UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE
CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION

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

# MANUAL

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

## Part VII

# Meteorological Measurements

updated: 06/2004
forms: 2006

# Contents

**1. OBJECTIVES ... 7**
**2. COMPONENTS OF THE METEOROLOGICAL MONITORING ... 7**
  2.1 VARIABLES MEASURED AT THE MONITORING STATIONS ... 7
  2.2 SITE CONSIDERATIONS ... 8
    *2.2.1 Measurements in the open field/large clearings or above the canopy ... 8*
    *2.2.2 Measurements in the stand ... 9*
  2.3 MANDATORY VARIABLES ... 9
    *2.3.1 Air temperature and relative humidity ... 9*
    *2.3.2 Wind speed and direction ... 9*
    *2.3.3 Solar radiation ... 9*
    *2.3.4 Precipitation ... 10*
**3. TECHNICAL RECOMMENDATIONS ... 10**
  3.1 SENSOR HEIGHT ... 10
  3.2 GENERAL TECHNICAL RECOMMENDATIONS ... 11
**4. DATA PROCESSING, STORAGE AND QUALITY CONTROL ... 11**
**5. EVALUATION AND INTERPRETATION OF METEOROLOGICAL DATA ... 12**
**6. DATA SUBMISSION ... 12**
**7. LEVEL II PLOTS WITHOUT METEOROLOGICAL MEASUREMENTS ... 12**
**8. METADATA AND BASIC CLIMATOLOGICAL INFORMATION ... 12**
**9. REFERENCES ... 13**
**ANNEXES ... 15**
  ANNEX 1: MEASUREMENT OF METEOROLOGICAL VARIABLES ... 16
    *Wind. ... 16*
    *Air temperature. ... 16*
    *Humidity. ... 16*
    *Precipitation. ... 16*
    *Soil temperature ... 17*
    *Soil moisture ... 18*
    *Stand precipitation ... 18*
    *Throughfall ... 18*
    *Stemflow ... 18*
    *UV-b radiation ... 18*
    *Photosynthetic active radiation ... 19*
  ANNEX 2: DATA VALIDATION, PROCESSING AND HANDLING OF MISSING DATA ... 20
    *Data validation ... 20*
    *Validation routines ... 20*
    *Treatment of missing data ... 20*
    *Data processing ... 21*
    *Processing of wind data ... 21*
  ANNEX 3: QUALITY ASSURANCE PROGRAMME WITHIN THE METEOROLOGICAL NETWORK ... 23
  ANNEX 4: USE OF METEOROLOGICAL DATA: STRESS INDICES AND PROCESS-BASED MODELS ... 26
    *Stress indices ... 26*
    *Process-based models ... 28*
  ANNEX 5: FORMS ... 33
  ANNEX 6: EXPLANATORY ITEMS ... 37

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## 3.2 Index

A

aggregation MET VII 21
anemometers MET VII 16
automatic station MET VII 11

B

bandwidth MET VII 19
basal area MET VII 18

C

calibration MET VII 11, 19, 23, 24
canopy MET VII 8
coldness MET VII 26
completeness MET VII 40

D

DAR-Q MET VII 39
data - missing MET VII 20
data logger MET VII 11, 20, 24
data submission MET VII 12
data substitution MET VII 21
data validation MET VII 20
deposition measurement MET VII 18
drought MET VII 18, 27

E

evaluation MET VII 12
evaporation MET VII 16
evapotranspiration MET VII 10, 27

F

fetch MET VII 8, 9
frost MET VII 17, 26
funnel MET VII 18

G

gauge MET VII 10, 16, 17
GSM MET VII 11, 17
gustiness MET VII 9
gutter MET VII 18

H

heat MET VII 26
heater MET VII 16
horizon MET VII 8
humidity - air MET VII 8, 9
humidity MET VII 7, 10, 16, 39, 40
hygrometer MET VII 16

I

ice MET VII 26
infiltration MET VII 17
interception MET VII 10
interpolation MET VII 21

L

light MET VII 9
lightning MET VII 11, 17
logbook MET VII 11

M

mandatory MET VII 8
mast MET VII 8, 17
matric potential MET VII 8, 39, 40
mean - running MET VII 21
measuring period MET VII 38
metadata MET VII 12
meteorological indices MET VII 26
model MET VII 20, 26, 28
moisture - soil MET VII 8, 18
monitoring period MET VII 38

