CHAPTER 1 — GENERAL

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 and forecasts, for the study of climate, for local weather-dependent operations (e.g. local aerodrome flying operations, construction work on land and at sea), for hydrology and agrometeorology, 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 practice in making meteorological measurements and observations.

There are many other sources of such advice, and users are referred to the appendix to this *Guide*, which is an extensive bibliography of theory and practice in instruments and methods of observation. The appendix also contains references to national practices, to national and international standards, and to the general literature. It also includes a list of 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. The other *Manuals* and *Guides* issued by WMO refer to particular applications of meteorological observations (see especially those relating to the Global Observing System (WMO, 1981*a* and 1989), aeronautical meteorology (WMO, 1990), hydrology (WMO, 1994), agricultural meteorology (WMO, 1981*b*), and climatology (WMO, 1983)).

On the recommendation of CIMO[1] several Regional Associations of WMO have set up Regional Instrument Centres (RIC) to maintain standards and provide advice. Their terms of reference and locations are given in Annex 1.A.

Throughout this *Guide*, uncertainty, when expressed statistically, is given at the 2σ or 95 per cent probability level, except where otherwise stated (see section 1.6).

1.1.2 *Representativeness*

The required density or resolution of observed data is related both to the time- and space-scales appropriate to the phenomena to be analysed and to the application. WMO (1981*a*) classifies horizontal scales of meteorological phenomena as follows:

(*a*) Small scale (less than 100 km), e.g. thunderstorms, local winds, tornadoes;

(*b*) Mesoscale (100 to 1 000 km), e.g. fronts, cloud clusters;

(*c*) Large scale (1 000–5 000 km), e.g. depressions, anticyclones;

(*d*) Planetary scale (more than 5 000 km), e.g. long upper tropospheric waves.

The horizontal scales are closely related to the time-scales of the phenomena; thus short-range weather forecasts require more frequent observations from a denser network over a limited area in order to detect any small-scale phenomena and subsequent development. As the length of the forecast period increases, so does the area over which observations are required.

A meteorological observation is intended to be representative of an area in accordance with its application. For instance, synoptic observations should typically be representative of an area up to 100 km around the station, to define the mesoscale and larger scales. For small-scale or local applications, the area may have dimensions of 10 km or much less. The exposure of the station is critical (see section 1.3.3), and errors of representativess 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 broad scale or mesoscale. However, even at unrepresentative stations the homogeneity of the observations in time may enable users to employ the data effectively.

Section 1.6 discusses the required and achievable accuracies of instrument systems. The stated achievable accuracies can be obtained with good instrument systems which are properly operated, but are not always obtained in practice. Good observational practices need skill, training, equipment, and support which are not always available in sufficient degree. Also good exposure and representativeness, on scales from a few metres to 100 kilometres, is difficult to achieve.

1.1.3 *Metadata*

Meteorological observations must always be according to exposure and the type and condition of the equipment and operations. Users may need to know the circumstances of the observations; this is now becoming 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 the station establishment and maintenance matters described in section 1.3, and concerning the changes which occur, including calibration and maintenance history (where applicable) and the changes in exposure and staff. Metadata are especially important for the elements that are particularly sensitive to exposure, such as precipitation, wind and temperature.

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[1] Recommended by the Commission for Instruments and Methods of Observation at its ninth session, 1985.

One particularly important form of metadata is data on the existence and availability of meteorological data and the metadata about them.

1.2 Meteorological observing systems

The requirements for observational data may be met by using *in situ* measurements or by remote sensing (including space-borne) systems, according to the ability of the various sensing systems to measure the elements needed. WMO (1981*a*) describes the requirements in terms of global, regional and national scales and according to application. 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 station according to particular application (e.g. surface synoptic station, upper-air station, climatological station, etc). 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.

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 (1981*a*). In this section, the observational requirements of a typical climatological station or a station of the surface synoptic network are considered.

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

Present weather	(Chapter 14)
Past weather	(Chapter 14)
Wind direction and speed	(Chapter 5)
Amount of cloud	(Chapter 15)
Type of cloud	(Chapter 15)
Height of cloud base	(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 type of cloud. However, with current technology, instruments for present and past weather, amount and height of cloud, and snow cover are not able to make observations of the whole range of the phenomena as can a human observer.

Some meteorological stations make upper-air measurements (Chapters 12 and 13, Part I), measurements of soil moisture (Chapter 11, Part I), ozone (Chapter 16, Part I) and atmospheric composition (Chapter 17, Part I), and some make use of special instrument systems 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 (Chapter 1, Part II).

