

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, 2003a; 1989), aeronautical meteorology (WMO, 1990), hydrology (WMO, 1994), agricultural meteorology (WMO, 1981) 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. Their terms of reference and locations are given in Annex 1.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, 1992a) and the *International Vocabulary of Basic and General Terms in Metrology* (ISO, 1993a).

1.1.2 Representativeness

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

In particular, applications have their own preferred timescales and space scales for averaging, station density and resolution of phenomena — small for agricultural meteorology, large for global long-range forecasting. Forecasting scales are closely related to the timescales of the phenomena; thus, shorter-range weather forecasts require more frequent observations from a denser network over a limited area in order to detect any small-scale phenomena and their quick development. Using various sources (WMO, 2003a; 2001; 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.

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

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.

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*b*). 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 (2003*a*) 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 (2003*a*). 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 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 (1993a).

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)

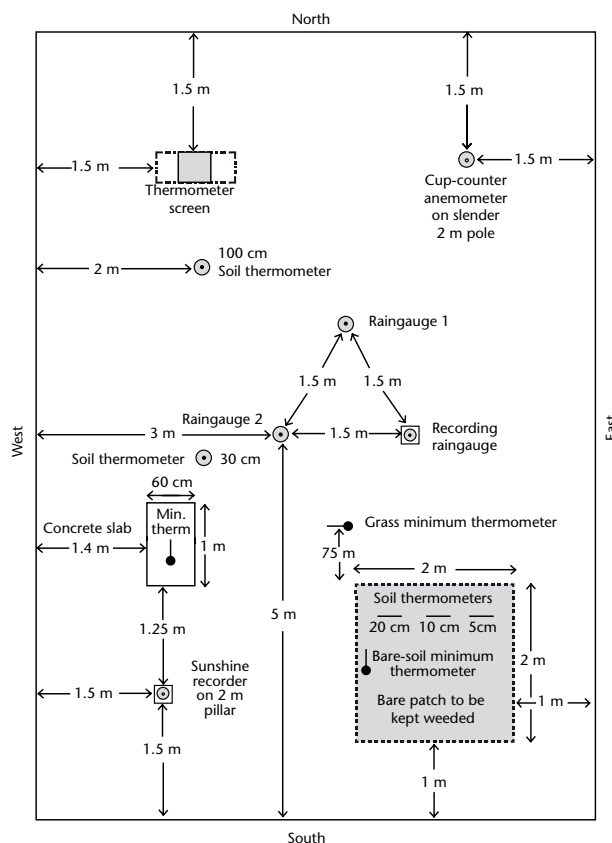


Figure 1.1. Layout of an observing station in the northern hemisphere showing minimum distances between installations

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, 1989);

- (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 rain-gauges. 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.² The coordinates of a station are:

- (a) The latitude in degrees with a resolution of 1 in 1 000;
- (b) The longitude in degrees with a resolution of 1 in 1 000;
- (c) The height of the station above mean sea level,³ namely, the elevation of the station, to the nearest metre.

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 rain gauge stands or, if there is no rain gauge, the ground beneath the thermometer screen. If there is neither rain gauge 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, 1993*b*).

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*a*).

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*b*).

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.

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.

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

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

The 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 (1989).

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 (1993a). Some of the definitions are as follows:

(Measurement) standard: A material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference.

Examples: 1 kg mass standard
100 Ω standard resistor

Notes:

1. A set of similar material measures or measuring instruments that, through their combined use, constitutes a standard is called a “collective standard”.
2. A set of standards of chosen values that, individually or in combination, provides a series of values of quantities of the same kind is called a “group standard”.

International standard: A standard recognized by an international agreement to serve internationally as the basis for assigning values to other standards of the quantity concerned.

National standard: A standard recognized by a national decision to serve, in a country, as the basis

for assigning values to other standards of the same quantity.

Primary standard: A standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity.

Secondary standard: A standard whose value is assigned by comparison with a primary standard of the same quantity.

Reference standard: A standard, generally having the highest metrological quality available at a given location or in a given organization, from which the measurements taken there are derived.

Working standard: A standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials.

Notes:

1. A working standard is usually calibrated against a reference standard.
2. A working standard used routinely to ensure that measurements are being carried out correctly is called a “check standard”.

Transfer standard: A standard used as an intermediary to compare standards.

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

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.

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, or values represented by a material measure, and the corresponding known values of a measurand (the physical quantity being measured).

Notes:

1. The result of a calibration permits the estimation of errors of indication of the measuring instrument, measuring system or material measure, or the assignment of marks on arbitrary scales.
2. A calibration may also determine other metrological properties.
3. The result of a calibration may be recorded in a document, sometimes called a calibration certificate or calibration report.
4. The result of a calibration is sometimes expressed as a calibration factor, or as a series of calibration factors in the form of a calibration curve.

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*b*) 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*b*). 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);⁴
- (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});⁵

4 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).

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

- (g) Precipitation intensity, R_i , in millimetres per hour (mm h^{-1}) or kilograms per m^{-2} per second ($\text{kg m}^{-2} \text{s}^{-1}$);⁶
- (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').

