

Chapter 2

Agricultural Meteorological Variables and their Observations

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2.1 Basic aspects of agricultural meteorological observations

Observations of the physical and biological variables in the environment are essential in agricultural meteorology. Meteorological considerations enter in assessing the performance of a plant or animal because their growth is a result of the combined effect of genetic characteristics (nature) and their response to environment (nurture). Without quantitative data, agrometeorological planning, forecasting, research and services by agrometeorologists cannot properly assist agricultural producers to survive and to meet the ever-increasing demands for food and agricultural by-products. Such data are also needed to assess the impacts of agricultural activities and processes on the environment and climate. The following sections provide guidance on the types of observations required, their extent, organization and accuracy, as well as on the instruments needed to obtain the data, with emphasis on those for operational and long-term stations. There are older books on measurements in the open but more recently the number with components useful in agricultural meteorology has reduced. Reference can here for example be made to books that have become more widely in use after the previous edition of this Guide was compiled such as Fritschen and Gay (1979), Greacen (1981), Meteorological Office (1981), Woodward and Sheehy (1983), Russell et al. (1989), Percy et al., (1989), Goel and Norman (1990), Kaimal and Finnigan (1994), Smith and Mullins (2001), Strangeways (2003) and WMO (1984; 1994, 2006, 2007) as well as for operational agrometeorology chapters in Rosenberg et al. (1983), Griffiths (1994), Baldy and Stigter (1997) as well as WMO (2001).

The observations required depend on the purpose for which they will be used. For the characterization of agroclimate, for climate monitoring and prediction as well as for the management of natural resources, national coverage over periods of many years is required. These data also provide the background for the shorter term decision making involved in activities such as response farming, monitoring of, and preparedness and early warning for natural disasters, along with forecasts for pests and diseases. For these activities, additional observations are needed. The preparation of advisories and services on farming methods, including irrigation and microclimate management and manipulation, also requires specialised data. Finally, the needs of research call for detailed and precise data according to each research topic. There are too many specialised methods to be included in this review, but almost all research projects require information on the background climatology which may be derived from the outputs of the long-term types of station listed below.

2.1.1 Data as parts of support systems to agrometeorological services

In Chapter 1, Annex 1B, data are considered parts of support systems to agrometeorological services. This applies to assessments as well as predictions. It should be stressed that this refers to real data, observed parameters, "ground truth". As mentioned already in Chapter 1, collection of good observations has gone out of fashion in many countries because of the illusion that computer-modelled estimates can replace them. Models can only be useful if they get real input data and if additional real observations are available to check the validity of model output.

When the data are to be related to agricultural operations, agricultural data are also essential, including the state of the crops and of animals. These complementary data are often collected by non-meteorological personnel. For all agrometeorological applications, in order to make information available to assist farmers all the time at the field level, to prepare advisories, and for longer term planning, it is necessary to combine the agricultural and the meteorological data. To make better use of the agrometeorological data in supporting agrometeorological services, and for effective transfer of the knowledge of agrometeorology to farmers at farm level, the science of information technology is also very useful (see also Chapter 17 of this Guide).

2.1.2 Physical climatic variables

Agricultural meteorology is concerned with every aspect of local and regional climates and the causes of their variations, thus making standard observation of climatic variables a fundamental necessity (e.g. Hubbard, 1994). It is also concerned with any climatic modifications which may be introduced by human management of agriculture, animal husbandry or forestry operations (e.g. Stigter, 1994a). Physical variables of climate are observed to assist the management of agricultural activities. Such management includes determining the time, extent and manner of cultivation and other agricultural operations (sowing, harvesting, planting, application of biocides and herbicides, ploughing, harrowing, rolling, irrigation, suppression of evaporation, design, construction and repair of buildings for storage, animal husbandry etc.) and different methods of conservation, industrial use and transportation of agricultural products.

Indispensable climatic parameters in the development of agricultural meteorology include, more or less, all those pertaining to geographical climatology, especially those permitting interpretation of physical processes in the lowest atmosphere and upper soil layers, which are the climatic determinants for the local or regional biosphere (Monteith and Unsworth, 1990). Parameters pertaining to energy and water balance are thus very important, such as precipitation, humidity, temperature, solar radiation and air motion. Further, certain physical and chemical characteristics of the atmosphere, precipitation and soil are also important in agricultural meteorology, e.g. pollutants such as CO₂, SO₂, dissolved and suspended matter in precipitation, thermal, hydrological contents and salinity of soil. These require specialised equipment which is available only at a few selected stations. Non-routine physical (and biological, see below) observations, such as those required for research, surveys and special services (e.g. Appendix II in Baldy and Stigter, 1997), are usually more detailed than standard observations and they usually need to be more accurate where processes must be studied instead of phenomena.

2.1.3 Biological variables

Besides scientific observation of the physical environment, the simultaneous evaluation of its effect on the objects of agriculture, i.e., plants, animals and trees, both as individuals and as communities, is also a prerequisite of agricultural meteorology. The routine observations provided by climatological and agrometeorological stations should be accompanied by routine biological observations. For the best results these observations should be comparable with those of the physical environment in extent, standard and accuracy. Biological observations generally are phenological or

phenometric in nature or both. Phenological observations are made to evaluate possible relations between the physical environment and the development of plants and animals while the phenometric types are made to relate the physical environment with biomass changes. The WMO *Technical Regulations* and some of the Technical Notes mentioned under the references section of this chapter include certain details about observations of this type. Literature is given in 2.3.2 and connections within this Guide in 2.4.2. Important observations include assessments of damage caused by weather, diseases and parasites as well as measurements of growth and yield.

2.1.4 Scale of observations

In agricultural meteorology observations are required on the macro-, meso- and micro-scale. On the larger scales it should make use of all available local observations of environmental physical parameters made by the international synoptic network of stations (see also 2.1.5). Practically they can be used in real time in agriculture. For parameters with very little spatial variation (e.g. sunshine duration) low density observation networks normally suffice for agricultural purposes. Most of the planning activities of agricultural undertaking, however, require higher density data. These can sometimes be obtained from synoptic stations observations by use of appropriate interpolations (Wieringa, 1998; WMO, 2001). For bio-meteorological research the micro-scale observations are often required.

New typical characteristic distances of these climatic scales are referred to in Chapter 1 of WMO (2006). There the Mesoscale is defined as 3 – 100 km, the Toposcale or Local scale as 100 m to 3 km and the Microscale as less than 100m (in the last case with the addition “for agricultural meteorology”). Indeed, a Mesoscale of 100 km does not feel right in agricultural production and Toposcale is also not the right term for a farm. However, in WMO (2006) it is also stated that in particular, applications have their own preferred time and space scales for averaging, station density and resolution of phenomena – small for agricultural meteorology, large for global long-range forecasting. With respect to agricultural meteorology this is (differently) discussed in WMO (2001) and in Keane (2001), partly after Guyot (1998).

It follows from the above that it is desirable that we can use observations from agricultural meteorological stations. Such stations are equipped to perform general meteorological and biological observations and are usually located at experimental stations or research institutes of agriculture, horticulture, animal husbandry, forestry and soil sciences. Frequencies of observation, the time scale to be applied for measurements and their averaging, depend on the phenomena and processes under study, their scales and rates of change. In WMO (2006) this is dealt with under “representativeness” (see also 2.2.2.1).

For research work in agricultural meteorology, standard instrumentation under standard environmental conditions are often useful, but in many cases special stations, with special equipment and non-standard exposure conditions, are required (e.g. Stigter, 1994b). For bio-meteorological research and for many agrometeorological problems, additional observations in confined areas, such as within crops, woods, agricultural buildings or containers for conservation or transportation of produce are often required.

2.1.5 Extent of observations

Agricultural meteorology can and should make use of all available local observations of environmental physical parameters from fixed points in the synoptic, climatological or hydrological networks including a broad range of area and point data derived from numerical weather analysis and predictions. This includes certain upper-air data (at least in the lower layers from up to 3000 m), e.g. upper winds (aerobiology), temperature and humidity profiles (for energy budgets). In fact, it is desirable that at a selection of these stations additional observations of more specific interest to agriculture be made.

Climatological and hydrological stations, which are often more representative of agricultural areas than synoptic stations, provide information (daily precipitation amounts, extreme temperatures, etc.) which are useful for operational agrometeorological purposes and in the management of risks and uncertainties. Since these networks of synoptic, climatological and hydrological stations are restricted in density or in kind of observation, it is desirable that these be supplemented by agricultural meteorological stations. The complete network should include all aspects of climatic and soil variations and each type of agricultural, horticultural, animal husbandry, hydro-biological, and forestry operations that exist in the country.

New possibilities for agricultural meteorology are offered by the availability of remote-sensing techniques (e.g. Milford, 1994), which make the evaluation possible of some variables of the physical environment and the biomass over extended areas and to guide interpolation. These types of data are useful to supplement agrometeorological information and to aid forecasting and warning services to agriculture.

2.1.6 Data without metadata are unreliable data

Meteorological observations do not inform us for sure about the state of the local atmosphere unless we know how the observations were made — the instrument, its installation height and exposure, used sampling and averaging times, and the way in which the measurements were processed. Specifications of all these links of the observation chain are called metadata, and their availability determines the value of measurements. Average wind speed observed at 2 m height will be about two-thirds of the wind speed at 10 m height. A maximum temperature observed with a fast thermometer above dry sand can be many degrees higher than the maximum observed nearby on the same day above wet clay with a slow thermograph. To judge content and quality of observations it is essential to know their metadata (Wieringa and Rudel, 2002).

Traditionally, for synoptic stations this issue was dealt with by WMO rules specifying standard instrument exposures and comparable observation procedures. However, the required very open terrain is not always available (even at airports) and many observation budgets are insufficient to meet the rules. Around 1990, climate investigations showed the great importance of knowing the actual station exposures etc., even for officially standardized synoptic stations. For agrometeorological stations, which make varying types of observations in varying terrain, metadata have always been important but generally were named "station history".

Therefore it is more important than ever that for agrometeorological stations records are made and kept of the instrumentation (type, calibration, maintenance), instrument exposures (mounting, siting, surroundings at toposcale), and observation

procedures (sampling, averaging, frequency of measurements, recording, archiving). Fuller specification of necessary metadata is given in section 2.2.5 of this chapter.

2.2. Agricultural meteorological stations

2.2.1 Classification

Reference should be made to Linacre (1992). According to the *WMO Technical Regulations*, each agricultural meteorological station belongs to one of the following categories:

- (a) *A principal agricultural meteorological station* is a station which provides detailed simultaneous meteorological and biological information and where research in agricultural meteorology is carried out. The instrumental facilities, range and frequency of observations, in both meteorological and biological fields, and the professional personnel are such that fundamental investigations into agricultural meteorological questions of interest to the countries or regions concerned can be carried out.
- (b) *An ordinary agricultural meteorological station* is a station that provides, on a routine basis, simultaneous meteorological and biological information and may be equipped to assist in research into specific problems; in general, the programme of biological or phenological observations for research will be related to the local climatic regime of the station and to local agriculture.
- (c) *An auxiliary agricultural meteorological station* is a station which provides meteorological and biological information. The meteorological information may include such items as soil temperature, soil moisture, potential evapotranspiration, duration of vegetative wetting, detailed measurements in the very lowest layer of the atmosphere; the biological information may cover phenology, onset and spread of plant diseases, etc.
- (d) *An agricultural meteorological station for specific purposes* is a station setup temporarily or permanently for the observation of one or several variables and/or of specified phenomena.

Stations corresponding to (a) are not common because of their requirements for trained professionals, technical personnel and equipment. In most countries the majority of agricultural meteorological stations belong to categories (b), (c) and (d).

2.2.2 Selection and layout of a station site

2.2.2.1 Selection of a representative site location

For observations their accuracy at a given time is a determinable fixed quality, but their representativity varies with their application. Representativity of a measurement is the degree to which it describes reliably the value of some parameter (e.g. humidity, or

wind speed) at a specified space scale for a specified purpose (WMO 2001). Instrumentation, exposure and observation procedures must be matched to achieve useful representation — e.g. local 2-minute averages for aviation, or hourly mesoscale averages for synoptic forecasts.

Therefore, when selecting a site for a station, the purpose of its observations must be decided first — should it be regionally representative, then even in a woody region an open location is preferable, because the station's observation must relate to the lower atmosphere of the region. If the station's establishment purpose is monitoring or operational support of some local agricultural situation, then it can be representative when its location is typical for that application, maybe in a forest, in a very humid area (for disease protection purposes) or at the bottom of a valley (for studying frost protection). Even so, locations should be avoided which are on or near steeply sloping ground, or near lakes, swamps or areas with frequent sprinkling or flooding.

The site of a weather station should be fairly level and under no circumstances it should be on concrete, asphalt, or crushed rock. Wherever the local climate and soil do not permit a grass cover, the ground should have natural cover common to the area, as far as possible. Obstructions such as trees, shrubs and buildings should not be too close to the instruments. Sunshine and radiation measurements permit no shadow during the greater part of the day; brief periods of shadows near sunrise and/or sunset may be unavoidable. Wind should not be measured closer to obstructions than ten times their height. Tree drip into rain gauges should be impossible.

