information. (Source: Bureau of Meteorology, Australia).

They include the quality control systems, metadata and various feedbacks between data users and observation system and network managers that help preserve the integrity of the climate data. A robust and secure climate database is the cornerstone to the development and delivery of good quality products and services. Organisations should strive to develop a data management policy that secures data on paper-based records as well as those collected by more direct means.

While much of the above concerns the need for climatologists to ensure the stability of climate observations they must also look at the opportunities presented by observation systems particularly with regard to new data types, including high resolution observations (Fig. 3.5).

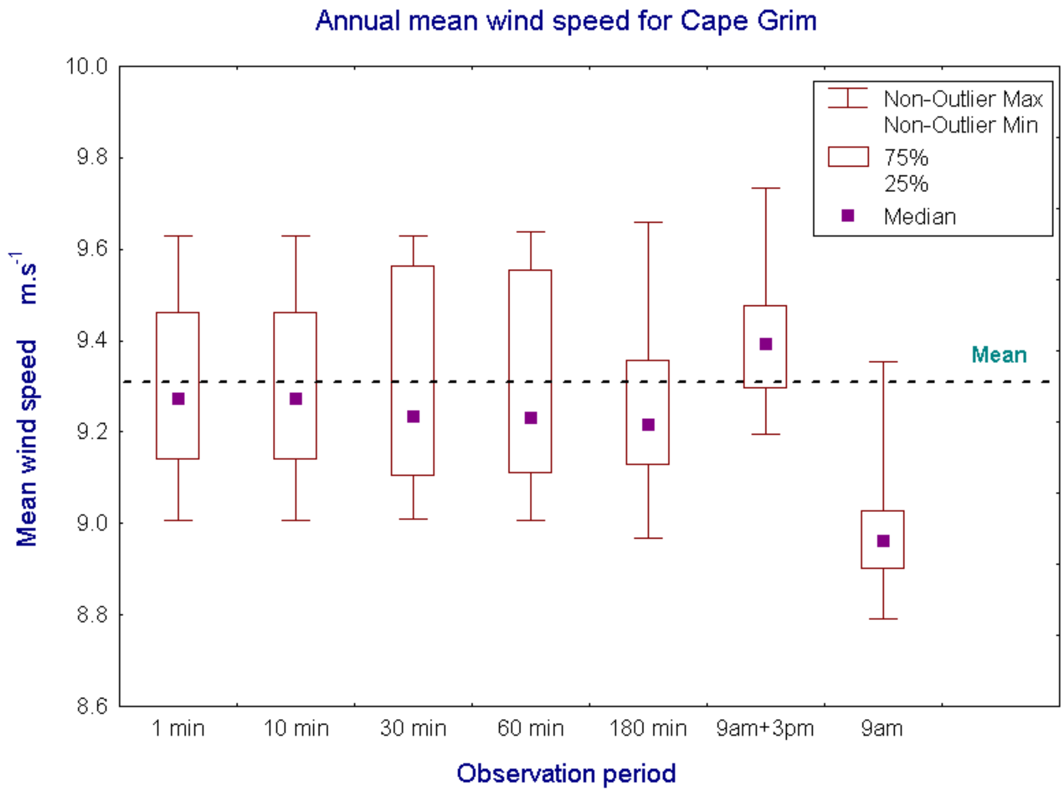


Figure 3.5. Increasing the observation frequency of highly variable elements such as wind speed improves the calculation of climate statistics such as the annual mean. (Source: Muirhead 2000)

Future use of these observations could effectively remove the limitations of having to derive daily means from hourly or daily observations and could also be used to derive new variables (e.g. climatologies of rapid changes).

4 Climate Observation Needs

A climatic element is defined (WMO 1996) as one of the properties or conditions of the atmosphere, from ground level to the upper troposphere which, when combined with other elements, describes the weather or climate at a given place for a given period of time. Important characteristics of climate observations were discussed in section 2. In climatology the most commonly used elements are air temperature (including maximum and minimum), precipitation (rainfall and snowfall), humidity, atmospheric motion (wind speed and direction) and atmospheric pressure. The GCOS community have identified lists of essential climate variables for the atmospheric, oceanic and terrestrial sectors that have a high impact on UNFCCC requirements (see Table 1 of GCOS (2003)).

For a range of common uses the requirements from land areas are for observation of daily maximum and minimum temperature and amount of precipitation. An Ordinary

Climatological Station is one that operates such an observing programme (as a minimum, see WMO (1996)).

It has to be emphasised that only homogeneous climatological records are suitable for many climatological purposes, especially for the evaluation of trends in climate (e.g. in climate change detection). In this respect the *Manual on the Global Observing System* (WMO 1981a) states that "each climatological station should be located at a place and under an arrangement that will provide for the continued operation of the station for at least ten years, and for the exposure to remain unchanged over a long period, unless it serves a special purpose that justifies its functioning for a shorter period". More recent research has emphasised the desire for continuous operation well beyond ten years.

For later use, the accuracy of measurement is rigorously defined (see WMO 1996) as "the closeness of the agreement between the result of a measurement and a true value of the measurand". As such it is a qualitative concept, since a true value is by nature indeterminate. However a common and less precise use of the term accuracy is in statements of the form "an accuracy of ±x", meaning an uncertainty of ±x at the 95% confidence level. The measurement uncertainty varies depending on the climate element, instrument and observation practice.

4.1 Climate elements

In a discussion of key climate elements for climatologists within NMHSs, broad-level guidance is provided here on accuracy requirements. However, even within climatology, these requirements can be expected to differ between application and also between countries. These issues are further discussed through the World Meteorological Organization initiative into determining future observational data requirements and redesign of the global observing systems (Appendix 2) and also through an example structure "Statement of Guidance" from the United Kingdom Met Office (Appendix 3).

4.1.1 Temperature

For air and sea surface temperature measurement, the *Guide to Meteorological Instruments and Methods of Observation* (WMO 1996) sets the required accuracy of the measurement system at ±0.1 K, with an achievable operational accuracy of ±0.2 K. For the daily extremes of air temperature the required accuracy is relaxed to ±0.5 K, though the achievable operational accuracy is again ±0.2 K. The reported resolution is 0.1 K.

An important point to keep in mind is that temperature is one of the meteorological quantities whose measurements are particularly sensitive to exposure (see section 6.3). Careful documentation of changes in non-climatic influences should be considered an essential part of a complete climatological record (see Guidelines on Climate Metadata and Homogeneity, WMO TD No. 1186 (WCDMP 2)).

4.1.2 *Precipitation*

Precipitation (frequency, intensity, type and quantity) is a key variable for specifying the state of the climate system. It varies considerably in space and time and requires a high-density network to observe its variability and extremes.

In general terms, the required accuracy for the amount of precipitation is ±0.1mm if ≤ 5mm, and ±2% if >5mm. For the depth of snow the values are ±1cm for ≤ 20 cm and ±5% if >20cm. The achievable operational accuracy for the amount of precipitation is estimated at ±5% (WMO 1996). This accuracy depends to a high degree on the exposure since the measurement of precipitation is very sensitive to exposure, and in particular to the wind. In fact, the main sources of error affecting gauge measurements are:

a) Systematic wind-field deformation above the gauge orifice (typically 2-10% for rain and 10-50% for snow);
b) Wetting loss on the internal walls of the collector; and
c) Wetting loss in the container when it is emptied (Typically 2-15% in summer and 1-8% in winter for b) and c) together).

In order to minimise the distortion of the precipitation by the wind, objects should not be closer to the gauge than a distance twice their height above the gauge orifice. However completely open exposure is not desirable given the impact of the wind-field deformation. The best sites for measuring precipitation are often found in places where objects act as an effective wind-break from all directions (e.g. in clearings within forests).

Given the considerable spatio-temporal variability of the precipitation field it must be borne in mind that point measurements (even the best) are only representative of a limited area, the size of which depends on length of accumulation period (accumulation tends to smooth out differences), physiographic homogeneity of the region, local topography and the precipitation mechanism. Remotely sensed precipitation measurements, through achieving a much greater spatial resolution than gauge or automatic station measurements, have the potential for greatly improving aerial precipitation estimations.

4.1.3 *Other standard elements from land stations*

A Principal Climatological Station, as defined in WMO (1981a*)*, operates a more extensive observation programme. At a minimum such stations should make observations of the following elements: weather, wind, cloud amount, type of cloud, height of cloud base, visibility, humidity, temperature (including extremes), atmospheric pressure, precipitation, snow cover, sunshine and/or solar radiation, soil temperature (at 5, 10, 20, 50, 100, 150 and 300 cm or a subset of these).

Snowfall and snow water equivalent are measured in most if not all countries with cold winter climates, although these observations are not always disseminated beyond the source country. In terms of solar radiation, measurement of the components global, direct and diffuse are often made. Downward infra-red (terrestrial/longwave) irradiance is also an important element.

Hourly readings are taken, or alternatively, observations must be made at least 3 times daily, in addition to an hourly tabulation from autographic records. However the progressive introduction of Automatic Weather Stations (AWSs, see 6.2.1) has made it possible to substantially increase the temporal resolution of the climatic records, reaching 10-minute sampling or, for some systems, one-minute. It is recommended to store these higher-resolution records in the climatological database.

Accuracy requirements for some of these elements are:

- humidity: dewpoint temperature ± 0.5 K, relative humidity ±3%
- atmospheric pressure: ± 0.1 hPa
- wind
  - speed: ± 0.5 m s^{-1} for ≤ 5 m s^{-1} ; ± 10% for > 5 m s^{-1}
  - direction: ± 5%
  - gusts: ± 10%
- sunshine duration: ± 0.1 h

For details see WMO (1996).

For precipitation and wind it is often necessary to operate stations that measure only these climate elements, especially where topography is varied, since their spatial variability can be considerably greater than that of temperature (see section 6.1). The local topography features affect wind measurements in particular. Despite difficulties in achieving "suitable" exposure, wind measurements are also required for urban areas.

The need for daily data to monitor changing extremes has been emphasised in recent years (e.g. Folland 2000). The predicted warming due to human-induced greenhouse gas emissions, while often relatively small when expressed as an average, may lead to substantial reductions in the return periods of extreme events. The latter often defines the climatic range of a sustainable ecosystem and so accurate measurements of extremes are essential in the assessment of impacts of climate change.

4.1.4 Marine Observations

Besides their use in operational planning of marine activities, climate information from the oceans is essential for understanding and forecasting the evolution of climate variability, including change. It is necessary to track the heat stored in the ocean and the exchanges of heat, moisture, momentum and gas species with the atmosphere. The key elements are air and sea surface temperature, dew point, visibility, weather, wind direction and speed, pressure, cloud information and wave period, height and direction. Sea-surface temperature is the most critical variable for applications involving the coupled atmosphere-ocean system (e.g. for seasonal-to-interannual prediction).