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

The values of other constants are given in WMO (1973; 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 $\pm x$ ”, which should read “an uncertainty of x ”.

1.6.1.2 Sources and estimates of error

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

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

- (a) Errors in the international, national and working standards, and in the comparisons made between them. These may be assumed to be negligible for meteorological applications;
- (b) Errors in the comparisons made between the working, travelling and/or check standards and the field instruments in the laboratory or in liquid baths in the field (if that is how the traceability is established). These are small if the practice is good (say $\pm 0.1 \text{ K}$ 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

⁶ Recommendation 3 (CBS-XII), Annex 1, adopted through Resolution 4 (EC-LIII).

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 (1993a), 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.

$$\langle \text{true value} \rangle = \langle \text{measured value} \rangle \pm \langle \text{uncertainty} \rangle$$

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.

Uncertainty (of measurement): A variable associated with the result of a measurement that characterizes the dispersion of the values that could be reasonably attributed to the measurand.

Notes:

1. The variable may be, for example, a standard deviation (or a given multiple thereof), or the half-width of an interval having a stated level of confidence.

2. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

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 (1993a).

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:

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

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.

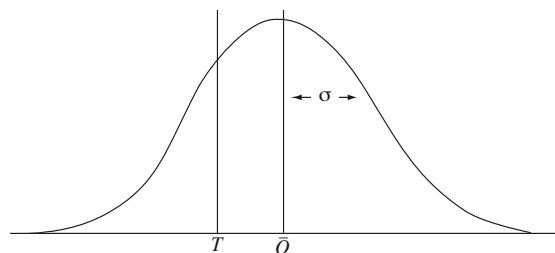


Figure 1.2. The distribution of data in an instrument comparison

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.

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, 1993; 1995):

- (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,⁷ the results may be displayed as in Figure 1.2.

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

In this situation, the following characteristics can be identified:

- (a) The systematic error, often termed bias, given by the algebraic difference $\bar{O} - T$. Systematic errors cannot be eliminated but may often be reduced. A correction factor can be applied to compensate for the systematic effect. Typically, appropriate calibrations and

⁷ However, note that several meteorological variables do not follow a Gaussian distribution. See section 1.6.4.2.3.

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 \bar{O} ;
- (c) The accuracy of measurement, which is the closeness of the agreement between the result of a measurement and a true value of the measurand. The accuracy of a measuring instrument is the ability to give responses close to a true value. Note that "accuracy" is a qualitative concept;
- (d) The uncertainty of measurement, which represents a parameter associated with the result of a measurement, that characterizes the dispersion of the values that could be reasonably attributed to the measurand. The uncertainties associated with the random and systematic effects that give rise to the error can be evaluated to express the uncertainty of measurement.

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:

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

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

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

Some values of k are as follows:

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:

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

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

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:

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

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%
<i>df</i>			
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:

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

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

$$\langle \text{true value} \rangle = \langle \text{measured value} \rangle \pm \langle \text{expanded uncertainty} \rangle = \langle \text{measured value} \rangle \pm 2 \sigma$$

1.6.4.4 Measurements of discrete values

While the state of the atmosphere may be described well by physical variables or quantities, a number of meteorological phenomena are expressed in terms of discrete values. Typical examples of such values are the detection of sunshine, precipitation or lightning and freezing precipitation. All these parameters can only be expressed by “yes” or “no”. For a number of parameters, all of which are members of the group of present weather phenomena, more than two possibilities exist. For instance, discrimination between drizzle, rain, snow, hail and their combinations is required when reporting present weather. For these practices, uncertainty calculations like those stated above are not applicable. Some of these parameters are related to a numerical threshold value (for example, sunshine detection using direct radiation intensity), and the determination of the uncertainty of any derived variable (for example, sunshine

duration) can be calculated from the estimated uncertainty of the source variable (for example, direct radiation intensity). However, this method is applicable only for derived parameters, and not for the typical present weather phenomena. Although a simple numerical approach cannot be presented, a number of statistical techniques are available to determine the quality of such observations. Such techniques are based on comparisons of two 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.B 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.B.⁸ 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 (1992*b*). 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

⁸ 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.

sensors or systems currently available are given in Annex 1.B.⁹ 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 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:¹⁰

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,¹¹ 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;

¹⁰ Recommended by the Commission for Instruments and Methods of Observation at its fourteenth session, held in 2006.

¹¹ A Web-based approach is recommended.

- (b) A RIC must maintain a set of meteorological standard instruments¹² 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;
- (k) meteorological and related environmental monitoring instruments according to **Capabilities** (b);
- (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) The RIC must cooperate with other RICs in the standardization of meteorological and related environmental instruments;
- (o) A RIC must regularly inform Members and report,¹³ 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.

Corresponding functions:

- (j) A RIC must assist Members of the Region in calibrating their national standard

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.

¹² For calibrating one or more of the following variables: temperature, humidity, pressure or others specified by the Region.

¹³ A Web-based approach is recommended.