O

$O_3$ MET VII 18
open field MET VII 8
optional MET VII 8
orifice MET VII 10

P

percolation MET VII 7
persistence MET VII 21
photon MET VII 19
photosynthesis MET VII 19
precipitation MET VII 7, 8, 9, 10, 16, 18, 39
pyranometer MET VII 9, 17

Q

quality assurance MET VII 23
quality control MET VII 11

R

radiation - global MET VII 9
radiation MET VII 9, 10
radiation - net MET VII 10
radiation - solar MET VII 7, 8, 9, 10, 17, 39, 40
radiation - UVb MET VII 8, 18, 39, 40
reference height MET VII 7
representativity MET VII 7
roughness MET VII 8, 9

S

snow MET VII 10, 16
snowmelt MET VII 17
solar panel MET VII 17
stemflow MET VII 8, 18, 39, 40
stress MET VII 26
summer MET VII 27
surface runoff MET VII 17
surface type MET VII 8

T

temperature MET VII........................................... 16
temperature - air MET VII................ 7, 8, 9, 10, 39
temperature - soil MET VII............. 8, 9, 10, 17, 39
tensiometer MET VII........................................... 18
test MET VII....................................................... 20
thermocouples MET VII..................................... 16
thermoelectric sensor MET VII .......................... 16
throughfall MET VII................................. 8, 18, 39
time domain reflectometry MET VII .................. 18
topography MET VII ............................................ 8
tower MET VII ............................................... 8, 17

V

vane MET VII................................................. 9, 16

W

water content MET VII................................. 39, 40
wavelength MET VII.......................................... 19
weather stations MET VII..................................... 7
wind MET VII ................................................ 7, 16
wind direction MET VII ..................8, 9, 10, 39, 40
wind rose MET VII............................................. 21
wind speed MET VII .......................8, 9, 10, 39, 40
winter MET VII .................................................. 26
WMO MET VII ...............................7, 8, 10, 19, 23

# 1. Objectives

Meteorological variables affect composition, structure, growth, health and dynamics of forest ecosystems. 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. Phenological observations are needed to calibrate the meteorological data to plant reactions at each site.

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). Data from neighbouring monitoring stations may be used for the Level II programme, provided that they are representative for the site.

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 and growth, and the crown condition of trees. The main objectives are to:

describe the meteorological conditions and changes at the Level II plots
investigate the meteorological conditions and supply possibilities for the explanation and relationship to the state of the ecosystem
identify and investigate stress factors for trees on the plot like extreme weather conditions and events (frost, heat, drought, storms)
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 budget, water availability for the stand, growth, nutrient cycling).

# 2. Components of the meteorological monitoring

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.

## 2.1 Variables measured at the monitoring stations

Meteorological variables as air temperature, relative humidity, precipitation, wind velocity and direction, and solar 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.

| Mandatory | Optional |
|---|---|
| precipitation | UV-b radiation |
| air temperature | soil temperatures |
| air humidity | soil moisture: matric potential, water content |
| wind speed | stand precipitation: quantity of throughfall and stemflow |
| wind direction | |
| solar radiation | |

**Table 1:** List of mandatory and optional meteorological variables.

### 2.2 Site considerations

Selecting the proper site for a meteorological station is as important as selecting the proper sensor for a particular application. All meteorological measurements are affected by the surface type and roughness, the soil moisture, the regional topography, and obstacles. The meteorological measurements should be free from obstacles such as trees, and steep slopes. Placement of the station and of the sensors should be given first consideration. 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 also be compatible with national weather service networks. Measurement recommendations are described in Annex 1.

Data from neighbouring meteorological stations may be used for the Level II purpose, provided that they are representative for the site. However, to represent the specific climatic conditions of forested areas and to avoid errors due to the large spatial variability of meteorological data, it is recommended to carry out the meteorological monitoring inside the forest area concerned. 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. Reflecting the spatial variability, of especially precipitation amounts and events, the maximum distance to a monitoring plot should not exceed 2000 metres. Under comparable conditions, comparable altitude and exposure are certainly more important than distance.

#### 2.2.1 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 2.7.

Another option is to set-up a tower inside the forest and to perform the measurements above the forest canopy. For a tower measuring above the canopy, fetch requirements must be fulfilled. The forest will exert a drag on the air and the fetch must be large enough to ensure that the boundary layer is in equilibrium with the forest area, which means that the meteorological variables are characteristic of the stand or the forest. 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).

