# Operational Manual

# FOR

# METEOROLOGICAL OBSERVATION

(PR-MSD-01)

JULY, 2025
NCHM

**National Centre for Hydrology and Meteorology**

# Manual

## To Meteorological Observation

(PR-MSD-01)

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| TSRD Division | MSD Division | NCHM Management |
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**Version 01**

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MSD-PR-01- Meteorological Observation

(Automatic Weather Stations and Agro-Meteorological Stations)

## REVISION STATUS

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# Preface

Meteorology is the science that studies the atmosphere, weather, and climate, focusing on the processes and phenomena of the Earth's atmosphere. It is an interdisciplinary field that combines knowledge from physics, chemistry, geography, and environmental science to understand the complex interactions between atmospheric conditions and various environmental factors. This meteorological observation manual is designed to provide a comprehensive overview of the comprehensive methods of meteorological observation for the National Centre for Hydrology and Meteorology that meet international standards.

The standards for meteorological observation have been published in the various guidelines and manuals by the World Meteorological Organization (WMO). The methods and procedures described in this manual are intended to complement the recommendations of these standards. The guidelines consist of four chapters dealing with Measurement Standards and Definition, Automatic Weather Station (AWS) Standards, Agricultural Meteorological Station (Class A station) standards and Quality Control.

This manual has been prepared by the Technical Standard and Research Division. We would like to express our sincere gratitude to the experts who contributed their time, knowledge, and expertise to prepare this manual.

# Content

# CHAPTER 1 INTRODUCTION

## 1.1 GENERAL

### 1.1.1 Background

The world's weather and climate systems are under increasing pressure due to factors such as population growth, economic development, and climate change, among others. The need for accurate weather forecasts, the dependence of various sectors such as agriculture, aviation, and energy on weather conditions, and the need for disaster preparedness and ecosystem protection all require better meteorological observation and analysis. Meteorological observation is a vital part of environmental monitoring and climate science. It is designed to meet specific needs, including those for weather forecasting, climate monitoring, and the study of atmospheric processes. The goal of observations of meteorological parameters is to collect reliable data for use in weather prediction and climate modeling, including for managing extreme weather events, integration into climate and environmental applications and services, and for research.

The national meteorological network consists of 20 Class A stations, 62 Class C stations and 85 Automatic Weather Stations. There are also snow monitoring sensors that operates parallel with some of the weather stations. Depending on the parameters observed and data transmision method, the meteorological stations in Bhutan are broadly classified into the following catagories;

a) Automatic Weather Stations (AWS)- These are automatic stations where the observed meteorological data are sensed, recorded and transmitted to the central database automatically.
b) Agrometeorological Stations (Class A)- These are agrometeorological stations observing agro-related parameters like soil temperature, moisture, evaporation rate, wind direction and speed, relative humidity, sunshine duration and rainfall are observed. The readings are taken at 09:00hrs and 15:00hrs each day by the field staff. The compiled data is sent to Headquarters for archival.
c) Climatological Stations (Class C)- These are Climatological stations where only the basic meteorological parameters like air temperature (max and min temperature), dry and wet temperature and rainfall is observed and is operated for long time climate analysis. The readings are taken at 09:00 hrs every day the part time observer. In addition, few stations located at high altitude also take snow depth and snow incidence measurement.

The meteorology observation involves selection of suitable equipment and technology for observation of different stations types and parameters, taking observation reading as per the required standards, quality control and networking of the observations readings. All of the above activities have been described in detail in the following chapters.

### 1.1.2 Document title

This document is identified as Meteorological Observation Manual, MSD-PR-01 prepared and maintained by Technical Standard and Research Division, National Centre for Hydrology and Meteorology.

### 1.1.3 Responsibility

In preparation of this manual, care has been taken to ensure that the information contained herein is accurate, reliable and complete. However, suggestions for improvements or comments concerning apparent errors or omissions should be forwarded in writing to the Management, NCHM.

The Management team shall comprise;

1) Director, NCHM
2) HWRSD, Chief
3) CSD, Chief
4) MSD, Chief
5) TSRD, Chief

Holders of hard-copies of this Manual are responsible for ensuring that the Manual is kept up to date. This includes inserting new chapters or chapter amendments in a timely manner and complying with any instructions on amendment advice.

### 1.1.4 Objective

The objective of the Meteorological Observation Manual is to provide a standardized set of procedures and protocols for conducting accurate meteorological observations, measurements, and data recording. The manual aims to ensure consistency, and reliability of Meteorological data by providing guidance on the functional requirement, proper data measuring standards, and quality control measures.

Overall, the objective of the Meteorological Observation Manual is to support meteorologists, engineers, and other professionals involved in meteorology-related research and management by providing them with a comprehensive and standardized set of guidelines for conducting meteorological observations. By following these guidelines, observers can ensure the accuracy and consistency of their data, which is essential for effective water resource management and decision making.

