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METEOROLOGICAL ELEMENTS AND THEIR OBSERVATION

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METEOROLOGICAL ELEMENTS AND THEIR OBSERVATION

1• GENERAL

1.1. Basic Aspects

1.1.1 Observations of the biophysical environment are essential in agricultural research, including forestry and livestock. The physical elements of climate are observed in order to assist in the evaluation of actual and future land use potentials and of such constraints in agriculture as are caused by the environment. To meet these requirements, agricultural meteorology needs reliable, quantitative data on the relevant climatic elements.

1.12 Indispensable climatic elements in agricultural meteorology include those pertaining to geographical climatology and especially those permitting interpretation of physical processes in the lower layers of the atmosphere and the upper soil layers. Elements pertaining to energy and water balance are thus very important, as well as other related phenomena, such as humidity, temperature, wind and precipitation.

1.1.3 In agricultural meteorology, macro and micro scale observations are required. While macro-scale observations provide information on the climatic background, most of the agricultural planning and research activities require data on the meso- or micro -climatic scales. Standard instrumentation and standard exposure conditions in agricultural meteorology, are important as far as comparability is concerned. However, in research work, instruments and exposure conditions are not always standard.

1.2 Meteorological Stations

1.2.1 Basic information on the physical environment can be obtained from observations made at stations of the synoptic, climatological and hydrological networks. Since these networks may be restricted in density and in kind of observation, it is desirable that they be supplemented by agricultural meteorological stations. Such stations are equipped to perform general meteorological and biological observations and are usually located in areas of particular interest for agriculture, horticulture, forestry, animal husbandry and soil sciences.

The site of a meteorological station should be located in a place truly representative of the natural conditions in the region concerned. The site should:

- be free from obstructions and be fairly level;
- have a sod cover if possible or natural cover common to the area;
- not be concrete, asphalt, rock;
- not be closer to any obstructions (trees, shrubs, buildings) more than eight to ten times their height;
- not be near to areas with cold drainage, flooding and frequent sprinkling;
- should be easily accessible for appropriate maintenance.

The lay out of a station will mainly depend on the number and type of instruments used. However,it has to comply with the following basic requirements:

- minimum tampering by animals and people (fence);
- instruments should, as far as possible, not be shaded by each other or the fence;
- instruments for air temperature measurements have to be properly screened against direct sunshine.

Meteorological observation time3

The time(s) meteorological observations are taken throughout the day, is an important criteria as far as comparability with data from other stations is concerned. For synoptic purposes it is important that observations are taken at the internationally agreed times, according to universal time or GMT. The main observation times are 0000, 1200, 1800 hr GMT with subsidiary times at 0300, 0900, 1500 and 2100 hr GMT. As in the climatological networks, night observations are rare, readings at three synoptical hours in the morning, at noon and in the evening are acceptable.
In agrometeorology, the comparability of observations is rather linked to the daily course of the sun and hence with local Mean Time. Common observation times are 0700, ,0800, or 0900 hr LMT in the morning, 1400, or 1500 hr LMT in the afternoon (appearance of the daily Max.Temp.) and 1900, 2000 or 2100 hr LMT in the evening. If only one daily observation is carried out it is usually a morning observation.
In agrometeorological research, observation times, are however very often imposed by the particular research objectives and plant physiological activity cycles.

2. MEASUREMENT OF METEOROLOGICAL ELEMENTS

2.1. Temperature and Heat Flux

2.1.1 General comments

2.1.11 Physical aspects

- Temperature is the condition of a body which determines its ability to communicate heat to other bodies or to receive heat from them.
- For meteorological purposes, temperature is referred to the Celsius scale (degree centigrade). 0 degrees centigrade is the normal ice point; 100 degrees centigrade is the normal boiling point of water. The relationship to the absolute thermodynamic Kelvin scale is given by:
  T degrees Celsius + 273.15= degrees Kelvin

2.1.12 Air Temperature

Air temperature should be measured in representative places at different levels adjacent to the soil in order to allow the study of its vertical distribution which is relevant for the climatic conditions of agricultural crops. As radiation is a serious source of error in measuring temperature, appropriate protection has to be provided (thermometer screens, small plastic screens, or roof shaped shelters). Another approach to minimize errors is the U3e of thermometers having sensitive elements with low response to radiation (e.g. electrical equipment). Proper ventilation has to be ensured as well.

2.1.13 Soil Temperature

Soil temperature is of particular interest for energy balance computations, for plant growth and various pest development assessments. The standard depth levels are 5, 10, 20, 50 and 100 cm. Soil temperature is measured under two standard types of soil cover - bare soil and short grass. Its simultaneous measurements under crops and trees shows the modifications of the temperature regime due to the plants and their management.

2.1.14 Special temperature measurements

For particular purposes, the temperature of water surfaces and water bodies (including ice and snow), plants (leaves, stems) and animals, can be of interest and has to be measured. Similarly, the ^ heat flux density, (units:$cal*cm^{-2}*s^{-1}$, W, $J*cm^{-2}*s^{-1}$) a quantity which is required where detailed heat balances must be ascertained..

2.1.2 Instruments

2.1.21 Physical principles of temperature measurements

To measure the temperature of a body, the following physical principles are mainly used:

- the expansion of liquids and metals
- the change of electrical resistance with temperature
- the thermo-electrical effects
- the black body radiation
- chemical reactions.

2.1.22 Thermometers and temperature sensors

2.1.221 Thermometers based on the expansion of liquids and metals.

The most common thermometers for standard observations in the air, soil and water are the differential expansion thermometers which include the liquid in glass, the liquid in metal and the bimetallic sensors.

- Different designs of liquid in glass (spirit or mercury) thermometers and soil thermometers.
  (Suppliers: A 1-5, B23, B24)
- Liquid in metal (e.g. mercury-in-steel) and Bourdon tube devices, make useful temperature recorders with the possibility of remote measurements up to 50 m.
- Bimetallic strips or helix, which change their curvature with temperature, are widely used in the construction of mechanical temperature recorders.
  (Suppliers:A 1-5, B 22)

2.1.222 Electrical resistance thermometers

- Electrical resistance sensors
  Metallic resistance thermometers are annealed elements, generally of nickel or platinum, whose electrical resistance increases with temperature. Most common are the platinum-wire hardglass sensors with a resistance of 100 ohms at 0 degrees centigrade. Their resistance temperature response is to a greater extent linear. Readings are made with appropriately scaled meters, such as power bridges.
  (Suppliers: A 2-5, B 25)
- Thermistors are solid semiconductors with large negative temperature coefficients. They are produced in various 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 in the resistance temperature relationship. Additional components are therefore required to obtain linear output.
  (Suppliers : A4,5,C2)

2.1.223 Sensors using thermo-electric effects

- Thermocouples

  Thermocouples are convenient temperature sensors because they are inexpensive and easy to make. For meteorological applications, copper-constantan thermocouples are the ones most frequently used. The weak thermal electromotive force response, of about 4O uV/degrees centigrade, can be increased by connecting several thermocouples in series, or using suitable d.c. amplifiers. Modern recorders provide for reference junction temperature measurements and/or compensation. With reference to the basic physical principle, thermocouple instruments are especially useful for differential measurements.

- Heat-flux plates

  Usually these instruments are thermopiles whose output is proportional to the temperature difference between the sides of a plate crossed by the flux.
  (Suppliers: A1, B,4)

- Diodes and transistors

  Diodes and transistors with outputs higher than 1uV/ degrees centigrade are used to construct sensitive and accurate thermometers for applications in plant environments.

- Katathermometers

  To measure the cooling effect of temperature and wind, Katathermometers are used. They 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, is measured.

2.1.224 Radiative sensors

Surface temperatures can be determined by using radiation measurements and applying the physical radiation laws (Stefan Boltzmann, W. Wien), to them. These methods are mainly applied in remote sensing from aircrafts and satellites.

2.1.225 The chemical transformation of saccarose to glucose and fructose in a solution is an exponential function of its pH value and temperature. This reaction is used to measure the average temperature (or rather the heat quantity received) over a longer period. To measure the state of transformation, a polarimeter is used. With respect to the non-linear response of the chemical reaction to temperature, satisfactory results with this method are mainly obtained where temperature variations are small (soil, water bodies).