In addition to the surface atmospheric variables, other elements of note include sea-surface salinity, and partial pressure of carbon dioxide, pCO_2. Ocean colour is used to indicate biological activity. Observations of ocean currents, the thermohaline circulation and the three dimensional structure of temperature and salinity are needed to determine the transport and storage of heat and carbon. Special attention is needed in coastal regions, and for boundary currents, choke points or overflow regions, biogeochemical variables, and primary productivity. Sea ice is important as an indicator of climate change as well as through its albedo feedback and its impact on polar ecosystems. Measurements from Voluntary Observing Ships (VOS) and buoys are crucial in the analysis of climate over the oceans and for seasonal-to-interannual and longer-term predictions.

4.1.5 Upper-air elements

Tropospheric and lower stratospheric measurements of temperature, humidity, wind speed and direction and cloud cover are essential to studies of atmospheric circulation and many meteorological applications (e.g. for aviation). The GCOS Upper Air Network (GUAN) of radiosondes can provide crucial data for climate change detection. The influence of the surrounding environment at a station is less crucial for upper-air observations than for surface measurements. Except for some influence in the boundary layer, radiosonde observations are generally not affected by an environmental change such as a station move over a distance of less than, say, 20 kilometres (see GCOS 2002). On the other hand variations in observing instruments generally have a much larger impact on upper air observations as described, for example, by Lanzante *et al* (2003).

4.1.6 Chemical Composition

Chemical atmospheric composition measurements are essential in order to monitor the forcing of the climate system, both natural and anthropogenic, and thus their importance in climate change prediction cannot be overstated. The Global Atmosphere Watch (GAW), conducted under the auspices of the WMO, currently has a network for determining the long-term trends in global-mean concentrations of non-reactive greenhouse gases (see section 5.1).

Ozone is not only a key greenhouse gas but also plays a role in filtering the UV radiation from the Sun. The monitoring of ozone depends upon complementary data from satellite and *in situ* measurements. The latter are not well distributed, and so there is a need for improved ozone *in situ* measurements (both ground-based and total column vertical profiles) to support the use of satellite data.

Aerosol concentrations in the atmosphere have a significant influence on atmospheric temperatures. The IPCC identified aerosols as the most uncertain climate forcing constituent and there are few systematic measurements of these. The most comprehensive observation source for aerosols is the optical depth measured by satellite and ground-based instruments. In addition, routine vertical profiling of scattering from ground and satellite LIDARS are under development. *In situ* measurements from aircraft and ground stations are needed.

Other applications of chemical composition measurements are to be found in areas such as the study and forecasting of animal, plant and human health and well-being - see WMO (2001), GCOS (1995) and WMO (1994). Additional elements to be measured both in the atmosphere and near the ground include reactive gas species and radionucleids, measurements of precipitation and particulate chemistry (as in acid rain) and ultra violet radiation.

4.1.7 Remote-Sensing Measurements

The spatial coverage of remote-sensing measurements (satellite, radar, etc) makes them highly complementary, but not a substitute for traditional ground-based observations. They do have the potential to fill data gaps, but calibration with *in* situ data is essential in order to ensure homogeneity with historical data. Elements convenient to measure or estimate by remote-sensing include precipitation, cloud amount, radiation fluxes, earth's radiation budget and albedo, upper oceanic biomass, ocean surface topography and wave height, sea ice cover and sea surface temperature.

The estimation of large scale air–sea fluxes has been revolutionised by satellite observations of global ocean wind stress. Passive microwave measurements give wind speed, while active scatterometers provide the full wind vector, both magnitude and direction. Furthermore it has been demonstrated that satellite scatterometers are more closely related to the wind stress vector than the vector wind, so their stresses should be more accurate than those derived from ship and buoy winds. The sparseness of marine precipitation observations pose sampling problems that only satellite remote sensing has rendered tractable on a global scale (Fig. 4.1).

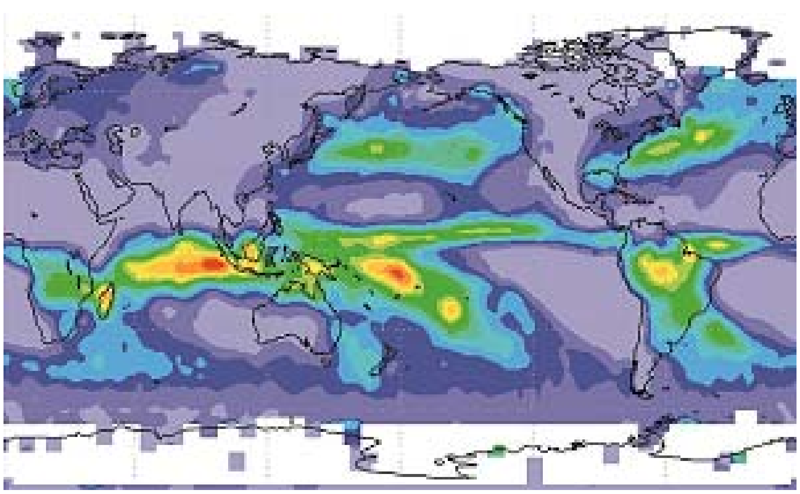


Figure 4.1. Average January precipitation (mm day^{-1}) over the period 1988-96 derived from the GPCP (Global Precipitation Climatology Project).

In particular, monthly precipitation totals are available from the Microwave Sounding Unit (MSU) since 1983 except for the polar regions, though with likely biases in the mid-latitude storm-tracks. The MSU data also provide valuable tropospheric and stratospheric temperature data.

Satellite-based products are an attractive alternative for the radiation in the heat flux estimation, allowing improvements over direct use of Numerical Weather Prediction reanalysis.

As mentioned before satellite observations cannot be viewed as a replacement for *in situ* observations. Some of their limitations for climate are:

- smaller precision than *in situ* observations, for example radiosonde measurements have a vertical resolution of about 100m, precision in temperature of 0.1K and errors in humidity of a few percent, which are better by about an order of magnitude than the best satellite sensors available;
- the lengths of the satellite records are still too short for climate detection purposes;
- there are problems with the calibration and the displacement of sensors that adversely affect the stability and homogeneity of their records; and
- the more advanced instruments will take years until they can satisfy the operational needs of the meteorological services.

4.2 Observations for key climate applications

4.2.1 Applications to agriculture and land use planning

Most of the elements that form the set usually observed or measured at a Principal Climatological Station are important for agriculture and land use planning. Additional elements that find application in this area include soil moisture, evaporation from soil and water surfaces, plant transpiration and run-off and water table. From observations of "weather" phenomena, hail, dew and fog have direct impact on agricultural activities. Soil temperatures at depths up to 100 cm are of particular importance. Since the strong gradients that can build up in the first few metres of the atmosphere are determinant for the conditions under which plants grow, air temperatures and humidity should ideally be measured at least at three heights between 5 cm and 200 cm, and wind at more than one level between the surface and 10 m. For a full description of needs and applications see the *Guide to Agricultural Practices* (WMO 1981b).

4.2.2 Hydrological Applications

For those NMHSs with responsibilities related to, for example, monitoring hydrological events, hydrological planning, and providing forecasts and warnings, specific variables have to be measured. These have not traditionally been considered priority climatic variables but enter in the description of the hydrological cycle, which in turn plays an important role in the variability of climate and in its prediction through soil conditions. Examples of these parameters are river, lake and reservoir stage, streamflow, sediment transport and/or deposition, rates of abstraction/recharge, water and snow temperatures, ice cover, water quality, chemical properties of water, evaporation, soil moisture, groundwater level, and flood extent (see WMO 1988).

River-discharge, being an areally-integrated variable (namely over the river-basin), is particularly valuable for the calibration, verification and validation of general circulation models (GCMs).

The Global Runoff Data Centre (GRDC) in Germany maintains monthly discharge data from over 6400 gauging stations, with daily data available for about half of these. However, data exchange with the GRDC is not yet done routinely. It is important to make progress in the timely exchange of data for the discharge of major rivers and other hydrological variables.

4.2.3 Climate Change Detection

The requirement of homogeneity in climate records takes its most stringent form for observations for climate change detection and attribution purposes. More generally, these observations should have a high standard of quality. Another basic requirement is that the climatological series should be long. Both of these requirements are in fact specified for baseline GCOS stations and Reference Climate Stations (see section 5).

However, an important fact to keep in mind is that the homogeneity and the length of a series are interrelated in such a way that the longer the climatological series the more stringent the homogeneity requirements should be. A small change at a given point in time in the magnitude of a variable due, for example, to a change in the surrounding environment of a station, may go unnoticed if the series length is short as the change often cannot be discerned from natural variability. As the length increases however, a small change will have more chance of being flagged as statistically significant. This means that data series length acts as a sort of magnifying glass for the detection of homogeneity breaks in the series. These homogeneity breaks, unless correctly identified as inhomogeneities in the series, will be misinterpreted as a change in the climate signal. It follows that strenuous efforts should be made in order to avoid any alteration that might introduce inhomogeneities (Fig. 4.2).

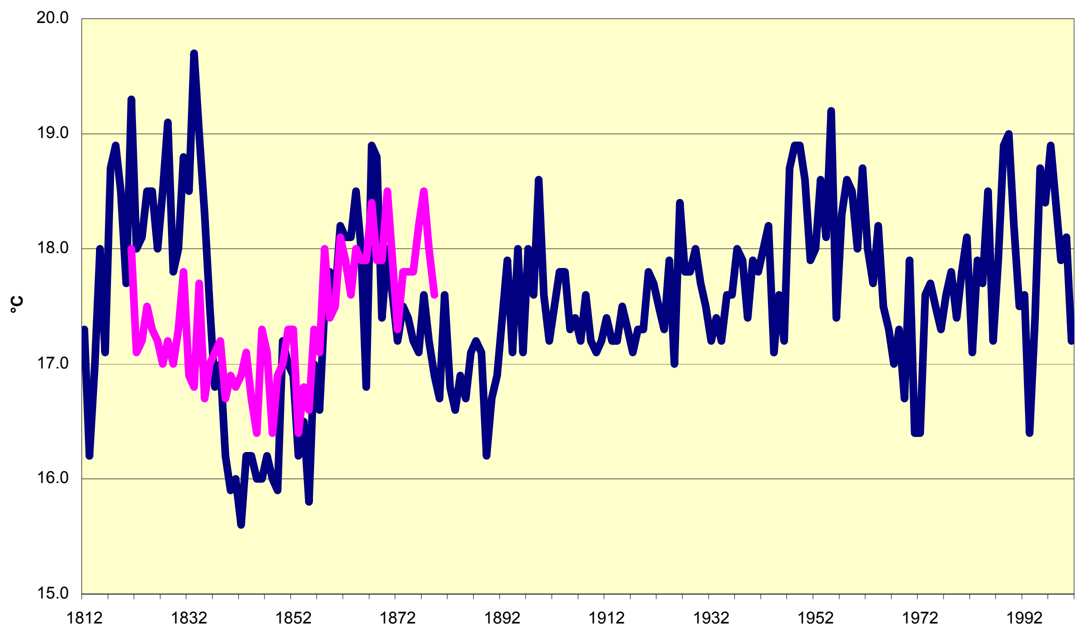


Figure 4.2 . The longest Spanish temperature series for San Fernando (dark line) can be homogenised with the help of another old series at the nearby Cádiz station (pink line) (Source: INM Spain, courtesy Carlos Almarza).

