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Continuous long-term measurements of soil–plant–atmosphere variables at an agricultural 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 to correctly quantify balances of water, energy and CO_2 in this system and to correctly model them. 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 an agricultural site under almost all weather conditions.

A long-term climate-monitoring system within the framework of NOPEX was set up in 1993–1994 at the Marsta Meteorological Observatory (MMO). It is situated in a flat agricultural area where annual crops are cultivated on a heavy clay soil. 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 wind speed, direction, and temperature, short- and long-wave radiation, soil temperature, soil-water contents, groundwater levels, and rainfall and snow depth. 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 has proven MMO to be an ideal site for intercomparison and intercalibration of radiometers and fast turbulence sensors, and for evaluation of other sensors, e.g., rain gauges. The long time series of radiation data have been valuable to establish numerical limits for a set of quality-control flags. MMO has served as a boundary-layer research station and results from NOPEX campaigns show how the dimensionless wind gradient depends not only on the traditional stability parameter z/L but also on the height of the convective boundary layer. Measurements at the observatory grounds and a neighbouring field show a considerable variability in surface properties, which must be accounted for when assessing budgets of heat and other scalars. Questions concerning long-term calibration plans, maintenance of sensors and

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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.

The full value of data generated by the MMO 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: Energy balance; Evaporation; Heat flux; Intercalibration; 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 and its biological and socio-economic impacts 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 global climate models (GCMs; Acronyms and Internet addresses are given at the end of the paper) resides with the understanding of processes at the land-surface–atmosphere interface. Most GCMs predict that climate change will be predominant at high latitudes and during the cold half of the year and this has motivated large-scale land-surface experiments like NOPEX (Halldin et al., 1998, 1999a) in northern Europe and BOREAS (Sellers et al., 1997) in north America. Recent studies in GCM modelling have shown that major improvements require availability of long-term, unbroken time series (quality controlled and satisfying basic energy and water budgets) from single representative surfaces (Viterbo and Beljaars, 1995). Furthermore, there is a growing need for a separate characterisation of the fluxes of a given area in terms of its few representative elements, which will allow for a better physical understanding of the mechanisms responsible for the soil–vegetation–atmosphere interactions of complex, real-world sites. Considerable improvements may be expected when long-duration representative data are available from different climatic regions.

Values of parameters in large-scale models can, on a global scale, only be retrieved from satellite observations. The development of algorithms for the determination of such parameters is critically depending on ground-truth observations at representative sites during all kinds of conditions. These need to be continuous long-term measurements in order to come up with statistically representative results, taking into account the time schedule of overpasses of earth-surface-sensing satellites (twice per day to once per month, typically). Also, episodic and seldom occurring events that may have a large importance for surface balances of energy and water as well as for the state of the surface and the atmosphere are difficult to capture within time-limited earth-surface experiments. The study of such events requires intensive, long-term data series of fluxes and states at the earth-surface–atmosphere interface.

Global-climate modelling and satellite-based global monitoring, thus, require extensive long-term, continuous monitoring of land-surface–atmosphere interaction processes and states. The required data considerably exceed standard measurement programmes performed at the stations of national and international meteorological and hydrological networks. Although intensive, continuous, and long-term surface data have been scientifically requested for a long time they have rarely been available until the 1990s. One reason for this is the technical complications in setting up combined systems to monitor surface processes for extended periods. Such integrated systems have become possible through the development of sensor technology, data storage, and data communications during the 1990s.

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 is available periodically between 1973 and 1984, and continuously from 1986 (Van Ulden and Wieringa, 1996) and have been valuable, e.g., in 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 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).

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 an agricultural site at the southern border of the boreal zone under almost all weather conditions. We demonstrate that such long time series can be guaranteed through long-term stability of the system, automated 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 cooperation with interested researchers and students in future projects.

2. The agricultural 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 that 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 coordinated 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;
- evaluation of the representativity of climatic conditions during CFEs.

The activities at the Marsta Meteorological Observatory (MMO), situated in an agricultural area, together with the continuous long-term measurements at a forested site (the Central Tower Site, CTS) in the Norunda Common (Lundin et al., 1999a), constitute the backbone of the CCM programme. The measurement system consists of:

- eddy-correlation measurements of fluxes;
- radiation budget and components;
- atmospheric profiles of wind, temperature and humidity;
- soil profiles of temperature and (unfrozen) water content;
- precipitation and snow pack.

2.1. Climate and location

The Marsta Meteorological Observatory is situated in central Sweden, 9 km north of central Uppsala (Fig. 1), in the southern part of the boreal forest zone. The average air temperature is 5.5°C (1961–1990), the average annual precipitation 527 mm, and the average Penman open-water evaporation 454 mm per year 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 southern NOPEX region as a whole but agricultural fields, lakes and bogs are interspersed in the landscape and agricultural fields dominate the region around MMO (Fig. 1). In contrast to the larger part of the boreal zone, agriculture is carried out in the region and has been so for more than a thousand years. The site is

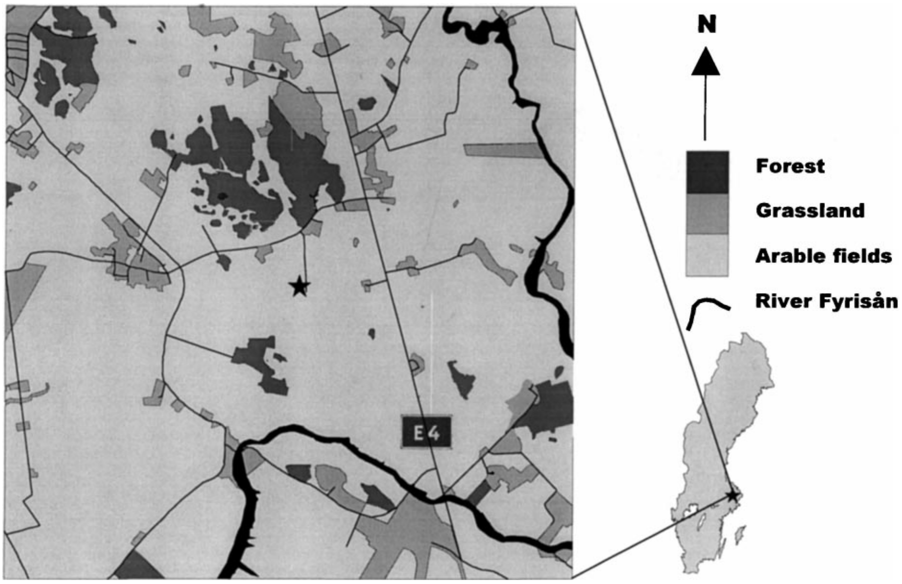

Fig. 1. Land use in a 5 km by 5 km square centred on the Marsta Meteorological Observatory (marked with a star) and the location of Marsta in Sweden (right).

situated in a region where the first appearances of Swedish culture can be traced.

The Marsta Meteorological Observatory was selected as a typical agricultural site with a fetch of 1–4 km (except in a northern and a small southwestern sector, where forest edges are situated 500 m away; Fig. 2). The site is surrounded by arable fields, which have been used for various crops over the years. There are nine farmers cultivating the fields within the nearest kilometre from the site. The MMO was an

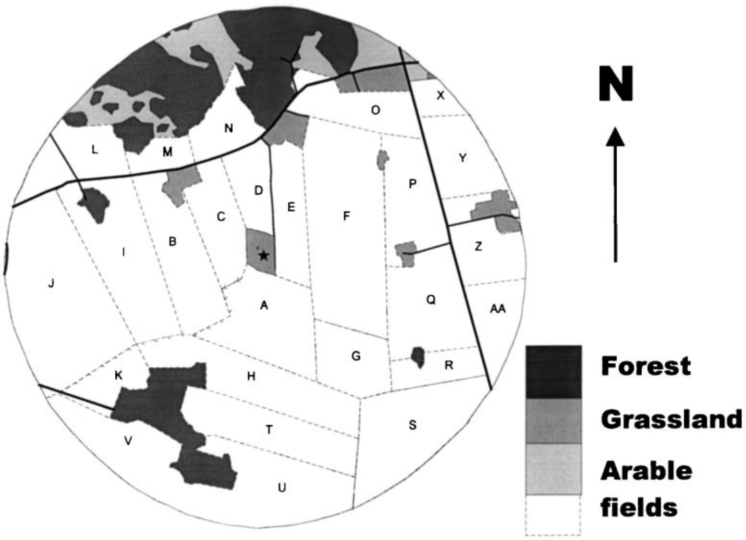

Fig. 2. Land within 1 km from the Marsta Meteorological Observatory (marked with a star). Crop species in the enumerated fields in 1995–1999 are given in Table 2.

obvious selection as agricultural site in the CCM programme because of its existing infrastructure, available records of weather observations, and a variety of data from different research projects.

