CHAPTER 2

CLIMATE OBSERVATIONS, STATIONS AND NETWORKS

2.1 INTRODUCTION

All national climate activities, including research and applications, are primarily based on observations of the state of the atmosphere or weather. The Global Observing System provides observations of the state of the atmosphere and ocean surface. It is operated by National Meteorological and Hydrological Services, national or international satellite agencies, and several organizations and consortiums dealing with specific observing systems or geographic regions. The WMO Global Observing System is a coordinated system of different observing subsystems that provides in a cost-effective way high-quality, standardized meteorological and related environmental and geophysical observations, from all parts of the globe and outer space. Examples of the observing subsystems relevant to climate are the Global Climate Observing System (GCOS) Surface Network (GSN), the GCOS Upper-Air Network (GUAN), Regional Basic Climatological Networks, Global Atmosphere Watch (GAW), marine observing systems, and the satellite-based Global Positioning System. The observations from these networks and stations are required for the timely preparation of weather and climate analyses, forecasts, warnings, climate services, and research for all WMO Programmes and relevant environmental programmes of other international organizations.

This chapter on observations follows the sequence of specifying the elements needed to describe the climate and the stations at which these elements are measured, instrumentation, siting of stations, network design and network operations. The guidance is based on the WMO *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8, fifth, sixth and seventh editions), the *Guide to the Global Observing System* (WMO-No. 488) and the *Guidelines on Climate Observation Networks and Systems* (WMO/TD-No. 1185). Each edition of the *Guide to Meteorological Instruments and Methods of Observation* has a slightly different emphasis. For example, the sixth edition contains valuable information on sensor calibration, especially of the basic instrumentation used at climate stations, but Tables 2 and 3 of the fifth edition provide more information about the accuracy of measurements that are needed for general climatological purposes. Cross references are provided in the sections below to other WMO publications containing more detailed guidance.

Guidance is also based on ten climate monitoring principles set forth in the *Report of the GCOS/GOOS/GTOS Joint Data and Information Management Panel* (Third Session, Tokyo, 15–18 July 1997, WMO/TD-No. 847):

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. The details and history of local conditions, instruments, operating procedures, data processing algorithms, and other factors pertinent to interpreting data (metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate monitoring products and assessments should be integrated into national, regional, and global observing priorities.
6. Operation of historically uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor areas, poorly observed parameters, areas sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully planned manner should be promoted.
10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.

These principles were established primarily for surface-based observations, but they also apply to data for all data platforms. Additional principles specifically for satellite observations are listed in section 2.3.4.

2.2 CLIMATIC ELEMENTS

A climatic element is any one of the properties of the climate system described in section 1.2.2. Combined with other elements, these properties describe the weather or climate at a given place for a given period of time. Every meteorological element that is observed may also be termed a climatic element. The most commonly used elements in climatology are air temperature (including maximum and minimum), precipitation (rainfall, snowfall and all kinds of wet deposition, such as hail, dew, rime, hoar frost and precipitating fog), humidity, atmospheric motion (wind speed and direction), atmospheric pressure, evaporation, sunshine, and present weather (for example, fog, hail and thunder). Properties of the land surface and subsurface (including hydrological elements, topography, geology and vegetation), of the oceans, and of the cryosphere are also used to describe climate and its variability.

The subsections below describe commonly observed elements for specific kinds of stations and networks of stations. Details are in the *Manual on the Global Observing System*, the WMO *Technical Regulations* (WMO-No. 49, in particular Volume III – *Hydrology*), and the *Guide to Agricultural Meteorological Practices* (WMO-No. 134). These documents should be kept readily available and consulted as needed.

2.2.1 **Surface and subsurface elements**

An ordinary climatological station provides the basic land area requirements for observing daily maximum and minimum temperature and amount of precipitation. A principal climatological station usually provides a broader range of observations of weather, wind, cloud characteristics, humidity, temperature, atmospheric pressure, precipitation, snow cover, sunshine and solar radiation. In order to define the climatology of precipitation, wind, or any other specific element, it is sometimes necessary to operate a station to observe one or a subset of these elements, especially where the topography is varied. Reference climatological stations (see section 2.5) provide long-term, homogeneous data for the purpose of determining climatic trends. It is desirable to have a network of these stations in each country, representing key climate zones and areas of vulnerability.

In urban areas weather can have a significant impact. Heavy rains can cause severe flooding; snow and freezing rain can disrupt transportation systems; and severe storms with accompanying lightning, hail and high winds can cause power failures. High winds can also slow or stop the progress of automobiles, recreational vehicles, railcars, transit vehicles and trucks. The urban zone is especially susceptible to land falling tropical storms because of the large concentrations of people at risk, the high density of man-made structures, and the increased risk of flooding and contamination of potable water supplies. Urban stations usually observe the same elements as principal climatological stations, with the addition of air pollution data such as low-level ozone and other chemicals and particulate matter.

Marine observations can be generally classified into physical-dynamical and biochemical elements. The physical-dynamical elements (such as wind, temperature, salinity, wind and swell waves, sea ice, ocean currents and sea level) play an active role in changing the marine system. The biochemical elements (such as dissolved oxygen, nutrients and phytoplankton biomass) are generally not active in the physical-dynamical processes, except perhaps at long timescales, and thus are called passive elements. From the perspective of most NMHSs, high priority should generally be given to the physical-dynamical elements, although in some cases biochemical elements could be important when responding to the needs of stakeholders (for example, observations related to the role of carbon dioxide in climate change).

In some NMHSs with responsibilities for monitoring hydrological events, hydrological planning, or hydrological forecasting and warning, it is necessary to observe and measure elements specific to hydrology. These elements may include combinations of river, lake and reservoir level; streamflow; sediment transport and deposition; rates of abstraction and recharge; water and snow temperatures; ice cover; chemical properties of water; evaporation; soil moisture; groundwater level; and flood extent. These elements define an integral part of the hydrologic cycle and play an important role in the variability of climate.

In addition to surface elements, subsurface elements such as soil temperature and moisture are particularly important for application to agriculture, forestry, land-use planning and land-use management. Other elements that should be measured to characterize the physical environment for agricultural applications include evaporation from soil and water surfaces, sunshine, short- and long-wave radiation, plant transpiration, runoff and water table, and weather observations (especially hail, lightning, dew and fog). Ideally, measurements of agriculturally important elements should be taken at several levels between 200 cm below the surface and 10 m above the surface. Consideration should also be given to the nature of crops and vegetation when determining the levels.

Proxy data are measurements of conditions that are indirectly related to climate, such as phenology, ice core samples, varves (annual sediment deposits), coral reefs and tree ring growth. Phenology is the study of the timing of recurring biological events in the animal and plant world, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species. Leaf unfolding, flowering of plants in spring, fruit ripening, colour changing and leaf fall in autumn, as well as the appearance and departure of migrating birds, animals and insects are all examples of phenological events. Phenology is an easy and cost-effective system for the early detection of changes in the biosphere and therefore complements the instrumental measurements of national meteorological services very well.