Accessibility to the weather station and the possibility to recruit good observers locally should also be criteria for selection of a site. Finally, for major stations their chance of semi-permanent location tenure with little change in the surroundings should be investigated.

2.2.2.2 Layout of station instruments

To minimize tampering by animals and people, it is very desirable to fence the weather station enclosure. A sample layout is shown in Figure 1 (Figure 1.1 of WMO, 2006). This layout is designed to eliminate as far as possible mutual interference of instruments or shadowing of instruments by fence posts. The door of the thermometer screen must open away from the sun, to ensure that direct sunlight does not enter the screen during observations. At equatorial and tropical stations, the screen will have doors opening to both the north and the south. A larger enclosure is recommended when small plants for phenological observations are used. A rather sheltered enclosure is not a good place for measuring wind, and then another better exposed nearby location may be preferable for the wind mast.

2.2.3 Primary handling of data

If the weather station is part of a network, another factor to be considered is the use of the data; whether for climatological or for real-time information purposes. If for the latter, a rapid communication system is necessary for data transmission, whether by land-line, radio or satellite. As to the former, under agenda point 10.3 of CAgM XIV (New Delhi, 2006) on the “Expert team on database management, validation and application of models, research methods at the eco-regional level”, it was emphasized that data should be entered locally as they are collected (either on an hourly or daily

basis) and that the data should be entered only once into a Database Management System (DBMS) and be made available to all portions of the National Meteorological and Hydrological Service (NMHSs). The DBMS system used should be capable of handling climatic and other types of data, such as ecological, hydrological, agricultural, and geo-referenced data and should be able to easily import data from a variety of formats. Also, all data should be directly inputted into a DBMS and then used by various software application packages. Some quality control (QC) of the data can be conducted locally as the data are being entered. Other QC such as spatial quality checks can be undertaken at the central database. It is important that all data, both raw and those processed for the long-term archive, should be backed up securely at every stage.

2.2.4 Networks

When agricultural meteorological stations are being established or reorganized, the number of stations within each region should depend on its extent, its climatic types and sub-types and the spatial variations of such factors as the natural vegetation, main crops and agricultural methods. As far as possible each large homogeneous phytogeographical region should be represented by at least one principal agricultural meteorological station.

Similarly, each characteristic area devoted to a particular aspect of agriculture, animal husbandry, hydrobiology or forestry should, wherever possible be represented by an ordinary agricultural meteorological station. Sufficient auxiliary agricultural meteorological stations should be installed to ensure adequate spatial density of the observations of the meteorological and biological variables of major agrometeorological concern to the country.

From another point of view, marginal areas of agriculture and silviculture will often deserve special attention. One main object of observations made in such areas would be to determine the boundary of the region where an individual crop could be grown successfully or a specific agricultural or silvicultural procedure might be profitable; another would be to ascertain the frequency and the typical geographical distributions of the main weather hazards, with a view to reducing as far as possible their adverse effects by protective measures.

Areas where agricultural production is markedly exposed to losses through plant and animal diseases are of special interest, as meteorological factors can be important in the development of these diseases. National parks and nature reserves, although usually not representative of the areas that are of major economic importance in agriculture, may provide good locations for reference stations where observations can be made over long periods under practically identical conditions.

The selection of these stations, whether principal, ordinary, auxiliary or for specific purposes, will vary from one country to another, but some general guidance may be given. Perhaps, the first consideration is that all agrometeorological stations should be located in regions of agricultural, silvicultural, pastoral or other forms of production. On representativity, see 2.2.2.1. Therefore, the following locations will often be very suitable for principal (and ordinary) stations:

- (a) At experimental stations or research institutes for agriculture, horticulture, animal husbandry, forestry, hydrobiology and soil sciences;

- (b) At agricultural and allied colleges;
- (c) In areas of importance for agriculture and animal husbandry;
- (d) In forest areas;
- (e) In national parks and reserves.

In the case of auxiliary stations and stations for specific purposes, selected farms should also be considered.

However, experience has shown that if, as in the case of observatories located in colleges, the observations are made by alternating groups of students who may be insufficiently trained for this purpose, very careful supervision will be needed to ensure observations of acceptable quality. In general, the observational accuracy should be a major consideration; quality must not be sacrificed for quantity.

No difficulties should normally arise in locating basic equipment in areas devoted to agriculture, horticulture and animal husbandry, since the terrain is usually relatively level and open, satisfying the general standards for locating agrometeorological and climatological stations.

Stations located in forested or silvicultural regions require special consideration. They should be representative of the general climate in the forest, and should reflect the effects of tree development within the forest. The exposure conditions and instrumental requirements of these stations are described in Chapter 11.

At CAgM XIV (New Delhi, 2006) it was restated that adequate density of (agrometeorological) stations and intra- and extrapolation of routine station data to agricultural field conditions remain great worries, particularly in developing countries. Automatic weather stations can assist in solving some of the related problems but instrument co-ordination, calibration and maintenance are serious issues to be considered with great attention, and even more so with automatic weather stations, again particularly in developing countries.

Special equipment required for non-routine observations, such as that needed for experiments, research and special agrometeorological services, is generally installed outside standard enclosures, for instance, within crops, above crop canopies or in areas under cultivation.

2.2.5. Documentation of agricultural meteorological stations

The necessary metadata information which should support reliable observations is described at length in WMO (2003) and more briefly in WMO (2006). Its acquisition is summarized below.

Full information should be available in the NMHS's of all agricultural meteorological stations in the country. For this purpose an up-to-date directory of these stations, whether controlled by the NMHS or by other services or agencies, should be maintained. In countries where there are many regional agrometeorological services or where networks are managed by farmers and commercial enterprises, there will be a need to constantly update this general directory at national level. The directory should archive for each station:

- (a) Station identification: name, network code number(s), category of station.
- (b) Geographical location: latitude and longitude (accurate in units of a few hundred meters, e.g. 0.001 degree), mapping of mesoscale region ($\approx 1 : 100\ 000$) with major terrain elevation changes; physical constants and profile of local soil.
- (c) Observing programme specification and history: for each parameter dates of beginning and end of records, of changes of instrument, of observation height or of site. Archive of all updates of station mappings (e) - (h) as described below. Description of observation routine procedures and basic data processing. Units in use. Routine transformations of observed parameters to archived data.
- (d) Station information contact: name of station-supervising organization or institution, identification (name, address, telephone or fax or e-mail) of observer(s) or other person(s) responsible for local measurements and/or their archiving.

To support and complement this national documentation, at individual stations the station observer(s) should maintain local documentation of the following metadata:

- (e) Toposcale map of surroundings (scale $\approx 1 : 5000$) as specified by CIMO (WMO 2006), including location and size of obstacles, of surrounding vegetation, and of significant terrain features (e.g. hills and hollows, lakes, built-up areas, roads). This map should be updated at least yearly.
- (f) Microscale map of station enclosure with location of instruments and their height above the ground, updated upon changes. Instrument shelter description.
- (g) Photos of the enclosure and all instrument positions outside the enclosure, showing them in their surroundings (i.e. from sufficient distance, 20 m or more), taken from all directions (at least six or eight -- identify direction on photoprint!), updated upon significant changes.
- (h) Horizon mapping of solar radiation observation (see WMO 2006), regularly updated.
- (j) Specification of all instruments: manufacturer and model, serial number, output type and sensitivity, recording or frequency of observation, beginning and end of use.
- (k) Regularly-used logbook with history of station activities: calibrations and other control activities, maintenance, all interruptions and missing observations, significant developments (e.g. nearby building activities, growth of vegetation).

For some parameters, "particular" metadata requirements are mentioned in section 2.4. It is advisable to consult WMO (2003) for the full metadata story, this is only a summary.

2.2.6 Inspection and supervision of stations

Agricultural meteorological stations maintained by the National Meteorological Service should be inspected at least once a year to check whether the exposure has not changed significantly and to ensure that observations conform to the appropriate standards and that the instruments are functioning correctly and are calibrated at the required times. The time interval between successive inspections of an individual station will depend upon the programme of the station and the qualifications of the local personnel responsible for the programme.

If agricultural meteorological observations are made by other authorities, co-operative arrangements or special agreements should be made to ensure adequate supervision and maintenance of the network, including calibrations of equipment.

2.2.7 Fixed agrometeorological stations

These stations are foreseen as operating for an extended period at a fixed place, and may be:

- a) *Minimum equipment stations.* Small portable screen, minimum and maximum thermometers, dry and wet-bulb thermometers, totalizing anemometer at a convenient height, and rain gauge. For screens which are not standard, the radiation error should be determined;
- b) *Standard equipment stations.* Standard screen instruments and rain gauge as in a) above, thermohygrograph, wind vane, windrun and sunshine recorder. These permit determination of evaporation using empirical methods;
- (c) *Semi-automatic stations.* When trained personnel are not available, semi-automatic stations are required with uninterruptible power supply to provide the measurements. There is no automatic data communication;
- (d) *Automatic stations.* These stations require less supervision but installation, calibration and inspection must be of a high standard. Uninterruptible power supply is required. Data from these stations can be used for direct computer processing. Initial and maintenance costs as well as proper calibrations may be limiting factors. Data should preferably also be communicated automatically.

2.2.8 Mobile stations

Mobile stations are used for surveys and research. Some mobile stations move continuously and others need equilibrium of sensors or certain periods for measurements, such as for local wind observations. When an extended but superficial survey of air temperature and humidity is required, the instruments are usually carried by vehicles. In these circumstances use is made of thermocouples and thermistors which have a rapid response (low “time constants”) and high sensitivity.

When using motor vehicles, all mechanical instruments should have anti-shock mounts and should be mounted so that the recording movement is perpendicular to the direction of the most frequent vibrations, to reduce their effect on the instruments.

2.2.9 Agricultural meso-climatological surveys

The objective of agricultural meso-climatological surveys is to determine meteorological variables or local special factors affecting agricultural production on a local meso-scale that are not representative of the general climate of the region. The surface relief (topo-climatology) and character (landscape), regional wind circulations, water bodies, forests, urban areas etc., come under these categories. Reference may be made to WMO TN 133. These surveys are particularly useful where high measurement densities are needed and in developing countries or sparsely populated regions, where network sites are widely separated. Additional data from temporary stations, functioning from one to five years are useful for comparison with those of the basic network and for evaluation of interpolation between the latter. Observations with special instruments, from fixed or mobile stations, may serve to complete the general pattern.

In the older literature, meso-climatology and topo-climatology were seen as studying the influence of the actual earth's surface on climate and of the climate on that surface. Many important factors which influence the local exchanges of energy and moisture were noted: configuration and roughness of the earth's surface, colour, density, thermal capacity, moisture content and permeability of the soil, properties of the vegetation covering it, albedo etc. More recent literature still uses the same approach (e.g. Geiger et al., 1995), adding exchanges of other gasses than water vapour, liquids, particles etc. CAgM XIV (New Delhi, 2006) agreed that special attention should be paid to peak values of rain, wind, and flows of water, sediment and other materials carried, because they are locally of great importance to agriculture.

The series of WMO Technical Notes (56, 86, 125, 161, and 179) presenting agroclimatological studies in several developing regions, published by the FAO/UNESCO/WMO Inter-agency project on agroclimatology from 1963 to 1982, does contain various aspects of meso-climatological surveys. The start of a newer agro-ecological approach, where mesoclimatological surveys are incorporated in wider production evaluations, can be found in Bunting (1987). Modern quantitative approaches in agroclimatology at the meso-scale using remote sensing and GIS technologies are found in this Guide as agrometeorological services (Chapters 4 and 6). They have often to be combined with classical measurements as ground truth or farm scale details (Salinger et al., 2000). The latter may be from fixed or mobile, standard or automatic equipment, while complementary observations to describe the special meso-climatic processes may sometimes be used (e.g. WMO, 2006 and below).

2.2.10 Complementary observations to describe special mesoclimatic processes

The spatial characterization, including the vertical, of mesoclimatic patterns of temperature, humidity, pressure and wind in the lower troposphere for research purposes are determined as follows:

- a) Aircraft meteorograph soundings on days presenting typical air masses for each season. It may be advantageous to carry out soundings at hours of minimum and maximum surface temperatures. The soundings which are made should be selected for the problem under study, vertically spaced every 100-150 m up to 800-1000 m, and then every 300-500 m up to 3000 m;

- b) Soundings up to 300-500 m, with a fixed meteorograph or radiosonde, suspended from an anchored balloon. To avoid wind motion, balloons were usually fixed with three bracing lines but modern instruments compensate for the movement if required;
- c) Wind structure. For the study of wind structure up to 300 m, anchored directional balloons and or sodars pointing into the direction of the wind may be used. For greater heights pilot balloons of low rate of ascent are used; their flights are followed from the ground with two theodolites. At night the balloons must be battery-illuminated. Smoke bombs may be useful to show wind direction as well as turbulence up to a limited height.

