PART I

MEASUREMENT OF METEOROLOGICAL VARIABLES

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CHAPTER 1

GENERAL

1.1 METEOROLOGICAL OBSERVATIONS

1.1.1 General

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

There are many other sources of additional advice, and users should refer to the references placed at the end of each chapter for a bibliography of theory and practice relating to instruments and methods of observation. The references also contain national practices, national and international standards, and specific literature. They also include reports published by the World Meteorological Organization (WMO) for the Commission for Instruments and Methods of Observation (CIMO) on technical conferences, instrumentation, and international comparisons of instruments. Many other Manuals and Guides issued by WMO refer to particular applications of meteorological observations (see especially those relating to the Global Observing System (WMO, 2010*b*; 2010*d*), aeronautical meteorology (WMO, 1990), hydrology (WMO, 2008), agricultural meteorology (WMO, 2010*a*) and climatology (WMO, 1983).

Quality assurance and maintenance are of special interest for instrument measurements. Throughout this Guide many recommendations are made in order to meet the stated performance requirements. Particularly, Part III of this Guide is dedicated to quality assurance and management of observing systems. It is recognized that quality management and training of instrument specialists is of utmost importance. Therefore, on the recommendation of CIMO,[1] several regional associations of WMO have set up Regional Instrument Centres (RICs) to maintain standards and provide advice regarding meteorological measurements. Their terms of reference and locations are given in Annex 1.A. In addition, on the recommendation of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology[2] (WMO, 2009) a network of Regional Marine Instrument Centres has been set up to provide for similar functions regarding marine meteorology and other related oceanographic measurements. Their terms of reference and locations are given in Part II, Chapter 4, Annex 4.A.

The definitions and standards stated in this Guide (see section 1.5.1) will always conform to internationally adopted standards. Basic documents to be referred to are the *International Meteorological Vocabulary* (WMO, 1992) and the *International Vocabulary of Basic and General Terms in Metrology* (ISO, 2008).

1.1.2 Representativeness

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

In particular, applications have their own preferred timescales and space scales for averaging, station density and resolution of phenomena — small for agricultural meteorology, large for global long-range forecasting. Forecasting scales are closely related to the timescales of the phenomena; thus, shorter-range weather forecasts require more frequent observations from a denser network over a limited area in order to detect any small-scale phenomena and their quick development. Using

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

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

various sources (WMO, 2001; 2010*d*; Orlanski, 1975), horizontal meteorological scales may be classified as follows, with a factor two uncertainty:

(a) Microscale (less than 100 m) for agricultural meteorology, for example, evaporation;
(b) Toposcale or local scale (100–3 km), for example, air pollution, tornadoes;
(c) Mesoscale (3–100 km), for example, thunderstorms, sea and mountain breezes;
(d) Large scale (100–3 000 km), for example, fronts, various cyclones, cloud clusters;
(e) Planetary scale (larger than 3 000 km), for example, long upper tropospheric waves.

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

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

Annex 1.B discusses site representativeness in further detail and provides guidelines on the classification of surface observing sites on land to indicate their representativeness for the measurement of different variables.

1.1.3 Metadata

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

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

1.2 METEOROLOGICAL OBSERVING SYSTEMS

The requirements for observational data may be met using in situ measurements or remote-sensing (including space-borne) systems, according to the ability of the various sensing systems to measure the elements needed. WMO (2010*d*) describes the requirements in terms of global, regional and national scales and according to the application area. The Global Observing System, designed to meet these requirements, is composed of the surface-based subsystem and the space-based subsystem. The surface-based subsystem comprises a wide variety of types of stations according to the particular application (for example, surface synoptic station, upper-air station, climatological station, and so on). The space-based subsystem comprises a number of spacecraft with on-board sounding missions and the associated ground segment for command, control and data reception. The succeeding paragraphs and chapters in this Guide deal with the surface-based system and, to a lesser extent, with the space-based subsystem. To derive certain meteorological observations by automated systems, for example, present weather, a so-called "multi-sensor" approach is necessary, where an algorithm is applied to compute the result from the outputs of several sensors.

1.3 GENERAL REQUIREMENTS OF A METEOROLOGICAL STATION

The requirements for elements to be observed according to the type of station and observing network are detailed in WMO (2010*d*). In this section, the observational requirements of a typical climatological station or a surface synoptic network station are considered.

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

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

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

Some meteorological stations take upper-air measurements (Part I, Chapters 12 and 13), measurements of soil moisture (Part I, Chapter 11), ozone (Part I, Chapter 16) and atmospheric composition (Part I, Chapter 17), and some make use of special instrument systems as described in Part II of this Guide.

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

1.3.1 Automatic weather stations

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

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

1.3.2 Observers

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

(a) To make synoptic and/or climatological observations to the required uncertainty and representativeness with the aid of appropriate instruments;
(b) To maintain instruments, metadata documentation and observing sites in good order;
(c) To code and dispatch observations (in the absence of automatic coding and communication systems);
(d) To maintain in situ recording devices, including the changing of charts when provided;
(e) To make or collate weekly and/or monthly records of climatological data where automatic systems are unavailable or inadequate;
(f) To provide supplementary or back-up observations when automatic equipment does not make observations of all required elements, or when it is out of service;
(g) To respond to public and professional enquiries.

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

1.3.3 Siting and exposure

1.3.3.1 Site selection

Meteorological observing stations are designed so that representative measurements (or observations) can be taken according to the type of station involved. Thus, a station in the synoptic network should make observations to meet

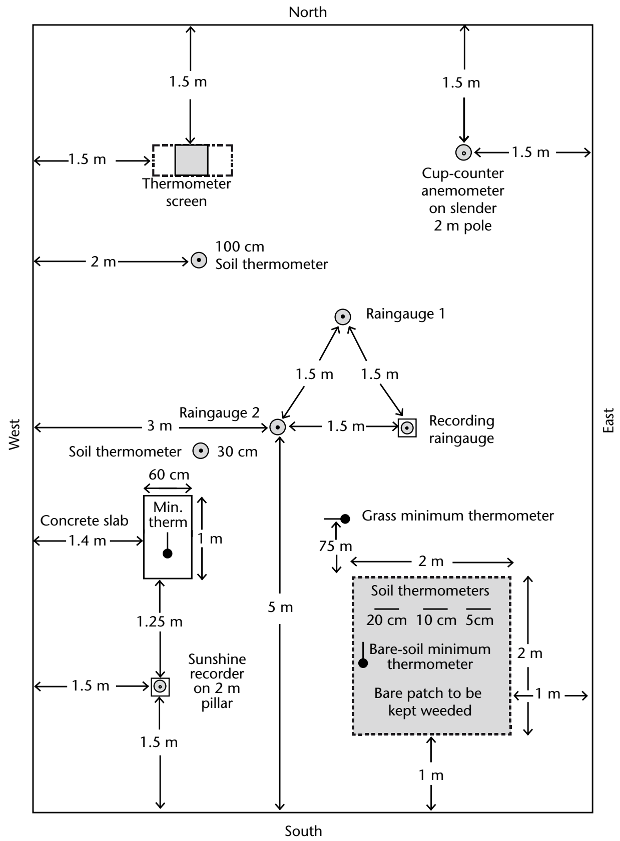


Figure 1.1. Layout of an observing station in the northern hemisphere showing minimum distances between installations

synoptic-scale requirements, whereas an aviation meteorological observing station should make observations that describe the conditions specific to the local (aerodrome) site. Where stations are used for several purposes, for example, aviation, synoptic and climatological purposes, the most stringent requirement will dictate the precise location of an observing site and its associated sensors. A detailed study on siting and exposure is published in WMO (1993).

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

(a) Outdoor instruments should be installed on a level piece of ground, preferably no smaller than 25 m x 25 m where there are many installations, but in cases where there are relatively few installations (as in Figure 1.1) the area may be considerably smaller, for example, 10 m x 7 m (the enclosure). The ground should be covered with short grass or a surface representative of the locality, and surrounded by open fencing or palings to exclude unauthorized persons. Within the enclosure, a bare patch of ground of about 2 m x 2 m is reserved for observations of the state of the ground and of soil temperature at depths of equal to or less than 20 cm (Part I, Chapter 2) (soil temperatures at depths greater than 20 cm can be measured outside this bare patch of ground). An example of the layout of such a station is given in Figure 1.1 (taken from WMO, 2010*b*);

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

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

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

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

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

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

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

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

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

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

1.3.3.2 Coordinates of the station

The position of a station referred to in the World Geodetic System 1984 (WGS-84) Earth Geodetic Model 1996 (EGM96) must be accurately known and recorded.[3] The coordinates of a station are (as required by WMO (2010)):

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

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

(c) The height of the station above mean sea level,[4] namely, the elevation of the station, in metres (up to two decimals).

These coordinates refer to the plot on which the observations are taken and may not be the same as those of the town, village or airfield after which the station is named.

The elevation of the station is defined as the height above mean sea level of the ground on which the raingauge stands or, if there is no raingauge, the ground beneath the thermometer screen. If there is neither raingauge nor screen, it is the average level of terrain in the vicinity of the station. If the station reports pressure, the elevation to which the station pressure relates must be separately specified. It is the datum level to which barometric reports at the station refer; such barometric values being termed "station pressure" and understood to refer to the given level for the purpose of maintaining continuity in the pressure records (WMO, 2010*e*).

If a station is located at an aerodrome, other elevations must be specified (see Part II, Chapter 2, and WMO, 1990). Definitions of measures of height and mean sea level are given in WMO (1992).

1.3.4 Changes of instrumentation and homogeneity

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

It is especially important to minimize the effects of changes of instrument and/or changes in the siting of specific instruments. Although the static characteristics of new instruments might be well understood, when they are deployed operationally they can introduce apparent changes in site climatology. In order to guard against this eventuality, observations from new instruments should be compared over an extended interval (at least one year; see the *Guide to Climatological Practices (*WMO, 1983) before the old measurement system is taken out of service. The same applies when there has been a change of site. Where this procedure is impractical at all sites, it is essential to carry out comparisons at selected representative sites to attempt to deduce changes in measurement data which might be a result of changing technology or enforced site changes.

3 For an explanation of the WGS-84 and recording issues, see ICAO, 2002.

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

1.3.5 Inspection and maintenance

1.3.5.1 Inspection of stations

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

The principal objective of such inspections is to ascertain that:
(a) The siting and exposure of instruments are known, acceptable and adequately documented;
(b) Instruments are of the approved type, in good order, and regularly verified against standards, as necessary;
(c) There is uniformity in the methods of observation and the procedures for calculating derived quantities from the observations;
(d) The observers are competent to carry out their duties;
(e) The metadata information is up to date.

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

1.3.5.2 Maintenance

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

Further information on station inspection and management can be found in WMO (2010*b*).

1.4 GENERAL REQUIREMENTS OF INSTRUMENTS

1.4.1 Desirable characteristics

The most important requirements for meteorological instruments are the following:
(a) Uncertainty, according to the stated requirement for the particular variable;
(b) Reliability and stability;
(c) Convenience of operation, calibration and maintenance;
(d) Simplicity of design which is consistent with requirements;
(e) Durability;
(f) Acceptable cost of instrument, consumables and spare parts.

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

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

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

1.4.2 Recording instruments

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

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

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

1.5 MEASUREMENT STANDARDS AND DEFINITIONS

1.5.1 Definitions of standards of measurement

The term "standard" and other similar terms denote the various instruments, methods and scales used to establish the uncertainty of measurements. A nomenclature for standards of measurement is given in the *International Vocabulary of Basic and General Terms in Metrology,* which was prepared simultaneously by the International Bureau of Weights and Measures, the International Electrotechnical Commission, the International Federation of Clinical Chemistry, the International Organization for Standardization, the International Union of Pure and Applied Chemistry, the International Union of Pure and Applied Physics and the International Organization of Legal Metrology and issued by ISO. The current version is JCGM 200:2008, available at http://www.bipm.org/en/publications/guides/vim.html. Some of the definitions are as follows:

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

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

Example 2: 100 Ω measurement standard resistor with an associated standard measurement uncertainty of 1 µΩ

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

Example 1: The international prototype of the kilogramme

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

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

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

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

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

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

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

Notes:
1. A working measurement standard is usually calibrated with respect to a reference measurement standard.
2. In relation to verification, the terms "check standard" or "control standard" are also sometimes used.

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

Note: The term "transfer device" should be used when the intermediary is not a standard.

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

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

Travelling standard: A standard, sometimes of special construction, intended for transport between different locations.

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

Example: The World Radiometric Reference

Notes:
1. A collective standard is usually intended to provide a single value of a quantity.
2. The value provided by a collective standard is an appropriate mean of the values provided by the individual instruments.

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

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

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

Notes:
1. A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.
2. Calibration should not be confused with adjustment of a measuring system, often mistakenly called "self-calibration", nor with verification of calibration.

1.5.2 Procedures for standardization

In order to control effectively the standardization of meteorological instruments on a national and international scale, a system of national and regional standards has been adopted by WMO. The locations of the regional standards for pressure and radiation are given in Part I, Chapter 3 (Annex 3.B), and Part I, Chapter 7 (Annex 7.C), respectively. In general, regional standards are designated by the regional associations, and national standards by the individual Members. Unless otherwise specified, instruments designated as regional and national standards should be compared by means of travelling standards at least once every five years. It is not essential for the instruments used as travelling standards to possess the uncertainty of primary or secondary standards; they should, however, be sufficiently robust to withstand transportation without changing their calibration.

Similarly, the instruments in operational use at a Service should be periodically compared directly or indirectly with the national standards. Comparisons of instruments within a Service should, as far as possible, be made at the time when the instruments are issued to a station and subsequently during each regular inspection of the station, as recommended in section 1.3.5. Portable standard instruments used by inspectors should be checked against the standard instruments of the Service before and after each tour of inspection.

Comparisons should be carried out between operational instruments of different designs (or principles of operation) to ensure homogeneity of measurements over space and time (see section 1.3.4).

1.5.3 Symbols, units and constants

1.5.3.1 Symbols and units

Instrument measurements produce numerical values. The purpose of these measurements is to obtain physical or meteorological quantities representing the state of the local atmosphere. For meteorological practices, instrument readings represent variables, such as "atmospheric pressure", "air temperature" or "wind speed". A variable with symbol a is usually represented in the form $a = \{a\}\cdot[a]$, where $\{a\}$ stands for the numerical value and [a] stands for the symbol for the unit. General principles concerning quantities, units and symbols are stated by ISO (1993) and IUPAP (1987). The International System of Units (SI) should be used as the system of units for the evaluation of meteorological elements included in reports for international exchange. This system is published and updated by BIPM (1998). Guides for the use of SI are issued by NIST (1995) and ISO (1993). Variables not defined as an international symbol by the International System of Quantities (ISQ), but commonly used in meteorology can be found in the *International Meteorological Tables* (WMO, 1966) and relevant chapters in this Guide.

The following units should be used for meteorological observations:

(a) Atmospheric pressure, *p*, in hectopascals (hPa);[5]
(b) Temperature, *t*, in degrees Celsius (°C) or *T* in kelvin (*K*);

Note: The Celsius and kelvin temperature scales should conform to the actual definition of the International Temperature Scale (for 2004: ITS-90, see BIPM, 1990).

(c) Wind speed, in both surface and upper-air observations, in metres per second ($m\ s^{-1}$);
(d) Wind direction in degrees clockwise from north or on the scale 0–36, where 36 is the wind from the north and 09 the wind from the east (°);
(e) Relative humidity, *U*, in per cent (%);
(f) Precipitation (total amount) in millimetres (mm) or kilograms per m^{-2} ($kg\ m^{-2}$);[6]
(g) Precipitation intensity, R_i, in millimetres per hour ($mm\ h^{-1}$) or kilograms per m^{-2} per second ($kg\ m^{-2}\ s^{-1}$);[7]
(h) Snow water equivalent in kilograms per m^{-2} ($kg\ m^{-2}$);
(i) Evaporation in millimetres (mm);
(j) Visibility in metres (m);
(k) Irradiance in watts per m^2 and radiant exposure in joules per m^2 ($W\ m^{-2}$, $J\ m^{-2}$);
(l) Duration of sunshine in hours (h);
(m) Cloud height in metres (m);
(n) Cloud amount in oktas;
(o) Geopotential, used in upper-air observations, in standard geopotential metres (m′).

