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Convention on Long-range Transboundary Air Pollution

International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests)

MANUAL

on

methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests

Part IX

Meteorological Measurements

Version 2020-1

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CONTENTS

1 Introduction

Meteorological variables affect composition, structure, growth, health and dynamics of forest ecosystems. The measurement of meteorological data at forest monitoring plots is essential for the interpretation of climate change effects. The magnitude and changes in time of the meteorological variables should be assessed as accurately as possible in order to be able to use the meteorological data as explanatory factors of the many other observations made at the Level II plots.

Meteorological data from national weather stations are in most cases not sufficient for representing forested areas. Geographic features affect airflow and limit the representativity of the meteorological data by spatial heterogeneity (e.g. location, altitude, exposition, slope).

Meteorological monitoring at the Level II plots provides local, inside forest area information on the basic driving and influencing factors for forest ecosystems. Meteorological data are used when deriving fluxes and deposition of air pollutants to forest stands, as well as the water- and element cycles, the vitality, growth and phenology, and the crown condition of trees.

2 Scope and application

This part of the manual aims at providing a consistent methodology to collect high quality, harmonized and comparable meteorological measurements for the intensive Level II plots of the monitoring programme. Harmonization of procedures is essential to ensure data comparability. To have their meteorological data used in the international database and evaluations, National Focal Centers and their scientific partners participating in the UN/ECE ICP Forests programme should follow the methods described here. Table 1 gives an overview on variables, reporting units, data quality and plausibility limits.

Table 1: List of mandatory and optional daily meteorological variables and their properties

Variable	Level I	Level II	Level II core	Repor-ting unit	DQO	Measurement resolution
Precipitation	no	m**	m	mm	the larger of 5 % or 0.1 mm *	0.3 mm
Air temperature	no	m**	m	°C	0.2 °C *	0.1 °C
Relative air humidity	no	m**	m	%	3 % *	
Global radiation	no	m**	m	W/m²	0.4 MJ/m² or 5 W/m² for ≤ 8 MJ/m² or ≤ 93 W/m²; 5% for > 8 MJ/m² or > 93 W/m² *	10 W/m²
Wind speed	no	m**	m	m/s	0.5 m/s for ≤ 5 m/s, 10% for > 5 m/s *	0.1 m/s
Wind direction	no	m**	m	angular degree	5.0 ° *	1.0 °
Soil Moisture: matric potential	no	o	m	kPa	± 0.5 kPa	
Soil Moisture: water content	no	o	m	Vol%	± 3 %	
Soil temperature	no	o	m	°C	0,2 °C	0.1 °C
Stand Precipitation (Throughfall and Stemflow)	no	o	m	mm	same definition as in Manual Part XIV - Depositon	0.3 mm
UV-b-radiation	no	o	o	W/m²	no specification available	
Atmospheric pressure	no	o	o	hPa	0.3 hPa *	0.1 hPa

DQO = Data Quality Objective (minimum acceptable accuracy) for measurements
* According to WMO 2008 No. 8
** at 10% of the plots
m – mandatory, o – optional

Meteorological measurements in the Intensive Monitoring Programme (Level II) are mandatory on at least 10 percent of the Level II plots of a country but are recommended on all Level II plots.

3 Objectives

The main objectives of meteorological monitoring are:

1. Collect data to describe the meteorological conditions and changes at the Level II plots;
2. investigate the meteorological conditions and contribute to the explanation and relationship to the state of the ecosystem;

3. identify and investigate stress indices and factors for trees on the plot like extreme weather conditions and events (e.g. frost, heat, drought, storms, floods);
4. build-up long time-series that fulfil requirements of further analysis (statistics and modelling) of ecosystem responses under actual and changing environmental conditions (e.g. water balance calculations, water availability for the stand, growth, nutrient cycling) as well as integrated evaluations in various aspects of the Level II plots (e. g. crown condition assessment, deposition, increment).

In addition to the fulfilment of the above-mentioned objectives, meteorological data are used for calculation of stress indices and water balance calculations. The meteorological data are also required for integrated evaluations in various aspects of the Level II plots (e. g. crown condition assessment, deposition, increment). A preliminary overview of applied evaluation methods and models is attached as Annex 4.

4 Location of measurements

Aspects of a well-run meteorological monitoring system include correct installation, use of proper equipment, correct instrument siting, correct maintenance and calibration practices together with frequent data review.

4.1 Measurement design

4.1.1 Location of the meteorological stations

Selecting the proper site for a meteorological station is as important as selecting the proper sensor for a particular application. Thus, placement of the station and of the sensors should be given first consideration. All meteorological measurements are affected by the surface type and roughness, the soil moisture, the regional topography, and obstacles nearby. The measurement of meteorological variables in forests is comparatively complex due to the three-dimensional structure of stands and the dynamics of growth during the rotation period. Therefore, meteorological measurements in forest stands should take into account both horizontal and vertical heterogeneity (Goldberg et al 2012). All mandatory meteorological variables should be measured on towers or on open fields to characterize the weather conditions that affect the canopy directly. Data from existing neighbouring meteorological stations may be used for the Level II purpose, provided that they are representative for the site. However, to better represent the specific climatic conditions of forested areas and to avoid errors due to the large spatial variability of meteorological data, the following criteria apply:

- It is recommended to carry out the meteorological monitoring inside the forest area concerned.
- The area where meteorological measurements are conducted should be free from obstacles such as trees, and steep slopes: ideally the meteorological monitoring at the Level II plots is located in an open field area or a clearing of the forest close to the plot.
- The maximum distance to a monitoring plot should not exceed 2000 metres.
- In addition, altitude and exposure should be as comparable as possible to the forest monitoring plot

To measure the situation under the canopy the small-scale variability of forest meteorological variables under the canopy must be taken into account. This is particularly

important for solar radiation, wind speed, stand precipitation and soil moisture (Goldberg et al 2012).

4.1.1.1 Measurements in the open field/large clearings or above the canopy

In general, the measurements (with the exception of soil temperatures, soil moisture and stand precipitation) may be taken at an open field station within the forest area in close proximity to the stand of the Level II plot. The open field measurements should be performed if possible from a standard (10-m) tower or mast. Sensor heights are presented in section 5.1.2.2. It is recommended that the distance from the measuring point at open field stations to the surrounding stands or other obstacles should be at least twice the height of a mature tree/obstacle. Conditions in a forested area make it difficult to fulfil this recommendation; still due to the large spatial variability of meteorological variables, it is better to measure near the plot even under non-ideal conditions, than far from it fulfilling all requirements. It is then important to report on the siting conditions e.g. to give a graphical description of the horizon and its change by the years (make a horizon sketch or use an horizontoscope).