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 to staffed weather stations.

1.3.2 *Observers*

Meteorological observers are required for a number of reasons:

(*a*) To make synoptic and/or climatological observations to the required accuracy with the aid of appropriate instruments;

(*b*) To maintain instruments 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.

Observers should be trained and/or certified by an appropriate Meteorological Service to establish their competence to make observations to the required standards. They should have the ability to interpret instructions for the use of instrumental and manual techniques that apply to their own particular observing systems. Guidance on the instrumental training requirements for observers will be given in Chapter 4, Part III.

1.3.3 *Siting and exposure*

1.3.3.1 Site selection

Meteorological observing stations are designed to enable representative measurements (or observations) to be made 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, e.g. aviation, synoptic and climatology, the most stringent requirement will dictate the precise location of an observing site and its associated sensors.

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 (detailed information appropriate to specific instruments and measurements is given in the succeeding chapters):

(*a*) Outdoor instruments should be installed on a level piece of ground, approximately 10 metres by 7 metres (the enclosure), 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 about 2 metres by 2 metres is reserved for observations of the state of the ground and of soil temperature at depths of less than 30 centimetres;

(*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 complied with, 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 on sites with exposures to satisfy their requirements and they need to be 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 observation 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 other than light winds and some degree of shelter is needed;

(*g*) If the instrument enclosure does not command a sufficiently extensive view over the surrounding country, their alternative viewpoints should be selected for observations of visibility;

(*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 should command a view of the open sea, but it should not be too near the edge of a cliff because the wind eddies created by the cliff will affect the measurements of the amount of precipitation and wind;

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

1.3.3.2 COORDINATES OF THE STATION

The position of a station must be accurately known and recorded. The coordinates of a station are:

(*a*) The latitude to the nearest minute;

(*b*) The longitude to the nearest minute; and

(c) The height of the station above mean sea-level, i.e. 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. For some purposes, greater precision may be required.

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, then 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).

If a station is at an aerodrome, other elevations must be specified (see Chapter 2, Part II, and WMO, 1990). Definitions of measures of height and of 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, e.g. through growth of trees or erection of buildings on adjacent plots. Sites should be chosen to minimize these effects, if possible. It is especially important to minimize the effects of changes of instrument and/or changes in 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) 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 that 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 not 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 and acceptable;

(*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 in the procedures for calculating derived quantities from the observations;

(*d*) The observers are competent to carry out their duties.

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 (e.g. 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 time-scales. It is especially important that a log be kept of instrument faults 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:

(*a*) Accuracy (according to the stated requirement for the particular variable);

(*b*) Reliability;

(*c*) Convenience of operation and maintenance;

(*d*) Simplicity of design (consistent with requirements);

(*e*) Durability.

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

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

Many of the recording instruments used in meteorology are of a type in which the motion of the sensing element is magnified by levers which 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 the 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 which 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, etc.) 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 tape 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 various instruments, methods and scales used to establish the accuracy of measurements. A nomenclature for standards of measurement is given by the International Organization for Standardization (ISO, 1993*a*), in collaboration with the International Organization of Legal Metrology, the International Bureau of Weights and Measures, and others. 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 measurements made 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.

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 a 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 Chapter 3, Part I (Annex 3.B) and Chapter 7, Part I (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 accuracy of primary or secondary standards; they should, however, be sufficiently robust to withstand transportation without changing their calibration.

Similarly, the instruments in operational use in 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 *Units and constants*

1.5.3.1 Units

The following units should be used for meteorological observations:

(*a*) Atmospheric pressure in hectopascals (hPa);
(*b*) Temperature in degrees Celsius (°C);
(*c*) Wind speed, in both surface and upper-air observations, in metres per second ($m\ s^{-1}$) or in knots (kt);
(*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 in per cent (%);
(*f*) Precipitation in millimetres (mm);

(*g*) Evaporation in millimetres (mm);
(*h*) Visibility in metres and kilometres (m, km);
(*i*) Irradiance in watts per m^2 and radiant exposure in joules per m^2 ($W\ m^{-2}$, $J\ m^{-2}$);
(*j*) Duration of sunshine in hours (h);
(*k*) Cloud height in metres (m);
(*l*) Cloud amount in oktas;
(*m*) Geopotential, used in upper-air observations, in standard geopotential metres (m′).

NOTE: 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.

