CHAPTER 6 — MEASUREMENT OF PRECIPITATION

CHAPTER 6

MEASUREMENT OF PRECIPITATION

6.1 General

This chapter describes the well-known methods of precipitation measurements at ground stations. It does not discuss measurements either which attempt to define the structure and character of precipitation, or which require specialized instrumentation, which are not standard meteorological observations (such as drop size distribution). Radar and satellite measurements, and measurements at sea, are found in other chapters.

Information on measurements of precipitation can also to be found in WMO (1994*a*), which includes, in particular, more detail on measurements of snow cover.

The general problem of representativeness is particularly acute in the measurement of precipitation. Precipitation measurements are particularly sensitive to exposure, wind and topography, and metadata describing the circumstances of the measurements are particularly important for users of the data.

Analysis of precipitation data is much easier and more reliable if the same gauges and siting criteria are used throughout the networks. This should be a major consideration in designing networks.

6.1.1 *Definitions*

Precipitation is defined as the liquid or solid products of the condensation of water vapour falling from clouds or deposited from air on the ground. It includes rain, hail, snow, dew, rime, hoar frost and fog precipitation. The total amount of precipitation which reaches the ground in a stated period is expressed in terms of the vertical depth of water (or water equivalent in the case of solid forms) to which it would cover a horizontal projection of the Earth's surface. Snowfall is also expressed by the depth of fresh snow covering an even horizontal surface.

6.1.2 *Units and scales*

The unit of precipitation is linear depth, usually in millimetres for liquid precipitation. Daily amounts of precipitation should be read to the nearest 0.2 mm and, if feasible, to the nearest 0.1 mm; weekly or monthly amounts should be read to the nearest 1 mm (at least). Daily measurements of precipitation should be made at fixed times. Less than 0.2 mm is generally referred to as a trace. The rate of rainfall is similarly expressed in linear measures per unit time, usually millimetres per hour.

Snowfall measurements are made in units of centimetres and tenths, to the nearest 0.2 cm. Less than 0.2 cm is generally called a trace. The depth of snow on the ground is usually measured daily in whole centimetres.

6.1.3 *Meteorological requirements*

Chapter 1 gives a broad statement of the requirements for accuracy, range and resolution for precipitation measurements, and gives 5 per cent as the achievable accuracy (at the 95 per cent confidence level).

The common observation times are hourly, three-hourly and daily, for synoptic and climatological purposes. For some purposes, a much greater time resolution is required to measure very high rainfall rates over very short periods. For some applications, storage gauges are used with observation intervals of weeks or months.

6.1.4 *Methods of measurement*

6.1.4.1 INSTRUMENTS

Precipitation gauges (often known as raingauges) are the most common instruments used to measure precipitation. Generally an open receptacle with vertical sides is used, usually in the form of a right cylinder, and with a funnel if its main purpose is to measure rain. Various sizes and shapes of orifice and gauge height are used in different countries, so the measurements are not strictly comparable. The volume or weight of the catch is measured, the latter in particular for solid precipitation. The gauge orifice may be at one of many specified heights above the ground or it can be at the same level as the surrounding ground. The orifice must be placed above the maximum expected depth of snow cover, and above the height of significant potential in-splashing from the ground. For solid precipitation measurement, the orifice is above the ground and an artificial shield is placed around it.

The measurement of precipitation is very sensitive to exposure, and in particular to the wind. Section 6.2 discusses exposure while section 6.4 discusses at some length the errors to which precipitation gauges are prone, and the corrections that may be applied.

This chapter also describes some other special techniques for measuring other types of precipitation (dew, ice, etc) and snow cover. Some new techniques which are arguably not yet ready for routine use are not described here, for example the optical raingauge, which makes use of optical scattering. Useful sources for information on new methods under development are the reports of recurrent conferences, such as the international workshops on precipitation measurement (Slovak Hydrometeorological Institute and Swiss Federal Institute of Technology, 1993; WMO, 1989*b*) and those organized by the Commission for Instruments and Methods of Observation (WMO, 1994*b*).

Point measurements of precipitation serve as the primary source of data for areal analysis. However, even the best measurement of precipitation at a point is only representative of a limited area, the size of which is a function of the length of accumulation period, the physiographic homogeneity of the region, local topography,

and the precipitation-producing process. Radar and, more recently, satellites are used to define and quantify the spatial distribution of precipitation. The techniques are described in Part II of this *Guide*. In principle, a suitable integration of all three sources of areal precipitation data into national precipitation networks (automatic gauges, radar, and satellite) can be expected to provide sufficiently accurate areal precipitation estimates on an operational basis for a wide range of precipitation data users.

Instruments that detect precipitation and identify its type, as distinct from measuring it, may be used as present weather detectors, and are referred to in Chapter 14, Part I.

6.1.4.2 Reference gauges and intercomparisons

Several types of gauges have been used as reference gauges. The main feature of their design is to reduce or control the effect of wind on the catch, which is the most serious reason for the different behaviours of gauges. They are chosen also to reduce the other errors discussed in section 6.4.

Ground-level gauges are used as reference gauges for liquid precipitation measurement. Because of the absence of wind-induced error they generally show more precipitation than any elevated gauge (WMO, 1984). The gauge is placed in a pit with the gauge rim at ground level, sufficiently distant from the nearest edge of the pit to avoid in-splashing. A strong plastic or metal anti-splash grid with a central opening for the gauge should span the pit. Provision should be made for draining the pit. Drawings of a pit gauge are given in WMO (1984).

The reference gauge for solid precipitation is the gauge known as the Double Fence Intercomparison Reference. It has octagonal vertical double fences surrounding a Tretyakov gauge, which itself has a particular form of wind deflecting shield. Drawings and a description are given by Goodison, Sevruk and Klemm (1989), in WMO (1985), and in the final report of the WMO intercomparison of solid precipitation gauges (Goodison, *et al.*, to be published).

Recommendations for comparisons of precipitation gauges against the reference gauges are given in Annex 6.A.[1]

6.1.4.3 Documentation

The measurement of precipitation is particularly sensitive to gauge exposure, so metadata about the measurements must be recorded meticulously to compile a comprehensive station history, in order to be available for climate studies.

Section 6.2 discusses the site information that must be kept: detailed site descriptions, including vertical angles to significant obstacles around the gauge, gauge configuration, height of the gauge orifice above ground and height of the wind speed measuring instrument above ground.

The following sections (especially section 6.4) on the various instrument types discuss the corrections that may be applied to precipitation measurements. Such corrections have uncertainties, and the original records and the correction formulae should be kept.

Any changes in the methods of observation should also be documented.

6.2 Siting and exposure

Any method of measuring precipitation should aim to obtain a sample which is representative of the true amount falling over the area which the measurement is intended to represent, whether on the synoptic, meso or microscales. The choice of site, as well as the systematic measurement error is, therefore, important. For a discussion of the effects of the site see Sevruk and Zahlavova (1994).

The location of precipitation stations within the area of interest is important, because the number and locations of the gauge sites determine how well the measurements represent the actual amount of precipitation falling in the area. Areal representativeness is discussed at length in WMO (1992*b*) for rain and snow. WMO (1994*a*) gives an introduction to the literature on the calculation of areal precipitation and corrections for topography.

The effects on the wind field of the immediate surroundings of the site can give rise to local excesses and deficiencies of precipitation. In general, objects should not be closer to the gauge than a distance twice their height above the gauge orifice. For each site, the average vertical angle of obstacles should be estimated, and a site plan should be made. Sites on a slope or on the roof of a building should be avoided. Sites selected for measurement of snowfall and/or snow cover should be in areas sheltered from the wind as much as possible. The best sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or where other objects act as an effective wind-break for winds from all directions.

