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Continuous long-term measurements of soil-plant-atmosphere variables at a forest site

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Abstract

It is a major challenge in modern science to decrease the uncertainty in predictions of global climate change. One of the largest uncertainties in present-day global climate models resides with the understanding of processes in the soil-vegetation-atmosphere-transfer (SVAT) system. Continuous, long-term data are needed in order to correctly quantify balances of water, energy and CO_2 in this system and to correctly model it. It is the objective of this paper to demonstrate how a combined system of existing sensor, computer, and network technologies could be set up to provide continuous and reliable long-term SVAT-process data from a forested site under almost all environmental conditions.

The Central Tower Site (CTS) system was set up in 1993–1994 in a 25 m high boreal forest growing on a highly heterogeneous till soil with a high content of stones and blocks. It has successfully monitored relevant states and fluxes in the system, such as atmospheric fluxes of momentum, heat, water vapour and CO_2, atmospheric profiles of temperature, water vapour, CO_2, short-and long-wave radiation, heat storage in soil and trees, sap-flow and a variety of ecophysiological properties, soil-water contents and tensions, and groundwater levels, rainfall and throughfall. System uptime has been more than 90% for most of its components during the first 5 years of operation.

Results from the first 5 years of operation include e.g., budgets for energy, water and CO_2, information on important but rarely occurring events such as evaporation from snow-covered canopies, and reactions of the forest to extreme drought. The carbon budget shows that the forest may be a sink of carbon although it is still growing. The completeness of the data has made it possible to test the internal consistency of SVAT models. The pioneering set-up at the CTS has been adopted by a large number of SVAT-monitoring sites around the world. Questions concerning tower maintenance, long-term calibration plans, maintenance of sensors and data-collection system, and continuous development of the computer network to keep it up to date are, however, only partly of interest as a research project in itself. It is thus difficult to get it funded from usual research-funding agencies.

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The full value of data generated by the CTS system can best be appreciated after a decade or more of continuous operation. Main uses of the data would be to evaluate how SVAT models handle the natural variability of climate conditions, quantification of water, carbon and energy budgets during various weather conditions, and development of new parameterisation schemes in global and regional climate models.

Keywords: Carbon balance; Energy balance; Evaporation; Heat flux; Long term; Radiation; SVAT monitoring; Water balance

1. Introduction

It is a major challenge in modern science to decrease the uncertainty in predictions of global climate change to a level where economically overwhelming policy agreements, such as the Kyoto protocol, can be based on firm ground. One of the largest uncertainties in present-day general circulation models (GCMs) resides with the understanding of processes in the soil-vegetation-atmosphere-transfer (SVAT) system[3]. Most GCMs predict that climate change will be predominant at high latitudes and during the cold half of the year. This has motivated the conduct of large-scale land-surface experiments like NOPEX (Halldin et al., 1998, 1999a) and BOREAS (Sellers et al., 1997). Recent studies in GCM modelling have shown that major improvements may be more dependent on the availability of long-term, unbroken time series from a single representative surface rather than on data from a large set of time-limited measurements giving an areally representative flux (Viterbo and Beljaars, 1995).

Large-scale land-surface experiments were initiated in the second half of the 1980s. The first ones were conducted through the first half of the 1990s (Shuttleworth, 1991) to improve understanding of SVAT processes in temperate regions of Europe and the USA. These initial experiments focused on the co-ordination of resource-demanding space-and airborne facilities with a range of land-based measurement activities during limited periods of time. Such a time-limited experimental layout had certain weaknesses. Co-operation between hydrologists and meteorologists was limited since many hydrological processes have a time-scale exceeding the lifetime of these initial experiments. Values of parameters in large-scale circulation models can only be retrieved from satellite observations on a global scale. The development of algorithms for such parameters depends critically on ground-truth observations at representative sites during all kind of conditions. Episodic and seldom-occurring events that may have a large importance for surface balances of water, carbon, etc., as well as for the state of the atmosphere are difficult to capture within time-limited land-surface experiments. The study of such events requires intensive, long-term data series of fluxes and states at the land-surface-atmosphere interface.

Although intensive, continuous, and long-term SVAT data have been scientifically requested for a long time they have not been available until the 1990s. There are two major reasons for this. The first has to do with the technical complications in setting up combined systems to monitor SVAT processes for extended periods. Such integrated systems have only become possible through developments in sensor technology, data storage, and data communications during the last decade. The other reason has to do with organisational and financial restraints in running such facilities.

Intensive, long-term measurements of fluxes and profiles were initiated in the early 1970s by the Dutch weather service (KNMI) to study air pollution problems and processes in the atmospheric boundary layer (ABL). Data from the 203 m KNMI tower in the flat agricultural landscape of Cabauw are available periodically between 1973 and 1984, and continuously from 1986 (Van Ulden and Wieringa, 1996) and have been valuable, e.g., in the development of SVAT schemes of GCMs (Viterbo and Beljaars, 1995). Continuous long-term fluxes from the Harvard forests (Goulden et al., 1996a, b) are available from 1990 but with significant gaps. Harvard-forest measurements focus on biologically interesting climatic variables in the forest-atmosphere system. When NOPEX was originally conceived (Halldin, 1992), it was a main objective to put equal emphasis on short-term, areal

[3] Acronyms and relevant Internet addresses are given at the end of the paper.

coverage and continuous long-term records from one agricultural site and one forested site. In the end of the 1990s there has been an exploding interest around the world in launching long-term SVAT flux sites (Valentini et al., 1996). Continuous, long-term flux measurements have also been launched over sea surface. As a part of a Baltic Sea (BALTEX) project, a station for air-sea interaction studies was established at the small and very low island Östergarnsholm, 4 km east of Gotland (Smedman et al., 1997). Wind, temperature, humidity and turbulent fluctuations at several heights are recorded on a continuous basis since May 1995 on a 30 m tower.

It is the objective of this paper to demonstrate how a combined system of existing sensor, computer, and network technologies could be set up to provide continuous and reliable long-term SVAT-process data from a forested site under almost all environmental conditions. We demonstrate that such long time series can be guaranteed through long-term stability of the system, simplified quality control, and limited maintenance through automated supervision. Data generated by the system give us possibilities to gain insights into rarely occurring phenomena, to monitor changes, to get synergetic information on SVAT processes, and to get basic data on phenomena that are not well understood on a long-term basis. We believe that such long-term data will be useful to foster co-operation with interested researchers and students in future projects.

2. The forested site and the NOPEX CCM programme

The two main field activities within NOPEX were conceived to strike a balance between the need to cover sufficiently long observation periods and the amount of resources required to carry out field campaigns covering relevant spatial scales. The long-term data-collection activities, the Continuous Climate Monitoring (CCM) programme, form the backbone of the NOPEX field programme. Field activities which require major financial and man-power resources, like airborne deployments, intensive remote-sensing ground-truth data collection, and establishment of a network of micrometeorological field stations, are co-ordinated in a series of *Concentrated Field Efforts* (CFE). CFE1 on 27 May–23 June, 1994, CFE2 on 18 April–14 July, 1995, and CFE3 on 12 March–19 April 1997, have already been carried out. The objectives of the CCM programme is to complement the CFEs by allowing:

- comparison between mass and energy balances estimated with different methods,
- calibration and test of models from long-term observation series,
- long-term tests of instruments and methods for estimation of surface fluxes,
- studies of rarely occurring events which may be important for mass and energy balances and
- evaluation of the representativity of climatic conditions during CFEs.