In practice, when designing a network, a change in the signal of a very small magnitude may be considered acceptable. For the Global Surface Network (GCOS 2002), the target requirements for acceptable changes are (the upper acceptable bounds are shown in parentheses): ≤ 0.1 K (0.3 K) for temperature, ≤ 0.1 K (0.3 K) for dew point and ≤ 1% (2%) for precipitation.

The GCOS plan (GCOS 1995) identifies climate change related requirements for measurement of elements of the global climate system. GCOS (2003) gives a list of essential climate variables in oder to meet the needs of the UNFCCC and the IPCC. In addition to the emphasis on homogeneity and length, the climate change detection problem has given rise to other demands on climate observations, for example:

- availability of maximum and minimum daily temperatures, since these allow not only computation of the daily mean but also the diurnal temperature range (DTR). The use of the DTR has become ever more common in climate change detection studies;
- moisture content values are also important, since climate model experiments indicate that temperature and atmospheric moisture content have the best signal-to-noise ratios;
- pressure values allow the analysis of atmospheric circulation changes, which affords an effective mechanism for addressing the climate change detection and attribution issue;

- to support the attribution of the causes of climate change it is vital to have independent, reliable estimates of variability from the palaeoclimate record. The emphasis should be on highly-resolved (better than annual) reconstructions over the last two millennia in order to be able to address synchronicity of records and establish absolute time sequences that can be synthesized regionally and globally. Another application of palaeoclimate reconstructions is in climate impact assessment studies as analogues of possible future climate; and
- non-meteorological records are becoming essential to the assessment of the state and evolution of climate and its impacts. Examples are changes in structure of natural ecosystems, biodiversity, areas occupied by plant and animal species, changes in agricultural productivity and forestry, disease and pest proliferation and phenological events.

4.3 Data Quality Considerations

All climate monitoring systems and climate data sets require improved data quality, continuity and homogeneity. This holds true for practically every climatological application, but becomes an essential need in terms of the ability to measure, detect or attribute climate change. For daily data, where accessibility is still too restricted, particularly rigorous quality control is called for. Chapter 3.2 of the *Guide to Climatological Practices* (WMO 2003) is devoted to quality control of climatological observations. The data should not be considered as satisfactory for permanent archiving until they have been subjected to an adequate level of quality control at the archiving centre. The technique that is recommended combines people with machines. The data quality software should provide a list of suspected data, but final decisions on correction or updating of the digital file should rest on the competent climatological service personnel. However, given the increases in data available to NMHSs (e.g. high resolution data from AWSs) and personnel restrictions, automatic quality checking maybe the only option for some future data. Figure 4.3 provides an example of modern quality control software.

Where application is possible, this two-tier approach ensures that no errors arise from the indiscriminate application of statistical or other objective techniques. These techniques are of an essentially stochastic nature, which means that a desirable increase in the detection power of erroneous observations comes usually only at the price of an undesirable increase in the likelihood of erroneously rejecting good observations, so that a compromise is reached by fixing a significance level. Since statistical objective techniques include an element of convention in the value of the significance level adopted, their outputs should not be blindly accepted in classifying an observation as an error. Graphical and map displays of data and data summaries are excellent tools for visual examinations that can be of great help, since the human mind is especially skilful at identifying spatial patterns.

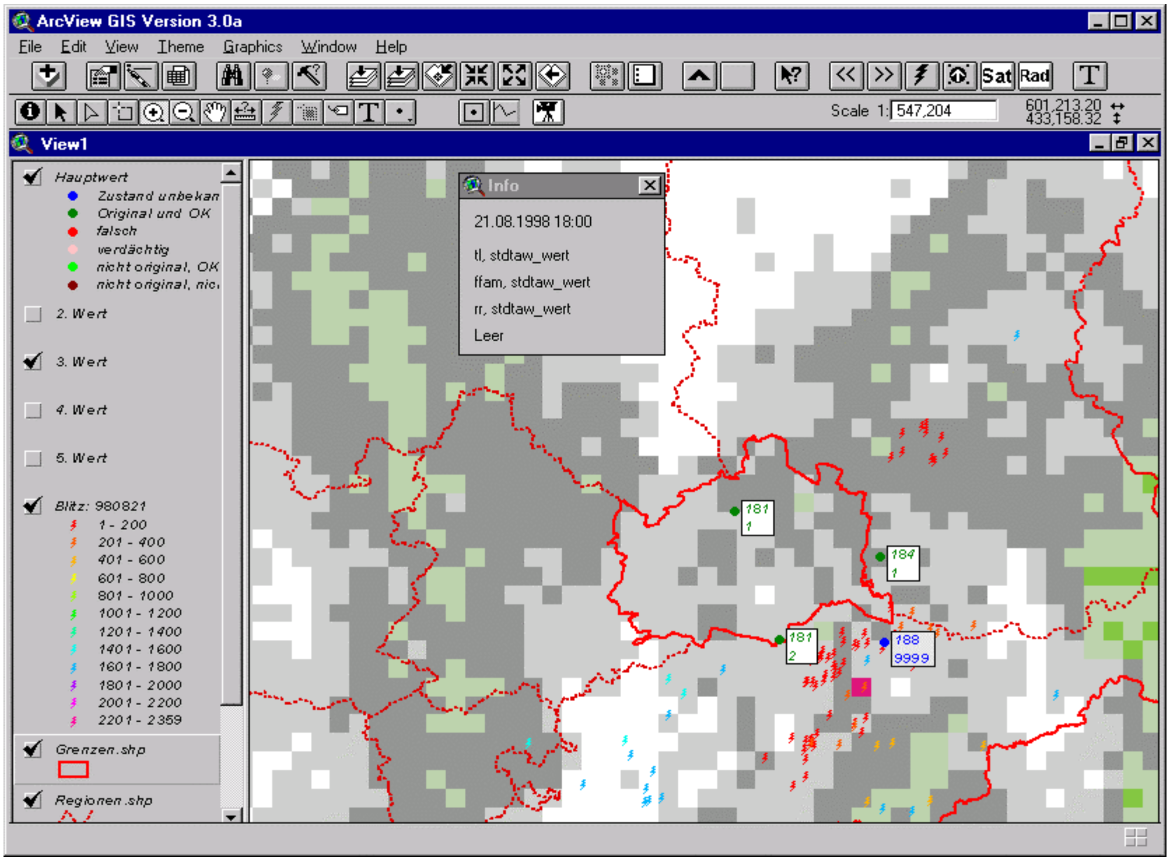


Figure 4.3. Example of a modern data quality monitoring facility allowing easier identification of data problems. (Source: Central Institute of Meteorology and Geodynamics ZAMG, Austria)

An important set of error checking are consistency tests, which exploit the fact that climatological data are interrelated in time and space. The three main types of consistency checks are internal, temporal, spatial where:

- Internal consistency tests draw on the physical relationships between different climatological elements. In many cases they take the form of logical tests of the type: if such an element lies in some range (or occurs at all), another should lie in another range (or occur at all), and so are relatively easy to programme. Internal consistency checks can be performed within the element itself (e.g. seasonal range checks, standard deviations);
- Temporal consistency tests are based on the persistence in time of climatological elements. Selected change thresholds depend on the element, the time of the year, the climatic region and the temporal separation between observations; and
- Spatial consistency tests exploit the smooth variation in space of climatological elements. Usually they involve the estimation of a given observation based on neighbouring observations from alike or similar climatic regions and comparison with the observed value. The range of accepted differences is dependent on type of element, the climatic region and spatial separation between stations. The

effectiveness of this test depends on the availability of suitable neighbouring stations.

Tolerance tests set upper and/or lower limits on the possible values of a climatological element (e.g. wind direction, cloud cover, etc), or in other cases where the theoretical range of values is infinite, the limits outside of which it is unlikely for the measurement to lie. In the latter case the limits are usually time and location dependent and have to be established by recourse to the archived values, or when these are not enough for such a purpose, by spatial interpolation methods. It is also important to monitor and address systematic biases in the outputs from instrumentation on a near real-time basis (see section 6.6).

The completeness of data records is very important, as any dataset containing a large amount of missing data is of little use to climatologists. Measures should be in place to ensure that a data record is as complete as can realistically be obtained. The minimum target requirement is for at least 99% of observations to be archived but 100% should be an organization's objective. In reality, this means that for any specific recording site there should be very few missing hours of observations each month and virtually none when considering any consecutive hours. It is recommended (WMO 1989) to apply the "3/5 rule", whereby if more than five daily values in total in a given month are missing, or more than three in succession, the monthly mean should not be computed and the year-month mean should be considered as missing. No missing daily totals are permitted for sunshine or rainfall (when rain is suspected). In a similar fashion the "3/5 rule" applies also to the computation of monthly 30-year standard normals derived from the year-month values. For other useful guidance regarding computation of means see WMO (1989).

When designing a climatological database it is necessary to provide record space for quality "flags", as well as for corrected or estimated data in addition to, but not in lieu of observed data. It is very important that the original raw data should be retained in the database.

Finally, metadata should be stored as an integral part of the climate observation data (or part of it) in the same database (see section 6.8).

4.4 Exchange of Observations

Probably the most cost effective action that an NMHS can take to improve the global observing system for climate is to internationally exchange the observations they are currently taking. The CCl's statement " that the accessibility and use of climate data was at least as important as its collection and archiving, and that WMO and NMHS policy and activity should reflect that comparable importance" was endorsed by the fifty-fourth session of the Executive Council and noted by the fourteenth World Meteorological Congress. At present it is still common to find barriers to the low cost, timely access of climatological data for public good, research or education applications. The situation is particularly serious in relation to daily data exchange, a type of data to which many

NMHS attach commercial value. While it is clear that charging for these data generates identifiable revenue streams, it is also understood that wider availability of data will result in a range of benefits accruing to society at large (e.g. derived from a better knowledge of climate and its future evolution). These benefits, though in many cases difficult to quantify, are none the less real and so they should be assessed against costs when choosing between different data pricing policies. The CCl is advising the Executive Council Advisory Group on the International Exchange of Data and Products on ways to obtain and summarize quantitative information on Members' policies and practices with respect to data provision and their outcomes in terms of costs and benefits of the different options.

Aside from these national databases there are many multinational regional or global datasets.