2.2. Humidity of the Air

2.2.1 General comments on air humidity measurements

2.2.11 Physical aspects

Air humidity is defined by the water vapour contained in the atmosphere. 20 definitions and specifications are given by WMO. The most relevant for agricultural meteorological purposes are:

- Vapour pressure "e": partial pressure of water vapour in moist air of the total atmospheric pressure "p". (units :mb)

- Saturation vapour pressure "E": maximal water vapour pressure at pressure p and temperature T. (unit : mb)

- Relative humidity "U":Ratio in percent of partial to saturation vapour pressure of a given total pressure p and at temperature T. 0 = 100 = e/E (unit :%)

- Dew point temperature "Td": Temperature at which the partial vapour pressure becomes equal to the saturation vapour pressure, (e s E; U = 100%) (unit: degrees centigrade)

- Saturation deficit "De": Difference between saturation and partial water vapour pressure at a given total pressure and temperature. (De=E-e; unit:mb)

- Mixing ratio "r": ratio of the mass of water vapour to the mass of dry air with which the water vapour is associated.(unit: g/Kg)

Note: Distinction has to be made between water vapour over water or ice.

2.2.12 Observation of air humidity

The humidity of the air should be measured in representative placed at different levels in the air layer adjacent to the soil (from ground level up to 10m). Observations* taken for special research projects will vary with the needs of the problems Under investigation. !

2.2.2 Instruments

2.2.21 Methods of measurement

- methods using the change in dimensions of hygroscopic
- substances (hair hygrometers).
- Thermpdynamic methods (psycrometer).
  Dry and wet bulb temperatures allow the calculation of the air humidity ,
- The absorption method uses the change of electrical resistance or capacity in chemically treated sensors.
- condensation method (dew and frost point hygrometers).

2.2.22 Water vapour sensors

2.2.221 Mechanical hygrometers

- Mechanical hygrometers and hygrographs.
  The change in length of hygroscopically sensitive hairs is used to construct "mechanical" hygrometers and hygrographs **measuring the relative humidity. Provided that ne extreme** temperatures and very low humidities (*<20%*) occur, these instruments meet the general requirements of accuracy (+3 to *5%)*. Hair hygrographs are the most frequently used standard recording instruments for humidity measurements in international networks. However, the following disadvantages have to be noted:
  non-linear response to humidity changes, changes in zero point require frequent cleaning and recalibration; sensitivity to destruction or errors through chemical pollution (e.g. ammonia gases), low response rate at low temperatures.
- There are simple hygrometers for direct readings and hygro graphs with adjustable mechanisms for direet recording on cylindric drums driven by clockwork. Similar hygrometric sensors have been constructed, where the change in length of the hair bundle operates an electrical potentiometer, which allows for remote control.
  (Suppliers: A 1-5, B 22)

2.2.222 Psychrometers

- Psychrometers basically consist of two thermometers one of which is measuring the air temperature (dry bulb thermometer) while the other is covered and kept moist to measure the "wet bulb temperature". For accurate measurements, provision has to be made:
- for appropriate protection aganst radiation;
- to avoid error due to conductive heat;
- • - to ensure adequate wetness of the wet bulb thermometer;
- that the thermometers used have approximately the same lag coefficient.
  Distinction is made between simple psychrometers without ventilation and artificially ventilated psychrometers.
  Nonventilated psychrometers are still in general use at climatological stations, but as ventilation (up to 2.5 m/s) affects the results considerably, the accuracy of these instruments vary with the conditions of natural ventilation. The error will usually be about *5%* relative humidity but can reach 10$ in dry air.

Artificially ventilated psychrometers, such as the Assmann type, the aspirated screen type, and the whirling type, are desiged to eliminate these errors to a large extent by providing forced ventilation of at least 2.5 m/s. (The sling or whirling type, however, needs particular attention to avoid errors caused by radiation). The general accuracy of these psychrometers depend mainly on the accuracy of the thermometers and the wet bulb reading. (An error of 0.5 degrees centigrade in the wet bulb reading will cause an error of M$ in relaltive humidity at -25 degrees centigrade but only 2% in relative humidity at +15 degree centigrade air temperature).

Psychrometers using liquid in glass thermometers allow for instant readings only. Recording psychrometers have been designed by using electrical temperature sensors and providing for permanent water supply for the "wet bulb" thermometer. Modern micro-processors, by applying the psychrometric formula immediately to the temperature (dry and wet bulb) readings of such psychrometers, allow for continuous recording of air humidity in technical units.
(SuppliersrA 1-5, 5, B 16, C M)

2.2.223 Absorption method

- Electrolytes which change their electrical resistance with relative humidity are used for measuring and recording the vapour content of the atmosphere. Lithium chloride or sulphanated polystyrene layers are most commonly used for these purposes. The non-linear resistance/humidity response of these sensors has to be considered as a disadvantage, especially in very dry or very humid conditions. The fact that these electrolytical sensors are easily contaminated by gas, smoke or oil vapours contained in the air necessitates great care in handling.
(Suppliers: A H, 5, B 5)
- There are also small humidity sensors which change electrical capacity with humidity. Their size (less than 1 cm) and fast response (approx. 1s) is of particular interest for agricultural meteorological applications. With an appropriate microelectronic circuit, a linear (approx. 1$) D.C. voltage output can be achieved.
(Suppliers: C 2, C 5)

2.2.224 Humidity sensors using the condensation methods

- Dew point hygrometers indicate dew point temperature rather than relative humidity. Using the princlple of cooling an air sample - which has to be delivered without changing its watervapour content to a measuring unit - until condensation takes place, these instruments are, in general, more complicated, more expensive but more accurate. One such instrument, an illuminated condensation mirror, is alternately cooled and heated by a circuit energised by a photocell relay which maintains the mirror at dew point temperature.

- **Peltier psychrometers**
  The Peltier cooling effect is applied to a small thermocouple until condensation takes place. When the electric circuit is opened, evaporation starts and the thermocouple junction will act as a wet-bulb thermometer. The generated electomotive force is proportional to the wetbulb depression and allows the determination of the water vapor pressure. This type of instruments are used for accurate measurement of water potential in plant tissues and soil samples.

2.3. Sunshine and Radiation

2.3.1 General comments

2.3.11 Physical aspects

Radiation fluxes to and from the earth's surface are most important meteorological elements for heat and energy balance assessments. As the energy conversion from solar radiation mainly takes place on the surface of the soil and of plants. This parameter is of special interest in agricultural meteorology.

- The duration of sunshine (units: hr per day) allows for estimates of the energy available for physical and biological processes

For accurate investigations, measurements of the different radiation (solar and terrestrial) fluxes are required. In meteorology, the following radiation fluxes are measured:

- Solar radiation fluxes (short wave length 0.29 - 4u)
  . Direct solar radiation is measured at normal incidence.
  . Global solar radiation: downward direct and diffuse solar radiation received on a horizontal surface from a solid angle of 2 PI.
  . Sky radiation: downward diffuse solar radiation received on a horizontal surface.
  . Reflected global radiation: Solar and diffuse radiation reflected by the surface (bare or covered by vegetation) (Albedo: Ratio between upward and downward global radiation fluxes).
- Terrestrial radiation fluxes: (long wave radiation 4 -100u)
  Terrestrial radiation is to be understood as the thermal radiation of the earth and the atmosphere.
- Total radiation fluxes
- Total radiation is to be understood as the sum of the solar and the terrestrial radiation. The flux of both radiation components passing through a horizontal plane is called net radiation.
- In agriculture, the spectral distribution of solar radiation especially in photosynthesis assessments is of great interest.

12 The measuring units of solar energy and their conversion coefficients are:

1 cal*cm-^{2}«min-^{1} = 4.1868 J • enr^{2}»min-1 = 0.069 W»cnr^{2}

1 J*cm^{-2*}min-^{1} = 0.238 cal»cm-^{2}min-^{1} = 0.0165 W*cm^{-2}

1 W •cm"^{2} =14.3 cal*cm^{-2}min-^{1} =60.5 J*cnT^{2*}min-^{1}

- In order to ensure the reliability and comparability of radiation measurements, the sensors have to be checked frequently and calibrated at regular intervals against reference instruments at national or regional centres as recommended by WMO.