Professor Köhler, who held the chair in meteorology at Uppsala University (1934–1955), got governmental funding in 1947 to establish a modern 'meteorological observatory' and constructions started in Marsta the same year. The station, with its instrumented 30 m tower, started producing high-quality data on the state of the lower part of the atmosphere about a year later. All the planned equipment was installed and started functioning in 1950. The station was then operated continuously in a 'climatological' mode for many years. Professor Liljequist, who succeeded Köhler in 1958, started to modernise the station, by erecting a much slimmer 30 m tower and installing new micrometeorological instrumentation. These installations were complemented in 1960 with instrumentation for air electricity and radioactivity. Studies in thunderstorm science, jointly with the department of high-voltage research at Uppsala University has been an important part of MMO activities since then (Israelsson, 1998). When professor Högström took over the chair in 1979, he had already performed boundary-layer studies in Marsta since 1965. These studies, aiming at establishment of firm relations for turbulent exchange processes in the atmospheric surface layer were carried out intensively (Smedman-Högström and Högström, 1973; Högström, 1974a; Högström and Smedman-Högström, 1974; DeHeer-Amissah et al., 1981) during the period 1968–1971. Intensive turbulence measurements were also carried out in the stable boundary layer above snow-covered ground in the winters of 1982 and 1983 (Smedman, 1988). In 1976, before the selection of MMO as a site for long-term measurements within NOPEX, the observatory had also become a centre for studies in acoustical meteorology. Since weather is the most important factor for outdoor sound propagation, it is of fundamental importance for calculation of the noise around various sources as traffic roads, industries, and aircraft (Larsson, 1997).

The site is located by a dead-end road that is only used by personnel visiting the observatory. The site is accessible by car and municipal bus services the whole year. A main building contains the data loggers for the different subsites, and the data communications. It also contains a workshop, office space, and space for temporary lodging. Permanently employed personnel served the observatory until May 1997. The observatory and the ground immediately surrounding it is owned by the Swedish state through Akademiska Hus, a company operating on the open market since the early 1990s. Uppsala University rents the observatory from this company.

2.2. Geology, soil properties, and vegetation

The MMO area is flat with variations in altitude of up to 10 m within the surrounding fields. Local variations up to 15 m can be found in the forested enclosures within the area. The soil consists of a heavy (40–60%) postglacial clay (Möller, 1993), fluvially deposited during the Bronze age (Lundegårdh and Lundqvist, 1956). The clay layer has a varying but often considerable depth down to the underlying Archean granite, generally rich in hornblende. The soil has a macro-aggregate structure typical for this type of clay soil. A soil-profile description based on 10 cm soil cores of the first metre, including physical and hydraulic properties was made in the field 100 m south-west of the main building (Table 1). Investigations in 1957 of soil-physical properties down to 2 m depth at a site about 500 m east of MMO demonstrate the spatial variability of soil properties within the site (Wiklert et al., 1983). The fields within the 1 km range of the flux and atmospheric profile measurements have mainly been cultivated with barley, wheat, rape, and peas (Table 2; Fig. 2). The growth season extends from May to September. The fields are normally ploughed in October and November and left bare during winter. Fields intended for fallow the following year are left unploughed in the autumn.

3. Description of the MMO monitoring system

The MMO is looked upon as a device for monitoring of the soil–vegetation–atmosphere-transfer (SVAT) system. The device consists of sensors in and at the ground, and in the atmosphere. Four subsites and a number of individual instruments within the confines of the observatory and at a nearby field contain these sensors, which are connected to data-

Table 1
Soil-physical properties at the Marsta Meteorological Observatory[a]

Depth (cm)	Clay content (%grav)	Silt content (%grav)	Sand content (%grav)	Porosity (%vol)	Water content at wilting point (%vol)	Pore-size-distribution index (−)	Air-entry pressure (10^{-4} MPa)	Saturated hydraulic conductivity (10^{-4} m s^{-1})
0–10	32.5	51.6	10.0	53.0	12.8	0.12	1.08	7.5
10–20	31.5	52.5	9.9	53.0	13.6	0.12	2.02	10.5
20–30	31.4	52.9	9.7	53.1	15.0	0.08	1.81	4.2
30–40	30.2	56.7	10.2	51.0	13.8	0.08	1.25	2.0
40–50	36.7	53.2	7.6	51.3	17.0	0.08	0.42	3.4
50–60	41.3	49.6	6.4	48.4	21.0	0.07	0.74	2.8
60–70	40.6	48.2	8.7	46.5	22.8	0.08	1.06	4.4
70–80	–	–	–	46.8	–	0.05	0.44	2.8
80–90	–	–	–	46.0	–	0.05	0.62	4.1
90–100	–	–	–	46.7	–	0.05	2.15	1.2

[a] Wilting point is defined as 1.5 MPa soil-water tension. Pore-size-distribution index, λ, and air-entry pressure, ψ_a, are parameters in the empirical function: $S_e = (\psi/\psi_a)^{-\lambda}$, where S_e is the effective saturation and ψ is soil-water tension.

collection systems at the subsites and in the main building (Fig. 3). The device, or site, is connected to a 63-A power line and two telephone lines. Parts of the data-collection system are connected via modem to the local area network (LAN) at the NOPEX Central Office in Uppsala.

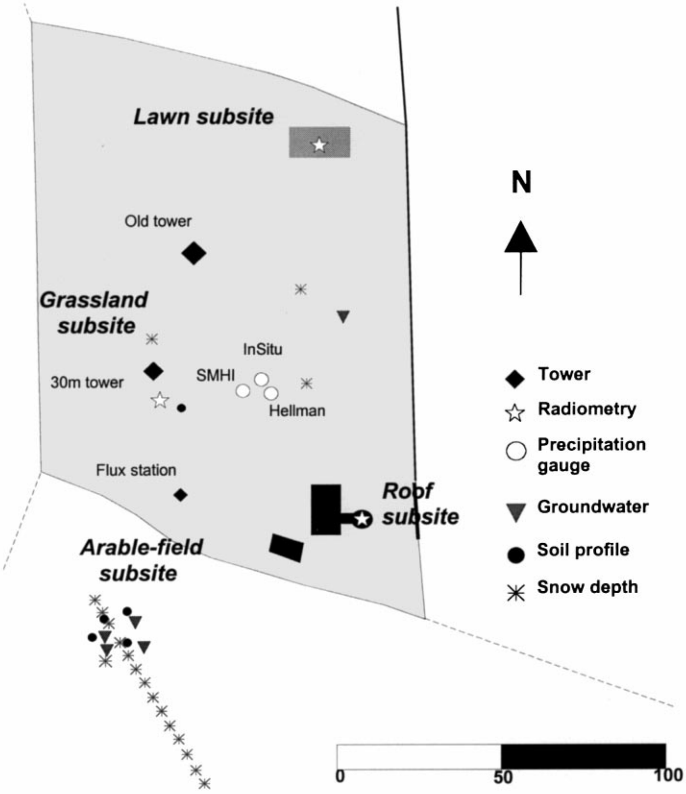

Fig. 3. Location of the four subsites and various instrumentation at the Marsta Meteorological Observatory in 1999 (scale in m).

Table 2
Crop species in the fields surrounding the Marsta Meteorological Observatory 1994/99 — barley (*Hordeum vilgare L.*), rape (*Brassica napus L.*), wheat (*Triticum aestivum L.*), oats (*Avena sativa L.*), peas (*Pisum sativum L.*) a hybrid between rye (*Secale cereale L.*) and wheat and fallow (various species)[a]

Field[b]	Year					
	1994	1995	1996	1997	1998	1999
A	–[e]	–[e]	Barley	Barley	Barley	Fallow
B	–[e]	–[e]	Rape	Barley	Wheat[c]	Peas
C	–[e]	–[e]	Barley	Wheat[c]	Barley	Wheat[c]
D	–[e]	–[e]	Barley	Rye-wheat	Fallow	Wheat[c]
E	Rape	Barley	Wheat[c]	Fallow	Wheat[c]	Barley
F	Barley	Fallow	Wheat[c]	Barley	Wheat[c]	Oats
G	–[e]	–[e]	Barley	Fallow	Rye-wheat	Wheat[d]
H	Barley	Wheat[c]	Barley	Barley	Rape	Barley
I	Barley	Barley	Barley	Rape	Wheat[c]	Barley
J	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
K	–[e]	Barley	Rape	Barley	Barley	Barley
L	–[e]	Rape	Barley	Barley	Rye-wheat	Barley
M	–[e]	Rape	Barley	Barley	Rye-wheat	Barley
N	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
O	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
P	–[e]	–[e]	Rape	Wheat[d]	Barley	Barley
Q	–[e]	–[e]	Rape	Barley	Barley	Wheat[d]
R	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
S	Oats	Rape	Wheat[d]	Barley	Barley	Barley
T	–[e]	Barley	Rape	Barley	Barley	Barley
U	Barley	Barley	Barley		Wheat[c]	Barley
V	Wheat[c]	Barley	Wheat[c]	Barley	Barley	Barley
X	–[e]	–[e]	–[e]	–[e]	–[e]	–[e]
Y	Barley	Wheat[c]	Oats	Barley	Barley	Barley
Z	Oats	Barley	Oats	Barley	Oats	Barley
AA	Oats	Rape	Wheat[d]	Oats	Barley	Barley

[a] Field designations from Fig. 2.
[b] Source: The nine farmers cultivating the fields around the Marsta Meteorological Observatory.
[c] Winter wheat.
[d] Spring wheat.
[e] No information available.