The activities at the Central Tower Site (CTS) in Norunda Common, together with the continuous long-term measurements on an agricultural site at the Marsta Meteorological Observatory (Halldin et al., 1999b), constitute the backbone of the CCM programme.The Central Tower Site on Norunda Common is situated in central Sweden, 30 km north of Uppsala (Fig. 1), in the southern part of the boreal forest zone. The mean air temperature is 5.5°C (1961–1990), the mean annual precipitation 527 mm, and the mean Penman open-water evaporation 454 mm year^{-1} at Uppsala. Winter conditions vary from mild, with few and short events of snow and cold weather, to extended cold-weather periods. Forests are dominating the region as a whole but agricultural fields, lakes and bogs are interspersed in the landscape (Fig. 1). Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) heavily dominate the forest, with a small fraction (15%) of deciduous trees, primarily birch (*Betula sp.*) In contrast to the larger part of the boreal zone, agriculture has been carried out in the region for more than a thousand years and the forest has been managed in a planned way at least during the last 200 years. The site is situated in a mature pine-spruce forest that is owned and managed by the common of the more than thousand-year-old Norunda jurisdictional district (*Norunda Härad*).

The centre of activities of the CTS is the 102 m mast. The measurement system consists of:

- eddy-correlation measurements of fluxes,
- radiation at two heights above the forest,

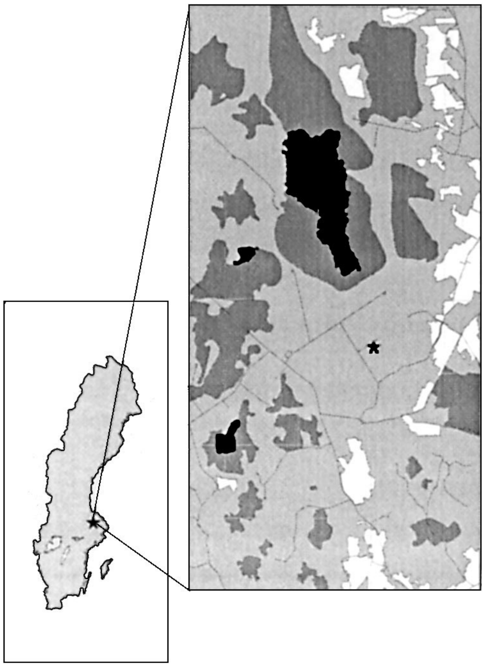

Fig. 1. Map of Sweden (scale ca 1 : 5 000 000) showing the location of Norunda Common and land use map (scale ca 1 : 160 000) showing the area around the tower (marked with a star). The black areas symbolise lakes; dark grey areas are peat bogs; light grey areas are forests and white areas are arable lands.

- atmospheric and within-canopy profiles of temperature, humidity, and CO_2,
- soil profiles of heat and (unfrozen) water content,
- heat storage in soil, biomass, canopy, and air,
- precipitation and throughfall,
- ecophysiological conditions of trees and ground vegetation.

The Norunda Common site was selected for its homogeneity and large stands, giving a fetch of more than 1 km in most directions and more than 20 km towards the Southwest, which is the prevailing wind direction. The site contains stands of various age and height. This is the reason behind setting up two ground stations, one in a 70-year-old stand and the other in a 100-year-old stand.

The tower is located by a dead-end forest road that is normally closed in order to avoid exhausts from motor vehicles to interfere with the CO_2 measurements (Fig. 2). The site is accessible by car all year around. Additional roadblocks at the main road further limit traffic in the area. 'The Greenhouse', a green equipment shed, contains the data-logger system for the tower and the data-communication system. It also contains a workshop and a small office for persons temporarily working at the site.

An important issue when operating a forest site with long-term ambitions is the control of forestry practices at and around the site. Normal forest management includes thinning of stands and finally clear cutting of the whole stand. Such operations will be incorporated into the CTS research plan. The Norunda Common site is leased from the landowner, the Norunda jurisdictional district, on a long-term contract and the leasing contract states which management practises are allowed. In practice, a good and close co-operation with the forester-in-charge guarantees a smooth site operation. Another aspect of site operation is impact of recreational interests such as hunting and forest trekking. We have good experiences from co-operation with the local hunting team that looks out for unauthorised persons at the site.

2.1. Geology and soil properties

The Norunda Common area is flat with small-scale variations in altitude of up to 10 m. The soil surface is highly uneven because of the presence of stones and blocks. Granite, sedimentary gneiss and leptite characterise the bedrock of the region. The soils are sandy-loamy tills with a high content of stones of all sizes and blocks up to 80 cm diameter. The gravimetric content of stones with a diameter larger than 20 cm was estimated to be around 15% in the area around the tower (100-year-old stand), whereas the content of fine material (<2 mm) was found to be around 30%. In the 70-year-old stand, the content of large stones is lower. The soils are podzolised and classified as dystric regosols. They consist of a thin organic layer, a reddish B-horizon and a yellowish-grey C-horizon. Soils are very compact below 70 cm; very few roots were found in the compacted subsoil. The groundwater table is highly variable. Compared to similar Swedish tills, the podzolisation of the Norunda tills is commonly weaker because of the content of limestone in the parent material, the slightly drier climate and the influence of grazing and other agricultural activities in the past. A soil-profile description, including chemical and physical properties (Table 1) was made in

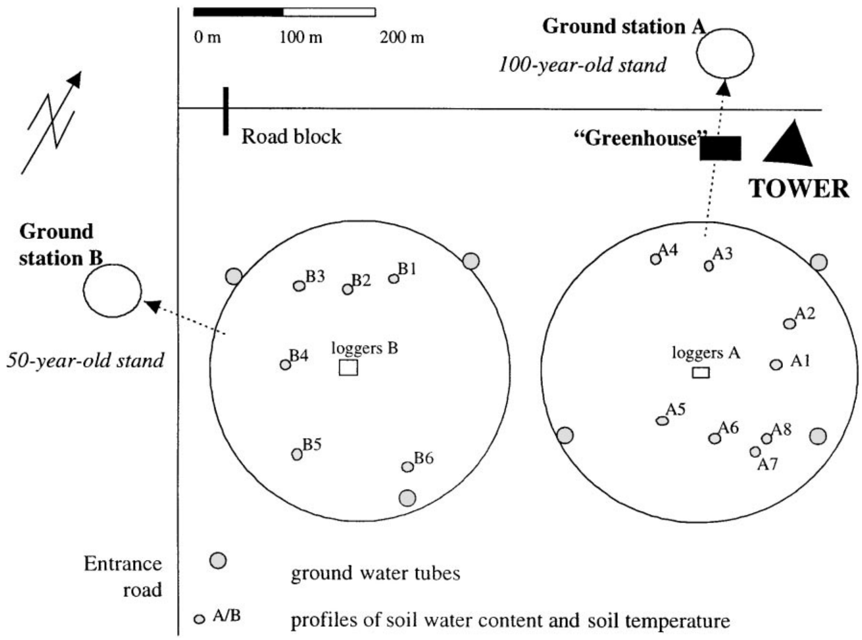

Fig. 2. Map showing tower and stands with soil measurements. The sap-flow and throughfall instruments are roving annually within the ground stations.

the two stands by Stähli et al. (1995). Lindahl (1996), estimates the saturated hydraulic conductivity in this heterogeneous material to 10^{-6}–10^{-4} m s^{-1}.

2.2. Stands and LAI

The stands within the 1 km range of the tower consist mainly of old and middle aged forest. About one quarter of the area consists of 100-year-old stands, half of the area of 50–100-year-old stands and one quarter of stands that are younger than 50 years. The canopy density varies mainly depending on species composition and the leaf area index (LAI) is coarsely estimated to be in the range 3–6 where pine dominated stands generally are thinner and spruce dominated are more dense. Most stands, including the surroundings

Table 1
Soil-physical properties (fine grain fractions) of the two stands at Norunda Common. Wilting point is defined as 1.5 MPa soil-water tension. Pore-size-distribution index, λ is a parameter in the analytical function: $S_e = (\psi/\psi_a)^{-\lambda}$ where S_e is effective saturation, ψ soil water tension and ψ_a is air entry pressure.