An ice core sample contains snow and ice and trapped air bubbles. The composition of a core, especially the presence of hydrogen and oxygen isotopes, relates to the climate of the time the ice and snow were deposited. Ice cores also contain inclusions such as windblown dust, ash, bubbles of atmospheric gas, and radioactive substances in the snow deposited each year. Various measurable properties along the core profiles provide proxies for temperature, ocean volume, precipitation, chemistry and gas composition of the lower atmosphere, volcanic eruptions, solar variability, sea surface productivity, desert extent and forest fires. The thickness and content of varves are similarly related to annual or seasonal precipitation, streamflow, and temperature.

Tropical coral reefs are very sensitive to changes in climate. Growth rings relate to the temperature of the water and to the season in which the rings grew. Analysis of the growth rings can match the water temperature to an exact year and season. Data from corals are used to estimate past El Niño–Southern Oscillation (ENSO) variability, equatorial upwelling, changes in subtropical gyres, trade wind regimes and ocean salinity.

Tree-ring growth shows great interannual variability and also large spatial differences. Some of the variation can be related to weather and climate conditions in the microscale and macroscale; plants can be viewed as integrative measurement devices for the environment. Since trees can live for centuries, annual growth rings in some tree species can provide a long historical indication (predating instrumental measurements) of climate variability. Because of the close relationship between plant development and weather and climate, phenological observation networks are run by the NMHSs in many countries.

Table 2.1 summarizes the most common surface and subsurface climatic elements that are observed for various networks or types of station.

2.2.2 **Upper-air elements**

Upper-air observations are an integral component of the Global Observing System. The spectrum of climate activities that require upper-air observations includes monitoring and detecting climate variability and change, climate prediction on all timescales, climate modelling, studies of climate processes, data reanalysis activities, and satellite studies concerning calibration of satellite retrievals and radiative transfer.

The longest record of upper-air observations has been obtained from balloon-based instruments combined with ground tracking devices in a radiosonde network. These radiosonde measurements provide a database of atmospheric variables dating back to the 1930s, although coverage is generally poor before 1957. The radiosonde data record is characterized by many discontinuities and biases resulting from instrument and operational procedural changes and incomplete metadata. Satellite observations have been available since the 1970s, and some have been assembled and reprocessed to create continuous records. Just as the radiosonde record has deficiencies, however, the satellite data also suffer from, among other things, limited vertical resolution, orbit drift, satellite platform changes, instrument drift, complications with calibration procedures, and the introduction of biases through modifications of processing algorithms. Other upper-air measurements have come from moving platforms such as aircraft. Observations from some high-mountain locations have also been considered part of the upper-air measurement system.

The main observational requirements for monitoring long-term upper-air changes are:

(a) A long-term (multidecadal), stable, temporally homogeneous record so that changes can confidently be identified as true atmospheric changes rather than changes in the observing system or as artefacts of homogenization methods;

(b) Good vertical resolution to describe the vertical structure of temperature, water vapour, and ozone changes, and of changes in the tropopause;

(c) Sufficient geographical coverage and resolution, so that reliable global and area trends can be determined;

(d) Observational precision finer than the expected atmospheric variations to allow clear identification of both variability and long-term changes. This requirement is particularly important for water vapour observations in the upper troposphere and stratosphere.

The essential climate elements from upper-air observations are given in the *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC* (WMO/TD-No. 1143) and the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*

Table 2.1. Examples of surface and subsurface elements for different station networks or types of stations

Element	*Ordinary climate*	*Principal climate*	*Marine*	*Hydrometeorological*	*Agrometeorological*	*Urban*	*Proxy*
Air temperature	●	●	●		●	●	
Soil temperature					●		
Water temperature			●	●			
Precipitation	●	●	●	●	●	●	
Weather		●	●		●	●	
Clouds		●	●		●	●	
Pressure		●	●		●	●	
Visibility		●	●		●	●	
Humidity		●	●		●	●	
Wind		●	●		●	●	
Solar radiation		●			●	●	
Sunshine		●			●	●	
Salinity			●				
Currents			●				
Sea level			●				
Waves			●				
Air–sea momentum			●				
Air–sea fluxes			●				
Ice			●	●			
Dissolved oxygen			●				
Nutrients			●				
Bathymetry			●				
Biomass			●				
Streamflow				●			
River stages				●			
Sediment flow				●			
Recharge				●			
Evaporation				●	●	●	
Soil moisture				●	●	●	
Runoff				●	●		
Groundwater				●	●		
Plant development						●	●
Pollen							●
Ice and sediment composition							●
Tree ring growth							●
Coral ring growth							●
Atmospheric chemicals						●	
Particulate matter						●	

(WMO/TD-No. 1219) as temperature, water vapour, pressure, wind speed and direction, cloud properties, radiance and radiation (net, incoming and outgoing). Because the chemical composition of the atmosphere is of major importance in climate prediction, climate change monitoring, ozone and other air-quality predictions, and in application areas such as the study and forecasting of animal, plant and human health and well-being (Chapter B2 in the *Technical Regulations*, the *Plan for the Global Climate Observing System (GCOS)*, Version 1.0 (WMO/TD-No. 681), and the *GCOS/GTOS Plan for Terrestrial Climate-related Observations*, Version 2.0 (WMO-No. 796)), it is important to understand the vertical structure of the composition of the global atmosphere. Chemical composition elements requiring measurement both in the free atmosphere and near the ground include concentrations of ozone and other greenhouse gases, such as carbon dioxide and methane, atmospheric turbidity (aerosol optical depth), aerosol total load, reactive gas species, and radionuclides. Measurements of acid rain (or more generally precipitation and particulate chemistry) and ultraviolet radiation are also needed. (See the *Integrated Global Atmospheric Chemistry Observations (IGACO) Report of IGOS-WMO-ESA* (WMO/TD-No. 1235) for details concerning the chemical composition of the atmosphere).

Upper-air measurements should capture the full range of climate regimes and surface types. Radiative transfer codes used to convert raw satellite radiances to geophysical parameters depend upon assumptions about the surface conditions. Therefore, different local environmental conditions should be represented, including both land and ocean areas.

2.2.3 Elements measured by remote-sensing

Satellites and other remote-sensing systems such as weather radar provide an abundance of additional information, especially from otherwise data-sparse areas, but are not as yet capable of providing, with the required accuracy and homogeneity, measurements of many of the elements that are reported from land-based surface stations. The spatial coverage they offer makes them complementary to, but not a substitute for, the surface networks. The elements that can be measured or estimated remotely are precipitation (with limited accuracy over small areas, ocean–atmosphere interfaces, highlands or steep orography); cloud amount; radiation fluxes; radiation budget and albedo; upper oceanic biomass, ocean surface topography and wave height; sea-ice cover; sea surface temperature; ocean surface wind vectors and wind speed; atmospheric temperature, humidity and wind profiles; chemical constituents of the atmosphere; snow cover; ice sheet and glacier extent; vegetation and land cover; and land surface topography.