2 Instruments

2.1 Methods of measurement

211 To measure the duration of sunshine to the nearest tenth of an hour, four physical principles are mainly used.

- radiation from the sun is focused to burn a trace in a chart;
- radiation from the sun is made to record a trace on photographic paper;
- thermometric (bimetallic) switches controlling either mechanical or electrical recording devices;
- photoelectrical sunshine switches.

212 To measure solar and terrestrial radiation, two basic physical principles are used:

- the absorptive and emissive properties of black and white surfaces resulting in temperature changes and differences when exposed to radiation fluxes. These changes and differences in temperature can be measured, and they give quantitative information on the radiative energy received;
- the photoelectric effects of various semiconductors (photoresistances, photoelements, photodiodes, phototransistors).

22 Measurement probes

221 Sunshine sensors

- To measure the duration of sunshine, the Campbell-Stokes recorder, where the focused radiation from the sun burns a trace in a chart, is most widely used in international networks. It is also recommended as an interim international reference instrument.
  (Suppliers: A 1-5)
- To allow for electrical recording of the duration of sunshine, different "detectors" using thermometric switch devices or photo electrical elements are available. However, measurements with these instruments should be checked against Campbell-Stokes results and eventually be corrected accordingly.
  (Suppliers: B 2, C 5)

2.3.222 Radiation Sensors

- Pyranometers and actinometers are used to measure the global radiation.
- Bimetallic actinographs are simple self-contained recorders. A mechanical linkage is used to record the temperature difference between a black coated bimetallic strip exposed to the sun and one or two similar bimetallic strips either painted white or shielded from solar radiation.
  (Suppliers: A 3)
- The Moll-Gorczynki pyranometer is a thermopile instrument, having a rectangular receiving surface which is covered by two concentric hemispheric glass domes. The Volachine pyranometer is of similar construction but has a circular receiving surface, hence no attention need be paid to orientation.
- Th Eppley pyranometer has two concentric silver rings for receiving surface. One of which is coated black and the other white. The temperature difference between the two rings is measured with thermojunctions.
- The Dirmhirm-Sauberer pyranometer uses black and white segments alternately mounted in the form of a star. Again the temperature difference is measured with thermojunctions which are in good thermal contact with the segments.

The above mentioned thermopile instruments are covered by hemispherical glass domes of 2mm thickness. They are usually well sealed and provision is made that the air inside be kept dry with silica gel. The time required for about 90$ response to a sudden change varies between 20 to 30 seconds. The temperature coefficient does not exceed -0.2$ per degree centigrade. The sensitivities are about 2 $mV/J*cm^{-2}*min^{-1}$ Their spectral range,including the wave length is from 0.3 to 3u.

For the standardisation of pyranometers, the preferred method is comparison with a standard pyrheliometer using the sun as a source. More often, one pyranometer is checked against another. This method requires a high quality reference instrument which is regularly calibrated against a recognized standard.

- Pyranometers with an appropriate device (disc or shadow ring) to screen off direct solar radiations are used to measure the sky radiation. For the measurement of reflected global radiation (albedo) pyranometers are exposed downwards.
- For measurements of shortwave radiation falling from the sun and sky and from soil or another reflection on a freely exposed object, the Bellani spherical pyranometer is used. The radiation is integrated over a spherical surface and over a certain time. Fairly accurate daily total radiation values can be obtained provided the instruments are scrupulously evacuated before filling with alcohol, properly exposed and well calibrated.

- Total radiation (solar and terrestrial) and net radiation (net flux downward and upward total radiation) are measured with black coated heat-flux photo-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 temperature compensation circuits.
- Most of the commercial net pyradiometers or balance meters use hemispherical windows to cover the circular or square receiving surfaces (1 to 30 cm). The material used is thin polythylene, having an integrated transmission in the spectral range from 0.3 to 100u.
- Plastic tube net radiometers are useful instruments for measuring relative values of average net radiation inside crop and forest canopies.
- By shielding one of the receiving surfaces and measuring the temperature of the instrument, net pyrradiameters can be used as pyrradiometers or pyrgeometers (for determination of the downward or upward long wave radiation). As the surface has an influence on the terrestrial radiation near the ground, the exposure of a pyrradiometer needs to be chosen with care to be representative for the neighbourhood.
- For measurements of energy-flux densities in selected spectral bands, solid-state sensors (photo-electric cells, photo-emissive elements, photo-resistors) are increasingly used as they produce larger outputs as thermopile instruments with respective filters. The. different adaptations of these types of instruments are of special interest in plant canopy research.
  (Suppliers: B 1, 3, 4, 5, 6, 26)

2.4 Precipitation

2.4.1 General comments

The amount of precipitation, rain, snow, ice and dew which reaches the ground in a stated period is expressed as the depth to which it would cover a horizontal surface if there were no loss by evaporation, run-off or infiltration, or if any part of the precipitation falling as snow or ice were melted (liquid equivalent).

As precipitation measurements should as much as posible, be representative for a larger area, the choice of site, the form and exposure of the gauge, the prevention against loss by evaporation as well as the effects of wind and splashing are important points which have to be observed.

The amount of precipitation is measured in millimeters, the readings being made to the nearest 0.2 mm; 10 mm should read to 2% of the total. Depth of snow is given in centimeters.

2.4.2 Instruments

2.4.21 Non-recording rain gauges

- Ordinary rain gauges usually have the form of a collector above a funnel leading into a receiver. The opening of the collector should have a receiving area of 200 to 500 cm^2. (The most common standards are: 200 cm^2, 324 cm^2 (diam: 8 inch) and 400 cm^2. However, in many countries 126 cm^2 (diam: 5 inch), are still used. The rim of the collector should have a sharp edge and should fall away vertically inside and be steeply levelled outside. It should be designed to prevent rain from splashing in and out. The receiving water container should have a narrow neck and be protected from radiation to prevent loss of water by evaporation.
- Weekly and monthly rain gauges must have a receiver with a capacity to store the catch over the period. To avoid evaporation losses, a known quantity of oil is placed in the receiver.
- The rain measures, measuring glass or dip rod, have to be graduated to correspond to the relative areas of cross section of the gauge orifice. A measuring cylinder should be made of a clear material (glass or moulded plastic), have a low coefficient of expansion, and its diameter should not exceed 3©S of the gauge diameter. Graduation should be in units of rainfall and at least every 0.2 mm should be marked. Dip rods are mainly used to measure rainfall in monthly or seasonal gauges. However, these measurement should be checked using cylinders as well.
- As far as the exposure *of* rain gauges is concerned, sites sheltered from wind but not from the rain should be chosen. Early disturbances of the airflow due to obstructions and the instrument itself have to be avoided. It is important that the orifice of the gauge be horizontally exposed and is high enough to prevent splashing from the ground. (In different countries standard heights of 30 to 150 cm are used).

2.4.22 Recording rain gauges

2.4.221 Rainfall recorders to record the total amount of rainfall.

- In the float type of instruments, the rain is led into a float chamber, and the vertical movement of a light float is recorded on a chart, when the level of the water rises. To provide a record over a longer period, these instruments are equipped with a device for emptying the float chamber once it becomes full. This is usually a siphoning process which should take no longer than 15 sec. and should start and end abruptly to minimise errors, as rain is not recorded during this process.

- In the tipping bucket type, the rain is led from the receiving collector to a light metal container divided into two compartments. This container or bucket is so balanced that when one compartment holds a predetermined weight of water, it tilts allowing the compartment to empty and the rain to fall into the other compartment. The tilting of the bucket is used to operate mechanically either a counter or recording device, or an electrical switch which allows for recording at a distance.

  The time the bucket needs to tip over leads to appreciable errors only in heavy rainfall. The discontinuous nature of the record is not satisfactory for use in very light rain, as the time of beginning and ending cannot be accurately determined. If detailed records are required the amount of rain per tilting process should be 0.1 mm but in many cases 0.25 or 0.5 mm "sensitivity" will be sufficient.