Another option is to perform the measurements above the forest canopy at a tower inside the forest. . If a new tower for meteorological measurements is planned, it should be noted that the forest will exert a drag on the air which is larger than over open land. The meteorological measurement should be made at a distance from the forest edge where the air masses have the characteristics of the forest area. Hence, one should take the distance of traverse across the uniformly rough canopy surface (fetch). Commonly applied fetch to height ratios are 20:1 (Gash, 1986) and up to 100:1 (Munro, 1975; Oke, 1987). The height is here defined as the height of the vegetation h minus the zero plane displacement height d (approximatively between 0.5 and 0.8 times the vegetation height, for closely spaced stands Oke (1987) gives d=2/3*h). The zero plane displacement height d may be visualized as representing the apparent level of the bulk drag exerted by the forest on the air (Oke 1987). The measurement tower should be so high, that all meteorological quantities measured belong to the local surface of the forest canopy. Fritschen & Gay (1979) give as a lower limit for the height of a tower hTower=d+5*z0 (z0: roughness length approx. 1/10*h). Normally tower heights range between 1.5*d (if d is larger than 0.6 times the vegetation height) up to 2*d. For the fetch then a traverse distance of 100*(htower-d) [in m] is required. If existing towers from other projects were used, siting conditions (e.g. fetch, tower and vegetation height and its change by the years) should be reported in detail.

4.1.1.2 Measurements in the stand

The meteorological measurements inside the stand are directly related to the measurements at the intensive Level II plots. Relevant meteorological variables inside the forest at or near the Level II plot are any radiation variables to describe the light dynamics, soil moisture to monitor the plant available water, soil temperatures, and stand precipitation (technical details in Annex 1). Various methods can be used to take spatial variability into account (Goldberg et al 2012):

a. systematic distribution of several, continuously registering sensors at fixed measuring points
b. mobile measuring devices that drive through the stand in a suitable manner
c. fixed meteorological base station in addition with temporary measurements at a close-meshed grid

4.2 Measurement equipment

Technical equipment, sensors and their placement are recommended to be in accordance to international World Meteorological Organisation standard (WMO - No. 8, No. 100, No. 168, see Annex 1), and should be compatible with national weather service networks. Measurement recommendations are described in Annex 1.

4.3 Data collection, transport and storage

Whenever possible automatic stations with quasi-continuous sensing of the meteorological variables should be used and data should be recorded by means of a data logger. The submission of data should be organised by downloading of records or exchange of memory cards. Afterwards the raw data should be preserved in a proper data base. For details of data handling see chapter 6.

5 Measurements

5.1 Variables measured and reporting units

Meteorological variables as air temperature, relative air humidity, precipitation, wind velocity and direction, and global radiation are mandatory measurements of the ICP Forests programme. These variables are essential for the calculation of deposition of air pollutants to the sites and for the derivation of percolation from the rooting zone. Table 1 presents the mandatory and the optional variables of the ICP Forests monitoring programme. For some variables, national standards are set as for measurements of precipitation. It is recommended to test and report the eventual resulting differences in e.g. precipitation amounts against the reference height. The height requirements should be in accordance with the WMO-Guidelines (1996) to ensure comparability with data from official weather stations and other monitoring sites.

Mostly a daily resolution of meteorological data is sufficient. Therefore, it is mandatory to report daily (00:00 – 24:00) means (arithmetic average of the whole day) or sums, respectively. But, because some models require hourly data it is also highly recommended to submit hourly (x:01 – x+1:00) means (arithmetic averages of the whole hour) or sums, respectively.

5.1.1 Mandatory variables at Level II plots

Short technical descriptions of the mandatory variables are given in the following sections. Descriptions of instruments and optional variables are placed in Annex 1.

5.1.1.1 Air temperature and relative air humidity

Air temperature and humidity sensors should be installed in a properly ventilated solar radiation shield for accurate ambient measurements. Mast-mounted sensors are usually positioned optimally at a height of 2 metres above ground level, on the north side of the mast.

Air temperature and relative air humidity must be reported as mean (arithmetic average of the period), minimum (lowest value of the time period) and maximum (highest value of the period) values whereas the units are degree Celsius (°C) for air temperature and relative percentage (%) for relative air humidity, respectively.

5.1.1.2 Wind speed and direction

Wind observations are most sensitive to shelter by high roughness or by obstacles, because the length of obstacle wakes is at least 10 times the obstacle height. The quality of wind sensors can therefore be diminished by poor exposure to local topography.

Wind sensors should be located over open terrain, if possible at standard height of 10 m above the ground to provide ambient wind monitoring. Open terrain means that the distance between the wind sensors and the nearest obstruction should be at least twice the height of a mature tree/obstacle. This is to avoid monitoring the wind turbulence created by the obstacle ("wind-milling“ of the direction vane and measurement of artificial gustiness by the wind speed sensor). This may, as mentioned earlier, be difficult to achieve. It is thus again important to report on the siting. It is not recommended to measure wind speed and direction in a clearing, unless the above mentioned distance requirements for open field are fulfilled. When measuring above the forest canopy the requirements of fetch must be fulfilled (see chapter 4.1.1.1).

For wind speed mean (arithmetic average of the period) values are required. To register also squalls additionally the maximum (highest value of the period) of wind speed should be reported. For wind speed the unit is meter per second (m/s). The wind direction has to be reported as the prevailing wind per time unit using the mode of all measurements of the time unit. The wind rose will be split into 12 sections of 30° starting from 15° onwards. The north direction is defined as 360°. The most frequent wind direction is reported by its middle value e.g.: 30° = the sector 15° - 45°, 60° for the sector 45° - 75° etc. and 360° for the sector 345° - 15°.

5.1.1.3 Global radiation

Direct solar radiation plus diffuse sky radiation to a horizontal plane surface comprising the spectral range from 0.3 to 3.0 µm are referred to as global radiation. It is measured by pyranometers. The pyranometers may be mast or pole mounted. The sensors should be mounted away from shadows, reflective surfaces, and sources of artificial radiation. Mounting the sensors on the southern part (either crossarm or sensor mounting arm) of the tower or the mast should minimise shading from other weather station structures. The height of the sensor is not critical for the accuracy of the measurement. However, sensors mounted at heights of about 2 m are easier to level and to clean.

The daily power of global radiation will be stated as the 24 hour (00:00 – 24:00) mean value (arithmetic average of the whole day) and maximum of the day both in Watt per square meter (W/m^2). From this the daily energy sum in mega joule per square meter ($MJ\ m^{-2}\ d^{-1}$) could be calculated by multiplying by 0.0864 [$M\ s\ d^{-1}$].

$$E_{gr}\ [MJ\ m^{-2}\ d^{-1}\ ] = P_{gr}\ [W\ m^{-2}] * 0.0864\ [M\ s\ d^{-1}]$$

where

E_{gr} = daily sum of global radiation energy

P_{gr} = daily mean of global radiation power

If hourly data are submitted, mean values (arithmetic average of the whole hour) of global radiation power in W/m^2 have to be reported.

5.1.1.4 Precipitation

Precipitation is also measured as a part of the deposition programme but with a frequency of up to several weeks. It is recommended to measure precipitation intensity more frequently e.g. to estimate evapotranspiration and to get information about the interception process.