Greater spatial and temporal coverage can be achieved with remote-sensing than with in situ observations. Remotely sensed data also supplement observations from other platforms and are especially useful when observations from other platforms are missing or corrupted. Although this is an advantage, there are problems in using remotely sensed data directly for climate applications. Most importantly, the short period of record means that remotely sensed data cannot be used to infer long-term climate variability and change. Also, remotely sensed data may not be directly comparable to in situ measurements. For example, satellite estimates of the Earth's skin temperature are not the same as temperature measurements taken in a standard screen, and the relationship between radar measurements of reflectivity and precipitation amounts collected in raingauges may be quite complex. It is possible with care, however, to construct homogeneous series that combine remotely sensed and in situ measurements.

2.3 INSTRUMENTATION

Climatological stations that are part of a national network should be equipped with standard approved instruments; the NMHS may supply the instruments. When equipment is supplied by other agencies or purchased by the observer, every effort should be made by a climate office to ensure compliance with national standards.

This section gives guidance on some basic surface instrumentation and on the selection of instruments. There are several other WMO publications that are necessary companions to this Guide, and should be readily available and consulted as needed. A thorough survey of instruments suitable for measuring climate and other elements at land and marine stations is provided in the *Guide to Meteorological Instruments and Methods of Observation*. Details of instrumentation needed for the measurement of chemical composition are given in the *International Operations Handbook for Measurement of Background Atmospheric Pollution* (WMO-No. 491), for agrometeorological elements in the *Guide to Agricultural Meteorological Practices*, and for hydrological purposes in the *Guide to Hydrological Practices* (WMO-No. 168).

When selecting instrumentation, including any associated data-processing and transmission systems, the 10 climate monitoring principles (section 2.1) should be followed. Several concerns should be considered when complying with these principles:

(a) Reliability;
(b) Suitability for the operational environment at the station of use;
(c) Accuracy;
(d) Simplicity of design;
(e) Reasons for taking observations.

Reliability requires that an instrument functions within its design specifications at all times. Unreliable instrumentation leads to data gaps, biases and other inhomogeneities. Reliable instruments need to be robust enough to cope with the full range of weather and physical extremes expected at the site, and possibly the handling that is part of manual observations.

Instruments must be suited both to the climate in which they must function, and to other equipment with which they must operate. For example, an anemometer head at a cold location will need to withstand icing, while one in a desert area will need to be protected against dust ingression. Sensors for use in an automatic weather station need to provide output suitable for automatic processing. The standard mercury-in-glass thermometer used at a manual recording site, for example, will need to be substituted by a temperature-sensitive probe, such as a thermocouple, whose response can be converted into an electronic signal. Instruments must also be sited so that they can be accessed and maintained.

Ideally, all instruments should be chosen to provide the high level of accuracy and precision required for climatological purposes. It is also important that the instrument can continue to provide the required level of accuracy for a long period of time, as instrument "drift" can lead to serious inhomogeneities in a climate record; accuracy is of limited use without reliability.

The simpler the instrumentation, the easier it is to operate and to maintain, and the easier it is to monitor its performance. It is sometimes necessary to install redundant sensors (for example, triple thermistors at automated data-logger stations) to properly track performance and reliability over time. Complex systems can easily lead to data inhomogeneities, data loss, high maintenance cost and changing accuracy.

The purpose of the observations generally dictates requirements for measurements. Types of instruments, installation of sensors, and characteristics of the instruments should be considered to ensure that measurement requirements can be met.

Details about these concerns, including instrument and measurement standards and recommended practices, are can be found in the *Guide to Meteorological Instruments and Methods of Observation*.

2.3.1 **Basic surface equipment**

There may be a variety of options for obtaining climate observations from surface stations. These options include equipping a station with, for example, basic instruments, autographic or automated output available for unmanned periods, or totally automated sensors. When considering the options, it is important to compare costs of personnel, maintenance and replacement. Price negotiation is often possible with manufacturers on the basis of, for example, quantities purchased, among other things.

Whenever possible, trained local personnel, such as a caretaker, should examine an observing site on a regular basis to keep surface conditions (such as grass growth) in check, perform basic maintenance of instruments (such as simple cleaning), examine for damage, and detect breaches of security. These tasks should be performed at least weekly at accessible, manned land stations. Inspection of sites and instruments at remote locations should be made as often as possible. Personnel should also be available to provide rapid maintenance response when critical systems fail.

Autographic and data-logger equipment exists for the recording of many climatic elements, such as temperature, humidity, wind and rates of rainfall. Data need to be transferred from autographic records to tables or digital form. Observers should ensure that the equipment is operating properly and that information recorded on charts, for example, is clear and distinct. Observers should be responsible for regularly verifying and evaluating the recorded data (by checking against direct-reading equipment) and for making time marks at frequent, specified intervals. The recorded data can be effectively used to fill gaps and to complete the record when direct observations are missed because of illness and other causes of absence from the observing station. Sections 1.4.2 and 1.4.3 of the *Guide to Meteorological Instruments and Methods of Observation* (fifth edition) give specific guidance on the maintenance and operation of recording instruments, drums and clocks.

Data from automatic weather stations (AWSs), at which instruments record and transmit observations automatically, are usually restricted to those readily obtained in digital form, although the range of sensors is wide and continues to evolve. Such stations have been used to supplement manned stations and to increase network densities, reporting frequencies and the quantities of elements observed, especially in remote and largely unpopulated areas where human access is difficult. Some of the sensitivity and accuracy requirements of these automated stations are given in the *Guide to Meteorological Instruments and Methods of Observation*; others are being developed, especially for studies of climate variability.

In many countries, AWSs have lowered operational costs. NMHSs choosing between manned and AWS observation programmes need to consider a number of issues. Notwithstanding the considerable potential for AWSs to provide high-frequency data, as well as additional data from remote locations, there are several significant costs associated with operating an AWS, including labour costs for maintenance and ensuring AWS reliability, labour availability, accessibility for installation and maintenance, the availability of suitable power sources, security of the site, and communications infrastructure. These aspects must be carefully weighed against the significant benefits, such as a denser or more extensive network. AWSs can be powerful alternatives to manned observational programmes and sometimes are the only option, but they require a strong organizational commitment to manage them.

Marine instrumentation includes drifting and moored data buoys, ice floats and subsurface floats. Although the data are collected remotely, the instruments are generally performing in situ measurements. They are a cost-effective means for obtaining meteorological and oceanographic data from remote ocean areas. As such, they form an essential component of marine observing systems and meteorological and oceanographic operational and research programmes. For example, the Tropical Atmosphere Ocean array of moorings has enabled timely collection of high-quality oceanographic and surface meteorological data across the equatorial Pacific Ocean for the monitoring, forecasting and understanding of climate swings associated with El Niño and La Niña.

2.3.2 Upper-air instruments

Historically, most climatological data for the upper air have been derived from measurements made for synoptic forecasting by balloon-borne radiosondes. A variety of techniques and instruments are used for the measurement of pressure, temperature, humidity and wind, and for processing instrumental output into meteorological quantities. It is important for each NMHS to issue suitable instruction manuals to each upper-air station for the proper use of equipment and interpretation of data. The *Manual on the Global Observing System* (WMO-No. 544, section 2.10.4.5) requires that prompt reports be made to the WMO Secretariat of changes in radiosonde type or changes in wind systems in operational use at a station.