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

6 Assuming that 1 mm equals 1 $kg\ m^{-2}$ independent of temperature.

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

Note: Height, level or altitude are presented with respect to a well-defined reference. Typical references are Mean Sea Level (MSL), station altitude or the 1013.2 hPa plane.

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

1.5.3.2 Constants

The following constants have been adopted for meteorological use:

(a) Absolute temperature of the normal ice point T_0 = 273.15 K (t = 0.00°C);
(b) Absolute temperature of the triple point of water T = 273.16 K (t = 0.01°C), by definition of ITS-90;
(c) Standard acceleration of gravity (g_n) = 9.806 65 $m\ s^{-2}$;
(d) Density of mercury at 0°C = $1.359\ 51 \cdot 10^4\ kg\ m^{-3}$.

The values of other constants are given in WMO (1966; 1988).

1.6 UNCERTAINTY OF MEASUREMENTS

1.6.1 Meteorological measurements

1.6.1.1 General

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

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

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

1.6.1.2 Sources and estimates of error

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

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

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

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

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

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

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

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

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

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

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

1.6.2 Definitions of measurements and their errors

The following terminology relating to the accuracy of measurements is taken from ISO (2008), which contains many definitions applicable to the practices of meteorological observations. ISO (1995) gives very useful and detailed practical guidance on the calculation and expression of uncertainty in measurements.

Measurement: A set of operations having the objective of determining the value of a quantity.

Note: The operations may be performed automatically.

Result of a measurement: Value attributed to a measurand (the physical quantity that is being measured), obtained by measurement.

Notes:
1. When a result is given, it should be made clear whether it refers to the indication, the uncorrected result or the corrected result, and whether several values are averaged.
2. A complete statement of the result of a measurement includes information about the uncertainty of the measurement.

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

Value (of a quantity): The magnitude of a particular quantity generally expressed as a unit of measurement multiplied by a number.

Example*:* Length of a rod: 5.34 m.

True value (of a quantity): A value consistent with the definition of a given particular quantity.

<true value> = <measured value> ± <uncertainty>

Notes:
1. This is a value that would be obtained by a perfect measurement.
2. True values are by nature indeterminate.

Accuracy (of measurement): The closeness of the agreement between the result of a measurement and a true value of the measurand.

Notes:
1. "Accuracy" is a qualitative concept.
2. The term "precision" should not be used for "accuracy".

Repeatability (of results of measurements): The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same measurement conditions.

Notes:
1. These conditions are called repeatability conditions.
2. Repeatability conditions include:
   (a) The same measurement procedure;
   (b) The same observer;
   (c) The same measuring instrument used under the same conditions (including weather);
   (d) The same location;
   (e) Repetition over a short period of time.
3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

Reproducibility (of results of measurements): The closeness of the agreement between the results of measurements of the same measurand carried out under changed measurement conditions.

Notes:
1. A valid statement of reproducibility requires specification of the conditions changed.
2. The changed conditions may include:
   (a) The principle of measurement;
   (b) The method of measurement;
   (c) The observer;
   (d) The measuring instrument;
   (e) The reference standard;
   (f) The location;
   (g) The conditions of use (including weather);
   (h) The time.
3. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.
4. Here, results are usually understood to be corrected results.

Measurement uncertainty (uncertainty of measurement, uncertainty): Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Notes:
1. Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.
2. The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability.
3. Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.

4. In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

Error (of measurement): The result of a measurement minus a true value of the measurand.

Note: Since a true value cannot be determined, in practice a conventional true value is used.

Deviation: The value minus its conventional true value.

Random error: The result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

Notes:
1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be taken, it is possible to determine only an estimate of random error.

Systematic error: A mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand.

Notes:
1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.

Correction: The value added algebraically to the uncorrected result of a measurement to compensate for a systematic error.

1.6.3 Characteristics of instruments

Some other properties of instruments which must be understood when considering their uncertainty are taken from ISO (2008).

Sensitivity: The change in the response of a measuring instrument divided by the corresponding change in the stimulus.

Note: Sensitivity may depend on the value of the stimulus.

Discrimination: The ability of a measuring instrument to respond to small changes in the value of the stimulus.

Resolution: A quantitative expression of the ability of an indicating device to distinguish meaningfully between closely adjacent values of the quantity indicated.

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

Stability (of an instrument): The ability of an instrument to maintain its metrological characteristics constant with time.

Drift: The slow variation with time of a metrological characteristic of a measuring instrument.

Response time: The time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits around its final steady value.

The following other definitions are used frequently in meteorology:

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

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

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

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

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

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

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

1.6.4 The measurement uncertainties of a single instrument

ISO (1995) should be used for the expression and calculation of uncertainties. It gives a detailed practical account of definitions and methods of reporting, and a comprehensive description of suitable statistical methods, with many illustrative examples.

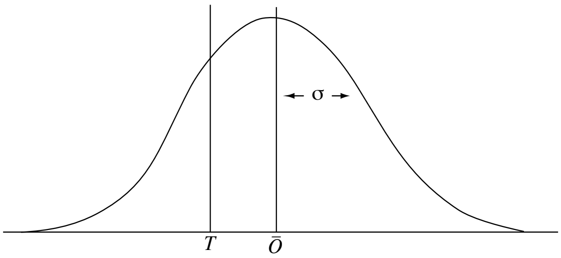


Figure I.2. The distribution of data in an instrument comparison

1.6.4.1 The statistical distributions of observations

To determine the uncertainty of any individual measurement, a statistical approach is to be considered in the first place. For this purpose, the following definitions are stated (ISO, 1995, 2008):
(a) Standard uncertainty;
(b) Expanded uncertainty;
(c) Variance, standard deviation;
(d) Statistical coverage interval.

If n comparisons of an operational instrument are made with the measured variable and all other significant variables held constant, if the best estimate of the true value is established by use of a reference standard, and if the measured variable has a Gaussian distribution,[8] the results may be displayed as in Figure 1.2.

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

In this situation, the following characteristics can be identified:
(a) The systematic error, often termed bias, given by the algebraic difference $\overline{O} - T$. Systematic errors cannot be eliminated but may often be reduced. A correction factor can be applied to compensate for the systematic effect. Typically, appropriate calibrations and adjustments should be performed to eliminate the systematic errors of sensors. Systematic errors due to environmental or siting effects can only be reduced;
(b) The random error, which arises from unpredictable or stochastic temporal and spatial variations. The measure of this random effect can be expressed by the standard deviation σ determined after n measurements, where n should be large enough. In principle, σ is a measure for the uncertainty of $\overline{O}$;
(c) The accuracy of measurement, which is the closeness of the agreement between the result of a measurement and a true value of the measurand. The accuracy of a measuring instrument is the ability to give responses close to a true value. Note that "accuracy" is a qualitative concept;
(d) The uncertainty of measurement, which represents a parameter associated with the result of a measurement, that characterizes the dispersion of the values that could be reasonably attributed to the measurand. The uncertainties associated with the random and systematic effects that give rise to the error can be evaluated to express the uncertainty of measurement.

8 However, note that several meteorological variables do not follow a Gaussian distribution. See section 1.6.4.2.3.

1.6.4.2 Estimating the true value

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

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

1.6.4.2.1 *Estimating the true value – n large*

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

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

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

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

Some values of k are as follows:

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

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

1.6.4.2.2 *Estimating the true value – n small*

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

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

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

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

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1} = \frac{n}{n-1} \cdot \sigma_0^2 \quad (1.6)$$

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

Some values of t are as follows:

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

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

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

1.6.4.2.3 *Estimating the true value – additional remarks*

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

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

1.6.4.3 Expressing the uncertainty

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

$$\langle \textit{expanded uncertainty} \rangle = k \cdot \sigma = 2 \cdot \sigma \qquad (1.7)$$

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

<true value> = *<measured value>* ± *<expanded uncertainty>* = *<measured value>* ±2 σ

1.6.4.4 Measurements of discrete values

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

1.6.5 Accuracy requirements

1.6.5.1 General

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

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

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

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

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

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

1.6.5.2 Required and achievable performance

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

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

The requirements for the variables most commonly used in synoptic, aviation and marine meteorology, and in climatology are summarized in Annex 1.D.[9] It gives requirements only for surface measurements that are exchanged internationally. Details on the observational data requirements for Global Data-processing and Forecasting System Centres for global and regional exchange are given in WMO (2010*c*). The uncertainty requirement for wind measurements is given separately for speed and direction because that is how wind is reported.

The ability of individual sensors or observing systems to meet the stated requirements is changing constantly as instrumentation and observing technology advance. The characteristics of typical sensors or systems currently available are given in Annex 1.D.[10] It should be noted that the achievable operational uncertainty in many cases does not meet the stated requirements. For some of the quantities, these uncertainties are achievable only with the highest quality equipment and procedures.

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

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

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

ANNEX 1.A

REGIONAL CENTRES

1. Considering the need for the regular calibration and maintenance of meteorological instruments to meet the increasing needs for high-quality meteorological and hydrological data, the need for building the hierarchy of the traceability of measurements to the International System of Units (SI) standards, Members' requirements for the standardization of meteorological and related environmental instruments, the need for international instrument comparisons and evaluations in support of worldwide data compatibility and homogeneity, the need for training instrument experts and the role played by Regional Instrument Centres (RICs) in the Global Earth Observing System of Systems, the Natural Disaster Prevention and Mitigation Programme and other WMO cross-cutting programmes, it has been recommended that:[11]

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

Capabilities:

(a) A RIC must have, or have access to, the necessary facilities and laboratory equipment to perform the functions necessary for the calibration of meteorological and related environmental instruments;
(b) A RIC must maintain a set of meteorological standard instruments and establish the traceability of its own measurement standards and measuring instruments to the SI;
(c) A RIC must have qualified managerial and technical staff with the necessary experience to fulfil its functions;
(d) A RIC must develop its individual technical procedures for the calibration of meteorological and related environmental instruments using calibration equipment employed by the RIC;
(e) A RIC must develop its individual quality assurance procedures;
(f) A RIC must participate in, or organize, inter-laboratory comparisons of standard calibration instruments and methods;
(g) A RIC must, when appropriate, utilize the resources and capabilities of the Region according to the Region's best interests;
(h) A RIC must, as far as possible, apply international standards applicable for calibration laboratories, such as ISO/IEC 17025;
(i) A recognized authority must assess a RIC, at least every five years, to verify its capabilities and performance;

Corresponding functions:

(j) A RIC must assist Members of the Region in calibrating their national meteorological standards and related environmental monitoring instruments;
(k) A RIC must participate in, or organize, WMO and/or regional instrument intercomparisons, following relevant CIMO recommendations;
(l) According to relevant recommendations on the WMO Quality Management Framework, a RIC must make a positive contribution to Members regarding the quality of measurements;
(m) A RIC must advise Members on enquiries regarding instrument performance, maintenance and the availability of relevant guidance materials;
(n) A RIC must actively participate, or assist, in the organization of regional workshops on meteorological and related environmental instruments;
(o) The RIC must cooperate with other RICs in the standardization of meteorological and related environmental measurements;
(p) A RIC must regularly inform Members and report,[12] on an annual basis, to the president of the regional association and to the WMO Secretariat on the services offered to Members and activities carried out;

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

Capabilities:

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

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

12 A Web-based approach is recommended.

(b) A RIC must maintain a set of meteorological standard instruments[13] and establish the traceability of its own measurement standards and measuring instruments to the SI;

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

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

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

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

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

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

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

Corresponding functions:

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

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

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

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

(n) A RIC must regularly inform Members and report,[14] on an annual basis, to the president of the regional association and to the WMO Secretariat on the services offered to Members and activities carried out.

2. The following RICs have been designated by the regional associations concerned: Algiers (Algeria), Cairo (Egypt), Casablanca (Morocco), Nairobi (Kenya) and Gaborone (Botswana) for RA I; Beijing (China) and Tsukuba (Japan) for RA II; Buenos Aires (Argentina) for RA III; Bridgetown (Barbados), Mount Washington (United States) and San José (Costa Rica) for RA IV; Manila (Philippines) and Melbourne (Australia) for RA V; , Bratislava (Slovakia), Ljubljana (Slovenia) and Trappes (France) for RA VI.

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

14 A Web-based approach is recommended.

ANNEX 1.B

SITING CLASSIFICATIONS FOR SURFACE OBSERVING STATIONS ON LAND

Environmental conditions of a site[15] may generate measurement errors exceeding the tolerances envisaged for instruments. More attention is usually given to the characteristics of the instrument than to the environmental conditions in which the measurement is made and it is often environmental conditions that distort results, influencing their representativeness, particularly when a site is supposed to be representative of a large area (i.e. 100 to 1 000 km^2).

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

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

Each type of measurement on a site is subject to a separate classification.

By linking measurements to their associated uncertainty levels, this classification may be used to define the maximum class number of a station in order to be included in a given network, or to be used for a given application. In a perfect world, all sites would be in class 1, but the real world is not perfect and some compromises are necessary. It is more valuable to accept this situation and to document it by means of this siting classification.

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

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

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

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

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

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

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

15 A "site" is defined as the place where the instrument is installed.

AIR TEMPERATURE AND HUMIDITY

Sensors situated inside a screen should be mounted at a height determined by the meteorological service (within 1.25 m to 2 m as indicated in this Guide). The height should never be less than 1.25 m. The respect of the higher limit is less stringent, as the temperature gradient versus height is decreasing with height. For example, the difference in temperature for sensors located between 1.5 and 2 m is less than 0.2°C.

The main discrepancies are caused by unnatural surfaces and shading:

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

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

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

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

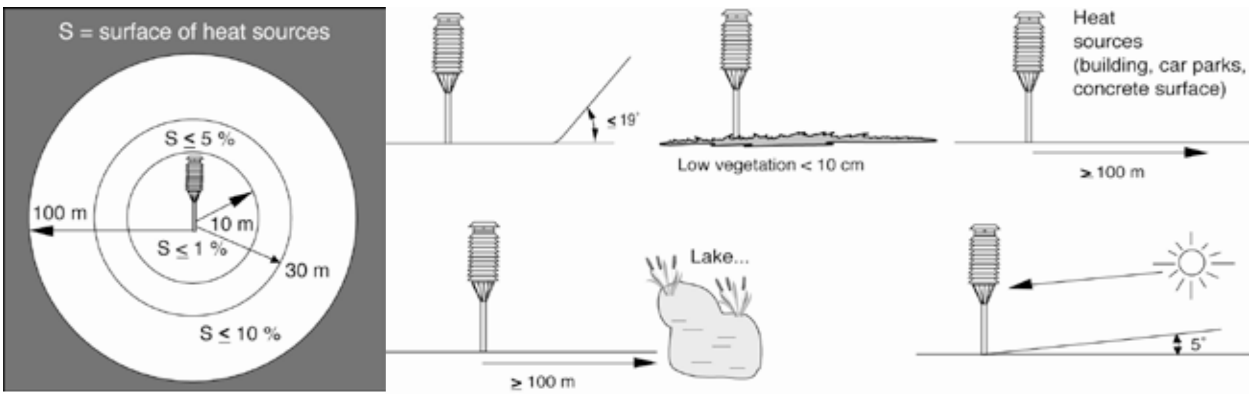
Class 1

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

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

(c) Measurement point situated:
   (i) At more than 100 m from heat sources or reflective surfaces (buildings, concrete surfaces, car parks, etc.);
   (ii) At more than 100 m from an expanse of water (unless significant of the region);
   (iii) Away from all projected shade when the sun is higher than 5°.