### 1.1.5 Scope

This manual outlines the operational guidelines and international standards for meteorological observation of Agrometeorological Station and AWS stations.

## 1.2 GENERAL REQUIREMENTS FOR METEOROLOGICAL STATION

The requirements for elements to be observed according to the type of station and observing network are detailed in WMO (2015). In this section, the observational requirements of a typical meteorological station or a surface synoptic network station are considered.

The following elements are observed at a station making surface observations. Details of those parameters are covered in the following chapters.

– Temperature

– Soil temperature

– Atmospheric pressure

– Relative humidity

– Wind direction and speed

– Precipitation

– Snow cover

– Solar radiation and/or sunshine

– Visibility

– Evaporation

– Present weather

– Past weather

– Cloud amount and type

## 1.3 AUTOMATIC WEATHER STATION

Most of the elements required for synoptic, climatological or aeronautical purposes can be measured by automatic instrumentation (Chapter 3). 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 standards of the instrument readings, and inspection and quality control apply equally to automatic weather stations and staffed weather stations.

## 1.4 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
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.

# CHAPTER 2 MEASUREMENT STANDARDS AND DEFINITION

## 2.1. DEFINITIONS OF STANDARDS OF MEASUREMENT

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

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

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

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

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

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

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

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

## 2.2. SYMBOLS, UNITS AND CONSTANTS

### 2.2.1. 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. General principles concerning quantities, units and symbols are stated in ISO (2009) and IUPAP (1987). The International System of Units should be used as the system of units for the evaluation of meteorological elements included in reports for international exchange. 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);
b) Temperature, t, in degrees Celsius (°C)
c) Wind speed, in both surface and upper-air observations, in metres per second (m s–1)
d) Wind direction in degrees clockwise from true north
e) Relative humidity, U, in per cent (%);
f) Precipitation (total amount) in millimetres (mm) or kilograms per square metre (kg m–2)
g) Precipitation intensity, Ri , in millimetres per hour (mm h–1) or kilograms per square metre per second (kg m–2 s–1)
h) Snow water equivalent in kilograms per square metre (kg m–2);
i) Evaporation in millimetres (mm);
j) Visibility in metres (m);
k) Irradiance in watts per square metre and radiant exposure in joules per square metre (W m–2, J m–2);
l) Duration of sunshine in hours (h);
m) Cloud height in metres (m);
n) Cloud amount in oktas;

### 2.2.2. Constants

The following constants have been adopted for meteorological use:

a) Absolute temperature of the normal ice point T0 = 273.15 K (t = 0.00 °C);
b) Absolute temperature of the triple point of water T = 273.16 K (t = 0.01 °C), by definition of ITS-90;
c) Standard acceleration of gravity (gn ) = 9.806 65 m s–2;
d) Density of mercury at 0 °C = 1.359 51 · 104 kg m–3.

The values of other constants are given in WMO (1966, 2011b).

## 2.3. UNCERTANITY OF MEASUREMENTS

### 2.3.1. Definitions of measurements and measurement errors

The following terminology relating to the accuracy of measurements is based on JCGM (2012), which contains many definitions applicable to the practices of meteorological observations. Very useful and detailed practical guidance on the calculation and expression of uncertainty in measurements is given in ISO/IEC (2008) / JCGM (2008).

Measurement: The process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.

Result of a measurement: A set of quantity values being attributed to a measurand together with any other available relevant information.

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

Value (of a quantity): A number and reference together expressing the magnitude of a quantity.

True value (of a quantity): The quantity value consistent with the definition of a quantity.

Accuracy (of a measurement): A qualitative term referring to the closeness of agreement between a measured quantity value and a true quantity value of a measurand. The accuracy of a measurement is sometimes understood as the closeness of agreement between measured quantity values that are being attributed to the measurand. It is possible to refer to an instrument or a measurement as having a high accuracy, but the quantitative measure of the accuracy is expressed in terms of uncertainty.

Uncertainty: A non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Repeatability: The closeness of agreement between indications or measured quantity values obtained on the same or similar objects under a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements over a short period of time.

Reproducibility: The closeness of agreement between indications or measured quantity values obtained on the same or similar objects under a set of conditions that includes different locations, operators and measuring systems, and replicate measurements.

Error (of measurement): Measured quantity value minus a reference quantity value.

Instrumental bias: Average of replicate indications minus a reference quantity value.

Random error: The component of measurement error that in replicate measurements varies in an unpredictable manner.

Systematic error: The component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

Correction: Compensation for an estimated systematic effect.

### 2.3.2. Sources and estimates of error

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

t 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

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

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

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

f) The exposure, which should ensure that the shelter is at a temperature which is representative of the region to be monitored. Nearby sources and heat sinks (buildings, other unrepresentative surfaces below and around the shelter) and topography (hills, land, water boundaries) may introduce large errors.