### 2.2.2 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).

## 2.3 Mandatory variables

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

### 2.3.1 Air temperature and relative humidity

Air temperature and humidity are basic meteorological variables used to understand the physiological activity of the trees, to follow the effects of climate on growth or to calculate the evaporation and transpiration.

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 2,0 metres above ground level, on the north side of the mast.

### 2.3.2 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 x obstacle heights. So the quality of wind sensors can be diminished by poor exposure to local topography.

Wind sensors should in general be located over open terrain, if possible at standard height of 10 metres 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 then again important to report on the siting conditions.

When measuring above the forest canopy one should take the distance of traverse across a uniformly rough surface (fetch). 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. Commonly applied fetch to height ratios are 20:1 (Gash, 1986) and up to 100:1 (Munro, Oke, 1975). The height is here defined as the height of the vegetation minus the zero plane displacement height (approximatively between 0.5 and 0.8 times the vegetation height). It is not recommended to measure wind speed and direction in a clearing, unless the above mentioned distance requirements for open field are fulfilled.

### 2.3.3 Solar 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 the 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.

### 2.3.4 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 processes 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.

# 3. Technical recommendations

## 3.1 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 resulting differences in precipitation amounts against the reference height should be tested and reported.

| Sensor for : | Sampling height (m) |
|---|---|
| wind speed | 10 m |
| wind direction | 10 m |
| air temperature | 2 m |
| relative humidity | 2 m |
| solar radiation | 2 m or as convenient |
| net radiation, | 2 m |
| UVB-radiation, | 2 m |
| photosynthetic active radiation | 2 m |
| precipitation | 1.5 m (near the ground) |
| soil temperature | 5, 10, 20, 50, 100, 150 cm |

Table 2: Recommended height requirements of the meteorological sensors.

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

### 3.2 General technical recommendations

Most existing meteorological stations under the Level II programme use automatic stations with quasi-continuous sensing of the meteorological variables. When designing an automatic weather station, the site specific weather conditions need to be kept in mind. 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 at field and laboratory. The lifetime of components should be known so that the exchange of spare parts can be done in time. A modular construction of instruments enables easy replacement of spares parts and reduces data losses.

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.

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 the waterproofness of 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 losses. 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 and with an overlapping period for validation of data of at least 1 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, which may not be available and that no transmitter may be available in remote mountainous areas.

## 4. Data processing, storage and quality control

Meteorological data should be processed to generate hourly averages or shorter period averages (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.

The management and processing of climatological and meteorological data also include quality control (QC). It is important to be able 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 processing 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 monitoring data. A list of guidelines for quality assurance and check points is attached as Annex 3.

## 5. Evaluation and interpretation of meteorological data

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 already applied evaluation methods and models is attached as Annex 4.

## 6. Data submission

Submitted data are aggregated to daily values (sum or average/mean, min. and max., respectively) and 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 in Annex 5).

## 7. Level II plots without meteorological measurements

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.

## 8. Metadata and basic climatological information

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. As 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.

## 9. References

Gash, J.H.C. 1986. Observations of turbulence downwind of a forest-heath interface. Boundary Layer Meteorology 36, 227-237.

Munro, D.S., Oke, T.R. 1975. Aerodynamic boundary layer adjustment over a crop in neutral stability. Boundary Layer Meteorology 9, 53-61.

WMO. 1981. “Guide to hydrologic practices, Vol. I: Data acquisition and processing,” WMO-No. 168. Geneva, Switzerland.

WMO. 1983. “Guide to hydrologic practices, Vol. II: Analysis, forecasting and other applications,” WMO-No. 168, 4th edition. Geneva, Switzerland.

WMO, 1983. Guide to Climatological Practices. Second Edition. WMO No. 100. Geneva, Switzerland. Supplement No. 1. Geneva, WMO 1984. Supplement No. 2. Geneva, WMO.

WMO, 1996. Guide to Meteorological Instruments and Methods of Observation. Sixth Edition. WMO No. 8. Secretariat of the World Meteorological Organisation, Geneva, Switzerland.