Horizon	Depth (cm)	Clay content (% grav)	Silt content (% grav)	Sand content (% grav)	Porosity (% vol)	Water content at wilting point (% vol)	Pore-size distrib. index (−)
100-year-old-stand							
AE/B_{S1}	0–25	5–9	26–43	45–63	44.1	6.4	0.29
B_{S2}	25–40	7	43	48	39.7	5.5	0.30
BC	40–51	4	24	72	39.2	3.4	0.24
C	51–70	2	24–29	70–74	39.2	3.4	0.24
70-year-old-stand							
Ah/B_{S1}	0–25	6–8	23–25	61–65	48.7	6.9	0.26
B_{S2}	25–49	4	27	65	42.5	5.9	0.25
BC	49–66	3	25	71	38.0	4.4	0.27
C	66–95	2	26	72	39.2	4.4	0.26

Fig. 3. Stands at Norunda Common and their leaf area indices. The figures within parenthesis give the number of stands in that particular class. The tower, marked with a star, is located in the centre of the 1 km-radius circle shown. A precipitation gauge is represented by a dot. The triangle marks the satellite site at the 70-year-old-stand, where various measurements are carried out.

of the tower, have an LAI of around 5 but some very dense stands reach 7 or more (Fig. 3). In one stand, ca. 70 years old, the needle area distributions have been determined in detail by destructive sampling and analyses (Morén et al., 1999). (Note that this stand was originally estimated to be only 50 years old and thus somewhat erroneously referred to as the 50-year-old stand.)

3. Description of the CTS monitoring system

The CTS is looked upon as a device for monitoring of the SVAT system. The device consists of sensors in the atmosphere, in and at the ground, and in various vegetation elements. A fenced 102 m tower supports the atmospheric sensors. All the sensors are connected to a data-collection system located in the 'Greenhouse', close to the tower, employing a sophisticated lightning protection system. The equipment shed is a modified, mobile 40 m^2 house. The device, or site, is connected to a 63 A electrical power line and has 10 telephone lines connected to the shed. The data-collection system is connected via modem to the local area network (LAN) at NOPEX Central Office in Uppsala and the telephone lines are dimensioned for future installation of ISDN.

3.1. Site location and tower construction

When the location for the NOPEX Central Tower Site was selected, the most important criteria were stand homogeneity and fetch. A minimum fetch of 1 km in all directions, implying a homogeneous stand of at least 3.1 km^2, was prescribed. Such large stands are very rare. A managed-forest landscape commonly consists of stands, typically smaller than 1 km^2 since management practises, land-owner borders, and interspersed bogs and lakes as well as agricultural fields give rise to patches on this smaller scale. The Norunda Common site is unique in the studied region for its size and homogeneity.

The tower, made by POTILA (Kokemäki, Finland), is a triangular stayed construction in galvanised steel. The tower legs are made of open angular profiles assembled with bolts. The tower side is 1.2 m and there are three levels of staying, the lower fastened at 30 m-radius and the two higher at 60 m-radius. The erection of the tower was done by Enator (Arboga, Sweden) who also fitted an inside ladder with a SWELOCK security rail (Bromma, Sweden), canalisation for cables, four rest platforms, Tykoflex obstruction lights (Tyresö, Sweden), mains outlets (220 V), signal inlets, and a specially designed lift for booms and instrumentation. Fifteen lightweight aluminium booms and three steel booms, extending 4.8 m and 5 m from the tower, respectively, can be fitted to any level. The booms can be slid sideways for mounting and maintenance of instruments. Headsets for communication between ground and tower personnel facilitate tower work.

The tower has a top-mounted lightning conductor and is grounded together with the equipment shed. Each stay is grounded at 2 m depth. All incoming power and telephone lines are connected to a common ground and a transient suppresser, cutting peaks up to 20 kA, is applied. All power outlets at the two ground stations are subject to transient suppression and are locally grounded. A copper wire, connected to the ground of the shed, is encircling each station to level out ground potentials. Additional transient suppressers are installed at each sensor and logger. The lightning protection system was designed by Åskskyddskonsult (Österbybruk, Sweden) and installed by In Situ (Ockelbo, Sweden).

In order to facilitate installation and maintenance, the attached booms are constructed so that they can be drawn into a position allowing work to be carried out from inside the tower. Special booms for mounting the eddy-correlation systems have been designed to minimise flow distortion. They are approximately 5 m long and have a rectangular cross section with an edge length of only 50 mm. The measuring paths of the sonic anemometer are located approximately 1 m above the boom. The booms are made of iron and are stiffer than the aluminium booms used for the profile system. They are mounted within an array of springs that makes them adjustable in two planes. In connection with a two-axis inclinometer that is incorporated in the base of each anemometer, the sonic anemometers can thus be adjusted vertically. The eddy-correlation booms can be slid sideways for maintenance in any kind of weather. The profile-system booms can get stuck during wintertime because of ice. Pending a redesign of the boom attachment, most of the maintenance (cleaning of ventilators, change of filters) must now be done just before the cold period in the hope that no further maintenance will be called for until spring or a warm-weather winter period.

Special care must be taken when making constructions on a forest site. Ideally, no disturbances should be caused to ground and vegetation. In order to not disturb the trees around the tower more than necessary, the tower was erected with a small mobile crane mounted on top of the uppermost tower segment. Trees were kept intact as close to the tower as practically possible. Care was taken not to damage trees or tree roots minimising the risk that they later may fall onto the tower or the stays. The 20 kV electric power lines and the telephone lines were canalised below ground, following the entrance road, in order to minimise disturbances. The tower causes unwanted effects on the measurements, mainly by distorting the wind profile and making reliable measurements in certain wind directions impossible. It also affects the temperature profiles somewhat, especially during warm summer days but we have found no significant effect on the humidity profiles.

3.2. Instrumentation

Sensors were located in the tower, at the ground stations, and at a nearby forest clearing (Tables 2 and 3). The design of the measurement and data-collection system was done in co-operation with In Situ (Ockelbo, Sweden), which also supplied the data-collection system and many of the sensors.

3.2.1. Atmospheric flux measurements

Turbulent fluxes of momentum, heat, water vapour, and CO_2 are measured at the heights of 35 m, 70 m, and 100 m by eddy-correlation systems (Grelle and Lindroth, 1999). Each system consists of a three-dimensional sonic anemometer, a fast-response thin-wire resistance thermometer, and a closed-path infrared gas analyser and operates with a sampling rate of 10 Hz. The use of an independent resistance thermometer to measure temperature fluctuations was necessary since the temperature signal from the sonic anemometer (the sound virtual temperature) is contaminated by noise at high wind speeds (Grelle and Lindroth, 1996; Grelle, 1997). This noise is correlated with the momentum flux and the sensible heat flux may be subject to a large error.