2.4.222 Intensity recorders

For recording rainfall intensities, the above mentioned amount recorders can be used provided the recording device allows for a timely resolution of 15 minutes. (5 min for special purposes). There are also instantaneous intensity recorders which utilize the relationship between the rate of flow of water through a restricted orifice and the head of water producing the flow ("Jardi" rate of rainfall recorder). To evaluate the amount of rain which has fallen, planimetric masurements of the area under the recorded trace are necessary, which is not an accurate and simple procedure.

2.4.23 Snow gauges

For measuring snowfall, gauges are used where the snow is melted by heating or by mixing with chemical anti-freezers. There are also rain recorders with heating devices which can be used for snowfall measurements as well. Heated recorders should be constructed in such a way as to avoid excessive evaporation when the heating is on.

2.4.24 Wetness detectors

Rain detectors or wetness detectors are used to record duration of precipitation. Conventional instruments are similar to hygrographs except that the sensing element - a string - is exposed openly to precipitation. Electrical sensors will close or open a switch when precipitation is falling on its surface. To speed up drying of the sensor after the rainfall, heating devices can be built in.

2.4.25 Measurement of dew

Dew, being essentially a nocturnal phenomenon, and relatively small in amount, is nevertheless of much interest in arid zones. The amount of dew deposited on a given surface in a stated period is usually expressed in the same units as rainfall: mm depth of dew.

A direct method of measuring dew is to expose a weighted plate of hygrosopic material (gypsum, blotting paper) at sunset and re-weight it after sunrise. This method requires accurate weighing and protection at sunrise to prevent evaporation. Qualitative assessment of dew is obtained by exposing filter paper "sensors" with dew spots. When wetted by dew, the spots will spread to an extent which depends on both the duration and intensity of dewfall. Dew duration recorders operate to a far extent in the'same way as the above mentioned wetness recorders.

For quantitative assssments, dew balances are used to weight the amount of moisture deposited on a surface with similar structure as leaves. The amount of dew on natural leaves can be measured by collecting it with blotting paper which is weighed while dry and after being pressed against the leaf. The leaf surface has, however, to be measured as well.

2.5 Mind.

2.5.1 General comments

2.5.11 Physical aspects

- Horizontal pressure differences, caused by temperature variations in the earth/atmospheric system, result in atmospheric motion or wind. Thus, thermal energy is converted to kinetic energy. In the layer near the ground one is concerned with winds of local and micro scale origins, as well as the modifications of airflows, generated on larger atmospheric scales, by the topography and the cover of the surface.
- In agricultural meteorology, the effects of the kinetic energy transfer of wind to the plant/soil system as well the effects of its mass transfer on the energy and water balance are of interest.

2.5.12 Units

By its physical nature two magnitudes are required when describing wind: its velocity and the direction from which it blows.

- Windspeed is usually indicated in: m/sec, km/h, or knots (= 1 nautical mile/h), but occasionally the non-linear Beaufort scale is used, which refers "forces" from 0 to 12 to the effects of wind on smoke, trees or water surfaces.
- The direction from which the wind blows is either given in accordance with the geographical directions (e.g. N,E,S,W) or in degrees: 1 to 360 (90 degrees = East, 180 degrees - South, 27 degrees = West, 360 degrees = North; 0 frequently stands for Calms).

- Wind can be conceived to be a vector which, in the polar system of coordinates, is defined by an azimuth and a distance in a unit of time, in representing the wind speed. As this system is only for bidimensional representation of the wind, the cartesian system of coordinates (X axis: North/- South; Y axis: West/East; Z axis : vertical) is used when vertical convection has to be considered as well.

2.5.13 Observation of wind

As the wind field, speed and direction near the ground are to a large extent influenced by the topography and the surface cover (vegetation - grass, crops, trees; artificial obstacles -buildings, walls), observation sites have to be chosen very carefully in order to be representative. For climatological purposes, wind should be observed at flat and openly exposed sites (distance to the next obstacle should be 10 times the height of the obstacle; not on top of the buildings which cause turbulences).

As standard height above ground, 10 m is generally recommended for wind measurements in climatology, but for agrometeorological purposes, measurements are very often made at 2m above ground.

Detailed microclimatic investigations on the windfield near the ground and its modification by the vegetation will require a purposeful choice of specific observation sites and measurement heights.

2.5.2 Instruments

2.5.21 Methods of measurements

Basically, the following three physical principles are used to measure wind.

- dynamic energy methods (dynamic and static pressure methods)
- heat transfer method
- sonic method

2.5.22 Measurement Instruments

2.5.221 Instruments using the dynamic methods

- The Wind Vane (Direction)

An assembly of a vane plate (which can have many shapes) and a needle is mounted on a vertical axis, which allows it to revolve freely. As a result of the mechanical action of the wind on the vane, the needle will be turned in the direction from which the wind blows. As the direction indicated by the vane, oscillates around the equilibrium point of the airflow (which can change direction rapidly over time), big efforts have been undertaken to minimise this drawback by different designs. The axis of the wind vane can be connected to a mechanical or electrical (contacts, potentiometer) device, which provide recording facilities and/or remote reading of the wind direction.

Instantaneous wind speed can be measured with a swinging plate, placed on a horizontal axis **of** rotation, **provided it is exposed perpendicular to the air flow. This can, to a certain extent, be achieved** by **a combination of a directional wind vane with the swinging plate.**

- **Anemometers (Wind velocity)**
  One of the most common instruments for measuring the wind speed are cup anemometers. A small "windmill" device with cups on a vertical axis of rotation, placed in the plane of the wind, will assume an angular velocity, which is a linear (within a large range) function of the wind speed, irrespective of the direction of the wind. The direction of rotation of cup anemometers is always the same. The time when the equilibrium speed is reaohed depends on the moving mass, while the minimum speed required to **start** the **anemometer** is **a function** of **its internal friction.** Cup anemometers with mechanical counting or recording devices are used to measure distances of **wind run** over **larger** time intervals, thus allowing mean wind speed to be caculated for these periods.
  By using electrical devices to count the anemometer revolutions (reedswitches, photo-diodes, etc), the internal friction of the instruments can be decreased, thus allowing for high sensitivities with low starting speeds.
  For measuring instantaneous (subject to the reaction time of the instrument) windspeed, cup anemometers are coupled with D.C. generators, the voltage output of which is a function of the wind speed.
- Propeller and vane anemometers with mechanical or electrical revolution counting devices or DC generators are also used to measure integrated or instantaneous wind speed. As these instruments require to be exposed perpendicular to the air flow, they have to be coupled with a directional vane, or be used under circumstances where changes in the direction of the air flow do not occur. As the angular speed of a propeller is a function of the wind speed and the sine of the angle between the direction of the air flow and the axis of the anemometer, it is posible to obtain wind data in cartesian coordinates by using three anemometers mounted rigidly In the X,Y,Z axis.
- The starting speed of standard cup, propeller and vane anemometers is between 0.5 to 1 m/s but high quality instruments can have threshholds as low as 0.1 m/s.
  (Suppliers: A 1-5, B 17, B 18, D 19, C 3, C 1)
- For very low windspeeds, particles drifting in the air (e.g. soap bubbles, smoke) can be used for qualitative rather than quantitative measurements. Upper air wind measurements use the same method with balloons having a known rate of climb. They are followed optically by theodolite, or by radio or radar waves. The angle from north and the azimuth measured at given intervals enable the calculation of the windspeed and the direction in the upper atmosphere layers.

2.5.222 Static instruments

These types of instruments depend on the hydrodynamlc principles of the dynamic and static pressure in streaming gases and liquids.

- The "Pitot tube", exposed in front of the air flow indicates the dynamic pressure, while a tube exposed parallel to the air flow shows the static pressure. If the pressure difference and the specific mass of the air are known, the windspeed can be deduced.
- With the "Venturi Tube", pressure measurements are taken at places having different cross sections. In the narrow section of the tube the air flow is accelerated, thus creating a lower pressure compared with the one in the wider section. Using a differential manometer, the instantaneous windspeed can be measured.

  Both the Pitot tube and the Venturi tube must be placed parallel to the airflow.

  (Suppliers: A 2)

2.5.223 Instruments using the heat transfer method.

- In "hot wire anemometers", an electrically heated wire is cooled by the air flow. As the amount of heat loss is proportional to the wind speed at normal incidence of the air ourrent, this principle can be used to measure the wind speed.