3.1. Site location and main installations

Fetch and homogeneity of surrounding fields was an important criterion when the MMO site was selected. A minimum fetch of 1 km in all directions, implying homogeneous fields of totally 3.1 km^2, was a goal (Fig. 2). The homogeneity requirement coincided with the requirement for a low and unobstructed horizon that minimises disturbances on radiation measurements (Fig. 4).

There are four subsites at and directly outside the observatory grounds (Fig. 3). The grassland subsite was funded as a facility for undergraduate education and does double duty in research and education. The arable-field subsite was funded for studies of winter conditions and was set up later than the other subsites. The roof and lawn subsites were established as core facilitities of the NOPEX CCM programme and are used for radiometer intercomparisons and to provide general radiation data for the NOPEX region. The location of other equipment at the observatory grounds has historical reasons.

The original 30 m tower from 1948 (somewhat resembling a small Eiffel tower) would have caused unacceptable disturbances on the atmospheric profile and flux measurements. It still causes disturbances on radiation measurements at 225–229° solar azimuth angles (Fig. 4). To perform high-quality atmospheric

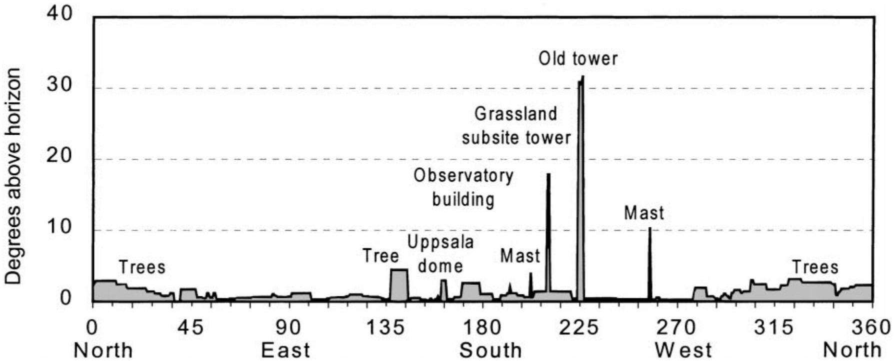

Fig. 4. The horizon as seen from the lawn subsite at the Marsta Meteorological Observatory in February 1997.

surface-layer measurements, a modern 30 m tower was erected in the spring of 1994 as part of the grassland subsite. This tower mainly causes disturbances 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. The new tower, made by WIBE (Mora, Sweden), is a triangular, stayed construction in galvanised steel with tower legs made of tubes. The tower side is 0.28 m and there are three staying levels. Seven galvanised steel booms, extending 1 m from the tower, can be fitted to any level. The booms can be slid sideways for mounting and maintenance of instruments. The measuring path of the sonic anemometer is located approximately 0.7 m above the boom.

The arable-land subsite consists of two installations. A 3.5 m rod was set up in April 1997 some 40 m south of the grassland tower to host a flux-measuring station (Fig. 3) for evaporation, sensible-heat, and CO_2 fluxes from the arable field south of the observatory. This station complements the installation for measurements of soil and snow properties made in the field. Equipment at this field is unearthed annually when the land is cultivated but a power line is permanently buried below the plough pan to allow easy re-establishment of the installation.

Incoming power and telephone lines are connected to a common ground and a transient suppresser to protect against lightning damages. Additional transient suppressers are installed at each end of the communication lines between data-storage computers in the observatory building and subsite loggers.

3.2. Instrumentation

The majority of instruments reside at the four subsites (Table 3). The design of the two radiometric subsites and data-collection systems was done in cooperation with InSitu (Ockelbo, Sweden), which also supplied the data-collection system and many of the sensors. InSitu also supplied most of the equipment to the arable-field subsite. Promicro AB (Sollentuna, Sweden) supplied the data-collection system for the atmospheric profile measurements at the grassland subsite.

3.2.1. Atmospheric profile measurements

Instruments for wind speed and direction, and air temperature and humidity are mounted at six heights (0.8, 1.9, 4.8, 10.1, 17.2, and 29.0 m) on the grassland tower (Smedman et al., 1999). Wind speed and direction are measured with in-house-designed and manufactured cup/wind-vane anemometers (Bergström and Lundin, 1993). These combined instruments give information on mean wind and turbulence conditions for the longitudinal wind components along the mean wind direction as well as the lateral wind component perpendicular to it. The anemometers are mounted on booms, pointing towards 305°, i.e., wind data from 110–150° are distorted. The anemometers are sampled at 1 Hz and data are stored as 10 min averages. Comparisons with hot-film-instrument measurements (Smedman et al., 1991) show good agreement for both turbulence statistics and spectra.

Ventilated and radiation-shielded Pt500 thermometers record air temperatures. Humidity is measured with wet- and dry-bulb thermometers according to the

Table 3
Long-term instrumentation at Marsta Meteorological Observatory (MMO)[a]

Quantity	Instrument	Type	Company location	Level(s) (m)	Comment
Grassland subsite					
Wind speed	Cup anemometer	MIUU	Uppsala	SPH	
Wind direction	Wind vane	MIUU	Uppsala	SPH	
Water-vapour concentration	Psychrometer	MIUU	Uppsala	SPH	Radiation-shielded and ventilated
Air temperature	Thermocouple	MIUU	Uppsala	SPH	Radiation-shielded and ventilated
Flux of momentum	Sonic anemometer	Gill Instruments Solent Scientific R2	Lymington, UK	10	
Flux of sensible heat	Sonic anemometer	Gill Instruments Solent Scientific R2	Lymington, UK	10	Sonic-anemometer virtual temperature
Air pressure	Aneroid barometer	144SC0811-BARO	Stockholm	0	
Net radiation	Net radiometer	Siemen Ersking	Fredrikssund, Denmark	1.4	Not ventilated
Shortwave radiation, global	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	1.4	Not ventilated
Shortwave radiation, reflected	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	1.2	Not ventilated
Longwave radiation, from sky	Pyrgeometer	Eppley PIR	Newport, USA	1.4	Battery-circuit operation, not ventilated or shaded
Longwave radiation, from ground	Pyrgeometer	Eppley PIR	Newport, USA	1.2	Battery-circuit operation, not ventilated or shaded
Soil temperature	Thermistors	MIUU	Uppsala	2, 5, 10, 30, and 63 cm	Stainless steel probes
Soil-heat flux	Heat-flux plates	Middleton	Aspendale, Australia	3 sensors, ca. 1 cm depth	
Arable-field subsite (started operation in 1997)					
Air temperature	Thermocouple	InSitu	Ockelbo, Sweden	0.8	Standard copper-constantan wires, radiation-shielded and ventilated
Soil-water content	TDR	Tektronix 1502B	Pittsfield, MA, USA	4 profiles, 10, 20, 40, 60, and 80 cm	Two-rod sensors, 25 cm long in two profiles, and three-rod sensors,30 cm long in two profiles
Soil temperature	Thermocouple	InSitu	Ockelbo, Sweden	2 profiles, 5, 10, 20, 40, 60, and 80 cm, 5 points at the soil surface	Copper-constantan wires
Groundwater level	Pressure transducer	Druck PDCR 830	Groby, UK	4 sensors, 3 m depth	
Snow depth	Sonic ranging sensor	Campbell SR50	Logan, Utah, USA	downfacing at 1.8 m	Travel time of ultrasonic pulse between sensor and surface is recorded
Snow depth	Snow stakes	–	–	70 m transect, 5 m apart	Manual observations in connection to snow events
Flux of momentum	Sonic anemometer	Gill Instruments Solent Research R3	Lymington, UK	3.5	
Flux of latent heat and carbon dioxide	Gas analyser	LI-COR LI-6262	Lincoln, USA	3.5	Connected to the sonic anemometer. Air is sucked through tubing and analysed at the ground level