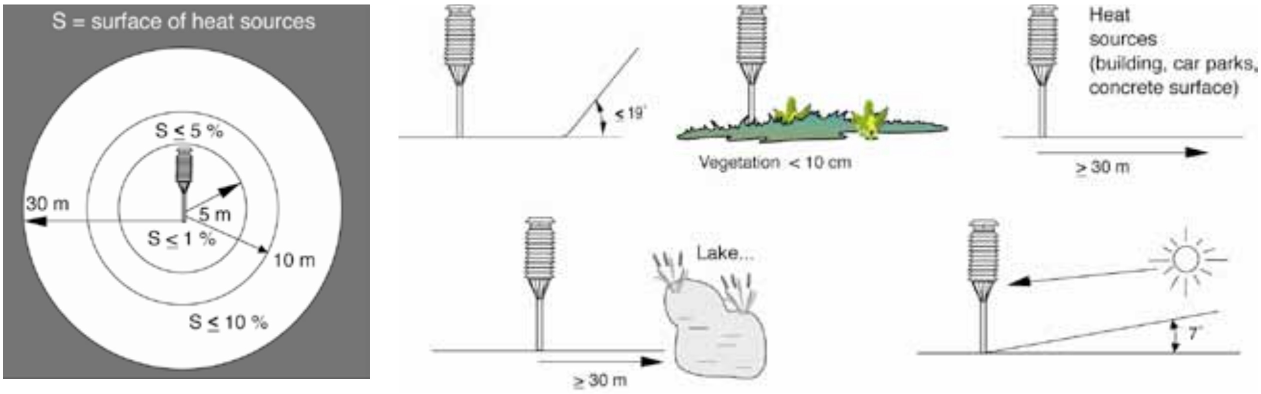
A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 per cent of the surface within a circular area of 100 m surrounding the screen, makes up 5 per cent of an annulus of 10–30 m, or covers 1 per cent of a 10 m circle.



Class 2

(a) Flat, horizontal land, surrounded by an open space, slope inclination less than ⅓ (19°);
(b) Ground covered with natural and low vegetation (<10 cm) representative of the region;
(c) Measurement point situated:
  (i) At more than 30 m from artificial heat sources or reflective surfaces (buildings, concrete surfaces, car parks, etc.);
  (ii) At more than 30 m from an expanse of water (unless significant of the region);
  (iii) Away from all projected shade when the sun is higher than 7°.

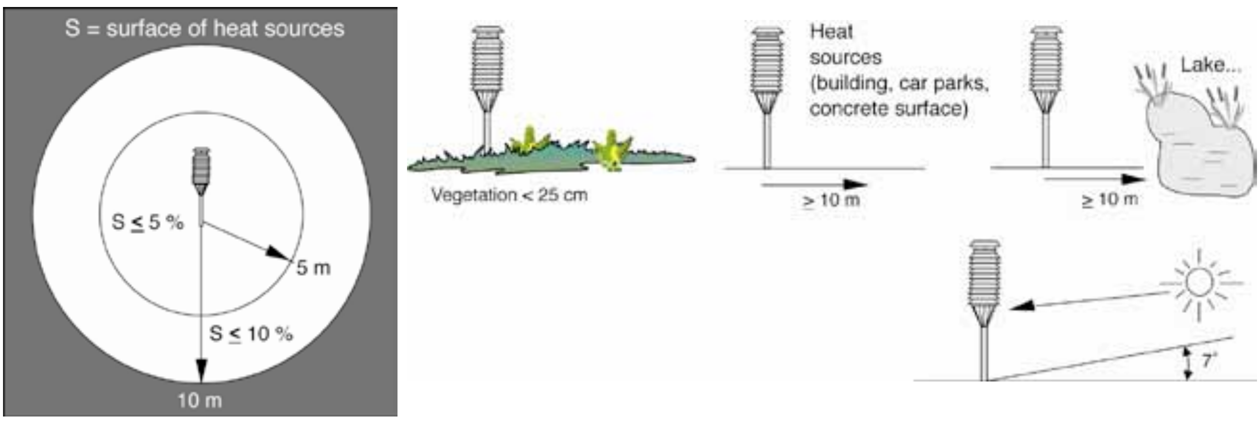
A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 per cent of the surface within a circular area of 30 m surrounding the screen, makes up 5 per cent of an annulus of 5–10 m, or covers 1 per cent of a 5 m circle.



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

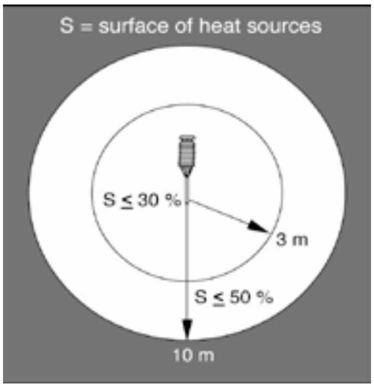
(a) Ground covered with natural and low vegetation (< 25 cm) representative of the region;
(b) Measurement point situated:
  (i) At more than 10 m from artificial heat sources and reflective surfaces (buildings, concrete surfaces, car parks, etc.);
  (ii) At more than 10 m from an expanse of water (unless significant of the region);
  (iii) Away from all projected shade when the sun is higher than 7°.

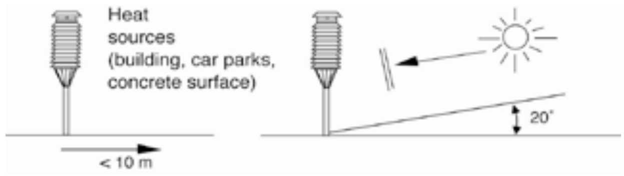
A source of heat (or expanse of water) is considered to have an impact if it occupies more than 10 per cent of the surface within a circular area of 10 m surrounding the screen or makes up 5 per cent of an annulus of 5 m.



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

(a) Close, artificial heat sources and reflective surfaces (buildings, concrete surfaces, car parks, etc.) or expanse of water (unless significant of the region, occupying:
  (i) Less than 50 per cent of the surface within a circular area of 10 m around the screen;
  (ii) Less than 30 per cent of the surface within a circular area of 3 m around the screen;
(b) Away from all projected shade when the sun is higher than 20°.





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

Site not meeting the requirements of class 4.

PRECIPITATION

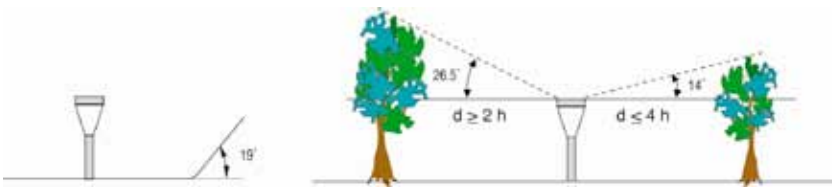
Wind is the greatest source of disturbance in precipitation measurements, due to the effect of the instrument on the airflow. Unless raingauges are artificially protected against wind, for instance by a wind shield, the best sites are often found in clearings within forests or orchards, among trees,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

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

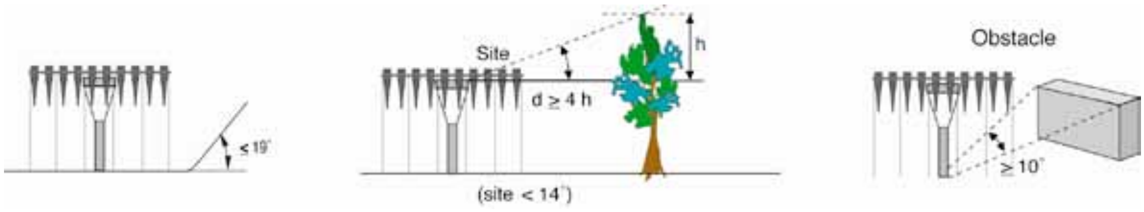
Reference for the heights of obstacles is the catchment's height of the rain gauge.

Class 1

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). Raingauge surrounded by obstacles of uniform height, seen under an elevation angle between 14° to 26° (obstacles at a distance between 2 to 4 times their height);
(b) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°). For a raingauge artificially protected against wind, the instrument does not necessarily need to be protected by obstacles of uniform height. In this case, any other obstacles must be situated at a distance of at least 4 times their height.

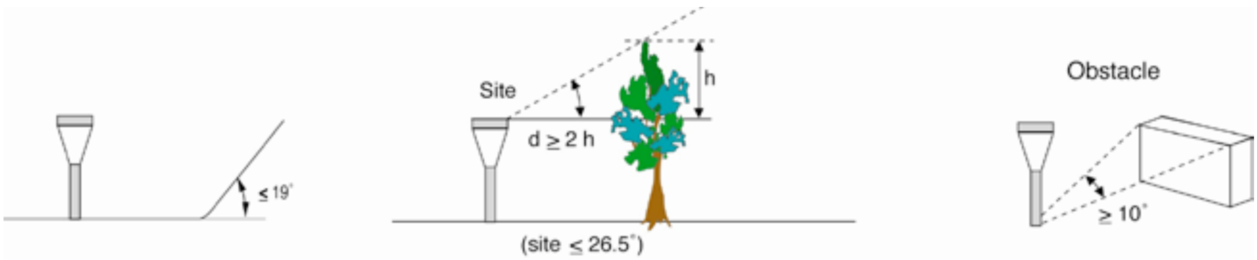


or



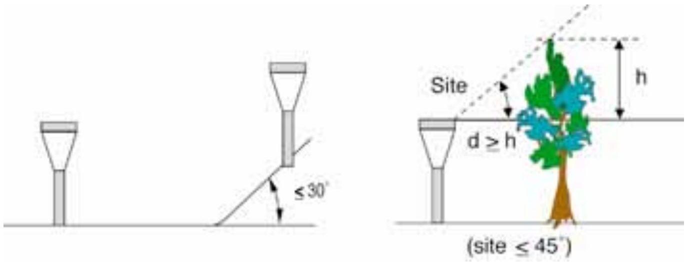
Class 2 (additional estimated uncertainty added by siting up to 5 per cent)

(a) Flat, horizontal land, surrounded by an open area, slope less than ⅓ (19°);
(b) Possible obstacles must be situated at a distance at least twice the height of the obstacle (with respect to the catchment's height of the raingauge).



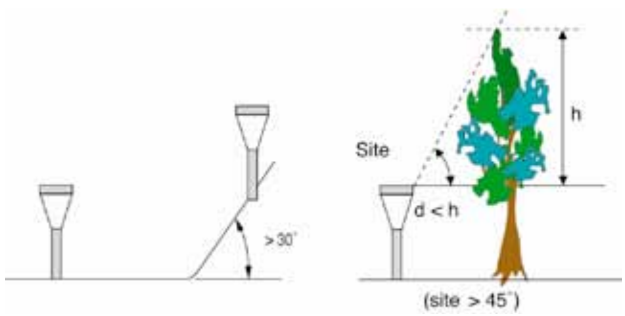
Class 3 (additional estimated uncertainty added by siting up to 15 per cent)

(a) Land is surrounded by an open area, slope less than ½ (≤ 30°);
(b) Possible obstacles must be situated at a distance greater than the height of the obstacle.



Class 4 (additional estimated uncertainty added by siting up to 25 per cent)

(a) Steeply sloping land (> 30°);
(b) Possible obstacles must be situated at a distance greater than one half (½) the height of the obstacle.



Class 5 (additional estimated uncertainty added by siting up to 100 per cent)

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

SURFACE WIND

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

ROUGHNESS

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

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

Therefore, roughness around the measuring site has to be documented. Roughness should be used to convert the measuring wind to the reference wind, but this procedure can be applied only when the obstacles are not too close. Roughness-related matters and correction procedure are described in Part I, Chapter 5.

The roughness classification, reproduced from the annex in Part I, Chapter 5, is recalled here:

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

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

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

ENVIRONMENT CLASSIFICATION

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

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

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

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

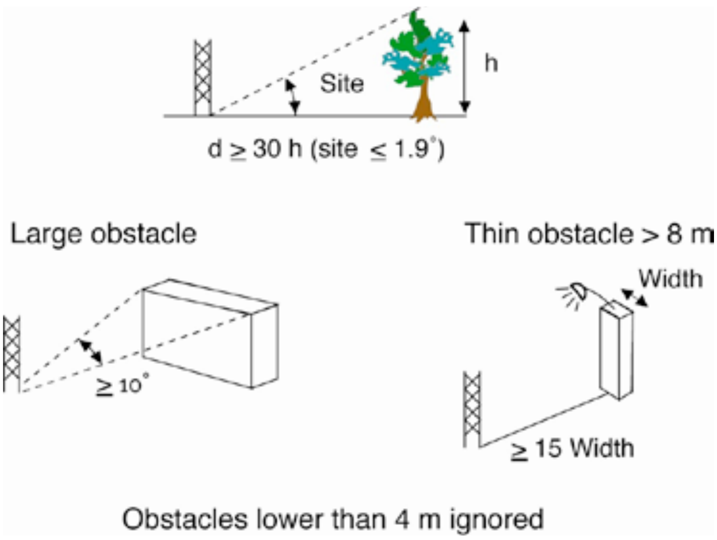
In the following, an object is considered to be an obstacle if its angular width is over 10°, except for tall thin obstacles, as mentioned below.

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

Class 1

(a) The mast should be located at a distance equal to a least 30 times the height of surrounding obstacles;
(b) Sensors should be situated at a minimum distance of 15 times the width of narrow obstacles (mast, thin tree) higher than 8 m;

Single obstacles lower than 4 m can be ignored.

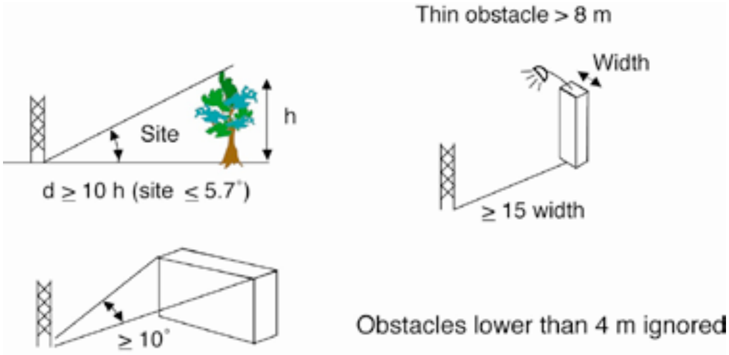


Roughness class index is between 2 to 4 (roughness length ≤ 0.1 m).

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

(a) The mast should be located at a distance of at least 10 times the height of the surrounding obstacles;
(b) Sensors should be situated at a minimum distance of 15 times the width of narrow obstacles (mast, thin tree) over 8 m high;

Single obstacles lower than 4 m can be ignored.



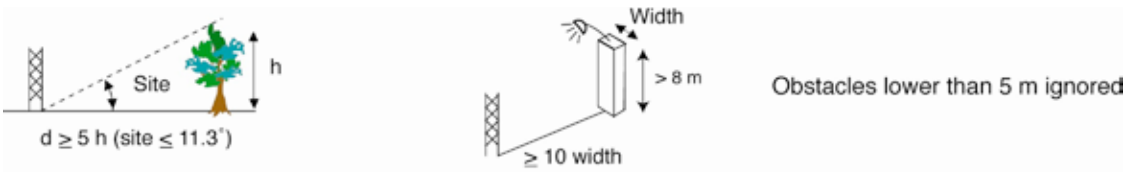
Roughness class index is between 2 to 5 (roughness length ≤ 0.25 m).

Note: When the mast is located at a distance of at least 20 times the height of the surrounding obstacles, a correction (see Part I, Chapter 5) can be applied. In case of nearer obstacles, a correction may be applied is some situations.