Preferably, however, the effects of the wind, and of the site on the wind, can be reduced by using a ground-level gauge for liquid precipitation or by making the airflow horizontal above the gauge orifice using the following techniques. These are listed in the order of decreasing effectiveness:

(*a*) In areas having homogeneous dense vegetation, the height of such vegetation should be kept at the same level as the gauge orifice by regular clipping;

(*b*) In other areas, by simulating the effect in (*a*) by the use of appropriate fence structures;

(*c*) By using wind shields around the gauge.

The surface surrounding the precipitation gauge can be covered with short grass, gravel or shingle, but hard, flat surfaces, such as concrete, should be avoided to prevent excessive in-splashing.

[1] Recommended by the Commission for Instruments and Methods of Observation at its eleventh session, 1994.

6.3 Non-recording precipitation gauges

Non-recording or manual methods of precipitation measurements require that an observer make these measurements.

6.3.1 *Ordinary gauges*

6.3.1.1 Instruments

The commonly used precipitation gauge consists of a collector placed above a funnel leading into a container where the accumulated water and melted snow are stored between observation times. Where solid precipitation is common and important, a number of special modifications are used to improve the accuracy of measurements. Such modifications include the removal of the raingauge funnel at the beginning of the snow season or the provision of a special snow cross to protect the catch from blowing out. Wind shields around the gauge reduce the error caused by deformation of the wind field above the gauge and by drifting of snow into the gauge. They are advisable for rain and essential for snow. A wide variety of gauges are in use (see WMO 1989*a*).

The stored water is either collected in a measure or poured out from the container into a measure, or its level in the container is measured directly with a graduated stick. The size of the orifice of the collector is not critical for liquid precipitation, but an area of at least 200 cm^2 is required if solid forms of precipitation are expected in significant quantity. An area of 200 to 500 cm^2 will probably be found most convenient. The most important requirements of a gauge are as follows:

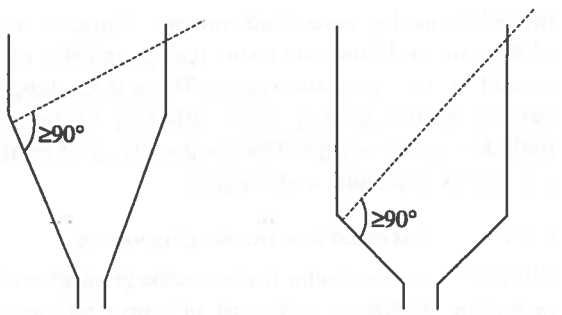
(*a*) The rim of the collector should have a sharp edge and should fall away vertically inside, and should be steeply bevelled outside; the design of the gauges used for measuring snow should be such that any tendency to constrict the orifice by accumulation of wet snow about the rim is small;

(*b*) The area of the orifice should be known to the nearest 0.5 per cent and the construction should be such that this area remains constant while the gauge is in normal use;

(*c*) The collector should be designed to prevent rain from splashing in and out. This can be done by having the vertical wall sufficiently deep and the slope of the funnel sufficiently steep (at least 45 per cent). Suitable arrangements are shown in the following figure;

(*d*) The construction should be such as to minimize wetting errors;

(*e*) The container should have a narrow entrance and be sufficiently protected from radiation to minimize the loss of water by evaporation. Precipitation gauges for use in locations where only weekly or monthly readings are practicable should be similar in design to the type used for daily measurements but with a container of larger capacity and stronger construction.



Suitable collectors for raingauges.

The measuring cylinder should be made of clear glass or plastic having a suitable coefficient of thermal expansion and should be clearly marked to show the size or the type of gauge with which it is to be used. Its diameter should be less than 33 per cent of that of the rim of the gauge; the smaller the relative diameter, the greater the precision of measurement. The graduations should be finely engraved; in general, there should be marks at 0.2 mm intervals and clearly figured lines at each whole millimetre. It is also desirable that the line corresponding to 0.1 mm be marked. The maximum error of the graduations should not exceed ±0.05 mm at or above the 2 mm graduation mark and ±0.02 mm below this mark.

To measure small precipitation amounts with adequate precision, the inside diameter of the measuring cylinder should taper off at its base. In all measurements, the bottom of the water meniscus should define the water level and the cylinder should be kept vertical when reading, to avoid parallax errors. Repetition of the main graduation lines on the back of the measure is also helpful for reducing such errors.

Dip-rods should be made of cedar wood, or other suitable material which does not absorb water appreciably and possesses only a small capillary effect. Wooden dip-rods are unsuitable if oil has been added to the collector to suppress evaporation. In this situation, rods of metal or other materials from which oil can be readily cleaned must be used. Non-metallic rods should be provided with a brass foot to avoid wear and be graduated according to the relative areas of cross-section of the gauge orifice and the collector; graduations should be marked at least every 10 mm and should include an allowance for the displacement due to the rod itself. The maximum error in the dip-rod graduation should not exceed ±0.5 mm at any point. A dip-rod measurement should be checked using a volumetric measure, wherever possible.

6.3.1.2 Operation

The measuring cylinder must be held vertical when it is being read, and the observer must be aware of parallax error. Snow collected in non-recording precipitation gauges should be either weighed or melted immediately after each observation and then measured, using a standard graduated measuring cylinder. It is also possible to measure precipitation catch by accurate weighing, a

procedure having several advantages. The total weight of the can and contents is measured and the known weight of the can is subtracted. There is no danger of spilling water and any water adhering to the can is included in the weight. The commonly used methods are, however, simpler and cheaper.

6.3.1.3 CALIBRATION AND MAINTENANCE

Whatever size of collector is chosen, the graduation of the measuring cylinder or stick must, of course, be consistent with it. The calibration of the gauge, therefore, includes checking the diameter of the gauge orifice and insuring that it is within allowable tolerances. It also includes volumetric checks of the measuring cylinder or stick.

Routine maintenance should include, at all times, keeping the gauge level in order to prevent an out-of-level gauge (see Rinehart,1983 and Sevruk, 1984). As required, the outer container of the gauge as well as the graduate should be kept clean at all times both inside and outside by using a long handle brush, soapy water, and clean water rinse. Worn, damaged or broken parts should be replaced, as required. The vegetation around the gauge should be kept trimmed to 5 cm (where applicable). The exposure should be checked and recorded.

6.3.2 *Storage gauges*

Storage gauges are used to measure total seasonal precipitation in remote and sparsely inhabited areas. Such gauges consist of a collector above a funnel, leading into a container which is large enough to store the seasonal catch (or the monthly catch in wet areas). A layer of not less than 5 mm of a suitable oil or other evaporation suppressant should be placed in the container to reduce evaporation (WMO, 1972). This layer should allow the free passage of precipitation into the solution below it.

An antifreeze solution may be placed in the container to convert any snow which falls into the gauge to a liquid state. It is important that the antifreeze solution remain dispersed. A mixture of 37.5 per cent by weight of commercial calcium chloride (78 per cent purity) and 62.5 per cent water makes a satisfactory antifreeze solution. Alternatively, aqueous solutions of ethylene glycol or of a mixture of ethylene glycol with methanol can be used. While more expensive, the latter solutions are less corrosive than calcium chloride and give antifreeze protection over a much wider range of dilution resulting from subsequent precipitation. The volume of the solution which is initially placed in the container should not exceed 33 per cent of the total volume of the gauge.

In some countries, this solution of antifreeze and oil is considered toxic waste and, therefore, harmful to the environment. Guidelines for the disposal of toxic substances should be obtained from local environmental protection authorities.

The seasonal precipitation catch is determined by weighing or measuring the volume of the contents of the container (as for ordinary gauges, see section 6.3.1). The amount of oil and antifreeze solution placed in the container at the beginning of the season and any contraction in the case of volumetric measurements must be carefully taken into account. Corrections may be applied as for ordinary gauges.

The operation and maintenance of storage gauges in remote areas pose several problems, such as capping of the gauge by snow or the difficulty in locating the gauge for recording the measurement, etc., which require specific control. Particular attention should be paid to assessing the quality of data from such gauges.