Table 3 (*Continued*)

Quantity	Instrument	Type	Company location	Level(s) (m)	Comment
Flux of sensible heat	Pt temperature sensor/ Speed-of-sound temp.	InSitu/Gill Instruments Solent Research R3	Ockelby, Sweden/ Lymington, UK	3.5	Connected to the sonic anemometer
Roof subsite					
Shortwave radiation, global	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	7	Ventilated
Shortwave radiation, direct	Pyrradiometer	Eppley NIP	Newport, USA	7	On sun-tracker
Shortwave radiation, diffuse	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	7	Ventilated, shaded
Photosynthetically active radiation	Quantum sensor	LI-COR LI-190SZ	Lincoln, USA	7	Incoming and outgoing
Longwave radiation, from sky	Pyrgeometer	Eppley PIR	Newport, USA	7	Ventilated, shaded
Solar radiation, 9 channels 5 nm wide	Sun photometer	CSEM SPM-2000	Neuchâtel, Switzerland[b]	7	On sun-tracker. Channels: 368, 411, 499, 675, 718, 777, 817, 862, 944 nm
Shortwave spectral radiation, 300–100 nm	Spectroradiometer	LI-COR LI-1800	Lincoln, USA	7	Kept at constant temperature, 6 nm spectral resolution
Position of sun	Sun-tracker	BRUSAG INTRA	Stäfa, Switzerland	7	Automatically self-adjusting
Lawn subsite					
Net radiation	Net radiometer	Dr. Bruno Lange LXV055	Berlin, Germany	1.7	Equipped with self-sustained, ventilated polyethylene domes
Shortwave radiation, reflected	Pyranometer	Kipp & Zonen CM21	Delft, The Netherlands	1.7	Ventilated, protected against precipitation
Longwave radiation, from ground	Pyrgeometer	Eppley PIR	Newport, USA	1.7	Ventilated, protected against precipitation
Other instrumentation					
Rain	Rain gauge	InSitu IS200W	Ockelbo, Sweden	1.4	The gauge has a very small wind error and no wetting losses; May–October
Rain	Rain gauge	R. Fuess/Hellman	Berlin-Steglitz, Germany	1.13	May–October
Rain	Rain gauge	SMHI	Norrköping, Sweden	1.55	Manual observation weekdays around 09:00 hours, halted May 1997
Groundwater level	Well/measuring-rod	–	–	–	Manual observations weekdays around 09:00 hours, halted May 1997
Boundary-layer profiles	Sounding balloon	Vaisala RS80-15	Helsinki, Finland	0–10 000	

[a] The Standard Profile Heights (SPH) are 0.84, 1.95, 4.78, 10.1, 17.2, and 29.0 m.

[b] CSEM photometer activities were transferred to INTEC, Bern, Switzerland in December 1996.

psychrometric method, using pairs of ventilated and radiation-shielded Pt500 sensors. The ventilation speed is 5–6 m s^{-1} in the common shields. The absolute dry temperature is only measured at the lowest height (0.8 m). Temperature differences are measured at the adjacent levels, following the principles of the air-temperature-measuring system described by Smedman-Högström and Högström (1973). The accuracy of the temperature-difference measurements is about ±0.02°C and for the absolute temperature the accuracy is estimated to be roughly ±0.1°C. Humidity data are based on differences in the measurements between dry- and wet-bulb temperatures at each level.

3.2.2. Atmospheric flux measurements

Atmospheric fluxes are measured with two devices. Three-dimensional sonic anemometers fulfil somewhat different purposes at two subsites.

The first device is mounted on the grassland tower at the 10 m height. Its primary purpose is to complement the atmospheric-profile measurements within the undergraduate education in meteorology. It operates with a sampling rate of 21 Hz and is mounted on a tilt-adjustable boom directed towards 245°. Given the 0.28 m triangular cross-section of the mast, only a small sector of the wind direction (40–80°) is distorted by it (Smedman et al., 1999).

The second device, on the 3.5 m rod, combines a sonic anemometer, a fast-response thin-wire resistance thermometer, and a closed-path infrared gas analyser. It operates with a sampling rate of 10 Hz. The main purpose of this device is to provide fluxes of evaporation, sensible heat, and CO_2 for SVAT modelling. The resistance thermometer is used to ascertain that the temperature signal from the sonic anemometer (the sound virtual temperature) is not contaminated by noise at high wind speeds as found for forest measurements by Grelle and Lindroth (1996), and Grelle (1997). They found this noise to be correlated with the momentum flux that caused a large error to the sensible heat flux.

The gas analyser, power supply, air pump, and flow regulator are placed in an insulated, heated, and ventilated box on the ground. A 4 m long tubing supplies the gas analyser with sample air. Although the system was ordered as identical to that developed at the Norunda Common forest site, the acquisition and processing software from that system could not be used because of small model change for the Solent anemometer. The RCOM data-aquisition software (Gill Instruments Ltd., 1996) instead handles data collection. Data processing is done off-line with in-house software. Turbulent fluxes are calculated on the basis of 30 min averages. The turbulent fluxes are corrected for sensor inclination, signal time lag caused by the length of the sampling tube, and air-density fluctuations because of water heat fluxes following recommendations within the EUROFLUX community (Grelle, 1999, personal communication). The flow distortion by the rod is assumed negligible since the sensors are mounted on top of it.

3.2.3. Radiation measurements

Radiation is measured at three different places at MMO (Halldin et al., 1999b; Smedman et al., 1999). The roof of the ‘balloon house’ (a round housing appended to the main building where sounding balloons were once launched) hosts a series of sky-facing instruments. A specially constructed, rigid scaffold on a lawn hosts ground-facing and double-sided instruments. These two installations aim at providing high-quality radiation data for the NOPEX region while at the same time providing a platform for intercalibration of a wide variety of radiometers. A smaller scaffold is connected to the grassland subsite to complement tower measurements with incoming and outgoing longwave radiation, and net radiation from standard instruments. The data from this latter installation are used in undergraduate education and serves as a backup when any of the other radiometers fail.

The platform on the roof hosts several high-quality instruments. The selection of the roof to house this installation was based on two considerations. It is difficult to get access to the roof without a special ladder and this prevents non-authorised persons from destroying the instruments or disturbing the measurements. The placement on the roof is also beneficial since only a small part of the horizon is obstructed. Special care has been taken to simplify intercalibration of several different radiometers. This is made possible by an aluminium profile where up to 20 different radiometers can be flexibly mounted. Power supplies (230 V AC, 5, 12, and 24 V DC) and a Campbell (Logan, Utah, USA) AM416 multiplexer and CR10 datalogger, with more than 20 differential-measurement channels free for temporarily mounted instruments, simplify the simultaneous handling of several radiometers. The permanent instrumentation on the roof is divided into three groups.

The first group consists of instruments mounted on an INTRA suntracker. This automatically adjusts its position after the sun when the direct sunshine is sufficiently strong. At other times it runs according to the astronomically determined position that best extrapolates previous real-time tracking of the sun. With a very precise and self-adjusting timekeeping it is assumed to always keep its position within 0.1° of the true solar position. A pyrheliometer and a nine-channel photometer are mounted on each flange of the tracker. A pyrgeometer and a pyranometer are mounted on the top of the tracker where they are shaded by discs that obstruct 5° of the sky centred on the sun. Three photometer units are built into a housing where they are kept at constant temperature and zero humidity. The photometer channels (368, 411, 499, 675, 718, 777, 817, 862, and 944 nm with a 5 nm resolution) were selected to obey WMO recommendations (Fröhlich and London, 1986) and in the same time overlap with the channels of the most commonly used satellites sensors (primarily Landsat/TM, SPOT/HRV, and NOAA/AVHRR). The pyranometer is continuously ventilated with a proprietary ventilator. The pyrgeometer uses a ventilator from its manufacturer. The pyrgeometer is equipped with a thermistor for the dome temperature. This allows compensation for the shortwave-induced error (Halldin and Lindroth, 1992).

The second group consists of a pyranometer for global shortwave radiation and a semiconductor device for photosynthetically active radiation. The pyranometer is ventilated with a proprietary ventilator. Both instruments are mounted on the aluminium profile prepared for intercalibration of other skyfacing instruments. The third group consists of a single instrument measuring the hemispherical shortwave radiation between 300 and 1100 nm with a 6 nm resolution.