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

(a) The mast should be located at a distance of at least 5 times the height of surrounding obstacles;
(b) Sensors should be situated at a minimum distance of 10 times the width of narrow obstacles (mast, thin tree) higher than 8 m.

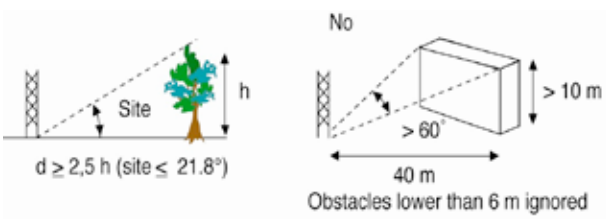
Single obstacles lower than 5 m can be ignored.



Class 4 (additional estimated uncertainty added by siting greater than 50 per cent)

(a) The mast should be located at a distance of at least 2.5 times the height of surrounding obstacles;
(b) No obstacle with an angular width larger than 60° and a height greater than 10 m, within a 40 m distance.

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



Class 5 (additional estimated uncertainty cannot be defined)

Site not meeting the requirements of class 4.

GLOBAL AND DIFFUSE RADIATION

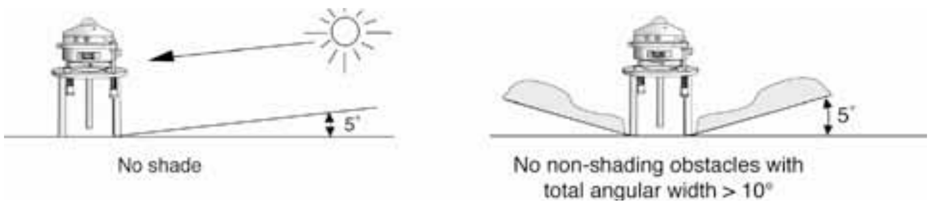
Close obstacles have to be avoided. Shading due to the natural relief is not taken into account for the classification. Non-reflecting obstacles below the visible horizon can be neglected.

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

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

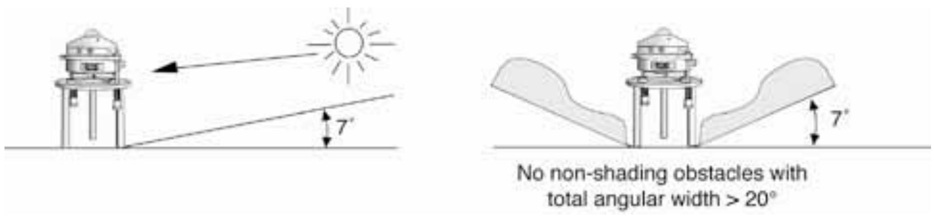
Class 1

(a) No shade projected onto the sensor when the sun is at an angular height of over 5°. For regions with latitude ≥ 60°, this limit is decreased to 3°;
(b) No non-shading reflecting obstacles with an angular height above 5° and a total angular width above 10°.



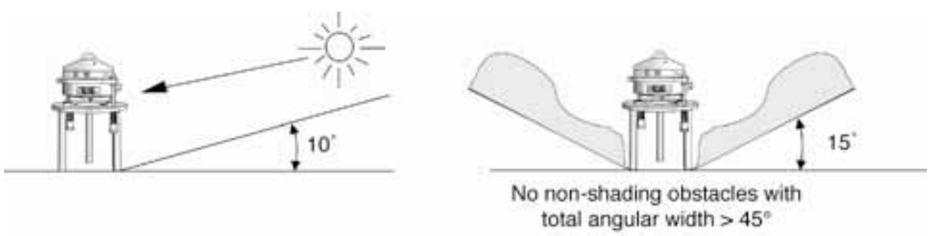
Class 2

(a) No shade projected onto the sensor when the sun is at an angular height of over 7°. For regions with latitude ≥ 60°, this limit is decreased to 5°;
(b) No non-shading reflecting obstacles with an angular height above 7° and a total angular width above 20°.



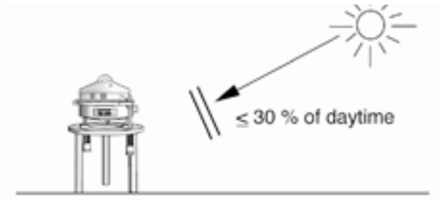
Class 3

(a) No shade projected onto the sensor when the sun is at an angular height of over 10°. For regions with latitude ≥ 60°, this limit is decreased to 7°;
(b) No non-shading reflecting obstacles with an angular height above 15° and a total angular width above 45°.



Class 4

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



No shade projected for more than 30 % of daytime

Class 5

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

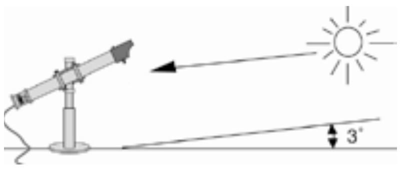
DIRECT RADIATION AND SUNSHINE DURATION

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

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

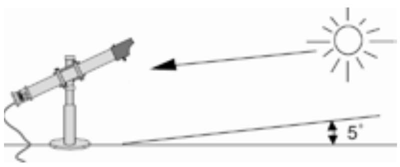
Class 1

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



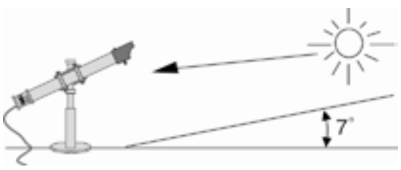
Class 2

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



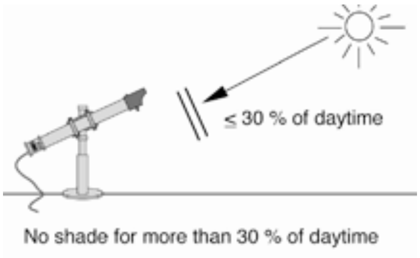
Class 3

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



Class 4

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



Class 5

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

ANNEX 1.C

STATION EXPOSURE DESCRIPTION

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

Station metadata should contain the following aspects of instrument exposure:

(a) Height of the instruments above the surface (or below it, for soil temperature);
(b) Type of sheltering and degree of ventilation for temperature and humidity;
(c) Degree of interference from other instruments or objects (masts, ventilators);
(d) Microscale and toposcale surroundings of the instrument, in particular:
  (i) The state of the enclosure's surface, influencing temperature and humidity; nearby major obstacles (buildings, fences, trees) and their size;
  (ii) The degree of horizon obstruction for sunshine and radiation observations;
  (iii) Surrounding terrain roughness and major vegetation, influencing the wind;
  (iv) All toposcale terrain features such as small slopes, pavements, water surfaces;
  (v) Major mesoscale terrain features, such as coasts, mountains or urbanization.

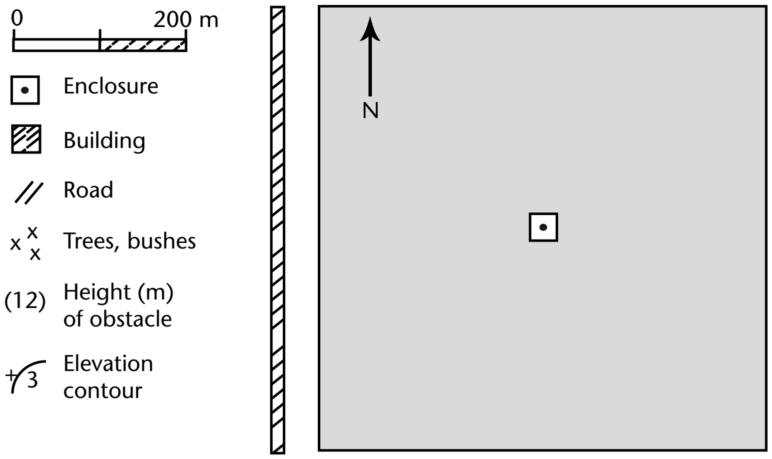
Most of these matters will be semi-permanent, but any significant changes (growth of vegetation, new buildings) should be recorded in the station logbook, and dated.

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

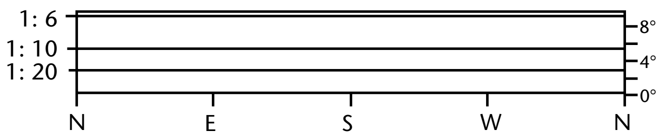
The necessary minimum metadata for instrument exposure can be provided by filling in the template given on the next page for every station in a network (see the figure below). An example of how to do this is shown in WMO (2003). The classes used here for describing terrain roughness are given in Part I, Chapter 5, of the Guide. A more extensive description of metadata matters is given in WMO (2010*b*).

Station Update

Elevation Latitude Longitude



Radiation horizon



Temperature and humidity: Sensor height

Artificial ventilation? yes/no

Surface cover under screen

Soil under screen

Precipitation: Gauge rim height

Wind: Anenomoter height Free-standing? yes/no

(if “no” above: building height , width , length .

Terrain roughness class: to N ,to E , to S, to W .

Remarks:

General template for station exposure metadata

ANNEX 1.D

OPERATIONAL MEASUREMENT UNCERTAINTY REQUIREMENTS AND INSTRUMENT PERFORMANCE

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

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
1.	**Temperature**								
1.1	Air temperature	–80 – +60°C	0.1 K	I	0.3 K for ≤ –40ºC 0.1 K for > –40ºC and ≤ +40ºC 0.3 K for > +40ºC	20 s	1 min	0.2 K	Achievable uncertainty and effective time-constant may be affected by the design of the thermometer solar radiation screen Time-constant depends on the air-flow over the sensor
1.2	Extremes of air temperature	–80 – +60°C	0.1 K	I	0.5 K for ≤ –40ºC 0.3 K for > –40ºC and ≤ +40ºC 0.5 K for > +40ºC	20 s	1 min	0.2 K	
1.3	Sea surface temperature	–2 – +40°C	0.1 K	I	0.1 K	20 s	1 min	0.2 K	
1.4	Soil temperature	–50 – +50°C	0.1 K	I		20 s	1 min	0.2 K	
2.	**Humidity**								
2.1	Dewpoint temperature	–80 – +35°C	0.1 K	I	0.1 K	20 s	1 min	0.25 K	Measurement uncertainty depends on the deviation from air temperature

	1	2	3	4	5	6	7	8	9
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
							Wet-bulb temperature (psychrometer)		
2.2	Relative humidity	0 – 100%	1%	I	1%	20 s	1 min	0.2 K	If measured directly and in combination with air temperature (dry bulb) Large errors are possible due to aspiration and cleanliness problems (see also note 11) Threshold of 0°C to be noticed for wet bulb
								Solid state and others	
						40 s	1 min	3%	Time constant and achievable uncertainty of solid-state sensors may show significant temperature and humidity dependence
3.	**Atmospheric pressure**								
3.1	Pressure	500 – 1 080 hPa	0.1 hPa	I	0.1 hPa	2 s	1 min	0.15 hPa	Both station pressure and MSL pressure Measurement uncertainty is seriously affected by dynamic pressure due to wind if no precautions are taken Inadequate temperature compensation of the transducer may affect the measurement uncertainty significantly MSL pressure is affected by the uncertainty in altitude of the barometer for measurements onboard ships
3.2	Tendency	Not specified	0.1 hPa	I	0.2 hPa			0.2 hPa	Difference between instantaneous values

	1	2	3	4	5	6	7	8	9
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
4.	**Clouds**								
4.1	Cloud amount	0/8 – 8/8	1/8	I	1/8	n/a		2/8	Period clustering algorithms may be used to estimate low cloud amount automatically
4.2	Height of cloud base	0 m – 30 km	10 m	I	10 m for ≤ 100 m 10% for > 100 m	n/a		~10 m	Achievable measurement uncertainty can be determined with a hard target. No clear definition exists for instrumentally measured cloud-base height (e.g. based on penetration depth or significant discontinuity in the extinction profile) Significant bias during precipitation
4.3	Height of cloud top	Not available							
5.	**Wind**								
5.1	Speed	0 – 75 m s^{-1}	0.5 m s^{-1}	A	0.5 m s^{-1} for ≤ 5 m s^{-1} 10% for > 5 m s^{-1}	Distance constant 2 – 5 m	2 and/or 10 min	0.5 m s^{-1} for ≤ 5 m s^{-1} 10% for > 5 m s^{-1}	Average over 2 and/or 10 min Non-linear devices. Care needed in design of averaging process Distance constant is usually expressed as response length Averages computed over Cartesian components (see Part III, Chapter 3, section 3.6 of this Guide) When using ultrasonic anemometers, no distance constant or time constant is needed. For moving mobile stations, the movement of the station needs to be taken into account, inclusive of its uncertainty.
5.2	Direction	0 – 360°	1°	A	5°	Damping ratio > 0.3	2 and/or 10 min	5°	

	1	2	3	4	5	6	7	8	9
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
5.3	Gusts	0.1 – 150 m s^{-1}	0.1 m s^{-1}	A	10%		3 s	0.5 m s^{-1} for ≤ 5 m s^{-1} 10% for > 5 m s^{-1}	Highest 3 s average should be recorded
6.	**Precipitation**								
6.1	Amount (daily)	0 – 500 mm	0.1 mm	T	0.1 mm for ≤ 5 mm 2% for > 5 mm	n/a	n/a	The larger of 5% or 0.1 mm	Quantity based on daily amounts Measurement uncertainty depends on aerodynamic collection efficiency of gauges and evaporation losses in heated gauges
6.2	Depth of snow	0 – 25 m	1 cm	I	1 cm for ≤ 20 cm 5% for > 20 cm	< 10 s	1 min	1 cm	Average depth over an area representative of the observing site
6.3	Thickness of ice accretion on ships	Not specified	1 cm	I	1 cm for ≤ 10 cm 10% for > 10 cm				
6.4	Precipitation intensity	0.02 mm h^{-1} – 2 000 mm h^{-1}	0.1 mm h^{-1}	I	(trace): n/a for 0.02 – 0.2 mm h^{-1} 0.1 mm h^{-1} for 0.2 – 2 mm h^{-1} 5% for > 2 mm h^{-1}	< 30 s	1 min	Under constant flow conditions in laboratory, 5% above 2 mm/h, 2% above 10 mm/h In field, 5 mm/h and 5% above 100 mm/h	Uncertainty values for liquid precipitation only Uncertainty is seriously affected by wind Sensors may show significant non-linear behaviour For < 0.2 mm h^{-1}: detection only (yes/no) sensor time constant is significantly affected during solid precipitation using catchment type of gauges
6.5	Precipitation duration (daily)	0 – 24 h	60 s	T	n/a	60 s			Threshold value of 0.02 mm/h

	1	2	3	4	5	6	7	8	9
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
7.	**Radiation**								
7.1	Sunshine duration (daily)	0 – 24 h	60 s	T	0.1 h	20 s	n/a	The larger of 0.1 h or 2%	
7.2	Net radiation, radiant exposure (daily)	Not specified	1 J m^{-2}	T	0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} 5% for > 8 MJ m^{-2}	20 s	n/a	0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} 5% for > 8 MJ m^{-2}	Radiant exposure expressed as daily sums (amount) of (net) radiation
8.	**Visibility**								
8.1	Meteorological optical range (MOR)	10 m – 100 km	1 m	I	50 m for ≤ 600 m 10% for > 600 m – ≤ 1 500 m 20% for > 1500 m	< 30 s	1 and 10 min	The larger of 20 m or 20%	Achievable measurement uncertainty may depend on the cause of obscuration Quantity to be averaged: extinction coefficient (see Part III, Chapter 3, section 3.6, of this Guide). Preference for averaging logarithmic values
8.2	Runway visual range (RVR)	10 m – 2 000 m	1 m	A	10 m for ≤ 400 m 25 m for > 400 m – ≤ 800 m 10% for > 800 m	< 30 s	1 and 10 min	The larger of 20 m or 20%	In accordance with WMO-No. 49, Volume II, Attachment A (2004 ed.) and ICAO Doc 9328-AN/908 (second ed., 2000) New versions of these documents may exist, specifying other values.
8.3	Background luminance	0 – 40 000 cd m^{-2}	1 cd m^{-2}	I		30 s	1 min	10%	Related to 8.2 RVR
9.	**Waves**								
9.1	Significant wave height	0 – 50 m	0.1 m	A	0.5 m for ≤ 5 m 10% for > 5 m	0.5 s	20 min	0.5 m for ≤ 5 m 10% for > 5 m	Average over 20 min for instrumental measurements
9.2	Wave period	0 – 100 s	1 s	A	0.5 s	0.5 s	20 min	0.5 s	Average over 20 min for instrumental measurements