There are several issues concerning the quality of radiosonde measurements for climate monitoring and climate change detection purposes. Radiation errors cause uncertainties in temperature. Standard radiosondes are not capable of measuring water vapour at low temperatures with sufficient accuracy. Sensor types, especially humidity sensors, have changed over time. The spatial coverage of radiosonde observations is not uniform; most stations are located on the land-surface territories of the northern hemisphere, while the southern hemisphere and ocean networks are much less dense. The historical record of radiosonde observations has innumerable problems relating to a lack of intercomparisons among types of radiosondes and sensor and exposure differences; metadata concerning instrumentation, data-reduction and data-processing procedures are crucial to utilizing radiosonde data in climate applications. New reference radiosondes are being developed to mitigate the deficiencies of the current standard radiosondes. A limited network of these will be used to calibrate and validate various satellite observations of both temperature and water vapour.

An upper-air observing system may change over time with technological advances. Hence, a key requirement of the network is sufficient overlap of systems to maintain continuity and allow full comparison of the accuracy and precision of the old and new systems. Measurement systems should be calibrated regularly at the site. It is imperative that instrument replacement strategies take into account changes in other networks, such as the use of satellites. The Climate Monitoring Principles (see section 2.1) should guide the development and operation of an upper-air observing system.

2.3.3 Surface-based remote-sensing

Remote-sensing can use either active or passive sensors. Active sensor systems emit some form of radiation, which is scattered by various targets; the sensors detect the backscatter. Passive sensors measure radiation being emitted (or modified) by the environment.

The most common surface-based active remote-sensing technique is weather radar. A short pulse of high-power microwave energy is focused by an antenna system into a narrow beam. This beam is scattered back by the target precipitation, with the backscattered radiation received, generally, by the same antenna system. The location of the precipitation can be determined from the azimuth and elevation of the antenna and the time between transmitting and receiving the reflected energy. The power of the received radiation depends on the nature of the precipitation, and the signal can be processed to estimate its intensity. Atmospheric and environmental conditions can adversely affect radar data, and caution should be exercised when interpreting the information. Some of these effects include returns from mountains, buildings, and other non-meteorological targets; attenuation of the radar signal when viewing weather echoes through intervening areas of intense precipitation; temperature inversions in the lower layers of the atmosphere, which bend the radar beam in such a way that ground clutter is observed where normally not expected; and the bright band, which is a layer of enhanced reflectivity caused by the melting of ice particles as they fall through the freezing level in the atmosphere, which can result in overestimation of rainfall. Use of radar data in climate studies has been limited by access and processing capabilities, uncertainties in calibration and calibration changes, and the complex relationship between reflectivity and precipitation.

Wind profilers use radar to construct vertical profiles of horizontal wind speed and direction from near the surface to the tropopause. Fluctuations of atmospheric density are caused by turbulent mixing of air with different temperatures and moisture content. Fluctuations in the resulting index of refraction are used as a tracer of the mean wind. Although they work best in clear air, wind profilers are capable of operating in the presence of clouds and moderate precipitation. When equipped with a radio-acoustic sounding system, profilers can also measure and construct vertical temperature profiles. The speed of sound in the atmosphere is affected by temperature. Acoustic energy is tracked through the atmosphere, and the temperature profile is estimated from the speed of the sound wave propagation.

Lightning detection is the most common passive surface-based remote-sensing. Lightning sensors scan a range of electromagnetic frequencies to detect electrical discharges inside clouds, between clouds, or between clouds and the ground. Characteristics of the received radiation (such as the amplitude, time of arrival, source direction, sign and other wave form characteristics) are measured, and from them characteristics of the lightning flash are inferred. One sensor cannot accurately locate lightning events; data from several sensors are concentrated in a central location in a central lightning processor. The processor computes and combines data from multiple sensors to calculate the location and characteristics of the observed lightning flashes. The accuracy and efficiency of a lightning-detector network drops progressively on its outer boundaries. The detection wave will propagate without too much attenuation with distance depending on the frequency band used, but if a lightning flash is too far away from the network (this distance varies with the stroke amplitude and the network configuration), the stroke may no longer be detected.

2.3.4 Aircraft-based and space-based remote-sensing

Many long-distance aircraft are fitted with automatic recording systems that report temperature and wind, and in some cases humidity, regularly while en route. Some aircraft record and report frequent observations during takeoff and descent to significantly augment the standard radiosonde data, at least throughout the troposphere. Such data are assimilated into operational meteorological analysis systems and, through programs of reanalysis, ultimately contribute substantially to the broader climate record.

Aircraft meteorological data-relay systems operate on aircraft that are equipped with navigation and other sensing systems. There are sensors for measuring air speed, air temperature and air pressure. Other data relating to aircraft position, acceleration and orientation are obtained from the aircraft navigation system. The aircraft also carry airborne computers for the flight management and navigation systems by which navigation and meteorological data are computed continuously and are made available to the aircrew. The data are automatically fed to the aircraft communication system for transmission to the ground, or alternatively, a dedicated processing package can be used on the aircraft to access raw data from the aircraft systems and derive the meteorological variables independently. Normally, messages transmitted to ground stations contain horizontal wind speed and direction, air temperature, altitude (related to a reference pressure level), a measure of turbulence, time of observation, phase of flight, and the aircraft position. The data are used by aviation controllers to ensure flight safety and by weather forecasters.

There are potentially a large number of error sources contributing to aircraft measurement uncertainty. An uncertainty of about 5 to 10 per cent in the calculation process can be expected. A further complication arises over the choices of sampling interval and averaging time. Examination of typical time series of vertical acceleration data often indicates a high variability of statistical properties over short distances. Variation of air speed for a single aircraft and between different aircraft types alters the sampling distances and varies the wavelengths filtered. While not as precise and accurate as most ground observing systems, aircraft data can provide useful supplemental information to meteorological databases.

Satellite data add valuable information to climate databases due to their wide geographical coverage, especially over areas with sparse or completely missing in situ data. Satellites are very useful for monitoring phenomena such as polar sea-ice extent, snow cover, glacial activity, sea level changes, vegetation cover and moisture content, and tropical cyclone activity. They also help improve synoptic analyses, an important component of synoptic climatology.

Sensing techniques make use of the emission, absorption and scattering properties of the atmosphere and the surface. The physical equations for radiative transfer provide information about the radiative properties of the atmosphere and the Earth's surface and, through inversion of the radiative transfer equation, geophysical properties such as temperature and moisture profiles, surface skin temperature, and cloud properties.

The figures and specifications of satellite platforms and sensors are in the *GCOS Guide to Satellite Instruments for Climate* (WMO/TD-No. 685). The elements, accuracy and spatial and temporal resolution of data measured by satellites are in the *Preliminary Statement of Guidance Regarding How Well Satellite Capabilities Meet WMO User Requirements in Several Application Areas* (WMO/TD-No. 913). The histories and future plans of satellite platforms and sensors are in the *GCOS Plan for Space-based Observations* (Version 1.0, WMO/TD-No. 684) and *Systematic Observation Requirements for Satellite-based Products for Climate* (WMO/TD-No. 1338). The technology of remote-sensing is progressing rapidly and the operational plans of platforms and sensors may be changed occasionally. Therefore, the latest documents should be referred to in using remote-sensing data. Reports published by the Committee on Earth Observation Satellites, available on the Internet, are helpful in seeking the latest information about satellites.