2.2.11 Detailed physical observations of a non-routine or non-permanent character (agricultural micrometeorological research)

Detailed accurate observations which are neither routine nor permanent are needed for fundamental research, and are usually carried out independently of the scheme of conventional agroclimatological observations. Phenomena and processes concerned were for example listed and explained in Stigter (1994c). Such observations are made to a high degree of accuracy by skilled, scientifically trained staff and mostly include micrometeorological measurements made with specially designed instruments. For observations as highly specific as these no general method can be formulated (see for example Woodward and Sheehy, 1983, Pearcy et al., 1989).

2.3 Observations to be carried out at agricultural meteorological stations.

2.3.1 Observations of the physical environment

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 various variables is recommended in WMO (2006) as given here in Table 2.

Table 2: WMO recommended minimum accuracy of some variables.

Variable	Accuracy required in daily values
Temperature (incl. max/min, wet and dry bulb, soil)	< ± 0.5°C
Rainfall	± 1 mm
Solar Radiation (incl. Sunshine)	10% (± 1h)
Evaporation	± 1 mm
Relative Humidity	± 5%

Photoperiod	10% (± 1 h)
Wind Speed	$\pm 0.5 \text{ m s}^{-1}$
Air pressure	$\pm 0.1 \text{ hPa}$

These measurements refer to the programme that should be followed for permanent or routine nation-wide observations. Nevertheless, the needs of agricultural meteorology frequently require additional and special information, mainly at principal and ordinary stations, such as the following:

- (a) results of agricultural meso-meteorological surveys;
- (b) data derived from remote sensing;
- (c) accurate physical observations on a non-routine basis (for agricultural micro-meteorological research).

Some general comments are offered in the following paragraphs concerning each of these variables or groups of variables. WMO (2007) gives more detailed guidance regarding climatological observations in general and contains material which is equally applicable, whether climatic variables are observed for routine climatological purposes or for the programme of an agricultural meteorological station. Detailed information is given in WMO (2006) regarding instruments to be used and observing practices to be followed. References to the various chapters of this Guide and to other publications relevant in this connection are mentioned in each subsection.

It must be stressed that the material contained in these publications and in the succeeding chapters of this Guide refer to the ultimate aims of an Agricultural Meteorological Service. The initial steps taken by any such Service can obviously be of a simpler character, but should be such that further expansion can be made along the lines indicated. Normally, only principal agricultural meteorological stations would attempt to take all the observations described herein.

2.3.1.1 Radiation and Sunshine

Reference may be made to Coulson (1975), Fritschen and Gay (1979), Iqbal (1983), WMO (1984), Goel and Norman (1990), WMO (2001), Strangeways (2003) and WMO (2006) as well as WMO-T.N.172. The duration of day length, which influences the flowering and growth of shoots of crop plants, should be recorded or obtained otherwise at all agricultural meteorological stations. This information should be supplemented wherever possible by data obtained from radiation instruments. Principal stations should make detailed observations of radiation including global solar radiation, Photosynthetically Active Radiation (PAR) and net all-wave radiation. The spectral distribution of solar radiation influences the growth and development of plants and efforts should be made to include it in the observing programme. Important components are ultra-violet (UV), PAR and near infra-red (NIR).

Most widely, 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. Beam Fraction Sensors without moving parts are now available also.

Solarimeters can also be used to measure the short-wave radiation reflected from a crop surface. An additional sensor is inverted, fitted with a shield to eliminate diffuse sky radiation, and mounted high enough over the surface so that the shadow it casts is a very small part of the surface area (crop canopy) being investigated. A pair of upward and downward facing solarimeters forms an albedometer. (The reflection coefficient of a surface is called the “albedo”).

Research results show that shade influences photosynthesis and temperature. At the macro level shade occurs due to clouds, mountain slopes, etc. At micro level shade varies due to the plant canopy itself, intercropping choices, surrounding trees etc. Photosynthesis is the major metabolic process in agriculture that depends on solar radiation. So, occurrences of shade, its distribution, duration and intensity influence the photosynthesis and therefore production processes. Shade and light also cause many morphological processes in plants and behavioral changes in animals. Though more shade is reducing agricultural production in many field crops, it is improving quality in many cases. In many fruit crops, fruit quality is improved with partial shade treatments. The effect of shade on crops can be measured using cloths that reduce insolation by required percent over plots of the experimental field. Tube solarimeters (made in tubular form for easy insertion horizontally under a crop canopy) are vital for measuring solar radiation and shade influence in crop growth, agroforestry and mulch studies. For details see 2.4.1.1, where also pyrgeometers for long wave radiation from sky and earth and infrared thermometers are mentioned.

2.3.1.2 Temperature of air

Reference should be made to Fritschen and Gay (1979), WMO (1984), Goel and Norman (1990), WMO (2001), Strangeways (2003) and WMO (2006). The temperature of the air should be measured in representative places, at different levels in the layer adjacent to the soil. It 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 it affects leaf production, expansion and flowering. At ordinary or auxiliary stations, however, the measurements will usually be restricted to the lowest few meters above the surface – the most significant layers for studying climatic conditions affecting agricultural crops, the growth and development, and also the layers having 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 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.

In order to study the diurnal variations of temperature, recording instruments should be used at least at one level. Where a continuous record of temperature is not possible, the maximum and minimum values should be recorded at two or three levels. Primarily, such measurements should be made under standard conditions, i.e., over a short grass cover maintained as far as possible unchanged throughout the year or, if this is impossible, over bare soil. Observations should be made, as far as possible, in the middle of a fairly large representative area (diameter 20-50 m) with level ground with soil or vegetation cover. At principal agricultural meteorological stations the measurements

should be supplemented by similar ones taken in various regional crops during the growing season. These supplementary observations should be carried out at the same levels as the observations over bare soil or grass, and also at levels immediately below and above the upper limit of the vegetation.

Exposure to radiation is a serious source of error in measuring atmospheric temperature. Probably the best method of measuring air temperature is by using freely exposed electrical equipment (resistance or thermocouple thermometers) having thin or reflective sensitive elements with a very low absorption of radiation. Where such instruments are not available, shade screens or ventilated thermometers may be used for levels at least 50 cm above bare soil or dense vegetation. Non-standard screens generally used at other meteorological stations run a risk of hampering the flow of air past the thermometers and, in bright sunshine and light winds to be heated to a temperature above that of the ambient air. The disadvantage is especially marked for measurements below the standard level of 1.25 to 2 m. Thermometer screens are therefore not recommended when the vertical distribution of temperature up to 2 or 3 m is desired, although small open reflective screens have been used with some success. It is necessary to protect thermometers in the open from precipitation by small roof-shaped shelters.

2.3.1.3. Temperature of soil

Reference should be made to Rosenberg et al. (1983), WMO (1984; 2001; 2006). Soil temperature directly influences crop growth because the sown seeds, plant roots, and microorganisms live in the soil. The physico-chemical as well as life processes 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 growth is affected.

Therefore the programme at all categories of agricultural meteorological stations should 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 (the observations being preferably not more than six hours apart).

When soil-temperature data are published, information should be given on the way the plot is maintained. The depths of the thermometers at 5, 10 and 20 cm should be checked periodically and maintained. Efforts should be made to ensure that good contact is maintained between the thermometer and the soil.

Regarding the surface of the plot where soil temperature is measured, two types of standard cover are used – bare soil and short grass. Wherever possible, simultaneous readings should be made under both standards for comparison. In many places, however, it may be difficult or even impossible to maintain plots conforming to both standards. Hence the one most suited to the region should be used. Also, wherever the standard surface is not representative of the surroundings, the instruments should be placed near the center of a large plot (for bare soil WMO (2006) recommends 2 x 2 m.). A comparison of soil-temperature observations under a standard cover and under crops show the modifications of the temperature regime due to the principal regional crops and their cultivation, depending on soil modification, soil shading and suppression of air movement over the soil (Mungai et al., 2000).

When soil temperatures are measured in a forest, the reference level for the depths of measurement should be clearly indicated: whether the upper surface of the litter, humus or mass layer is considered to be at 0 cm; or whether the soil-litter interface is taken as zero reference. These details and any seasonal changes therein should be quoted when the data are published (for further details, see Chapter 11 of this guide).

Whenever the ground is frozen or covered with snow, it is of special interest to know the soil temperature under the undisturbed snow, the depth of the snow and the depth of frost in the soil. Measurement of the thermal properties of the soil (e.g. specific heat, thermal conductivity), temperature profiles and changes in these profiles should be included.

2.3.1.4 Atmospheric pressure

Reference should be made to Murthy (1995 and 2002). The lower pressures experienced as altitude increases have important consequences for high altitude plant life. At high altitudes and low atmospheric pressures the solubility of carbon dioxide and oxygen in water are reduced. Some plants show stunted growth at higher altitudes as concentrations of oxygen and carbon dioxide reaches low concentrations. Plants with strong root system 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 if air density is needed within $\pm 5\%$ then pressure variations have to be taken into account. Usually, a station will record pressure as part of their data for climatological work.

2.3.1.5 Wind

Reference should be made to Mazzarella (1972), Wieringa (1980), WMO (1984), Kaimal and Finnigan (1994), Stigter et al. (1998), WMO (2001, 2006). Wind transports heat in either sensible or latent form between lower and higher layers of the atmosphere as well as from lower to higher latitudes. Moderate turbulence promotes the consumption of CO₂ 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, etc. 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 (e.g., lodging or leaf damage) and forests (wind throw). 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 topocscale 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 (e.g. crops) and any nearby obstacles, in order to be above significant flow interference. Lower-level wind measurements are not representative at topocscale and cannot well be corrected either, so they cannot be used as local reference or for comparison with other stations (WMO 2001). 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 3-second gust in each averaging period.

This basic programme may be supplemented, where circumstances permit, by measurements of wind speed at one or more levels between the surface and 10 m; wind direction varies little in that layer. Except for layers rather close to the ground this can be done by means of sensitive cup anemometers or propeller vanes that, however, lose accuracy because of the need for them to rotate into the wind (WMO, 2006). Any more ambitious programme should be carried out at principal agricultural meteorological stations or operationally with mobile stations, as recently done in Africa (Stigter et al., 2005). Wind speed and gustiness then is measured at various levels right down to the ground by means of anemometers of high sensitivity, with parallel temperature measurements at those levels.

2.3.1.6 Air humidity and soil moisture (including leaf wetness)

Reference should be made to WMO (1984, 2001, 2006).

2.3.1.6.1 Humidity

Humidity is closely related to rainfall, wind and temperature. Different humidity related parameters such as relative humidity, vapour pressure, dew point and other derived ones 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 work above and within vegetation.

2.3.1.6.2 Soil moisture

Reference may be made to Greacen (1981), Vining and Sharma (1994), Smith and Mullins (2001) and WMO (2001; 2006). In scheduling irrigation the estimation of moisture content is the basic requirement. The soil water content can be determined by direct methods such as gravimetric and volumetric determinations and indirect methods, including the use of devices such as tensiometers, resistance blocks, neutron moisture meters and Time Domain Reflectometry (TDR), see 2.4.1.6.2.

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. Often levels will be selected in relation to the effective rooting depths of the plants. Until it is possible to make reliable continuous recordings at some of these levels, it is recommended that observations be made at regular intervals of about ten days; for the shallower depths, shorter intervals (seven or five day) will be necessary. In areas with snow cover, more frequent observations are required when the snow is melting.

Standard soil-moisture observations should be made below a natural surface representative of the uncultivated regional environment. Simultaneous observations in areas devoted to principal regional crops, and covering all cultural operations, will show modifications introduced by agricultural processes. These soil-moisture measurements are particularly useful in verifying soil-moisture values estimated from meteorological measurements. Further discussion of soil-moisture problems may be found in WMO TNs 21 and 97. In operational agrometeorology, the problem of on-farm measuring density was dealt with by Ibrahim et al. (1999), who subsequently accurately determined water waste in irrigated groundnut and sorghum (Ibrahim et al., 2002). Oluwasemire et al. (2002) discussed a sampling method in intercropping conditions, while infiltration of rainwater and use of this soil moisture could be followed simply in the field by Mungai et al. (2000).

The following additional parameters will contribute to gaining better understanding of soil-moisture conditions:

- a) Field capacity and other hydrological constants of the soil;
- b) Permanent wilting point; and
- c) Depth of groundwater.

2.3.1.6.3 Leaf wetness and dew

The weather provides liquid water not only by precipitation, but also by dew, which is not the same as leaf wetness but one of its possible causes. Dew (fall) occurs in a humid atmosphere when temperature falls and wind is weak, resulting in condensation both on the vegetation and on the soil. Dew often occurs due to distillation of water from (wet) soil (dew rise). Guttation occurs on vegetation when its internal water pressure is excessive. In some very dry regions dew may well be a significant source of moisture in maintaining plant life (Acosta Baladon, 1995).

Leaf wetness can result from precipitation, from dew or from guttation. Knowledge of leaf wetness duration (LWD) is extremely vital information for the protection of crops against fungi and diseases (WMO T.N. 192), which can not be deduced usefully either with rules of thumb such as $RH > 90$ per cent. Actual monitoring has so far been carried out only in a few countries on a routine basis with specific agrometeorological requirements in mind. Studies and recordings of LWD also help in developing early warning systems and plant protection, in understanding soil evaporation and in improving leaf surface water evaporation modeling. Calibration of sensors in this way also enhanced.