6.4 Errors and corrections in precipitation gauges

It is convenient to discuss at this point the errors and corrections that apply in some degree to most precipitation gauges, whether recording or non-recording. The particular cases of recording gauges are discussed in section 6.5.

Comprehensive accounts of errors and corrections can be found in WMO (1982, 1984, 1986) and, specifically for snow, in WMO (1994*b*) and Goodison, *et al.* (to be published). Details of the models currently used for adjusting raw precipitation data in Canada, Denmark, Finland, Russia, Switzerland and the United States are given by WMO (1982). WMO (1989*a*) gives a description of how the errors occur. There are collected conference papers on the topic in WMO (1986, 1989*b*).

The amount of precipitation measured by commonly used gauges may be less than the actual precipitation reaching the ground by up to 30 per cent or more. Systematic losses will vary by type of precipitation (snow, mixed snow and rain, and rain). The systematic error of measurement of solid precipitation is commonly large and may be of an order of magnitude greater than those normally associated with measurements of liquid precipitation.

For many hydrological purposes it is necessary first to make adjustments to the data in order to allow for the error prior to making the calculations. The adjustments cannot, of course, be exact (and may even make things worse). Thus, the original data should always be kept as the basic archives both to maintain continuity and to serve as the best base for future improved adjustments if, and when, they become possible.

The true amount of precipitation may be estimated by correcting for some or all of the various error terms listed below:

(*a*) Error due to systematic wind-field deformation above the gauge orifice: typically 2 to 10 per cent for rain and 10 to 50 per cent for snow;

(*b*) Error due to the wetting loss on the internal walls of the collector;

(*c*) Error due to the wetting loss in the container when it is emptied: typically 2 to 15 per cent in summer and 1 to 8 per cent in winter, for (*b*) and (*c*) together;

(*d*) Error due to evaporation from the container (most important in hot climates): 0 to 4 per cent;
(*e*) Error due to blowing and drifting snow;
(*f*) Error due to the in- and out-splashing of water: 1 to 2 per cent;
(*g*) Random observational and instrumental errors.

The first six error components are systematic and are listed in order of general importance. The net error due to blowing and drifting snow and to in- and out-splashing of water can be either negative or positive, while net systematic errors due to the wind field and other factors are negative. Since the errors listed as (*e*) and (*f*) above are generally difficult to quantify, the general model for adjusting the data from most gauges takes the following form:

$$P_k = kP_c = k\,(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3)$$

where P_k is the adjusted precipitation amount, k is the adjustment factor for the effects of wind field deformation, P_c is the amount of precipitation caught by the gauge collector, P_g is the measured amount of precipitation in the gauge, ΔP_1 is the adjustment for the wetting loss on the internal walls of the collector, ΔP_2 is the adjustment for wetting loss in the container after emptying, and ΔP_3 is the adjustment for evaporation from the container.

The corrections are applied to daily or monthly totals or, in some practices, to individual precipitation events.

In general, the supplementary data needed to make such adjustments include the wind speed at the gauge orifice during precipitation, drop size, precipitation intensity, air temperature and humidity, and characteristics of the gauge site. Wind speed and precipitation type or intensity may be sufficient variables to determine the corrections. Wind speed alone is sometimes used. At sites where such observations are not made, interpolation between those observations made at adjacent sites may be used for making such adjustments, but with caution, and for monthly rainfall data only.

For most precipitation gauges, wind speed is the most important environmental factor contributing to the undermeasurement of solid precipitation. These data must be derived from standard meteorological observations at the site in order to provide daily adjustments. In particular, if wind speed is not measured at gauge orifice height, it can be derived by using a mean wind speed reduction procedure after having knowledge of the roughness of the surrounding surface and the angular height of surrounding obstacles. A suggested scheme is shown in Annex 6.B[2]. This scheme is very site-dependent and estimation requires a good knowledge of the station and gauge location. Shielded gauges catch more precipitation than their unshielded counterparts, especially for solid precipitation. Therefore, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind speed on measurements of solid precipitation.

Wetting loss is another cumulative systematic loss from manual gauges which varies with precipitation and gauge type; its magnitude is also a function of the number of times the gauge is emptied. Average wetting loss can be up to 0.2 mm per observation. At synoptic stations where precipitation is measured every six hours, this can become a very significant loss. In some countries, wetting loss has been calculated to be 15–20 per cent of the measured winter precipitation. Correction for wetting loss at the time of observation is a feasible alternative. Wetting loss can be kept low in a well-designed gauge. The internal surfaces should be of a material which can be kept smooth and clean; paint, for example, is unsuitable but baked enamel is satisfactory. Seams in the construction should be minimized.

Evaporation losses vary by gauge type and time of year. Evaporation loss is a problem with gauges which do not have a funnel device in the bucket, especially in late spring. Losses of over 0.8 mm per day have been reported. Losses during winter are much less than during comparable summer months, ranging from 0.1–0.2 mm per day. These losses, however are cumulative. In a well-designed gauge, only a small water surface is exposed, its ventilation is minimized, and the water temperature is kept low by a reflective outer surface.

It is clear that in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, corrections to the actual measurements are necessary. In all cases where precipitation measurements are adjusted in an attempt to reduce errors, it is strongly recommended that both the measured and adjusted values be published.

6.5 Recording precipitation gauges

Automatic recording of precipitation has the advantage that it can provide better time resolution than manual measurements, and it is possible to reduce the evaporation and wetting losses. They are of course subject to the wind effects discussed in section 6.4.

Three types of automatic precipitation recorder are in general use: the weighing-recording type, the tilting or tipping-bucket type, and the float type. Only the weighing type is satisfactory for measuring all kinds of precipitation, the use of the other two types being for the most part limited to the measurement of rainfall. Some new automatic gauges which measure precipitation without moving parts are available. These gauges use devices such as capacitance probes, pressure transducers, and optical or small radar devices to provide an electronic signal which is proportional to the precipitation equivalent.

[2] A wind reduction scheme recommended by the eleventh session of the Commission for Instruments and Methods of Observation, 1994.

6.5.1 *Weighing-recording gauge*

6.5.1.1 Instruments

In these instruments, the weight of a container together with the precipitation accumulated therein is recorded continuously, either by means of a spring mechanism or with a system of balance weights. All precipitation, both liquid and solid forms, is recorded as it falls. This type of gauge normally has no provision for emptying itself; the capacity (i.e. maximum accumulation between recharge) ranges from 150 to 750 mm. The gauges must be maintained to minimize evaporation losses, which can be accomplished by adding sufficient oil or other evaporation suppressants to the container to form a film over the water surface. Any difficulties arising from oscillation of the balance in strong winds can be reduced with an oil damping mechanism or, if recent work is substantiated, by suitably programming a microprocessor to eliminate this effect on the readings. Such weighing gauges are particularly useful for recording snow, hail, and mixtures of snow and rain, since the solid precipitation does not require melting before it can be recorded. For winter operation, the catchment container is charged with an antifreeze solution (see section 6.3.2) to dissolve the solid contents. The amount of antifreeze depends on the expected amount of precipitation and the minimum temperature expected at the time of minimum dilution.

The weight of the catchment container, measured by a calibrated spring, is translated from a vertical to an angular motion through a series of levers or pulleys. This angular motion is then communicated mechanically to a drum or strip chart or digitized through a transducer. The accuracy of these types of gauges is related directly to their measuring and/or recording characteristics which can vary with manufacturer.