5 Special climate networks

While climatologists make use of observations from a wide variety of networks and systems, it has been necessary to define a number of specific climate networks in order to help ensure that the specific needs of climate, e.g. for continuous and homogeneous observations, are addressed. A discussion of the most commonly defined climate networks follow.

5.1 Networks of the Global Climate Observing System

The Global Climate Observing System (GCOS) was established in 1992 to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. It is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU). GCOS is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability including climate change, and for supporting research toward improved understanding, modelling and prediction of the climate system. It addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. Refer GCOS (1995) for the GCOS plan.

According to GCOS (2003), the GCOS strategy envisages five complementary types of network that will provide observations. These are:

- Comprehensive global observing networks including regional and national *in situ* networks as well as satellites, which provide observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific climate variable;
- Baseline global observing networks, which involve a limited number of observations at selected locations that are globally distributed and provide long-

term high-quality data records of key global climate variables, as well as calibration for the comprehensive networks;

- Reference networks, which provide highly-detailed and accurate observations at a few locations for calibration purposes. (Note that these are not to be confused with Reference Climate Stations, which serve an entirely different purposes and may be more akin to baseline networks at a national level);
- Research networks, which can provide estimates of the local variability of key variables to evaluate models and/or provide comprehensive data sets to understand climate processes; and
- Ecosystems networks, where a number of different variables are measured at several locations within a specific ecosystem and are used to characterize that ecosystem.

Although an ultimate goal, it is presently unrealistic to attempt to establish and operate networks at all five levels for all climate variables. Priority is currently given within GCOS to the establishment of key baseline networks making in situ observations, selected comprehensive networks many of which use satellite technology, the long-term operation of a number of research networks and a selected number of reference networks. As the terrestrial ecosystems networks develop, more use will likely be made of them for climate monitoring.

The key atmospheric baseline networks for the purposes of this report are the GCOS Surface Network (GSN, Fig. 5.1) and the GUAN (Fig. 5.2). GCOS (2003) broadly describes the GSN and the GUAN. GCOS (2002) describes the broader observational requirements, including the operational best practices and principles as well as the responsible centres for monitoring, analysis and data archiving. A range of ocean networks contribute to the goals of GCOS, including a subset of the Voluntary Observing Ships (VOS) scheme termed VOSCLIM, which will be used to improve the ocean surface observations.

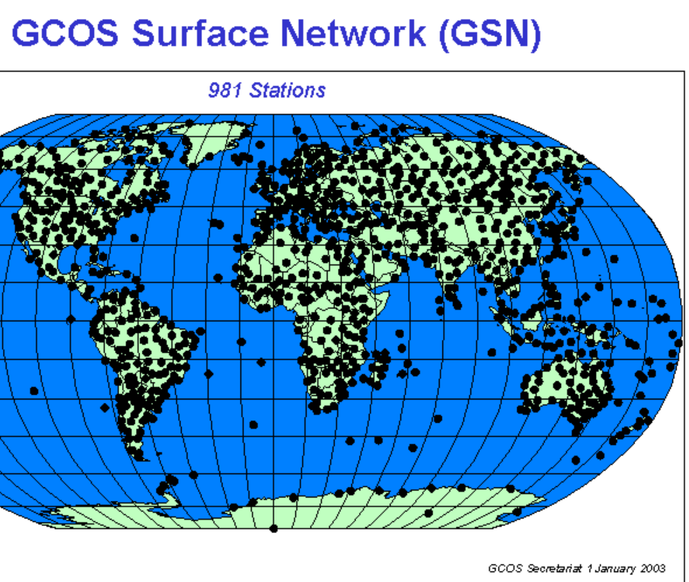


Figure 5.1. The GCOS Surface Network. (Source: GCOS Secretariat)

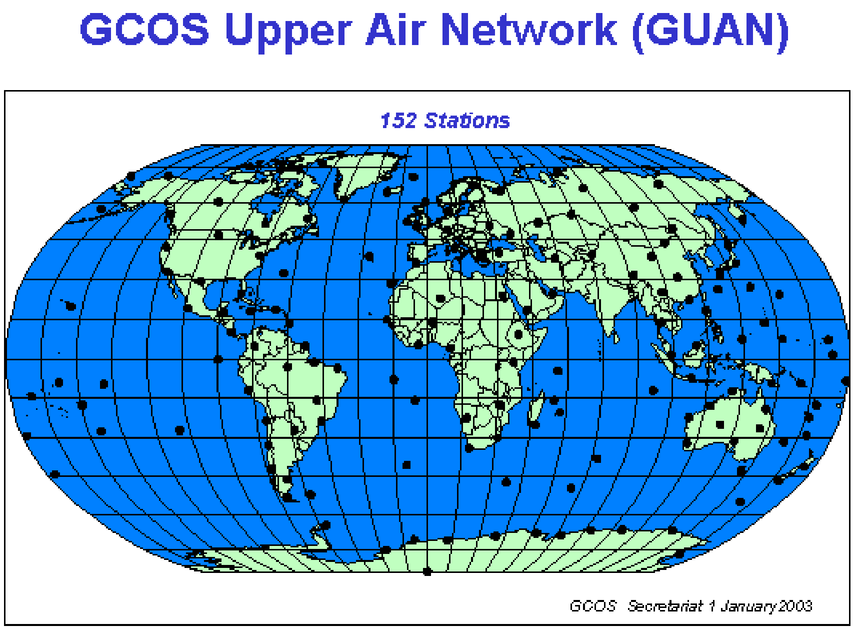


Figure 5.2. The GCOS Upper Air Network. (Source: GCOS Secretariat)

The objectives of the Global Atmospheric Watch (GAW) are to provide reliable long-term observations of the chemical composition of the atmosphere and related parameters in order to improve our understanding of atmospheric chemistry, and to organize assessments in support of formulating environmental policy. The GAW currently have networks for determining the long-term trends in the meridional distribution of non-reactive greenhouse gases. It includes monitoring of variables such as solar irradiance and aerosols as well as carbon dioxide, methane, and ozone and other long-lived greenhouse gases. The following terrestrial networks have been established: Ecosystem networks (GT Net); Global Terrestrial Network for Glaciers (GTN-G), Global Terrestrial Network for Permafrost (GTN-P); and the World Hydrological Cycle Observing System (WHYCOS). Planning for GTN-H (hydrologic) is continuing.

5.1.1. GSN

The GSN contains about a quarter of the 4000 stations within the World Weather Watch reference synoptic network. These stations were selected on the basis of past performance and global representation according to Peterson et al. (1997). The GSN has been specifically designed to determine the variability, including extremes, of surface air temperature over land at global, hemispheric and continental scales. In addition to estimating change and rates of change of surface temperature over decadal time scales, it is also used to make similar estimates for precipitation and pressure. The GSN also provides a mechanism for continued quality control and assessment of the record from the full surface network.

5.1.2. GUAN

The GUAN is a baseline network of about 150 stations selected from the full upper-air network on the basis of past performance and global representation. It intends to provide reliable measurements of large-scale temperature variations for heights up to 5hPa in the free atmosphere for the detection of climate change. Other variables, such as humidity and wind speed and direction are also extremely valuable. The GUAN also provides a mechanism for continued quality control and assessment of the record from the full radiosonde network.

5.2 Regional Basic Climatological Network

Building on the Regional Basic Synoptic Network concept of the World Weather Watch program, the RBCN initiative provides support to regional-scale climate monitoring through aiming to increase the international exchange of monthly climate data through reporting CLIMAT messages from more stations. Members are urged to include Reference Climate Stations (RCSs) in their national selections and additional stations considered necessary for regional-scale climate monitoring.

5.3 Reference Climate Stations

An RCS is defined as follows: "A climatological station, the data of which are intended for the purpose of determining climatic trends. This requires long periods (not less than thirty years) of homogeneous records, where human-influenced environmental changes have been and/or are expected to remain at a minimum. Ideally the records should be of sufficient length to enable the identification of secular [over time] changes of climate" (WMO 1986). These stations have requirements very similar to the GSN but national networks will often be denser to ensure that specific country data requirements for long-term climate change needs are met – including data for impacts and adaptation.

6 Climate Observation Networks and Systems: Responding to Stakeholder Needs

Climate data requirements are described in the preceding sections. These data requirements are generally linked to uncertainty, resolution, continuity, homogeneity, representativeness, timeliness, format, accessibility, etc. for the intended application. More succinctly, climate monitoring requires a long term commitment to quality and stability (Trenberth et al., 2002). Increasingly, NMHSs are taking a systems approach to ensuring that these requirements are met. These quality management systems (QMS) are developed to address all aspects of monitoring programs, from the planning phase, through equipment selection, procurement and installation, operations, inspection and maintenance to data reporting, processing and archiving (WMO 1996). In other words, QMS is intended to ensure that observational networks and support systems meet the needs of key stakeholders, that they are life-cycle managed, operated and maintained to defined standards and operating procedures, and are sustainable, that is, take into consideration present and projected budgetary conditions and technological obsolescence projections for the monitoring program.

This section will focus largely on observational networks and systems whose primary purpose is climate related. Emphasis will be placed on in-situ networks and AWSs, the latter due to their growing popularity. It should be noted, however, that many of the best practices, procedures and systems approach described here apply to observational networks in general. Despite increasing practicability for fulfilling data coverage requirements in data sparse regions of the globe, satellite-based observational systems are not included in this discussion as they are considered an evolving technology, augmentative but not replacements for in-situ networks currently in place. Similar comments apply to other observing technologies such as weather radars, AMDAR (Aircraft Meteorological Data Relay), GPS-Met, wind profilers and lidars, which thus far have had greater usage for weather forecasts and warnings. These new technologies have the potential to, in time, be useful sources of climatological informations.

6.1 Network Design

Network density and station distribution depend on the particular application. National climate networks should be able to provide a satisfactory representation of the climate characteristics of the country**.** The rate of spatial and temporal variation for meteorological elements varies by element. For example, the network density requirement for characterizing temperature is usually much less than precipitation. WMO provides density criteria guidelines for climatological networks. Additional approaches include various objective analysis techniques and methodologies for specific applications. The simplest approach would be to identify homogeneous climatic regions and ensure that each region is adequately sampled. More sophisticated methods would examine the particular characteristics and merits of the available stations (e.g. Peterson et al. 1997, Collins et al. 1999) or use objective analysis to aid network selection (e.g. Daley 1993, Jones and Trewin 2000).

In designing climate networks, there should be strong recognition, that to be most cost effective, these networks can and should support other applications and purposes as well. For example, in some countries, reference climate stations also provide valuable information in real time for weather forecasting and agrometeorological applications. Even Ordinary Climatological Stations, measuring daily temperature and precipitation and snow cover (if applicable), can provide low cost data for nowcasting and forecast verification if the data are reported on a timely basis.