As in the case of surface-based remote-sensing, satellite and other airborne sensors can be classified into two groups: passive and active. Passive sensors include imagers, radiometers and sounders. They measure radiation emitted by the atmosphere or the Earth's surface. Their measurements are converted into geophysical information such as vertical profiles of water vapour, temperature and ozone; cloud information; surface ocean and land temperatures; and ocean and land colour. The wavelength at which a sensor operates influences the resulting information, with different wavelengths having different advantages and disadvantages.

Active sensors include radar, scatterometers and lidar. They measure the backscattered signal from an observing target when it is illuminated by a radiation source emitted from the platform. Their advantage is that the accurate range of an observing target can be obtained by measuring a time lag between an emission and its return, while the use of a tightly focused and directional beam can provide positional information. Backscattered signals can be converted into wind speed and direction, ocean dynamic height and wave spectrum, ocean wind stress curl and geostrophic flow, cloud properties, precipitation intensity, and inventories of glacial extent.

Sometimes, information can be derived from satellite data that was not originally intended for climatological purposes. For example, the Global Positioning System uses a network of dozens of satellites to assist in navigation. But by measuring the propagation delay in Global Positioning System signals, it is possible to estimate atmospheric water vapour content.

Two complementary orbits have been used for operational environmental satellites: geostationary and polar-orbiting. In geostationary orbit, about 36 000 km above the Equator, a satellite will orbit the Earth once every 24 hours. The satellite therefore remains stationary relative to the Earth and can thus provide a constant monitoring capability and the ability to track atmospheric features and infer winds. Polar-orbiting satellites are typically about 800 km above the surface, moving almost north–south relative to the Earth. Most of the globe is observed by the suite of instruments on the operational polar-orbiting satellites twice per day about 12 hours apart. The inconvenience of only two passes each day is balanced by the higher spatial resolution and greater range of instruments carried, and the ability to see high latitudes that are poorly captured from geostationary orbit.

As is the case with the treatment of in situ data, the climate community must recognize the need to provide scientific data stewardship of both the "raw" remotely sensed measurements and the data processed for climate purposes. In addition to the ten principles listed in section 2.1, satellite systems should also adhere to the following principles:

1. Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained.
2. Overlapping observations should be ensured for a period sufficient to determine inter-satellite biases.
3. Continuity of satellite measurements (elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.
4. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured.
5. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.
6. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.
7. Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.

8. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on decommissioned satellites.
9. Complementary in situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.
10. Random errors and time-dependent biases in satellite observations and derived products should be identified.

2.3.5 Calibration of instruments

It is of paramount importance, for determining the spatial and temporal variations of climate, that the relative accuracy of measurement of individual sensors in use in a network at one time be measured and periodically checked, and similarly, that the performance of replacement sensors and systems can be related to that of those replaced. The *Manual on the Global Observing System* states that all stations shall be equipped with properly calibrated instruments. Details on calibration techniques can be found in the *Guide to Meteorological Instruments and Methods of Observation*. For climatology it is not generally sufficient to rely upon manufacturers' calibrations and it is wrong to assume that a calibration will not drift or otherwise change with time.

Comparisons of instrumental or system measurements should be made with portable standard instruments when replacement instruments are issued to a station and at each regular inspection of the station (see section 2.6.6). Travelling standards should be checked against national reference standards before and after each period of travel, and they should be robust in transport and withstand calibration changes. Records of instrument changes and calibration drifts must be kept and made available as metadata, as they are essential to the assessment of true climate variations (see section 2.6.9).

During inspections of remotely sited AWSs, observations should be taken using the travelling standards for later comparison with the recorded AWS output as received at the data reception point. Some NMHSs have automated fault or instrumental drift detection procedures in place, which compare individual measurements with those from a network and with values analysed from numerically fitted fields. These automated procedures are useful for detecting not only drift, but also anomalous step changes.

Some NMHSs operate their own calibration facilities, or use accredited calibration companies. Regional calibration facilities within WMO are responsible for keeping and calibrating standards, certifying an instrument's conformity to standards, organizing instrument evaluations, and providing advice about instrumental performance.

The *GCOS Plan for Space-Based Observations* details calibration, inter-calibrational overlapping records and metadata requirements for space-based remote sensors. The plan of the Global Space-Based Inter-Calibration System is to compare the radiances simultaneously measured by satellite pairs at the crossing points of their ground track, in particular where a polar orbiter and a geostationary satellite cross paths. This inter-calibration will give a globally consistent calibration on an operational basis.

Weather radar calibration requires the measurement of system characteristics such as transmitted frequency and power, antenna gain, beam widths, receiver output and filter losses. Performance monitoring ensures that other system characteristics, such as antenna orientation, side lobes, pulse duration and pulse shape, beam patterns and receiver noise levels, are within acceptable limits.

Drifts of lightning detection sensors or central lightning processor parameters are problems that should be detected with regular data analyses (for example, cross-checking of sensor behaviour and analysis of stroke parameters). Comparison should also be made with other observations of lightning activity, such as manual observations of "thunder heard" or "lightning seen", or observations of cumulonimbus clouds. As with weather radars, monitoring and calibration of the characteristics of the system should be a routine process.

2.4 THE SITING OF CLIMATOLOGICAL STATIONS

The precise exposure requirements for specific instruments used at climatological stations, aimed at optimizing the accuracy of the instrumental measurements, are discussed in Part III of the *Manual on the Global Observing System*, the *Guide to Meteorological Instruments and Methods of Observation*, and *Representativeness, Data Gaps and Uncertainties in Climate Observations* (WMO/TD-No. 977). These publications are a necessary companion to this Guide.

The representativeness and homogeneity of climatological records are closely related to the location of the observing site. A station sited on or near a steep slope, ridge, cliff, hollow, building, wall or other obstruction is likely to provide data that are more representative of the site alone and not of a wider area. A station that is or will be affected by the growth of vegetation, including even limited tree growth near the sensor, growth of tall crops or woodland nearby, erection of buildings on adjacent land, or increases (or decreases) in road or air traffic (including those due to changes in the use of runways or taxiways) will provide neither broadly representative nor homogeneous data.

A climatological observing station should be sited at a location that permits the correct exposure of the instrumentation and allows for the widest possible view of the sky and surrounding country if visual data are required. Ordinary and principal climatological stations should be sited on a level piece of ground covered with short grass; the site should be well away from trees, buildings, walls and steep slopes and should not be in a hollow. A plot size of about 9 metres by 6 metres is sufficient for outdoor temperature and humidity-sensing instruments, and an area of 2 metres by 2 metres of bare ground within the plot is ideal for observations of the state of the ground and soil temperature measurements. A slightly larger plot (10 metres by 7 metres) is preferable if the site is to enclose a raingauge in addition to the other sensors.

A rule used by many NMHSs is that the distance of any obstruction, including fencing, from the raingauge must be more than twice, and preferably four times, the height of the object above the gauge. In general terms, anemometers require exposure at a distance from any obstruction of at least 10, and preferably 20, times the height of the obstruction. The different exposure requirements of various instruments may give rise to a split site, where some elements are observed from one point while others are observed nearby, with data from all the elements combined under the one site identifier.