6.5.1.2 Errors and corrections

Except for error due to the wetting loss in the container when it is emptied, weighing recording gauges are susceptible to all of the other sources of error discussed in section 6.4. It should also be noted that automatic recording gauges alone cannot identify the type of precipitation. A significant problem with this type of gauge is that precipitation, particularly freezing rain or wet snow can stick to the inside of the orifice of the gauge and not fall into the bucket until some time later. This severely limits the ability of weighing-recording gauges to provide accurate timing of precipitation events. Another common fault with weighing type gauges is wind pumping. This usually occurs during high winds when turbulent air currents passing over and around the catchment container cause oscillations in the weighing mechanism. By using programmable data logging systems, errors associated with such anomalous recordings can be minimized by averaging readings over short-time intervals, i.e. one minute.

Some potential errors in manual methods of precipitation can be eliminated or at least minimized by using weighing-recording gauges. Random errors in measurement associated with human observer error and certain systematic errors, particularly evaporation and wetting loss, are minimized. In some countries, trace observations are officially given a value of zero, thus, resulting in a biased underestimate of the seasonal precipitation total. This problem is minimized with weighing type gauges, since even very small amounts of precipitation will accumulate over time.

The correction of weighing gauge data on an hourly or daily basis may be more difficult than on longer time periods, such as monthly climatological summaries. Ancillary data from the automatic weather stations, such as wind at gauge height, air temperature, present weather or snow depth, will be useful in interpreting and correcting accurately the precipitation measurements from automatic gauges.

6.5.1.3 Calibration and maintenance

Weighing-recording gauges usually have few moving parts and, therefore, should seldom require calibration. Calibration commonly involves the use of a series of weights which, when placed in the bucket or catchment container, provide a predetermined value equivalent to an amount of precipitation. Calibrations should normally be done in a laboratory setting and should follow the manufacturer's instructions.

Routine maintenance should be done every three to four months depending on precipitation conditions at the site. Both the exterior and interior of the gauge should be inspected for loose or broken parts and to ensure that the gauge is level. Any manual read-out should be checked against the chart or tape record to insure consistency before removing and annotating the record. The bucket or catchment container should be emptied, inspected, cleaned, if required, and recharged with oil for rainfall-only operation or with antifreeze and oil if solid precipitation is expected (see section 6.3.2). The recording device should be set to zero in order to make maximum use of the gauge range. The tape or chart supply as well as the power supply should be checked and replaced, if required. A volt-ohmmeter may be required to set the gauge output to zero when a data logger is used or to check the power supply of the gauge or recording system.

6.5.2 *Tipping-bucket gauge*

The tipping-bucket raingauge is suitable for measuring the rate of rainfall as well as the accumulated totals, at rates up to 200 mm hr^{-1} or more.

6.5.2.1 Instruments

The principle behind the operation of this instrument is simple. A light metal container or bucket divided into two compartments is balanced in unstable equilibrium about a horizontal axis. In its normal position, the bucket rests against one of two stops, which prevents it from tipping over completely. Rain water is conducted from a

collector into the uppermost compartment and, after a predetermined amount has entered the compartment, the bucket becomes unstable and tips over to its alternative rest position. The bucket compartments are shaped in such a way that the water is emptied from the lower one. Meanwhile subsequent rain falls into the newly positioned upper compartment. The movement of the bucket as it tips over can be used to operate a relay contact to produce a record consisting of discontinuous steps; the distance between each step on the record represents the time taken for a specified small amount of rain to fall. This amount of rain should not exceed 0.2 mm if detailed records are required.

The bucket takes a small but finite time to tip and, during the first half of its motion, additional rain may enter the compartment which already contains the calculated amount of rainfall. This error can be appreciable during heavy rainfall (250 mm hr^{-1}), but it can be controlled. The simplest method is to use a device like a siphon at the foot of the funnel to direct the water to the buckets at a controlled rate. This smooths out the intensity peaks of very short-period rainfall. Alternatively, a device can be added to accelerate the tipping action; essentially, a small blade is impacted by the water falling from the collector and is used to apply an additional force to the bucket, varying with rainfall intensity.

The tipping-bucket gauge is particularly convenient for automatic weather stations because it lends itself to digital methods. The pulse generated by a contact closure can be monitored by a data logger and totalled over selected time periods to provide precipitation amount. It may also be used with a chart recorder.

6.5.2.2 Errors and corrections

The tipping-bucket raingauge has sources of error somewhat different from other gauges, so special precautions and corrections are advisable. Some sources of error include:

(*a*) The loss of water during the tip in heavy rain can be minimized but not eliminated;

(*b*) With the usual design of the bucket, the exposed water surface is large in relation to its volume so that appreciable evaporation losses can occur, especially in hot regions. This error may be significant in light rain;

(*c*) The discontinuous nature of the record may not provide satisfactory data during light drizzle or very light rain. In particular, the time of onset and cessation of precipitation cannot be accurately determined;

(*d*) Water may adhere to both the walls and the lip of the bucket resulting in rain residue in the bucket and additional weight to be overcome by the tipping action. Tests on waxed buckets produced a 4 per cent reduction in the volume required to tip the balance over non-waxed buckets. Volumetric calibration can change, without adjustment of the calibration screws, by variation of bucket wettability through surface oxidation or contamination by impurities and variations in surface tension;

(*e*) The stream of water falling from the funnel onto the exposed bucket may cause over-reading, depending on the size, shape and position of the nozzle;

(*f*) The instrument is particularly prone to bearing friction and improper balancing of the bucket due to the gauge not being level.

Careful calibration can provide corrections for the systematic parts of these errors. The measurements from tipping-bucket raingauges may be corrected for effects of exposure as for other types of precipitation gauge.

Heating devices can be used to allow for measurements during the cold season, particularly of solid precipitation. However, the performance of heated tipping-bucket gauges has been found to be very poor as a result of large errors due to both wind and evaporation of melting snow. Therefore, these types of gauges are not recommended for use in winter precipitation measurement in regions were temperatures fall below 0°C for prolonged periods of time.

6.5.2.3 Calibration and maintenance

Calibration of the tipping bucket is usually accomplished by passing a known amount of water through the tipping mechanism at various rates and by adjusting the mechanism to the known volume. This procedure should be done under laboratory conditions.

Due to the many error sources, the collection characteristics and calibration of tipping-bucket raingauges are a complex interaction of many variables. Daily comparisons with the standard raingauge can provide useful correction factors, and is good practice. The correction factors may vary from station to station. Correction factors are generally greater than 1.0 (under-reading) for low intensity rain, and less than 1.0 (over-reads) for high intensity rain. The relationship between the correction factor and intensity is not linear but forms a curve.

Routine maintenance should include cleaning the funnel and buckets of accumulated dirt and debris, as well as ensuring that the gauge is level. Replacing annually the tipping mechanism with a newly calibrated unit is highly recommended.

6.5.3 *Float gauge*

In this type of instrument, the rain passes into a float chamber containing a light float. As the level of the water within the chamber rises, the vertical movement of the float is transmitted, by a suitable mechanism, to the movement of a pen on a chart. By suitably adjusting the dimensions of the collector orifice, the float, and the float chamber, any desired chart scale can be used.

In order to provide a record over a useful period (24 hours is normally required) either the float chamber has to be very large (in which case a compressed scale on the chart is obtained), or a mechanism must be

provided for emptying automatically and quickly the float chamber whenever it becomes full, so that the pen returns to the bottom of the chart. Usually a siphoning arrangement is used. The actual siphoning process should begin precisely at the predetermined level with no tendency for the water to dribble over at either the beginning or the end of the siphoning period, which should not be longer than 15 s. In some instruments, the float chamber assembly is mounted on knife edges so that the full chamber overbalances; the surge of the water assists in the siphoning process and when the chamber is empty, it returns to its original position. Other rain recorders have a forced siphon which operates in less than five seconds. One type of forced siphon has a small chamber which is separate from the main chamber and which accommodates the rain that falls during siphoning. This chamber empties into the main chamber when siphoning ceases, thus ensuring a correct record of total rainfall.