The WMO guides can be ordered at:
(Secretariat of the World Meteorological Organization
Avenue Guiseppe-Motta 41, Casa postale No 2300
CH - 1211 Geneva 2, Switzerland)

# Annexes

**Annex 1:** Measurement of meteorological variables (soil temperature, soil moisture, stand precipitation and UV-b radiation)

**Annex 2:** Data processing and handling of missing data

**Annex 3:** Quality Assurance Programme within the Meteorological Network - Recommendations

**Annex 4:** Interpretation of meteorological data: stress indices and process-based models

**Annex 5:** Forms

**Annex 6:** Explanatory items

## Annex 1: Measurement of meteorological variables

This annex gives general (not exhaustive) information on the instruments for meteorological measurements of wind speed, wind direction, temperature, relative humidity, precipitation and solar radiation. 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 3.

### Wind.

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.

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.

### Air temperature.

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

### 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.

### 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.

| Meteorological variable | System accuracy | Measurement resolution |
|---|---|---|
| Wind speed | ± 0.2 m/s + 5% of observed | 0.1 m/s |
| Wind direction | ± 5 degrees | 1.0 degrees |
| Air and soil temperature | ± 0.5 °C | 0.1 °C |
| Relative humidity | ± | |
| Precipitation | ± 0.5 mm | 0.3 mm |
| Solar radiation | ± 5% of observed | 10 $W/m^2$ |

**Table 3:** Recommended system accuracy and resolutions (WMO, 1996)

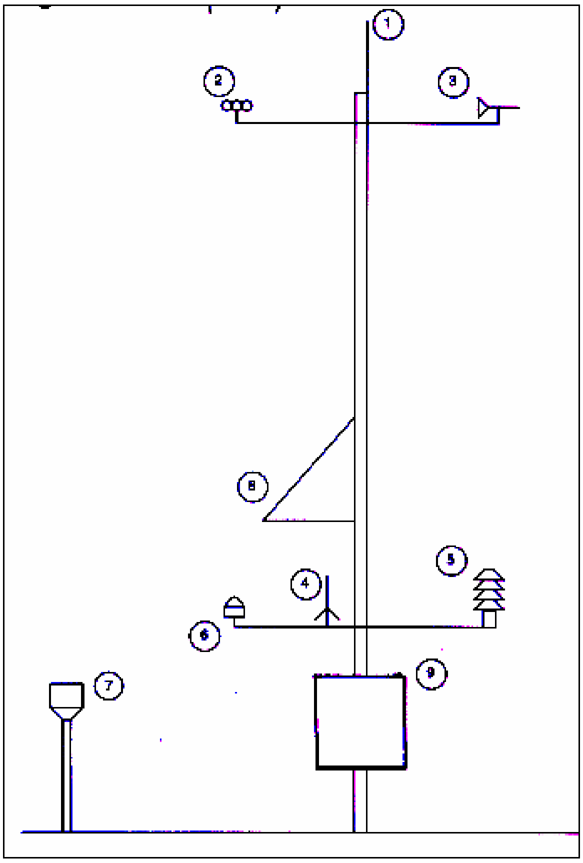

**Figure 1:** An example of a meteorological tower for measurements in open field. 1: lightning conductor, 2: wind speed at 10 m (cup anemometer), 3: wind direction at 10 m, 4: GSM antenna (2 m), 5: air temperature and relative humidity sensors at 2 m, 6: global radiation (pyranometer) at 2 m, 7: rain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

### 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 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.

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.

**Soil moisture**

Soil moisture measurement provides valuable information about the possible occurrence of drought episodes specific for tree species. 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 least one depth (-40 cm, or corresponding soil horizon) is recommended.

It makes sense to use of the both complementary methods: Tensiometer to measure soil matric potential (up to 800 hPa) and Time Domain Reflectometry (TDR) to measure volumetric soil water content (0-100 vol. %). For each depth the data of all measuring points of a Level II plot should be averaged and stored.

**Stand precipitation**

Precipitation in forest stands reaches the ground by throughfall and by stemflow.

**Throughfall**

Throughfall may be gathered by using 10-15 funnels, bottles or buckets or 1-2 gutters per plot. Placing of both types of collectors should be systematic. It is possible to use the same collectors as for wet deposition. In this case the instructions for deposition measurements (see Part VI) on the permanent observation plots should be considered. 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.

**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 | $m^2$ |

**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.

### 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

Relevant WMO-Guides to
Meteorological instruments and methods of observation: WMO - No. 8
Climatological practices: WMO - No. 100
Hydrological practices: WMO - No. 168

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CH - 1211 Geneva 2, Switzerland)

## Annex 2: 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 3: 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.