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;
(*b*) Absolute temperature of the triple point of water $T = 273.16$ K;
(*c*) Standard normal gravity $(g_n) = 9.806\ 65\ m\ s^{-2}$;
(*d*) Density of mercury at 0°C = $1.359\ 51 \cdot 10^4\ kg\ m^{-3}$.

Values of other constants are given in WMO (1988; 1973).

1.6 Accuracy of measurements

1.6.1 *Meteorological measurements*

1.6.1.1 GENERAL

This section deals with those definitions which 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. It first discusses some issues which 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 of this discussion, see Chapters 1 and 2, Part III.

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 to be encouraged. Nevertheless, in this *Guide* the common and less precise use of accuracy has been permitted, as in "an accuracy of ±x", which should read "an uncertainty of ±x, at the 95 per cent confidence level".

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 conditions of measurement.

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 the other meteorological quantities. For temperature, the sources of error in an individual measurement are:
(*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. 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 particular circumstances;
(*f*) The exposure, which should ensure that the shelter is at a representative temperature. Nearby sources and sinks of heat (buildings, other unrepresentative surfaces surrounding the shelter) and topography (hills, land-water boundaries) may introduce large errors.

The effects of the last three or four of these sources of error can be kept small with very careful operations and convenient terrain for siting on the one hand, but they may contribute to very large errors (which may nevertheless be manageable for some statistical purposes if there have been no changes) on the other hand. However, they are sometimes overlooked in the discussion of errors, as though the laboratory calibration of the sensor could define the errors completely. Systematic and random errors both arise at all the above stages.

Establishing the true value is difficult in meteorology. 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. The effects of exposure are best determined by comparing station data against numerically-analysed fields using neighbouring stations, and this is an effective operational quality-control procedure.

The differences between the individual observations at the station and the values interpolated from the analysed field are due to the errors in the field as well as to the performance of the station. However, over a period of time, the average error at each point in the analysed field may be assumed to be zero if the surrounding stations are adequate for a good 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 over a long term may, thus, be made quite small (if the circumstances at the station do not change), and this is the basis of studies of climate change.

1.6.2 *Definitions of measurements and their errors*

The following terminology relating to the accuracy of measurements is extracted from ISO (1993*a*), which contains many definitions applicable to the practices of meteorological observations. ISO (1993*b*) gives very useful and detailed practical guidance on the calculation and expression of uncertainty in measurements.

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

NOTE: The operations may be performed automatically.

Result of a measurement: Value attributed to a measurand, 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 metres.

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

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 conditions of measurement:

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 conditions of measurement.

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. Results are here 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 of it), 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 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 made, 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 accuracy are extracted from ISO (1993*a*).

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 constant its metrological characteristics 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:

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

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.

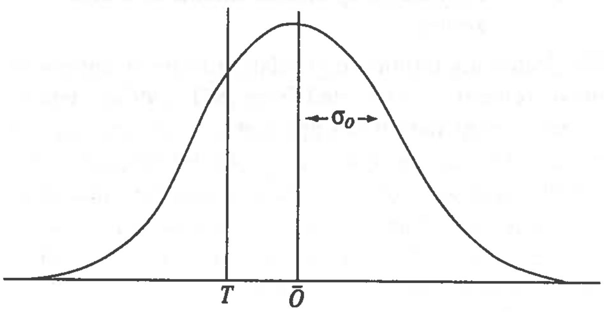
Lag error: The error which a set of measurements may possess due to the finite response time of the observing instrument.

1.6.4 *The measurement uncertainties of a single instrument*

ISO (1993*b*) 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 exposition of suitable statistical methods, with many illustrative examples.

1.6.4.1 The statistical distributions of observations

If n comparisons of an operational instrument are made with the measured variable and all other significant variables held constant, if the true value is established by use of a reference standard, and if the measured variable has a Gaussian distribution, then the results may be displayed as in the following figure:



The distribution of data in an instrument comparison.

where T is the true value, $\bar{O}$ is the mean of the n values O observed with one instrument, and σ_o 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, given by the algebraic difference $\bar{O} - T$;

(*b*) The precision, related to the standard deviation σ_o. If this is small, then operational observations may be reproducible within close statistical limits. If the standard deviation is large, then observations may be reproducible, but only within wide statistical limits, and may be considered a non-precise or uncertain measurement;

(*c*) The accuracy, expressed by the magnitude of:

$$(\bar{O} - T) \pm f(\sigma_o, n) \qquad (1.2)$$

where f is a probability function. It is necessary to have a large value of n to establish the standard deviation and the character of the error curve.