6.2 Sensor and Equipment Selection

National networks, especially those intended for detection of climate trends, variations and changes, must be equipped with standard, approved instrumentation. A process or plan should be in place to ensure that occurs in an orderly way.

First, a careful determination of stakeholder requirements must occur through consultation. These include requirements for uncertainty (accuracy), resolution and range, robustness, and suitability for the intended operating environment. For example, are they suitable for operating in cold climates? Do they retain their accuracy in extreme temperature conditions? Further information is provided in Appendices 1 and 2.

The process (Fig. 6.1) should include a review of performance requirements against manufacturer specifications, laboratory testing against a reference standard traceable to a national primary standard to determine uncertainty and repeatability, and engineering quality and design. The test and evaluation process should include field-testing in operational environments. This usually requires having multiple test sites and a test period of one year to capture the expected range of climatic conditions and to acquire a statistically significant dataset. The field test plan must be carefully designed to determine performance under various measurement ranges and environmental conditions. Field-testing could include comparisons to calibrated field reference standards (when available), identical model products (functional precision) and other sensors/systems currently in operational use.

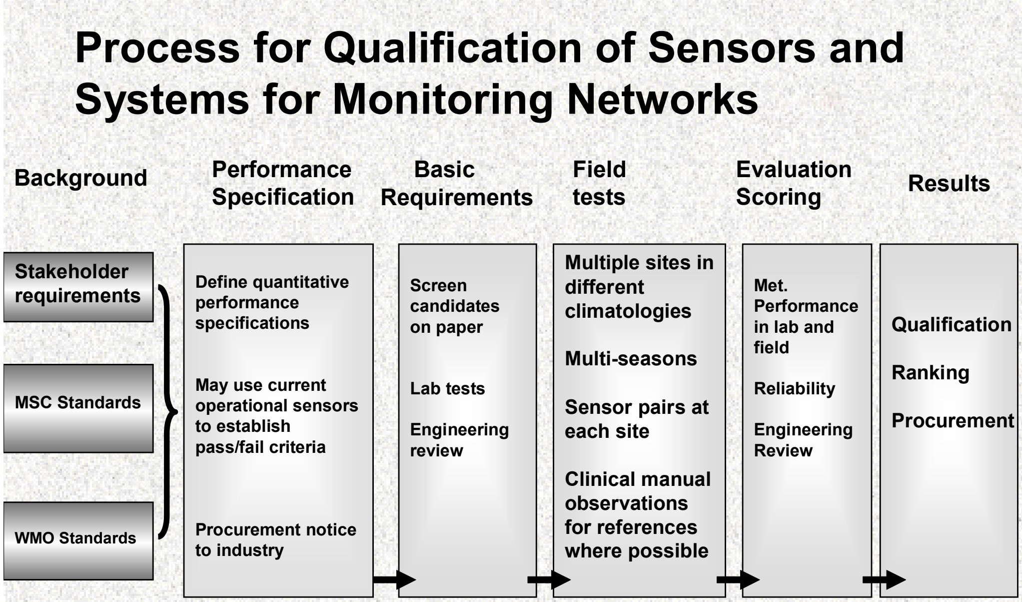


Figure 6.1. A schematic illustrating a recommended test and qualification process for sensors and equipment. (Source: Meteorological Service of Canada)

The test, evaluation and qualification process can be time consuming but will pay dividends in the end. It is recommended that NMHSs take advantage of inter-comparison studies conducted by WMO's Commission for Instruments and Methods of Observation (CIMO), cooperate in the sharing of test results and promote and support the use of Regional Instrument Centres (RICs) in this regard.

6.2.1 Automatic Weather Stations

AWSs are taking on a rapidly increasing role in taking meteorological observations. They have been used to increase network densities, reporting frequencies and elements observed, especially in remote and largely unpopulated regions where access is difficult (Fig. 6.2).

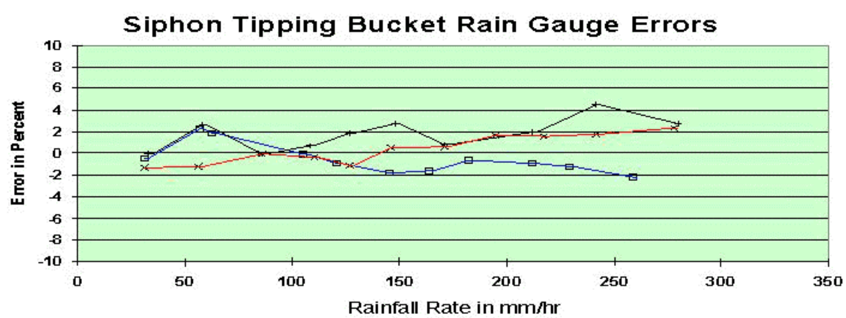
Figure 6.2. A remote coastal automatic station showing helicopter landing pad and other features such as solar panels. (Source: Meteorological Service of Canada)

They also have been used to augment manned stations both as aids and during hours when no observer is on duty. For many meteorological elements (e.g. temperature, wind, pressure) they have proven to be more accurate than human based observations as long as they are operated under an appropriate quality management framework; for others, such as precipitation, there are measurement issues that have to be addressed. Although in many countries they have proven to lower operational costs it is recommended that cost/benefit studies be undertaken when deciding between manned and AWS observation programs. In addition to the initial AWS equipment procurement and installation costs (the latter can be much more expensive than the equipment due to factors such as remoteness and accessibility), the NMHS must consider many other life cycle management costs and issues. These include the availability of suitable power sources for the AWS and maintainability in remote locations.

Sensors and equipment approved for manned observation programs can, in many cases, be incompatible or error prone if considered for AWS operations. The measurement of precipitation is illustrative.

Most manned surface stations whether they are categorized as an Ordinary or Principal Climatological station, employ standard rain gauges to measure rainfall amounts and rulers or graduated snowboards to measure snowfall and snow depth on ground where pertinent. Often, snow water equivalent is measured by removing the graduated cylinder from the standard rain gauge and installing a nipher shield to minimize wind effects. Supplementary observations, such as rate of rainfall, employ conventional tipping bucket rain gauges (TBRGs). These are usually calibrated to a prescribed rate of rainfall (e.g. the error could be 0% at 50mm/h) and then corrected by comparison to a co-located standard rain gauge.

For AWS operations, TBRGs are a relatively inexpensive instrument for providing both rainfall amounts and rates, especially in warm climates. Some NMHSs attempt to overcome the problem of not having a co-located standard rain gauge available for correction purposes, by employing siphoning TBRGs that have a fairly flat error profile over a range of realizable rainfall rates, and thus are relatively easy to correct through algorithms (Fig. 6.3).



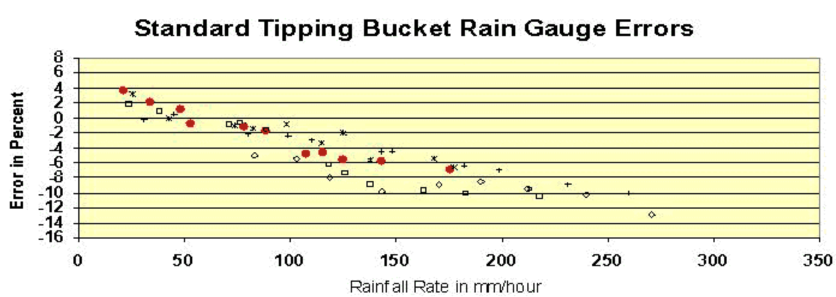


Figure 6.3. Error profiles of ordinary tipping bucket rain gauges versus siphoning TBRGs. (Source: Meteorological Service of Canada)

It is not recommended to heat TBRGs to expand their applicability to solid precipitation, i.e. snow, and so such gauges could be closed seasonally. Studies have shown that heated TBRG performance is poor due to the effects of wind and evaporation of melting snow.

In cold climates where snow is a significant factor, it is recommended that all weather precipitation weighing gauges (Fig. 6.4) be a component of the AWS instrument complement. These gauges measure total precipitation and do not, in themselves, distinguish between liquid or solid precipitation. There are, however, measurement issues that have to be addressed. They may significantly under catch in the presence of wind. Catch efficiency as a function of wind speed should be determined and the wind speed should be measured at gauge orifice height so that the precipitation amount can be corrected. They are also prone to wind pumping that can cause oscillations in the weighing mechanism. Algorithms can correct these oscillations. They also require prescribed charges of antifreeze to promote melting of snow and oil to inhibit evaporation. Snow and ice may stick to the walls of the gauge and not be reported until they melt and fall in to the collecting bucket at a later time. Ultrasonic ranging devices are often used to measure snow depth on ground.

Figure 6.4. An all weather precipitation weighing gauge. This particular one is a Geonor T-200, used by a number of meteorological services. (Source: Meteorological Service of Canada).

As noted earlier, climatic, geographic and operational influences and constraints often influence instrumentation and equipment selection. For example, the inclusion of some radiation instrumentation on AWSs, such as pyranometers that require frequent cleaning, should be limited to those AWS where people can be available to carry out the cleaning. Anemometers for use on moored buoys are often subject to harsh environments and can be short-lived operationally (Fig. 6.5). Consideration should be given to systems with few moving parts, example, sonic anemometers.

Figure 6.5. A moored 1.7 metre buoy employed in part of the Canadian network. (Source: Meteorological Service of Canada)

To reiterate, AWSs can be powerful alternatives to human based observational programs and often the only option. But, they are only as good as the organizational commitment to quality manage them.

6.2.2 Other Networks – Radiosonde Systems

These systems, used to measure pressure, temperature, humidity and upper winds, are crucial to studies of upper air climate change. They have to operate over a wide range of conditions, +50 to –90C for temperature, 1050 to 5 hpa for pressure and 1 to 100% relative humidity (WMO 1996). The cost and quality of balloons, radiosondes and their ground processing systems are important influences on performance. Cost and availability are also important consideration when making decisions on using helium versus hydrogen as the lifting gas. Radiosondes should be capable of providing an intelligible signal to the ground-tracking receiver for the full range of the flight. GPS and Loran based NAVAID wind finding are employed by many NMHSs. Wind finding using radiotheodolite techniques often has lower height performance due to limiting slant range angles. NMHSs are strongly encouraged to participate in or utilize the findings and recommendations of radiosonde inter-comparison studies and tests carried out under the auspices of WMO's CIMO.

6.3 Siting and Installations

An observation site should be representative of the climatic regime for which it is intended. Sites on steep slopes, in hollows, in proximity to pronounced features such as buildings, topographical influences, for example, ridges, should be avoided. Otherwise, the site becomes representative of local features only.

Stations measuring baseline or background atmospheric composition, specifically those part of the GAW program have very stringent siting criteria – no significant change in land use practices within 30-50 km of the site and minimal effects of local and regional air pollution (WMO 2003).