A heating device (preferably controlled by a thermostat) should be installed inside the gauge if there is the possibility that water might freeze in the float chamber during the winter. This will prevent damage to the float and float chamber and will enable rain to be recorded during that period. A small heating element or electric lamp is suitable where a mains supply of electricity is available, otherwise other sources of power may be employed. One convenient method uses a short heating strip wound around the collecting chamber and connected to a large capacity battery. The amount of heat supplied should be kept to the minimum necessary in order to prevent freezing, because the heat may reduce the accuracy of the observations by stimulating vertical air movements above the gauge and by increasing evaporation losses.

A large undercatch by unshielded heated gauges, caused by the wind and the evaporation of melting snow has been reported in some countries, as for weighing gauges (see section 6.5.1.2).

With the exception that calibration is performed by using a known volume of water, maintenance of this gauge is similar to the weighing-recording gauge (see section 6.5.1.3).

6.6 Measurement of dew, ice accumulation, and fog precipitation

6.6.1 *Measurement of dew and leaf wetness*

The deposition of dew is essentially a nocturnal phenomenon and, although relatively small in amount and locally variable, is of much interest in arid zones; in very arid regions, it may be of the same order of magnitude as the rainfall. The exposure of plant leaves to liquid moisture from dew, fog and precipitation also plays an important role in plant disease, insect activity, and the harvesting and curing of crops.

In order to assess the hydrological contribution of dew, it is necessary to distinguish between dew formed:

(*a*) As a result of the downward transport of atmospheric moisture condensed on cooled surfaces, known as dew-fall;

(*b*) By water vapour evaporated from the soil and plants and condensed on cooled surfaces, known as distillation dew;

(*c*) As water exuded by leaves, known as guttation.

All three forms of dew may contribute simultaneously to the observed dew, although only the first provides additional water to the surface, and the latter usually results in a net loss. A further source of moisture results from fog or cloud droplets being collected by leaves and twigs and reaching the ground by dripping or by stem flow. All forms of precipitation are sometimes referred to as occult precipitation.

The amount of dew deposited on a given surface in a stated period is usually expressed in units of kg m^{-2} or in millimetres depth of dew. Whenever possible, the amount should be measured to the nearest tenth of a millimetre.

Leaf wetness may be described as light, moderate or heavy, but its most important measures are the time of onset or duration.

A review of the instruments designed for measuring dew and the duration of leaf wetness, as well as a bibliography are given in WMO (1992*a*).

The following methods for the measurement of leaf wetness are considered.

The amount of dew depends critically on the properties of the surface, such as its radiative properties, size, and aspect (horizontal or vertical). It may be measured by exposing a plate or surface, natural or artificial, with known or standardized properties, and by assessing the amount of dew by weighing it, by visually observing it, or by making use of some other quantity such as electrical conductivity. The problem lies in the choice of the surface, because the results obtained instrumentally are not necessarily representative of the deposit of dew on the surrounding objects. Empirical relationships between the instrumental measurements and the deposition of dew on a natural surface should, therefore, be established for each particular set of conditions of surface and exposure; empirical relationships should also be established to distinguish between the processes of dew formation if that is important for the particular application.

A number of instruments are in use for the direct measurement of the occurrence, amount, and duration of leaf wetness and dew. Dew-duration recorders use either elements which themselves change in such a manner as to indicate or record the wetness period, or electrical sensors in which the electrical conductivity of the surface of natural or artificial leaves changes in the presence of water due to rain, snow, wet fog or dew. In dew balances, the amount of moisture deposited in the form of precipitation or dew is weighed and recorded. In most instruments providing a continuous trace, it is possible to distinguish between moisture deposits

caused by fog, dew or rain by considering the type of trace. The only certain method of measuring net dewfall by itself is by the use of a very sensitive lysimeter (see Chapter 10, Part I).

In WMO (1992*a*) two particular electronic leaf wetness instruments are advocated for development as reference instruments and various leaf wetting simulation models are proposed. Some use an energy balance approach (the inverse of evaporation models), while others use correlations. Many of them require micrometeorological measurements. Unfortunately, there is no recognized standard method of measurement to verify them.

6.6.2 *Measurement of ice accumulation*

Ice can accumulate on surfaces as a result of several phenomena. Ice accumulation from freezing precipitation, often referred to as glaze, is the most dangerous type of icing condition. It may cause extensive damage to trees, shrubs, and telephone and power lines, and create hazardous conditions on roads and runways. Hoar frost (commonly called frost) forms when air with a dew point temperature below freezing is brought to saturation by cooling. Hoar frost is a deposit of interlocking ice crystals formed by direct sublimation on objects, usually of small diameter, such as tree branches, plant stems, leaf edges, wires, poles, etc. Rime is a white or milky and opaque granular deposit of ice formed by the rapid freezing of super-cooled water drops as they come into contact with an exposed object.

METHODS OF MEASUREMENT

At meteorological stations, the observation of ice accumulation is generally more qualitative than quantitative, primarily due to the lack of a suitable sensor. Ice accretion indicators, usually made of anodized aluminium, are used to observe and report the occurrence of freezing precipitation, frost or rime icing.

Observations of ice accumulation can include both the measurement of the dimensions and the weight of the ice deposit as well as a visual description of its appearance. These observations are particularly important in mountainous areas where such accumulation on the windward side of a mountain may exceed the normal precipitation. A system consisting of rods and stakes with two pairs of parallel wires — one pair oriented north-south and the other east-west — can be used to accumulate ice. The wires may be suspended at any level and the upper wire of each pair should be removable. At the time of the observation, both upper wires are removed, placed in a special container, and taken indoors for melting and weighing of the deposit. The cross-section of the deposit is measured on the permanently fixed lower wires.

Recording instruments are used in some countries for continuous registration of rime. A vertical or horizontal rod, ring, or plate is used as the sensor and the increase in the amount of rime with time is recorded on a chart. A simple device called an ice-scope is used to determine the appearance and presence of rime and hoar frost on a snow surface. The ice-scope consists of a round plywood disk, 30 cm in diameter, which can be moved up or down and set at any height on a vertical rod fixed in the ground. Normally, the disk is set flush with the snow surface to collect the rime and hoar frost. Rime is also collected on a 20-cm diameter ring fixed on the rod, 20 cm from its upper end. A wire or thread 0.2–0.3 mm in diameter, stretched between the ring and the top end of the rod, is used for the observation of rime deposits. If necessary, each sensor can be removed and weighed.

ICE ON PAVEMENTS

Sensors have been developed and are in operation to detect and describe ice on roads and runways, and to support warning and maintenance programmes.

With a combination of measurements, it is possible to detect dry and wet snow and various forms of ice. One sensor using two electrodes embedded in the road flush with the surface measures the electrical conductivity of the surface and readily distinguishes between dry and wet surfaces. A second measurement, of ionic polarizability, determines the ability of the surface to hold an electrical charge; a small charge is passed between a pair of electrodes for a short time, and the same electrodes measure the residual charge, which is higher when there is an electrolyte with free ions, such as salty water. The polarizability and conductivity measurements together can distinguish between dry, moist and wet surfaces, frost, snow, white ice and some de-icing chemicals. However, because the polarizability of the non-crystalline black ice is indistinguishable from water under some conditions, the dangerous black ice state can still not be detected with the two sensors. In at least one system, this problem has been solved by adding a third specialized capacitive measurement which detects the unique structure of black ice.

The above method is a passive technique. There is an active *in situ* technique which uses either a heating element, or both heating and cooling elements, to melt or freeze any ice or liquid present on the surface. Simultaneous measurements of temperature and of the heat energy involved in the thaw-freeze cycle are used to determine the presence of ice and to estimate the freezing point of the mixture on the surface.

Most *in situ* systems include a thermometer to measure the road surface temperature. The quality of the measurement depends critically on the mounting (especially the materials) and exposure, and care must be taken to avoid radiation errors.