It is not recommended to use heated rain and snow sensors due to evaporation loss leading to an underestimation of the amount of rain. The precipitation gauges should be located in a relatively flat, open area. Specific windshields can be helpful to diminish the wind-induced failure for more accurate catch. The orifice of the gauge must be in horizontal plane, open to the sky.

Precipitation will be stated as sum value in millimetre (mm).

5.1.2 Technical recommendations

5.1.2.1 General technical recommendations

Most existing meteorological stations under the Level II programme use automatic stations with quasi-continuous sensing of the meteorological variables.

Data are usually recorded by means of a data logger, which is installed in a box to prevent electronics from high humidity, preferably on or nearby the mast. The whole equipment should be protected against lightning and all the cables should be shielded against electromagnetic fields. Also waterproof cable connections should be guaranteed by using high quality industrial standards. The data logger should function reliably even at extremely low temperatures to minimise data loss. The power supply can be ensured by batteries connected to solar and/or wind generators.

On the Level II plots where meteorological observations are made manually it is recommended that automatic measurements are introduced whenever possible.

5.1.2.2 Sensor height

Standard height requirements are presented in Table 2. The mentioned heights are in accordance with WMO-Guidelines (1996) to ensure comparability with data from official weather stations and other monitoring sites. Some national standard heights exist for precipitation measurements. The height of the gauge orifice above the ground should be as low as possible because the wind velocity increases with height, but it should be high enough to prevent splash from the ground. A height between 0.5 and 1.5 m is used in many countries. In those areas that have little snow and where the surroundings are such that there is no risk of the ground being covered by puddles, even in heavy rain, precipitation is often measured at a height of 0.3 m. Where these conditions are not satisfied, a standard height of one metre is recommended. The resulting differences in precipitation amounts against the reference height should be tested and reported.

Table 2: Recommended height requirements for installation of the meteorological sensors.

Sensor for :	Sampling height (m)
wind speed	10 m
wind direction	10 m
air temperature	2 m
relative air humidity	2 m
global radiation	2 m or as convenient
UV-b-radiation	2 m
precipitation	1 m (near the ground)
Stand precipitation	same definition as in Manual Part XIV on Depositon
soil temperature	open field: in 2 depth of -5, -10, -20, -50, -100, -150 cm stand plot: in depth intervals 0 – -20 cm, -20 – -40 cm, -40 – -80 cm
soil moisture	in depth intervals 0 – -20 cm, -20 – -40 cm, -40 – -80 cm
atmospheric pressure	2 m

Supplementary recommendations on instrumentation and siting of the optional variables are given in Annex 1.

5.2 Quality Assurance and Quality Control

The management and processing of climatological and meteorological data include quality control (QC). It is important to check the consistency of the data coming from the stations for a single observation term, to calculate derived variables, to verify the values using an enlarged set of tests including tests for temporal variability, to fill data gaps and estimate replacement values for obviously erroneous data points, and to be able to correct actual as well as historical data (more guidelines on data validation and the handling of missing data are presented in Annex 2).

The National Focal Centres (NFC) are responsible for data processing, data storage and quality control. Data from the national meteorological institutes should be used to supplement the meteorological plot data. A list of guidelines for quality assurance and check points is available in Annex 3.

5.2.1 Quality Assurance in the field

The sensors and instruments need to be running reliably and give the reported accuracy even under extreme weather conditions. The performance of the instruments and sensors should be documented.

The instruments should have clear instructions about calibration procedures and recalibration intervals both in field and laboratory. The lifetime of components should be known so that the exchange of spare parts can be performed in time. A modular construction of instruments enables easy replacement of spare parts and reduces data loss.

Once or twice a year a general check of electronic components, such as cables, connectors, and analogue/digital converters, should be carried out by simulating electronically the output signals of sensors according to their specifications. The

meteorological stations should be reviewed frequently and the meteorological equipment should be calibrated with regular intervals. Visual inspections are made at each site to check whether the sensors are accurately reflecting the current conditions e.g. by comparing them to handheld instruments, to verify power supply and the correct operating of data logger and sensors. A formalised logbook, containing all details to be checked, facilitates the maintenance and the evaluation of data.

On Level II plots where meteorological observations are made manually it is recommended that automatic measurements are introduced whenever possible and with an overlapping period for validation of data of at least one year. After this period the data of automatic measurements are to be submitted, including information about transformation, if necessary, of the values of the former “manual data” to the new “automatic data”. GSM (Global Systems of Mobile Telecommunication) systems may be useful in remote areas for continuous data surveillance. The drawbacks are the need of a high amount of energy and that no transmitter may be available in remote mountainous areas.

5.2.2 Plausibility limits

All measured data must be checked for plausibility. The lower and upper plausibility limits of meteorological parameters within the ICP Forests monitoring program are given in Table 3 both for daily and hourly values. Due to the large extent of meteorological data it is recommended to test the raw data automatically for plausibility and select the implausible values.

Table 3: Plausibility limits of meteorological parameters

	Daily values		hourly values	
Variable	**Plausibility limits, lower**	**Plausibility limits, upper**	**Plausibility limits, lower**	**Plausibility limits, upper**
Precipitation	0 mm	150 mm	0 mm	50 mm
Air temperature	-50 °C	+50 °C	-50 °C	+50 °C
Relative air humidity	10 %	100 %	0 %	100 %
Global radiation	0 W/m²	550 W/m²	0 W/m²	In the daytime: 1100 W/m² at night: 15 W/m² or: 75 % of extraterrestrial radiation
Wind speed	0 m/s	40 m/s	0 m/s	40 m/s
Wind direction	0 °	360 °	0 °	360 °
Soil Moisture: Matric potential Water content	 10 kPa 0 %	 -150 kPa 100 %	 10 kPa 0 %	 -150 kPa 100 %
Soil temperature	-20 °C	+30°C	-20 °C	+30°C
Stand Precipitation	0 mm	150 mm	0 mm	50 mm
Atmospheric pressure	500 hPa	1 080 hPa	500 hPa	1 080 hPa

5.2.3 Data completeness

Usually meteorological measurements are made quasi-continuously and are then aggregated to daily values (means or sums). Depending on the character of a parameter the requirement on the completeness is lower or higher. Parameters with a higher fluctuation during the day require a higher completeness than parameters which fluctuate less (Table 4). Daily precipitation could only be calculated if the whole day was measured (completeness = 100 %). If one is sure that there was no precipitation during a time without measurement (e.g. via comparison with another precipitation measurement in proximity), those data gaps could be filled with the value “0”. For the majority of the other parameters a completeness of 95 % will be tolerable to calculate daily values. This means that isolated gaps will be no longer than one hour. Only soil-parameters are more even. Thus, for soil moisture and soil temperature a completeness of 50 % seems to be tolerable for calculating daily means. Guidelines on filling data gaps on an hourly basis can be found in Annex 2. For data from neighbouring meteorological stations from other operators (e.g. national weather service) the requirements on completeness can differ and will be accepted.