Stations should be on a level piece of ground (to the extent possible) and should be well exposed, away from obstacles and obstructions that could influence the observation including instrument performance. A general rule often employed is that the distance of any obstacle from the instrument gauge should be 2 to 4 times the height of the object above the gauge. Anemometers require even more exposure, the distance of any obstruction being prescribed as at least 10 times the height of the obstruction (WMO 2003). These restrictions may sometimes require splitting of the site, example, the anemometer location being some distance from the rest of the instrumentation.

When selecting station sites, network planners and administrators should consider locations where there is a high probability that exposure is unlikely to change over the long term and that the site is secure through long-term agreements, leases or ownership..

Factors such as security, care-taking, power, protection against flooding, etc. must also be taken into account. Many NMHSs develop instrument compound guidelines that prescribe sensor location and proximity to one another, buffer zones and security fencing. Underlying surfaces could include short-cropped well-maintained grasses or gravel.

NMHSs are strongly encouraged to have network installation guidelines and procedures in effect, including those provided by manufacturers for specific equipment. It is critical that instrument pads are well seated and leveled, that trenching for power and signal cables follow prescribed directions. Under some extreme conditions, such as some arctic or sub-arctic locations, where freeze/thaw cycles can produce ground slumping or upheaval, gravel beds are prescribed for the instrument compound.

Upon completion of the installation, and especially so for AWSs, it is very important to carry out prescribed proof-of-performance testing for the station.

6.4 Observations and Reporting

In addition to employing nationally approved instrumentation and adhering to good siting and installation practices, standard instrumentation configurations, and specifically for AWS, standardization of associated application and signal-processing software is encouraged for ensuring the quality and homogeneity of the observed data.

Temperature and humidity sensors should be protected from exposure to solar insolation and soiling through the use of tested and approved ventilated shields; precipitation gauges employed for measuring solid and liquid precipitation should also be shielded to minimize wind effects, nipher shields where human intervention is available to remove snow capping, alter-type shielding elsewhere.

For RCSs, some organisations aim to configure three temperature sensors on each AWS to combat against the subtle effects of sensor drift and catastrophic failure of one or even two of the sensors, i.e. provide built-in redundancy. Similarly, in addition to the standard 10 metre anemometers, some NMHSs also install an anemometer at elevated precipitation gauge height (e.g. all-weather weighing precipitation gauges) so that the observed precipitation data can be corrected for wind effects.

Regardless of the observation program, whether or not it is human or AWS based, or a combination thereof, it is incumbent on the NMHS to have readily available up to date manuals of observations that delineate prescribed standards and procedures. For example, for Ordinary Climatological Stations, temperature and precipitation should be measured at least twice a day, at fixed times that remain unchanged – often 0800 and 1800 hours locally (WMO 2003). If possible, these should coincide with synoptic times as indicated in the *WMO Manual on Global Observing Systems*. If only one-per-day observations are possible then it is recommended that the observation time take place around 0800 in the morning. Note that precipitation amounts and maximum temperatures recorded in the morning observation are credited to the previous day.

A complete and accurate record of the observations must be maintained; otherwise, their utility becomes increasingly limited. NMHSs should ensure there are standard reporting forms for programs ranging from twice (or once) a day daily temperature and precipitation to the hourly and synoptic programs of the more comprehensive principal climate station. Increasingly, some NMHS are developing electronic data entry systems that eliminate the need for observers to be knowledgeable about meteorological observation codes. In addition to the hourly and synoptic observations collected by NMHSs through national landline and satellite based communications components of the Global Telecommunications System (GTS), provisions should be made for mailing other climate reports on a scheduled basis to the NMHS unit responsible for data processing and archiving. Alternatively, systems such as internet-based, touch-tone telephone and programmable data entry pad reporting provide the opportunity for use of the climate observations in the near real-time for various applications including weather nowcasting. Further, these systems are much more efficient since they eliminate the need for subsequent abstracting and digitizing of data, introduce internal consistency data checks and provide feedback to the observers that can reduce errors.

For AWS, the central processing system main functions are data acquisition, data processing, data storage and data transmission. Applications software are required for initialization, sampling of sensors output, averaging, converting sensor output to climatological data, quality control, data reduction, message formatting and checking, data transmission and display. As this software obviously determines the meteorological report, it is critical that this software be standardized for national networks.

Most AWS are polled via landline from central communication centers where their reports are re-packaged into various data bulletin groups. Most also depend on conventional electrical power sources. Remote AWS or marine data buoys require alternative power sources such as batteries and/or solar panels and/or windmills and rely on various satellite communication options for data transmission. These include data collection through meteorological synchronous satellites such as GOES. For example, Canadian moored marine buoys employ GOES as their primary data communications service and system ARGOS as a backup. The latter is limited by the characteristics of polar orbiting satellites. Ship observations are often transmitted by commercial systems such as INMARSAT, systems that are very reliable and often offer two-way communications.

Radiosonde upper air soundings ideally take place twice daily at 1200 and 0000 UTC. It is recommended that prior to flight, the operator should carry out control checks in an indoor ventilated chamber with reference sensors. The measured differences should be used to adjust the calibration curve before flight. For accuracy purposes, the surface observation should be taken immediately after balloon release. The radiosonde instrument payload should be suspended well below the balloon, at least 20 metres, to mitigate against the effects of balloon wake (WMO 1996) and to minimize the pendulum motion (Fig. 6.6). Where flight paths take place over populated areas, parachutes are often required. In addition, to the extent possible, radiosondes should be environmentally safe. Replacement radiosondes (second releases) should be flown when problems with signal reception, premature balloon burst, or other problems are encountered which would otherwise result in unacceptable errors or missing data.

Some stations within national surface and upper air networks are designated stations within the GSN and GUAN. Criteria for selecting these stations include geographical importance, quality, reliability and longevity. Each month, these data should be sent to designated World Data Centers via CLIMAT and CLIMAT TEMP messages. There are continued concerns regarding the reporting frequency and data quality of a considerable number of these transmitted reports. GCOS (2002) has further details on best practice requirements.

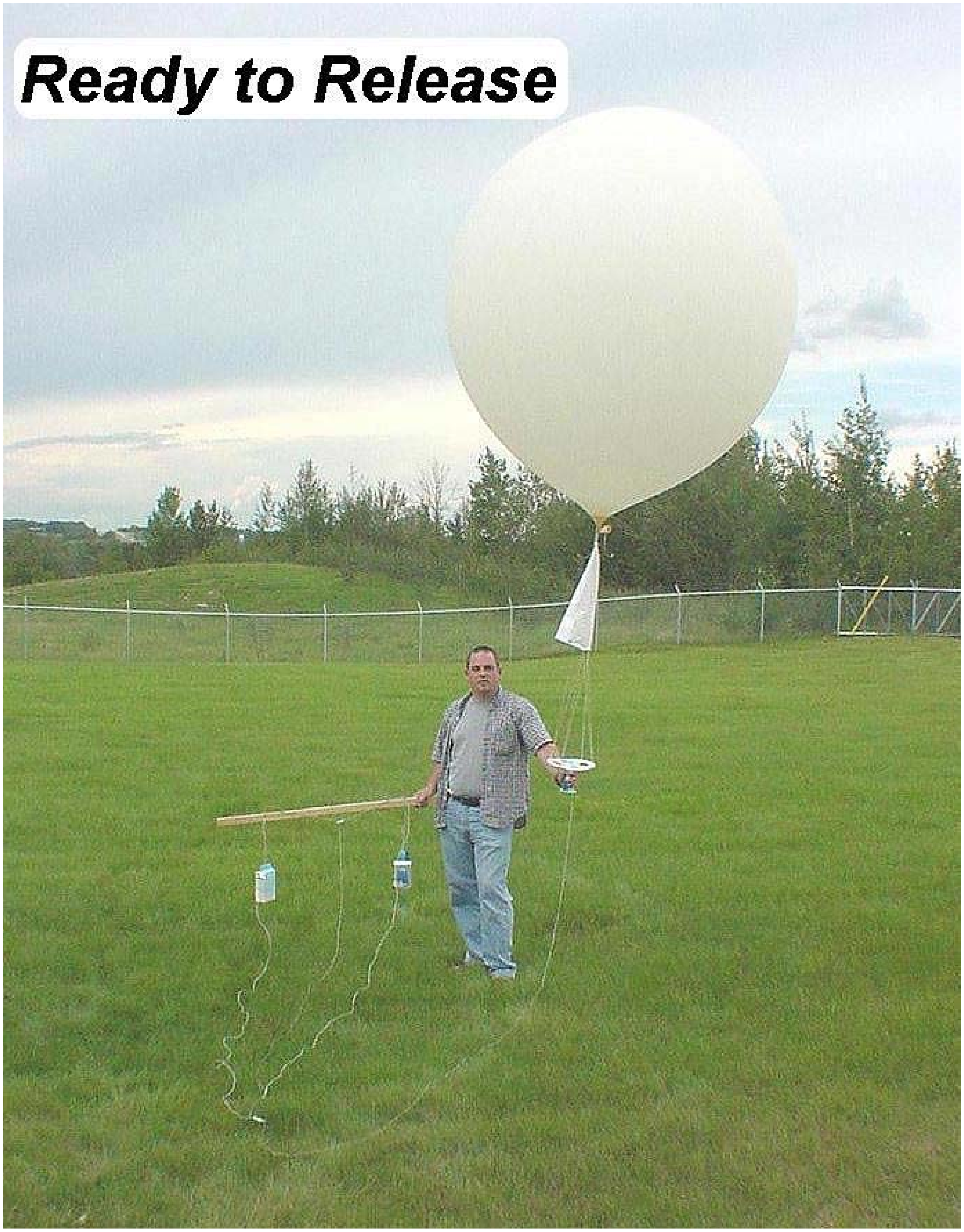


Figure 6.6. Observer preparing to launch radiosonde. (Source: Meteorological Service of Canada)

Regardless of the method of transmission employed, data communications systems must be robust and reliable.

6.5 Inspection, Maintenance and Calibration of Instruments

Observing systems and instrumentation must be regularly maintained so that the observations do not deteriorate in quality and reliability. This includes "housekeeping" of the site such as cutting of the grass, cleaning of the instruments and performing recommended checks by observers or other on-site staff. Equipment should be repaired or replaced within prescribed time intervals that take into account life expectancies of instrumentation.

Maintenance cycles are also determined by the type of equipment and operating environment. For example, in climates where seasonal changes determine start and end of the observing program, tipping bucket rain gauges sites should be visited twice a year, at the beginning of the season and at the end to close the program. All-weather precipitation weighing gauge sites may have to be visited several times a year to prevent overflow and re-charge the anti-freeze and oil solutions, depending on the gauge capacity and climatic conditions. These steps are often stipulated by environmental regulations and directives of the country and/or state.