	1	2	3	4	5	6	7	8	9
	Variable	*Range*	*Reported resolution*	*Mode of measurement/ observation*	*Required measurement uncertainty*	*Sensor time constant*	*Output averaging time*	*Achievable measurement uncertainty*	*Remarks*
9.3	Wave direction	0 – 360°	1°	A	10°	0.5 s	20 min	20°	Average over 20 min for instrumental measurements
10.	**Evaporation**								
10.1	Amount of pan evaporation	0 – 100 mm	0.1 mm	T	0.1 mm for ≤ 5 mm 2% for > 5 mm	n/a			

Notes:
1. Column 1 gives the basic variable.
2. Column 2 gives the common range for most variables; limits depend on local climatological conditions.
3. Column 3 gives the most stringent resolution as determined by the *Manual on Codes* (WMO-No. 306).
4. In column 4:
   I = Instantaneous: In order to exclude the natural small-scale variability and the noise, an average value over a period of 1 min is considered as a minimum and most suitable; averages over periods of up to 10 min are acceptable.
   A: = Averaging: Average values over a fixed period, as specified by the coding requirements.
   T: = Totals: Totals over a fixed period, as specified by coding requirements.
5. Column 5 gives the recommended measurement uncertainty requirements for general operational use, i.e. of Level II data according to FM 12, 13, 14, 15 and its BUFR equivalents. They have been adopted by all eight technical commissions and are applicable for synoptic, aeronautical, agricultural and marine meteorology, hydrology, climatology, etc. These requirements are applicable for both manned and automatic weather stations as defined in the *Manual on the Global Observing System* (WMO-No. 544). Individual applications may have less stringent requirements. The stated value of required measurement uncertainty represents the uncertainty of the reported value with respect to the true value and indicates the interval in which the true value lies with a stated probability. The recommended probability level is 95 per cent ($k = 2$), which corresponds to the 2 σ level for a normal (Gaussian) distribution of the variable. The assumption that all known corrections are taken into account implies that the errors in reported values will have a mean value (or bias) close to zero. Any residual bias should be small compared with the stated measurement uncertainty requirement. The true value is the value which, under operational conditions, perfectly characterizes the variable to be measured/observed over the representative time interval, area and/or volume required, taking into account siting and exposure.
6. Columns 2 to 5 refer to the requirements established by the CBS Expert Team on Requirements for Data from Automatic Weather Stations in 2004.
7. Columns 6 to 8 refer to the typical operational performance established by the CIMO Expert Team on Surface Technology and Measurement Techniques in 2004.
8. Achievable measurement uncertainty (column 8) is based on sensor performance under nominal and recommended exposure that can be achieved in operational practice. It should be regarded as a practical aid to users in defining achievable and affordable requirements.
9. n/a = not applicable.
10. The term *uncertainty* has preference over *accuracy* (i.e. uncertainty is in accordance with ISO standards on the uncertainty of measurements (ISO, 1995)).
11. Dewpoint temperature, relative humidity and air temperature are linked, and thus their uncertainties are linked. When averaging, preference is given to absolute humidity as the principal variable.

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CHAPTER 2

MEASUREMENT OF TEMPERATURE

2.1 GENERAL

2.1.1 Definition

WMO (1992) defines temperature as a physical quantity characterizing the mean random motion of molecules in a physical body. Temperature is characterized by the behaviour whereby two bodies in thermal contact tend to an equal temperature. Thus, temperature represents the thermodynamic state of a body, and its value is determined by the direction of the net flow of heat between two bodies. In such a system, the body which overall loses heat to the other is said to be at the higher temperature. Defining the physical quantity temperature in relation to the "state of a body" however is difficult. A solution is found by defining an internationally approved temperature scale based on universal freezing and triple points.[1] The current such scale is the International Temperature Scale of 1990 (ITS-90)[2] and its temperature is indicated by T_{90}. For the meteorological range (–80 to +60°C) this scale is based on a linear relationship with the electrical resistance of platinum and the triple point of water, defined as 273.16 kelvin (BIPM, 1990).

For meteorological purposes, temperatures are measured for a number of media. The most common variable measured is air temperature (at various heights). Other variables are ground, soil, grass minimum and seawater temperature. WMO (1992) defines air temperature as "the temperature indicated by a thermometer exposed to the air in a place sheltered from direct solar radiation". Although this definition cannot be used as the definition of the thermodynamic quantity itself, it is suitable for most applications.

1 The authoritative body for this scale is the International Bureau of Weights and Measures/Bureau International des Poids et Mesures (BIPM), Sèvres (Paris); see http://www.bipm.org. BIPM's Consultative Committee for Thermometry (CCT) is the executive body responsible for establishing and realizing the ITS.

2 Practical information on ITS-90 can be found on the ITS-90 website: http://www.its-90.com.

2.1.2 UNITS AND SCALES

The thermodynamic temperature (T), with units of kelvin (K), (also defined as "kelvin temperature"), is the basic temperature. The kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The temperature (t), in degrees Celsius (or "Celsius temperature") defined by equation 2.1, is used for most meteorological purposes (from the ice-point secondary reference in Table 2 in the annex):

$$t/°\mathrm{C} = T/\mathrm{K} - 273.15 \qquad (2.1)$$

A temperature difference of one degree Celsius (°C) unit is equal to one kelvin (K) unit. Note that the unit K is used without the degree symbol.

In the thermodynamic scale of temperature, measurements are expressed as differences from absolute zero (0 K), the temperature at which the molecules of any substance possess no kinetic energy. The scale of temperature in general use since 1990 is the ITS-90 (see the annex), which is based on assigned values for the temperatures of a number of reproducible equilibrium states (see Table 1 in the annex) and on specified standard instruments calibrated at those temperatures. The ITS was chosen in such a way that the temperature measured against it is identical to the thermodynamic temperature, with any difference being within the present limits of measurement uncertainty. In addition to the defined fixed points of the ITS, other secondary reference points are available (see Table 2 in the annex). Temperatures of meteorological interest are obtained by interpolating between the fixed points by applying the standard formulae in the annex.

2.1.3 Meteorological requirements

2.1.3.1 General

Meteorological requirements for temperature measurements primarily relate to the following:
(a) The air near the Earth's surface;
(b) The surface of the ground;

(c) The soil at various depths;
(d) The surface levels of the sea and lakes;
(e) The upper air.

These measurements are required, either jointly or independently and locally or globally, for input to numerical weather prediction models, for hydrological and agricultural purposes, and as indicators of climatic variability. Local temperature also has direct physiological significance for the day-to-day activities of the world's population. Measurements of temperature may be required as continuous records or may be sampled at different time intervals. This chapter deals with requirements relating to (a), (b) and (c).

2.1.3.2 Accuracy requirements

The range, reported resolution and required uncertainty for temperature measurements are detailed in Part I, Chapter 1, of this Guide. In practice, it may not be economical to provide thermometers that meet the required performance directly. Instead, cheaper thermometers, calibrated against a laboratory standard, are used with corrections being applied to their readings as necessary. It is necessary to limit the size of the corrections to keep residual errors within bounds. Also, the operational range of the thermometer will be chosen to reflect the local climatic range. As an example, the table below gives an acceptable range of calibration and errors for thermometers covering a typical measurement range.

Thermometer characteristic requirements

Thermometer type	*Ordinary*	*Maximum*	*Minimum*
Span of scale (˚C)	–30 to 45	–30 to 50	– 40 to 40
Range of calibration (˚C)	–30 to 40	–25 to 40	–30 to 30
Maximum error	<0.2 K	0.2 K	0.3 K
Maximum difference between maximum and minimum correction within the range	0.2 K	0.3 K	0.5 K
Maximum variation of correction within any interval of 10˚C	0.1 K	0.1 K	0.1 K

All temperature-measuring instruments should be issued with a certificate confirming compliance with the appropriate uncertainty or performance specification, or a calibration certificate that gives the corrections that must be applied to meet the required uncertainty. This initial testing and calibration should be performed by a national testing institution or an accredited calibration laboratory. Temperature-measuring instruments should also be checked subsequently at regular intervals, the exact apparatus used for this calibration being dependent on the instrument or sensor to be calibrated.

2.1.3.3 Response times of thermometers

For routine meteorological observations there is no advantage in using thermometers with a very small time-constant or lag coefficient, since the temperature of the air continually fluctuates up to one or two degrees within a few seconds. Thus, obtaining a representative reading with such a thermometer would require taking the mean of a number of readings, whereas a thermometer with a larger time-constant tends to smooth out the rapid fluctuations. Too long a time-constant, however, may result in errors when long-period changes of temperature occur. It is recommended that the time-constant, defined as the time required by the thermometer to register 63.2 per cent of a step change in air temperature, should be 20 s. The time-constant depends on the air-flow over the sensor.

2.1.3.4 Recording the circumstances in which measurements are taken

Temperature is one of the meteorological quantities whose measurements are particularly sensitive to exposure. For climate studies in particular, temperature measurements are affected by the state of the surroundings, by vegetation, by the presence of buildings and other objects, by ground cover, by the condition of, and changes in, the design of the radiation shield or screen, and by other changes in equipment. It is important that records should be kept not only of the temperature data, but also of the circumstances in which the measurements are taken. Such information is known as metadata (data about data).

2.1.4 Measurement methods

In order to measure the temperature of an object, a thermometer can be brought to the same temperature as the object (namely, into thermodynamic equilibrium with it), and the temperature of the thermometer itself can then be measured.

Alternatively, the temperature can be determined by a radiometer without the need for thermal equilibrium.

Any physical property of a substance which is a function of temperature can be used as the basis of a thermometer. The properties most widely used in meteorological thermometers are thermal expansion and the change in electrical resistance with temperature. Radiometric thermometers operate in the infrared part of the electromagnetic spectrum and are used, among other applications, for temperature measurements from satellites. A special technique to determine the air temperature using ultrasonic sampling, developed to determine air speeds, also provides the average speeds of the air molecules, and as a consequence its temperature (WMO, 2002*a*).

Thermometers which indicate the prevailing temperature are often known as ordinary thermometers, while those which indicate extreme temperature over a period of time are called maximum or minimum thermometers.

There are various standard texts on instrument design and laboratory practice for the measurement of temperature thermometry, such as Jones (1992) and Middleton and Spilhaus (1960). Considering the concepts of thermometry, care should be taken that, for meteorological applications, only specific technologies are applicable because of constraints determined by the typical climate or environment.

2.1.4.1 Thermometer exposure and siting

Radiation from the sun, clouds, the ground and other surrounding objects passes through the air without appreciably changing its temperature, but a thermometer exposed freely in the open can absorb considerable radiation. As a consequence, its temperature may differ from the true air temperature, with the difference depending on the radiation intensity and on the ratio of absorbed radiation to dissipated heat. For some thermometer elements, such as the very fine wire used in an open-wire resistance thermometer, the difference may be very small or even negligible. However, with the more usual operational thermometers the temperature difference may reach 25 K under extremely unfavourable conditions. Therefore, in order to ensure that the thermometer is at true air temperature it is necessary to protect the thermometer from radiation by a screen or shield that also serves to support the thermometer. This screen also shelters it from precipitation while allowing the free circulation of air around it, and prevents accidental damage. Precipitation on the sensor will, depending on the local air-flow, depress the sensor temperature, causing it to behave as a wet-bulb thermometer. Maintaining free circulation may, however, be difficult to achieve under conditions of rime ice accretion. Practices for reducing observational errors under such conditions will vary and may involve the use of special designs of screens or temperature-measuring instruments, including artificial ventilation. Nevertheless, in the case of artificial ventilation, care should be taken to avoid unpredictable influences caused by wet deposition in combination with evaporation during precipitation, drizzle, fog, and the like. An overview of concepts of temperature measurement applicable for operational practices is given by Sparks (1970).

In order to achieve representative results when comparing thermometer readings at different places and at different times, a standardized exposure of the screen and, hence, of the thermometer itself is also indispensable. For general meteorological work, the observed air temperature should be representative of the free air conditions surrounding the station over as large an area as possible, at a height of between 1.2 and 2.0 m above ground level. The height above ground level is specified because large vertical temperature gradients may exist in the lowest layers of the atmosphere. The best site for the measurements is, therefore, over level ground, freely exposed to sunshine and wind and not shielded by, or close to, trees, buildings and other obstructions. Sites on steep slopes or in hollows are subject to exceptional conditions and should be avoided. In towns and cities, local peculiarities are expected to be more marked than in rural districts. Temperature observations on the top of buildings are of doubtful significance and use because of the variable vertical temperature gradient and the effect of the building itself on the temperature distribution.

2.1.4.2 Temperature standards

Laboratory standards

Primary standard thermometers will be held and maintained at national standards laboratories. A national meteorological or other accredited calibration laboratory will have, as a working standard, a high-grade platinum resistance thermometer, traceable to the national standard. The uncertainty of this thermometer may be checked periodically in a water triple-point cell. The triple point of water is defined exactly and can be reproduced in a triple-point cell with an uncertainty of $1 \cdot 10^{-4}$ K.

Field standards

The WMO reference psychrometer (WMO, 1992) is the reference instrument for determining the relationship between the air temperature measured by conventional surface instruments and the true air temperature. This instrument has been designed to be used as a free-standing instrument and not for deployment within a screen or shelter; it is the most accurate instrument available for evaluating and comparing instrument systems. It is not intended for continuous use in routine meteorological operations and is capable of providing a temperature measurement with an uncertainty of 0.04 K (at the 95 per cent confidence level). See Part I, Chapter 4, for further information.

2.2 LIQUID-IN-GLASS THERMOMETERS

2.2.1 General description

For routine observations of air temperature, including maximum, minimum and wet-bulb temperatures, liquid-in-glass thermometers are still commonly used. Such thermometers make use of the differential expansion of a pure liquid with respect to its glass container to indicate the temperature. The stem is a tube which has a fine bore attached to the main bulb; the volume of liquid in the thermometer is such that the bulb is filled completely but the stem is only partially filled at all temperatures to be measured. The changes in volume of the liquid with respect to its container are indicated by changes in the liquid column; by calibration with respect to a standard thermometer, a scale of temperature can be marked on the stem, or on a separate scale tightly attached to the stem.

The liquid used depends on the required temperature range; mercury is generally used for temperatures above its freezing point (–38.3°C), while ethyl alcohol or other pure organic liquids are used for lower temperatures. The glass should be one of the normal or borosilicate glasses approved for use in thermometers. The glass bulb is made as thin as is consistent with reasonable strength to facilitate the conduction of heat to and from the bulb and its contents. A narrower bore provides greater movement of liquid in the stem for a given temperature change, but reduces the useful temperature range of the thermometer for a given stem length. The thermometer should be suitably annealed before it is graduated in order to minimize the slow changes that occur in the glass with ageing.

There are four main types of construction for meteorological thermometers, as follows:
(a) The sheathed type with the scale engraved on the thermometer stem;
(b) The sheathed type with the scale engraved on an opal glass strip attached to the thermometer tube inside the sheath;
(c) The unsheathed type with the graduation marks on the stem and mounted on a metal, porcelain or wooden back carrying the scale numbers;
(d) The unsheathed type with the scale engraved on the stem.