Table 4: Minimum requirement on completeness of meteorological parameters for the calculation of daily values

Variable	minimum degree of completeness daily	minimum degree of completeness hourly
Precipitation	100 %	100 %
Air temperature	95 %	50 %
Relative air humidity	95 %	50 %
Global radiation	100 % of daily light	In the daytime 100 %
Wind speed	Max =100 % Mean = 95	Max = 100 % Mean = 95 %
Wind direction	95 %	95 %
Soil Moisture: Matric potential Water content	50 % 50 %	50 % 50 %
Soil temperature	95 %	50 %
Stand Precipitation	100 %	100 %

5.2.4 Data quality objectives or tolerable limits

The minimum acceptable accuracy for the measurement of meteorological variables (achievable measurement uncertainties) is summarized in Table 1. All reported values should have been measured according to the methods described in Annex 1.

5.2.5 Data quality limits

The results are considered of sufficient quality when a minimum frequency of data fit the data quality objectives (see chapter 5.2.4). Data which not fulfil the quality objectives and/or are implausible should be treated as gaps. The data quality limits for aggregated meteorological parameters are given in chapter 5.2.3 and Table 4.

6 Data handling

6.1 Data submission procedures and forms

Submitted data are aggregated mandatory to daily (00:00 to 24:00) and optionally in addition to hourly (e.g. 00:00 to 01:00, 01:00 to 02:00 …) values (sum or average/mean, min. and max., respectively). Whereas daily data should be submitted validated and gap filled, submission of hourly data which were only checked for validity and without gap filling is acceptable. An overview of aggregation and units for the submission of daily data is given in Table 5. For hourly data it is sufficient to submit mean and sum values, respectively. Data must be forwarded to the relevant data centre for each plot in standardised forms, together with information on completeness of measurements and background information on the methods, models and interpretations used. (Technical details and

forms at the ICP Forests data submission online documentation https://icp-forests.org/documentation/Surveys/MM/MEM.html).

Table 5: Definition of variables, units and aggregation for submission of daily data

Variable		Units	Mean	Sum	Min.	Max.	Remarks
PR	Precipitation	mm		x			Total precipitation (including snow, etc.)
AT	Air Temperature	°C	x		x	x	
RH	Relative Air Humidity	%	x		x	x	
WS	Wind Speed	m/s	x			x	
WD	Wind Direction	°	x				Prevailing wind direction (0 = North, 270 = West)
SR	Global Radiation	W/m²	x				
UR	UV-b-Radiation	W/m²	x				
TF	Throughfall	mm		x			sum of daily values
SF	Stemflow	mm		x			to be recalculated from litres into mm
ST	Soil Temperature	°C	x		x	x	
MP	Soil Matric Potential	kPa	x		x	x	
WC	Soil Water Content	Vol %	x		x	x	
AP	Atmospheric Pressure	hPa	x		x	x	

6.2 Data validation

On plots where meteorological measurements are not carried out, data from national weather stations situated nearby, may be used by the NFC. In general these data do not need to be reported to the data centre, if they do not meet the requirements of the Level II plots. It is up to the NFC to decide, if such data are representative of the plot area

6.3 Transmission to co-ordinating centres

All validated data should be sent yearly to the European central data storage facility at the ICP Forests Programme Co-ordinating Centre. A detailed time scheduled is provided by the relevant bodies.
For the submission of the data to PCC the forms are to be used as indicated in Table 6.

Table 6: Forms for submission of meteorological data

Reduced plot file information	.PLM
daily meteorological data	.MEM
hourly meteorological data	.MEH

6.4 Data processing guidelines

Meteorological data should be processed to generate hourly averages or shorter period averages or sums (5, 10, or 15-minute interval). Shorter averaging may be desirable for analysing short-term phenomena or reviewing the data for intermittent sensor errors. Downloading of records or exchange of memory cards should occur as soon as possible for a fast identification of eventual errors not detected by field workers. More guidelines on data processing are presented in Annex 2.

6.5 Data reporting

Reporting of the meteorological set-up including a site characterisation, a technical description of the set-up, sensor characteristics, reading and recording intervals, valid range and error setting, data conversion and compression is a mandatory part of the monitoring work.

The landuse and the topography of the immediate surroundings, and preferably also the meteorological conditions (wind rose, climatological data) should be available in the form of maps, tables and diagrams. For each plot the long-term climatic situation shall be determined as precisely as possible, at least by climatic diagrams using monthly values of precipitation and temperature. If no actual plot data are available, existing data (e.g. from nearby or representative weather stations, from climate atlas, models etc) shall be used. This will be reported only once.

Each National Focal Centre must submit information on deviations from the above recommended procedures or changes of methods. Periodical quality control evaluations may be requested by the Programme Coordinating Centre to be part of integrated evaluations. References to any publications arising from the work on the Level I/ II plots should be notified so that they can be listed on the ICP Forests website.

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Annex I - Measurement of meteorological variables

This annex gives general (not exhaustive) information on the instruments for meteorological measurements of wind, temperature, relative air humidity, precipitation, soil moisture and global radiation. A standard design of a meteorological station is shown in figure 1. The choice of an instrument for a particular application should be guided by the data quality objectives of the application: as a minimum these objectives should include the accuracy and the resolution of the data needed by the application. Other considerations are the cost of the instrument, the cost of routine maintenance, the needs of ruggedness and sensitivity. More comprehensive guidelines on instrumentation are found in WMO (no. 8).

It is recommended that the instruments meet the performance specifications presented on Table 1.

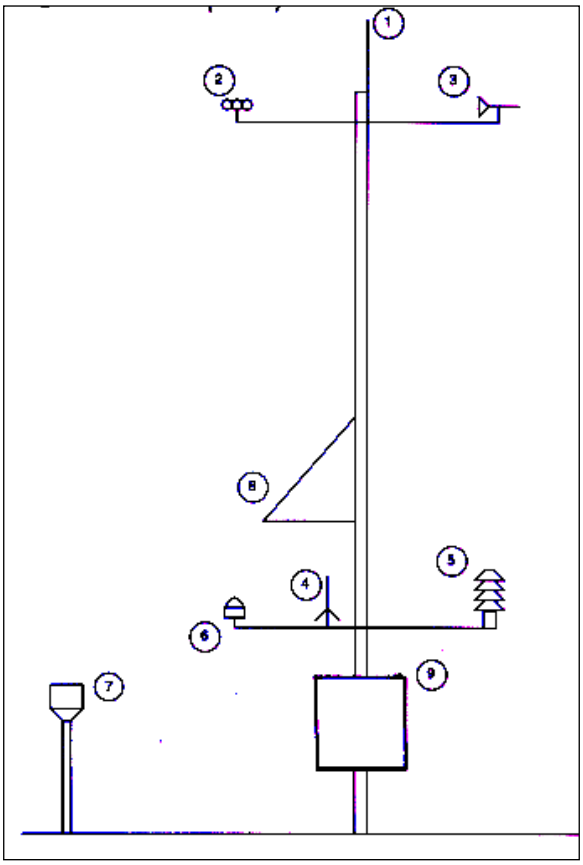

Figure 1: An example of a meteorological tower for measurements in open field. 1: lightning conductor, 2: wind speed at 10 m (cup anemometer), 3: wind direction at 10 m, 4: GSM antenna (2 m), 5: air temperature and relative air humidity sensors at 2 m, 6: global radiation (pyranometer) at 2 m, 7: rain gauge at 1 m height and 5-10 m upwind the mast/tower, 8: solar panel for power supply. Temperature and relative air humidity sensors are placed on the northern side of the tower, global radiation at the southern side of the tower.