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.

# CHAPTER 3 AUTOMATIC WEATHER STATION

## 3.1. GENERAL REQUIREMENT

In order to meet the above range of applications, the AWS will, in summary, provide for features from amongst the following:

- Sensors, together with the items required to provide an appropriate sensor exposure
- Sufficient data channels for meteorological sensors plus any requirement for additional channels
- Manual entry of data which are not to be measured automatically, for reasons which may include, for instance, complexity, economy or obstructions to vision~ typically visibility, present weather and cloud height may fall into this category
- Data storage capacity for a nominal two (2) days to facilitate later collection ofdata in the event that communications links are temporarily disrupted. In some cases this may need to be increased to allow for delays in detection and rectification of a failure;
- Preparation offully-formed messages for transmission in accordance with predefined formats, which will depend on the purpose for which the data are required
- Automatic message transmission at programmed times, typically every 15 mins
- Operation from the mains power supply and/or battery supplies, perhaps with solar cell recharging,
- Any ancillary facilities necessary to ensure satisfactory long term operation of the equipment such as specialist test equipment and operation and maintenance manuals;
- Protection against lightning and other induced currents;
- Suitably weather proof environmental housing(s) for electronic circuitry etc, and any other necessary protection, such as against fire, vandalism, and local fauna and flora.

## 3.2. SITING CONSIDERATION

It is important that careful consideration of the terrain, climate and environment in which the AWS is likely to be installed is taken into consideration in every facet of planning and design of the AWS.

Possible sources for information relating to siting of meteorological instruments are:

World Meteorological Organization, Guide to Meteorological Instruments andMethods of Observation; Sixth Edition (WMO-No. 8).

Bureau of Meteorology Australia, Guidelines For The Siting and Exposure of MeteorologicalInstruments andObservingFacilities, Observation Specification No. 2013.1.

National Center for Hydrology and Meteorology Instrumentation Manual (MSD-PR-02)

## 3.3. QUANTITIES AND SPECIFICATIONS FOR THE MEASUREMENT

### 3.3.1. Wind Speed

Definition: The rate at which air moves past a fixed point with respect to the Earth's surface.

Data use: Meteorology, climate, engineering, agriculture, aviation etc.

Measurement units: Metres per second (ms·I ).

Resolution: 0.1 ms·l

Uncertainity: ±1 ms·l or 10% ofreading, whichever is the greater.

Integration period: 3 s for wind gust measurement; mean wind speed for specified periods (usually 2 or 10 min) to be derived

General Sensor Exposure: Standard exposure is at a height of 10 m above flat ground. Distance from obstructions-tofree-flow-of-air by a minimum of 10 (preferably 30) times the height ofthe obstruction.

### 3.3.2. Wind Direction

Defination: The mean direction from which air is moving past a fixed point with respect to the Earth over a given interval oftime.

Data use: Meteorology, climate, engineering, agriculture, aviation etc.

Measurement units: Degrees (C)

Resolution: 5 Degree

Uncertainity: ±5 Degree

Integration period: Mean wind direction for specified periods (usually 2 or 10 minutes) to be derived

General Sensor Exposure: As for wind speed. Direction head to be set to True North not Magnetic North.

### 3.3.3. Air (Dry Bulb) Temperature

Defination: Temperature is the condition which determines the direction ofthe net flow of heat between two bodies. In such a system, that body which overall loses heat to the other is said to be at the higher temperature.

Data use: Meteorology, climate, engineering, agriculture, aviation,

Measurement units: Degrees Celsius (°C).

Resolution: 0.1 °C

Uncertainity: ±0.3 °C

Integration period: 1 minute

General Sensor Exposure: Inside a suitable instrument shelter, height of 1.25m to 2:0m preferred. No obstruction should be closer than 4 times the height of that obstruction.

### 3.3.4. Wet Bulb Temperature

Definition: The ratio in percent of the observed vapour pressure to the saturation vapour pressure with respect to water at the same temperature and pressure.

Data use: Provides information on water content ofthe atmosphere. Used to estimate relative humidity.

Measurement units: Degrees Celsius (°C).

Resolution: 0.1 °C

Uncertainty: ±0.3 °C

Integration period: 1 minute

General Sensor Exposure: Inside a suitable instrument shelter, height of 1.25m to 2:0m preferred. No obstruction should be closer than 4 times the height of that obstruction.

### 3.3.5. Relative Humidity

Definition: The ratio in percent of the observed vapour pressure to the saturation vapour pressure with respect to water at the same temperature and pressure.

Data use: Provides information on water content ofthe atmosphere. Meteorology, energy budget research, agriculture, engineering etc.

Measurement units: % RH

Resolution: 1% for RH

Uncertainty: 5% for RH upto 50%, 3% for RH > 50%

Integration period: 1 minute.