The stems of some thermometers are lens-fronted to provide a magnified image of the mercury thread.

Types (a) and (b) have the advantage over types (c) and (d) that their scale markings are protected from wear. For types (c) and (d), the markings may have to be reblackened from time to time; on the other hand, such thermometers are easier to make than types (a) and (b). Types (a) and (d) have the advantage of being less susceptible to parallax errors (see section 2.2.4). An overview of thermometers, designed for use in meteorological practices is given by HMSO (1980).

Whichever type is adopted, the sheath or mounting should not be unduly bulky as this would keep the heat capacity high. At the same time, the sheath or mounting should be sufficiently robust to withstand the normal risks associated with handling and transit.

For mercury-in-glass thermometers, especially maximum thermometers, it is important that the vacuum above the mercury column be nearly perfect. All thermometers should be graduated for total immersion, with the exception of thermometers for meauring soil temperature. The special requirements of thermometers for various purposes are dealt with hereafter under the appropriate headings.

2.2.1.1 Ordinary (station) thermometers

This is the most accurate instrument of all meteorological thermometers. Usually it is a mercury-in-glass-type thermometer. Its scale markings have an increment of 0.2 K or 0.5 K, and the scale is longer than that of the other meteorological thermometers.

The ordinary thermometer is used in a thermometer screen to avoid radiation errors. A support keeps it in a vertical position with the bulb at the lower end. The form of the bulb is that of a cylinder or an onion.

A pair of ordinary thermometers can be used as a psychrometer if one of them is fitted with a wet-bulb[3] sleeve.

2.2.1.2 Maximum thermometers

The recommended type for maximum thermometers is a mercury-in-glass thermometer with a constriction in the bore between the bulb and the beginning of the scale. This constriction prevents the mercury column from receding with falling temperatures. However, observers can reset by holding it firmly, bulb-end downwards, and swinging their arm until the mercury column is reunited. A maximum thermometer should be mounted at an angle of about 2° from the horizontal position, with the bulb at the lower end to ensure that the mercury column rests against the constriction without gravity forcing it to pass. It is desirable to have a widening of the bore at the top of the stem to enable parts of the column which have become separated to be easily united.

2.2.1.3 Minimum thermometers

As regards minimum thermometers, the most common instrument is a spirit thermometer with a dark glass index, about 2 cm long, immersed in the spirit. Since some air is left in the tube of a spirit thermometer, a safety chamber should be provided at the upper end which should be large enough to allow the instrument to withstand a temperature of 50°C without being damaged. Minimum thermometers should be supported in a similar manner to maximum thermometers, in a near-horizontal position. Various liquids can be used in minimum thermometers, such as ethyl alcohol, pentane and toluol. It is important that the liquid should be as pure as possible since the presence of certain impurities increases the tendency of the liquid to polymerize with exposure to light and after the passage of time; such polymerization causes a change in calibration. In the case of ethyl alcohol, for example, the alcohol should be completely free of acetone.

Minimum thermometers are also exposed to obtain grass minimum temperature.

2.2.1.4 Soil thermometers

For measuring soil temperatures at depths of 20 cm or less, mercury-in-glass thermometers, with their stems bent at right angles, or any other suitable angle, below the lowest graduation, are in common use. The thermometer bulb is sunk into the ground to the required depth, and the scale is read with the thermometer in situ. These thermometers are graduated for immersion up to the measuring depth. Since the remainder of the thermometer is kept at air temperature, a safety chamber should be provided at the end of the stem for the expansion of the mercury.

For measuring temperature at depths of over 20 cm, mercury-in-glass thermometers, mounted on wooden, glass or plastic tubes, with their bulbs embedded in wax or metallic paint, are recommended. The thermometer-tube assemblies are then suspended or slipped in thin-walled metal or plastic tubes sunk into the ground to the required depth. In cold climates, the tops of the outer tubes should extend above the ground to a height greater than the expected depth of snow cover.

The technique of using vertical steel tubes is unsuitable for measuring the diurnal variation of soil temperature, particularly in dry soil, and calculations of soil thermal properties based on such measurements could be significantly in error because they will conduct heat from the surface layer.

The large time-constant due to the increased heat capacity enables the thermometers to be removed from the outer tubes and read before their temperature has had time to change appreciably from the soil temperature.

When the ground is covered by snow, and in order that the observer may approach the line of thermometers without disturbing the snow cover, it is recommended that a lightweight bridge be constructed parallel to the line of thermometers. The bridge should be designed so that the deck can be removed between readings without affecting the snow cover.

3 Wet-bulb temperatures are explained in Part I, Chapter 4.

2.2.2 Measurement procedures

2.2.2.1 Reading ordinary thermometers

Thermometers should be read as rapidly as possible in order to avoid changes of temperature caused by the observer's presence. Since the liquid meniscus, or index, and the thermometer scale are not on the same plane, care must be taken to avoid parallax errors. These will occur unless the observer ensures that the straight line from his/her eye to the meniscus, or index, is at a right angle to the thermometer stem. Since thermometer scales are not normally subdivided to less than one fifth of a degree, readings to the nearest tenth of a degree, which are essential in psychometry, must be made by estimation. Corrections for scale errors, if any, should be applied to the readings. Maximum and minimum thermometers should be read and set at least twice daily. Their readings should be compared frequently with those of an ordinary thermometer in order to ensure that no serious errors develop.

2.2.2.2 Measuring grass minimum temperatures

The grass minimum temperature is the lowest temperature reached overnight by a thermometer freely exposed to the sky just above short grass. The temperature is measured with a minimum thermometer such as that described in section 2.2.1.3. The thermometer should be mounted on suitable supports so that it is inclined at an angle of about 2° from the horizontal position, with the bulb lower than the stem, 25 to 50 mm above the ground and in contact with the tips of the grass. When the ground is covered with snow, the thermometer should be supported immediately above the surface of the snow, as near to it as possible without actually touching it.

Normally, the thermometer is exposed at the last observation hour before sunset, and the reading is taken the next morning. The instrument is kept within a screen or indoors during the day. However, at stations where an observer is not available near sunset, it may be necessary to leave the thermometer exposed throughout the day. In strong sunshine, exposing the thermometer in this way can cause the spirit to distil and collect in the top of the bore. This effect can be minimized by fitting a cotton sock on a black metal shield over the safety chamber end of the thermometer; this shield absorbs more radiation and consequently reaches a higher temperature than the rest of the thermometer. Thus, any vapour will condense lower down the bore at the top of the spirit column.

2.2.2.3 Measuring soil temperatures

The standard depths for soil temperature measurements are 5, 10, 20, 50 and 100 cm below the surface; additional depths may be included. The site for such measurements should be a level plot of bare ground (about 75 cm^2) and typical of the surrounding soil for which information is required. If the surface is not representative of the general surroundings, its extent should not be less than 100 m^2. When the ground is covered with snow, it is desirable to measure the temperature of the snow cover as well. Where snow is rare, the snow may be removed before taking the readings and then replaced.

When describing a site for soil temperature measurements, the soil type, soil cover and the degree and direction of the ground's slope should be recorded. Whenever possible, the physical soil constants, such as bulk density, thermal conductivity and the moisture content at field capacity, should be indicated. The level of the water table (if within 5 m of the surface) and the soil structure should also be included.

At agricultural meteorological stations, the continuous recording of soil temperatures and air temperatures at different levels in the layer adjacent to the soil (from ground level up to about 10 m above the upper limit of prevailing vegetation) is desirable.

2.2.3 Thermometer siting and exposure

Both ordinary thermometers and maximum and minimum thermometers are always exposed in a thermometer screen placed on a support. Extreme thermometers are mounted on suitable supports so that they are inclined at an angle of about 2° from the horizontal position, with the bulb being lower than the stem.

The siting and exposure of grass minimum thermometers is as prescribed in section 2.2.2.2. At a station where snow is persistent and of varying depth, it is possible to use a support that allows the thermometers to be raised or lowered to maintain the correct height above the snow surface.

2.2.4 Sources of error in liquid-in-glass thermometers

The main sources of error common to all liquid-in-glass thermometers are the following:
(a) Elastic errors;
(b) Errors caused by the emergent stem;
(c) Parallax and gross reading errors;
(d) Changes in the volume of the bulb produced by exterior or interior pressure;
(e) Capillarity;
(f) Errors in scale division and calibration;
(g) Inequalities in the expansion of the liquid and glass over the range considered.

The last three errors can be minimized by the manufacturer and included in the corrections to be applied to the observed values. Some consideration needs to be given to the first three errors. Error (d) does not usually arise when the thermometers are used for meteorological purposes.

2.2.4.1 Elastic errors

There are two kinds of elastic errors, namely reversible and irreversible errors. The first is of importance only when a thermometer is exposed to a large temperature range in a short period of time. Thus, if a thermometer is checked at the steam point and shortly afterwards at the ice point, it will read slightly too low at first and then the indicated temperature will rise slowly to the correct value. This error depends on the quality of the glass employed in the thermometer, and may be as much as 1 K (with glass of the highest quality it should be only 0.03 K) and would be proportionately less for smaller ranges of temperature. The effect is of no importance in meteorological measurements, apart from the possibility of error in the original calibration.

The irreversible changes may be more significant. The thermometer bulb tends to contract slowly over a period of years and, thus, causes the zero to rise. The greatest change will take place in the first year, after which the rate of change will gradually decrease. This alteration can be reduced by subjecting the bulb to heat treatment and by using the most suitable glass. Even with glass of the highest quality, the change may be about 0.01 K per year at first. For accurate work, and especially with inspector or check thermometers, the zero should be redetermined at the recommended intervals and the necessary corrections applied.

2.2.4.2 Errors caused by the emergent stem

A thermometer used to measure air temperature is usually completely surrounded by air at an approximately uniform temperature, and is calibrated by immersing the thermometer either completely or only to the top of the mercury column (namely, calibrated by complete or partial immersion). When such a thermometer is used to determine the temperature of a medium which does not surround the stem, so that the effective temperature of the stem is different from that of the bulb, an error will result.

For meteorological applications, the most likely circumstance where this might be encountered is when checking the calibration of an ordinary thermometer in a vessel containing another liquid at a temperature significantly different from ambient temperature and only the bulb or lower part of the stem is immersed.

2.2.4.3 Parallax and gross reading errors

If the thermometer is not viewed on the plane that is perpendicular to the stem of the thermometer, parallax errors will arise. The error increases with the thickness of the thermometer stem and the angle between the actual and the correct line of sight. This error can be avoided only by taking great care when making an observation. With mercury-in-glass thermometers suspended vertically, as in an ordinary screen, the thermometer must be viewed at the horizontal level of the top of the mercury column.

Errors can also occur because observers usually disturb the surroundings in some way when they approach to read the thermometer. It is, therefore, necessary for observers to take the readings to the nearest tenth of a degree as soon as possible. Gross reading errors are usually 1, 5 or 10° in magnitude. Such errors will be avoided if observers recheck the tens and units figure after taking their initial reading.

2.2.4.4 Errors due to differential expansion

The coefficient of cubical expansion of mercury is $1.82 \cdot 10^{-4}$ K^{-1}, and that of most glass lies between $1.0 \cdot 10^{-5}$ and $3.0 \cdot 10^{-5}$ K^{-1}. The expansion coefficient of the glass is, thus, an important fraction of that of mercury and cannot be neglected. As neither the coefficients of cubical expansion of mercury and glass nor the cross-sectional area of the bore of the stem are strictly constant over the range of temperature and length of the stem being used, the scale value of unit length of the stem varies along the stem, and the thermometer has to be calibrated by the manufacturer against a standard thermometer before it can be used.

2.2.4.5 Errors associated with spirit thermometers

The expansion coefficients of the liquids used in spirit thermometers are very much larger than those of mercury, and their freezing points are much lower (ethyl alcohol freezes at –115°C). Spirit is used in minimum thermometers because it is colourless and because its larger expansion coefficient enables a larger bore to be used. Spirit thermometers are less accurate than mercury thermometers of similar cost and quality. In addition to having the general disadvantages of liquid-in-glass thermometers, spirit thermometers have some peculiarities to themselves:

(a) Adhesion of the spirit to the glass: Unlike mercury, organic liquids generally wet the glass. Therefore, when the temperature falls rapidly, a certain amount of the liquid may remain on the walls of the bore, causing the thermometer to read low. The liquid gradually drains down the bore if the thermometer is suspended vertically;
(b) Breaking of the liquid column: Drops of the liquid often form in the upper part of the thermometer stem by a process of evaporation and condensation. These can be reunited with the main column, but errors may be caused at the beginning of the process before it is noticed. The column is also often broken during transport. This error is reduced during manufacture by sealing off the thermometer at its lowest temperature so that it contains the maximum amount of air in the stem;
(c) Slow changes in the liquid: The organic liquids used tend to polymerize with age and exposure to light, with a consequent gradual diminution in liquid volume. This effect is speeded up by the presence of impurities; in particular, the presence of acetone in ethyl alcohol has been shown to be very deleterious. Great care has therefore to be taken over the preparation of the liquid for the thermometers. This effect may also be increased if dyes are used to colour the liquid to make it more visible.

The reduction of errors caused by breakage in the liquid column and the general care of spirit thermometers are dealt with later in this chapter.

2.2.5 Comparison and calibration in the field and laboratory

2.2.5.1 Laboratory calibration

Laboratory calibrations of thermometers should be carried out by national testing institutions or accredited calibration laboratories. For liquid-in-glass thermometers, a liquid bath should be employed, within which it should be possible to maintain the temperature at any desired values within the required range. The rate of temperature change within the liquid should not exceed the recommended limits, and the calibration apparatus should be provided with a means of stirring the liquid. The reference thermometers and thermometers being tested should be suspended independently of the container and fully immersed, and should not touch the sides.

Sufficient measurements should be taken to ensure that the corrections to be applied represent the performance of the thermometer under normal conditions, with errors due to interpolation at any intermediate point not exceeding the non-systematic errors (see Part III, Chapter 4).

2.2.5.2 Field checks and calibration

All liquid-in-glass thermometers experience gradual changes of zero. For this reason, it is desirable to check them at regular intervals, usually about once every two years. The thermometers should be stored in an upright position at room temperature for at least 24 h before the checking process begins.

The ice point may be checked by almost filling a Dewar flask with crushed ice made from distilled water and moistening it with more distilled water. The space between the ice pieces as well as the bottom of the vessel should be free from air. The water should remain 2 cm beneath the ice surface. An ordinary Thermos flask will accommodate the total immersion of most thermometers up to their ice point. The thermometers should be inserted so that as little of the mercury or spirit column as possible emerges from the ice. An interval of at least 15 min should elapse to allow the thermometer to take up the temperature of the melting ice before a reading of the indicated temperature is taken. Each thermometer should be moved backwards and forwards through the mixture and immediately read to a tenth part of the scale interval. Further readings at 5 min intervals should be taken and a mean value computed.

Other points in the range can be covered by reference to a travelling standard or inspector thermometer. Comparison should be made by immersing the reference thermometer and the thermometer, or thermometers, to be tested in a deep vessel of water. It is generally better to work indoors, especially if the sun is shining, and the best results will be obtained if the water is at, or close to, ambient temperature.

Each thermometer is compared with the reference thermometer; thermometers of the same type can be compared with each other. For each comparison, the thermometers are held with their bulbs close together, moved backwards and forwards through the water for about 1 min, and then read. It must be possible to read both thermometers without changing the depth of immersion; subject to this, the bulbs should be as deep in the water as possible. Most meteorological thermometers are calibrated for total immersion; provided that the difference between the water and air temperature is not more than 5 K, the emergent stem correction should be negligible. Often, with the bulbs at the same depth, the tops of the columns of mercury (or other liquid) in the reference thermometer and the thermometer being checked will not be very close together. Particular care should therefore be taken to avoid parallax errors.