2.3.1.7 Precipitation (clouds and hydrometeors)

Reference should be made to Meteorological Office (1981), Murthy (1995), Baldy and Stigter (1997, for forms in which rain water reaches the soil) and Murthy (2002), WMO (2006). Also Technical Note 55 may be useful.

At an agricultural meteorological station, visual observations and automatic instrumentation to measure total cloud coverage i.e., 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), hoarfrost, rime fog, etc.

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 rain gauge. Hail is the precipitation of solid ice that is formed inside cumulonimbus clouds, the thunderstorm producing clouds. It is measured according to individual hail stone size or its liquid equivalency. Advanced techniques like remote sensing provide a quick and clear illustration of hail storm patterns. Data obtained by meteorological radar can usefully supplement rainfall measurements and may make it possible to identify and locate hydrometeors which are particularly harmful to agriculture (hail, very heavy showers), with a view to taking appropriate action (Wieringa and Holleman, 2006).

There are still examples of volunteers doing a great job in simply increasing rainfall measurement densities for disaster detection, these days in richer countries making use of the newly available means of communication (e.g. Walsh, 2006). Another such network in which simple rainfall measurements are made in combination with agriculturally important hail and snow was described by O'Driscoll (2006). The importance of such simple rainfall data for modern farming can also be read from a USA site like www.agweb.com.

The extent and depth of snow cover should be observed regularly where appropriate; it may be desirable to give information about water equivalent and consistency of the snow cover, for instance, one or twice per week.

Especially in dry climates with large daily fluctuations of temperature, the amount of water deposited in the form of dew (or rime) may be of great importance in the water balance of the biosphere. In addition the duration and amount of dew are important in connection with certain plant diseases (see also 2.3.1.6).

2.3.1.8 Evaporation and water-balance measurements

Reference should be made to Rosenberg et al. (1983), WMO (1984, 1994, 2001; 2006, 2007) and WMO Technical Notes Nos. 11, 21, 26, 83, 97 and 126. 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, in the existing conditions of soil moisture.

There are suitable publications that explain the updated internationally agreed energy balance calculations of crop evaporation (e.g. Hough et al., 1996; Allen et al., 1998, Monteith and Unsworth, 2007) while their applications under on-farm tropical field conditions are now also reported (e.g. Ibrahim et al., 2002). Particular attention is drawn to the difficulty of measuring potential evapotranspiration for a small wet surface within a large dry area (oasis effect). Observations of the following, which contribute towards knowledge of the water balance, should be made whenever possible:

a) Evaporation from a free water surface;

b) Height of the water table;

c) Irrigation water applied.

Generally, water is applied in fields by different irrigation methods depending upon the crop and soil condition: surface irrigation, sub-surface irrigation, sprinkler irrigation, and drip irrigation. Surface irrigation includes flooding, check basin, basin, border strip and furrow irrigation. Flooding is exclusive for low land rice. The check basin method is adopted when the field is quite large and is not easy to level the entire field. The field is divided into small plots surrounded by small bunds on all four sides. In the basin method only the basin around the trees is irrigated. It is suitable for fruit crops. In the border strip method the field is divided into number of strips by bunds of around 15 cm height. The area between two borders is the border strip. In furrow irrigation, different methods were included like deep furrow, corrugation, alternate furrow or skip irrigation, wide spaced furrow irrigation, within row irrigation.

Surface irrigation methods are most economic and easily operated. There is no requirement of additional input but the method requires leveling of the field, high labour cost and there is low water distribution efficiency (e.g. Ibrahim et al., 2000). In the case of subsurface methods, where water gradually wets the root zone through capillary movement, weeds are less of a problem due to dry surface soil. Evaporation losses are minimized, but in this type of irrigation maintenance of pipelines is problematic. Micro-irrigation, adopted where water is scarce, includes drip and sprinkler irrigation and it is suitable for horticultural crops.

Because of the great importance of water resources for agriculture, a detailed knowledge of the factors affecting the different terms of local soil water budgets and larger scale water balances is highly desirable. The programme of observations for agricultural meteorology must therefore include hydrological observations, such as lake and watershed water balances and the water stages in an adjacent lake or river, which are important in connection with river floods significant for agriculture. The cooperation with NMHSs is necessary in this direction (WMO, 1994, 2007).

2.3.1.9 Fluxes of weather variables (derived from measured quantities)

The term 'flux' means the rate of flow of fluid, particles or energy through a given surface. The basis of modern micrometeorology is the 'energy budget'. This may be formed over a surface (lake, large field of crop) or volume (individual tree). The key to the energy budget is the partition of the types or forms of energy at a surface. A surface cannot store any of the heat it receives from net radiation. Therefore, the net all-wave radiation must be partitioned into other forms of energy which include storage of energy by the soil (ground heat flux) or body of water, energy used in evaporation or gained from condensation (latent heat flux), energy used to heat the air or gained from cooling the air (sensible heat flux), and the energy associated with biological process such as photosynthesis, respiration etc. Net radiation is the difference between total incoming and outgoing radiation of all wave lengths, and is a measure of the energy available at the surface that drives the above processes. The knowledge of 'energy budget' is also useful in devising 'frost protection methods' by altering any of the fluxes (ground heat, sensible heat and latent heat). Excellent textbooks give the mathematical details and applications (e.g. Monteith and Unsworth, 2007).

2.3.1.10 Remote sensing and GIS

Reference should be made to Goel and Norman (1990), Milford (1994), Sivakumar et al. (2004), WMO (2006). Remotely sensed data provide in many ways an enhanced and very feasible areal supplement to manual local observations, with a very short time delay between data collection and transmission. It can improve information on crop conditions for an early warning system. Due to the availability of new tools, such as Geographic Information Systems (GIS), management of an incredible quality and quantity of data such as traditional digital maps, database, models, etc., is now possible. GIS refers to tools used in organization and management of geographical data, and is a rapid means for combining various maps and satellite information sources in models that simulate the interactions of complex natural systems. RS and GIS in combination will continue to revolutionize the inventory, monitoring, and measurement of natural resources on a day-to-day basis. Likewise these technologies are assisting in modeling and understanding biophysical processes at all scales of inquiry (Holden, 2001, Sivakumar et al., 2004). Chapter 4 of this Guide provides details and examples.

2.3.1.11 Recorders and integrators

Reference should be made to Woodward and Sheehy (1983). Recorders and integrators (for totals or period averages) are the devices between the sensing of an environmental variable and the final site of computations on that variable. A variety of techniques is available for use of transducers in this process (between sensors and display or recording). To convert a transducer output into a state suitable for human vision or for recording, translation devices are useful. The electrical translators, amplifiers, etc., belong to this category. The techniques of interfacing between the transducer and the human eye are the most rapidly evolving. Interfacing devices are generally classified into two categories viz., analogue and digital. Analogue devices provide a visual representation of transducer outputs marked on scales. Digital devices provide a numerical readout of the transducer output.

A tube is the characteristic link for devices that measure pressure (e.g. manometer, bourdon tube etc). Mechanical linkages are used between temperature sensors, constructed as bimetal strips or helices, and a display, such as a meter or a chart. Hair hygrometers and barometers also rely on mechanical linkages. The problems of electrical interfaces can be virtually eliminated by replacing electrical conductors by fiber-optic links. Transmission of data from a remote location to a convenient receiving station is readily achieved by transmitting the data using radio or telemetric linkage.

Choosing the appropriate set of instruments is a complex procedure when considerable range of instrumentation is available for displaying and recording the output from transducers. Small numbers of transducers can be efficiently interfaced with visual display and manual recording. A chart recorder is useful if automatic recording is required. Where large numbers of transducers are required, automatic recording and display is a necessity. Care should be taken to provide sufficient visual displays of current measurements to allow checkups and control of the observation chain. If all the channels are of similar voltage, with similar response times, then a complex data logger is probably not required; a data acquisition unit may suffice. When data computation is required, for example for linearization of thermocouple voltages and conversion of voltages to environmental units, then a data logger with programming steps contained in a read-only memory may be sufficient.

Particular metadata for recording of sensor signals are signal transmission data, such as cable length (for signal loss estimation), and amplification or modification of the signal.

2.3.2 Observations of biological nature

Reference should be made to Slatyer and McIlroy (1961), WMO (1982), Woodward and Sheehy (1983), Russell et al. (1989), Pearcy et al. (1989), Baker and Bland (1994), Lowry and Lowry (2001). Biological observations (physical, physiological and phenological measurements of canopies, leaves, roots, growth and yields, see Baker and Bland, 1994) are needed before relationships between weather and various aspects of agriculture are explained. Such observations give, at least, a qualitative but, preferably, a quantitative measure of the response of a plant or animal to weather conditions. The biological observations assist agrometeorologists in solving the problems that arise from the relations between plants, animals and pests on one hand, and the relationships of growth and yield of plants and animals with weather on the other. It should never be forgotten that such observations are made on living organisms with an inherent variability that should be taken into account in sampling methods.

As a working method for bioclimatic investigations, phenology should lay down standards for the observation of those periodic processes that are of the greatest importance for agricultural crops. In the case of annual crops, a wide variety of bioclimatic factors must be taken into consideration. They include whether the crops are winter, summer or mid-season crops, how far they are sensitive to low and high air and soil temperatures, the requirement of Growing Degree Days and other heat units in use, irrigation and other agronomic management. Observations of the start, climax and end of each phase are carried out. First for those crops which cover the entire ground (difficult to observe) and second for the crops planted in rows (easy to observe). In the case of perennial plants the observations are carried out on individuals, each of which, when taken in isolation, represents a repetitive sample. Three to five fruit trees, forest trees or shrubs of the same age and planted in representative locations in the orchard, wood or plantation are sufficient to give accurate phenological averages.

In explaining the effects of the annual weather cycle on the growth and development of living organisms, it is necessary to record

- a) whether the phenological process follows a pattern adjusted to the meteorological pattern; only the representative moments of phases will be observed;
- b) whether the phenological pattern and its phases are interrupted by weather phenomena; it is now essential to carry out simultaneous observations of the stage of development of all the visible phases of the individual plant.

Therefore, each user of biological observations must remember their limitations as to general applicability; often the best methods for recording them differ from country to country. As a general principle, it is essential that the accuracy and extent of biological observations matches those of meteorological observations with which they are to be associated.

Biological observations can be conveniently divided into six broad categories:

- a) network observations of natural phenomena taken over a large geographical area, dealing with wild plants, animals, birds and insects;
- b) network observations (similar to (a)) and quantitative measurements on the periodical growth and yields of cultivated plants and farm animals. They should include observations on dates of certain events in animal and plant life as well as cultural operations: dates of ploughing, sowing/planting, weeding, spraying, irrigation (including quantities) and harvesting (including quantities) in the case of plants; calving, milk production, etc. in animals. These data are required for the objective study of the relationship between environmental factors and agricultural production;
- c) Observations of damage to cultivated crops, weeds, animals etc., caused by meteorological factors; occurrence of certain pests and diseases in plants and animals, their severity and areas in which centers of infection are situated; damage caused by atmospheric events, e.g. hail, drought, frost, storms and their accompanying phenomena;
- d) Detailed observations, of high accuracy or considerable complexity – required during a specific experiment at a research station or experimental site (see for example Baker and Bland, 1994);
- e) Network observations of a less complex character than in (d) above, taken over a much greater geographical area and at a large number of sites, which are required for operational use or administrative action shortly after they are taken, i.e., for immediate use;
- f) Global biological observations for assessing the areal extent of specific biological events.

These are elaborated on in the following paragraphs.

2.3.2.1 Observations of natural phenomena

These observations concern weather effects on wild plants and animals that are, for the most part, free from deliberate human interference. Because of this relative freedom, these data are regarded as providing a form of integration of local climate, and as such may prove suitable for use as an operational parameter. Wild flowers, trees and shrubs are suitable for these observations as also are migrating birds and hibernating animals.

The organization of these observations should be similar to that for cultivated plants and may often be identical in extent and procedure. Some countries make much use of volunteer non-scientific observers for this work and many countries conduct phenological investigations of the types described here.

2.3.2.2. Observations for agroclimatological use

In this category are phenological observations on cultivated crops and trees, on farm animals, and on general activities on the land that are all required to form an

accurate picture of the agricultural year. They differ from those in the operational-use category, in that the observations are made on a wider selection of phenomena at a permanent network of reporting stations. The observations are subsequently analyzed, published or otherwise permanently recorded by a central authority, but without any degree of operational urgency.

The network can be less dense than required for operational purposes but should cover the entire country and not be confined to any smaller area of specialized agricultural production. The observations can be simpler in character than those specified in some sections of this Chapter, but an agreed and fully understood standard of observation is essential. They normally consist of the recording of dates on which certain events take place and of measurements of growth and yields.

Each country should select its own standard programme of observations, then draw up a standard set of instructions for reporting and recording them, bearing in mind that items of such a programme will serve as a basis for introducing an operational system in the future, as the need arises.