The gas analyser, power supply, air pump, and flow regulator are placed in an insulated, heated, and ventilated box on the tower below each eddy-correlation boom. This is necessary to keep the length of tubing supplying the gas analyser with sample air as short as possible in order to minimise signal damping. Data are collected and processed by the SOLCOM data-acquisition software (Grelle, 1997a). Turbulent fluxes are calculated on the basis of 10 and 30 min averages and the ‘micrometeorological’ sign convention is used, i.e., positive fluxes are directed upwards. The sonic anemometers have been calibrated to correct for flow distortion (Grelle and Lindroth, 1994). The turbulent fluxes are corrected for sensor inclination, signal time lag caused by the length of the sampling tube, frequency loss caused by both tube

Table 2
Long-term instrumentation at Central Tower Site (CTS) at Norunda Common. The Standard profile heights (SPH) are 8.49, 13.51, 18.98, 24.47, 28.01, 31.69, 36.91, 43.75, 58.54, 72.96, 87.51, and 100.57 m

Quantity	Instrument	Type	Company location	Level (s) [m]	Comment
Permanent instrumentation					
In the tower and equipment shed					
Wind speed and direction	Sonic anemometer	Gill Instruments Solent Basic	Lymington, UK	2801, 36.91, 43.75, 58.54, and 87.51 m	
Water-vapour and carbon-dioxide concentration	Gas analyser	LI-COR LI-6262	Lincoln, USA	SPH	Air is sucked through a heated tubing system from each SPH and analysed at the ground level
Air pressure	Indoors pressure sensor	Väisala PTA 427	Helsinki, Finland	1.7 m	
Air temperature	Thermocouple	In Situ	Ockelbo, Sweden	SPH	Standard copper-constantan wires, radiation-shielded and ventilated
Flux of momentum	Sonic anemometer	Gill Instruments Solent Scientific	Lymington, UK	35, 70, and 100 m	
Fluxes of latent heat and carbon dioxide	Gas analyser	LI-COR LI-6262	Lincoln, USA	35, 70, and 100 m	Connected to the sonic anemometer
Flux of sensible heat	Pt temperature sensor			35, 70, and l00 m	Connected to the sonic anemometer
Tilt of anemometer	Inclinometer	Sensorex 42430	Hadsund, Denmark	35, 70, and 100 m	
Net radiation	Net radiometer	Dr. Bruno Lange LXV055	Berlin, Germany	68 and 98 m	Equipped with polythene domes, ventilated
Short-wave radiation, global	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	102 m	Ventilated
Short-wave radiation, reflected	Pyranometer	Kipp & Zonen CM11	Delft, The Netherlands	68 and 98 m	Ventilated
Photosynthetically active radiation	Quantum sensor	LI-COR LI-1905Z	Lincoln, USA	98 m	Incoming and outgoing
Surface temperature	IRthermometer	Everest 4000	Fullerton, USA	102 m	Fixed at 45° from nadir to the East
Surface temperature	IR thermometer	Everest 4000	Fullerton, USA	95 m	Pan-tilt mounted, periodical operation
Rain	Rain gauge	In Situ IS200 W	Ockelbo, Sweden	102 m	
Precipitation flag	Precipitation detector	Väisala DPD12A	Helsinki, Finland	102 m	Indicates precipitation/no precipitation
In the 100-year-old stand, surrounding the tower (Ground Station A)					
Soil-water content	TDR	Tektronix 1502B	Pittsfield, MA, USA	3–5 level in 8 profiles	Campbell PB30-58 sensors used
Soil temperature	Thermocouple	In Situ	Ockelbo, Sweden	5 levels in 8 profiles	Stainless steel probes
Vegetation temperature	Thermocouple	In Situ	Ockelbo, Sweden	6 sensors in each of 5 trees, 34 sensors in one tree	Thin wire
Tree sap flow	Tissue-heat-balance sap-flow meter	Environmental measuring systems P609.2	Brno, Czech Republic	12/24 measuring channels, roving	1993, 1994

Soil-heat flux	Heat-flux plates	REBS HFT-1	Seattle, WA, USA	4 sensors, *c*. 6 cm depth	
Rainfall at ground level in the forest	Throughfall gauge	In Situ	Ockelbo, Sweden	5 gauges, roving	Each collector is 10 m by 0.1 m
Groundwater level	Pressure transducer	Grundteknik AB IDAS	Stockholm, Sweden	2 sensors, 3 m depth	
Transpiration	Heat-balance device	Environmental measuring systems	Brono, Czech Republic	6 trees	
In the 70-year-old stand, 400 m from the tower (Ground Station B)					
Soil-water content	TDR	Tektronix 1502C	Pittsfield, MA, USA	3–5 levels in 6 profiles	Campbell PB30–58 sensors used
Soil-temperature	Thermocouple	In Situ	Ockelbo, Sweden	6 levels in 6 profiles	Stainless stell probes
Vegetation temperature	Thermocouple	In Situ	Ockelbo, Swede	6 sensors in each of 6 trees	Thin wire
Tree sap flow	Tissue-heat-balance sap-flow meter	Environmental measuring systems P609.2	Brno, Czech Republic	12/24 measuring channels, roving	1994 to 1997
Soil-heat flux	Heat-flux plates	REBS HFT-1	Seattle, WA, USA	4 sensors, *c* 6 cm depth	
Precipitation at ground level in the forest	Throughfall gauge	In Situ	Ockelbo, Sweden	5 gauges, roving	Each collector in 10 m by 0.1 m
Fluxes of water and carbon dioxide	Chamber system	In Situ	Ockelbo, Sweden	2 systems, roving	To/from branches, stems, and forest floor
Groundwater level	Pressure transducer	Druck	Groby, UK	2 Sensors, 3 m depth	
In a clear cutting, 400 m from the tower					
Rain	Rain gauge	In Situ IS200 W	Ockelbo, Sweden	1.3 m	The gauge has a very small wind error and no wetting losses

Table 3
Instrumentation at Central Tower Site (CTS) at Norunda Common used during the establishment period

Quantity	Instrument	Type	Company location	Level(s) [ml	Comment
Soil-water content	TDR, manual	Tektronix 1502B w Campbell PB30–58 sensors	Pittsfield, MA, USA	top 30 cm (vertically installed); every 10 m on a 400 m and an 800-in-transect starting at the tower	June 1995
	TDR, continuous	Tektronix 1502B w Campbell PB30–58 sensors	Pittsfield, MA, USA	top 30 cm (vertically installed); in connection with sap flow measurements in the 70-year- old stand	July 1995
Soil-water tension	Tensiometers, profiles	Soilmoisture Equipment Corp	Santa Barbara, CA, USA	4 profiles; down to 1 m depth in the 100-year-old stand	June 1994
	Tensiometers, profiles	Soilmoisture Equipment Corp	Santa Barbara, CA, USA	3 profiles; down to 1 m depth in the 70-year-old stand	June 1994
	Tensiometers, spatial distribution	Soilmoisture Equipment Corp	Santa Barbara, CA, USA	vertically installed, 15 cm depth; c. 30 tensiometers in the 70-year-old stand	June 1994/ May 1995
Groundwater level	Pressure transducer, transect	Druck	Groby, UK	every 10 m on a 400 m and an 800 m-transect in the 70-year-old stand	July 1995

attenuation and sensor-response time (Leuning and Moncrieff, 1990), and air-density fluctuations because of sensible heat fluxes (Webb et al., 1980). The sonic anemometers are mounted on tilt-adjustable booms directed towards 210°. Given the triangular cross-section of the mast with 1.2 m edge length, only a small sector of the wind direction is contaminated by flow distortion caused by the mast.

3.2.2. Ecophysiological flux measurements

Sap-flow rate is measured with a sap-flow meter based on the tissue-heat-balance (THB) method of Čermák et al. (1973), Kučera et al. (1977). The technique does not require calibration and provides sap-flow rate in volume per time unit. In most cases we applied two measuring points for each of the sample trees. Tree samples covered both pine and spruce and several selection methods were tested during 1994–97. Data were sampled once a minute and stored as average values every 15 min. We used tree biometric parameters and Marklund (1988) Swedish biomass functions to scale tree fluxes into stand transpiration (Cienciala et al., 1999a, b).