The lawn subsite on the northern side of the MMO is the outcome of experiences gained by Halldin and Lindroth (1992) and Mölder et al. (1995). The specially constructed scaffold where double-sided or ground-facing instruments are to be mounted must be seen as little as possible by the instruments while at the same time be as rigid as possible to prevent radiometer denivellation. The ground below should be as homogeneous as possible but should still consist of real, growing vegetation. A special blend of sturdy grass species was selected and the carefully levelled lawn was established in the autumn of 1993. A lawn that is subjected to draught cannot be kept thermally homogeneous and an irrigation system, buried in the ground, was installed when establishing the lawn. Plastic tubing was buried below ground to allow the ramp to be fed with signal and power lines without disturbing the surface. Two horizontal 6 m aluminium profiles (10 cm × 10 cm) are kept 4 dm apart, 1.7 m above ground on two sets of vertical double steel tubes. The steel tubes are anchored to the ground in 1 m concrete wastewater pipes filled with concrete. This prevents flexing of the scaffold during dry summers when soil shrinking could otherwise destabilise the fundaments. The scaffold is painted in dull green on the sides facing the instruments. A horizontally mounted box on the side of the scaffold houses a Campbell AM416 multiplexer and a CR10 logger to account for more than 20 differential-measurement channels free for temporarily mounted instruments. Power is supplied as 230 V AC, 5, 12, and 24 V DC. A special pump unit supplies dry, recirculating air to net radiometers that must have their domes inflated. Special arms mounted on the aluminium profile allow instruments to be sturdily mounted 1.5 m away from it. A total of seven instruments can be mounted simultaneously on the ramp with negligible disturbances to each other.

The standard instrumentation on the ramp is one ground-facing pyranometer (for reflected shortwave radiation) and one ground-facing pyrgeometer (for emitted longwave radiation). Both instruments are mounted between the aluminium profiles and equipped with ventilators and precipitation protection. A net radiometer with two thermopiles and separate measurement of body temperature allows measurement of net radiation, and incoming and outgoing longwave radiation. The net radiometer is mounted on an arm 1.5 m south of the aluminium profiles. It is equipped, since the summer of 1998, with a proprietary set of thin steel rods to prevent birds from destroying the thin sky-facing polyethylene dome.

3.2.4. Ground measurements

Soil-physical measurements are carried out at two places at MMO. Permanently deployed sensors are buried in the grass-covered soil around 10 m southeast of the grassland tower. A second installation is made in the arable field around 100 m southwest of the main observatory building.

At the grassland subsite, soil temperatures are measured in one profile at 2, 5, 10, 30, and 63 cm depths. Three soil-heat-flux plates are installed 1 cm below the ground. Absolute soil temperatures are measured at each level. The soil-heat-flux plates are traditional instruments sensing a temperature difference with a thermopile between small steel plates (Smedman et al., 1999). In addition to this, groundwater level has been sampled manually once per workday in a shallow well on the observatory grounds. These manual observations were halted in May 1997 when permanent personnel were no longer deployed at the observatory.

Measurements in the arable field started in November 1997. Temperatures are measured in two profiles at 5, 10, 20, 40, 60, and 80 cm depths. The liquid-water content of the soil is measured in four profiles (two coinciding with the temperature profiles) at 10, 20, 40, 60, and 80 cm. Groundwater levels are also monitored at four points down to 3 m depth. The measurement points are located as a square with 5 m sides. Measurements and storage of data are made every hour. Soil temperature is measured with thermocouples, connected via multiplexers to a data logger. All connections 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. An insulating cover was added at the inside 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). Horizontally inserted soil probes are of two types. An older type with two 25 cm metal rods is used in two profiles and a newer type with three 30 cm rods in the other two profiles. The probes are connected via multiplexers to a TDR instrument connected to a second logger. The water content is later calculated using a third-order equation presented by Topp et al. (1980). The groundwater level is monitored continuously with pressure transducers connected to a third logger.

3.2.5. Rainfall and snow

Precipitation is measured with different gauges. Rainfall is measured with an InSitu IS200W weighing gauge (Seibert and Morén, 1995, 1999; Seibert et al., 1999), a recording Hellmann gauge, and a Swedish standard gauge. Neither the InSitu nor the Hellmann gauges are suitable for snowfall measurements. The SMHI gauge is used operationally in the Swedish synoptic network to provide data on both rain and snowfall. The errors associated with snowfall measurements are, however, considerable and these data should be used with caution. The idea with the InSitu gauge is to minimise the systematic errors caused by wind and wetting losses. This is done by a special windshield (Lindroth, 1991) and a construction where the entire collecting device is weighed. Rainfall is computed from the increase of the accumulated weight. Seibert and Morén (1999) compared the catch of the InSitu and Hellmann gauges at Marsta. Their results support the hypothesis that systematic errors are reduced. The InSitu gauge measured about 3% (wind losses) and about 0.2 mm per event (wetting losses) more than the Hellmann gauge. For events of low intensity combined with high wind speed the differences were largest (23%). The temporal resolution is 10 min for the InSitu gauge, 30 min for the Hellmann gauge and once per day for the standard Swedish gauge. Operation of the manual gauge was halted in May 1997 when permanent personnel was no longer deployed at the observatory.

Measurement of snow on the ground has been done in two ways. Manual observations of snow depth according to the routines of the Swedish national weather service has been done once per workday until May 1997. These depths are averages of three snow-stake observations at the observatory grounds. Snow depth has been measured at the arable-field subsite since the autumn of 1997. One sonic sensor monitors snow depth with hourly resolution. A 70 m transect of 15 snow stakes, oriented from southeast to northwest (i.e., perpendicular to the main wind direction), has been used to complement the automatic measurements. Manual observations have been taken in connection to snowfall events.

3.2.6. Sounding systems

Regular atmospheric soundings are not performed at the MMO but the observatory permanently hosts equipment for dedicated field campaigns, e.g., CFE1 (Bergström, 1999), CFE2, and CFE3. Vaisala RS80-15 sondes and receiver are complemented with pibal-tracking equipment.

The Vaisala RS80-15 sonde consists of a thermometer, a hygrometer, and a barometer. The thermometer is a capacitive sensor, the hygrometer a thin-film capacitor, and the barometer a capacitive aneroid. The accuracies are ±0.1°C for temperature, ±2% for relative humidity, and ±0.5 hPa for pressure. The radio soundings produce data on height, temperature, potential temperature, dew-point temperature, relative and specific humidity, and air pressure.

Wind-direction and wind-speed soundings are made with a pibal-tracking technique. A balloon, filled with hydrogen gas, is released and its movements followed by a telescoping theodolite. Two scales on the theodolite, one for the azimuth and one for the elevation are each connected to a potentiometer. The potentiometer voltages, which vary with the angles, are converted to frequencies, which in turn are recorded on cassette tapes. The frequencies are read from the tapes by a Campbell logger and transmitted to a personal computer. With the aid of calibration curves and the assumption that the ascending velocity of the balloons is 4 m s^{-1} throughout the tracking, the information is finally converted into profiles of wind speed and direction.

3.3. Data-collection systems

One or two loggers serve each of the four subsites. The grassland subsite feeds data into two different loggers located in the main observatory building. The first logger (Promicro AB) is used to sample data from the slow-response sensors (atmospheric profiles of wind, temperature, and humidity, soil-temperature profiles, ground-heat flux, and radiation) with a time resolution of 1 s. This logger is connected to a PC by an RS232 cable. A modified logger programme is used to store the data on hard disk as on-line-processed 10 min averages. The system restarts automatically after power failure. The other system consists of a PC which digitally collects data from the sonic anemometer at 21 Hz. Data are sampled for 55 min (starting at even hours) and stored on hard disk. The remaining 5 min of each hour is used to make a preliminary online evaluation of turbulence statistics, such as variances and fluxes, which are also stored on hard disk and presented on a monitor. Every 10th day, the 21 Hz raw data are backed up to tape. Tapes are changed every second month and the 21 Hz raw data are processed correcting for aerodynamical errors caused by flow distortion around the instrument. The corrected 21 Hz wind and temperature (from speed of sound) data are then stored on CD together with 10 min average turbulence statistics

Each of the two radiometer subsites is served by Campbell AM416 relay multiplexers and CR10 loggers located in weather-tight plastic boxes, which are kept dry with regularly exchanged small silica-gel pouches. The radiometers are sampled every 6 s and 5 min average values are stored. Both radiometer loggers are connected to a standard PC in the main observatory building and data are transferred with Campbell software at 1 h intervals. Three files (21KB for the lawn subsite, 40KB for the roof instruments except the spectroradiometer which generates a separate file between 200KB and 1.3MB per day depending on daylength) containing the radiation data is stored every night. The sun-tracker is directly connected to the PC via an RS-422 interface. The spectroradiometer is also directly connected to the PC, which triggers new spectral sweeps every 5 min. The PC controlling the loggers is connected to a Windows NT network server. This server connects via modem each night to deliver data to the database server at the NOPEX Central Office.