The necessity for continuity, reliability and uniformity must be impressed on the observers, who may be volunteers with little scientific training. Each should be given a recording notebook of pocket size, which not only has space for the appropriate entries but also contains the necessary instructions and illustrations. Note books should be retained at the observing site; entries should be transcribed into standard forms of transmission to the central authority at convenient regular intervals.

2.3.2.3. Observations of direct and indirect damage due to weather

2.3.2.3.1 General weather hazards

Weather hazards which may cause loss or damage to soils, plants and animals are usually snow, ice, frost, hail, heavy rain, weather conditions leading to high air pollution, unseasonable heat or cold, drought, strong winds, floods, sand and dust-storms high and low (crop) level ozone (see WMO, 2006), etc. The secondary effects of weather likely to have adverse effects on agricultural production include forest and grass fires and the incidence of pests and diseases.

In some cases, an adequate observational system will have been included, particularly in relation to pests and diseases, forest fires, or the effects of any regularly occurring hazard, such as snow or frost. Regular systems for observing weather damage can also be incorporated into the categories described above in this chapter. Where such systems do not exist, however, special arrangements should be made to assess the extent of damage accurately.

The nature of the observations varies with the type of hazard and can be selected only by each individual country, or by a group of countries with similar climates. They must, however, be clearly specified to eliminate the risk of inaccurate assessments. Furthermore, observation systems must be devised in anticipation of damage, so that action can be taken by selected observers immediately after the unusual weather has occurred. It is also important that good scientific information is available on the causes of the damage. A good recent example is for hail (Wieringa and Holleman, 2006).

2.3.2.3.2 Greenhouse gases

Similarly, contemporary agrometeorologists must understand that climate change and its variability because of greenhouse gases related to agricultural production

indirectly cause enormous damage to the environment as also to agriculture. Over recent decades, the earth has become warmer than expected due to the increased presence in the atmosphere of gases such as carbon dioxide (CO₂), chlorofluorocarbons (CFCs), methane (CH₄) and Nitrous oxide (N₂O). CH₄ and N₂O are the gases mainly responsible for global warming as a consequence of agriculture, while deforestation leads to less CO₂ absorption from the atmosphere. An increase of these gases in the atmosphere enhances retention of the re-radiated heat and thus adds to the warming of the earth's surface and lower atmosphere. Observations on these gases and the production related processes behind their rates of release are therefore necessary for those purposes. Research results of agronomists and soil scientists relevant to these problems for example proved that the soil texture has a significant role on the magnitude of CH₄ emission from rice fields. This is because percolating irrigation water removes organic acids by aeration and high percolation rates in light soils.

2.3.2.3.3 Soil erosion

Soil erosion and related phenomena are other major forms of damages caused directly or indirectly by weather. Soil erosion is the process of detachment of soil particles from the parent body and transportation of the detached soil particles by wind and water. They cause further problems in water provision to and biological damage in crops and in operational agrometeorology observations are therefore necessary wherever this is or becomes a major problem (e.g. Mohammed et al., 1995).

The detaching agents are falling raindrops, channel flow and wind. The transporting agents are flowing water, rain splash and wind. Depending on the agents of erosion it is called as water erosion or wind or wave erosion. There are three stages of sand movement by wind, all of them usually occurring simultaneously. The first one is "suspension" (the movement of fine dust particles smaller than 0.1 mm diameter by floating in the air). Wind velocities above 3.0 kmhr⁻¹ (0.8 ms⁻¹) are capable of lifting silt and very fine sand particles to heights greater than 3 to 4.5 km. Soil particles carried in suspension are deposited when the sedimentation force is greater than the force holding the particles in suspension. Suspension does not usually account for more than 15% of total movement.

The second is "Saltation" which is the movement of soil particles by a short series of bounces along the ground surface. It is due to the direct pressure of wind on soil particles and their collision with other particles. Particles less than 0.5 mm in diameter are usually moved by saltation. This process may account for 50-70% of total movement. The third is surface creep, the rolling and sliding of soil particles along the ground surface due to impact of particles descending and hitting during saltation. Movement of particles by surface creep causes abrasion of soil surface leading to breakdown of non-erodable soil aggregates due to impact of moving particles. Surface creep moves coarse particles larger than 0.5-2.0 mm diameter. This process may account for 5-25% of the total movement. Measurements of dust, saltating and creeping sand as well as related soil and crop hazards and defense mechanisms are essential in operational agrometeorology of affected areas (e.g. Mohammed et al., 1996, Sterk, 1997).

Soil losses by sheet and rill water erosions are most critical in sub-humid and humid areas, whereas wind erosion exacts a higher toll in semi arid and arid areas. For both types of soil erosion the maintenance of soil cover at or near the soil surface offers the most effective means of controlling soil and water loss and can be easily quantified

(Kinama et al., 2007). Conservation tillage systems are undoubtedly among the most significant soil and water conservation practices developed in modern times but are, in some places, traditional farming practices (Reijntjes et al., 1992). Quantification of their impacts should be improved.

2.3.2.3.4 Water run-off and soil loss

The portion of the precipitation that is not absorbed by the soil but finds its way into the streams after meeting the persisting demands of evaporation, interception and other losses is termed run-off. In some humid regions, the loss may rise as high as 50-60% of the annual precipitation. In arid sections, it is usually lower unless the rainfall is of the torrential type. Although the loss of water itself is deplorable, the soil erosion that accompanies it is usually more serious. The surface soil is gradually taken away and this means a loss not only of the natural fertility, but also of the nutrients that have been artificially added. Also, it is the finer portion of this soil that is always removed first, and this fraction, as already emphasized is highest in fertility. A recent example in operational agrometeorology of measuring (diminishing) soil loss and water run off from sloping agricultural land is given by Kinama et al. (2007).

2.3.2.4 Detailed biological observations

As in the case of physical observations mentioned above, detailed accurate biological observations are needed for fundamental research. Such observations are made by scientifically trained personnel to ensure great accuracy. WMO's *Technical Regulations* list the types of biological observations which may be required. However, it must be stressed that these observations require high precision since they have been especially selected for research purposes. Because these kinds of observations are neither routine nor permanent it is impossible to recommend general methods suitable for all purposes. This work may be carried out either under natural conditions in the field or under laboratory conditions, which may often involve the use of climate-control chambers, wind tunnels, microscopes and other experimental tools, to study the reactions of both plants and animals to single or complex meteorological factors.

It is always important to measure both the physical and physiological responses of living organisms, e.g. in plants, the carbon dioxide intake, osmotic pressure, chemical constitution, leaf area, dry-matter index, and growth rate; in animals, basal metabolism, pulse and respiration rate, rectal temperature, blood volume and composition, blood pressure, composition of food etc.

Care must be taken in control-chamber experiments because the climate simulation often does not represent open field or natural conditions quantitatively or qualitatively. In order to achieve reliable results, it may be necessary to select a sound statistical experimental design under natural conditions. In this kind of research, teamwork is highly recommended.

2.3.2.5 Observations for operational use

In general the mean data provides a strong basis for comparison with current data since departure from normal provide most useful information for operational use. These are observations needed by regional or central authorities to assist them in taking

administrative action, making functional forecasts, or giving technical advice. Although they must be standard in nature, so that observations from different sources can be compared, such yardsticks as 30 years averages start to become somewhat meaningless in the light of a rapidly changing climate. Other approaches need to be developed that take time trends and increasing variability into account simultaneously.

Such observations will be needed from a large number of sites that form a national network, and will be made by skilled or semi-skilled observers who have received adequate training to meet the desired observational standards. Arrangements must be made to communicate these observations as quickly as possible to the regional or central authorities. Postal services may be adequate but more rapid means like internet, fax, radio etc., may often be needed.

The density of the network may be limited by the availability of efficient observing staff. All areas of the country concerned with one type of operational requirement should be adequately covered. Ideally, the network density will depend on the type of problem, the crop types and distributions, the soil variations, the climate and the population density in the region that determine the general and repetitive sampling rates.

The exact nature of the biological observations must be strictly specified by the authorities in an agreed pattern, preferably accompanied by good illustrations. Under this heading are observations on yield, which may concern small experimental plots or regional or national areas of production. In planning these observations, the agrometeorologist should collaborate with statisticians and agricultural experts. Wherever necessary, he should encourage the agricultural authorities to obtain the data in a form suitable for establishing weather-yield relationships. For regional or national yields he should make himself aware of the accuracy of the yield measurements.

The meteorological and biological data are analyzed simultaneously by regional and central authorities that take operational decisions after proper analyses. A summary of the season's work should be prepared and either published or permanently retained for reference, so that the experience of each year is always available for subsequent consideration.

Some examples of information required for operational use are:

- a) *Forest fires*
The state of the forest litter and its susceptibility to burning (see chapter 8);
- b) *Diseases*
The state of the plant, the presence and release of spores, the incidence and spread of infection;
- c) *Pests*
The hatching of harmful insects; the build-up of insect populations, or their invasion from other territories.
- d) *Weather hazards*
The state of crops, and whether they are at a stage particularly susceptible to weather hazards; animals under stress due to unseasonal climate or other severe weather conditions.

e) *Farming operations*

The progress made in the farming year – in order to make weather forecasters aware of the operational implications of forthcoming weather.

2.3.2.6 Global biological observations

Besides the local observations described in sections above, there are now modern methods for globally evaluating the distributions of biological phenomena such as:

a) (i) *Aerophotogrammetry* (conventional photography)

This is for the mapping of relief and for determining the types of natural vegetation and crops, their phenological state, soil type, cattle distribution, etc. Flying height of the aircraft must correspond to the photographic resolution of the phenomenon under study (through use of multi-spectral photography). Although this is diminishing in the developed world, in the developing world it could be still important if enough funds and hardware can be available.

(ii) *Aerial photography* (particular wavelengths)

Remote sensing with special film, sensitized to a region of the visible spectrum, or to infra-red radiation, gives valuable information on albedo, intensity and ground emission active in the energy balance. Scanners have also become available. Information can be obtained on soil-moisture deficit; drought stress in vegetation; composition of plant community and its phenological condition; state of crops and cattle.

b) *Satellite observations*

Satellite images are useful, especially for extended areas (Chapter 4). Estimates of rainfall and of vegetation indices are routinely available, although they have very variable accuracy depending on latitude, observing system etc.

2.4 Instruments used at agricultural meteorological stations

Most of the instruments included as basic equipment at an agrometeorological station are described in WMO (2006). Short descriptions of some agrometeorological instruments generally used for specific applications are given below. There is a clear need for frequent recalibration of all instruments.

2.4.1 Measurement of the physical environment

2.4.1.1 Radiation and sunshine

Reference may again be made to Coulson (1975), Fritschen and Gay (1979), Iqbal (1983), WMO (1984), Goel and Norman (1990), WMO (2001), Strangeways (2003) and WMO (2006) as well as WMO-T.N.172. Some basic remarks on mounting instrumentation have already been given in 2.3.1.1. Global solar radiation (direct and diffuse solar radiation) is measured with *pyranometers* containing thermocouple junctions in series as sensors. The sensors are coated black to have uniform thermal response at all spectral wavelengths. With filters non-PAR radiation can be measured and the difference between solarimeter outputs with and without filters gives PAR data. Stigter and Musabilha (1982) did this for the first time elaborately in the tropics. Solid-state sensors (photo-electric solar cells, photo-emissive elements, photo resistors etc.) may be used where radiation can be assumed to have constant spectral distribution (e.g. solar radiation within limits). Different types of *photometers and ultra-violet illuminometers*, which are adaptations of these, are used in agrometeorological research.

Light, as indispensable for photosynthesis, is one of the major components of the short wave radiation. What is measured with a *lux meter* is not light intensity, but luminance, that is defined as luminous flux density intercepted per unit area. Quantum sensors which measure the PAR directly in the range 0.4 to 0.7 micrometers are available. Ideally crop profile measurements with quantum sensors should be done on perfectly clear or uniformly overcast days. However, if this is not possible the problem is partially overcome by expressing the values at each level relative to the incident radiation. These profiles are compared with leaf-area profiles when the light requirements of crops are being studied.

Tube radiometers for use in crops and agroforestry are inherently less accurate than instruments with a hemispherical dome, but can be of great use in estimating the average radiation below a crop canopy or mulch relative to that above it. When mounted N – S, the sensitivity varies with the angle of the solar beam to the axis, particularly in the tropics (Mungai et al., 1997). This adds to errors due to high ambient temperatures under low wind speeds and errors due to condensation inside the tubes. Calibrations as a function of time and ambient conditions can largely cope with such errors but filtered tubes for photosynthetically active radiation appeared unreliable in the tropics (Mungai et al., 1997). To measure the fractional transmission of solar radiation through a crop canopy, a number of tubes are placed beneath the canopy. Their numbers and arrangement depend on the uniformity of the crop stands (Mungai et al., 2000). A reference measure of incident solar radiation above the canopy is needed. For crop studies the output for each tube is usually integrated over periods of a day or longer during the growing season. Integrators or loggers are ideal for this purpose. The values of fractional interception are subsequently calculated from the integrals (e.g. Mungai et al., 2000).