  The heat loss of the exposed wire results in a temperature difference to an unexposed control wire. This differential temperature is usually controlled with thermocouples.

  Either the temperature difference is used to deduce the speed of the air flow or the exposed wire is heated up to the temperature of the unexposed one, in which case the current required can be referred to the windspeed.

  Vertical mounting of the measuring wires makes this instrument independent of the direction of the wind in one plane.

  Cross wire sensors are used for measurements of turbulent motion to separate the wind components.
- The same physical principle is used in the "hot bead anemometer", where the hot wires are replaced by small heated beads. These have the advantage that the heat transfer is less dependent on the direction of the air current; on the contrary their response is slower.

  The small size and high sensitivity makes this type of anemometer particularly useful for measurements of low wind speeds (down to 0.02 m/s) in plant canopies.

  (Suppliers: A 2, A 4, A 5)

2.5.224 Sonic anemometers.

As the rate of propagation of sound waves depends (independently of the temperature) on the displacement of the air, this oan be used to measure the wind speed.
If the direction of the sound waves coincides with the wind direction, this will result in an acceleration of the speed of propagation or vice-versa.
If the air flow is not in the same direction as the propagation of the wave, the latter will thereby be distorted as a function of the sine of the angle formed between the two directions.
Sonic anemometers are composed of four sets of wave generators and receivers installed on opposite sides of a H-S and E-W axis. Such a setup allows for measurements of average wind speed and direction, within the plane of the detectors. By adding more sets of wave generators and receivers on the vertical axis, this method can be used to build tridimensional measuring devices.
The important instrumentation (wave generators, receivers, signal analysers, computers) and the complete installation of this type of anemometer makes it not only very expensive but also unsuitable for agrometeorological field applications.
(Suppliers: C 2)

2.6 Evaporation

2.6.1 General comments

As the water loss from the surface depends on a variety of meteorological parameters, such as air humidity, temperature, radiation, wind and atmospheric pressure, an accurate determination of this component of the water balance equation causes considerable problems. Although theoretical approaches, based either on the energy budget or the mass transfer method, allow for estimations of this meteorological parameter, direct measurements are often preferred.
However, a common problem to all direct measurements is the representativeness of the installation, relative to the "natural" conditions of the above mentioned meteorological parameters.

The amount of water loss is analogous to rainfall expressed in mm of height of the water column evaporated.

2.6.2 Instruments to measure potential evaporation

2.6.21 Piche evaporimeter

This evaporation gauge consists of a graduated glass tube which is closed on the upper side. To the lower, open side a disc of blotting paper (usually 3cm diameter) is fixed with a clip. Filled with distilled water, the water loss from the paper surface is referred to the evaporative demand of the air. Although it is a cheap and a widely used instrument, the results are of rather limited value in water budget assessments. Hence it should be used only for special applications of a qualitative rather than quantitative nature.

2.6.22 Evaporation tanks

Evaporation pans or open water tanks exposed to the environmental conditions are most commonly used to measure evaporation. A large number of different designs, sizes and methods of installations are used throughout the world. The most commonly used Evaporationpan Types are:

- Class A Pan: Round evaporation pan made of stainless steel or galvanised iron sheets. Diameter: 120.6 cm, Height:25.4 cm. Installation: Horizontally on a wooden gate above the ground appro*. 13 cm height.
- Colorado Sunken Pan: Square evaporation pan size: 92 x 92 cm 46 cm deep, Installation: buried to the level of the ground.

In most cases, evaporation pans have to be protected against animals by wire grids. As the grids modify the windfield around the instrument, it becomes necessary to apply correction coefficients to the measurements.

The water level is controlled with a graduated hook gauge set on a still well, or with a fixed point, to which the pan is refilled each time a measurement is made, with a calibrated graduation.

For continous recording, mechanical water level recorders can be connected to the evaporation pan, or water level gauges with an electrical output can be used with appropriate recording devices.

For special applications, recording evaporation balances (evaporation surface 250 cm), or other devices using porous ceramic discs or spheres have been designed (Evaporimeter "Bellani","Livingstone").

2.6.23 Instruments to measure potential or actual evapotranspiration.

Lysimeters are field tanks of varying types and dimensions containing natural soil and vegetation. Provisions are made which allow a detailed assessment of the water budget inside the tank (by measurements of the precipitation and drainage, weighing the entire tank, soil moisture measurements inside the tank).

In order to meet the requirements for representativity and homogeneity, both in soil structure and vegetation, lysimeters should not be too small in size (surface >3 m^2, depth > 1 m) . Thus, lysimeters require rather a high capital input upon installation and further, to obtain valid research results, important maintenance efforts as well.

(Suppliers: A 1-5, C 6)

<u>Potential Evaporation</u>: Evaporation from a free water surface

<u>Potential Evapotranspiration:</u> Maximum water loss from a surface covered with vegetation, when water supply to the soil is not limited.

<u>Actual evapotranspiration:</u> Water loss from a plant/soil combination under existing meteorological, soil and biological conditions.

2.7 Atmospheric Pressure

2.7.1 General comments

Atmospheric pressure is regularly measured at stations of the international meteorological network for synoptical and weather forecast purposes. In agricultural meteorology, this parameter has no direct importance and it is therefore, not included in the standard observation programme.
However, atmospheric pressure data is required for such computations as air humidity and evaporation. Generally, mean pressure values as given by the altitude/pressure relationship is sufficient, or otherwise data from nearby synoptic stations can be used.

2.8 Soil moisture

2.8.1 General Comment.

The porous structure of the soils (e.g. the space between the solid soil particles) allow the storage of water which can be used either for evaporation or for transpiration by plants. Quantitative assessments of the stored water or soil moisture are therefore important requirements for agricultural and hydrological studies.
The amount of water that can be stored depends on the volume of the "pore space", but however, this will not be fully available for plants because of absorptive and capillary forces exerted by the soil on the water. Thus, both physical and chemical soil properties have an important influence on the soil moisture characteristics which determine the soil-water-plant relationship.

2.8.11 Soil-water-Plant relationships; (Definitions)

2.8.111 Soil moisture content

Soil moisture content is the quantity of water contained per unit (volume or weight) of soil at any given time and is often expressed as a percentage of the dry soil. It is also common to indicate the moisture content in terms of mm of water per meter of soil (mm/m). A relationship between these two measurement terms can be established, but requires information on the bulk density of the soil.

2.8.112 Soil moisture potential

Soil moisture potential refers to the potential energy of soil water with respect to free water. Although the total soil moisture potential has three components, i.e. the gravitational, osmotic and capillary or matric potential, it is often referred to the last one only, especially with regard to its relative importance. (Gravitiational potential can usually be neglected and the osmotic component must only be considered in heavily fertilized or saline soils).

In unsaturated soils, capillary forces create a negative pressure or "matric suction" which is expressed in pressure units. (Pascal; 10$ Pa = 1 bar). Soil suction ranges from nearly 0 Pa in fully saturated soils to 10? Pa in completely dry soils.

2.8.113 Relationship between soil moisture potential and moisture content.

It is possible to convert matric soil potential to moisture oontent, but there is no general relationship for all soils. Furthermore, there is no unique function for any given soil, because due to hysteresis, the relation between soil water suction and soil water content is not single valued. Approximate conversion coefficients for individual soils are therefore generally obtained by field experiments, although laboratory methods do exist as well.

In hydrological and technical applications, data referring to the moisture oontent is usually required, while for plant physiology and hydraulic problems, moisture potential measurements are more important. In agriculture, both quantities are used.

2.8.114 Soil moisture saturation

Soil is considered "saturated" when all or almost all "pore space" is filled with water.

Soil moisture potential:approx. 0 - 1 0 KPa

2.8.115 Field capacity (FC)

The amount of water retained against gravity after drainage of a saturated soil is called field capacity.

Soil moisture potential:approx. 1 0 - 3 0 KPa

2.8.116 Permanent wilting point (WP)

The permanent wilting point describes the soil moisture status where plants cannot remove soil water fast enough against capillary forces, to prevent the leaves from wilting.