Fluxes of water vapour and CO_2 to and from branches, trunks and forest floor are measured with open-chamber systems (described by Morén and Lindroth, 1999), which were designed to maintain near-ambient conditions within the chambers (Lindroth et al., 1999). They consist of a chamber made of transparent polyethylene foil, a pump unit and a control and measuring unit. A fan sucks air through the chambers and the flow rate is measured with high-accuracy propeller-anemometer. Air is sampled at the inlet and outlet of each chamber and the differences in water and CO_2 content of the samples is measured with an infrared gas analyser. To improve accuracy of the differential concentration measurement, the air streams to the sample and reference channels are reversed after each 5 min measurement cycle. With one chamber connected, the system gives 10 readings of water and CO_2-gas concentrations every hour, and with two chambers, five readings for each of the chambers every hour. Each reading is an average of 60 measurements: 30 measurements every third second before reversing and another 30 after reversing.

3.2.3. Atmospheric profile and radiation measurements

Sonic anemometers were chosen for the profile measurements of wind speed, to guarantee higher long-term stability of calibration factors than can be achieved with ordinary cup anemometers. Also, sonic anemometers can work uninterrupted during precipitation events. An overflow signal occurs if they are covered with a too thick ice layer. The anemometers have been checked in a wind tunnel, and small deviations from the manufacturer's calibration and the angular dependence have been taken into account. An accuracy of about 2% is reached for wind speeds up to 15 m s^{-1}.

The measurements of temperature, humidity and CO_2 profiles are described by Mölder et al. (1999b) and data are presented by Mölder et al. (1999c). Temperatures at different levels are measured relative to a single reference point, the 100.6 m level. Water vapour and CO_2 concentrations are measured with a single gas analyser. Therefore, even if there are small offset errors present, the differences in concentration are measured correctly. Concentrations at every measurement height are highly fluctuating, the fluctuations being even greater than the average differences between the highest and lowest measurement levels above the stand. Special continuous-flow mixing chambers between the tubing coming from the tower and the gas analyser solved this problem. Insulation and heating of the tubing prevent condensation of water vapour during summer periods, but cool summer nights and winter periods are problematic.

Net radiation and reflected short-wave radiation were measured at three heights (33, 68, 98 m) in 1994 to discover if there was any differences caused by different footprints (Mölder et al., 1999c). Height differences were well within the measurement errors. Since the effective radiation footprint of the forest was uniform over the 65 m height interval, the sensors from the 33 m level were removed in 1995. A fixed infrared (IR) thermometer has a field of view of 15° and is looking at the most uniform part of the forest near the tower. Another IR-thermometer, with a 4° field of view, was mounted on a Pan-Tilt unit during the summers of 1994 and 1995 to study the directional radiation temperature of the forest (Mölder and Lindroth, 1999).

3.2.4. Ground measurements

With regard to the soil-physical measurements, the two stands are similarly instrumented (Kellner et al., 1999): Temperature down to 1 m depth is measured at 5 depths at the 100-year-old stand and at 6 depths at the 70-year-old stand. The liquid-water content is measured at 3–5 levels, intended to be at the same depth as temperature.

Soil temperature is monitored with thermocouples (soldered in stainless steel tubes), connected via multiplexers to a Campbell (Logan, Utah, USA) CR10 data logger. All connections in each stand are placed in a central box where a reference temperature is given by a Pt100 sensor. Special care had to be taken to avoid effects of temperature gradients inside the connection box. The logger box was placed on the ground with all incoming cables going through a sand bed to give them a uniform temperature. A 10 cm insulating cover was added at the outside of the box to protect from the influence of daily air-temperature variations.

Soil-water content is monitored with the TDR technique (Topp et al., 1980). The soil probes consist of two 30 cm parallel metal rods inserted horizontally at a given depth and connected via multiplexers to the TDR instrument. The TDR instruments are equipped with Campbell Scientific's SDM 1502 Communications Interface and controlled by a Campbell CR 10 data logger. The data logger uses the algorithm described by Baker and Allmaras (1990) to calculate the apparent probe length and stores the quotient of apparent and actual probe length. The water content is later calculated using a third-order equation presented by Topp et al. (1980). Measurements were performed during the period June 1994–October 1995 in the 100-year-old stand while the 70-year-old stand was monitored June–September 1994 and then continuously since June 1995. Measurements and storage of data are made every half-hour.

Tensiometers were installed for measurements during July–September 1994 in four of the profiles in the 100-year-old stand and in three profiles in the 70-year-old stand down to 75 cm depth. Data were sampled by Campbell CR10 data loggers and stored as 30 min-averaged values.

Vertical tubes of 3 m length were drilled into the soil at three positions in each stand. The groundwater level is monitored continuously in two tubes in each stand, once per hour. Three of the tubes are instrumented with pressure transducers connected to a data logger. Data are retrieved manually from these loggers. The fourth tube is instrumented with a Druck pressure transducer connected to a Campbell BDR320 logger, equipped with a modem and mobile phone system (In Situ, Ockelbo, Sweden) from which data are retrieved automatically once a day.

3.2.5. Rainfall and throughfall

An improved net-precipitation measurement system using load cells was specially designed by In Situ Instruments (Ockelbo, Sweden) for use in the NOPEX CCM programme. The system is composed of a rainfall gauge for measurements of gross precipitation and troughs for throughfall measurements. Rainfall is measured on a clearing about 400 m from the tower (Seibert et al., 1999; Fig. 3) with a new type of rain gauge which minimises the systematic errors caused by wind and wetting losses (Seibert and Morén, 1999). This is achieved by a special windshield (Lindroth, 1991) and a construction where the entire collecting device is weighted. Rainfall is then computed from the increase of the accumulated weight. One rain gauge of the new type was also installed at the top of the central tower. Here the measurements are affected by considerable noise caused by wind-induced vibrations. A tentative comparison indicated that the catch of this gauge was about 80 of the amount measured in the clearing.

Throughfall gauges are placed at five randomly determined locations in each of the 70- and 100-year-old stands (Fig. 3). Each throughfall gauge consists of two 5 m long and 0.1 m wide V-shaped aluminium troughs resting on a stainless container attached to a tripod (Lundberg et al., 1997). The entire gauge, consisting of both troughs and containers, is weighed with a load cell. Data are stored every 10 s and filtering performed to eliminate the noise caused by wind gusts lifting the troughs. Evaporation from the container is also compensated for (Lundberg et al., 1997). Throughfall measurements were made during the 1995 and 1996 growth seasons in both the 70 and 100-year stands (Lundberg et al., 1999). The gauges have been used for special studies in different parts of the Norunda Common from 1997.

Measurement of snowfall, snow on the ground and snow intercepted by the canopy has not been performed. Such measurements require special equipment and are not done routinely anywhere in the world. Lundberg and Halldin (2000a, b) review the possibilities for measurements of snow and snow interception and indicate ways to implement such gauges/sensors/surveys in and around the Norunda Common.

3.2.6. Heat storage

Heat storage is measured in soil, air, and vegetation (Kellner et al., 1999). The vertical heat flux at the soil surface is measured at two selected locations in each stand with heat-flux plates placed at a depth of 5–7 cm in the humus layer just above the mineral soil. These measurements should only be considered as estimates because of the heterogeneity of the soil surface. The heat storage in the air is obtained through the temperature-profile measurements whereas vegetation heat storage is measured with thin-wire thermocouples. The sensors are small enough to allow measurements of temperature in individual needles. A total of 100 thermocouples are installed in trees at the two stands. Six trees at each stand are set up with six sensors in each. One of the trees in the 100-year-old stand has 28 additional sensors to study temperature distribution within a tree.

3.3. Calibration and maintenance procedures

Many of the sensors are calibrated only once and in some cases we relied on manufacturer calibration. Such calibration decisions were done both because of problems to uncover soil sensors without disturbing the measurements and because calibration procedures are less well defined. The soil temperature sensors, e.g., were only calibrated before installation. They rely on a well-established measurement technique and we believe that they are very stable. Rainfall and throughfall gauges were also just calibrated initially, by placing a known weight onto the collecting device at different starting values for the accumulated weight. The soil-heat-flux plates employ factory calibration factors and like all traditional heat-flux plates their output depend on the inevitable disturbance they create to the thermal flow for a variety of reasons. Tensiometers were calibrated in a laboratory. They need considerable maintenance since they are sensitive to dry conditions. The special characteristics of the stony till soil suggests that specially calibrated functions for the TDR system may be needed. Regular calibrations of the groundwater pressure transducers must be performed since they may be unstable with time. This is so because the position of the pressure transducers is sensitive to accidental movements.