Surface temperature radiometers are used for measurements of infra-red radiation emitted from near or remote surfaces. They are mainly used as hand-held remote sensors to measure temperatures of radiating irregular surfaces such as soil, plant cover and animal skin and require knowledge of the emissivity coefficient of the observed surface (WMO, 2001). Operational precautions were given by Stigter et al. (1982).

Pyrgeometers are used for the measurement of long-wave radiation from the sky (when upward looking) or from the earth (facing downward).

Net all-wave radiometers (measuring net flux of downward and upward total radiation i.e. solar, terrestrial and atmospheric) contain black-coated heat-flux plate

sensors, in which thermocouples are embedded to measure the temperature difference between the two sides of a thin uniform plate with well-known thermal properties. Errors due to convection and plate temperature are avoided by using forced ventilation, appropriate shields, and built-in temperature compensation circuits. *Net radiometers or net pyrrometers or net exchange radiometers or balancemeters* may have a standard (about 6 cm) diameter for regular use or a miniature (about 1 cm) diameter for special work on radiation exchange from plant organs or small animals.

Standard meteorological stations usually measure only sunshine duration. The traditional instrument to observe this is the *Campbell-Stokes sunshine meter*. WMO abolished the world standard status of this sunshine meter in 1989, as the process of evaluating the burns on its daily cards was both cumbersome and arbitrary. Instead, sunshine duration has been defined as the time during which direct radiation (on a plane perpendicular to the Sun's beam) is larger than 120 Wm^{-2} . This definition makes it possible to now use automatic sunshine recorders (e.g. WMO, 2001, 2006).

Particular metadata of radiation measurements are: (1) wavelength transmission spectral window of pyranometer dome; (2) sunshine recorder threshold radiation value; (3) horizon mapping for each instrument measuring radiation or sunshine; (4) procedures or means to keep radiometer domes clean and clear.

2.4.1.2 Temperature of air

Reference should again be made to Fritschen and Gay (1979), WMO (1984), Goel and Norman (1990), WMO (2001), Strangeways (2003) and WMO (2006). Also WMO TN 315 is useful. General issues were discussed in 2.3.1.2. Besides the standard instruments there are several others used in agrometeorological surveys and research.

Small and simple radiation screens, some of which are aspirated when this does not destroy temperature profiles, are useful for special field work. High outside reflectivity, low heat conductivity, high inside absorption and good ventilation are desirable requirements in the construction materials and design. An idea of the radiation errors can for example be determined by simultaneous, replicated observations with the ventilated Assmann psychrometer at the hours of maximum and minimum temperature.

The most common thermometers for standard observations in air are those generally called *differential expansion thermometers*, which include liquid-in-glass, liquid-in-metal, and bimetallic sensors. Because of their sizes and characteristics many of these instruments are of limited use for other than conventional observations. However, spirit-in-glass, mercury-in-glass, and bimetallic sensors make useful *maximum and minimum* temperature measurements. When temperature observations are required in undisturbed and rather limited spaces, the most suitable sensors are electrical and electronic thermometers which permit remote readings to be made.

Resistance thermometers are metallic annealed elements, generally of nickel or platinum, whose electrical resistance increases with temperature; readings are made with appropriately scaled meters such as power bridges.

Thermocouples are convenient *temperature sensors* because they are inexpensive and easy to make. Those most frequently used in the environmental temperature range are copper-constantan thermocouples, which have a thermal electromotive force response of about $40 \mu\text{V}^\circ\text{C}^{-1}$. This relatively weak response can be increased by connecting several thermocouples in series or using stable solid-state d.c.amplifiers. Thermocouples are excellent for measuring temperature differences

between the two junctions, e.g. dry- and wet-bulb temperatures, or gradients. When they are used to measure single temperatures or spatial average temperatures (such as surface temperatures, using thermocouples in parallel), there is always need for one junction to be at a known steady reference temperature.

Thermistors are temperature sensors increasingly used in agricultural and animal micrometeorology. They are solid semi-conductors with large temperature coefficients and are produced in various small shapes such as beads, rods and flakes. Their small size, high sensitivity and rapid response are valuable characteristics, offset however by their lack of linear response (less than metallic resistances) in the resistance-temperature relationship. Additional components are therefore required to achieve linear output.

Diodes and transistors with a constant current supply which provide outputs much higher than $1 \text{ mV}^\circ\text{C}^{-1}$ have been used to construct sensitive and accurate thermometers for application in plant environments.

Infrared thermometers were discussed in 2.4.1.1. A *black-globe thermometer* is a blackened copper sphere commonly 15 cm in diameter, with a thermometer or thermocouple inserted. When a black globe thermometer is exposed in the open or under a ventilated shelter, the effects of different radiation fluxes are integrated with that of convective heat (wind and air temperature). Installed inside closed barns or stables, under still air conditions, it gives the average radiant temperature of soil, roof and walls at equilibrium.

Particular metadata for temperature measurement are: (1) height of sensor; (2) description of employed screens (dimensions, material, ventilation).

2.4.1.3 Temperature of soil and other bodies

2.4.1.3.1 Soil

Reference should again be made to Rosenberg et al. (1983), WMO (1984; 2001; 2006). All sensors mentioned in 2.4.1.2 may be used, although the thermocouple must be of a sturdy construction, provided that presence of the sensor does not affect the temperature being measured. Mercury in glass type soil thermometers are frequently used. For measurements of the soil temperature at shallow depths these thermometers are bent in between angles 60° and 120° for convenience. At greater depths lagged thermometers are lowered into tubes. Care should be taken to see that water does not enter the tubes. Alternatively, shielded thermocouples or thermistors can be used. Temperature of deeper soil layers can be measured with glass thermometers, thermistors, thermocouples, diodes and platinum resistance thermometers when good contact is made with the soil.

In cold and temperate climates where the soil is often deeply frozen and snow-covered, when continuous soil-temperature records are not available or when many observing points are needed, different types of *snow-cover and soil-frost depth gauges* can be used. These instruments generally consist of a water-filled transparent tube, encased in a plastic cylinder that is fixed in the soil. The tube is periodically removed from its plastic casing to determine the depth to which the entrapped water is frozen. If the fixed cylinder extends sufficiently far above the soil surface it can be used as a snow-cover scale provided the exposed part is graduated.

For the soil surface temperature, non-contact infrared thermometers are preferable as long as emissivity is known and again the presence of the sensor does not

affect the temperature being measured by shading or otherwise influencing the natural radiation balance (e.g. Stigter et al., 1982).

Particular metadata for soil temperature profile measurements are instrument depths, and regular specifications of the actual state of the surface.

2.4.1.3.2 Other bodies

Like the soil, plant parts such as leaves, stems, roots, fruits etc., have mass and heat capacity. The temperature of all these organs, can be measured with platinum resistance thermometers, thermistors, thermocouples, infrared thermometers, diodes etc. if the instruments do not influence the energy balance of those bodies. To measure their surface temperatures, and those at the outside surface of animals, small contact sensors like thermocouples and thermistor or non-contact methods should be used.

In animal micrometeorology special and relatively simple instruments have been used to simulate the cooling power of the air or the heat load over the homeothermic animal body. Kata thermometers are spirit-in-glass thermometers with a rather big bulb of accurately determined area. With these the time required for a fixed amount of cooling after the thermometer has been warmed above body temperature is measured. Such a reading is an index integrating the cooling effect of temperature and wind.

A practical thermo-anemometer is the heated-globe anemometer, which provides a reasonable value of the cooling power of air motions in climatic chambers and other indoor environments. It is constructed with a chrome-plated sphere of 15 cm diameter heated by a nichrome wire that can receive a variable power input. Several thermocouples in parallel with one junction fixed internally to the globe wall measure the temperature of the globe wall. The voltage of the heater is regulated to give a differential air-globe temperature of 15° C. The power needed to maintain a steady temperature is a function of the ventilation. However, a correction factor for thermal radiation of walls, ground, and roof may be required if these are significantly hotter than the air.

2.4.1.4 Atmospheric pressure

Reference should be made to WMO (2006). Analyzed pressure fields are useful in agricultural meteorology. These pressure fields must be accurately defined because all the subsequent predictions of the state of the atmosphere depend to a greater extent on these fields. In mercury barometers the pressure of the atmosphere is balanced against the weight of the column of the mercury, whose length is measured using a scale graduated in units of pressure. Of the several types of mercury barometers, fixed cistern and Fortin are most common. For the purpose of comparison pressure readings may need to be corrected for ambient air temperature.

In electronic barometers, transducers transform the sensor response in to a pressure-related electrical quantity in the form of either analogue or digital signals. Aneroid displacement transducers, digital piezo-resistive barometers, cylindrical resonator barometers fall into this category. Calibration drift is one of the key sources of error with electronic barometers. Therefore the ongoing cost of calibration must be taken in to consideration when planning to replace mercury barometers with electronic ones.

Aneroid barometers have the advantage over conventional mercury barometers that they are compact and portable. Another important pressure measuring device is the Bourdon tube barometer. It consists of a sensor element (aneroid capsule), which changes its shape under the influence of pressure, and transducers which transform the change

into a form directly usable by the observer, such as on a barograph. The display may be remote from the sensor.

2.4.1.5 Wind

Reference should again be made to Mazzarella (1972), Wieringa (1980), WMO (1984), Kaimal and Finnigan (1994), Stigter et al. (1998), WMO (2001, 2006). Wind speed and direction measured with standard instruments under standard exposure are fundamental requirements of the science of agricultural meteorology. The most common routine observation is the wind run, providing an average over the measuring period. That period should be at least ten minutes for smoothing out typical gustiness, and at most an hour because surface wind has a very pronounced diurnal course. However, different instruments are used when it is necessary to observe the more detailed structure of air motion, e.g. in agricultural meso- and micrometeorological studies. In such cases wind speeds are measured with cup anemometers of high sensitivity at low velocities or with electrical thermo-anemometers or sonic anemometers.

Sensitive *cup anemometers* are the most common in routine and research use, measuring all wind components with an angle of attack with the horizontal smaller than about 45°. The best have a low stalling speed (threshold of wind speed below which the anemometers does not rotate) of about 0.1 m s⁻¹, because friction loads have been minimized. The rotation produces an electrical or phototransistor signal which is registered by a recorder or counter. Such transducers also allow separate recording of gustiness.

Sensitive *propellers*, if mounted on a vane, can be an alternative for cups (WMO, 2006) but are these days mainly used in research instruments (WMO, 2001). *Pressure tube anemometers* on a vane are reliable, but so unwieldy that they are disappearing in favor of smaller instruments. A new instrument for horizontal wind speed and direction measurement is the *hot-disk anemometer*, which has the advantage that it has no moving parts. For steady wind direction measurement, wind vanes must have fins whose height exceeds their length.

Sonic anemometers, sensing the transport speed of sound pulses in opposite directions along a line, so being totally linear, respond quickly enough to measure turbulence and have become useful in flux measurements in research. However, they cannot be used in small spaces and their calibration shifts in wet weather.

For research of wind speeds in restricted spaces, such as crop canopies and surfaces, several kinds of thermo-anemometers are used. The *hot-wire anemometer* is an electrically heated wire, of which the heat loss is a function of the airspeed at normal incidence to the wire. It is particularly useful for low-speed winds but very fragile, and in polluted surroundings it loses its calibration so it cannot be used operationally. Because of the dependence of wire heat transfer on wind direction, crossed-wire sensors can be used to separate the wind components in turbulent motion.

Hot-bead anemometers have heated beads, of which heat transfer is less dependent on wind direction but has a slower response. Thermocouples or thermistors sense differences in temperature between heated and non-heated beads, which differences are a function of the wind speed. Shaded Piche evaporimeters have also been used as cheap interpolating and extrapolating ancillary anemometers in agroforestry under conditions of not too high turbulence and low temperature and humidity gradients (Kainkwa and Stigter, 2000; Stigter et al., 2000).

Particular metadata for wind measurement are: (1) response times of instruments; (2) sensor height; (3) exposure, i.e. adequate description of surrounding terrain and obstacles; (4) type of anemometer signal, its transmission and its recording; (5) sampling and averaging procedure; (6) unit specification (m/s, knots, km/hr, or some type of miles per hour).

2.4.1.6 Air humidity and soil moisture (including leaf wetness)

2.4.1.6.1 Humidity

Reference should again be made to WMO (1984), Griffiths (1994) and WMO (2001, 2006) as well as WMO TN 21. The most commonly used hair hygrometers and hair hygrographs may give acceptable values only if great care is taken in their use and maintenance. The accuracy of other equipment has improved. Besides standard *psychrometers equipped with mercury-in-glass thermometers, portable aspirated and shielded psychrometers and mechanical hygrometers*, many instruments have been developed to measure different aspects of air humidity. Since, the above-mentioned routine instruments are bulky and inadequate for remote reading, they are unsuitable for many agrometeorological observations. For observations in undisturbed and small spaces, electrical or electronic instruments are used. The best method for measuring humidity distribution in the layers near the ground is also by using thermo-electric equipment, unventilated thermocouple psychrometers being most suitable in vegetation (e.g. Rosenberg et al., 1983; WMO, 2001). Ventilated psychrometers may be used for levels at least 50 cm above bare soil or dense vegetation.