Soil moisture potential : approx. 1 - 1 . 5 MPa (These values, however depend to a large extent not only on the soil types but also on the plant physiological characteristics)

2.8.117 Available water capacity (AWC)

The available water capacity indicates the amount of water the soil is able to supply to plants. This amount is determined by the difference between the actual soil moisture content and the moisture content at the permanent wilting point. Accordingly, it has its maximal value at field capacity (in drained soils) and becomes zero at the wilting point. The AWC is usually expressed in mm of water per meter of depth of the soil.

Data on "AWC" is required to assess the length of periods plants can survive without external water supply (e.g. rain or irrigation-) during dry spells or the dry season.

2.8.12 Sampling for soil moisture measurements

With regard to the natural heterogeneity of soil structures and soil moisture regimes, usually large numbers of samples are necessary to obtain a representative estimation of the soil moisture storage in a given area of investigation, both in space and in time. As this may require considerable efforts and financial resources, it is important to establish an apropriate sampling programme, which takes into account a number of factors affecting the soil-moisture regime, such as, topography, soil type, depth of the groundwater table, obstacles and farming practices. Therefore, when planning a measurement programme, it is advisable to make a preliminary investigation to determine the optimal sampling pattern, the necessary number of sampling points, the sampling frequency and of course the most suitable measurement technique.

2.8.2 Soil moisture measurements

2.8.21 Measurement of soil moisture content

Soil-moisture content can be measured directly by using the gravimetric method, the "acetylene" method or lysimeters. Physical changes of soil properties related to changes in the soil-water content are used for indirect measurement methods.

2.8.211 Gravimetric method

The amount of soil water is determined from weighed soil samples which are oven dried at 105 °C until there is no further change in weight (usually 24 hours). The moisture content is given by the weight difference of the sample before and after drying and is expressed in percentage by the weight of the dry soil. As this method requires only simple and cheap equipment (e.g. auger, balance, oven) and gives direct results, it is the most widely used one and also the one used to calibrate instruments in other methods.
One major disadvantage is the effort required to obtain the necessary number of samples to yield significant moisture averages in soils with big variations in composition and texture or low absolute water content. The other is the fact that, the sampling disturbs the soil which makes this method unsuitable for continuous monitoring.

2.8.212 "Acetylene" method

This technique to measure the water-content of a fine or sandy soil sample is based on the principle that water will react with calcium carbide to form acetylene gas and that the quantity of gas produced is proportional to the amount of water (provided that there is sufficient calcium carbide available) in the sample. When this chemical reaction is carried out in a tight pressure cylinder, the quantity of gas formed can be measured with a pressure gauge. Appropriate calibration of the gauge allows direct reading of the water content in percentage.
Equipment using this method has proved to be very useful for field surveys of soil-moisture, where immediate results are required.

2.8.213 Lysimeter method

Lysimeters are containers filled with soil and where provisions are made to control the weight either occasionally or continuously. The changes in weight can be referred to changes in total soil moisture in the lysimeter. Because of the great cost of constructing a lysimeter capable to simulate natural conditions, this method is only practicle for special small scale experiments.

2.8.214 Neutron method

The neutron method is based on the principle that, high-energy neutrons emitted from a radioactive sub-surface source are slowed down mainly by the hydrogen atoms of the free soil water. Thus, the density of slow neutrons in the vicinity of the source is nearly proportional to the soil-moisture content within 15-35 cm of the probe.

These soil-moisture probes consist of a radioactive high-energy neutron source and a slow neutron detector; connected by cable to an electronic measurement device, the probes are inserted into the soil through previously installed access tubes. Once these access tubes are installed, soil-moisture profile measurements can be repeated without further disturbances of the soil structure, which makes these instruments particularly suitable for long term monitoring. However, the low accuracy of this method in the top layers of the soil constitutes a certain disadvantage in agricultural applications.

To obtain absolute values of the soil-water content from neutron probe measurements, a site specific calibration using the garvimetric sample method is necessary.

With regard to the great advances made in recent years in inproving the Neutron moisture-meter design, this method is now considered to be the most accurate and efficient indirect method for soil-moisture measurements.

2.8.215 The Gamma absorption method

A radio-active source inserted into the soil through an access tube emits gamma rays which are partially absorbed by the soil. The attenuation of the radioactive intensity is measured by a detector inserted into a second parallel access tube. This method does not measure soil-moisture directly but uses the effect that different soil-water contents produce different soil densities.

As many technical problems have not yet been solved satisfactorely, the application of this method has not been successful in widespread field applications.

2.8.216 The heat conductivity method

Another indirect method to estimate the soil-moisture content involves the relationship between soil-heat conductivity and water content. To establish this relationship, detailed soil specific mesurements of the heat conductivity and calibrations against the soil-water content have to be carried out. Although, once this relationship is established, simple soil-temperature measurements could be used to derive the soil-water content, little research has so far been done to develop this method.

2.8.22 Mesurement of soil moisture potential

2.8.221 The tensiometer method

Tensiometers are used for direct mesurements of soil-moisture suction in the range of 0 to 100 KPa. The instrument consists of a porous oup filled with water and buried in the soil. The movement of the water to the soil creates a negative pressure or suction, the equilibrium value of which can be measured by a vacuum gauge. This vacuum gauge can either be a directly read manometer (e.g. Bourdon or mercury type) or a strain-gauge based pressure transducer used together with an electrical indicator or recording device. When the matric suction approaches the value of the atmospheric pressure, air enters the porous cups and useful readings can no longer be made. Therefore, tensiometers may be useful in irrigation oontrol, but are of limited value for other agricultural applications, except in sandy soils where the soil-water suction remains within the available range of operation. Another inconvenience of the tensiometer is that it often stimulates root growth in the vicinity of the cup (higher soil-moisture) which decreases the representativeness of the measurement.

2.8.222 The psychrometric method

This indirect method of measuring the soil-water potential uses a small chamber of porous material which is buried in the soil. The equilibrium air humidity inside this chamber is taken as a measure for the soil-moisture potential. To obtain the air humidity inside the chamber, Peltier psychrometers are used. (See section 2.2.224) To convert the obtained air humidity values to soil-moisture potential, calibration curves have to be established empirically. As this involves rather complicated measurements and procedures, this method is so far not very wide spread.

2.8.223 Electrical resistance blocks

The electrical resistance between electrodes embedded in a block of water-absorbent material varies with its moisture content. If such a block is brought in good contact with the surrounding soil, a moisture equilibrium between the soil and the block will establish and the resistance measured between the electrodes can be empirically related to the soil moisture potential. Similarly, a calibration against the gravimetric method may allow the conversion of electrical resistance values to soil-water content.

Individual calibrations should be made for each block and every particular soil, but the calibration procedure may be simplified provided the blocks are sufficiently homogeneous. However, errors are also encountered because of the hysteresis between the wetting and the drying curve, the unstability of the calibration in time, and other influences such as the presence of soluble salts in the soil and temperature coefficients.

Despite these restrictions, electrical resistance blocks appear to be quite suitable for investigations, with an emphasis on soil-water changes in time, rather than on absolute values. For such purposes, the probes can be buried in great numbers at various sites and depths. The electrical output can easily be used for remote reading and recording without further interference in the soil structure. This and the comparatively low cost of both the probes and the measurement equipment have contributed to the wide use of this method. There are various water-absorbent materials which are used to construct these soil-moisture blocks;

- Gypsum blocks are most useful at water potentials ranging from 100 KPa to 1.5 MPa, while in wetter soils these units tend to disintegrate too quickly.
- Nylon units consist of stainless steel electrodes separated and wrapped with three pieces of nylon fabric and they are assembled in perforated stainless steel casings. They are sensitive at higher soil-water contents than the gypsum units (approx. 10 KPa) but require special care when installing, in order to assure correct soil-probe contact.
- In fiber glass blocks, the electrodes are separated by fiberglass cloth but otherwise they are similiar in design and characteristics to the nylon units.
- To reduce the shortcomings of the above resistance blocks, (low sensitivity at high water contents, bad contact with the surrounding soil etc.) various units of combined materials have been designed and tested.