The RMS (root mean square) is often used as an approximation of the standard deviation.

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, then 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 we can indicate only certain limits within which the true value can be expected to lie. In order to do this, we have to choose a statistical probability (level of confidence) for the limits and have to know the error distribution of the means.

A very useful and clear treatment of this notion and related subjects is given by Natrella (1966). A 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 observation 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:

$$\text{Upper limit:}\quad L_U = \overline{X} + z \cdot \frac{\sigma}{\sqrt{n}} \qquad (1.3)$$

$$\text{Lower limit:}\quad L_L = \overline{X} - z \cdot \frac{\sigma}{\sqrt{n}} \qquad (1.4)$$

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 z is a factor, according to the chosen level of confidence, which can be obtained from tables of the (one-sided) normal distribution.

Some values of z follow:

Level of confidence (one sided)	95%	97.5%	99.5%
z	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 we wish to state the level of confidence that the true value will lie between both limits, then both the upper and lower outside zones have to be considered. With this in mind, it can be seen that z takes the value 1.96 for a 95 per cent probability 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 observation errors have a Gaussian or near-Gaussian distribution. In this situation, and for a chosen level of confidence, we can obtain the upper and lower limits from:

$$\text{Upper limit:}\quad L_U \approx \overline{X} + t \cdot \frac{\hat{\sigma}}{\sqrt{n}} \qquad (1.5)$$

$$\text{Lower limit:}\quad L_L \approx \overline{X} - t \cdot \frac{\hat{\sigma}}{\sqrt{n}} \qquad (1.6)$$

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:

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n-1} = \frac{n}{n-1} \cdot \sigma_0^2 \qquad (1.7)$$

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

Some values of t follow:

Level of confidence (one-sided)	95%	97.5%	99.5%
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 we wish to state the level of confidence that the true value will lie between the two limits, allowance has to be made as 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 z as n becomes large and it can be seen that the values of z are very nearly equalled by the values of t when *df* equals 60. For this reason, tables of z (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 in so far 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, we do not know the level of confidence. It is desirable, therefore, that the systematic error be fully determined.

1.6.5 *Accuracy requirements*

1.6.5.1 General

The accuracy 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 one sets out to determine, 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 have 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 unncessary; and

(*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 users of the data, on the other.

1.6.5.2 Required and achievable performance

The performance of a measuring system includes its reliability, capital, recurrent and life-time cost, and spatial resolution, but here the performance under discussion is confined to accuracy (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 here were the most authoritative at the time of writing, and may be taken as useful guides to 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[2]. It gives requirements only for surface measurements which are exchanged internationally. The uncertainty requirement for wind measurements is given for speed and direction separately because that is how wind is reported.

Annex 1.C[3] states the requirements of Global Data-processing System centres for three-dimensional and surface fields. It describes the data needed to obtain optimum results for numerical weather prediction, in respect of short- and medium-range forecasting applications.

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.B[4]. It should be noted that the achievable operational accuracy in many cases does not meet the stated requirements. However, the achievable accuracies in all cases are better than the limiting values beyond which the data obtained would have negligible value (level (*b*) in WMO's 1970 categories). For some of the quantities, these accuracies are achievable only with the highest quality equipment and procedures.

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[2] Stated by the Meeting of Experts on Operational Accuracy Requirements (1991) and approved by the forty-fourth session of the Executive Council (1992) for inclusion in this edition of the *Guide*.

[3] Adopted by the Commission for Basic Systems, at its extraordinary session (1994).

[4] Stated by the CIMO Working Group on Surface Measurements (1993), and confirmed for inclusion in this *Guide* by the eleventh session of the Commission for Instruments and Methods of Observation (1994).

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ANNEX 1.A

REGIONAL INSTRUMENT CENTRES (RICs)

1. Considering the need for regular calibration and maintenance of meteorological instruments to meet the increasing needs for high quality meteorological and hydrological data, the requirements of Members for standardization of meteorological instruments, the need for international instrument comparisons and evaluations and for training of instrument experts, it was recommended to establish Regional Instrument Centres.[5]

2. Regional Instrument Centres are designated to carry out the following functions:

(*a*) To keep a set of meteorological standard instruments linked with recognized international or national standards and to log their performance and elements of comparison;

(*b*) To assist Members of the Region in calibrating their national standard meteorological instruments or in comparing them with the standard instruments mentioned in (*c*) below and to keep the Members of the Region and the WMO Secretariat informed on the available standard instruments;

(*c*) To be prepared to certify the instruments' conformity with the standards with reference to WMO recommendations;

(*d*) To organize instrument evaluations and comparisons, following standard methods;

(*e*) To advise Members of the Region concerned on their enquiries regarding instrument performance and the availability of relevant guidance material;

(*f*) To assist WMO in organizing regional symposia, seminars or workshops on the maintenance, calibration, and comparison of meteorological instruments by providing laboratory and field installations, as well as assistance with regard to demonstration equipment and expert advice;

(*g*) To keep a library of books and periodicals on instrument theory and practices;

(*h*) To cooperate with other Regional Instrument Centres to provide standardization of meteorological instruments.