General Sensor Exposure: Inside a suitable instrument shelter, height of 1.25m to 2:0m preferred. No obstruction should be closer than 4 times the height of that obstruction.

#### 3.3.6. Soil Temperature

Definition: Temperature of the soil at various depths.

Data use: Agriculture, geology, energy budget analysis etc.

Measurement units: Degrees Celsius (°C).

Resolution: 0.1 °C

Uncertainty: ±0.3 °C

Integration period: 1 minute

General Sensor Exposure: Standard soil depths (including some or all of5, 10, 15, 20, 30, 50 and 100 cm).

#### 3.3.7. Atmospheric Pressure

Definition: The force per unit area exerted by virtue ofthe weight ofthe atmosphere above.

Data use: Meteorology, climate etc.

Measurement units: HectoPascals (hPa)

Resolution: 0.1 hPa

Uncertainty: ±0.3 to 0.5 hPa, however in soine applications ±1 hPa acceptable.

Integration period: 60 second average

General Sensor Exposure: Can be housed in any convenient place providing it is adequately coupled to the atmosphere and protected from the weather and temperature changes or gradients.

### 3.3.8. Precipitation (Rainfall and Snowfall)

Defination: The liquid or solid products ofthe condensation ofwater vapour falling from clouds or deposited from air on the ground, including rain, hail, show, dew, rime, hoar frost and fog

Data use: Meteorology, climate, hydrology, engineering, agriculture etc.

Measurement units: Millimetres (mm).

Resolution: 0.2 mm

Uncertainity: ±0.2 mm or ±3% of reading,

General Sensor Exposure: The collector rim ofthe gauge should be mounted at a standard height, depending on local practice (e.g. ground level (pit gauge) or 300mm). Obstructions to free air flow over the gauge should not be closer than 4 times its height above the gauge.

### 3.3.9. Depth of Snow

Defination: The depth offresh snow covering an even horizontal surface.

Data use: Road authority, tourism, engineering etc.

Measurement units: Centimetres (cm).

Resolution: 1 cm

Uncertainity: ±2.5 cm

General Sensor Exposure: Should be kept at sufficient height to capture the snow height.

### 3.3.10. Evaporation

Definition: Quantity of water, evaporated from an open water surface or from the ground.

Data use: Agriculture, hydrology, agriculture etc

Measurement units: Millimetres (mm).

Resolution: 0.2 mm, 0.1 mm preferred

Uncertainty: ±0.2 mm to 10 mm, ±2% above 10 mm

Integration period: The change of level is generally a measure of evaporation and rainfall combined, and corrections need to be applied to allow for any rain which may have fallen into the pan.

General Sensor Exposure: Level site with free air flow. Minor obstmctions should not be closer to the pan than 4 times their height. The pan should be stood on a wooden pallet which keeps it 5 to 10 cm above a natural surface, ie. a surface typical ofthe area around the observations site.

### 3.3.11. Solar Radiation - Global

Definition: Global solar irradiance is a measure of the rate of total incoming solar energy on a horizontal plane at the Earth's surface. An exposure is a time integral of an irradiance.

Data use: Energy budget models, agriculture etc.

Measurement units: Watts per square metre (Wm-2 ) for instantaneous values (irradiance) Joules per square metre (Jm-2 ) for integrals (exposure)

Resolution: 5 Wm-2 for irradiance, 1 MJm-2 d-1 .

Uncertainty: ±5% in daily

Integration period: 1 day, unless otherwise specified by user.

General Sensor Exposure: For solar elevation greater than 5 0, shadows should not fall on sensor; not more than 3% ofsky above a horizontal plane through the sensor should be obscured; location near white or highly reflecting surfaces should be avoided. Easy access is required for regular cleaning and checking.

### 3.3.12. Sunshine Duration

Definition: Sunshine duration is defined to be the sum ofall time periods during the day when the direct solar irradiance equals or exceeds 120 Wm-2 . Sunshine duration can be derived from continuous direct irradiance measurement.

Data use: Energy budget models, agriculture etc.

Measurement units: Hours (hr).

Resolution: 0.1 hr

Uncertainty: ±2% ofreading

Integration period: 1 day unless otherwise specified.

General Sensor Exposure: For accurate measurement, the instruments field ofview should be unobstructed along the direct solar path at all times of the day and year.

### 3.3.13. Soil Moisture

Definition: A measure ofthe water content ofsoil:

Data use: Agriculture, hydrology.

Measurement units: Weight of H20 as % ofweight of dry soil.

General Sensor Exposure: The choice oflocation for the sensor is of crucial importance ifthe measurement is to be representative for the intended application. Considerations include inclination, topography, soil type, depth of water table, obstacles and application peculiarities

### 3.3.14. Visibility

Definition: For a human observer, the meteorological visibility by day is defined as the greatest distance at which a black object ofsuitable dimensions, situated near the ground, can be seen and recognised when observed against a scattering background offog, sky, etc.