A1.1 Wind

A1.1.1 Wind speed

Lightweight low friction three-cup anemometers or propeller anemometers should be used for measuring wind speed. Sensors with high accuracy at low wind speeds and a low

starting threshold should be used. Sonic anemometers and hot wire anemometers may also be used, but are more appropriate for direct measurements of turbulence.

A1.1.2 Wind direction

Wind direction should be measured directly using a wind vane or may be derived from measurements of wind components. The wind must compass to the North.

A1.2 Temperature

Temperature should be measured using resistance temperature devices (e.g. platinum wires), which meet the performance specifications. Thermoelectric sensors are not recommended because of their limited accuracy and complex circuitry.

A1.2.1 Air temperature

The specification of air temperature measurements is defined in chapter 5.1.1.1.

A1.2.2 Soil temperature

Soil temperature measurements provide information on the soil thermal characteristics such as the depth of frost penetration into the soil and the duration that the soil remains frozen. It is of interest to hydrologists because it affects surface runoff infiltration and snowmelt.

The World Meteorological Organisation (WMO) recommends for open field measurements the following standard depths of 5, 10, 20, 50, 100, and 150 cm. It is recommended to measure soil temperature at two depths as a minimum. When soil temperature is measured together with to soil moisture inside of the forest the depth of sensors should be in accordance with the location of soil moisture sensors (A1.5).

The measurement site for soil temperature should preferably be in undisturbed soil typical for the surface of interest. Owing to the high spatial variation the measurement should be repeated at a number of points (minimum two) in the stand for each layer. Soil thermometers should be placed in good contact to the soil matrix.

A1.3 Relative air humidity

Humidity should be measured using a dew point, lithium chloride or thin-film capacitor hygrometer. As for air temperature measurements it is recommended to shield the humidity sensors against radiation and precipitation.

A1.4 Precipitation

A1.4.1 Open field precipitation

The two main classes of precipitation measuring devices are the floating or tipping bucket rain gauge, and the weighing rain gauge. Both measure total liquid precipitation and precipitation rate.

The tipping bucket rain gauge is a commonly used instrument and is a relatively accurate and reliable instrument. Measurement errors may occur under heavy rainfall because precipitation is lost during tipping action. The tipping buckets may be equipped with heaters to melt the snow in wintertime. This is not recommended as total precipitation may be underestimated due to evaporation of the frozen precipitation caused by the heater element.

The weighing rain gauge has the advantage that all forms of precipitation are weighed and recorded as soon as they fall in the gauge. No heater is needed to melt the snow, reducing the problem of evaporation. But the weighing rain gauge is much more sensitive to strong winds.

A1.4.2 Stand precipitation

Precipitation in forest stands reaches the ground by throughfall and by stemflow. It is possible to use the same collectors as for wet deposition. In this case the instructions for deposition measurements (see Manual Part XIV) on the permanent observation plots should be considered.

A1.4.3 Throughfall

Throughfall may be gathered by using at least 10-15 funnels, bottles or buckets or 1-2 gutters of 10m length per plot. Placing of both types of collectors should be systematic. In general only throughfall measurement by gutters allows automatic sensing and electronic storage of aggregated values, as recommended for daily values to be forwarded to the relevant data centre.

A 1.4.4 Stemflow

Stemflow collectors are to be attached to about 5-10 trees of different tree classes of the predominant species. Stemflow varies substantially between trees with upward pointing branches and smooth bark (e.g. deciduous trees, 5-40 % of stand precipitation) and trees with downward pointing branches (e.g. spruce with less than 3 % of stand precipitation). Thus stemflow monitoring depends largely on tree species composition and is necessary in stands of e.g. beech, chestnut, young oaks, and eucalyptus.

The stemflow part of precipitation may be calculated by the relation of stem basal area of the plot to plot area following the formula:

$h_{SF} = (v_{SF} / g) \times (G / A)$

h_{SF}	precipitation by stemflow	mm
v_{SF}	stemflow of the measured tree	dm^3
g	basal area of the measured tree	m^2
G	basal area of all trees of the plot	m^2
A	area of the plot	m^2

A.1.5 Soil moisture

Soil moisture measurement provides valuable information about the possible occurrence of drought episodes specific for tree species. For soil moisture measurements at least three replications should be installed in sufficient distance among each other. It should be carried out either in defined depth providing the main rooting zone of the trees on the plot or in the relevant soil horizons. If soil water is already sampled for soil solution analysis, the same depths should be used for soil moisture measurement. At each location soil moisture sensors should be installed within the fixed depth intervals 0 - 20, 20 - 40 and 40 - 80 cm. When forest floor thickness (OF + OH layer) is more than 5 cm, the moisture of the organic layer should be also measured.

It makes sense to use of the both complementary methods: Tensiometer to measure soil matric potential (up to -80/-150 kPa) and Time Domain Reflectometry (TDR) to measure volumetric soil water content (0-100 vol. %). Since the volumetric water content could be measured over entire range, it is recommended to do this measurement primarily if it's not possible to do both. If the water retention characteristic of the soil was measured (see sub-manual X SA14), the matric potential could be calculated from the soil water content data.

For each depth the data of all measuring points of a Level II plot should be averaged and stored.

A 1.6. Solar radiation

A1.6.1 Global radiation

The specification of global radiation measurements is defined in chapter 5.1.3.

A 1.6.2 UV-b radiation

The possible damaging effects of UV-B radiation, caused by thinning of the stratospheric ozone content to biological systems have been discussed. Because of the very steep slope of energy flux in the wavelength band of 280-315 nm, accurate values can only be measured by scanning the spectrum with high resolution (1 nm). As the available instrumentation covers a wide range of accuracy, besides costs and necessary energy supply, it is recommended to add clear information on the used methods/instruments, ranges and peak wavelength when forwarding the data. The necessary instrumentation is, however, costly and not appropriate for field stations.

Stratospheric processes mostly determine the radiation energy at ground level. This means that data from official weather or environmental network stations some tens of kilometres away can be used, taking into account the altitudinal dependency of radiation received. Using non-scanning type sensors, peak wavelength and bandwidth have to be standardized to allow transboundary comparisons.