RECORDING OF METEOROLOGICAL ELEMENTS

General

Meteorological data can be obtained by direct readings of measuring instruments, and by instruments providing a continuos record of the parameter over time. Instruments for direct readings are usually simpler and cheaper than the latter, but the type of information obtained is of instantaneous character and the amount of data which can be collected depends to a large extent on the availability of trained staff. Recording instruments have been designed for practically all meteorological parameters using various physical principles as described in the previous sections. Generally they can be divided into mechanical and direct recording Instruments and in electrical recording assemblies.

Calibration of Meteorological Instruments

Just as any physical measuring instrument, meteorological instruments have to be calibrated to meet comparability requirements. Initial calibrations are usually made by the supplier of the equipment, but many instruments need to be checked or recalibrated after transportation and installation. Recalibrations are a "must" after repairs or replacement of essential parts of the instruments. As the ageing process in most instruments affects the "zero" level and eventually the sensitivity, it is advisable to recalibrate at regular intervals to maintain the equipment's accuracy and the comparability of data obtained. The most common way to calibrate meteorological instruments is by comparison with standard instruments. These are usually kept at national centres and checked from time to time against international standards. However, certain instruments and high-precision calibrations sometimes require rather sophisticated calib- ration equipment and have, therefore, to be sent to specialised laboratories.

Manual Recording of Meteorological Data

Observation with instruments which do not have self-recording devices are made by individual readings at given observation times. These readings are written into an appropriately designed observation book. (The temptation to note field data on loose leaves and to transfer it later to the observation books should be avoided). This note-book has to be designed in accordance with the observation programme and should, in addition, provide space for the application of calibration coefficients to actual measurements and for basic calculations (e.g.humidity, averages, tools etc). For stations which do not have self-recording instruments, the observation book constitutes the basic document and it is extremely important that it is properly kept and duly completed in accordance with the initial instructions. From this basic document, data can be transferred to monthly summaries and be extracted for special analyses.

For stations which have self recording instruments, it is nevertheless important to maintain an observation book although it will serve for control purposes rather than for direct data recording.

3.4 Mechanical Recording Instruments

As already mentioned, there are physical principles available for measuring meteorological parameters, which result in changes of the length of the sensing element or where the sensor exerts a force. This can be transmitted mechanically with or without amplification to a recording system, which is usually based on a clock driven paper strip, either of the drum or endless belt type. With regard to the magnitude of the movements and/or the exerted forces and the technical possibilities for mechanical amplification, mechanical recorders have a limited accuracy and the distance between the sensing element and the recording device has to be kept small. The main advantage of mechanical recorders are the relatively low cost, easy maintainance and their independence from an external power supply (except that the clock drives have to be wound up at regular intervals.)

The variations over time of the parameter to be measured are displayed in graphical form on diagram chart. Generally, these charts have an appropriate time unit imprint to facilitate the analysis. As in most cases this chart analysis (the transfer of graphical "values" to numerical data) is carried out manually and considerable "manpower" input has to be considered; this, however, depends on the type of record and the details requested.

3.5 Electrical Recording Instruments

Electrical recording assemblies consist of a sensor or detector component and the recording device. As electrical signals can be transmitted over bigger distances without major problems, such set-ups are particularly recommended where "remote" measuring is required, to minimise the interference with natural environmental conditions. A further advantage is the amplification possibilities for electrical signals by electronic circuits to obtain high accuracy outputs. The power supply, on the other hand, represents a frequent drawback for electrical measurement units in field applications.

3.5.1 Electrical sensors

For electrical measurement assemblies, sensors are used which produce electrical signals "ipso facto" (voltage, differences in potential, resistance) to be referred to the parameters under consideration, or detectors are used where initial mechanical "signals" (longitudinal changes, rotations etc.) are transformed into electrical ones by appropriate devices (potentiometer, switches ,etc).

2 Recorders

Depending on the signal output of the sensor, the following types of recorders are used:

- null-balance potentiometric recorders to amplify d.c. voltage signals
- galvanometric recorders, with or without amplification, for current signals
- Wheatstone bridges for electrical resistance measurements

Single or dual channel recorders are mainly constructed as continuous line recorders. In multiple channel recorders, (6-12) the different sensors are consecutively connected (by switches or relays) to the measuring unit. Equipped with a multicolor printing device, these records result in dotted lines. The switching interval can be determined, but has usually a lower limit, depending on the mechanical Inertia of the switching systems and the measuring and the printing device.
As with the mechanical recorders, the measurements result in graphical displays on a diagram chart, which again, usually need to be analysed manually for further interpretations and/or computations.
To reduce the chart analysis requirements, electrical recorders with integrators have been designed to integrate signal inputs over a given time interval. To obtain mean or total values of continuous observations directly, some of these integrators allow for a digital outprint of the values, which facilitates the anlysis.

Electronic Measurement and Recording Devices

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 meteorological measurement purposes. While on the sensor side, this technology has not resulted in major changes, it has largely affected the measurement and recording instruments, including data handling and analysis.

1 Instruments for direct readings

Together with electrical sensors, the use of integrated circuit chips has allowed the construction of highly sensitive, low weight, digital read out instruments for most of the meteorological parameters. Their main advantage compared to the classical instruments is the possibility of the built in "conversion" from electrical sensor outputs to technical units, including complex linearizations.

5.6.2 Electronic recorders and integrators

Electronic integrators with very low power consumption and considerable electronic memory capacity for data storage are available for measurements of radiation, wind, rain and other elements. The stored data can be recalled from the memory manually, but transfer possibilities to magnetic charts or tapes are frequently built in features of this type of equipment. The power requirements of a few MW allow battery operation over long periods, which makes these integrators in connection with appropriate sensors, particularly suitable for use at remote observation sites.

3.6.3 Data loggers

The subsequent use of integrated electronic circuits and micro- processor chips has led to the construction of automatic environmental control systems and automatic weather stations.

Simpler systems do provide for sensor excitation, the conversion of sensor readings into technical units and the recording of this data on magnetic tapes, from where it can be transferred to computers for further analysis (calculation of averages, totals, frequency distributions, et). More complex systems can process the input data (including averaging, totaling, etc.) in accordance with user-defined programmes, before storing it on magnetic tapes, putting it out on paper prints, or transferring it to network centres through telecommunication lines. The advantage of such a system is a higher resolution through higher sampling frequencies. However, with regard to the products offered, there is a wide range of features available for data loggers to meet the user requirements in the field of meteorological and environmental measurements.

It is admitted that complete environmental control and data acquisition systems will require considerable capital input, but the advantages offered by these systems, compared to "conventional" measurement equipment, will, in many cases, justify the investment costs for data loggers.

REFERENCES

W H O : Guide to Agricultural Meteorological Practices
WMO Nr.134, 1981 Geneva

W H O : Guide to Meteorological Instrument and Observing Practices.WMO Nr.8 Geneva Fifth Edition 1983

F A 0 : Agrometeorological Stations,Irrigation and Drainage Papers Nr.27 Rome 1976

F A 0 : Irrigation and Drainage Paper 1 Rome 1972

J.SEEMANN.Y.I. CHIRKOV.J.LOMAS.B.PRIMAULT : "Agrometeorology"
Springer-verlag 1979

OTHERS : Technical information as provided by various leaflets from equipment suppliers.

APPENDIX

LIST OF COMPANIES SUPPLYING METEOROLOGICAL EQUIPMENT

General comments

Meteorological equipment - conventional and modern electric and/or electronic sensors, as well as recorders and data acquisition systems - are produced by big international companies, as well as by small specialised manufacturers. The latter, especially cooperate in many cases with national research institutes, in the development of new instuments, or get new devices tested and certified by officially recognized institutions. Equipment for special applications are often developed in research laboratories of national meteorological services or agricultural institutions and are not produced commercially and are therefore difficult to obtain.

With rising technological standards, many companies offering meteorological measuring systems tend or need to use components produced by other specialized manufacturers. This applies, in particular, to modern electronic sensors, recording and data acquisition systems used in agricultural meteorology.

It frequently happens that requirements (sensitivities of sensors, power supply, environmental conditions of operation, type of recorder output) for measuring programs cannot be met by equipment offered by a single company. So it may become necessary to buy components from different suppliers and to "assemble" the measuring plant in accordance with the particular requirements. In this case, frequent problems are the "what to buy where", the assessment of the compatibility of different components, the installation "in situ" and the calibration of the equipment.