These comparisons should be made at least three times for each pair of thermometers. For each set of comparisons, the mean of the differences between readings should not exceed the tolerances specified in the table in section 2.1.3.2.

Soil thermometers may be tested in this manner, but should be left in the water for at least 30 min to allow the wax in which the bulbs are embedded to take up the temperature of the water. The large time-constant of the soil thermometer makes it difficult to conduct a satisfactory check unless the temperature of the water can be kept very steady. If the test is carefully carried out in water whose temperature does not change by more than 1 K in 30 min, the difference from the corrected reading of the reference thermometer should not exceed 0.25 K.

2.2.6 **Corrections**

When initially issued, thermometers identified by a serial number should be provided with either a dated certificate confirming compliance with the uncertainty requirement, or a dated calibration certificate giving the corrections that should be applied to the readings to achieve the required uncertainty.

In general, if the errors at selected points in the range of a thermometer (for example, 0°C, 10°C, 20°C) are all within 0.05 K, no corrections will be necessary and the thermometers can be used directly as ordinary thermometers in naturally ventilated screens and as maximum, minimum, soil or grass minimum thermometers. If the errors at these selected points are greater than 0.05 K, a table of corrections should be available to the observer at the place of reading, together with unambiguous instructions on how these corrections should be applied.

Thermometers for which certificates would normally be issued are those:
(a) For use in ventilated psychrometers;
(b) For use by inspectors as travelling standards;
(c) For laboratory calibration references;
(d) For special purposes for which the application of corrections is justified.

For psychrometric use, identical thermometers should be selected.

2.2.7 **Maintenance**

2.2.7.1 **Breakage in the liquid column**

The most common fault encountered is the breaking of the liquid column, especially during transit. This is most likely to occur in spirit (minimum) thermometers. Other problems associated with these thermometers are adhesion of the spirit to the glass and the formation by distillation of drops of spirit in the support part of the bore.

A broken liquid column can usually be reunited by holding the thermometer bulb-end downward and tapping the thermometer lightly and rapidly against the fingers or something else which is elastic and not too hard. The tapping should be continued for some time (5 min if necessary), and afterwards the thermometer should be hung, or stood, upright in a suitable container, bulb downward, for at least 1 h to allow any spirit adhering to the glass to drain down to the main column. If such treatment is not successful, a more drastic method is to cool the bulb in a freezing mixture of ice and salt, while keeping the upper part of the stem warm; the liquid will slowly distil back to the main column. Alternatively, the thermometer may be held upright with its bulb in a vessel of warm water, while the stem is tapped or shaken from the water as soon as the top of the spirit column reaches the safety chamber at the top of the stem. Great care must be taken when using this method as there is a risk of bursting the thermometer if the spirit expands into the safety chamber.

2.2.7.2 Scale illegibility

Another shortcoming of unsheathed liquid-in-glass thermometers is that with time their scale can become illegible. This can be corrected at the station by rubbing the scale with a dark crayon or black lead pencil.

2.2.8 Safety

Mercury, which is the liquid most commonly used in liquid-in-glass thermometers, is poisonous if swallowed or if its vapour is inhaled. If a thermometer is broken and the droplets of mercury are not removed there is some danger to health, especially in confined spaces. (Advice on cleaning up after a breakage is given in Part I, Chapter 3, in section 3.2 on mercury barometers.) There may also be restrictions on the carriage of mercury thermometers on aircraft, or special precautions that must be taken to prevent the escape of mercury in the event of a breakage. The advice of the appropriate authority or carrier should be sought.

2.3 MECHANICAL THERMOGRAPHS

2.3.1 General description

The types of mechanical thermographs still commonly used are supplied with bimetallic or Bourdon-tube sensors since these are relatively inexpensive, reliable and portable. However, they are not readily adapted for remote or electronic recording. Such thermographs incorporate a rotating chart mechanism common to the family of classic recording instruments. In general, thermographs should be capable of operating over a range of about 60 K or even 80 K if they are to be used in continental climates. A scale value is needed such that the temperature can be read to 0.2 K without difficulty on a reasonably sized chart. To achieve this, provisions should be made for altering the zero setting of the instrument according to the season. The maximum error of a thermograph should not exceed 1 K.

2.3.1.1 Bimetallic thermograph

In bimetallic thermographs, the movement of the recording pen is controlled by the change in curvature of a bimetallic strip or helix, one end of which is rigidly fixed to an arm attached to the frame. A means of finely adjusting this arm should be provided so that the zero of the instrument can be altered when necessary. In addition, the instrument should be provided with a means of altering the scale value by adjusting the length of the lever that transfers the movement of the bimetal to the pen; this adjustment is best left to authorized personnel. The bimetallic element should be adequately protected from corrosion; this is best done by heavy copper, nickel or chromium plating, although a coat of lacquer may be adequate in some climates. A typical time-constant of about 25 s is obtained at an air speed of 5 m s^{-1}.

2.3.1.2 Bourdon-tube thermograph

The general arrangement is similar to that of the bimetallic type but its temperature-sensitive element is in the form of a curved metal tube of flat, elliptical section, filled with alcohol. The Bourdon tube is less sensitive than the bimetallic element and usually requires a multiplying level mechanism to give sufficient scale value. A typical time-constant is about 6 s at an air speed of 5 m s^{-1}.

2.3.2 Measurement procedures

In order to improve the resolution of the reading, thermographs will often be set, in different seasons, to one of two different ranges with corresponding charts. The exact date for changing from one set of charts to the other will vary according to the locality. However, when the change is made the instrument will need to be adjusted. This should be done either in the screen on a cloudy, windy day at a time when the temperature is practically constant or in a room where the temperature is constant. The adjustment is made by loosening the screw holding the pen arm to the pen spindle, moving the pen arm to the correct position and retightening, the screws. The instrument should then be left as is before rechecking, and any further adjustments made as necessary.

2.3.3 Exposure and siting

These instruments should be exposed in a large thermometer screen.

2.3.4 Sources of error

In the thermograph mechanism itself, friction is the main source of error. One cause of this is bad alignment of the helix with respect to the spindle. Unless accurately placed, the helix acts as a powerful spring and, if rigidly anchored, pushes the main spindle against one side of the bearings. With modern instruments this should not be a serious problem. Friction between the pen and the chart can be kept to a minimum by suitably adjusting the gate suspension.

2.3.5 Comparison and calibration

2.3.5.1 Laboratory calibration

There are two basic methods for the laboratory calibration of bimetallic thermographs. They may be checked by fixing them in a position with the bimetallic element in a bath of water. Alternatively, the thermograph may be placed in a commercial calibration chamber equipped with an air temperature control mechanism, a fan and a reference thermometer.

Comparisons should be made at two temperatures; from these, any necessary changes in the zero and magnification can be found. Scale adjustments should be performed by authorized personnel, and only after reference to the appropriate manufacturer's instrument handbook.

2.3.5.2 Field comparison

The time-constant of the instrument may be as low as one half that of the ordinary mercury thermometer, so that routine comparisons of the readings of the dry bulb and the thermograph at fixed hours will, in general, not produce exact agreement even if the instrument is working perfectly. A better procedure is to check the reading of the instrument on a suitable day at a time when the temperature is almost constant (usually a cloudy, windy day) or, alternatively, to compare the minimum readings of the thermograph trace with the reading of the minimum thermometer exposed in the same screen. Any necessary adjustment can then be made by means of the setting screw.

2.3.6 Corrections

Thermographs would not normally be issued with correction certificates. If station checks show an instrument to have excessive errors, and if these cannot be adjusted locally, the instrument should be returned to an appropriate calibration laboratory for repair and recalibration.

2.3.7 Maintenance

Routine maintenance will involve an inspection of the general external condition, the play in the bearings, the inclination of the recording arm, the set of the pen, and the angle between the magnification arm and recording arm, and a check of the chart-drum clock timing. Such examinations should be performed in accordance with the recommendations of the manufacturer. In general, the helix should be handled carefully to avoid mechanical damage and should be kept clean. The bearings of the spindle should also be kept clean and oiled at intervals using a small amount of clock oil. The instrument is mechanically very simple and, provided that precautions are taken to keep the friction to a minimum and prevent corrosion, it should give good service.

2.4 ELECTRICAL THERMOMETERS

2.4.1 General description

Electrical instruments are in widespread use in meteorology for measuring temperatures. Their main virtue lies in their ability to provide an output signal suitable for use in remote indication, recording, storage, or transmission of temperature data. The most frequently used sensors are electrical resistance elements, semiconductor thermometers (thermistors) and thermocouples.

2.4.1.1 Electrical resistance thermometers

A measurement of the electrical resistance of a material whose resistance varies in a known manner with the temperature of the material can be used to represent the temperature.

For small temperature changes, the increase in resistance of pure metals is proportional to the change in temperature, as expressed in equation 2.2:

$$R_T = R_0 \, [1 + \alpha \, (T - T_0)] \tag{2.2}$$

where $(T - T_0)$ is small; R_T is the resistance of a fixed amount of the metal at temperature T; R_0 is its resistance at a reference temperature T_0, and α is the temperature coefficient of resistance in the vicinity of T_0.

With 0°C as the reference temperature, equation 2.2 becomes:

$$R_T = R_0\ (1 + \alpha \cdot t) \tag{2.3}$$

For larger temperature changes and for certain metallic alloys, equation 2.4 expresses the relationship more accurately:

$$R_T = R_0\ [1 + \alpha\ (T - T_0) + \beta\ (T - T_0)^2] \tag{2.4}$$

With 0°C as the reference temperature, equation 2.4 becomes:

$$R_T = R_0\ (1 + \alpha \cdot t + \beta \cdot t^2) \tag{2.5}$$

These equations give the proportional change in resistance of an actual thermometer, so that values for the coefficients α and β can be found by calibration of the thermometer concerned. Based on these results, the inverse function, namely, t as a function of R, can be derived. Such a function may be expressed in terms of a linear series of $(R_0 - R_T)$, namely, $t = t\ (R_0 - R_T) = c_1\ (R_0 - R_T) + c_2\ (R_0 - R_T)^2 + \dots$.

A good metal resistance thermometer will satisfy the following requirements:

(a) Its physical and chemical properties will remain the same through the temperature measurement range;
(b) Its resistance will increase steadily with increasing temperature without any discontinuities in the range of measurement;
(c) External influences such as humidity, corrosion or physical deformations will not alter its resistance appreciably;
(d) Its characteristics will remain stable over a period of two years or more;
(e) Its resistance and thermal coefficient should be large enough to be useful in a measuring circuit.

Pure platinum best satisfies the foregoing requirements. Thus, it is used for the primary standard thermometers needed for transferring the ITS-90 between instrument locations. Platinum thermometers are also used for secondary standards and for operational sensors.

Practical thermometers are artificially aged before use and are commonly made from platinum alloys, nickel and occasionally tungsten for meteorological purposes. Usually they are hermetically sealed in a ceramic sheath. Their time-constant is smaller than that of liquid-in-glass thermometers.

2.4.1.2 Semiconductor thermometers

Another type of resistance element in common use is the thermistor. This is a semiconductor with a relatively large temperature coefficient of resistance, which may be either positive or negative depending upon the actual material. Mixtures of sintered metallic oxides are suitable for making practical thermistors, which usually take the form of small discs, rods or spheres and are often glass-coated. The general expression for the temperature dependence of the resistance, R, of the thermistor is given in equation 2.6:

$$R = a\ \exp\ (b/T) \tag{2.6}$$

where a and b are constants and T is the temperature of the thermistor in kelvins.

The advantages of thermistors from a thermometric point of view are as follows:

(a) The large temperature coefficient of resistance enables the voltage applied across a resistance bridge to be reduced while attaining the same sensitivity, thus reducing or even eliminating the need to account for the resistance of the leads and its changes;
(b) The elements can be made very small, so their very low thermal capacities can yield a small time-constant. However, very small thermistors with their low thermal capacity have the disadvantage that, for a given dissipation, the self-heating effect is greater than for large thermometers. Thus, care must be taken to keep the power dissipation small.

A typical thermistor has a resistance which varies by a factor of 100 or 200 over the temperature range –40 to 40°C.

2.4.1.3 Thermocouples

In 1821 Seebeck discovered that a very small contact electromotive force was set up at the place where two different metals touched. If a simple circuit is made with two metals and with the conjunction at the same temperature, there will be no resultant electromotive force in the circuit because the two electromotive forces, one at each junction, will exactly oppose and cancel one another. If the temperature of one junction is altered, the two electromotive forces no longer balance and there is a net electromotive force set up in the circuit; a current will then flow. When there are several junctions, the resultant electromotive force is the algebraic sum of the individual electromotive forces. The magnitude and sign of the contact electromotive force set up at any one junction depend on the types of metals joined and the temperature of the junction point, and may be empirically represented for any two metals by the expression:

$$(E_T - E_s) = \alpha\,(T - T_s) + \beta\,(T - T_s)^2 \qquad (2.7)$$

where E_T is the contact electromotive force at a temperature T and E_s is the electromotive force at some standard temperature T_s, α and β being constants. If there are two junctions at temperatures T_1 and T_2, the net electromotive force E_n (the thermal electromotive force) is given by $(E_1 - E_2)$, where E_1 is the electromotive force at temperature T_1 and E_2 is the contact electromotive force temperature $T_2 \cdot E_n$ can also be represented by a quadratic formula of the type given for $(E_T - E_s)$ to a good approximation:

$$E_n = E_1 - E_2 \qquad (2.8)$$

$$E_n = a\,(T_1 - T_2) + b\,(T_1 - T_2)^2 \qquad (2.9)$$

where a and b are constants for the two metals concerned. For most meteorological purposes, it is often possible to neglect the value of b, as it is always small compared with a.

Thermocouples are made by welding or soldering together wires of the metals concerned. These junctions can be made very small and with negligible heat capacity.

When used to measure temperature, a measurement is taken of the electromotive force set up when one junction is maintained at a standard known temperature and the other junction is allowed to take the temperature whose value is required. This electromotive force can be directly related to the difference in temperature between the two junctions by previous calibration of the system, and thus the unknown temperature is found by adding this difference algebraically to the known standard temperature.

In meteorology, thermocouples are mostly used when a thermometer of very small time-constant, of the order of 1 or 2 s, and capable of remote reading and recording is required, usually for special research tasks. A disadvantage, if the absolute temperature is required, is the necessity for a constant-temperature enclosure for both the cold junction and ancillary apparatus for the measurements of the electromotive force that has been set up; thermocouples are best suited for the measurement of differential temperatures, since this complication does not arise. Very high accuracy can be achieved with suitably sensitive apparatus, but frequent calibration is necessary. Copper-constantan or iron-constantan combinations are suitable for meteorological work, as the electromotive force produced per degree Celsius is higher than with rarer and more expensive metals, which are normally used at high temperatures.

2.4.2 Measurements procedures

2.4.2.1 Electrical resistances and thermistors

Electrical resistance and thermistor thermometers may be connected to a variety of electrical measurement circuits, many of which are variations of resistance bridge circuits in either balanced or unbalanced form. In a balanced bridge, an accurate potentiometer is adjusted until no current flows in an indicator, with the position of the potentiometer arm being related to the temperature. In an unbalanced bridge, the out-of-balance current may be measured by a galvanometer; however, this current is not simply a function of the temperature and depends in part on other effects. An alternative which avoids this situation is to use a constant current source to power the bridge and to measure the out-of-balance voltage to obtain the temperature reading.

In the case of remote measuring, it should be taken into consideration that the wire between the resistance thermometer and the bridge also forms a resistance that alters depending on the temperature. Suitable precautions can be taken to avoid such errors.

Digital voltmeters can be used in conjunction with a constant current source to measure the temperature-dependent voltage drop across the thermometer element; the output can be scaled directly in temperature. Also, the digital output can be stored or transmitted without loss of accuracy and, thus, be available for further use. The digital output of the digital voltmeters can be subsequently converted back to an analogue voltage, if desired, to feed a recorder, for example.