Prevention of unauthorized entry is a very important consideration, and may require enclosure by a fence. It is important that such security measures do not themselves compromise the site exposure. Automatic stations will normally need a high level of security to protect against animal and unauthorized human entry; they also require the availability of suitable and robust power supplies, and may possibly need additional protection against floods, leaf debris and blowing sand.

Ordinary and principal climatological stations should be located at such sites and should be subject to such administrative conditions that will allow the continued operation of the station, with the exposure remaining unchanged, for a decade or more. For stations used or established to determine long-term climate change, such as reference climatological stations and other baseline stations in the GCOS network, constancy of exposure and operation is required over many decades.

Observing sites and instruments should be properly maintained so that the quality of observations does not deteriorate significantly between station inspections. Routine, preventive maintenance schedules include regular "housekeeping" at observing sites (for example, grass cutting and cleaning of exposed instrument surfaces, including thermometer screens) and manufacturers' recommended checks on instruments. Routine quality control checks carried out at the station or at a central point should be designed to detect equipment faults at the earliest possible stage. Depending on the nature of the fault and the type of station, the equipment should be replaced or repaired according to agreed priorities and time intervals. It is especially important that a log be kept of instrument faults and remedial action taken where data are used for climatological purposes. This log will be the principal basis for the site's metadata and hence becomes an integral part of the climate record. Detailed information on site maintenance can be found in the *Guide to Meteorological Instruments and Methods of Observation* (sixth edition).

Additional constraints on siting apply to GAW stations established to provide data on atmospheric chemical composition, as discussed in Chapter B2 of the *Technical Regulations*. These constraints include the need for no significant changes in land-use practices within 50 kilometres of the site, and freedom from the effects of local and area pollution from, for example, major population centres, industrial and extensive farming activities, highways, volcanic activity and forest fires. Both global and regional GAW stations should be within 70 kilometres of an upper-air synoptic station.

The nature of urban environments makes it impossible to conform to the standard guidance for site selection and exposure of instrumentation required for establishing a homogeneous record that can be used to describe the larger-scale climate. Nonetheless, urban sites do have value in their own right for monitoring real changes in local climate that might be significant for a wide range of applications. Guidelines for the selection of urban sites, installation of equipment and interpretation of observations are given in *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites* (WMO/TD-No. 1250). Fundamental to the guidance is the need to clearly understand the purpose of making the observations and to obtain measurements that are representative of the urban environment. In many urban situations it will be possible to conform to standard practices, but flexibility in siting urban stations and in instrumentation may be necessary. These characteristics further heighten the importance of maintaining metadata that accurately describe the setting of the station and instrumentation.

2.5 THE DESIGN OF CLIMATOLOGICAL NETWORKS

A network of stations is several stations of the same type (such as a set of precipitation stations, radiation measuring stations or climatological stations), which are administered as a group. Each network should be optimized to provide the data and perform as required at an acceptable cost. Most optimizing methods rely on data from a pre-existing network, available over a long enough period to correctly document the properties of the meteorological fields. They are based on both temporal and spatial statistical analyses of time series. It is difficult to assess a priori how long the data series must be because the number of years necessary to capture variability and change characteristics may vary with the climatic element. It has been common practice to assume that at least ten years of daily observations are necessary to produce the relevant base statistical parameters for most elements, and at least thirty years for precipitation. Observed global and regional climatic trends and variability in many areas of the globe over the past century suggest, however, that such short periods of record may not be particularly representative of similar periods to follow.

The identification of redundant stations allows network managers to explore options for optimizing the network, for example, by eliminating the redundant stations to reduce costs or by using the resources to establish stations at locations where observations are needed for a more effective realization of the network objectives. Network managers should take advantage of the relatively high spatial coherence that exists for some meteorological fields, such as temperature. Techniques used to evaluate the level of redundancy of information include the use of the spatial variance–covariance matrix of the available stations, multiple linear regression, canonical analysis and observation system simulation experiments (see Chapter 5).

The density and distribution of climatological stations to be established in a land network within a given area depend on the meteorological elements to be observed, the topography and land use in the area, and the requirements for information about the specific climatic elements concerned. The rate of variation of climatic elements across an area will differ from element to element. A sparse network is sufficient for the study of surface pressure, a fairly dense network for the study of maximum and minimum temperature, and very dense networks for examining the climatology of precipitation, wind, frost and fog, especially in regions of significant topography.

Stations should be located to give representative climatic characteristics that are consistent with all types of terrain, such as plains, mountains, plateaus, coasts and islands, and surface cover such as forests, urban areas, farming areas and deserts within the area concerned. Station density should be dependent upon the purposes for making the observations and the uses of the data. For data used in sectoral applications within an area, there may be a need for a greater density of stations where activities or health are sensitive to climate, and a lesser density in locations with fewer people. When planning a land network, compromises often have to be made between the ideal density of stations and the resources available to install, operate and administer the stations.

The distribution of stations in the Regional Basic Synoptic Network from which monthly surface climatological data are collected should be such that every 250 000 square kilometres are represented by at least one station and by up to 10 evenly spread stations if possible. The distribution of stations from which monthly upper-air climatological data are collected should be such that every 1 000 000 square kilometres are represented by at least one station. Networks of principal climatological stations should have a maximum average separation of 500 kilometres, and for climate purposes upper-air stations should have a maximum average separation of 1 000 kilometres.

Each Member should establish and maintain at least one reference climatological station for determining climate trends. Such stations need to provide more than 30 years of homogeneous records and should be situated where anthropogenic environmental changes have been and are expected to remain at a minimum. Information on agrometeorological and hydrometeorological networks and sites can be found in the *Guide to Agricultural Meteorological Practices* and the *Guide to Hydrological Practices*, respectively, and additional guidance is provided in the *Manual on the Global Observing System*.

A nation's environmental information activities are often conducted by many parties whose contributions are complementary and at times overlapping. A nation benefits from environmental information collected and disseminated by both governmental agencies and non-governmental entities (including private companies, utilities and universities). Formal partnerships between the NMHS and these other parties are highly desirable for optimizing resources. Because data and information obtained from non-NMHS sources are not usually under the control of the NMHS, metadata are critical for the most effective use of the information. As for stations maintained by the NMHS, metadata on instrumentation, siting, processing procedures, methodologies and anything else that would enhance the use of the information should be obtained and documented. The metadata should also be maintained and accessible. To promote the open and unrestricted exchange of environmental information, including weather observations, it is highly desirable that the NMHS be granted full use of all the climate data and information obtained from partnerships, without restriction, as if they were its own data. An appropriate contract or "memorandum of understanding" between the NMHS and other organizations may need to be drafted and signed at the senior management level.

In addition to data from standard and private networks of climatological stations, there are sometimes observational data from networks of temporary stations established in connection with research and study programmes, as well as measurements made in mobile transects and profiles. The NMHS should endeavour to obtain these data and associated metadata. Although the data may not be ideal for typical archiving, they will often prove to be quite valuable as supplementary information, for example, for investigations of specific extreme events. When these observations are collected from data-poor areas, they are highly valuable.