A.1.6.3 Photosynthetic active radiation

The radiation spectrum of 400-700 nm used by plants for photosynthesis is referred to as photosynthetic active radiation (PAR) and amounts to about 50% of the global radiation. So called quantum sensors count the number of photons in this spectrum falling per unit time and area through a spectral filter on a blue enhanced photocell, regardless of their energy. This is called the photon flux density in units of µEinstein or µmol photons(quanta)/m2/s.

The sensor should have a working range from 0 to 5mmol photons/m2/s. Quality criteria are high linearity (1%), long term stability (<±2%) and small temperature dependence (±0.15%). Maintenance of the sensors is reduced to cleaning the sensor surface and to checking the levelling. Although routine calibration should not be necessary the ageing of filter material and photocells under specific field conditions should be taken into account.

A 1.7 Atmospheric pressure

Atmospheric pressure is defined as the pressure produced by the mass of the air under the power of gravity, due to the weight of the air column from the surface of the soil to the outer boundary of the atmosphere at a distinct area. It is measured by barometers.

At sea level, atmospheric pressure averages 1013.2 hPa. The value varies by weather conditions, and ranges e.g. in Germany from 950 to 1060 hPa at sea level. With increasing elevation atmospheric pressure decreases.

Due to the fact that atmospheric pressure is spatially much less variable than temporally, it is possible to use modified values from a nearby weather station. For calculation of the modified values, the following formula from the German weather service is recommended:

$$p_0 = p(h)e^x,\ x = \frac{g_0}{R^*(T(h) + Ch \bullet E + \alpha\frac{h}{2}}h$$

with:

p_0		Atmospheric pressure at sea level
p(h)		Atmospheric pressure at barometer level (in hPa, 0.1 hPa accuracy)
g_0	9.80665 m/s²	Gravitational acceleration
R^*	287.05 m²/s²K)	Universal gas constant for dry air
h		Height of the barometer (in m with accuracy of 1 dm)
T(h)		Local temperature (in K)
α	0.0065 K/m	Vertical gradient of temperature
E		Water pressure
Ch	0.12 K/hPa	Co-value for E to reflect the average change of water pressure by the elevation

Relevant WMO-Guides to

Meteorological instruments and methods of observation: WMO - No. 8

Climatological practices: WMO - No. 100

Hydrological practices: WMO - No. 168

(Secretariat of the World Meteorological Organization
Avenue Guiseppe-Motta 41, Casa postale No 2300
CH - 1211 Geneva 2, Switzerland)

Annex II - Data validation, processing and handling of missing data

After the field data are collected and transferred to the computing environment, the next steps are to validate and process data. This annex provides guidance for the validation and processing of meteorological data.

Data validation

There are many causes of erroneous data: damaged or malfunctioning sensors, loose or broken wire connections, damaged hardware, data logger malfunctions, static discharges, sensor calibration drift, icing conditions among others.

Data validation is used to determine whether the collected data have an acceptable completeness and reasonableness and to eliminate erroneous values. This step transforms raw data into validated data and is crucial to maintain high rates of data completeness during the monitoring programme. Therefore the data must be validated as soon as possible within a few days after transfer. It is very important to store the original raw data; the validation steps should be made on a copy of the original data set.

Data can be validated manually or automatically using computer software. The two main parts of data validation are data screening and data verification. Data screening may be performed using a series of validation routines or algorithms to screen all the data for questionable or erroneous values. It is recommended to print a data validation report which lists the suspect values. Data verification requires a case-by-case decision on what to do with the suspect values – retain them as valid, reject them as invalid or replace them with redundant valid values. A qualified person familiar with monitoring equipment and the local meteorology should make this part of data validation.

Validation routines

General system checks. Two simple tests may be performed to evaluate the completeness of the collected data. A check of whether the number of data field is equal to the number of measured parameters for each record and a check of whether there are any missing sequential data values.

Measured parameter checks. These tests consist of range tests, relational tests and trend tests. Range tests are the simplest and most commonly used validation tests. The measured data are compared to allowable upper and lower limiting values. If the value meets a criterion then it is considered as valid. It is recommended to have several criteria checks because a single criterion is unlikely to detect all problems. Relational tests are based on expected physical relationships between various variables and ensure that physically improbable situations are not reported in the data without verification. Trend tests are based on the rate of change in a value over time.

Treatment of missing data

After the raw data have been subjected to the validation checks, what should be done with the suspect data? Some of the values may be real, unusual occurrences while others are simply bad. A qualified person should examine the validation report to determine their

acceptability. Invalid data should be assigned and replaced with a validation code. A common designation for data rejection could be assigning a validation code (e.g. –900 series with numbers that represent various rejection explanations). Missing data or invalid data should be flagged or replaced as appropriate depending on the use of the data.

Many models require hourly meteorological data and will not accept missing or invalid data. For use in such models it is recommended to fill out one-hour gaps with estimates based on linear interpolation or persistence. Missing data of precipitation are problematic e.g. during thunderstorms with short lasting and high density of precipitation.

If redundant sensors are used then the rejected value from the primary sensor may be substituted with it as long as the data passed all validation criteria.

Substitution for missing data should only be made to complete the data set for modelling applications; substitutions should not be used to attain the 90% completeness requirement for many applications of meteorological data.

The goal of substitution should be to replace missing data with a “best estimate” so as to minimise the probable error of the estimate:

Persistence is the use of data from the previous time period (hour). This procedure is applicable for most meteorological variables for isolated one-hour gaps; caution should be used when the gaps occur during day/night transition periods.

Interpolation is applicable for most meteorological variables for isolated one-hour gaps and, depending on circumstances, may be used for more extended periods (several hours) for selected variables e.g. temperature. As in the case of persistence, caution should be used when the gaps occur in day/night transition periods. Linear interpolation is often being used for small gaps (2-3 half-hourly means missing). For longer gaps another gap filling method is used which uses mean daily courses to fill gaps in half-hourly or hourly data. Differences in methods are based on the length of the time interval, which is used to calculate the mean daily course (usually 4 to 15 days). Further, a so-called running mean can be applied (i.e. the 15 days previous to the gap are used to calculate the daily course). On the other hand, the entire time period can be cut into short periods, where gaps within one period are filled with the representative half-hourly value from the mean daily course for that period.

Data processing

When the data validation is completed, the data are subjected to data processing procedures to evaluate the meteorological conditions of the site.

Averaging and sampling strategies. Hourly aggregation (averages or sums [precipitation] or frequencies [wind direction]) may be assumed. This averaging time is used in most models, e.g. growth models. The hourly averages may be obtained by averaging samples over an entire hour or by averaging a group of shorter period averages. If the hourly average is to be based on shorter period averages, then it is recommended to take 10- or 15-minute intervals. At least 2 valid 15-minute periods are required to represent the hourly period. The use of shorter period averages in calculating an hourly value has the advantages to minimise the effects of meander under light wind conditions in the calculation of the standard deviation of the wind direction. It also provides more complete information when reviewing the data for periods of transition. It may also allow the recovery of data that might otherwise be lost if only part of the hour is missing.