Routine maintenance and inspection usually take place concurrently. It is recommended by WMO that Ordinary Climatological Stations be inspected at least once every three years, principal climate stations at least once a year and AWSs at least twice a year. Without strict adherence to prescribed inspection and maintenance programs and schedules, the quality of AWS observations can deteriorate dramatically and rapidly. Before visiting a station, inspectors and maintainers should be current on all information available for the station, including recent trends in data quality, date and type of last repairs, calibrations, etc.

At each inspection of a human-based observation station, the inspector should determine that observer training is up to date, the observer(s) is competent, and advice is given as necessary on matters such as recording and reporting of observations, calculation of derived measurements, cleaning of instruments, etc.

The inspector should ensure the equipment is in good working order, is configured in prescribed patterns in compounds and verifies against relevant standards. The relative accuracy of individual sensors in use must be known. As such the instruments must be correctly calibrated before use. Calibrations usually take place in NMHS facilities, RICs or certified commercial laboratories. Comparisons in the field should be made with portable standards instruments (e.g. traveling barometer), which are also checked against regional and/or national standards before and after each tour. The portable standards should be able to withstand potential calibration changes while in transport.

Detailed inspection records must be prepared routinely and retained. These include records of instrument changes, calibration drifts, differences from traveling standards, repairs, exposure and surrounding landscape changes, etc.

It is strongly urged that NMHSs have up to date inspection and maintenance procedures documented and readily available.

6.6 Near Real-Time Quality Assurance and Quality Control

Prescribed inspection and maintenance do not fully prevent sensor/system failure or error. Observer error or data communication system malfunctions can also occur. Therefore, it is important that quality assurance systems are in place so that, if necessary, timely corrective actions can be made.

On-site where there are observers, quality monitoring can include internal and temporal consistency checks of the observation and sequence of observations manually or by automated means (see section 4.3). AWS and marine buoys have on-board test equipment that includes power failure detector, watchdog timers, and test circuits and programs to monitor battery voltage, aspirators, etc. These checks can be augmented by software that performs intra- and inter-sensor and message checks.

Some NMHSs employ centralized semi- or fully automated approaches to near real-time QA/QC. Monitoring software tools that are available on a 24 hours, seven days a week basis and sometimes accompanied by human intervention, can provide early detection of problems. QA checks should be based on known performance characteristics of sensors and systems. These QA systems can also take advantage of AWS reporting frequencies and special polling capabilities, which *inter alia* allow for retrieval of missing data. The QA monitoring systems include automated or manual timely notification of observers, inspection and maintenance specialists so that corrective action can take place as soon as possible, rather than the discovery of systematic problems weeks or even months later during the processing of data for archiving. These systems can also detect systematic bias in instruments, which has so far largely been the domain of post-homogeneity data analysis.

6.7 Performance Measurement

It is also important to measure performance on a program- or network basis. In effect, these are measures of the health of a program in terms of quality, effectiveness and efficiency. Measures could include frequency and character of observational errors, reporting percentages, completeness, timeliness – e.g., what is the percentage of observations received by collection centers within prescribed time frames? They could also include percentages of time that standards are attained – for example, the percentage that national radiosonde balloon releases reach prescribed heights. Life cycle management metrics could include information on how often routine station inspection and maintenance occurred within prescribed frequency of visits, the number of unscheduled maintenance trips, how often systems were replaced within prescribed timeframes, numbers of repairs, etc.

6.8 Metadata

Not only is metadata important for users of observed data, it is absolutely essential for management of the networks and support systems, including planning and scheduling of inspections and maintenance, maintaining equipment inventories and capital replacement planning. The metadata could include basic station information such as station identification, lat/long, elevation, observing program, operating schedules and data communications, station agreements and contracts, site photos and maps, instrumentation – models, installation dates, replacement costs, operating software and algorithms, inspection and maintenance – reported problems, date and type of repairs, calibrations, etc. As implied in section 6.6, inspection reports are a valuable source of much of this information. These report forms can be paper or electronic, the latter offering several advantages such as timeliness and elimination of further need to abstract the information into digital formats. However it is important to design data entry systems for station and network information systems that are user friendly and provide ease of access via portable computers during station inspection trips. Further, good database queries and data visualization are recommended for using these metadata systems.

6.9 Training and Education

The importance of having well trained, informed personnel can't be stressed too much.

The degree of observer training depends on the complexity of the observing program. Training for hourly, synoptic, principal climate station or radiosonde programs is extensive, leading to certification. Detailed instruction includes training on standards and procedures for visual and instrument observations, coding (if necessary) and reporting. It includes training on the functioning of instruments in use, day-to-day maintenance and calibration checks, use of calibration tables where required, and data entry systems and transmission methods. Contractors, volunteers or partner agencies participating in basic daily temperature and precipitation cooperative climate programs should be provided instructional booklets that could include copies of correctly completed reports. Instruction may also be provided on electronic data entry methods and systems if relevant. Regardless of the program, inspectors should monitor the performance of the observer on a routine basis so that remedial actions can be taken.

The ever-increasing reliance on electronic technology has caused some NMHS to revise their recruiting and training programs for technical specialists responsible for maintaining the networks. For example, some NMHSs now require recruits to have prescribed electronics education from technical colleges, and then progress them through Occupational Training Programs that train them on basic meteorology and climatology, observational programs and instrumentation supplemented by specialty courses on inspection, specific systems such as AWS, etc. Training approaches could include classroom instruction, web-based distance learning, CDs and on the job training under the tutelage of an experienced senior technician. Detailed information on training for technical specialists can be found in the *WMO Guide to Meteorological Instruments and Methods of Observation* (WMO 1996).

Whether training is to be for an observer or technical support specialist, the curriculum should include training on occupational health and safety related to national or state level labour codes. Personnel and contractors, involved in the installation, maintenance or removal of equipment, should be well appraised of pertinent environmental regulations and directives.

Finally, many NMHSs rely on partnerships with other agencies with the objective of optimizing network densities and distribution through cost sharing or contributed data agreements. This is especially relevant to AWSs which are in widespread use by many agencies within some countries. As much as possible standardized approaches to operating stations is desirable including sensor selection, siting, installation, maintenance, observing program, reporting, etc. It benefits the NMHS to make available to these partners guidelines for the implementation, operation and maintenance of AWS for meeting quality objectives.

6.10 Managing Change

When significant changes, such as station re-location, replacement of a sensor type with another, or conversion from a manual to an AWS observing program are planned for stations used for climatological purposes, the WMO recommends that the observation program be overlapped for at least one year, and preferably two years (Fig.6.7).

Figure 6.7. Old and new side by side. Comparison data being collected at Helsinki to ensure continuity and homogeneity of climate records collected from the former manual station, which operated from 1844. (Source: Finnish Meteorological Institute, Finland)

In keeping with quality management system approaches, NMHSs should also consider the use of formal processes to ensure the orderly management of change to national network monitoring programs. For example, the Meteorological Service of Canada (MSC) has established a Change Management Board (CMB) to oversee that process (MSC 2002). The scope includes all systems, instruments, algorithms, processes, procedures and related documentation that influence the acquisition, processing, reporting and archiving of observations from the national meteorological and climatological networks. Membership on the board includes management representatives from national and regional components of the monitoring program and key internal stakeholders such as the national archives and climate research. The CMB is delegated decision-making authority by the national monitoring program senior manager and evaluates all change requests and commissions technical investigations, if necessary. Decisions are based on consensus – issues can be elevated to the program lead or a senior management committee if consensus is not reached. Responsibilities include ensuring that there is a clear and transparent change request process available for proponents of change and that change requests are reviewed and processed in a timely manner. The board defines specific tasks for Task Groups when necessary (e.g. an instrument test and evaluation strategy) and also maintains an up-to-date baseline listing of approved systems, configurations and applications for use. All change requests, decisions and supporting documentation are made available on the national monitoring program website.

7 Conclusions

Climatologists can play an active role in helping to ensure that observation networks and systems perform to standards acceptable to climate data users. This role will include understanding, promulgating and, in some cases, directly implementing the key principles of climate monitoring. Climatologists will also need to communicate their needs through developing statements of requirements, which will include information on the accuracy, frequency and spatial coverage of climate observations. The needs for special climate networks will also need to be communicated and the climatologist will often perform a key role in monitoring the performance of these networks. The pace of change in observation system and networks will not slow down in the twenty-first century and, as a result, changes to observational networks and systems will need very careful management to ensure that the continuity and homogeneity of climate observations are preserved.

Appendix 1

USER REQUIREMENTS DOCUMENTS

The World Meteorological Organization, largely through its Commission for Basic Systems (CBS) has been active in determining future observational data requirements and redesign of the global observing systems (WMO 2003). The CCl is participating on observations for climate.

The principles within the WMO Rolling Requirements Review (RRR) procedure (WMO 2000) are useful in order to address user requirements in a generic, technology-independent manner, and also considering cost-benefits. Given the rapid pace of change of both requirements and capabilities (existing and planned) the RRR is to be carried out periodically.

The RRR procedure consists of four stages:

(i) a review of users' requirements for observations;

(ii) a review of the observing capabilities of existing and planned observing systems;

(iii) a "Critical Review" of the extent to which the capabilities (ii) meet the requirements (i); and

(iv) a "Statement of Guidance" based on (iii).

User Requirements

The requirements for observations are stated quantitatively in terms of relevant parameters, such as:

- Processing of data (e.g. averaging times, mean and extreme values);
- Accuracy/Resolution of data;
- Spatial resolution (horizontal and/or vertical);
- Preferred locations (e.g. to represent topography);
- Temporal resolution (frequency);
- Timeliness of data receipt (e.g. daily); and
- Completeness of record archived (e.g. minimum % acceptable, averaged over the year)

For each parameter the requirements are expressed in terms of an upper boundary or "maximum" and a lower boundary or "minimum".

The "maximum" requirement is the value that, if exceeded, does not yield significant improvements in performance for the application in question. This upper limit is bound to change as applications evolve and better observations become more useful.

The “minimum” requirement is the value below which the observation does not yield any significant benefit for the application in question. A system just satisfying this lower limit will generally not be cost-effective, so it should not be used as a minimum target level.

Critical Review

The CR process compares user requirements with system capabilities, in terms of the extent to which the capabilities of the system (present and proposed) meet the stated requirements. The following criteria should be satisfied by the CR:

- ✓ its presentation must be concise and attractive, and understandable to senior managers and decision makers;

- ✓ the user requirements and system capabilities must be accurate;

- ✓ its results must accurately reflect the extent to which current systems are useful in practice, whilst drawing attention to those areas in which they do not meet some or all of the user requirements; and

- ✓ the process must be as objective as possible.

Statement of Guidance

Based on the CR, the SoG draws conclusions and identifies priorities for actions. It is of a more subjective nature than the CR, and includes judgements concerning, for example, the relative importance of observations of different variables.