2.4.2.2 Thermocouples

There are two main methods of measuring the electromotive force produced by thermocouples:

(a) By measuring the current produced in the circuit with a sensitive galvanometer;
(b) By balancing the thermoelectric electromotive force with a known electromotive force, so that no current actually flows through the thermocouples themselves.

In method (a), the galvanometer is connected directly in series with the two junctions. Method (b) will generally be used if a measuring uncertainty of better than 0.5 per cent is required. This procedure does not depend on the magnitude of, or changes in, the line resistance since no current flows in the balanced condition.

2.4.3 Exposure and siting

The requirements relating to the exposure and siting of electrical thermometers will, in general, be the same as those for liquid-in-glass thermometers (see section 2.2.3). Exceptions include the following:

(a) The measurement of extreme values: Separate maximum and minimum thermometers may no longer be required if the electrical thermometer is connected to a continuously operating data recording system;
(b) The measurement of surface temperatures: The radiative properties of electrical thermometers will be different from liquid-in-glass thermometers. Electrical thermometers exposed as grass minimum (or other surface) thermometers will, therefore, record different values from similarly exposed conventional thermometers. These differences may be minimized by placing the electrical thermometer within a glass sheath;
(c) The measurement of soil temperatures: The use of mercury-in-glass thermometers in vertical steel tubes is quite unsuitable for the measurement of the diurnal variation of soil temperature because of heat conduction from the surface. It is possible to obtain readings that are much more representative by deploying electrical thermometers in brass plugs, inserted at the required depth into an undisturbed vertical soil face, the latter having been exposed by trenching. Electrical connections are brought out through plastic tubes via the trench, which is then refilled in such a way to restore, as far as possible, the original strata and drainage characteristics.

2.4.4 Sources of error

2.4.4.1 Electrical resistances and thermistors

The main sources of error in a temperature measurement taken with electrical resistance thermometers are the following:

(a) Self-heating of the thermometer element;
(b) Inadequate compensation for lead resistance;
(c) Inadequate compensation for non-linearities in the sensor or processing instrument;
(d) Sudden changes in switch contact resistances.

Self-heating occurs because the passage of a current through the resistance element produces heat and, thus, the temperature of the thermometer element becomes higher than that of the surrounding medium.

The resistance of the connecting leads will introduce an error in the temperature reading. This will become more significant for long leads, for example, when the resistance thermometer is located at some distance from the measuring instrument; the reading errors will also vary as the temperature of the cables changes. These errors can be compensated for by using extra conductors, ballast resistors and an appropriate bridge network.

Neither the electrical resistance thermometer nor the thermistor is linear over an extended temperature range but may approximate a linear output if the range is limited. Provision must, therefore, be made to compensate for such non-linearities. This is most likely to be required for thermistors, to achieve a usable meteorological range of measurement.

Sudden changes in switch contact resistance can occur as switches age. They may be variable and can go undetected unless regular system calibration checks are performed (see section 2.4.5).

2.4.4.2 Thermocouples

The main sources of error in the measurement of temperature using thermocouples are the following:

(a) Changes in the resistances of the connecting leads with temperature. This effect may be minimized by keeping all the leads as short and compact as possible, and well insulated;

(b) Conduction along the leads from the junction when there is a temperature gradient in the vicinity of the temperature measuring point;
(c) Stray secondary thermal electromotive forces due to the use of metals that are different from the thermocouple metals in the connecting circuit. The temperature differences in the remainder of the circuit must, therefore, be kept as low as possible; this is especially important when the electromotive forces to be measured are small (periodical recalibration will be necessary to allow for this);
(d) Leakage currents can occur from neighbouring power circuits. This can be minimized by suitable screening of the leads;
(e) Galvanic currents can be set up if any leads or junctions are allowed to get wet;
(f) Changes in temperature in the galvanometer alter its characteristics (chiefly by changing its resistance). This will not affect the readings by the potentiometric method to any degree, but will affect direct-reading instruments. This effect can be minimized by keeping the temperature of the galvanometer as near as possible to that at which the circuit was calibrated;
(g) In the potentiometric measurement, changes in the electromotive force of the standard cell against which the potentiometer current is adjusted and changes in the potentiometer current between adjustments will cause corresponding errors in the measured electromotive force. These errors will normally be small, provided that the standard cell is treated correctly, and that adjustments of the potentiometer current are made just before taking a temperature measurement.

Errors (a) and (f) emphasize the superiority of the potentiometric method when a very high degree of accuracy is required.

2.4.5 Comparison and calibration

2.4.5.1 Electrical resistances and thermistors

The basic techniques and procedures for the laboratory calibration and field checking of electrical thermometers will be the same as for liquid-in-glass thermometers (see section 2.2.5). In general, however, it will not be possible to bring a resistance thermometer indoors since checks should include the thermometer's normal electrical leads. Checks will therefore have to be carried out with the thermometers in the screen. Accurate comparative measurements of the temperatures indicated by the electrical thermometer and a reference mercury-in-glass or local indicating resistance thermometer will be difficult to achieve unless two observers are present. Since the measurement instrument is an integral part of the electrical thermometer, its calibration may be checked by substituting the resistance thermometer by an accurate decade resistance box and by applying resistances equivalent to fixed 5 K temperature increments over the operational temperature range. The error at any point should not exceed 0.1 K. This work would normally be performed by a servicing technician.

2.4.5.2 Thermocouples

The calibration and checking of thermocouples require the hot and cold junctions to be maintained at accurately known temperatures. The techniques and instrumentation necessary to undertake this work are generally very specialized and will not be described here.

2.4.6 Corrections

When initially issued, electrical thermometers (which have a serial number) should be provided with either:
(a) A dated certificate confirming compliance with the appropriate standard; or
(b) A dated calibration certificate giving the actual resistance at fixed points in the temperature range. These resistances should be used when checking the uncertainty of the measuring instrument or system interface before and during operation. The magnitude of the resistance difference from the nominal value should not, in general, be greater than an equivalent temperature error of 0.1 or 0.2 K.

2.4.7 Maintenance

The regular field checks should identify any changes in system calibration. These may occur as a result of long-term changes in the electrical characteristics of the thermometer, degradation of the electrical cables or their connections, changes in the contact resistance of switches or changes in the electrical characteristics of the measuring equipment. Identification of the exact source and correction of such errors will require specialized equipment and training and should be undertaken only by a maintenance technician.

2.5 RADIATION SHIELDS

A radiation shield or screen should be designed to provide an enclosure with an internal temperature that is both uniform and the same as that of the outside air. It should completely surround the thermometers and exclude radiant heat, precipitation and other phenomena that might influence the measurement. Screens with forced ventilation, in which air is drawn over the thermometer element by a fan, may help to avoid biases when the microclimate inside the screen deviates from the surrounding air mass. Such a deviation only occurs when the natural wind speed is very low (< 1 m s^{-1}). When such artificial ventilation is used, care should be taken to prevent the deposition of aerosols and rain droplets on the sensor which decrease its temperature towards the wet-bulb temperature. As a shield material, highly polished, non-oxidized metal is favourable because of its high reflectivity and low heat absorption. Nevertheless, thermally insulating plastic-based material is preferable because of its simple maintenance requirements. Thermally insulating material must be used if the system relies on natural ventilation.

The performance of a screen (response behaviour and microclimate effects introducing unwanted biases) depends predominantly on its design, in which care must be taken to ensure both radiation protection and sufficient ventilation. Since the start of meteorological temperature measurements, very diverse types of screens have been designed. Following the introduction of temperature measurements taken in automatic weather stations, the variety of these designs has increased significantly (see WMO, 1998*a*). Because of differences in specific applications, the degree of automation and climatology, it is difficult to recommend one specific type of design suitable for worldwide measurements. Nevertheless, many investigations and intercomparisons on designs and their performance have been carried out. A clear overview of screen designs is given by WMO (1972). Results of thermometer screen intercomparisons are reported by Andersson and Mattison (1991); Sparks (2001); WMO (1998*b*; 1998*c*; 1998*d*; 2000*a*; 2000*b*; 2002*b;* 2002*c*; 2002*d*); and Zanghi (1987).

An international standard (ISO/DIS 17714) defines most relevant screen types and describes the methods to determine or compare screen performances (ISO, 2004).

2.5.1 Louvred screens

Most of the numerous varieties of louvred screen rely on natural ventilation. The walls of such a screen should preferably be double-louvred and the floor should be made of staggered boards, but other types of construction may be found to meet the above requirements. The roof should be double-layered, with provisions for ventilation of the space between the two layers. In cold climates, owing to the high reflectivity of snow (up to 88 per cent), the screen should also have a double floor. At the same time, however, the floor should easily drop or tilt so that any snow entering the screen during a storm can be removed.

The size and construction of the screen should be such that it keeps the heat capacity as low as practicable and allows ample space between the instruments and the walls. The latter feature excludes all possibility of direct contact between the thermometer sensing elements and the walls, and is particularly important in the tropics where insolation may heat the sides to the extent that an appreciable temperature gradient is caused in the screen. Direct contact between the sensing elements and the thermometer mounting should also be avoided. The screen should be painted both inside and outside with white, non-hygroscopic paint.

When double walls are provided, the layer of air between them serves to reduce the amount of heat that would otherwise be conducted from the outer wall to the inner enclosure, especially in strong sunshine. When the wind is appreciable, the air between the walls is changed continually so that the conduction of heat inwards from the outer walls is further decreased.

The free circulation of air throughout the screen helps the temperature of the inner wall adapt to ambient air changes. In this way, the influence of the inner wall upon the temperature of the thermometer is reduced. Also, the free circulation of air within the screen enables the thermometer to follow the ambient air changes more quickly than if radiative exchanges alone were operative. However, the air circulating through the screen spends a finite time in contact with the outer walls and may have its temperature altered thereby. This effect becomes appreciable when the wind is light and the temperature of the outer wall is markedly different from the air temperature. Thus, the temperature of the air in a screen can be expected to be higher than the true air temperature on a day of strong sunshine and calm wind, and slightly lower on a clear, calm night, with errors perhaps reaching 2.5 and –0.5 K, respectively, in extreme cases. Additional errors may be introduced by cooling due to evaporation from a wet screen after rain. All these errors also have a direct influence on the readings of other instruments inside the screen, such as hygrometers, evaporimeters, and the like.

Errors due to variations in natural ventilation can be reduced if the screen is fitted with a suitably designed forced ventilation system that maintains a constant and known ventilation rate, at least at low wind speeds. Care should be taken in the design of such systems to ensure that heat from the fan or an electrical motor does not affect the screen temperature.

In general, only one door is needed, with the screen being placed so that the sun does not shine on the thermometers when the door is open at the times of observation. In the tropics, two doors are necessary for use during different periods of the year. Likewise, in polar regions (where the sun is at a low angle) precautions should be taken to protect the inside of the screen from the direct rays of the sun either by a form of shading or by using a screen which is mounted so that it can be turned to an appropriate angle while the door is open for readings.

Although most screens are still made of wood, some recent designs using plastic materials offer greater protection against radiation effects because of an improved louvre design that provides a better air-flow. In any case, the screen and stand should be constructed of sturdy materials and should be firmly installed so that errors in maximum and minimum thermometer readings caused by wind vibration are kept to a minimum. In some areas where wind vibration cannot be entirely damped, elastic mounting brackets are recommended. The ground cover beneath the screen should be grass or, in places where grass does not grow, the natural surface of the area.

The screen should be kept clean and repainted regularly; in many places, repainting the screen once every two years is sufficient, but in areas subject to atmospheric pollution it may be necessary to repaint it at least once a year.

2.5.2 Other artificially ventilated shields

The main alternative to exposure in a louvred screen, which is either naturally or artificially ventilated, is to shield the thermometer bulb from direct radiation by placing it on the axis of two concentric cylindrical shields and drawing a current of air (with a speed between 2.5 and 10 m s^{-1}) between the shields and past the thermometer bulb. This type of exposure is normal in aspirated psychrometers (see Part I, Chapter 4). In principle, the shields should be made of a thermally insulating material, although in the Assmann psychrometer the shields are made of highly polished metal to reduce the absorption of solar radiation. The inner shield is kept in contact with a moving stream of air on both sides so that its temperature, and consequently that of the thermometer, can approximate very closely to that of the air. Such shields are usually mounted with their axes in a vertical position. The amount of direct radiation from the ground entering through the base of such shields is small and can be reduced by extending the base of the shields appreciably below the thermometer bulb. When the artificial ventilation is provided by an electrically driven fan, care should be taken to prevent any heat from the motor and fan from reaching the thermometers.

The design of the WMO reference psychrometer takes careful account of the effects of radiation and the use of artificial ventilation and shielding to ensure that the thermometer element is at equilibrium at the true air temperature (see Part I, Chapter 4).

ANNEX

DEFINING THE FIXED POINTS OF THE INTERNATIONAL TEMPERATURE SCALE OF 1990

The fixed points of the International Temperature Scale of 1990 (ITS-90) of interest to meteorological measurements are contained in Table 1, while secondary reference points of interest to meteorological measurements are contained in Table 2.

The standard method of interpolating between the fixed points uses formulae to establish the relation between indications of the standard instruments and the values of the ITS-90. The standard instrument used from –259.34 to 630.74°C is a platinum resistance thermometer for which the resistance ratio R_{100}/R_0 is 1.385 0; R_{100} is the resistance at 100°C and R_0 is the resistance at 0°C.

From 0 to 630.74°C, the resistance at temperature t is provided by the equation:

$$R_t = R_0\,(1 + A \cdot t + B \cdot t^2) \qquad (1)$$

where R_t is the resistance at temperature t of a platinum wire, R_0 is its resistance at 0°C and A and B are constants which are found from measurements at R_t at the boiling point of water and the freezing point of zinc.

From –189.344 2°C to 0°C, the resistance at temperature t is provided by the equation:

$$R_t = R_0\,(1 + A \cdot t + \mathrm{B} \cdot t^2 + C \cdot (t–100) \cdot t^3) \qquad (2)$$

where R_t, R_0, A and B are determined as for equation 1 above and C is found by measurement at the boiling point of oxygen.

Table 1. Defining fixed points on the ITS-90

Equilibrium state	*Assigned value of ITS*	
	K	*°C*
Equilibrium between the solid, liquid and vapour phases of argon (triple point of argon)	83.805 8	–189.344 2
Equilibrium between the solid, liquid and vapour phases of mercury (triple point of mercury)	234.315 6	–38.834 4
Equilibrium between the solid, liquid and vapour phases of water (triple point of water)	273.160 0	0.01
Equilibrium between the solid and liquid phases of gallium (freezing point of gallium)	302.914 6	29.764 6
Equilibrium between the solid and liquid phases of indium (freezing point of indium)	429.748 5	156.598 5

Table 2. Secondary reference points and their temperatures on the ITS-90

Equilibrium state	*Assigned value of ITS*	
	K	*°C*
Equilibrium between the solid and vapour phases of carbon dioxide (sublimation point of carbon dioxide) at standard atmospheric pressure p_0 (1 013.25 hPa). The temperature t as a function of the vapour pressure of carbon dioxide is given by the equation: $t = [1.210\ 36 \cdot 10^{-2}\ (p–p_0) – 8.912\ 26 \cdot 10^{-6}(p–p_0)^2 – 78.464]$ °C where p is the atmospheric pressure in hPa, in the temperature range 194 to 195 K	194.686	–78.464
Equilibrium between the solid and liquid phases of mercury (freezing point of mercury) at standard atmospheric pressure	234.296	–38.854
Equilibrium between ice and air-saturated water (ice-point) at standard atmospheric pressure	273.150	0.00
Equilibrium between the solid, liquid and vapour phases of phenoxybenzene (diphenyl ether) (triple point of phenoxybenzene)	300.014	26.864

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