There are two remote sensing methods under development which lend themselves to car-mounted systems. The first method is based on the reflection of infrared and microwave radiation at several frequencies (about 3 000 nm and 3 GHz, respectively). The microwave reflections can determine the thickness of the water layer

(and hence the risk of aquaplaning), but not the ice condition. Two infrared frequencies can be used to distinguish between dry, wet, and icy conditions. It has also been demonstrated that the magnitude of reflected power at wavelengths around 2 000 nm depends on the thickness of the ice layer.

The second method applies pattern recognition techniques to the reflection of laser light from the pavement, to distinguish between dry and wet surfaces, and black ice.

6.6.3 *Measurement of fog precipitation*

Fog consists of minute water droplets suspended in the atmosphere to form a cloud at the surface of the Earth. Fog droplets have diameters from about 1 to 40 μm and fall velocities from less than 1 to approximately 5 cm s^{-1}. In fact, the fall speeds of fog droplets is so low that, even in light winds, the drops will travel almost horizontally. When fog is present, the horizontal visibility is usually less than 5 km; it is rarely observed when the temperature and dew point differ by more than 2°C.

Meteorologists are generally more concerned with fog as an obstruction to vision than as a form of precipitation. However, from a hydrological standpoint, there exists forested high elevation areas which experience frequent episodes of fog as a result of the advection of clouds over the surface of the mountain, where the consideration of precipitation alone may seriously underestimate the water input to the watershed (Stadtmuller and Agudelo, 1990). More recently, the recognition of fog as a water supply source in upland areas (Schemenauer and Cereceda, 1994*b*) and as a wet deposition pathway (Schemenauer and Cereceda, 1991; Vong, Sigmon and Mueller, 1991) have led to the requirement for standardizing methods and units of measurement.

The following methods for the measurement of fog precipitation are considered.

There have been a great number of measurements for the collection of fog by trees and by various types of collectors over the last century, but it is difficult to compare quantitatively the collection rates. The most widely used fog measuring instrument consists of a vertical wire mesh cylinder centrally fixed on the top of a raingauge in a way that it is fully exposed to the free flow of the air. The cylinder size is 10 cm in diameter and 22 cm in height, and the mesh size is 0.2 · 0.2 cm (Grunow, 1960). The droplets from the moisture-laden air are deposited on the mesh and drop down into the gauge collector where they are measured or registered in the same way as rainfall. Some problems with this instrument are its small size, the lack of representativeness with respect to vegetation, the storage of water in the small openings in the mesh, and the ability of precipitation to enter directly into the raingauge portion, which confounds the measurement of fog deposition. In addition, the calculation of fog precipitation by simply subtracting the amount of rain in a standard raingauge (Grunow, 1963) from that in the fog collector leads to erroneous results anytime wind is present.

An inexpensive, 1 m^2 standard fog collector and standard unit of measurement is proposed by Schemenauer and Cereceda (1994*a*) to quantify the importance of fog deposition to forested high elevation areas and to measure the potential collection rates in denuded or desert mountain ranges. The collector consists of a flat panel made of a durable polypropylene mesh and mounted with its base 2 m above ground. The collector is coupled to a tipping-bucket raingauge to determine deposition rates. When wind speed measurements are made in conjunction with the fog collector, reasonable estimates of the proportions of fog and rain being deposited on the vertical mesh panel can be made. The output of this collector results in litres of water. Since the surface area is 1 m^2, this gives a collection in 1 m^{-2}.

6.7 Measurement of snowfall and snow cover

The authoritative texts on this topic are WMO (1994*a*) and WMO (1992*b*), which cover the hydrological aspects, including the procedures, for snow surveying on snow courses. The following is a brief account of some simple and well-known methods, and a brief review of the instrumentation.

Snowfall is the depth of freshly fallen snow deposited over a specified period (generally 24 hours). Thus, snowfall does not include the deposition of drifting or blowing snow. For the purposes of depth measurements, the term snow should also include ice pellets, glaze, hail, and sheet ice formed directly or indirectly from precipitation. Snow depth usually means the total depth of snow on the ground at the time of observation.

The water equivalent of a snow cover is the vertical depth of the water which would be obtained by melting the snow cover.

6.7.1 *Depth of snowfall*

Direct measurements of the depth of fresh snow on open ground are made with a graduated ruler or scale. A sufficient number of vertical measurements should be made in places where drifting is considered absent in order to provide a representative average. Special precautions should be taken so as not to measure any previously fallen snow. This can be done by sweeping a suitable patch clear beforehand or by covering the top of the old snow surface with a piece of suitable material (such as wood with a slightly rough surface, painted white) and measuring the depth accumulated on it. On a sloping surface (to be avoided, if possible) measurements should still be made with the measuring rod vertical. If there is a layer of old snow, it would be incorrect to calculate the depth of the new snow from the difference between two consecutive measurements of total depth of snow since lying snow tends to become compressed and to suffer

ablation. Where extensive drifting of snow has occurred, a greater number of measurements are needed to obtain a representative depth.

6.7.2 *Direct measurements of snow cover depth*

Depth measurements of snow cover or snow accumulated on the ground are made with a snow ruler or similar graduated rod which is pushed through the snow to the ground surface. Representative depth measurements by this method may be difficult to obtain in open areas since the snow cover undergoes drifting and redistribution by the wind, and may have embedded ice layers that limit penetration with a ruler. Care should be taken to ensure that the total depth is measured, including the depth of any ice layers which may be present. A number of measurements are made and averaged at each observing station.

A number of snow stakes, painted with rings of alternate colours or other suitable scale, provide a convenient means of measuring the total depth of snow on the ground, especially in remote regions. The depth of snow at the stake or marker may be observed from distant ground points or from aircraft by means of binoculars or telescopes. The stakes should be painted white to minimize the undue melting of snow immediately surrounding them. Aerial snow depth markers are vertical poles (of variable length, depending on the maximum snow depth) with horizontal cross arms mounted at fixed heights on the poles and oriented with reference to the point of observation.

The development of an inexpensive ultrasonic ranging device to provide reliable snow depth measurements at automatic stations has provided a feasible alternative to the standard observation, both for snow depth and for fresh snow fall (Goodison, *et al.*, 1988). This sensor can be utilized to quality control automatic recording gauge measurements by providing additional details on the type, amount, and timing of precipitation. It is capable of an accuracy of ±2.5 cm.

6.7.3 *Direct measurements of snow water equivalent*

The standard method of measuring water equivalent is by gravimetric measurement using a snow tube to obtain a sample core. This method serves as the basis for snow surveys, a common procedure in many countries for obtaining a measure of water equivalent. The method consists of either melting each sample and measuring its liquid content or by weighing the frozen sample. A measured quantity of warm water or a heat source can be used in melting the sample.

Cylindrical samples of fresh snow may be taken with a suitable snow sampler and either weighed or melted. Details of the available instruments and sampling techniques are described in WMO (1994*a*). Often a standard raingauge overflow can is used for this method.

Snow-gauges measure snowfall water equivalent directly. Essentially, any non-recording precipitation gauges can also be used to measure the water equivalent of solid precipitation. Snow collected in these types of gauges should be either weighed or melted immediately after each observation, as described in section 6.3.1.2. The recording-weighing gauge will catch solid forms of precipitation as well as liquid forms, and record the water equivalent in the same manner as liquid forms (see section 6.5.1).

The water equivalent of solid precipitation can also be estimated using the depth of fresh snowfall. This measurement is converted to water equivalent by using an appropriate specific density. Although the relationship stating that 1 cm of fresh snow equals the equivalent of 1 mm of water may be used with caution for long-term average values, it may be highly inaccurate for a single measurement, as the specific density ratio of snow may vary between 0.03 and 0.4.