3. The following Regional Instrument Centres have been designated by the Regional Associations concerned: Seddika-Oran (Algeria), Cairo (Egypt), Nairobi (Kenya), and Gaborone (Botswana) for RA I; Beijing (China) and Tsukuba (Japan) for RA II; Buenos Aires (Argentina) for RA III; and Trappes (France) for RA VI.

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[5] Recommended by the Commission for Instruments and Methods of Observation at its ninth session, 1985.

ANNEX 1.B

OPERATIONAL ACCURACY REQUIREMENTS AND TYPICAL INSTRUMENT PERFORMANCE

(1) *Variable*	(2) *Range*	(3) *Reported resolution*	(4) *Mode of measurement/ observation*	(5) *Required accuracy*	(6) *Sensor time constant*	(7) *Output averaging time*	(8) *Achievable operational accuracy*	(9) *Remarks*
1. **Temperature**								
1.1 Air temperature	−60 – +60 K	0.1 K	I	±0.1 K	20 s	1 min	±0.2 K	Achievable accuracy and effective time constant may be affected by the design of thermometer solar radiation screen.
1.2 Extremes of air temperature	−60 – +60 K	0.1 K	I	±0.5 K	20 s	1 min	±0.2 K	
1.3 Sea-surface temperature	−2 – +40 K	0.1 K	I	±0.1 K	20 s	1 min	±0.2 K	
2. **Humidity**								
2.1 Dewpoint temperature	<−60 – +35 K	0.1 K	I	±0.5 K	20 s	1 min	±0.5 K	If measured directly. Tending to ±0.1 K when relative humidity nearing saturation.
2.2 Relative humidity	5 – 100%	1%	I	±3%	*Wet-bulb temperature:* 20 s	1 min	±0.2 K	Large errors are possible due to aspiration and cleanliness problems. If measured directly. Tending to ±1% when relative humidity nearing saturation.
					Solid state and others: 40 s	1 min	±3 – 5%	Solid state sensors may show significant temperature and humidity dependence.
3. **Atmospheric pressure**								
3.1 Pressure	920 – 1 080 hPa	0.1 hPa	I	±0.1 hPa	20 s	1 min	±0.3 hPa	Range to sea-level. Accuracy seriously affected by dynamic pressure due to wind and temperature coefficient of transducer.
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)*
4. **Clouds**								
4.1 Cloud amount	0 – 8/8	1/8	I	±1/8	n/a		± 1/8	Period (30 s) clustering algorithms may be used to estimate low cloud amount automatically.
4.2 Height of cloud base	< 30 m – 30 km	30 m	I	±10 m for ≤100 m ±10% for >100 m	n/a		≈10 m repeatability*	*Accuracy difficult to determine since no definition exists for instrumentally-measured cloud base height.
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	Dist. cont. 2 – 5 m	2 and/or 10 min	±0.5 m s-1	Average over 2 and/or 10 minutes. Non-linear devices. Care needed in design of averaging process.
5.2 Direction	0 – 360°	10°	A	±5%	1 s	2 and/or 10 min	±5°	
5.3 Gusts	5 – 75 m s-1	0.5 m s-1	A	±10%		3 s	±0.5 m s-1	Highest 3 s average should be recorded.
6. **Precipitation**								
6.1 Amount	0 – >400 mm	0.1 mm	T	±0.1 mm for ≤ 5 mm ±2% for > 5 mm	n/a	n/a	±5%	Accuracy depends on aerodynamic collection efficiency of gauges and evaporation losses in heated gauges.
6.2 Depth of snow	0 – 10 m	1 cm	A	±1 cm for ≤20 cm ±5% for >20 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				
7. **Radiation**								
7.1 Sunshine duration	0 – 24 h	0.1 h	T	±0.1 h	20 s	n/a	±2%	
7.2 Net radiation	Not specified	1 MJ m-2 d-1	T	±0.4 MJ m-2 d-1 for ≤8 MJ m-2 d-1 ±5% for >8 MJ m-2 d-1	20 s	n/a	±5%	
8. **Visibility**								
8.1 MOR	<50 m – 70 km	50 m	I	±50 m for ≤500 m ±10% for >500 m		3 min	±10 – 20%	Achievable instrumental accuracy may depend on the cause of obscuration.