2.6 STATION AND NETWORK OPERATIONS

Guidance material in this section concerns mainly observations at ordinary climatological stations (at which observations are usually made twice a day, but in some cases only once a day, and include readings of extreme temperature and precipitation). Guidance is also given regarding precipitation stations (stations at which one or more observations of precipitation only are made each day). Regulatory and guidance material for principal climatological stations (which usually also function as synoptic observing stations) and other types of climatological stations is found in the *Manual on the Global Observing System*.

2.6.1 Times of observations

Observations at ordinary climatological and precipitation stations should be made at least once (and preferably twice) each day at fixed hours that remain unchanged throughout the year. At principal climatological stations, observations must be made at least three times daily in addition to an hourly tabulation from autographic records, but non-autographic observations are usually taken hourly. From a practical viewpoint, times of observation should fit the observers' working day, usually one morning observation and one afternoon or evening observation. If daylight saving time is used for a part of the year, the observations should continue to be made according to the fixed local time; the dates when daylight saving time commences and ends must be recorded. If at all possible, the times of observation should coincide with either the main or intermediate standard times for synoptic observations (0000, 0300, 0600 Coordinated Universal Time (UTC), and so on). If conditions dictate that only one observation a day is possible, this observation should be taken between 0700 and 0900 local standard time.

In selecting the schedule for climatological observations, times at or near the normal occurrence of daily minimum and maximum temperatures should be avoided. Precipitation amounts and maximum temperatures noted at an early morning observation should be credited to the previous calendar day, while maximum temperatures recorded at an afternoon or evening observation should be credited to the day on which they are observed.

Times of observation are often different among networks. Summary observations such as temperature extremes or total precipitation made for one 24-hour period (such as from 0800 on one day to 0800 on the next day) are not equivalent to those made for a different 24-hour period (such as from 0000 to 2400).

If changes are made to the times of observations across a network, simultaneous observations should be carried out at a basic network of representative stations for a period covering the major climatic seasons in the area at the old and new times of observation. These simultaneous observations should be evaluated to determine if any biases result from the changed observation times. The station identifiers for the old and new times of observations must be unique for reporting and archiving.

2.6.2 Logging and reporting of observations

Immediately after taking an observation at a manual station, the observer must enter the data into a logbook, journal or register that is kept at the station for this purpose. Alternatively, the observation may be entered or transcribed immediately into a computer or transmission terminal and a database. Legislation or legal entities (such as courts of law) in some countries may require that a paper record or a printout of the original entry be retained for use as evidence in legal cases, or there may be difficulties associated with the acceptance of database-generated information. The observer must ensure that a complete and accurate record has been made of the observation. At a specified frequency (ranging from immediately to once a month), depending on the requirements of the NMHS, data must be transferred from the station record (including a computer database) to a specific report form for transmittal, either by mail or electronically, to a central office.

Climatological station personnel must ensure that there is a correct copy of the pertinent information in the report form. In the case of paper records, the need for good, clear handwriting and "clean" journals and report forms should be emphasized. It is quite common for more information, perhaps pertaining to unusual weather phenomena and occurrences, to be entered in the local record than is required by the central office. The on-station record must be retained and readily accessible so that the station personnel can respond to any inquiries made by the central office regarding possible errors or omissions in the report form. Some services request observers to send logbooks to the national climate centre for permanent archiving.

Some national climate centres require that station personnel calculate and insert monthly totals and means of precipitation and temperature so that the data may be more easily checked at the section or central office. In addition, either the climate centre or observer should encode data for the CLIMAT messages, as described in the *Handbook on CLIMAT and CLIMAT TEMP Reporting* (WMO/TD-No. 1188), if appropriate. Software to encode the data has been developed by WMO. The observer should note in the station logbook and on the report forms the nature and times of occurrence of any damage to or failure of instruments, maintenance activities, and any change in equipment or exposure of the station, since such events might significantly affect the observed data and thus the climatological record. Where appropriate, instructions should be provided for transmitting observations electronically. If mail is the method of transmission, instructions for mailing should be provided to the station, as well as pre-addressed, stamped envelopes for sending the report forms to the central climate office.

2.6.3 On-site quality control

General guidance on on-site quality control of observations and reports is given in Part V of the *Manual on the Global Observing System* and detailed guidance is given in Part VI of the *Guide to the Global Observing System*. The procedures described below should be followed when there is an observer or other competent personnel on site.

Checks should be made for gross errors, against existing extremes, for internal consistency in a sequence of observations, for consistency in the sequence of dates and times of observation, for consistency with other elements and calculations, and of the accuracy of copies and of encoded reports. These checks can be done either manually or by using automated procedures. If there are errors, remedial action such as correcting the original data and the report should be taken before transmission. Errors detected after transmission should also be corrected, with the corrected report then transmitted. Checks should also be made, and any necessary amendments recorded and corrections transmitted, if a query about data quality is received from an outside source. Records of an original observation containing an error should include a notation or flag indicating that the original value is erroneous or suspect. On-site quality control must also include the maintenance of the standard exposure of the sensors, of the site, and of the proper procedures for reading the instrumentation and checking autographic charts.

Any patterns of measurement error should be analysed, for example, to see if they relate to instrument drift or malfunction, and summaries of data or report deficiencies should be prepared monthly or annually.

2.6.4 Overall responsibilities of observers

In general, the NMHS of each Member will specify the responsibilities of observers. The responsibilities should include the competent execution of the following:

(a) Making climatological observations to the required accuracy with the aid of appropriate instruments;
(b) Maintaining instruments and observing sites in good order;
(c) Performing appropriate quality checks;
(d) Coding and dispatching observations in the absence of automatic coding and communication systems;
(e) Maintaining in situ recording devices and electronic data loggers, including the changing of charts when provided;
(f) Making or collating weekly or monthly records of climatological data, especially when automatic systems are unavailable or inadequate;
(g) Providing supplementary or backup observations when automatic equipment does not observe all required elements, or when the equipment is out of service.

2.6.5 Observer training

Observers should be trained or certified by an appropriate meteorological service to establish their competence to make observations to the required standards. They should have the ability to interpret instructions for the use of instrumental and manual techniques that apply to their own particular observing systems. Guidance on the instrumental training requirements for observers is given in Chapter 4, Part III, of the *Guide to Meteorological Instruments and Methods of Observation* (sixth edition).

Often, observers are either volunteers or part-time employees, or take observations as part of their other duties. They may have little or no training in climatology or in taking scientific observations, and thus will depend on a good set of instructions. Instructional booklets for ordinary climatological and precipitation station observers should be carefully prepared and made available to observers at all stations. The instructions should be unambiguous and simply outline the tasks involved, being limited to that information which the observer actually needs to know in order to perform the tasks satisfactorily. Illustrations, graphs and examples could be used to stimulate the interest of the observer and facilitate the understanding of the tasks to be undertaken every day. Sample copies of correctly completed pages of a logbook or journal and of a report form should be included in the instruction material available to an observer. Ideally, a climate centre representative should visit the site, install the station and instruct the observer.