Processing of wind data

The distribution of wind speed and direction at a given location is often presented in form of a “wind rose” which is a polar plot of the frequency of wind flow as a function of wind direction. Guidelines of processing the wind data can be found at the WebMET - The Meteorological Resource Center (www.webmet.com/met_monitoring/toc.html).

Annex III - Quality assurance programme within the meteorological network

In order to guarantee a sufficient quality of the data from the meteorological stations, the following recommendations, which are far from being exhaustive, are made for the quality assurance and quality control:

1. All equipment used should completely conform to the technical requirements defined by the WMO (World Meteorological Organisation, Geneva, Switzerland) and the national meteorological institutions.
2. The selected equipment should be developed for use in networks. There are many meteorological stations on the market, but only a few are really developed for long term use and for network requirements. This does not necessarily mean that the stations are much more expensive.
3. Training of local foresters during the installation is recommended and necessary so that they are able to make simple maintenance and technical checks of the performance of the station.
4. A technical manual should be made available to each local operator. This manual helps the operator to remember simple maintenance procedures more easily and avoids too frequent phone calls for small problems.
5. Local operators should make at least weekly checks in the field.
6. It is of great advantage to have the stations built with easily exchangeable parts (modules), which can easily be sent by express mail and exchanged by the local operator. The maintenance can be made in a very short time and no repairs have to be done in the field (greater independence of the weather during maintenance in the field). This means a gain in time, which reduces the number of missing values, and in the need of manpower, which reduces the costs.
7. From the beginning of the measurements, a stock of spare parts and of spare stations should be kept permanently, which can be used immediately in the field.
8. The technical manager of the network should be able to repair malfunctions within 48-72 hours after having been informed of their existence.
9. The technical manager, besides the weekly checks, should do annual visits to each station by the local operators.
10. The staff of the co-ordination centre should carry out at least annual controls and calibrations in the field, when they are not the technical managers of the meteorological stations.
11. It is an advantage, if the stations are connected to the telephone network. This allows for an automatic transmission of the data, maintenance information including battery tension, temperature inside the station every 2-3 days, or even more frequently. In this way errors are recognised very early and can therefore be eliminated within a few days, reducing the number of missing values.
12. It is recommended that all stations have memory-cards in addition to the local memory of the data logger. In this way, data are constantly stored both at the internal memory of the stations as well as on a memory card (double storage); in case of problems with the telephone transmission or other technical errors, the memory card can be sent by mail.
13. At stations working with memory-cards only, at least fortnightly mailing of the memory cards is recommended. (The storage of the logger should content a multiply of the data

sent by m-card, not to loose data by magnetic influences mailing the cards: for example 4 weeks storage at a biweekly service at the station)

14. Annual calibration of all sensors is recommended, in order to trace their quality with the years. The technical manager of the network needs not necessarily to be the one calibrating the sensors. Subcontracted institutions or private companies can do it. Refer always to the national standards used for calibration and work with institutions accredited for this type of work.
15. It is important to follow-up each sensor individually (using individual numbers attached to each sensor) from the beginning of its installation until the end of its existence. This can be done with a special table in the database, which contains e.g.:
    - the history of each sensor
    - the calibration results (changing coefficients)
    - the date of calibration
    - the date of its installation at the one or the other station (sensors are rotating every year, after calibration, from one to the other station).
16. After each data transmission it is necessary to validate the data, if possible automatically using special programmes. This will allow early detection of problems, which are not easily seen by simple data checks.
17. If the technical manager is not the co-ordination centre, a monthly transmission of the data to the co-ordination centre of the intensive monitoring network is recommended. The transmission is a proof that data have passed, in a short time, a minimum of quality checks.
18. The monthly mailing of bulletins (providing means, maximum and minimum values of all the measured variables) to the local operators as well as to other foresters who might use them for their every day work, is an activity which keeps their motivation high for these types of measurements.
19. Annual meetings with all local operators in order to present the results of the work on the data, and to discuss mutual problems, helps to keep the whole operation coherent.
20. Regular work (analysis and interpretation) on the data is important in order to detect more detailed problems.
21. There are several advantages when working with a private company, which produces the equipment and which at the same time technically manages the network:

Flexibility

One can impose what one wants, as long as one pays (That's also true for the quality assurance programme), this is not so easy with public institutions. It does not mean necessarily that the costs of the technical management are higher than those of the public institutions
As a producer of stations the company takes advantage of its experience as a technical manager of a network, which leads to improvements of the stations steady development

When working with a private company, the co-ordination centre of the intensive monitoring network must define a certain number of control variables, in order to make co-ordination and control by the technical manager easier.

Annex IV - Use of meteorological data: stress indices and process-based models

Stress indices

Meteorological factors are usually registered automatically in intervals of 10 or 15 minutes. The high density of meteorological data enables a detailed analysis of potential meteorological stress on the observed forest stands. Raspe (2001) has compiled the literature definitions of several meteorological key variables indicating potential meteorological stress.

A collection of meteorological indices and their literature sources are given in Table 7.

In term of temperature stress like coldness and heat, short term effects characterised by extremities and long term effects which were characterised not by single days but by periods have to be distinguished. Another important block of meteorological stress variables are connected with precipitation as are drought and wetness of the soil.

Table 7: Selected indicators of meteorological stress using temperature and precipitation

Name	Calculation	Source
Temperature		
Frost Stress		
Ice days	Σ days with T_{max} < 0 °C	BayFORKLIM (1996)
Frost days	Σ days with T_{min} < 0 °C	BayFORKLIM (1996)
Frost index	Σ((ΣT_{min})/20-Tmin) > 8°C for T_{min} < -3°C	LIU (1998)
Frequency of cold days	Σ days with T_{mean}- 10; -15; -20 °C	KÖNIG et al. (1989)
Extreme air-frost	Σ days with extreme T_{min} (Bay. < -25 °C)	KÖNIG et al. (1989)
Frost alternation	Σ days with 0-value alternations	KÖNIG et al. (1989)
Frost shock	24 h ΔT □ 15 K (T > 0 °C → T < -3 °C) day 1: T_{max} > 10 °C → day 2: T_{min} < -3 °C	MAYER et al. (1988) KÖNIG et al. (1989)
Late frost	Σ days with T_{min} ≤ 0 °C (April - May) Σ T_{min} ≤ 0 °C (April – May) Σ((number of day with T_{mean}≤0)*(|T_{min}|+1)	ANONYMUS (1998)