Cost-benefit Considerations

Cost-benefit considerations should enter in the decision process on the design implementation and operation of observing systems. For a single observing system, in the context of a single application, the following generic cost-benefit relations exist:

- Below the cost corresponding to the “minimum” user requirement there is no significant benefit. Costs above the cost corresponding to the “maximum” user requirement yield no significant increase in benefits;
- There is a point of equal cost and benefit. Usually, for an interval of costs above this value, benefits will be greater than costs, i.e. benefits are possible by implementing the system; and
- The point of optimal cost-benefit is, in general, lower than the point of “maximum requirement”. Reaching the latter usually involves considerable additional cost.

Appendix 2

This document is a summary of a United Kingdom Met Office's Statement of Guidance (SOG) document (UKMO 2003). This summary version is produced with the consent of the UKMO but has been drafted by the authors of this WMO guidance document. It essentially retains the broad structure and headings of the original document, which contains much discussion under those headings, and is provided here as a sample SOG.

Statement of Guidance for Surface Climate Observations over Land Areas of the UK

Introduction

This document covers meteorological observations made over surface land areas of the UK that may be used for climatological purposes. It does not cover the climatological requirement for observations over the oceans or in the upper air.

The methodology used for addressing requirements for observations is an internal Rolling Requirement Review (RRR). Two documents have already been produced in stages 1 and 2 of the RRR process for Climate Observations, the User Requirement and the Critical Review. This Statement of Guidance draws on these two documents to address the deficiencies identified and provides a strategy for meeting user needs.

Issues are considered under 7 broad headings. The source of the identified requirements is indicated by a letter: N for NCIC; B for business; I for international, M for climate monitoring and R for research. The GCOS principles are designated by the letter G (G1 refers to principle 1, etc).

1. Stations and Networks

(a) WMO recommended categorisation of stations should be maintained (I).

(b) Stations should be representative, with respect to topography and land use, of an area in accordance with its application. Typically this might be a 15km radius for temperature. Different environments should be reflected within the network – urban, coastal and upland (N,G5,B,I,R).

(c) There should be stations in each large (100-150,000) urban conurbation (B).

(d) The environment of stations used for climate monitoring should be remote from the influence of man (M).

(e) Stations should provide a record of at least 10 years, preferably 30 years or more (N,G6,G9,B,I,R).

(f) Existing long period stations should be preserved including around 20 Reference Climatological Stations used for climate monitoring purposes including the 3 CET stations (M,N,G6,B,I,R).

(g) High priority should be given to filling gaps in the network (G7).

(h) There should be a 12 month overlap where new stations are established to replace existing long period stations (G2,B,R).

2. Elements, Distribution, Frequency, Resolution and Accuracy

Note: Numbers separated by a slash / denote the minimum and maximum requirement specifications.

2.1 General

(a) Observing processes should deliver data of adequate accuracy and with biases sufficiently small to resolve climate variations (N,G8,I,R).

(b) Different elements should be collocated (N,M).

(c) High resolution data should be available to document extreme weather events (G4). Data at 1 minute resolution for limited periods should be available on request (R).

2.2 Air Temperature

(a) Spatial resolution of 60/30 km (N); about 150 km (M,I); 50 km (B).

(b) Temporal resolution of hourly with 12-hourly max and min (N,M,B,I)

(c) Resolution of 0.2/0.05 deg C and accuracy of 0.5/0.1 deg C (N,M,B,I).

2.3 Surface and Soil Temperatures

(a) Spatial resolution of 60/30 km (N); about 150 km (M); 50 km (B).

(b) Daily temporal resolution (N,M,B); hourly at 10 cm (N).

(c) Resolution of 0.2/0.05 deg C
Accuracy of 0.5/0.1 deg C for soil temperature
Accuracy of 0.75/0.3 deg C for surface temperature (N,M,B).

(d) Soil temperatures at 30 cm required for historical continuity (N).

2.4 Wind speed and direction

(a) Spatial resolution of 70/20 km. Wind observations are required from every major area of high ground in the UK(N,R).

(b) Wind in urban areas should be made at the highest location outside the urban canopy (N).

(c) Temporal resolution of hourly (N) with a subset of at least 10 stations providing sub hourly data (N)

(d) Direction resolution of 10/5 deg and accuracy of 15/5 deg (N). Speed resolution of 1.0/0.5 kn and an accuracy of 1.0/0.5 kn or 10/5% (N). Accurate resolution of low wind speeds is essential (N,R).

Wind measurements should be made at a site having an exposure meeting WMO recommendations (N).

2.5 Relative humidity and vapour pressure

(a) Spatial resolution of 60/30 km (N, B); about 150 km (M).

(b) Hourly temporal resolution (N,M,B); daily min (N).
(c) Resolution (RH) of 2/0.5 % and accuracy of 5/1 % for RH < 75% and 2/0.5 % for RH > 75% (N,M,B). (The figures of percent refer to the error in the measured value, not the percent error of the measured value)

2.6 Rainfall

(a) Spatial/temporal resolution of
Daily (0900) 50/5 km (M,N,B)
Hourly 30/5 km (N,B,R)
(b) A selection of stations producing data with a time resolution of 5 min or better for hydrological purposes (B)
(c) Resolution of 0.5/0.05mm and accuracy of 0.3/0.1mm (<4mm) and 7.5%/2.5% (>4mm) – (M,N,B,R)

2.7 Sunshine

Spatial resolution of 120/60 km (N,B).
Daily temporal resolution (N,B)
Resolution of 0.2/0.1hr and accuracy of 0.4/0.2 hr (N,B). Meet exposure standards.
Parallel deployment of Campbell-Stokes recorders at a few stations for continuity purposes (M,N,R).

2.8 Radiation
Spatial resolution of 80/50 km (N,B).
Hourly temporal resolution plus daily max (N,B)

Resolution of 20/10 kjm-2 and accuracy of 7/4% (N,B).
At least one station should provide solar and terrestrial data of high quality and high time resolution.

2.9 Snow Depth
Spatial resolution of 50/20 km (N).
Hourly temporal resolution plus daily max (N)
Resolution of 1/0.5 cm and accuracy of 2/0.5 cm (N).

2.10 Other meteorological elements

3. Observing Practice

(a) There should be continuity of exposure of instruments (N,G1).

(b) There should be continuity of observing practice (N, G1, I).

(c) Where system changes occur at a station there should be an overlap of at least 12 months (N, G2, I).

(d) WMO recommendations or other accepted standards should be followed (N, I).

4. Timeliness and Completeness

(a) Some data are needed in near real time (B).

(b) Some data are needed within a few days of the end of the month (N).

(c) The data record should be at least 99% complete with virtually no consecutive hours missing (N).

(d) Archived CET data should be 99.5% complete. Any gaps should not be correlated with weather conditions (M).

5. Communication and Archiving

(a) A climate archive should be maintained giving easy access to the data (N,G10,B,I,R).

(b) Data should be exchanged internationally in agreed formats (M,I).

(c) Records in non-electronic format should be converted for efficient electronic access (G7).

6. Observations Metadata

7. Quality Assurance

(a) Quality control should be performed on the data to ensure homogeneity and accuracy (G10).

(b) Processes should be put in place to ensure stated quality is achieved.

The UK SOG contains the following annexes (not reproduced in these Guidelines):

Annex 1. Improvements in the short to medium term

Annex 2. Requirements for the Next Generation AWS

Annex 3. RCS (R), CLIMAT (C), GCOS (G) and CET (E) stations

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Glossary

Change Management Program
In the context of climate observation networks and systems, refers to a program established to ensure that any changes in systems, instruments, algorithms, procedures, procedures, processes and related documentation that influence the collection, processing, reporting and archiving of climate observations are dealt with in a manner that minimises the deleterious impact on those networks, systems and data outputs.

Climatological Normal
Period averages computed for a uniform and relatively long period comprising at least three consecutive ten-year periods. Climatological standard normals are averages computed for consecutive periods of 30 years as follows: 1 January 1901 to 31 December 1930, 1 January 1931 to 31 December 1960, etc.

Climate observation
An observation used to describe or understand the climate system, which may include measurements of physical, chemical and biological properties, representing atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. The attributes of continuity and homogeneity are generally given high priority.

Climate observation network
An inter-connecting arrangement of observation systems designed to provide meteorological or related observations suitable for climatological purposes over some defined area.

Climate observation system
An observation system (e.g. automatic weather station, radiosonde, buoy) designed to measure, and often record and transmit, meteorological or related observations suitable for climatological purposes.

Climate system- The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and land-use change.

GAW
The Global Atmosphere Watch program was established in 1989 to to provide reliable long-term observations of the chemical composition of the atmosphere and related parameters in order to improve our understanding of atmospheric chemistry, and to organize assessments in support of formulating environmental policy.

GCOS

The Global Climate Observing System was established in 1992 and is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU). GCOS is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system, for detecting and attributing climate change, for assessing the impacts of climate variability including climate change, and for supporting research toward improved understanding, modelling and prediction of the climate system.

GSN
The GCOS Surface Network contains about a quarter of the 4000 stations within the World Weather Watch reference synoptic network and has been specifically designed to determine the variability, including extremes, of surface air temperature over land at global, hemispheric and continental scales. It is also used to make similar estimates for other variables.

GUAN
The GCOS Upper Air Network is a baseline network of about 150 stations selected from the full upper-air network on the basis of past performance and global representation. It intends to provide reliable measurements of large-scale temperature variations for heights up to 5hPa in the free atmosphere for the detection of climate change. Other variables, such as humidity and wind speed and direction are also extremely valuable.

Ordinary Climatological Station
A climatological station at which observations are made at least once daily including readings of extreme temperatures and precipitation amount.

Principal Climatological Station
Operates a more extensive observation programme than an Ordinary Climatological Station. At a minimum such a station should make observations of the following elements: weather, wind, cloud amount, type of cloud, height of cloud base, visibility, humidity, temperature (including extremes), atmospheric pressure, precipitation, snow cover, sunshine and/or solar radiation, soil temperature at various depths.

RCS
A Reference Climate Station (or Reference Climatological Station) is a climatological station, the data of which are intended for the purpose of determining climatic trends. This requires long periods (not less than thirty years) of homogeneous records, where human-influenced environmental changes have been and/or are expected to remain at a minimum. Ideally the records should be of sufficient length to enable the identification of secular [over time] changes of climate.

RBCN
The Regional Basic Climatological Network provides support to regional-scale climate monitoring through aiming to increase the international exchange of monthly climate data

through reporting CLIMAT messages from more stations. Members are encouraged to include RCSs within their RBCN.

Remote sensing
The collection and recording of data from a distant point, e.g. radar and satellite-based observations of the atmosphere as opposed to on-site (*in situ*) sensing.

Return period
The period of time that has to pass on average until a given threshold of a variable is surpassed. It is equal to the inverse of the probability that the threshold is surpassed.

Significance level
The maximum probability of rejecting a true null hypothesis in a statical hypothesis test, usually denoted by α_0.