Data use: Aviation, road authority, meteorology etc.

Measurement units: metres (m) or kilometres (km).

Resolution: 100m

Uncertainty: ±10%

Integration period: 1 or 2 minutes.

General Sensor Exposure: The sensor should be placed in a position that is representative ofthe site topography for which the measurement is required. Locations adversely affected by local atmospheric pollution should be avoided. The sample volume of air ofthe sensor should where possible be at 1.5m above ground level.

# CHAPTER 4 AGROMETEOROLOGICAL STATION

## 4.1. OBSERVATION TO BE CARRIED OUT AT AGRO-MET STATIONS

The observing programme at agricultural meteorological stations should include observations of some or all of the following variables characterizing the physical environment: solar radiation, sunshine and cloudiness, air and soil temperature, air pressure, wind speed and direction, air humidity and soil moisture, evaporation and precipitation (including observations of hail, dew and fog). The water balance, evapotranspiration and other fluxes may be deduced from these and other measurements. Minimum accuracy for the different variables is recommended in WMO (2008b) as given in Table below:

| Variable | Accuracy required in daily values |
|---|---|
| Temperature, including max/min, wet and dry bulb, soil | < ±0.5ºC |
| Rainfall | ±1 mm |
| Solar radiation | 10% (±1h) |
| Evaporation | ±1 mm |
| Relative humidity | ±5% |
| Photoperiod | 10% (±1h) |
| Wind speed | ±0.5 ms–1 |
| Air pressure | ±0.1 hPa |

## 4.2. RADIATION AND SUNSHINE

The duration of day length, which influences the flowering and growth of shoots of crop plants, should be recorded or obtained at all agricultural meteorological stations. This information should be supplemented wherever possible by data obtained from radiation instruments.

Most commonly, a solarimeter (pyranometer) is mounted horizontally and measures the total solar irradiance on a horizontal surface. In addition, a shade ring (or occulting disk) may be used to cast a shadow on the sensitive area, eliminating the direct beam. The instrument then indicates only the diffuse (sky) radiation. The power of the direct beam may be calculated by subtracting the diffuse reading from the total radiation.

### 4.3. AIR TEMPERATURE

The temperature of the air should be measured in representative places, at different levels in the layer adjacent to the soil. Measurements should be made at principal agricultural meteorological stations from ground level up to about 10 m above the upper limit of the prevailing vegetation because air temperature affects leaf production, expansion and flowering. At ordinary or auxiliary stations, however, the measurements will usually be restricted to the lowest few metres above the surface, which are the most significant layers for studying climatic conditions affecting agricultural crops, their growth and development; these are also the layers with the largest gradients and most rapid fluctuations. To study the vertical distribution of temperature within the lowest two metres of the atmosphere, measurements should be made at three levels at the least, selected from the following heights: 5, 10, 20, 50, 100, 150 and 200 cm. Observations taken for special research projects vary with the needs of the problems under investigation.

### 4.4. TEMPERATURE OF SOIL

Soil temperature directly influences crop growth because the sown seeds, plant roots and micro-organisms live in the soil. The physicochemical as well as life processes in agriculture are also directly affected by the temperature of the soil. Under low soil temperature conditions, nitrification is inhibited and the intake of water by roots is reduced. Extreme soil temperatures injure plants and thereby affect growth.

The observing programme at all categories of agricultural meteorological stations should therefore also include soil temperature measurements. The levels at which soil temperatures are observed should include the following depths: 5, 10, 20, 50 and 100 cm. At the deeper levels (50 and 100 cm), where temperature changes are slow, daily readings are generally sufficient. At shallower depths the observations may comprise, in order of preference, either continuous values, daily maximum and minimum temperatures, or readings at fixed hours.

### 4.5. ATMOSPHERIC PRESSURE

The lower pressures experienced as altitude increases have important consequences for plant life at high altitude. At high altitudes and low atmospheric pressures the solubility of carbon dioxide and oxygen in water is reduced. Some plants show stunted growth at higher altitudes as concentrations of oxygen and carbon dioxide reach low levels. Plants with strong root systems and tough stems can live under increased wind speeds at low pressures in high-altitude areas. It is usually adequate to know the altitude at which an event takes place, but in some cases pressure variations have to be taken into account. Usually, a station will record pressure as part of the data for climatological work.

### 4.6. WIND

Wind transports heat in either sensible or latent form between lower and higher layers of the atmosphere and from lower to higher latitudes. Moderate turbulence promotes the consumption of $CO_2$ by crops during photosynthesis. Wind prevents frost by disrupting a temperature inversion. Wind dispersal of pollen and seeds is natural and necessary for certain agricultural crops, natural vegetation, and so on. As far as the action of wind on soil is concerned, it causes soil erosion and transport of particles and dust. Extreme winds cause mechanical damage to crops (for example, lodging or leaf damage) and forests (windthrow). Knowledge of the wind is also necessary for environmentally sensitive spray application and for the design of wind protection. For the main regional crops, it may be useful to make observations of wind profiles inside and above the crop canopies for a better understanding of exchange properties.