The choice of the net radiometer was based on its good performance in a study by Halldin and Lindroth (1992). It was also among the best in a later study made by Mölder et al. (1995). According to our experience, the manufacturer has provided reliable calibration coefficients in the short- and long-wave spectra. A problem for all the upward-facing radiation sensors is wet snow covering the sensor. Dry snow is usually blown away by heavy winds. Net radiometers have been regularly calibrated against a standard kept at the Marsta Meteorological Observatory (Halldin et al., 1999b). Regular calibration is needed for the gas analysers and the IR-thermometer. Calibrations are performed 2–3 times per year for the profile-system analyser, with the aid of a water-vapour generator (LI-610, LI-COR) and a CO_2 reference gas (400 ppm). Although its offset has been checked more frequently, only the long-term changes have been corrected. The IR-thermometers have been calibrated against a black-body whose temperature can gradually be changed. The IR-thermometers that stand the humidity problem and keep their calibration for at least a half of a year usually continue doing so for several years.

Maintenance needs, like calibration procedures, cannot be described in a general way but only as a series of individual tasks, which must be carefully planned for the CTS as a whole. Problems encountered for soil measurements have mainly been associated with humidity (corrosion damage to the logger junctions) when the lids of some boxes fail. A further complication has been that the connections to the soil probes for TDR measurements were not protected for rust. They are thus sensitive to corrosion resulting in failures on some probes. Another problem with the TDR instrument was an internal-volatile-memory failure. The regular net-radiometer calibrations did not indicate any degradation in the optical properties of the expensive domes, which should be replaced twice annually according to the manufacturer. The domes were, thus, only replaced once per year to avoid that repeated exposition of cold winter weather made them brittle and prone to crack. Maintenance of the tower is required at regular intervals. Control of corrosion and state of the stays must be done every 5–10 years, depending on location, by an authorised company.

3.4. Data-collection system

The distributed data-collection system consists of two Campbell CR10 loggers at each stand, one for the TDR system and one for the other sensors. Two loggers are serving the tower, one for the Pan-Tilt-mounted IR thermometer and the tower-mounted rain gauge and one for the other sensors. The IS200W rain gauge on the clearing is connected to a Campbell BDR320 logger. The seven loggers are connected in a network using coaxial cable and multidrop interfaces (Campbell MD9). The network is controlled by a PC with a Campbell SC532 interface. Most sensors are connected to the loggers via Campbell AM416 relay multiplexers. The TDR instruments are directly connected to their loggers, with Campbell SDMX50 multiplexers between the instrument and the sensors. Communication on the network is administered by Campbell data-logger support software.

Each atmospheric flux-measurement system is connected to the serial port of a PC. All profile and radiation data are, via three multiplexers, measured and stored on a single data-logger at 6 s intervals. The signals from the gas analyser are measured twice at the same measurement level, but only the last reading is kept for further analysis. It takes 2 min 24 s to measure one full profile of water-vapour and CO_2 concentrations. The data are transferred to a PC with Campbell software at 1 h intervals. A file (700–800 Kb) containing the profile data is stored every night. The PC controlling the logger system also acts as a Windows NT network server. This server connects via modem each night to deliver data to the database server at the NOPEX Central Office (Fig. 4). The data are finally stored in the SINOP database (Lundin et al., 1999).

4. Results

Profile measurements have shown that a roughness sublayer exists over the forest, implying that ordinary semi-logarithmic profiles are not valid below a height of 50–60 m. Moreover, the gradients above this layer are so small that they are difficult to measure with present-day measurement technique. It was possible, however, to determine the displacement height of this forest and to find the corrected flux-profile relationships for the roughness sublayer by combining profile

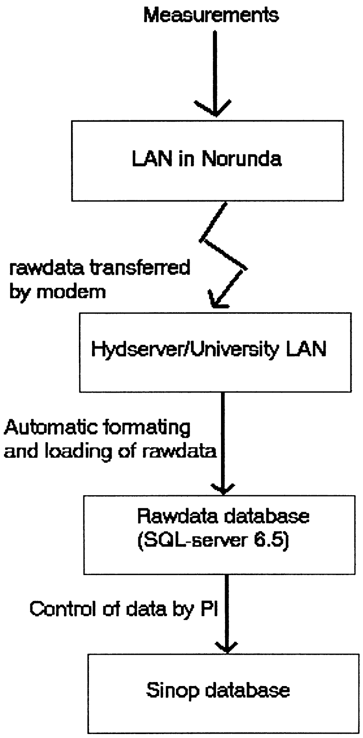

Fig. 4. Data flow from the sensors at Norunda Common to the SINOP database.

and eddy-correlation measurements (Mölder et al., 1999a). The roughness sublayers extend to 45 m for wind velocity and 57 m for scalar properties. The corrected relations were subsequently used to calculate the roughness lengths for wind speed and temperature (Mölder et al., 1999a). Many approaches and models rely on the semi-logarithmic profiles of meteorological variables. Knowledge of the depth of the roughness sublayer is needed to choose a proper height for such an analysis. The findings of Mölder and Lindroth (1999) enabled Grelle et al., (1999) and Iritz et al. (1999) to choose the 70 m eddy-correlation and the 73 m profile levels. It is common to verify SVAT models by comparing model-calculated fluxes with those obtained from an eddy-correlation system. Such a model may be tuned to give correct fluxes but is still internally inconsistent. Such inconsistencies are discovered through multi-criteria testing and this can only be performed with simultaneous data on profiles and/or surface temperature.

Northern-hemisphere forests have been suggested as the missing sink in the global carbon budget. The respiration of CO_2 in the CTS stand during nights and wintertime has been found such a substantial term (Grelle and Lindroth, 1996) that the Norunda forest acts as an overall carbon source. Concern is now expressed for the highly temperature-dependent balance between tree photosynthesis and respiration, especially from the ground. The profile measurements, which can give an estimate of short-term CO_2 storage, complement the eddy-correlation measurements above the stand in this context. Furthermore, the chamber measurements of CO_2 exchange within the stand make it possible to distinguish between tree-canopy and ground contributions to the total CO_2 flux from the stand.

The eddy-flux-system construction is based on experiences of harsh climate gained during an Arctic expedition (Grelle et al., 1994) and the system has proved suitable for unattended long-term measurements (Grelle and Lindroth, 1996). In particular, time series of high-frequency raw data and spectral analyses indicate that reliable measurements are made also during rain events. Valid data have been recorded for more than 97% of the time after start in May 1994.

Branch transpiration by means of chambers and sap flow at the base of a tree stem by means of the THB method were measured simultaneously (Fig. 5). This revealed the role of capacitance in tree tissues and resistance along the conductive pathway, which can be used to parameterise non-steady-state SVAT models. The sap-flow measurements were used to detect and

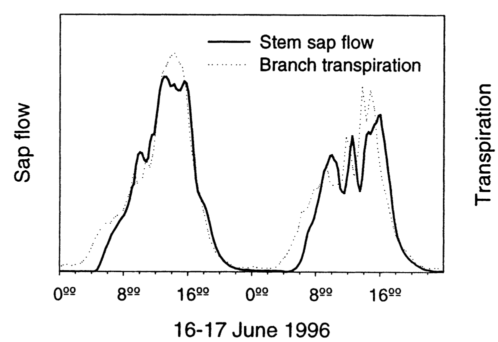

Fig. 5. Sap-flow dynamics at the base of a tree stem and transpiration dynamics of a branch in the middle of the green crown. Data from a 24 m high Scots pine tree in the Norunda Common forest. Sap flow and transpiration are shown in relative units to simplify comparison.

quantify water deficit for a stand on a daily basis (Cienciala et al., 1997) and analysed with a diurnal resolution for species separately (Cienciala et al., 1998a). The largest quantitative difference between species occurred during spring periods: Spruce started to transpire earlier than pine. Spruce transpiration was always better correlated to evaporative demand as compared to pine for spring periods (Cienciala et al., 1999). Sap-flow measurements were used for a detailed stand-water-budget analysis (Grelle et al., 1997) and parameterisation of a biogeochemistry model (Cienciala et al., 1998b).