Another aspect which should be considered when acquiring an environmental measurement unit is the data analysis. It is advisable to check on the compatibility of the data output and the data processing facilities, either already existing or envisaged for the set-up.

The list of suppliers below is given in an attempt to assist in addressing requests for detailed descriptions and quotations of meteorological equipment, but must by no means be considered to be complete.

A useful publication with further references of suppliers of equipment used in meteorology and in plant/crop studies is "Equipment for Field and Laboratory studies of whole Plant and Crop Photosynthesis and Productivity Research"-M.J.Bingham and S.P.Long, Technical Support unit, Dept. of Biology, University of Essex.

A. SUPPLIERS FOR A COMPLETE RANGE OF METEOROLOGICAL INSTRUMENTS

A1. Cassela
London Ltd
Regent House
Britannia Walk
London, N1 7ND
U.K. (Telex 261641)
Products: Complete range of conventional meteorological instruments

A2. Wilh. Lambrecht
P.O. Box 76
D - 3400 Gottingen
Germany
(Telex 96862)
Products: Complete range of conventional instruments, electrical sensors and recorders; AWS.
Speciality! Wind measuring instruments

A3. S.I.A.P.
Vid. Massarenti 412
I - 4040100 Bologna
Italy
(Telex 511197)
Products: Complete range of conventional and electrical met. instruments including AWS.

AM. Weather Measure
Systron Donner
P.O. Box 41257
Sacramento
CA. 95841, (Telex WUD 377-310)
U.S.A.
Products: Complete range of conventional and electrical meteorological instruments; AWS, commercializing as well as instruments from other manufacturers.

A5. Weatheronics
P.O. B. 41039
Sacramento CALIF. U.S.A.
(Telex: 377-395)
Products: Complete range of conventional and electrical meteorological instruments; AWS, commercializing as well as instruments from other manufacturers.

B. SUPPLIERS WITH A RESTRICTED RANGE OF PRODUCTS

- Sunshine and Radiation Equipment

B1. The Eppley Lab. Inc.
12 Sheffield Ave
Newport
Rhode Island 02840
U.S.A.
Products: Complete range of Radiation Instruments.

B2. Haenni Instr.
Ch - 3303 Jegenstorff
Bern
SWITZERLAND
(Telex 32386)
Products: Sunshine Detectors

B3. Li-Cor
P.O. Box 4425
Lincoln
Nebraska 68509, TWX 910 621 8116
U.S.A.
Products: Instruments for biological and environmental sciences
Speciality: Photo electrical and Radiation instruments

B4. Middleton Instruments
P.O. Box 442
South Melbourne
Vic. 3205
AUSTRALIA
(Telex: 32486)
Product: Radiation instruments (Thermopile and Photo electric instruments).

B5. Ph.SCHENK
P.0.B.3
A-1212 Wien
AUSTRIA
Products: Radiation sensors and recorders Air humidity measurement equipment
Speciality:Radiation sensors (Pyranometers and Pyrradiometers)

B6. Swiss Teco Instr.,
Ctegweg, Eichenwies
Ch-9463
Oberrient
SWITZERLAND
Products: Radiation Instruments
- Soil and plant water potential instruments

B7. P.M.S. Instruments Co
2750 N.W. Royal Oaks Drive
Carvallis, Oregon 97330
U.S.A.
Products: Plant water potential instruments

B8. Soiltest Inc.
2205 Lee Street
Evanston Illinois 60202
U.S.A.
(Telex 72-4496)
Products: Large range of testing instruments for agricultural and soil sciences; some conventional meteorological equipment.

B9. Wescor Inc.,
459 South Main Street
Logan Utah 84321
U.S.A.
(Telex TWX 910 971 5870 WEC0R0
Products: Water Potential systems.

B10. Westgate Agronomics
1015 Pitner Ave
Evanston
Illinois 60202
U.S.A.
(Telex - 681422)
Products: Soil measurement instruments.

-Miscellaneous (WIND, RAIN, HUMIDITY, TEMPERATURE ETC)

B11. Benoit Et Freres
Rue Marcellin Berthelot
F - 95140 Alfortville
France
Products: Direct reading raingauges (400 cm^2)

B12. Environmental Measurements Ltd
Raleigh Park Road
Oxford 0X2 2BB
U.K.
Products: Rain Recorders (Logger types)

B13. Gulton
The Hyde
Brighton
Sussex BN2 4JU (tlx:87172)
England
U.K.

B14 Th. Haywood and Sons Ltd
33 Avery Hill Road
New Eltham
London SE 9 2BW
U.K.
Product: Rain gauges and Recorders.

B15. Kroneis
Iglaseegasse 30-32
A-1191 Wien
AUSTRIA
Products: Met. Sensors for Wind, Rain, Humidity Pressure.

B16. J.R.D. Merrill
Speciality Equipment
R.F.D. Box 140A
Logan Utah, 8M321
U.S.A.
Products: Special Psychrometers

B17. Met. One Inc.
P.O. Box 1937
Grants Pass
Oregon 97526
U.S.A.
Products: Wind sensors

B18 R.W. Munro
Cine Road
Bounds Green
London N11 2LY (tlx:24130)
England
UK
Products: Complete Range of wind measuring systems, rain gauges, barometers.

B19. Northumbrian Energy Workshop Ltd
Tanners Yard
Gilsgate Hexham
Northumberland
U.K.
Products: Wind measurement equipment
Speciality: Wind logger

B20. Paulstra-sites
61 Rue Marius Aufon
F-92300
FRANCE
Products: Meteo Screens (Plastic)

B21. Precis Mechanique
14 Rue Denis Papin
F-95870 Bezons
FRANCE
Products: Conventional Met. Equipment Barometers, Rain recorders.

B22. J. Richard
116-120 Quai de Bezong
F-95100 Argenteuil
FRANCE
Products: Conventional Temperature, Humidity, Pressure-recorders.

B23. Thermo Schneider
Postfach 58
D-Wertheim/Main 1
WEST-GERMANY
Products: Liquid in Glass Thermometers.

B24. Freres Thibault
F-77190 Danmarie Les LYS
FRANCE
Products: Thermometers.

B25. Degussa
Hanau
WEST-GERMANY
Products: Thermometers
Speciality: Platinium resistance thermometers.

B26. KIPP - ZONEN
Netherlands
Products: Radiometers, Pyranometers

C. SUPPLIERS FOR AUTOMATIC WEATHER STATIONS AND RECORDERS.

C1. Austrian Research Center
Seibersdorf
A-2444 Seibersdorf
AUSTRIA
(Telex 0144353)
Products: AWS, Mobile and Stationary; Using components from other manufacturers

C2. Campbell Scientific Inc.
P.O. Box 551
Logan Utah 84321
U.S.A.
(Telex 453058)
Products: Complete AWS Systems, (using components from other suppliers.
Speciality: Measurement and Control systems (Data loggers and data Processors)

C3. Cimel Electronique
13 Bvd Rochechouart
F-7500
Paris
FRANCE
Products: Meteorological Data, Acquisition system.

C4. Didcot Instruments Ltd
Station Road
Abington
Oxon
Ox 14 3LD
U.K.
Products: AWS using components from other manufacturers.

C5. Vaissala O.Y.
PL 26 SF - 00421
Helsinki 42
Finland
(Telex 122832 Vsala SF)
Products: AWS including complete data transfer and processing. (uses partly components from other suppliers)
Speciality: Capacitive Humidity Sensor

C6. Compagnie Industrmelle Radioelectrique
Bundesgasse 16
CH-3001 BERNE
SWITZERLAND
Products: Automatic weather stations, Lysimeters

D. RECORDERS

D1. Rimco
Analite Pty. Ltd
P.O. Box 11
Oakleigh
Vic
AUSTRALIA 3166
(Distributed in AUS by "Medos Company Pty Ltd)
Products: AWS
Speciality:Self contained and rugged recorders for up to 12 month operation.

D2. Grant Inst.,
Barrington
Cambridge, CB2 5QZ
England (Telex 81328)
U.K.
Products: Chart recorders - Cassette data recorders - Memory recorders.

D3. Leeds and Northrup.;D4.Philips.;D5 Siemens.; and others.