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.

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 4: 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 1.
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 4:** 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 | $\Sigma((\Sigma T_{min})/20\text{-Tmin}) > 8°C$<br>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 $\Delta T_{.}$ 15 K (T > 0 °C → T < -3 °C)<br>day 1: $T_{max} > 10$ °C → day 2: $T_{min} < -3$ °C | MAYER et al. (1988)<br>KÖNIG et al. (1989) |
| Late frost | Σ days with $T_{min} \leq 0$ °C (April - May)<br>Σ $T_{min} \leq 0$ °C (April – May)<br>Σ((number of day with $T_{mean} \leq 0$)*($\lvert T_{min} \rvert$+1) | ANONYMUS (1998) |
| 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<br>Σ days with pentade $T_{min} < 0$ °C<br>Σ $T_{mean}$ °C during winter<br>$T_{min}$ und $T_{mean}$ of the winter | ANONYMUS (1998) |
| Heat Stress | | |
| Heat indices | Σ days with $T_{max} > 30$ °C (= tropical days)<br>Σ days with $T_{max} > 35$ °C (= heat days) | REINDS (1998) |

| | | |
|---|---|---|
| Summer indices | $\Sigma\ T_{mean} > 5$ °C<br>$\Sigma\ T_{mean} > 5$ °C (during growing season) | REINDS (1998) |
| Precipitation | | |
| Drought Stress | | |
| Comparison with the long standing average | Monthly, half-yearly, yearly, growing season | Arbeitskreis Standorts-kartierung (1996) |
| Frequency of low precipitation | Σ pentads with NF = 0 mm or ≤ 1 mm | ANONYMUS (1998) |
| Frost dryness | $\Sigma\ (T_{max} - T_{min})$<br>if $T_{min} < -3$ °C and $T_{max} > 10$ °C | MAYER et al. (1988) |
| Evapotranspiration | $CWB = P - ET_p$<br>$Et_a / ET_p$ | REINDS (1998)<br>Arbeitskreis Standorts-kartierung (1996) |

## References

Anonymous (1998): Influence of weather conditions on the vitality of beetch and Scots pine - A case study over the past nine years.

Arbeitskreis Standortskartierung (1996): Forstliche Standortsaufnahme. IHW-Verlag, Eching bei München, 5. Aufl., 352 S.

BayFORKLIM (Bayerischer Klimaforschungsverbund) (1996): Klimaatlas von Bayern. Meteorologisches Institut der Universität München.

König, C., Mayer, H. (1989): Klimastatistik, Beurteilung im Hinblick auf neuartige Waldschäden. Münchner Universitäts-Schriften, Fakultät für Physik, Wissenschaftliche Mitteilungen 64, 646 S.

Liu, J.C., Nüßlein, S., Mößmer, R. (1998): Zusammenhang zwischen Kronenzustand und Zuwachsentwicklung von Fichte, Kiefer, Buche und Eiche auf Dauerbeobachtungsflächen zum Waldzustand in Bayern unter Berücksichtigung von Witterungseinflüssen. Projektbericht zum Projekt V01 Teilprojekt DWE "Ergänzende Wachstumskundliche Aufnahmen auf Dauerbeobachtungsflächen zum Waldzustand". Bayerische Landesanstalt für Wald und Forstwirtschaft / SG III.

Mayer, H., König, C., Rall, A. (1988): Identifikation von Witterungsereignissen mit pflanzenphysiologischer Stresswirkung für Waldbäume. Forstw. Cbl. 131-140.

Raspe S., (2001). Identification of meteorology based key parameters. In “Report on the Combined Workshop and Expert Meeting of the Expert Panels on Meteorology and Phenology”, Lousa, Portugal, October 18-21, 2000. Pan-European Programme for the Intensive Monitoring of Forests Ecosystems (EU/ICP Forests).

Reinds, G.J. (1998): Meteorological stress. Tentative agenda for the 3rd combined SAG/NFC meeting (Heerenveen, 16 - 18 September 1998) Session 3: Next year’s evaluation activities.