An observer must gain familiarity with the instruments, and should be aware in particular of the sources of possible error in reading them. The instructions should include a descriptive text with simple illustrations showing the functioning of each instrument. Detailed instructions regarding methods to be used for day-to-day care, simple instrument maintenance and calibration checks should be given. If correction or calibration tables are necessary for particular observing and recording tasks, the observer should be made thoroughly familiar with their use. Instructions should also cover the operation of computer terminals used for data entry and transmissions.

Instructions must cover visual as well as instrumental observations. Visual observations are particularly prone to subjective error and their accuracy depends on the skill and experience acquired by the observer. Since it is very difficult to check the accuracy or validity of an individual visual observation, as much guidance as possible should be given so that correct observations can be made.

To complement the instruction material, personnel responsible for station management in the climatological service should contact observing stations regarding any recurring observing errors or misinterpretation of instructions. Regular inspection visits provide the opportunity to address siting or instrument problems and to further the training of the observer.

Some climate centres arrange special training courses for groups of volunteer observers. Such courses are especially useful in creating a uniform high standard of observations, as a result of the training given and the availability of time to address a wider range of problems than may be raised by a single observer at an on-site visit.

2.6.6 Station inspections

Principal climatological stations should be inspected once a year. Ordinary climatological stations and precipitation stations should be inspected at least once every three years, or more frequently if necessary, to ensure the maintenance and correct functioning of the instruments and thus a high standard of observations. Automated stations should be inspected at least every six months. Special arrangements for the inspection of ship-based instruments are described in the *Guide to Meteorological Instruments and Methods of Observation* (fifth edition).

Before each inspection, the inspector should determine to the fullest extent possible the quality of information and data received from each station on the itinerary. At each inspection, it should be confirmed that:

(a) The observer's training is up to date;
(b) The observer remains competent;
(c) The siting and exposure of each instrument are known, recorded and still the best obtainable;
(d) The instruments are of an approved pattern, in good order and verified against relevant standards;
(e) There is uniformity in the method of observation and procedures for calculating derived quantities from the observations;
(f) The station logbook is well maintained;
(g) The required report forms are sent punctually and regularly to the climate centre.

Inspection reports should include sketches, photographs or diagrams of the immediate observing site, indicating physical objects that might influence the observed values of the climatic elements. The reports must also list any changes in instruments and any differences in readings between instruments and travelling standards, changes in exposure and site characteristics from the previous visit, and dates of appropriate comparisons and changes. Inspectors must also be prepared to advise observers on any problems arising in the transmission of data, including automated data-entry and transmission systems. Inspection reports are an important source of metadata for use in determining the homogeneity of a climate record and should be retained indefinitely, or the information therein should be transferred to a computerized database (see section 3.1).

2.6.7 Preserving data homogeneity

Unlike observations taken solely to support the preparations of forecasts and warnings, the availability of a continuous, uninterrupted climate record is the basis for many important studies involving a diverse array of climatological communities. Homogeneous climate datasets are of the utmost importance for meeting the needs of climate research, applications and user services.

Changes to a site, or its relocation, are major causes of inhomogeneities. The 10 principles of climate monitoring (see section 2.1) should be followed when relocation of a climatological station is necessary, when one station is to be replaced by another nearby, or when instrument systems change. Where feasible and practical, both the old and new observing stations and instrumentation should be operated for an overlapping period of at least one year, and preferably two or more years, to determine the effects of changed instruments or sites on the climatological data. The old and new sites should have unique station identifiers for both reporting and archiving. Specific guidance is given in the *Guidelines for Managing Changes in Climate Observation Programmes* (WMO/TD-No. 1378).

2.6.8 Report monitoring at collection centres

Data collection or archiving centres need to check the availability and quality of information at the time when it is due from observers, and they should have additional responsibilities concerning data from automated measuring or transmission systems. Since such centres normally process large volumes of information, computerized checking systems save much effort.

The first task is to check that the expected observations have arrived and that they have been submitted at the correct time. If the expected observations are not available, the observer should be contacted to determine the reason. In the case of automated systems, “caretakers” must provide information on visible signs of failure as soon as possible to the authority responsible for maintenance of the observing and transmission systems.

Checks on the quality of data received from manned or automated sites should include those described in section 2.6.3. Other checks are useful and can be readily made in computerized monitoring. They include checks against data from neighbouring stations, a variety of statistical checks, checks against preset limits, temporal consistency and inter-element consistency. Chapters 4 and 5 describe some of the techniques for checking data.

Monitoring shortly after observations are taken, either on site or remotely, is of limited value unless action is initiated to quickly remedy problems. Information must be fed back to the observers, caretakers, inspectors, and instrument or system maintainers or manufacturers, and then information on the actions taken must be fed back again to the monitoring centre. Copies of all reports must be kept.

2.6.9 Station documentation and metadata

The efficient use of climatological data requires the climatological or other responsible section to maintain complete documentation of all stations in the country for all networks and observing platforms. These metadata are essential and should be kept current and be easily obtainable in the form of station catalogues, data inventories and climate data files. The World Meteorological Organization is currently developing metadata standards based on International Organization for Standardization (ISO) metadata standards, especially the ISO 19100 series. The guidance given below should be followed unless it is superseded by published climate metadata standards.

Basic station metadata should include station name and station index number (or numbers); geographical coordinates; elevation above mean sea level; administrator or owner; types of soil, physical constants and profile of soil; types of vegetation and condition; local topography description; description of surrounding land use; photographs and diagrams of the instrumentation, site and surrounding area; type of AWS, manufacturer, model and serial number; observing programme of the station (elements measured, reference time, times at which observations and measurements are made and reported, and the datum level to which atmospheric pressure data of the station refer); and contact information, such as name and mailing address, electronic mail address, and telephone numbers.

Documentation should contain a complete history of the station, giving the dates and details of all changes. It should cover the establishment of the station, commencement of observations, any interruptions to operation, and eventually the station’s closure. Comments from inspection visits (see 2.6.6) are also important, especially comments about the site, exposure, quality of observations and station operations.

Instrument metadata should include sensor type, manufacturer, model and serial number; principle of operation; method of measurement and observation; type of detection system; performance characteristics; unit of measurement and measuring range; resolution, accuracy (uncertainty), time constant, time resolution and output averaging time; siting and exposure (location, shielding and height above or below ground); date of installation; data acquisition (sampling interval and averaging interval and type); correction procedures; calibration data and time of calibration; preventive and corrective maintenance (recommended and scheduled maintenance and calibration procedures, including frequency, and a description of procedures); and results of comparison with travelling standards.

For each individual meteorological element, metadata related to procedures for processing observations should include the measuring and observing programme (time of observations, reporting frequency and data output); the data processing method, procedure and algorithm; formulae for calculations; the mode of observation and measurement; the processing interval; the reported resolution; the input source (instrument and element); and constants and parameter values.

Data-handling metadata should include quality control procedures and algorithms, definitions of quality control flags, constants and parameter values, and processing and storage procedures. The transmission-related metadata of interest are method of transmission, data format, transmission time and transmission frequency.

Upper-air stations have metadata requirements that are similar to those of surface stations. In addition, they must maintain metadata on each of the expendable instruments used (such as radiosondes).

2.7 REFERENCES AND ADDITIONAL READING

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