(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
8. **Visibility** *(contd.)*								
8.2 RVR	50 m – 1 500 m	25 m	A	±25 m for ≤150 m ±50 m for >150 – ≤500 m ±100 m for >500 – ≤1 000 m ±200 m for >1 000 m		1 and 10 min		
9. **Waves**								
9.1 Wave height	0 – 30 m	0.1 m	A	±0.5 m for ≤5 m ±10% for >5 m	0.5 s	20 min	±10%	Average over 20 minutes for instrumen- tal 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 minutes for instrumen- tal measurements.
9.3 Wave direction	0 – 360°	10°	A	±10°	0.5 s	20 min	20°	Average over 20 minutes for instrumen- tal measurements.
10. **Evaporation**								
10.1 Amount of pan evaporation	0 – 10 mm	0.1 mm	T	±0.1 mm for ≤5 mm ±2% for >5 mm				

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 give 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 one minute is considered as a minimum and most suitable; averages over periods of up to 10 minutes are acceptable.

   A : Averaging. Average values over a fixed time period, as specified by the coding requirements.

   T : Totals. Totals over a fixed time period(s), as specified by coding requirements.
5. Column 5 gives the recommended accuracy requirement for general operational use. Individual applications may have less stringent requirements. The stated value of required accuracy 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, which corresponds to the 2-second 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 accuracy requirement. The true value is that 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 stated by the Meeting of Experts on Operational Accuracy Requirements, held in 1991.
7. Columns 6 to 8 refer to the typical operational performance stated by the CIMO Working Group on Surface Measurements in 1993.

ANNEX 1.C

STATEMENT OF OBSERVATIONAL DATA NEEDS FOR GLOBAL DATA-PROCESSING SYSTEM CENTRES

(*a*) Three-dimensional fields

Variable	*Horizontal resolution (km)*	*Vertical resolution (km)*	*Temporal resolution (hours)*	*Accuracy (RMS error)*
Wind (horizontal)[1,2]	100	0.1 up to 2 0.5 up to 16 2.0 up to 30	3	2 m s^{-1} in the troposphere 3 m s^{-1} in the stratosphere
Temperature (T) [3]	100	0.1 up to 2 0.5 up to 16 2.0 up to 30	3	0.5 K in the troposphere 1 K in the stratosphere
Relative humidity (RH)	100	0.1 up to 2.0 0.5 up to the tropopause	3	5% (RH)

(*b*) Surface fields

Variable	*Horizontal resolution (km)*	*Temporal resolution*	*Accuracy (RMS error)*
Pressure	100	1 hour	0.5 hPa
Wind[4]	100	1 hour	2 m s^{-1}
Temperature	100	1 hour	1 K
Relative humidity	100	1 hour	5%
Accumulated precipitation[5]	100	3 hours	0.1 mm
Sea-surface temperature	100	1 day	0.5 K
Soil temperature	100	3 hours	0.5 K
Sea-ice cover	100	1 day	10%
Snow cover	100	1 day	10%
Snow equivalent-water depth	100	1 day	5 mm
Soil moisture, 0–10 cm	100	1 day	0.02 m^3 m^{-3}
Soil moisture, 10–100 cm	100	1 week	0.02 m^3 m^{-3}
Percentage of vegetation	100	1 week	10% (relative)
Soil temperature, 20 cm	100	6 hours	0.5 K
Deep soil temperature, 100 cm	100	1 day	0.5 K
Albedo, visible	100	1 day	1%
Albedo, near infrared	100	1 day	1%
Long-wave emissivity	100	1 day	1%
Ocean wave height	100	1 hour	0.5 m

NOTES:
1. Accuracy specified as RMS vector error.
2. Hourly wind data from geostationary satellites and from wind profilers are also required. Tropospheric horizontal and vertical resolution and accuracy can be met by a space-based Doppler wind lidar in a sun-synchronous orbit.
3. Geopotential height can be retrieved from specified T and RH with sufficient accuracy.
4. Wind at 10 metres over land. Over sea, height in the range 1 to 40 metres (to be transmitted with the observation).
5. Required principally for model validation, not time-critical.