Agricultural meteorological stations need toposcale reference observations of both wind speed and direction, preferably at 10 m height, but at least at three times the height of any nearby vegetation (for instance, crops) and any nearby obstacles, in order to be above significant flow interference. Lowerlevel wind measurements are not representative at toposcale and cannot be properly corrected either, so they cannot be used as local reference or for comparison with other stations (WMO, 2001b). Horizontal distance to obstacles should be at least 10 times their height. When possible, the wind speed gustiness should be obtained along with average wind, for instance by recording the largest three-second gust in each averaging period.

### 4.7. AIR HUMIDITY

Humidity is closely related to rainfall, wind and temperature. Different humidity-related parameters such as relative humidity, vapour pressure, dewpoint and other derived characteristics are explained in many textbooks. They play a significant role in crop production and strongly determine the crops grown in a region. Internal water potentials, transpiration and water requirements of plants are dependent on humidity. Extremely high humidity is harmful as it enhances the growth of some saprophytic and parasitic fungi, bacteria and pests, the growth of which causes extensive damage to crop plants. Extremely low humidity reduces the yield of crops.

Like temperature and for the same reasons, the humidity of the air should be measured in representative places, at different levels in the layer adjacent to the soil at principal agricultural meteorological and other category stations. The procedures for air temperature should also be followed for this weather variable, including taking measurements above and within vegetation.

## 4.8. SOIL MOISTURE

Soil moisture should be measured at all principal stations and, wherever possible, at other agricultural meteorological stations. Although rigid standardization is neither necessary nor, perhaps, even desirable, these measurements should, wherever possible, be made from the surface to depths of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm. In deep soils, with a high rate of infiltration, measurements should be extended to greater depths. In areas with snow cover, more frequent observations are required when the snow is melting.

## 4.9. PRECIPITATION AND OKTAS

At an agricultural meteorological station, visual observations and automatic instrumentation to measure total cloud coverage, that is, all sky camera observations, may be made at regular intervals to measure the total amount of cloud. In addition, cloud type and height of cloud base are required for studies of the radiation balance. Observations of hydrometeors are useful for many agricultural purposes. They include rain and drizzle (including intensity), snow (including thickness and density of snow cover, and water equivalent), hail (including water equivalent and size of hailstones), dew (amount and duration), hoar frost, rime fog, and so forth.

The amount of precipitation should be measured in the morning and evening as at synoptic stations. Additional measurements are desirable and the intensity of precipitation could be obtained by means of a recording raingauge

## 4.10. EVAPORATION AND WATER BALANCE MEASUREMENTS

Measurement of evaporation from free water surfaces and from the soil, and of transpiration from vegetation, remains of great importance in agricultural meteorology. Potential evapotranspiration is defined as the amount of water that evaporates from the soil–air interface and from plants when the soil is at field capacity. Actual evapotranspiration is defined as the evaporation at the soil–air interface, plus the transpiration of plants, under the existing conditions of soil moisture.

## 4.11. NETWORK OPERATIONS

### 4.11.1. Times of observations

Observations at the Argometeorological stations should be made at least twice each day. If at all possible, the times of observation should coincide with either the main or intermediate standard times for synoptic observations (0000, 0300, 0600 Coordinated Universal Time (UTC), and so on).

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

### 4.11.2. Logging and Reporting of Observations

Immediately after taking an observation at a manual station, the observer must enter the data into a logbook that is kept at the station for this purpose. Alternatively, the observation may be entered or transcribed immediately into a computer or transmission terminal and a database.

The observer must ensure that a complete and accurate record has been made of the observation.

### 4.11.3. Overall Responsibility of Observers

The responsibilities of observer should include the competent execution of the following:

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

# CHAPTER 5 QUALITY CONTROL

The Manual on the Global Observing System (WMO, 2015) prescribes that certain quality-control procedures must be applied to all meteorological data to be exchanged internationally. Level I and Level II data, and the conversion from one to the other, must be subjected to quality control. WMO (2017a) prescribes that quality-control procedures must be applied by meteorological data processing centres to most kinds of weather reports exchanged internationally, to check for coding errors, internal consistency, time and space consistency, and physical and climatological limits, and it specifies the minimum frequency and times for quality control.

General guidance on procedures is given in WMO (2010). It emphasizes the importance of quality control at the station, because some errors occurring there cannot be subsequently corrected, and also points out the great advantages of automation. WMO (1993a) gives rather detailed descriptions of the procedures that may be used by numerical analysis centres, with advice on climatological limits, types of internal consistency checks, comparisons with neighbouring stations and with analyses and prognoses, and provides brief comments on the probabilities of rejecting good data and accepting false data with known statistical distributions of errors.