Name	Calculation	Source
Early-Autumn frost	T_{min} < -3 °C before end of growing season	KÖNIG et al. (1989)
Winter indices	Σ days with T_{mean} < 0 °C Σ days with pentade T_{min} < 0 °C Σ T_{mean} °C during winter T_{min} und T_{mean} of the winter	ANONYMUS (1998)
Heat Stress		
Heat indices	Σ days with T_{max} > 30 °C (= tropical days) Σ days with T_{max} > 35 °C (= heat days)	REINDS (1998)
Summer indices	Σ T_{mean} > 5 °C Σ T_{mean} > 5 °C (during growing season)	REINDS (1998)
Precipitation		
Drought Stress		
Comparison with the long standing average	Monthly, half-yearly, yearly, growing season	Arbeitskreis Standortskartierung (1996)
Frequency of low precipitation	Σ pentads with NF = 0 mm or ≤ 1 mm	ANONYMUS (1998)
Frost dryness	Σ (T_{max} - T_{min}) if T_{min} < -3 °C and T_{max} > 10 °C	MAYER et al. (1988)
Evapotranspiration	CWB = P – ET_p Et_a / ET_p	REINDS (1998) Arbeitskreis Standortskartierung (1996)

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Process-based models

Table 8: Limited overview of process based models on growth, dynamics, water-balance and nutrient cycling of European forests, requiring detailed meteorological information

Acronym	Full name	Reference/Author
ArcEGMO-PSCN		BECKER et al., 2002 and PFÜTZNER, 2009
ASTER		Loustau et al., 1992
BIOMASS		McMurtrie
BIOME-BGC	Biome = an area characterized by its flora, fauna, and climate BGC = BioGeochemical Cycles	Thornton et al. 2002 http://www.ntsg.umt.edu/
CARDYN		Veroustraete, 1994
COMMIX	COMpetition in MIXed forests	Bartelink
COUP	Coupled heat and mass transfer model for soil-plant atmosphere systems	Jansson and Karlberg, 2001
DyDOC	DynamicDOC model	Michalzik et al., 2003
EXE[2]	Energy, water, and momentum eXchange and Ecological dynamics	Martin, 1992
EXPECT-FORSOL	FOREst Soil module EXPloring the Environment Consequences for Tomorrow	Braat et al. 1991
FIWALD[1]	Fichten WALD (Spruce stand)	Schall, 1991
FORCLIM[2]		Bugmann, 1994
FORECE[2]		Kienast and Kuhn, 1989
FORGRO[1]	FOREst GROwth	Mohren, 1987
ForM-S[1]	FOREst Model Series	Arp and Oja, 1992
FORSKA-[2]		Prentice et al., 1993
FORSUM[1]	FOREst Succession Model	Krauchi and Kienast, 1993
GOTILWA	Growth Of Trees Is Limited by WAter	Gracia
GROMIT		Ludlow et al, 1990
HYBRID		Friend et al., 1995
HydrAll		Magnani & Grace, 1996
LWF-BROOK90	LWF-BROOK90	Hammel and Kennel, 2001
MAGIC[1]	Model of Acidification of Ground water In Catchments	Cosby et al., 1985
NAP1	Nutrient Availability and Productivity	Van Oene, 1992
NICCCE	Nitrogen Isotopes and Carbon Cycling in coniferous Ecosystems	Van Dam and Van Breemen, 1995
NuCM	Nutrient Cycling Model	Munson et al., 1992
PnET-CN-CHESS[1]	Photosynthesis and Evapotranspiration Carbon and Nitrogen Interactions	Aber and Federer, 1992

PROFILE[1]		Warfvinge et al., 1993
SICA-SIMFORG		Kellomäki
SOILVEG[1]	SOIL VEGetation model	Berdowski et al., 1991
STASH		Sykes et al., 1996
STANDFLUX		Tenhunen
SWIF[1]	Soil Water In Forested Ecosystems	TikTak and Bouten, 1992
TRAGIC		Hauhs et al., 1996
TREEDYN3	TREE DYNamics model	Bossel, 1994
TREGRO[1]	TREe GROwth model	Weinstein et el., 1991
WATBAL		Starr, 1999
WATERSTOF[1]	WATER en STOF transport	Wesseling and Van Grinsven, 1991
WHNSIM	Water-, heat-, and nitrogen simulation	Huwe, B., 1990

[1] source: Van Grinsven, Ecological Modelling 83 (1995). Special Issue: Modelling Water, Carbon and Nutrient Cycles in Forests
[2] source: Smith, Climatic Change 34 (1996). Special Issue: The Application of Patch Models of Vegetation Dynamics to Global Change Issues.
[3] source: Addition common models in Germany
See these references for detailed information on each of these models.

Table 9: Tentative indication of the characteristics and meteorological requirements of the models.

Model	Characteristics	Meteorological requirements
ArcEGMO-PSCN	GIS-based, multi-scale modelling system for spatially distributed simulation of hydrological sub-processes in river catchments.	T,P,H,R,W (d)
ASTER	stand hydrology	T, P, H (d)
BIOMASS	stand growth (C, H2O balance)	T,P,H,R,W (d)
BIOME-BGC	calculating the water, carbon and nitrogen budgets for vegetation, soil and litter compartments of terrestrial biomes	T,P,H,R,W (d)
CARDYN	regional forest growth (from remotely sensed data)	T,R,P? (d)
COMMIX	tree growth, competition for light	R (d)
COUP	soil-plant-atmosphere system	P,R,T,H,W? (<d)
DyDOC	DOC fluxes	T and throughfall
EXE[2]	patch	R,T,P,H,W (<d)
EXPECT-FORSOL		P,R,T,H,W?, (a)
FIWALD[1]		P,R,T,H (d)
FORCLIM[2]	patch	
FORECE[2]	patch	
FORGRO[1]	stand growth (C, H2O, nutrients)	T,P,H,R,W (<d)
ForM-S[1]		T,P,R,H,W? (rn-a)
FORSKA-[2]	patch	
FORSUM[1]		T?,P,R,H,W? (d)
GOTILWA	growth *Quercus illex*	T,P,R,W? (d)
GROMIT	individual tree	T,R
HYBRID	patch	T,P,R,H,W (<d)
HydrAll		
LWF-BROOK90	hydrology, water budget	T,P,R,H,W (d)
MAGIC[1]		P (a)
NAP1	soil	? (a)
NICCCE		P R T,H,W?(<d)
NuCM	nutrient cycling	T,P,R,H,W (d)
PnET-CN-CHESS[1]		P,R,T,H,W?(<d)
PROFILE[1]		
SICA-SIMFORG	patch	
SOILVEG[1]		P,R,T,H,W? (<d)
STASH	patch	
STANDFLUX		R,T,P? (<d)
SWIF[1]		P (<d)
TRAGIC	tree	P,R,T,H,W (d)

TREEDYN3	tree, stand	P,R,T,H,W (d)
TREGRO[1]	tree	P,R,T,H,W (d)
WATBAL	simple, single layer capacity type model for water balance of forest stands (plot) with freely draining soils.	P,R,T, (d/m)
WATERSTOF[1]	soil	P,R,H? (<d)
WHNSIM	hydrology, water budget	T,P,R,H,W (d)

P = Precipitation, R = Radiation, T = Temperature, H = Air Humidity, W = Wind speed
(d) = daily, (m) = monthly, (a) = annual

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Annex V - Minor changes after 2020

Date	Minor change to latest published version in 2020	Affected sections of this document