ANNEX 1.B
OPERATIONAL MEASUREMENT UNCERTAINTY REQUIREMENTS AND INSTRUMENT PERFORMANCE

(1) <i>Variable</i>	(2) <i>Range</i>	(3) <i>Reported resolution</i>	(4) <i>Mode of measurement/ observation</i>	(5) <i>Required measurement uncertainty</i>	(6) <i>Sensor time constant</i>	(7) <i>Output averaging time</i>	(8) <i>Achievable measurement uncertainty</i>	(9) <i>Remarks</i>
1. Temperature								
1.1	Air temperature -80 – +60°C	0.1 K	I	0.3 K for ≤ -40°C 0.1 K for > -40°C and ≤ +40°C 0.3 K for > +40°C	20 s	1 min	0.2 K	Achievable uncertainty and effective time-constant may be affected by the design of the thermometer solar radiation screen Time-constant depends on the air-flow over the sensor
1.2	Extremes of air temperature -80 – +60°C	0.1 K	I	0.5 K for ≤ -40°C 0.3 K for > -40°C and ≤ +40°C 0.5 K for > +40°C	20 s	1 min	0.2 K	
1.3	Sea surface temperature -2 – +40°C	0.1 K	I	0.1 K	20 s	1 min	0.2 K	
2. Humidity								
2.1	Dewpoint temperature -80 – +35°C	0.1 K	I	0.1 K	20 s	1 min	0.5 K	
2.2	Relative humidity 0 – 100%	1%	I	1%	20 s	1 min	0.2 K	Wet-bulb temperature (psychrometer) 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)
					40 s	1 min	3%	Solid state and others Solid state sensors may show significant temperature and humidity dependence

(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement/ observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
3. Atmospheric pressure								
3.1 Pressure	500 – 1 080 hPa	0.1 hPa	I	0.1 hPa	20 s	1 min	0.3 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
3.2 Tendency	Not specified	0.1 hPa	I	0.2 hPa			0.2 hPa	Difference between instantaneous values
4. Clouds								
4.1 Cloud amount	0/8 – 8/8	1/8	I	1/8	n/a		2/8	Period (30 s) 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 is undetermined because 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							

(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement/ observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
5. Wind								
5.1 Speed	0 – 75 m s ⁻¹	0.5 m s ⁻¹	A	0.5 m s ⁻¹ for ≤ 5 m s ⁻¹ 10% for > 5 m s ⁻¹	Distance constant 2 – 5 m	2 and/or 10 min	0.5 m s ⁻¹ for ≤ 5 m s ⁻¹ 10% for > 5 m s ⁻¹	Average over 2 and/or 10 min Non-linear devices. Care needed in design of averaging process Distance constant is usually expressed as response length Averages computed over Cartesian components (see Part III, Chapter 3, section 3.6 of this Guide)
5.2 Direction	0 – 360°	1°	A	5°	1 s	2 and/or 10 min	5°	
5.3 Gusts	0.1 – 150 m s ⁻¹	0.1 m s ⁻¹	A	10%		3 s	0.5 m s ⁻¹ for ≤ 5 m s ⁻¹ 10% for > 5 m s ⁻¹	Highest 3 s average should be recorded
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 Average depth over an area representative of the observing site
6.2 Depth of snow	0 – 25 m	1 cm	A	1 cm for ≤ 20 cm 5% for > 20 cm				
6.3 Thickness of ice accretion on ships	Not specified	1 cm	I	1 cm for ≤ 10 cm 10% for > 10 cm				

(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement/observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
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		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
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 – ≤ 1 600 m 20% for > 1 500 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

(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement/ observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
8.2 Runway visual range (RVR)	10 m – 1 500 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% 20 m or 20% 20 m or 20% 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)
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 \leq 5 m 10% for $>$ 5 m	Average over 20 min for instrumental measurements
9.2 Wave period	0 – 100 s	1 s	A	0.5 s	0.5 s	20 min	0.5 s	Average over 20 min for instrumental measurements
9.3 Wave direction	0 – 360°	1°	A	10°	0.5 s	20 min	20°	Average over 20 min for instrumental measurements
10. Evaporation								
10.1 Amount of pan evaporation	0 – 100 mm	0.1 mm	T	0.1 mm for ≤ 5 mm 2% for > 5 mm	n/a			

Notes:

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

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 log-book, 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 Figure 1.3). An example of how to do this is shown in WMO (2003*b*). 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 (2004).

Station	Update	
Elevation	Latitude	Longitude
<div style="display: flex; align-items: flex-start;"> <div style="width: 20%; padding-right: 10px;"> <p>0 200 m</p> <ul style="list-style-type: none"> Enclosure Building Road x Trees, bushes (12) Height (m) of obstacle Elevation contour </div> <div style="width: 80%;"> </div> </div>		
Radiation horizon		
Temperature and humidity:		
	Sensor height	
Surface cover under screen	Artificial ventilation?	yes/no
Soil under screen		
Precipitation: Gauge rim height		
Wind: Anemometer height		
	Free-standing?	yes/no
(if "no" above: building height , width , length .		
Terrain roughness class: to N , to E , to S, to W .		
Remarks:		

Figure I.3. General template for station exposure metadata

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