The ground-based instruments in the arable-field subsite (TDR, thermocouples, pressure transducers, and snow-depth sensor) are connected to three Campbell CR10 loggers and data are downloaded manually to a portable PC every 7–14 days. The arable-field flux station is connected directly to a PC in the observatory building via an RS-232 interface. Raw 10 Hz data are stored on a removable hard disk that is replaced once a week. The raw data are permanently stored on CDs every fortnight.

The InSitu rain gauge is connected to a Campbell BDR320 logger. Data from this logger are downloaded to a portable PC once a month or more frequently as part of the rainfall and runoff measurements within the NOPEX small-catchment programme (Rodhe et al., 1999; Seibert et al., 1999). Fluxes and other entities calculated from the raw data at all subsites and instruments are finally stored in the SINOP database (Lundin et al., 1999b).

3.4. Calibration and maintenance procedures

Many of the sensors are calibrated only once and in some cases we rely on manufacturer calibration. Such calibration decisions were done both because of problems to unearth soil sensors without disturbing the measurements and because calibration procedures are less well defined. The soil temperature sensors in the grassland profile, e.g., were only calibrated before installation. They rely on a well-established measurement technique and we believe that they are very stable. The soil-heat-flux plates at the grassland subsite employ calibration factors determined during the Marsta micrometeorological field project (Högström, 1974b) and like all traditional heat-flux plates their output depends on the inevitable disturbance they create to the thermal flow. The weighing rainfall gauge was calibrated initially by placing a known weight onto the collecting device at different starting values for the accumulated weight. This calibration was repeated frequently in the first year of measurements and the calibration factor was found to be almost constant over time. The constancy of the calibration factor is still controlled at monthly or bimonthly intervals in connection with maintenance of the gauge.

All anemometers on the grassland tower were calibrated before they were mounted. Calibrations were performed in a large wind tunnel at the Royal Institute of Technology in Stockholm (KTH). This tunnel has an octagonal cross section 1.2 m high and 1.5 m wide. The anemometers were mounted on a short boom pointing upstream, and placed in the centre of the tunnel. Calibrations were made at a number of speeds from 3 to 30 m s^{-1}, and a Pitot tube was used to check the tunnel speed at the measurement point. A second-order polynomial was adapted to the calibration data and used in the evaluation. Comparisons revealed that the different anemometers gave almost identical calibration curves when calibrated with one and the same cup. The cups were somewhat more individual, differing at most about ±0.5%. An average calibration curve has been used in evaluating data from all anemometers.

The sensors for absolute temperatures in the atmospheric-profile system were checked in a calibration bath between 0 and 30°C at 5°C steps. The temperature difference measurements were checked for zero difference at the same temperatures. Corrections for temperature dependence of the zero differences are applied in the evaluation.

The sonic anemometer in the grassland tower was calibrated in the same wind tunnel as the anemometers to correct for aerodynamical errors caused by flow distortion around the instrument. The corrections are applied to each individual measurement before any statistics are determined. Regular calibration is needed for the gas analyser in the arable-field flux station. Calibrations are performed once per year with the aid of a water-vapour generator (LI-610, LI-COR) and a CO_2 reference gas (400 ppm).

Both radiometer subsites have as objective to serve as intercalibration stations, e.g., for participants in NOPEX CFEs. They must, thus, serve such users with reference measurements. Three reference instruments (for shortwave, longwave, and net radiation) are kept indoors in a dark cabinet at MMO. The shortwave instrument can be traced to the existing world standards, the World Radiation Reference (WRR) through annual intercomparisons with reference instrument at the WMO Regional Radiation Centre at SMHI. There are no existing standards for longwave and net radiation. Besides the original manufacturer calibration, the longwave reference instrument has once been calibrated against the Swedish instrument that served as a reference in an IEA international intercomparison of pyrgeometers (Dehne et al., 1993). Future plans include an exchange of this reference pyrgeometer with one equipped according to Philipona et al. (1995). 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. All other pyranometers, pyrgeometers and net radiometers in the CCM programme are calibrated against these reference instruments once a year or every second year. The calibration of the spectroradiometer relies on calibration equipment from the manufacturer. The sun photometer is sent to the World Radiation Centre in Davos at irregular intervals (first at time of delivery and a second time in early 1998).

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 MMO as a whole. The TDR instrument turns off itself at temperatures below –15°C and must be restarted manually. This has caused some data loss. The snow-depth stakes and the snow-depth-sensor tripod tend to be lifted by frost heave, which requires manual correction. The weighing rain gauge is not intended for snow measurements and is brought indoors around November and put back into service around April, depending on weather conditions. The mechanical anemometer bearings are cleaned and lubricated when needed (a deterioration is seen in wind-profile plots), approximately once every second year. The arable-field flux station uses identical hardware to those used at the forested Central Tower Site but intake filters must be shifted twice a month at MMO, compared to four times per year above the forest, because of the much dirtier air.

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 are, thus, only replaced once per year to avoid that repeated exposition of cold winter weather which make them brittle and prone to crack. The largest maintenance problem with the net radiometer has to do with the appetite of some birds on the easily damaged polyethylene domes. Regular maintenance of radiometers calls for control of levelling, cleaning domes (from bird spilling and dust), and exchange of silica gel. The 30 m tower and its stayings are visually controlled/maintained once per year.

3.5. Automated maintenance and quality control

Systematic work on automation of maintenance and quality control at MMO has started with the radiometric measurements. These measurements are downloaded automatically every night around 01:00 hour from MMO to a database with raw data at the NOPEX Central Office in Uppsala. Scripts are developed to transform the raw data (voltages and resistances) into useful physical entities while at the same time screening for data that contain errors. The automation makes use of the fact that many correlated variables are measured at MMO. The procedures largely follow the suggestions laid out by the BSRN programme within WCRP/GEWEX (Gilgen et al., 1995; Hegner et al., 1998). Various offsets are calculated and compensated for before screening. The first step in the screening is to test whether variable values are within the physically reasonable limit. The extraterrestrial solar radiation is an example of an upper bound for all shortwave fluxes. The bounds are variable in time and depend on the elevation and azimuth of the sun. In this step we also eliminate values that are caused by the old tower obstructing the lawn measurements. In the next step a number of quotients are calculated, i.e., global radiation measured directly and calculated as a sum of direct and diffuse radiation, net radiation measured directly and calculated as a component sum, and longwave radiation measured with the pyrgeometer and deduced from net radiometer data. Evaluation of 1994–1997 data has allowed us to establish numerical limits for these quotients. Data that fall outside of the limits are being flagged and taken aside. All other data are automatically recalculated to real entities, e.g., incoming longwave radiation or reflected shortwave radiation, and directly fed into SINOP, the System for Information in NOPEX (Lundin et al., 1999b). Time-series diagrams of the data are finally produced to allow a visual inspection of any remaining problems. Regular maintenance is documented on PC-based forms and can be used to trace problems back in time.

4. Results

The Marsta Meteorological Observatory has served all the goals of the CCM programme, and it has been specifically useful as a facility to carry out tests of instruments and methods for estimation of surface fluxes. There were three subprojects during CFE1 in 1994 and CFE2 in 1995 related to intercomparison of radiometers, fast humidity sensors, and sonic anemometers.