6.7.4 *Snow pillows*

Snow pillows of various dimensions and materials are used to measure the weight of snow that accumulates on the pillows. The most common pillows are flat circular containers (with a diameter of 3.7 m) of rubberized material filled with a antifreeze mixture of methyl alcohol and water or a methanol-glycol-water solution. The pillow is installed on the surface of the ground, flush with the ground, or buried under a thin layer of soil or sand. In order to prevent damage to the equipment and to preserve the snow cover in its natural condition, it is recommended that the site be fenced in. Under normal conditions, snow pillows can be used for 10 years or more.

Hydrostatic pressure inside the pillow is a measure of the weight of the snow on the pillow. To measure the hydrostatic pressure by means of a float-operated liquid-level recorder or a pressure transducer provides a method of continuous measurement of the water equivalent of the snow cover. Variations in the accuracy of the measurements may be induced by temperature changes. In shallow snow cover, diurnal temperature changes may cause expansion or contraction of the fluid in the pillow, thus giving spurious indications of snowfall or snow melt. In deep mountain areas, diurnal temperature fluctuations are unimportant except at the beginning and end of the snow season. The access tube to the measurement unit should be installed in a temperature-controlled shelter or in the ground to reduce the temperature effects.

In situ and/or telemetry data acquisition systems can be installed to provide continuous measurements of snow water equivalent through the use of charts or digital recorders.

Snow pillow measurements differ from those made with standard snow tubes, especially during the snowmelt period. They are most reliable when the snow cover does not contain ice layers, which can cause "bridging" above the pillows.

A comparison of the water equivalent of snow determined by snow pillow, with measurements done by

the standard method of weighing, shows that these may differ by five to 10 per cent.

6.7.5 *Radioisotope snow-gauges*

Nuclear gauges measure the total water equivalent of the snow cover and/or provide a density profile. They are a non-destructive method of sampling and are adaptable to *in situ* recording and/or telemetry systems. Nearly all systems operate on the principle that water, snow, or ice attenuates radiation. As with other methods of point measurement, siting in a representative location is critical for interpreting and applying point measurements as areal indices.

Gauges used to measure total water content consist of a radiation detector and a source, either natural or artificial. One part (e.g. detector/source) of the system is located at the base of the snow pack and the other at a height greater than the maximum expected snow depth. As snow accumulates, the count rate decreases in proportion to the water equivalent of the snow pack. Systems using an artificial source of radiation are used at fixed locations to obtain measurements only for that site. A system using naturally occurring uranium as a ring source around a single pole detector has been successfully used to measure packs up to 500 mm of water equivalent, or 150-cm depth.

A profiling radioactive snow-gauge at a fixed location provides data on total snow water equivalent and density and permits an accurate study of the water movements and density changes that occur with time in a snow pack (Armstrong, 1976). A profiling gauge consists of two parallel vertical access tubes, spaced approximately 66 cm apart, which extend from a cement base in the ground to a height above the maximum expected depth of snow. A gamma ray source is suspended in one tube and a scintillation gamma-ray detector, attached to a photomultiplier tube, in the other. The source and detector are set at equal depths within the snow cover and a measurement is made. Vertical density profiles of the snow cover are obtained by taking measurements at about 2-cm increments of depth. A portable gauge (Young, 1976) which measures the density of the snow cover by backscatter rather than transmission of the gamma rays offers a practical alternative to digging deep snow pits, while instrument portability allows assessment of areal variations of density and water equivalent.

6.7.6 *Natural gamma radiation*

The method of gamma-radiation snow surveying is based on the attenuation by snow of gamma radiation emanating from natural radioactive elements in the top layer of the soil. The greater the water equivalent of the snow, the more the radiation is attenuated. Terrestrial gamma surveys can consist of a point measurement at a remote location, a series of point measurements, or a selected traverse over a region (Loijens, 1975). The method can also be used on aircraft. The equipment includes a portable gamma-ray spectrometer which utilizes a small scintillation crystal to measure the rays in a wide spectrum and in three spectral windows (i.e. potassium, uranium, and thorium emissions). With this method, measurements of gamma levels are required at the point, or along the traverse, prior to snow cover. In order to obtain absolute estimates of the snow water equivalent it is necessary to correct the readings for soil moisture changes in the upper 10 to 20 cm of soil for variations in background radiation resulting from cosmic rays, instrument drift, and the washout of radon gas (which is a source of gamma radiation) in precipitation with subsequent build-up in the soil or snow. Also, in order to determine the relationship between spectrometer count rates and water equivalent, supplemental snow water equivalent measurements are initially required. Snow tube measurements are the common reference standard.

The natural gamma method can be used for snowpacks having up to 300 mm water equivalent; with appropriate corrections, its precision is ±20 mm. The advantage of this method over the use of artificial radiation sources is the absence of a radiation hazard.

References

Armstrong, R. L., 1976: The application of isotopic profiling snow-gauge data to avalanche research. *Proceedings of the Forty-fourth Annual Western Snow Conference*, Atmospheric Environment Service, Canada, pp. 12–19.

Goodison, B. E., *et al.*, 1988: The Canadian automatic snow depth sensor: a performance update. *Proceedings of the Fifth-sixth Annual Western Snow Conference*, Atmospheric Environment Service, Canada, pp. 178–181.

Goodison, B. E., Sevruk, B. and Klemm, S., 1989: WMO Solid Precipitation Measurement Intercomparison: Objectives, Methodology and Analysis. In: International Association of Hydrological Sciences, 1989: Atmospheric deposition. *Proceedings*, Baltimore Symposium, May, IAHS Publication No. 179, Wallingford.

Goodison, B. E., *et al. The WMO Solid Precipitation Measurement Intercomparison* (to be published).

Grunow, J., 1960: The productiveness of fog precipitation in relation to the cloud droplet spectrum: physics of precipitation. Geophysical Monograph. No. 5, *Proceedings of the Cloud Physics Conference*, Woods Hole, Massachussetts, 1959, American Geophysical Union Publication. No. 746, pp. 110–117.

Grunow, J., 1963: *Weltweite Messungen des Nebelniederschlags nach der Hohenpeissenberger Methode*. International Union of Geodesy and Geophysics, General Assembly, Berkeley, California, 19–31 August 1963, International Association of Scientific Hydrology Publication No. 65, pp. 324–342.

Loijens, H. S., 1975: Measurements of snow water equivalent and soil moisture by natural gamma radiation. *Proceedings of the Canadian Hydrological Symposium-75*, 11–14 August 1975, Winnipeg, pp. 43–50.

Rinehart, R. E., 1983: Out-of level instruments: errors in hydrometeor spectra and precipitation measurements. *Journal of Climate and Applied Meteorology*, 22, pp. 1404–1415.

Schemenauer, R. S. and Cereceda, P., 1991: Fog water collection in arid coastal locations. *Ambio*, Volume 20, Number 7, pp. 303–308.

Schemenauer, R. S. and Cereceda, P., 1994*a*: A proposed standard fog collector for use in high elevation regions. *Journal of Applied Meteorology*, Volume 33, Number 11, pp. 1313–1322.

Schemenauer, R. S. and Cereceda, P., 1994*b*: Fog collection's role in water planning for developing countries. *Natural Resources Forum*, Volume 18, Number 2, pp. 91–100.

Sevruk, B., 1984: Comments on "Out-of-level instruments: errors in hydrometeor spectra and precipitation measurements". *Journal of Climate and Applied Meteorology*, 23, pp. 988–989.

Sevruk, B. and Zahlavova, L., 1994: Classification system of precipitation gauge site exposure: evaluation and application. *International Journal of Climatology*, 14, pp. 681–689.

Slovak Hydrometeorological Institute and Swiss Federal Institute of Technology, 1993: Precipitation measurement and quality control. *Proceedings of the International Symposium on Precipitation and Evaporation* (B. Sevruk and M. Lapin, eds.). Bratislava, 20–24 September 1993, Volume I, Bratislava and Zurich.

Smith, J. L., Halverson, H. G. and Jones, R. A., 1972: *Central Sierra Profiling Snowgauge: A Guide to Fabrication and Operation*. USAEC Report TID-25986, National Technical Information Service, U.S. Department of Commerce, Washington, D.C.