For measuring relative humidity directly, use has been made of *lithium chloride or sulphonated polystyrene layers*, since the electrical resistance of these electrolytes changes with relative humidity. However, these electrolytic sensors become affected by air contamination and high relative humidity conditions and are therefore to be used with great care and frequent recalibration. For example *resistive polymer film* humidity sensors are increasingly used. Instruments are usually contaminant resistant and common solvents, dirt, oil, and other pollutants do not affect the stability or accuracy of the sensor.

Electrical dew-point hygrometers indicate dew point rather than relative humidity. For example, the *lithium chloride dew-point hydrometer* measures the equilibrium temperature of a heated soft fiberglass wick impregnated with a saturated solution of lithium chloride. This temperature is linearly related to atmospheric dew point. However, the response of the instrument under low relative humidity conditions is not so good.

More expensive and complicated, but more accurate, instruments require that the air be sampled and delivered, without changing its water-vapour content, to a measuring unit. One such instrument, an illuminated condensation mirror, is alternately cooled and heated by a circuit energized by a photocell relay, which maintains the mirror at dew-point temperature. *Infra-red gas analyzer hygrometers* (IRGAs) are based on the fact that water vapour absorbs energy at certain wavelengths and not others. Two sampling tubes are also used to measure absolute values of water-vapour concentration at two levels, at the same time as their differences.

Single or double-junction peltier psychrometers are extensively used for accurate measurement of water potential values in plant tissues and soil samples. They are generally based on the Peltier effect in chromel-constantan junctions and the water

potentials are derived from measurements of equilibrium relative humidity in representative air.

Particular metadata for any type of hygrometry are regular notes in the station logbook of maintenance activities, such as psychrometer wick replacement or cleaning of sensor surfaces. Moreover it should be recorded if sensors are ventilated. Because so many different humidity parameters are in use, the metadata should specify not only the actually used parameters and units, but also contain information on the way in which the archived humidity data were calculated from original observations (conversion tables, graphs, small conversion programmes).

2.4.1.6.2 Soil and grain moisture

Reference may be made to Greacen (1981), Gardner (1986), Vining and Sharma (1994), Dirksen (1999), Smith and Mullins (2001) and WMO (2001; 2006). Also WMO TN 97 describes instruments used for the measurement of soil moisture. Time and space variation of soil-moisture storage is the most important component of the water balance for agrometeorology. Several instruments have been constructed to measure soil-moisture variations at a single point but they avoid the variability of soils in space and depth (e.g. Ibrahim et al., 1999, 2002). Gardner (1986) still described as a relevant indirect method of obtaining soil water content “measurement of a property of some object placed in the soil, usually a porous absorber, which comes to water equilibrium with the soil”. Blotting paper is popular here and they may be also useful for soil potential determinations, characterizing the water supplying power of the soil in representation of root hairs.

Subjective methods of estimating soil moisture have been used with satisfactory results in some regions where regular observations in a dense network are necessary and suitable instruments lacking. Skilled observers, trained to appreciate the plasticity of soil samples with any simple equipment, form the only requirement for this method. Periodic observations and simultaneous determinations of soil texture at depths, by competent technicians, allow approximate charts to be constructed.

The direct methods of soil water measurement facilitate implementation of easy follow up methods at operational levels. Gravimetric observations of soil water content have been in use for a long time in many countries. An auger to obtain a soil sample, a scale for weighing it, and an oven for drying it at 100-105^oC are used for the purpose. Comparison of weights before and after drying permits evaluation of moisture content which is expressed as a percentage of dry soil or, where possible, by volume (in mm) per meter depth of soil sample. Because of large sampling errors and high soil variability the use of three or more replicates for each observational depth is recommended (see also WMO TN 21). The volumetric method is useful to measure the absolute amount of water in a given soil and it has known volumes of soil sampled.

Tensiometers measure soil-moisture tension, which is a useful agriculture quantity, especially for light and irrigated soils. The instrument consists of a porous cup (usually ceramic or sintered glass) filled with water, buried in the soil and attached to a pressure gauge (e.g. a mercury manometer). The water in the cup is absorbed by the soil through its pores until the pressure deficiency in the instrument is equal to the suction pressure exerted by the surrounding soil. Next to this direct measurement an indirect measurement of soil moisture tension can be obtained from electrical resistance blocks.

Electrical resistance blocks of porous materials (e.g. gypsum), the electrical resistance of which changes when moistened without alteration of the chemical

composition, can be calibrated as a simple measure of soil moisture content. It was for example operationally used successfully by Mungai et al. (2000).

Among *radioactive methods*, the *neutron probe* measures the degree to which high energy neutrons are thermalized in the soil by the hydrogen atoms in the water. It determines volumetric water content indirectly *in-situ* at specific soil depths using a pre-designed network of access tubes (Ibrahim et al., 1999). The neutron scattering and slowing method was until recently most widely used, relatively safe and simple to operate. The total neutron count per unit time is proportional to the moisture content of a sphere of soil of which the diameter is larger when the soil is drier. Soil moisture is measured with the *gamma radiation probe* by evaluating differential attenuation of gamma rays as they pass through dry and natural soils. This method generally requires two probes introduced simultaneously into the soil a fixed distance apart, one carrying the gamma source and the other the receiver unit.

Time Domain Reflectometry (TDR) determines the soil water content through measuring the dielectric constant of the soil, which is a function of the volumetric water content. It is obtained by measuring the propagation speed of alternating current pulses of very high frequency (>300 MHz). The pulses are reflected at inhomogeneities, either in the soil or at the probe soil interface, and the travel time between the reflections is measured. From the travel time the dielectric constant is determined and in that way the volumetric water content of the soil. As with neutron scattering, this method can be used over a large range of water contents in the soil. It can be used directly within the soil or in access tubes. Compared to the neutron scattering method, the spatial resolution is better, calibration requirements are less severe and the cost is lower (WMO, 2001).

In agriculture another important measurement needed is the moisture content of grains which influences viability and general appearance of the seed before and after storage. It is important to know the moisture content immediately after harvest, prior to storage, shipment and after long periods of storage etc. The methods for measuring moisture content are generally classified as reference methods, routine methods and practical methods. The phosphorous pentoxide (moisture is absorbed by this chemical) and Karl Fisher method (water is extracted from seed using a reagent) come under reference methods. The “oven dry method” is categorized as routine method in which the seed moisture is determined by removing the moisture from the seeds in an oven. Among the practical methods the moisture content determination by using samples in infrared moisture meters is easy as compared to others. WMO TN 101 deals with some of the above but also with practical methods using electrical resistance sensors. The latter were successfully used by Abdalla et al. (2001).

2.4.1.6.3 Leaf wetness and dew

Reference should be made to Getz (1992) and WMO (2001). The very large number of instruments that have been developed for the measurement of dew or duration of leaf wetness (WMO T.N. 55) indicates that not even a moderately reliable method has yet been found. Two main categories of Leaf Wetness Duration (LWD) sensors being used are: (i) mechanical sensors with recorders and (ii) electric sensors, which exploit the conductivity variation as a function of wetness.

In addition to electric conductivity measurements of dew (variations on both natural and artificial surfaces), principles of mechanical dew measurement are (i) modification of the length of the sensor as a function of wetness, (ii) deformation of the

sensor, (iii) water weighing type (dew balance recorder), (iv) adsorption on blotting paper, with or without chemical signaling. There is also visual judgment of drop size on prepared wooden surfaces (Duvdevani).

Porcelain plates (Leick), pieces of cloth and other artificial objects can share in any dew fall or distillation occurring on a given natural surface. Unless they are more or less flush with that surface and have similar physical properties (surface structure, heat capacity, shape, dimension, flexibility, color and interception) they will not indicate reliably the amount of dew that the surface receives. If exposed above the general level of their surroundings, as is normal with Duvdevani blocks and usually appears to be the case with more refined “drosometer” devices, their behavior will diverge from that of the surface below, and the observed amounts of dew may bear little relation to the dew on adjacent natural surfaces.

Weighing type instruments, modified hygrographs with a hemp thread instead of a hair bundle, and systems with surface electrodes that connect when the surface is wet, all have their problems (WMO, 2001). The surface-electrode instruments are the simplest to read, but again do not measure real leaf wetness, because the sensor is again a fake leaf, with different heat capacity etc.

2.4.1.7 Precipitation (clouds and hydrometeors)

Reference should be made to Meteorological Office (1981), WMO (1994, 2006). WMO Technical Notes 21, 83 and 97 also provide information and guidance concerning instruments such as rain gauges and totalisators, rain recorders (float and tipping bucket types) and snow gauges. Many of these require lower accuracy in agrometeorology than as standard climatological measurements. For some purposes no great precision in rainfall is needed, for example in classifying days as either “wet” or “dry” for insurance claims or when only rough ideas are wanted of accumulation of rainfall over agricultural fields over an ongoing season compared to the same period in earlier years, a topic most farmers will be interested in. The same applies in school (agricultural) environmental science teaching. In Mali the National Meteorological Directorate is of the opinion that farmers need to have a means of measuring rainfall if they wish to derive full profit from the agrometeorological information disseminated by rural radio, and farmer raingauges are now locally manufactured (Rijks, 2003).

A few additional remarks are appropriate here on a number of instruments used for specific work and on their operation. Hailfall observations cannot be automatized, because the only useful observation method so far is employment of a network of hail pads.

It should first be noted that since close to 150 years wind, and therefore particularly height and shape of the rain gauge, have correctly been seen as by far the most important factors determining errors in rainfall measurement.

When cost is important, including needs for high measuring densities, raingauges smaller in size than the normal standard are employed, but they are unsuitable for snow. Sometimes these are made of plastic and shaped like a wedge, sometimes they are plastic or other can like receptacles. Commercially the former are often called “raingauges according to Diem” or “farmer raingauges”, the latter, if from plastic, “clear view raingauges”. Inexpensive rain gauges and small-size totalizer rain gauges are used for

studying the small-scale distribution of precipitation, as in limited meso climates, forest or crop interception, shelterbelt effects, etc.

In addition to routine rainfall measurements agricultural practices need the amount, duration and intensity of precipitation at the time of floods and related disasters. As the severe weather systems affecting coastal areas originate in seas and oceans the ocean based data collections through ships and buoys are necessary. Also, installation of automatic weather stations that meet the necessary criteria will help monitoring and early warning coastal zones about hazardous weather. However, capability for disseminating the weather data, topography and vulnerability of the coastal zone to severe weather decide on the weather station network requirements. In vulnerable coastal zones a dense network of observations is required to diagnose and plan in advance the mitigation of weather related hazards.

Radar, sometimes together with satellite remote sensing, is increasingly used to estimate both point and area rainfall from characteristics of cloud structure and water content. These data complement the surface raingauge networks in monitoring and mapping rainfall distribution but it is essential that representative actual observations at the surface are used when taking decisions on the track of the storm for forecasting purposes. Such derived rainfall data need ongoing intensity calibration.

Particular metadata for precipitation measurement are: (1) raingauge rim diameter and rim height above ground; (2) presence of a nipher screen or some other airflow modification feature; (3) presence of overflow storage; (4) manner, if any, of dealing with solid precipitation (heating, snow cross).

2.4.1.8 Evaporation and water-balance

Standard instruments used for measuring the different components of the water balance for climatological and hydrological purposes (such as here screened and open pan evaporimeters, lysimeters) are also employed in agricultural meteorology. The same literature as in 2.4.1.7 should be referred to, together with WMO (1984; 2001).

2.4.1.8.1 Evaporation

While it is possible to estimate actual or potential evapotranspiration from observed values of screen or open pan evaporimeters or from integrated sets of meteorological observations, more accurate, direct observations are often preferred. Actual evapotranspiration is measured by using soil evaporimeters or lysimeters, which are field tanks of varying types and dimensions, containing natural soil and a vegetation cover (grass, crops or small shrubs). Potential evapotranspiration (PET) can be measured by lysimeters containing soil at field capacity and a growing plant cover. A surface at almost permanent field capacity is obtained by regular irrigation or by maintaining a stable water table close to the soil surface. A strict control must be kept of infiltration from rainfall of excess water supply. The reliability of observation by lysimeters depends upon the conditions at the instrumental surface and below it being very similar to the conditions of the surrounding soil.

Among the different lysimeters the most important ones for agricultural applications are Thornthwaite lysimeters (drainage type), Popoff lysimeters (combined drainage and weighing type), weighing lysimeters and hydraulic lysimeters (more robust weighing type). Lysimeters are used for measurement of evaporation, transpiration, evapotranspiration (ET), effective rainfall, drainage, chemical contents of drainage water,

to study climatic effects of ET on the performance of crops. Lysimetry is one of the most practical and accurate methods for short term ET measurements, but a number of factors cause a lysimeter to deviate from reality viz., changes in the hydrological boundaries, disturbance of soil during construction, conduction of heat by lateral walls, etc.

Atmometers or “small surface” evaporimeters are also still in use, among which the cheap Piche can be utilized anywhere in meteorology and agriculture if the physics are well understood (Stigter and Uiso, 1981). Shaded Piche evaporimeters were used to replace humidity and wind speed data in the aerodynamic term of the Penman equation in Africa (Ibrahim et al., 1989).