## 5.1. MANUAL OBSERVATION AND STAFFED STATIONS

The observer or the officer in charge at a station is expected to ensure that the data leaving the station have been quality controlled, and should be provided with established procedures for attending to this responsibility. This is a specific function, in addition to other maintenance and record-keeping functions, and includes the following:

a) Internal consistency checks of a complete synoptic or other compound observation: In practice, they are performed as a matter of course by an experienced observer, but they should nevertheless be an explicit requirement. Examples of this are the relations between the temperature, the dew point and the daily extremes, and between rain, cloud and weather;

b) Climatological checks: These for consistency: The observer knows, or is provided with charts or tables of, the normal seasonal ranges of variables at the station, and should not allow unusual values to go unchecked;

c) Temporal checks: These should be made to ensure that changes since the last observation are realistic, especially when the observations have been made by different observers;

d) Checks of all arithmetical and table look-up operations;

e) Checks of all messages and other records against the original data.

## 5.2. AUTOMATIC WEATHER STATIONS

At AWSs, some of the above checks should be performed by the software, as well as engineering checks on the performance of the system. The following diagram shows WMO recommended practices for observing quality control of AWS stations.

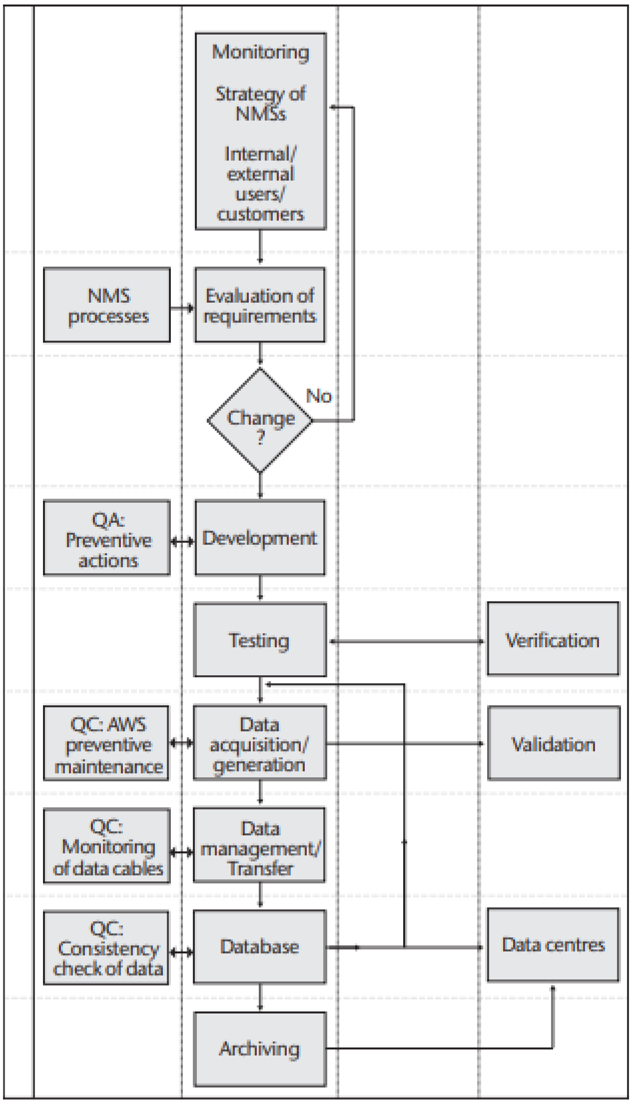


Figure 1: Process for QC at AWS station

## 5.3. INTERACTION WITH FIELD STATIONS

If quality is to be maintained, it is absolutely essential that errors be tracked back to their source, with some kind of corrective action. For data from staffed stations this is very effectively done in near real time, not only because the data may be corrected, but also to identify the reason for the error and prevent it from recurring.

It is good practice to assign a person at a data centre or other operational centre with the responsibility for maintaining near-real-time communication and effective working relations with the field stations, to be used whenever errors in the data are identified.

## 5.4. PERFORMANCE MONITORING

The management of a network, or of a station, is greatly strengthened by keeping continuous records of performance, typically on a daily and monthly schedule. The objective of performance monitoring is to review continually the quality of field stations and of each observing system, such as for pressure measurement, or the radiosonde network.

There are several aspects to performance monitoring, as follows:

a) Advice from NCHM HQ should be used to record the numbers and types of errors detected by quality-control procedures;

b) Data from each station should be compiled into synoptic and time-section sets. Such sets should be used to identify systematic differences from neighbouring stations, both in spatial fields and in comparative time series. It is useful to derive statistics of the mean and the scatter of the differences. Graphical methods are effective for these purposes;

c) Reports should be obtained from field stations about equipment faults, or other aspects of performance.