Stadtmuller, T. and Agudelo, N., 1990: Amount and variability of cloud moisture input in a tropical cloud forest. *Proceedings*, Lausanne Symposia, August/November, IAHS Publication No. 193, Wallingford.

Vong, R. J., Sigmon, J. T. and Mueller, S. F., 1991: Cloud water deposition to Appalachian forests. *Environmental Science and Technology*, 25, pp. 1014–1021.

World Meteorological Organization, 1972: Evaporation losses from storage gauges. *Papers Presented at the Symposium on Distribution of Precipitation in Mountainous Areas* (B. Sevruk). Geilo Symposium, Norway, 31 July–5 August 1972, Volume II, WMO-No. 326, Geneva, pp. 96–102.

World Meteorological Organization, 1982: *Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use* (B. Sevruk). Operational Hydrology Report No. 21, WMO-No. 589, Geneva.

World Meteorological Organization, 1984: *International Comparison of National Precipitation Gauges with a Reference Pit Gauge* (B. Sevruk and W. R. Hamon). Instruments and Observing Methods Report No. 17, WMO/TD-No. 38, Geneva.

World Meteorological Organization, 1985: *International Organizing Committee for the WMO Solid Precipitation Measurement Intercomparison*. Final report of the first session (distributed to participants only), Geneva.

World Meteorological Organization, 1986: *Papers Presented at the Workshop on the Correction of Precipitation Measurements* (B. Sevruk, ed.). Zurich, Switzerland, 1–3 April 1985, Instruments and Observing Methods Report No. 25, WMO/TD-No. 104, Geneva.

World Meteorological Organization, 1989*a*: *Catalogue of National Standard Precipitation Gauges* (B. Sevruk and S. Klemm). Instruments and Observing Methods Report No. 39, WMO/TD-No. 313, Geneva.

World Meteorological Organization, 1989*b*: *Papers Presented at the International Workshop on Precipitation Measurements* (B. Sevruk, ed.). St. Moritz, Switzerland, 3–7 December 1989, WMO Instruments and Observing Methods Report No. 48, WMO/TD-No. 328, Geneva.

World Meteorological Organization, 1992*a*: *Report on the Measurement of Leaf Wetness* (R. R. Getz). Agricultural Meteorology Report No. 38, WMO/TD-No. 478, Geneva.

World Meteorological Organization, 1992*b*: *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture* (B. Sevruk, ed.). Operational Hydrology Report No. 35, WMO-No. 749, Geneva.

World Meteorological Organization, 1994*a*: *Guide to Hydrological Practices*. Fifth edition, WMO-No. 168, Geneva.

World Meteorological Organization, 1994*b*: *Papers Presented at the WMO Technical Conference on Instruments and Methods of Observation (TECO-94)* (Goodison, *et al.*). Geneva, 28 February–7 March 1994, Instruments and Observing Methods Report No. 57, WMO/TD-No. 588, Geneva.

World Meteorological Organization, 1994*c*: WMO Solid Precipitation Measurement Intercomparison: Preliminary Results (B. E. Goodison, *et al.*). *Papers Presented at the WMO Technical Conference on Instruments and Methods of Observation (TECO-94)*. Geneva, 28 February–7 March 1994, Instruments and Observing Methods Report No. 57, WMO/TD-No. 588, Geneva.

Young, G. J., 1976: A portable profiling snow-gauge: results of field tests on glaciers. *Proceedings of the Forty-fourth Annual Western Snow Conference*, Atmospheric Environment Service, Canada, pp. 7–11.

ANNEX 6.A

PRECIPITATION INTERCOMPARISON SITES

The Commission for Instruments and Methods of Observation, at its eleventh session held in 1994, made the following statement regarding precipitation intercomparison sites:

> The Commission recognized the benefits of national precipitation sites or centres where past, current and future instruments and methods of observation for precipitation can be assessed on an ongoing basis at evaluation stations. These stations should:
>
> (*a*) Operate the WMO recommended gauge configurations for rain (pit gauge) and snow (Double Fence Intercomparison Reference (DFIR)). Installation and operation will follow specifications of the WMO precipitation intercomparisons. A DFIR installation is not required when only rain is observed;
>
> (*b*) Operate past, current, and new types of operational precipitation gauges or other methods of observation according to standard operating procedures and evaluate the accuracy and performance against WMO recommended reference instruments;
>
> (*c*) Make auxiliary meteorological measurements which will allow the development and tests for the application of precipitation correction procedures;
>
> (*d*) Provide quality control of data and archive all precipitation intercomparison data, including the related meteorological observations and the metadata, in a readily acceptable format, preferably digital;
>
> (*e*) Operate continuously for a minimum of 10 years;
>
> (*f*) Test all precipitation correction procedures available (especially those outlined in the final reports of the WMO intercomparisons) on the measurement of rain and solid precipitation;
>
> (*g*) Facilitate the conduct of research studies on precipitation measurements. It is not expected that the centres provide calibration or verification of instruments. They should make recommendations on national observation standards and should assess the impact of changes in observational methods on the homogeneity of precipitation time-series in the region. The site would provide a reference standard for calibrating and validating radar or remote-sensing observations of precipitation.

ANNEX 6.B

SUGGESTED CORRECTION PROCEDURES FOR PRECIPITATION MEASUREMENTS

The Commission for Instruments and Methods of Observation, at its eleventh session held in 1994, made the following statement regarding the correction procedures for precipitation measurements:

> The correction methods are based on simplified physical concepts as presented in the *Instruments Development Inquiry* (Instruments and Observing Methods Report No. 24, WMO/TD-No. 231). They depend on the type of precipitation gauge applied. The effect of wind on a particular type of gauge has been assessed by using intercomparison measurements with the WMO reference gauges — the pit gauge for rain and the Double Fence Intercomparison Reference (DFIR) for snow as is shown in the *International Comparison of National Precipitation Gauges with a Reference Pit Gauge* (Instruments and Observing Methods Report No. 17, WMO/TD-No. 38) and by the preliminary results of the WMO Solid Precipitation Measurement Intercomparison. The reduction of wind speed to the level of the gauge orifice should be made according to the following formula:
>
> $$u_{hp} = (\log h z_o^{-1}) \cdot (\log H z_o^{-1})^{-1} \cdot (1 - 0.024\alpha)\, u_H$$
>
> where u_{hp} is the wind speed at the level of the gauge orifice, h is the height of the gauge orifice above ground, z_o is the roughness length (0.01 m for winter and 0.03 m for summer), H is the height of the wind speed measuring instrument above ground, u_H is the wind speed measured at the height H above ground, and α is the average vertical angle of obstacles around the gauge.

The latter depends on the exposure of the gauge site and can be based either on the average value of direct measurements, on one of the eight main directions of the wind rose of the vertical angle of obstacles (in 360°) around the gauge, or on the classification of the exposure using metadata as stored in the archives of Meteorological Services. The classes are as follows:

Class	*Angle*	*Description*
Exposed site	0– 5	Only a few small obstacles such as bushes, group of trees, a house
Mainly exposed site	6–12	Small groups of trees or bushes or one or two houses
Mainly protected site	13–19	Parks, forest edges, village centres, farms, group of houses, yards
Protected site	20–26	Young forest, small forest clearing, park with big trees, city centres, closed deep valleys, strongly rugged terrain, leeward of big hills

Wetting losses occur with the moistening of the inner walls of the precipitation gauge. They depend on the shape and the material of the gauge, as well as on the type and frequency of precipitation. For example, for the Hellmann gauge they amount to an average of 0.3 mm on a rainy and 0.15 mm on a snowy day; the respective values for the Tretyakov gauge are 0.2 mm and 0.1 mm. Information on wetting losses for other types of gauges can be found in *Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use* (WMO-No. 589).