**Process-based models**

**Table 5:** Limited overview of process based models on growth, dynamics, water-balance and nutrient cycling of European forests, requiring detailed meteorological information

| Acronyme | Full name | Reference/Author |
|---|---|---|
| ASTER | | Loustau et al., 1992 |
| BIOMASS | | McMurtrie |
| 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[1] | 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[1] | 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 |
| WATERSTOF[1] | WATER en STOF transport | Wesseling and Van Grinsven, 1991 |
| WHNSIM | Water-, heat-, and nitrogen simulation | Huwe, B., 1990 |

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[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 6**: Tentative indication of the characteristics and meteorological requirements of the rnodels.

| Model | Characteristics | Meteorological requirements |
|---|---|---|
| ASTER | stand hydrology | T, P, H (d) |
| BIOMASS | stand growth (C, H2O balance) | 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 | patch | R,T,P,H,W (<d) |
| EXPECT-FORSOL |  | P,R,T,H,W?, (a) |
| FIWALD |  | P,R,T,H (d) |
| FORCLIM | patch |  |
| FORECE | patch |  |
| FORGRO | stand growth (C, H2O, nutrients) | T,P,H,R,W (<d) |
| ForM-S | . | T,P,R,H,W? (rn-a) |
| FORSKA-2 | patch |  |
| FORSUM |  | 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) |
| HydrAII |  |  |
| LWF-BROOK90 | hydrology, water budget | T,P,R,H,W (d) |
| MAGIC |  | P (a) |
| NAP | soil | ? (a) |
| NICCCE |  | P R T,H,W?(<d) |
| NuCM | nutrient cycling | T,P,R,H,W (d) |
| PnET-CN-CHESS |  | P,R,T,H,W?(<d) |
| PROFILE |  |  |
| SICA-SIMFORG | patch |  |
| SOIL-SOILN |  |  |
| SOILVEG |  | P,R,T,H,W? (<d) |
| STASH | patch |  |
| STANDFLUX |  | R,T,P? (<d) |
| SWIF |  | P (<d) |
| TRAGIC | tree | P,R,T,H,W (d) |
| TREEDYN3 | tree, stand | P,R,T,H,W (d) |
| TREGRO | tree | P,R,T,H,W (d) |
| WATERSTOF | soil | P,R,H? (<d) |
| WHNSIM | hydrology, water budget | T,P,R,H,W (d) |

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

## References

Aber J.D. & Federer C.A, 1993. A generalized, lumped-parameter model of photosynthesis, evapotranspiration, and net primary production in temperate and boreal forests. Oecologia 92: 463-474.

Arp P. & Oja T., 1992. Sulphate/nitrate loadings on forest soils: forest biomass and nutrient cycling modelling. In: Critical Loads for Nitrogen - A Workshop Report, Nord, 41: 307-358.

Berdowski J.J..M., Van Heerden C., Van Grinsven J.J.M., Van Minnen J.G. and De Vries W.,1991. SoilVeg: a model to evaluate effects of acid atmosphere deposition on soil and forest. I: model principles and application procedures. DPPA rep.114.1 02, RIVM, Bilthoven, The Netherlands.

Bossel H., 1994. TREEDYN3 forest simulation model. Mathematical model, program documentation, and simulation results. Berichte des Forschungszentrums Waldoecosysteme, Reihe B 35, Goettingen, pp 118.

Braat L.C., Bakema A.H., De Boer K.F. Kok, R.M., Meijers R.M. & Van Minnen J.G., 1991. EXPECT: outline of an integrated model for environmental scenario analysis and impact assessment. RIVM report 253102001, Bilthoven, The Netherlands.

Bugmann H., 1994. On the ecology of mountainous forests in a changing climate: a simulation study. PhD. Thesis no. 10638. Swiss Federal Institute of Technology, Zürich, Switzerland, 258 pp.

Cosby B.J., Hornberger G.M., Galloway J.N. & Wright R.F., 1985. Modelling the effects of acid deposition: assessment of a lumped-parameter model of soil water and stream-water chemistry. Water Resource Research 21: 51-63.

Friend A.D., Stevens A K, Knox R.G. and Cannell M.G.R. 1995. A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). Ecological Modelling

Hammel K. & Kennel M. 2001. Charakterisierung und Analyse der Wasserverfügbarkeit und des Wasserhaushalts von Waldstandorten in Bayern mit dem Simulationsmodell BROOK90. Forstliche Forschungsberichte München, 185, pp.135.