These types of records are very effective in identifying systematic faults in performance and in indicating corrective action. They are powerful indicators of many factors that affect the data, such as exposure or calibration changes, deteriorating equipment, changes in the quality of consumables or the need for retraining. They are particularly important for maintaining confidence in automatic equipment.

The results of performance monitoring should be used for feedback to the field stations, which is important to maintain motivation. The results also indicate when action is necessary to repair or upgrade the field equipment.

Performance monitoring is a time-consuming task, to which the network manager must allocate adequate resources. WMO (1988) describes a system to monitor data from an AWS network, using a small, dedicated office with staff monitoring real-time output and advising the network managers and data users. Miller and Morone (1993) describe a system with similar functions, in near real time, making use of a mesoscale numerical model for the spatial and temporal tests on the data.

## 5.5. METADATA

Data inhomogeneities should, as far as possible, be prevented by appropriate quality-assurance procedures with respect to quality control. However, this cannot always be accomplished as some causes of inhomogeneities, such as the replacement of a sensor, can represent real improvements in measuring techniques. It is important to have information on the occurrence, type and, especially, the time of all inhomogeneities that occur. After obtaining such information, climatologists can run appropriate statistical programs to link the previous data with the new data in homogeneous databases with a high degree of confidence. Information of this kind is commonly available in what is known as metadata — information on data — also called station histories. Without such information, many of the above-mentioned inhomogeneities may not be identified or corrected. Metadata can be considered as an extended version of the station administrative record, containing all possible information on the initial set-up, and type and times of changes that occurred during the life history of an observing system. As computer data management systems are an important aspect of quality data delivery, it is desirable that metadata should be available as a computer database enabling computerized composition, updating and use.

### 5.5.1. Element of Metadata

A metadata database contains initial set-up information together with updates whenever changes occur. Major elements include the following:

a) Network information:
    - The operating authority, and the type and purpose of the network;

b) Station information:
    - Administrative information;
    - Location: geographical coordinates, elevation(s)
    - Descriptions of remote and immediate surroundings and obstacles
    - Instrument layout
    - Facilities: data transmission, power supply, cabling
    - Climatological description

c) Individual instrument information
    - Type: manufacturer, model, serial number, operating principles;
    - Performance characteristics;
    - Calibration data and time;
    - Siting and exposure: location, shielding, height above ground;
    - Measuring or observing programme;
    - Times of observations;
    - Observer;
    - Data acquisition: sampling, averaging;
    - Data-processing methods and algorithms;
    - Preventive and corrective maintenance;
    - Data quality

## 5.6. INSPECTIONS

Field stations should be inspected regularly, preferably by specially appointed, experienced inspectors. The objectives are to examine and maintain the work of the observers, the equipment and instrument exposure, and also to enhance the value of the data by recording the station history. At the same time, various administrative functions, which are particularly important for staffed stations, can be performed.

Inspections reports are part of the performance monitoring record. It is highly advisable to have a systematic and exhaustive procedure fully documented in the form of inspections and maintenance handbooks, to be used by the visiting inspectors. Procedures should include the details of subsequent reporting and follow-up. The inspector should attend, in particular, to the following aspects of station operations:

a) Instrument performance: Instruments requiring calibration must be checked against a suitable standard. Atmospheric pressure is the prime case, as all field barometers can drift to some degree. Mechanical and electrical recording systems must be checked according to established procedures. More complex equipment such as AWSs and radars need various physical and electrical checks. Anemometers and thermometer shelters are particularly prone to deterioration of various kinds, which may vitiate the data. The physical condition of all equipment should be examined for dirt, corrosion and so on;

b) Observing methods: Bad practice can easily occur in observing procedures, and the work of all observers should be continually reviewed. Uniformity in methods recording and coding is essential for synoptic and climatological use of the data;

c) Exposure: Any changes in the surroundings of the station must be documented and corrected in due course, if practicable. Relocation may be necessary.

Inspections of manual stations also serve the purpose of maintaining the interest and enthusiasm of the observers. The inspector must be tactful, informative, enthusiastic and able to obtain willing cooperation.

A prepared form for recording the inspection should be completed for every inspection. It should include a checklist on the condition and installation of the equipment and on the ability and competence of the observers. The inspection form may also be used for other administrative purposes, such as an inventory.

It is most important that all changes identified during the inspection should be permanently recorded and dated so that a station history can be compiled for subsequent use for climate studies and other purposes.

## ABBREVIATIONS AND ACRONYMS

AWS – Automatic Weather Station

CSD - Cryosphere Service Division

DBMS - Database Management System

GPS - Global Positioning System

HWRSD – Hydrology and Water Resources Service Division

ISO – Indian Organization for Standardization

MSD - Metoerological Service Division

NCHM – National Centre for Hydrology and Meteorology

RGoB - Royal Government of Bhutan

TSRD – Technical Standard and Research Division

USGS - United State Geological Survey

WMO - World Meteorological Organization

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