Almost 60 radiometers, 27 pyranometers, 20 net radiometers, 9 sensors for photosynthetically active radiation, and a few pyrgeometers were intercalibrated during CFE1 and CFE2. The intercomparison confirmed the great uncertainty in the functioning of many net radiometers found by Halldin and Lindroth (1992), Mölder et al. (1995), and Smith et al. (1997). Many net radiometers have different responsivity in the short- and the longwave ranges and calibration factors from the manufacturers are generally not satisfactory. Pyranometers were much more reliable and all could be made to function without systematical errors within their given accuracy. The intercomparison was also useful as a way to screen some instruments that gave physically reasonable output but

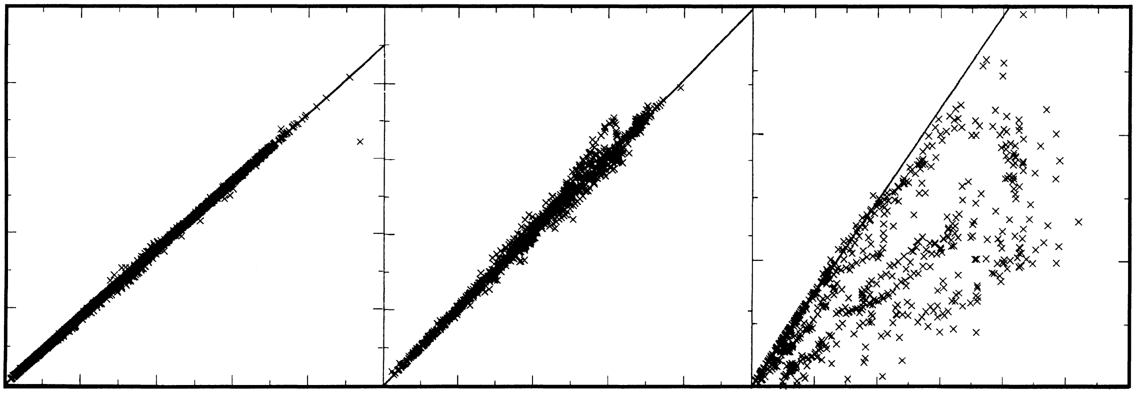

Fig. 5. Examples of radiometer intercalibration in June–July 1994, following CFE1. The left diagram shows a pyranometer of the same class as the reference, the middle diagram a correctly functioning pyranometer of somewhat lower quality, and the third diagram a malfunctioning net radiometer. Units are relative with calibrated instrument output on the ordinate against the reference instrument output on the abscissa.

turned out to be unreliable compared to a well-kept reference (Fig. 5).

Intercomparison of devices measuring sensible and latent heat fluxes is still a question where basic methodological research is needed. A pragmatic solution to the problem during the NOPEX CFE1 was to combine a test of fast-response sensors at MMO with an anemometer that was roving between the participating flux-measuring sites. Four fast-response humidity sensors were intercompared at MMO in late May 1994. The four sensors all represented different measurement principles; two IR hygrometers, one UV hygrometer, and one fast wet-bulb thermometer. The different devices turned out to differ up to 2 g m^{-3} or 25% of the maximal value. This low absolute precision was not unexpected since only the deviations from the average values are used to calculate fluxes. The deviations were better correlated between the instruments, but the wind velocity significantly modified the spectral influence of the time response. Sensitivity to precipitation and high relative air humidities were also identified (Foken et al., 1994).

Direct comparisons were made between fluxes measured with two types of eddy-correlation instruments during CFE1 and CFE2, the MIUU hot-film instrument (Högström, 1982, Bergström and Högström, 1987) and a Solent Scientific R2 anemometer. The comparisons were made at the 10 m height on the grassland tower, and the instruments were mounted on separate booms pointing towards 185° and 245°. The horizontal distance between the instruments was 1 m and the direction between the instruments was 125°/305°. Data were evaluated for winds from the sector 165°–265° to avoid errors caused by the instruments influencing each other. Data from the hot-film instrument were sampled with 20 Hz, while data from the sonic instrument were sampled with 21 Hz. Both instruments had been calibrated in a wind tunnel to correct for aerodynamical errors caused by flow distortion around the instruments. The hot-film instrument was equipped with a 0.015 mm Pt-wire for temperature measurements, while the speed-of-sound data were used for temperature-variance and heat-flux calculations with the sonic instrument. Mean values and turbulence statistics were determined as 10 min averages.

Only small systematic deviations were observed for mean wind speed and standard deviation of horizontal wind components (Table 4). The vertical wind component and the temperature deviated somewhat more and the sonic anemometer gave much higher vertical heat fluxes than the thin-film instrument (Fig. 6). The difference in heat flux was probably a consequence of using the speed of sound to estimate temperature. Humidity fluctuations affect the speed-of-sound fluctuations since the speed is directly related to air density but not to temperature. The speed-of-sound temperature is, thus, closely related to the virtual temperature, T_v. The relative magnitude of humidity to temperature fluctuations depends on meteorological and ground conditions. The direct comparison shown in Fig. 6 cannot, therefore, be used to correct heat

Table 4
Quotients between mean wind speed (u) and some turbulence statistics (σ_u, σ_v, σ_w, σ_T = standard deviation of longitudinal, lateral and vertical wind components and temperature, $u'w'$ = momentum flux, and $w'T'$ = kinematic heat flux) as measured by the MIUU hot-film instrument and the Solent sonic anemometer

u	σ_u	σ_v	σ_w	σ_T	$u'w'$	$w'T'$
0.982	0.997	1.032	1.047	0.864	1.160	0.724

fluxes measured with sonic anemometers, but merely be seen as an example of an error which may result from using the speed of sound to estimate temperature.

Since humidity fluctuations were not measured during the comparisons, we had no direct method to confirm that the heat-flux difference was a consequence of using virtual instead of true temperature. The virtual heat flux from the sonic can, however, be transformed into ordinary heat flux if the Bowen ratio, β, is known (Johansson et al., 2000)

$$\overline{w'T'} = \frac{\overline{w'T'_{\mathrm{v}}}}{(1 + (0.07/\beta))}$$

Bowen ratios were derived from simultaneous gradients of potential temperature and humidity, with the assumption that the exchange coefficients for heat and humidity are equal. The Bowen ratio is often large in dry climates and the correction less than 10%. The crop in this experiment (6 days during CFE1 and 8 days during CFE2) was growing profusely and β was regularly much less than unity. This gave, for a longer period than covered by the comparison, an average correction of 18%, with progressively larger values for decreasing values of $\overline{w'T'_{\mathrm{v}}}$ (Fig. 6). This does not explain the whole difference but may be a representative correction during the growth season.

Problems have been identified with the latent-heat-flux measurements during winter conditions. Details behind this are still unclear but it was obvious from comparisions of spectra between vapour, virtual temperature and wind that the gas analyser lost data at about 1 Hz. A new configuration of the fan and the gas analyser has improved the spectra. The identification of the humidity measurements as a root to the problem

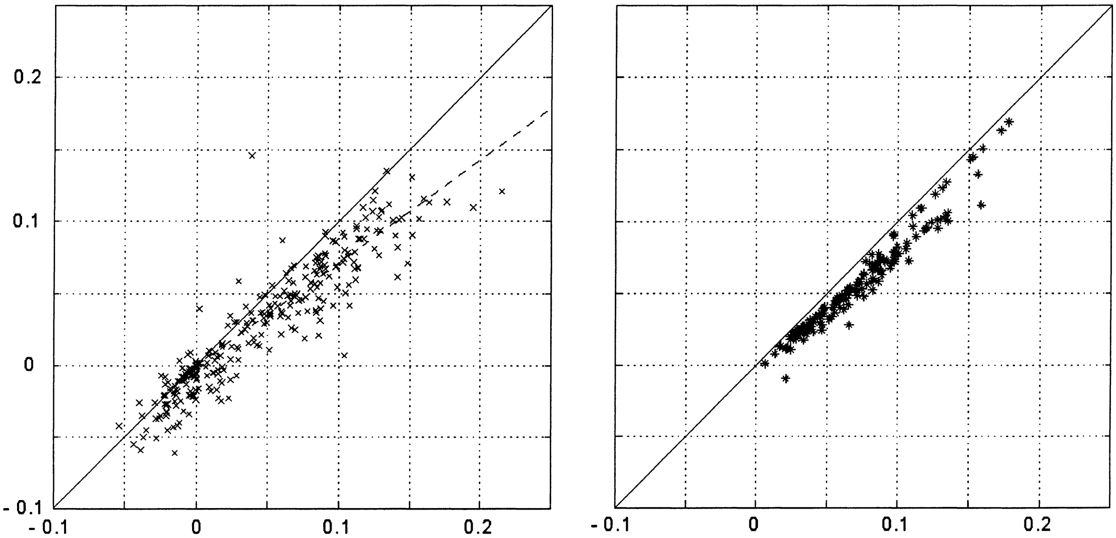

Fig. 6. Kinematic heat fluxes (Km s^{-1}) measured by the MIUU hot-film instrument (abscissa), using a Pt-wire for temperature measurements, and by a Solent Scientific R2 anemometer (ordinate), using the speed of sound to determine the temperature. Data from 6 days in June–August 1994. The dashed line corresponds to $w'T' = 0.72\ w'T_{\mathrm{v}}'$ (left). Solent fluxes based on virtual temperatures corrected for humidity fluctuations with the Bowen ratio determined from profiles of temperature and humidity (abscissa) and Solent fluxes calculated directly from the virtual temperature (ordinate). Data from 14 days during CFE1 and CFE2 (right).