Hauhs M., Kastner-Maresch A. & Rost-Siebert K, 1996. A model relating forest growth to ecosystem-scale budgets on energy and nutrients. Ecological Modelling

Huwe B. 1990. WHNSIM. Ein Modell zur Simulation des Wasser-, Wärme- und Stickstoffhaushalts landwirtschaftlich genutzter Böden. Programmdokumentation Institut für Bodenkunde u. Standortslehre Fachgebiet Bodenphysik, Universität Hohenheim, pp96. (http://eco.wiz.uni-kassel.de/model_db/mdb/whnsim.html)

Jansson P.-E. & Karlberg, L. 2001. Coupled heat and mass transfer model for soil-plant- atmosphere systems. Royal Institute of Technology, Dept. of Civil and Environmental Engineering, Stockholm, 321 pp.

Kienast F. & Kuhn N., 1989. Simulating forest succession along ecological gradients on southern central Europe. Vegetation 79: 7-20.

Krauchi N. & Kienast F., 1993. Modelling subalpine forest dynamics as influenced by a change in environment. Water, Air and Soil pollution 68: 185-197.

Loustau D., Berbigier P. & Granier A., 1992. Interception loss, throughfall and stemflow in a maritime pine stand II. An application of Gash' analytical model of interception. Journal of hydrology 138: 469-485.

Ludiow A.R., Randle T.J. & Grace J.C. 1990. Developing a process-based growth model for Sitka spnuce. In: R.K Doxon, R.S. Meidahl, G.A. Ruark & W.G. Warren (Eds.): Process Modelling of Forest Growth Responses to Environmental Stress. Timber Press, Portland, OR, U.S.A. 249-262,

Magnani F. & Grace J.1996. HydrAll - Simulating optimal carbon allocation and tree growth under hydraulic constraints in Scots pine (Pinus sylvestris L.) Annals of Botany (in press).

Martin P.H., 1992. EXE: a climatically senstitive model to study climate change and CO2 enrichment effects on forests. Australian Journal of Botany 40: 717-735.

Michalzik, B., Tipping, E., Muldr, J., Gallardo Lando, J.F., Matzner, E., Bryant, C.L., Clarke, N., Lofts, S., Esteban V. 2003. Modelling the production and transport of dissolved organic carbon in forest soils. Biogeochemistry 66: 241-264.

Mohren G.M.J., 1987. Simulation of forest growth, applied to Douglas fir stand in The Netherlands. PhD Thesis, Agricultural University Wageningen, The Netherlands.

Munson R.K., Liu S., Gherini S.A., Johnson D.W., Wilkinson K.J., Hudson R.J.M., White K.S. & Summers K.V. 1992. NuCm Code Version 2.0: An IBM PC Code for Simulatiing Nutrient Cycling in Forest Ecosystems. Prepared by TETRE TECH, INC. Hadley, Massachusetts, Lafayette, California.

Prentice I.C., Sykes M.T., & Cramer W., 1993. A simulation model for the transient effects of climate change effects on forest landscapes. Ecological Modelling 65: 51-70.

Schall P., 1991. Productivity and vitality of spruce stands: dynamic feedback simulation for responses to different annual and seasonal levels of magnesium supply from soil. Vegetation 92: 111-118.

Tiktak A. and Bouten W., 1992. Modelling soil water dynamics in a forested ecosystem. III: model description and evaluation of discretization. Hydrological Processes 6: 455-465.

Van Dam D. & Van Breemen N., 1995. NICCCE: a model for cycling of nitrogen and carbon isotopes in coniferous ecosystems. Ecological Modelling 79: 255-275.

Van Oene H., 1992. Acid deposition and forest nutrient imbalances: a modelling approach. Water, Air and Soil Pollution 6: 33-50.

Veroustraete F., 1994. On the use of a simple deciduous forest model for the interpretation of climate change effects at the level of carbon dynamics. Ecological Modelling 75/76: 221-237.

Warfvinge P. Falkengren-Grerup U., Sverdrup H. & Andersen B., 1993. Modelling long-term cation supply in acidified forest stands. Environmental Pollution 80: 209-221.

Weinstein D.A., Beloin R.M. & Yanei R.D. 1991. Modelling changes in red spruce carbon balance in response to interacting ozone and nutrient stresses. Tree Physiology 9: 127-146.

Wesselink L.G., & Van Grinsven J.J.M., 1991. Modelling of soil acidification in Dutch and West-German forest ecosysterns. Dutch Priority Programme on Acidification, Rep. 202.1, RIVM, Bilthoven, The Netherlands.