Canopy-water storage was determined by two methods: the water balance of canopy, which gave 3.3 mm, and the so-called minimum method based on plots of throughfall versus rainfall, which gave a much lower value of 1.5 mm (Grelle et al., 1997). The combined measurements of rainfall, evaporation and throughfall facilitated analysis of canopy-storage capacity and the aerodynamic resistance without extensive and complex measurements of canopy characteristics (Lankreijer et al., 1999). The analysis was based on commonly used interception models and showed that the models do not simulate the interception process correctly.

The water budget for the two stands was estimated by measurements of rainfall, throughfall, tree transpiration, forest floor evaporation, and total evaporation during the 1995 growth season (Grelle et al., 1997). The accumulated total evaporation was 322 mm, transpiration was 243 mm, forest floor evaporation was 56 mm and interception evaporation was 74 mm. Seasonal interception evaporation constituted 30% of the precipitation. The evaporation components do not exactly match the total because the total evaporation was measured in the tower, representing the old stand, whereas the components were measured in the younger stand.

The continuous measurement of state variables and flows makes it possible to catch events that normally would be difficult to capture. Evaporation from the forest during and after a snowstorm has been shown to be considerable (Fig. 6). Snow fell over the whole NOPEX region on 3 October 1994. The water equivalent of the snow was 7.1 mm at Ultuna, 35 km southeast of the Norunda Common site. Temperature was well above zero at ground level so the snow was wet. The measurements showed practically zero evaporation (Fig. 6) when the snow fell. The skies cleared up in the early morning the following day and evaporation reached a maximum of about 180 W m^{-2}. The maximum evaporation rate fell to about 100 W m^{-2} and 40 W m^{-2} during the following two days and total daytime evaporation decreased from 1.7 to 0.23 mm during the 3-day period. The actual evaporation correlated better with the equilibrium rate than with the potential evaporation rate, assuming zero surface resistance, as estimated by the Penman (1953) equation (Fig. 6). The better correlation to equilibrium rates than to the potential rates indicated that the forest was de-coupled from the atmosphere, i.e., that evaporation was mainly controlled by radiation during this event.

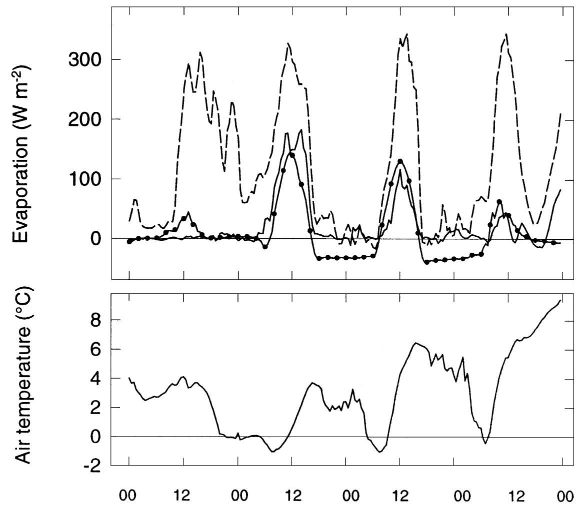

Fig. 6. Measured and estimated evaporation from the Norunda Common forest during 3–6 October 1994 (snow fell on 3 October). Top: actual evaporation (solid line), equilibrium evaporation (line with symbols) and potential (see text for explanation) evaporation (dashed line). Bottom: Air temperature during the same period.

5. Discussion

After almost 5 years of operation of the Central Tower Site we can conclude that it was possible to set up and successfully operate a continuous, long-term monitoring of a boreal-forest SVAT system. CTS has served as a valuable reference site for airborne activities and for temporary sites within the NOPEX area during the CFE programmes. Analyses of Gottschalk et al. (1999) have shown that combined forest-flux data from CTS and agricultural-flux data from the Marsta Meteorological Observatory can be weighted to give representative fluxes from the whole NOPEX region during spring and summer conditions.

Two types of climate-monitoring systems that produce valuable data for development of climate models have emerged in the last decade. The Cabauw (Van Ulden and Wieringa, 1996) and Lindenberg (Müller et al., 1995; Foken et al., 1997) systems have been set up with a focus on studies of the lowest part of the atmospheric boundary layer and can be labelled as ABL-monitoring sites. They have been complemented with equipment to also yield information on biologically and hydrologically interesting factors. The Harvard forest site (Goulden, 1996a, b) has a focus on biologically interesting processes governing fluxes of trace gases, water, and CO_2 and is one of the earliest examples of what can be labelled as a SVAT-monitoring system. Such systems are commonly equipped with towers shorter than 50 m. The majority of new systems now being set up in the framework of the global FLUXNET (encompassing EUROFLUX and AMERIFLUX) belong to the SVAT-monitoring category. The unique feature of the CTS, in combination with the Marsta Meteorological Observatory, is that it qualifies to both ABL and SVAT labels.

Many sites worldwide are now labelled 'continuous'. Our experience from more than $4\frac{1}{2}$ years of operation is that we can obtain long-term datasets with high accuracy and complete records for over 90% of the time, at least for the most important parts of the system. If activity at 'continuous' sites will prevail for extended periods, it will be important to document the percentage of downtime. Since a main purpose with long-term continuous monitoring is to catch rarely occurring phenomena it may be insufficient to have a system running 90% of the time. It is likely that the remaining time, when records are lacking, contain the most important events. Our experience is that problems occur primarily because of extreme weather conditions like thunderstorms during summer and blizzards during winter. It is normally impossible to perform maintenance or reparation during such conditions and they are, furthermore, often associated with power failures. It will not be possible to have personnel permanently located at CTS on a 24 h basis. Such intensive maintenance and control cannot even be motivated during very short campaigns. The best way to increase accuracy and uptimes is to further automate on-line quality controls in combination with alarm to personnel on-duty. Even an automated system will be costly to maintain over weekends and vacation periods. An analysis of the required system availability is recommended before further plans are laid out.

Further development of ABL- and SVAT-monitoring systems should focus on two problems. The first is the systematic description and analysis of downtimes. Do these pertain to special weather conditions, are they more common during winter, do they represent a major part of the water balance of the system? How do we interpolate data from such missing periods? The second relates to the life-length of installations and instruments and how replacement can be planned as part of maintenance and calibration routines. One should note that a big problem when analysing traditional meteorological data series has been changes in sensors or data-collection routines (Robinson, 1999).

5.1. Instrumentation and data collection

Grelle (1997b), made a detailed error analysis of the eddy-correlation system that indicates an overall error of 1.8% on the sensible heat flux, 7.3% on the latent heat flux, and 5.7% on the CO_2 flux. The accuracy of height differences in air temperature, water-vapour and CO_2 concentrations were first estimated and then checked against measurements, the first two differences against a Thermometer Interchange System (TIS) and the last against eddy-correlation results. The errors were within 0.03 K, 0.015 g kg^{-1}, and 0.8 mg kg^{-1} for temperature, specific humidity and CO_2 content, respectively.