Devices for measuring net radiation, soil heat flux and sensible and advected heat are needed in energy budget methods, while continuous measurements of wind speed, temperature and water-vapour profiles are needed for the aerodynamic method (see also Allen et al., 1998; Hough et al., 1996). When adequate instrumentation facilities and personnel are available, it is possible to compute actual evapotranspiration using energy-balance or mass-transfer methods. Certain semi-empirical methods which require relatively simple climatological measurements to provide estimates of PET are often of little value when evaporation is limited by water supply.

Microlysimeters are very small lysimeters, for soil evaporation measurements, which can be put into the ground and used for short times, such that disturbance of the soil boundary condition does not appreciably effect evaporation from the soil. Precautions to be taken and a measuring protocol were given by Daamen et al. (1993) and operationally applied by Daamen et al. (1995) and Kinama et al. (2005).

Particular metadata for pan evaporation are the pan dimensions and rim height, and any employment of pan defense against thirsty animals (e.g. wire netting).

2.4.1.8.2 Irrigation

Water balance studies are incomplete without proper reference to different methods of irrigation because water with acceptable quality is becoming a more and more scarce resource for agriculture and this sector is the most prolific user of water. This was already dealt with in 2.3.1.8. Measurements and calculations particularly include soil moisture conditions, water use efficiencies and water flow conditions in canals of different dimensions, including the smallest field channels (e.g. Ibrahim et al., 1999, 2000, 2002).

2.4.1.9 Fluxes of weather variables (derived from measured quantities)

Reference should be made to Fritschen and Gay (1979), Kaimal and Finnigan (1994), Griffiths (1994), Murthy (1995, 2002), Allen et al. (1998) and WMO (2001).

A reliable, but complex, method to measure atmospheric fluxes is that of ‘eddy covariances’. In this method very fast response devices such as hot-wire, hot-film, or sonic anemometers are used to measure wind and similarly fast response sensors are used to measure the remaining quantities. These include the IR gas analyzer (for water vapour and CO₂) and fine wire temperature sensors. The correlation of instantaneous departures from the mean of the wind and other variables provides an estimate of the flux. Eddy covariance systems use commercially available instruments like a three axis sonic anemometer and IR gas analyzer, controlled by software which also calculates and displays the surface fluxes of momentum, sensible and latent heat and carbon dioxide.

The Bowen ratio (the ratio of the sensible to latent heat fluxes) energy balance

method is a reliable technique for obtaining evaporation rates and is one of the most frequently used methods for estimation of surface energy balance components and evaporation. The required observations are differences in temperature and humidity between two levels or in a profile. The Bowen Ratio Energy Balance (BREB) system provides continuous estimation of evaporative loss. This system is less complex than eddy covariances and needs reduced maintenance and power consumption.

In all the studies pertaining to flux measurements the temperature profile observations are supported with direct measurement of the soil heat flux density. Heat-flux densities in the soil or in plant or animal tissues are measured close to the interface between air and soil, plant and animal with *transducers or heat-flux plates*. Generally these instruments are thermopiles whose output is proportional to the temperature difference between the sides of a plate crossed by the flux. Such thermopiles are usually constructed by winding a constantan spiral on a glass or plastic plate, copper-plating half of each winding in such a way that portions of the plated and non-plated constantan remain exposed in the upper and the lower sides. The conductivity of the plate material should match the heat transmission of the medium measured. For soils, the small plates are typically buried at a compromise depth of 10 cm. Deeper depth than this makes them unrepresentative for soil heat flux at the surface, but very shallow placement leaves very thin covering soil layer, which then may dry out or crack. The presence of plant roots also has to be considered (WMO, 2001).

2.4.1.10 Remote sensing and GIS

Reference should be made to Goel and Norman (1990), Milford (1994), WMO (2006). The remotely sensed image is typically composed of picture elements (pixels), which vary in size from a few metres to a few kilometres across. For each pixel an associated digital number (DN) or Brightness Value (BV) depicts the average radiance from that pixel within a spectral band which is specified by the relevant sensor. For useful information such as a vegetation index to be derived from the raw data, it is usually necessary to process the data from more than one band. A geometrical correction is necessary to ensure that the location of each pixel in an image is accurately known, a process known as rectification

Where an image is to be viewed, image enhancements improve its quality as perceived by the human eye. The Linear and Non-linear Contrast Stretch are done to improve the resolving power and detectability of the image. Later, the number of changes in BV per unit distance for any particular part of an image called “Spatial Filtering” is done at low and high frequency levels. The edge enhancement in the spatial domain using linear technique is done to highlight point, lines and edges in the images. Band ratioing is done to reduce the differences in brightness values from identical surface materials.

Images may be transformed within a Geographic Information System (GIS), for example by Principal Component Analysis that creates new images from the uncorrelated values of different images. This analysis is used for spectral pattern recognition and image enhancement. Two or more different images may then be combined to form a new one using a variety of different techniques. Then supervised and unsupervised classifications are taken up to find complexity of terrain. Finally accuracy assessment is carried out for use of all these techniques in operational agricultural meteorology. In addition the concepts of GIS are useful for efficient planning and decision making at farmer level, to integrate information from many sources and to generate new

information such as the slope of the region, wind direction, possible flow of water at disasters times and other risks. Much more detail is in Chapter 4.

2.4.1.11 Recorders, integrators and AWS's

Reference should be made to Woodward and Sheehy (1983). Meteorological data can be obtained by direct reading (instantaneous) of measuring instruments and also by instruments providing a continuous record of the parameters over time, with mechanical or electrical or other analogue or digital displays. All the instruments have to be calibrated to meet comparability requirements and recalibrations are a 'must' after repairs or replacement of essential parts of the instruments. The most common way to calibrate is by comparison with standard instruments kept at national centers and specialized laboratories and checked from time to time against international standards.

2.4.1.11.1 Mechanical and electrical devices

Observations with instruments which do not have self-recording devices are made by individual readings at the given observation times and written into an appropriately designed observations book, in accordance with the instructions. From this basic document, data can be transferred to monthly summaries and be extracted for special analysis.

In mechanical reading instruments the changes of the length of the sensing element or sensor force is transmitted mechanically with or without amplification to a recording system that is usually based on clock driven paper strip either of the drum or endless belt type. The variations over time of the parameter to be measured are displayed in graphical form or diagram chart. The main advantages of mechanical recorders are their relatively low cost, easy maintenance and independence from an external power supply.

In electrical recording instruments sensors are used which produce electrical signals (voltage, differences in potential, resistance, etc.) to be referred to the parameters under considerations, or detectors are used where initial mechanical 'signals' (longitudinal changes, rotation, etc.) are transformed into electrical ones by appropriate devices (potentiometer, switches, etc.). Depending on the signal output of the sensor different recorders viz., null balance potentiometric recorders, galvanometric recorders, Wheatstone bridges for electrical resistance measurements etc., are used.

2.4.1.11.2 Micro processors

With the progress in micro-electronic technologies over the recent years more and more instruments using integrated circuits and micro processors are being designed for the purpose of measurement of meteorological parameters. Together with electrical sensors, the use of integrated circuit chips has allowed the construction of highly sensitive and low weight digital read out instruments. They have the advantage of the built in 'conversion' from electrical sensor outputs to technical units including complex linearizations. The subsequent use of integrated electronic circuits and microprocessor chips has led to the construction of automatic environmental control systems and automatic weather stations.

Electronic integrators with memory capacity for data storage that can be recalled are also available. For any particular logger memory the duration of record available depends on the number of sensors and the frequencies of observation

2.4.1.11.3 Automatic Weather Stations

Reference is made to Hubbard and Sivakumar (2001), WMO (2006). An automatic weather station (AWS) is defined as a meteorological station at which observations are made and transmitted automatically. If required, they may be interrogated either locally or from an editing station. Most of the variables required for agricultural purposes can be measured by automatic instrumentation. As the capabilities of automatic systems increase, the ratio of purely automatic stations to observer-staffed weather stations (with or without automatic instrumentation) increases steadily. The guidance regarding citing and exposure, changes of instrumentation, and inspection and maintenance apply equally to automatic weather stations as that of staffed-weather stations. AWSs are used to satisfy several needs, ranging from a single aid-to-the – observer at manned stations to complete replacement of observers at full automatic stations. A general classification of these stations includes stations which provide data in real time and those which record data for non-real time or off-line analysis. It is not unusual, however, for both these functions to be discharged by the same AWS.

When planning the installation and operation of a network of AWSs it is of the utmost importance to consider the various problems associated with maintenance and calibration facilities, with their organization and with the training and education of technical staff. In general, an AWS consists of sensors installed around a meteorological tower, housed in appropriate environmental shields, a central processing system for sensor data acquisition and conversion into computer-readable format, and some peripheral equipment such as a stabilized and uninterruptible power supply.

The agricultural meteorological demands made on sensors for use with AWSs are not very different from those made on sensors for conventional use. Siting of an agricultural AWS is a very difficult matter and much research remains to be done in this area. The general principle is that a station should provide measurements that are, and remain, representative of the surrounding area, the size of which depends on agricultural meteorological application. The distance over which any station-measured parameter can be extrapolated also varies, from small for precipitation to large for incoming radiation (Wieringa, 1998). An AWS usually forms part of a network of meteorological stations and transmits its processed data or messages to a central network processing system by various data telecommunication means. The cost over a few years of servicing a network of automatic stations can greatly exceed the cost of their purchase. The sensors with electrical outputs show drifts in time and, consequently, need regular inspection and calibration.

2.4.2 Measurements of biological and related phenomena

Reference should be made to the literature mentioned in 2.3.2. Because it follows from the explanations in that section that Chapters 4, 6, 7 and 10 till 14 all deal in some of their sections with biological measurements and related phenomena, we have sorted out below only a few additional issues that got much attention relatively recently and are not widely dealt with elsewhere in this Guide. We are still talking about measurements at or near agricultural meteorological stations.

2.4.2.1 Measurement of soil erosion

A universal soil loss equation has been developed to measure/estimate water and wind erosion factors. It is discussed in Hudson (1993) and Chapter 10 of this Guide. Water erosion field measurements are dealt with in Hudson (1993) and WMO (1994) and particle analyses in Vining and Sharma (1994), while general field measurements for wind erosion have been discussed by Zobeck et al. (2003). Spaan and Stigter (1991) and Mohammed et al. (1995, 1996) discussed the operational use of simple field measurements in wind erosion studies. Soil erosion (deflation) and deposition (accumulation) occur as a consequence of transport and these are scientifically quantified as height differences (e.g. Mohammed et al., 1995, Sivakumar et al., 1998). When properly designed and carefully executed erosion pins provide sound data on these changes. They are meaningful and visibly impressive to farmers and extension workers. They allow large numbers of measurements to be taken with low cost and are extremely useful to measure the changes in surface elevations of soils exposed to wind and or water erosion (e.g. Hudson, 1993).

2.4.2.2 Measurement of run-off

The equipment for measurement of runoff includes Weirs and Parshall flumes, which are suitable to measure the runoff from small watersheds, and water recording equipment: water storage recorders that continuously record the water level in a stream. In studies on agriculture of sloping lands, runoff plots are successfully managed and soil loss and water runoff can be quantified (e.g. Kinama et al., 2007).

2.4.2.3 Measurement of leaf area, canopy structure and photosynthesis

It is desirable to express plant growth on leaf area basis. The leaves are the primary photosynthetic organs of the plant. After destructive sampling (removing the leaves from the plant) the leaf area can be measured by using a leaf area meter. This instrument is portable, but expensive. It has a transparent belt conveyer to spread the leaves and has a digital display to indicate the leaf area. More simply, the leaf area can also be estimated by graphical methods, the L.B.K. method (Length x Width x Constant), the dry weight method, the paper weight method etc. The leaf area is normally expressed in relation to ground area as the Leaf Area Index (LAI), which is the ratio between the total leaf area of a plant to the ground area occupied by the plant. To have more production, the plant should be able to utilize maximum amount of light for which optimum spacing should be followed. The LAI helps to fix optimum spacing to utilize the maximum sunlight for photosynthesis.

There are different optical methods for measuring LAI that are well established. Canopy structures can also be quantified that way. Details may be found in Percy et al. (1989), Russell et al. (1989), Goel and Norman (1990), Baker and Bland (1994). Details on leaf, plant and stand photosynthesis measurements and their development and growth consequences can be found there as well but now we get again closer to specialized research where agrometeorologists either collaborate or use the results from. Many methods are used successfully, but they are not as accurate or rapid as IRGA systems. A sensitive technique for rapid measurements of CO₂ concentrations with attached leaves sealed in Plexiglas chambers is also in vogue. Other related instruments include those measuring stomatal conductance, sap flow, leaf water potential and dendrometers, etc. The mentioned literature has details.

Measurements of crop production including the weight of above ground dry matter, total dry matter, economic yield etc. are frequently taken at agricultural meteorological stations, or in adjacent fields. These are useful to relate the production to climatic variables over periods from weeks to the whole season.

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