The throughfall-gauging system was designed to give time-series data with a high temporal resolution and sufficient areal representativity. The load-cell-based system has made measurements possible on a fairly low budget. The system is limited to direct monitoring of throughfall and only give indirect information on the intercepted water. A complete set-up for interception-process studies would require complementary equipment to directly measure the intercepted mass (e.g., the microwave or displacement-transducer methods). Indications of temperature dependence were found for the load cells at high temperatures

(Seibert and Morén, 1995; Lundberg et al., 1997). The error remaining after wind, evaporation, and high-temperature corrections was normally much less than 0.01 mm h^{-1}. A safe distance between the troughs and the legs of the tripods was needed to guarantee that a correct weight was recorded. Literature data on throughfall variability from similar stands, in conjunction with a geographical-information-system (GIS) technique, were used to estimate the area-averaged accuracy for the throughfall data. Assuming that the spatial throughfall pattern at the Norunda Common site was in accordance with patterns from similar stands, the relative error of the measured averages from the five gauges in each stand was estimated to have a maximum error of 20% at a confidence level of 99% (Lundberg et al., 1997).

The high stone content made it difficult to place the 30 cm long rods of the TDR in the fine soil material. The depths of water-content monitoring are, thus, not uniform. The stony soil also made the installations difficult to carry out without disturbing the natural conditions. If there are air pockets round the probes, created when forcing the probes into the hard-worked soil, they result in an underestimation of water content. Large stones can give lower values of the water content if they are located in the nearest centimetres of the TDR probes, giving a smaller dielectric constant (= lower water content) than the average of the adjacent soil. The water-flow distribution in the soil is influenced by the distribution of large stones and the water flow is probably preferential. Even when water content has been measured in several profiles, the absolute values of the measured water content was rather uncertain. The relative change in water content can still be monitored with satisfying accuracy. Some technical problems pertain to the TDR system. The algorithm used by the logger to interpret the reflectance curve sometimes fails to find the right start and end of the trace. This is primarily seen at small depths in wintertime. The main cause is probably that the cables to the rods are too long, which gives reflectance traces that are difficult to interpret at certain water contents.

The heat-flux plates showed no problems with ageing when compared with each other. The plates are not ideal sensors since the thermal properties change with water content. This problem is accentuated during wintertime. The freezing of the ground, together with repeated melting-freezing cycles may create ice lenses at the top layer so the sensors give bad signals. Heat-flux measurements at the soil surface are further complicated by the heterogeneity of the soil. One source of uncertainty for this site is the uneven distribution of heat on the surface where the vegetation is absorbing the solar radiation only in part. Other uncertainties are the uneven thickness of the organic top layer and that the heat conductivity of the bare parts of stones and blocks is much larger than that of the fine material overgrown by mosses and other organic material. Consequently, if we measure the heat flux in the fine material we underestimate the input through the big blocks, which may be the dominating.

The data-collection system has been operating smoothly and without large problems, despite the fact that several persons have used common data loggers for their measurement systems. The need for synchronisation of various parts of the logger system was identified as important. This is especially crucial if local time is used in the system. In this respect the use of, e.g., UTC is to favour but it may cause problems since it deviates from normal office time. Several updates of software and hardware have been undertaken. Good planning and testing is recommended, as the pace of development is not the same for all manufacturers of software and hardware. Some DOS applications, e.g., do not run under Windows NT since direct hardware access is not allowed.

5.2. Maintenance and operational issues

The planning phase of the CTS project started in 1991 and lasted for 3 years, involving a large number of persons. Considerable time was spent on locating the site and designing the measurement system. During 1993 all permits for the tower erection were obtained and the tower was ready for operation by the end of the year. This process consumed a half man-year. In the initial phase, when instruments were mounted and tested, 5–6 persons worked full time for almost half a year to get all systems working. Ph.D. students performed most of the practical installation and maintenance work. This was a good solution for the initial phase but is less good for the operational phase. The long-term operation puts a strong demand for permanent staff connected and devoted to the operation of the site. The most time-consuming task is handling of the continuous flow of data.

Most maintenance problems that can be foreseen can also be monitored. Manual maintenance will still be required in order to discover unforeseen problems. Since labour costs are high and most funding authorities are unwilling to take on long-term salary duties, there is a need for an automated maintenance system for sensors and infrastructure of the site. Such a system should monitor the status and report maintenance needs. Experiences from the first 5 years of operation tell us to expect reports on fans that are not working, extensive ice cover on sensors, clogged filters or inlets, and too high humidity in junction boxes. The design of an automated maintenance monitoring system has been discussed and some aspects have been introduced within the current project.

The ambitions in 1999 are to operate the CTS continuously for at least another 10 years, assuming that interest from the scientific community and funding agencies pertain. The long time-series such an operation would produce would include a spectrum of weather events and trends caused both by climate change and stand development. Forestry activities, such as clear cutting of a sector, could be done in order to study management influences. It should be possible to revisit the NOPEX site for another CFE using next generation of sensors and to study their backwards compatibility with the ones used today.

6. Conclusions

A combined system for long-term, continuous, and intensive measurements of most key variables in the soil-plant-atmosphere system has been set up in a 25 m high boreal forest growing on a highly heterogeneous soil with a high content of large stones. Despite such difficult conditions it has been possible to combine present-day sensor, computer, and network technology into a system with an uptime of more than 90% for most of its components. The pioneering work at CTS has been followed at a large number of SVAT-monitoring sites around the world.

A number of new components evolved and modifications of existing systems had to be made, e.g., throughfall gauges, fast-response temperature sensors, and heated tubing system for the gas analysers, in the process of making the system operational. The present reliability and accuracy of the system is satisfactory. A half-time technician is a minimum requirement to keep the system running at the present quality level.

Enthusiastic Ph.D. students and researchers from Uppsala University and the Swedish University of Agricultural Sciences built up the system during the initial phase. The organisation of CTS must be changed and long-term, planned issues come more into focus to guarantee a high-quality operation during a long time period. Questions concerning tower maintenance, long-term calibration plans, maintenance of sensors and data-collection system, and continuous development of the computer network to keep it up to date is only partly of interest as a research project in itself. It is thus difficult to get it funded from usual research funding agencies.

The CTS system has already given much new knowledge about the SVAT system but the full value of data generated by it can best be appreciated after a decade or more of continuous operation. Main uses of the data would be to evaluate how SVAT models handle the natural variability of climate conditions, quantification of water, carbon and energy budgets during various weather conditions, and development of new parameterisation schemes in global and regional climate models.

7. Acronyms

AMERIFLUX	Long-term CO_2 flux measurements of the Americas; http://cdiac.esd.ornl.gov/programs/ameriflux/
BALTEX	Baltic Sea Experiment; http://w3.gkss.de/baltex/baltex_home.html
BOREAS	Boreal Ecosystem - Atmosphere Study; http://boreas.gsfc.nasa.gov/
EUROFLUX	Long term CO_2 and water vapour fluxes of European forests and interactions with the climate system; http://www.unitus.it/eflux/euro.html
ISDN	Integrated Services Digital Network
NOPEX	Northern Hemisphere Climate-Processes Land-Surface Experiment; http://www.hyd.uu.se/nopex/

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The contributions of the various authors of this paper were: Lundin was responsible for the planning of the CTS project as well as the tower projecting and the system design. Halldin was the co-ordinator of the NOPEX project and together with Lindroth involved in the system design. Grelle and Lindroth mounted and managed the flux system. Cienciala and Morén installed and managed the ecophysiology– measurement systems. Stähli installed the ground-measurement system and Kellner managed it. Seibert managed precipitation measurements and Lundberg was responsible for the throughfall measurements. Mölder was responsible for mounting and managing the profile and radiation systems. Nord designed, installed and managed the data communication system and Hjelm has mapped the site and worked with data management.

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