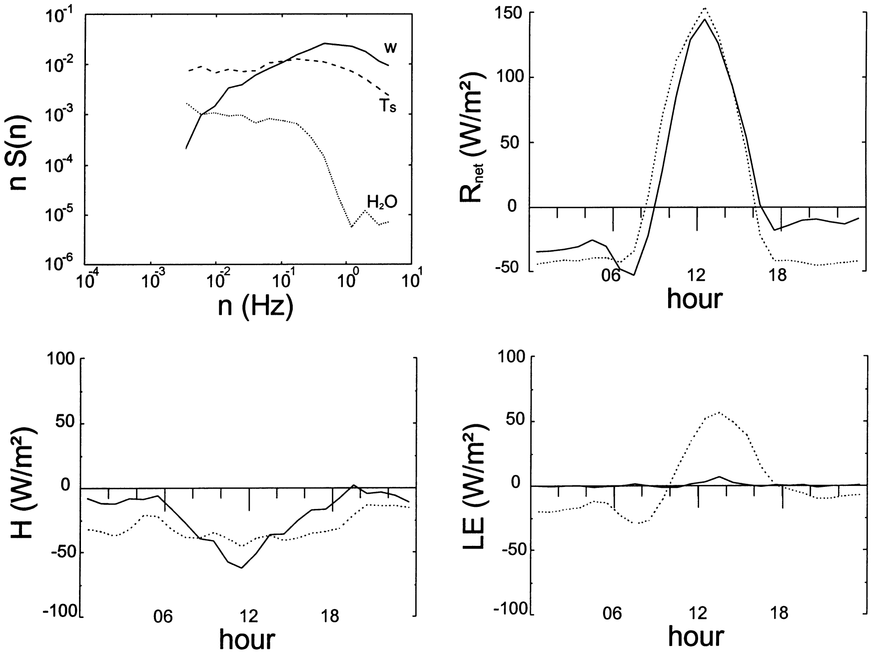

Fig. 7. Top left: power spectra from the arable-field flux station estimated from 32 768 samples on 19 February 1998, 13:00–13:55 hours, showing an unrealistic frequency loss in the water-vapour signal compared to vertical wind-speed and sonic temperature signals. Top right; bottom left–right: net radiation (R_{net}) from the grassland subsite (solid), and sensible (H) and latent (LE) heat fluxes from the arable-field flux station compared with SVAT-model estimates (dashed).

was supported by SVAT modelling that reasonably well mimicked measured net radiation and sensible heat fluxes, while measured and modelled latent heat fluxes were of different magnitudes (Fig. 7). With the present trend of standardising on certain makes of eddy-correlation equipment worldwide, this points to the need of careful assessment of this ‘standard’ equipment during the widest possible range of conditions.

Comparison of the amounts caught by the new rain gauge to that of standard gauges at the MMO and other sites indicated that the new gauge reduced the systematic errors (Seibert and Morén, 1999; Fig. 8). While the accuracy of the rainfall measurement was improved for the point scale, the problem of spatial variability remains to be tackled. From experience we know that precipitation varies from point to point even within small distances. Sandsborg (1973, 1973–1974) performed systematic studies of the spatial precipitation distribution within a region around Uppsala. Both authors found huge variations. Sandsborg (1973–1974) concluded that precipitation values from a gauge more than 3 km away only poorly represented the conditions at a specific site. Similar results were obtained from nine Hellmann gauges, which were installed around the MMO during CFE1 and CFE2. These gauges allowed the computation of the areal rainfall in the Sundbromark catchment (11.5 km^2), in which the MMO is located (Seibert and Morén, 1995). The results again demonstrated the spatial variability of rainfall and how much daily areally-covering rainfall values differed from the rainfall measured at the MMO (Fig. 8). The use of the new gauge is advantageous because of its accuracy and the ability to measure rainfall with high temporal resolution. On the other hand it has to be recognised that the errors introduced through a too widely spaced network of gauges may be larger than those caused by the systematic errors of standard gauges. Development of automated algorithms to increase uptime of instruments and improve the quality of data has been one objective of the CCM programme at Marsta. Improved data on shortwave radiation can, e.g., be achieved if combined with measurements of net longwave radiation since the main zero offset of a bolometric pyr-

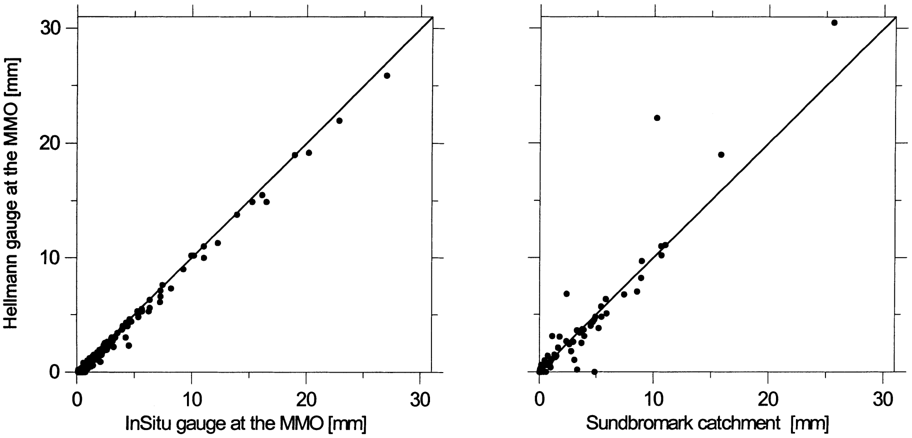

Fig. 8. Accumulated rainfall, per event from the summer months of 1994–1996, measured with a Hellmann gauge at the MMO and the InSitu gauge (left; modified from Seibert and Morén, 1999). Daily rainfall in the Hellmann gauge at the MMO compared to the areal rainfall for the Sundbromark catchment, computed as an average from nine Hellmann gauges with data from the summer months 1994 (right; modified from Seibert and Morén, 1995).

anometer is related to net longwave exchange between the pyranometer and the sky/ground. This zero offset can be observed at night but remains part of the pyranometer signal throughout the daylight hours, especially during clear days. McArthur (1998) recommends a method for BSRN to calculate this offset. Night-time offset values of individual pyranometers should be correlated to the net infrared radiation. Wardle et al. (1996) found an approximately linear relationship between the zero offset of a ventilated Kipp and Zonen CM11 pyranometer and the net thermal irradiance of an Eppley PSP pyrgeometer. The zero offset was analysed at Marsta for time periods when the sun was below –18° (i.e., excluding astronomical twilight conditions) and the ground snowfree. The sun never reaches below –18° in Marsta (55°55′33N) between 20 April and 21 August. In order to base the analysis on a sufficient amount of 5 min data, data sets from several periods were combined (Table 5). Shortwave irradiances were taken from the ventilated Kipp and Zonen CM21 pyranometers used for global shortwave (R_{SG}) and diffuse shortwave (R_{SDIFF}) radiation. The net infrared irradiance was taken from the thermopile signal (V_{NL}) of the sky-facing Eppley PSP pyrgeometer. We found a good linear correlation for both pyranometers (Table 5). There was no systematic yearly tendency observed for the slope (a) and intercept (b) of the fitted lines, so the data sets were further combined. The zero offset for R_{SG} (Z_G) and R_{SDIFF} (Z_D) were found to be of the same

Table 5
Correlation coefficient (r^2), slope (a) and intercept (b) for the relationship between signals (mV) of pyranometers for global (V_{SG}) and diffuse (V_{SDIFF}) shortwave radiation vs the thermopile signal (mV) of a sky-facing pyrgeometer (V_{NL}), when the sun elevation was less than –18°[a]

Period		N	V_{SG} vs V_{NL}			V_{SDIFF} vs V_{NL}		
			r^2	a	b	r^2	a	b
A	23 August–13 September 1995	900	0.81	0.034	0.002	0.90	0.045	0.001
B	23 August–30 September 1996	2370	0.83	0.046	0.006	0.92	0.051	0.001
C	1–19 April and 23 August–30 September 1997	3105	0.85	0.051	0.007	0.90	0.050	0.0005
D	1–19 April 1998	726	0.94	0.041	0.004	0.65	0.048	0.005
E	A + B + D	6375	0.84	0.047	0.006	0.92	0.049	0.0002
F	A + B + C + D	7101	0.84	0.046	0.006	0.85	0.050	0.001

[a] N is the number of 5 min observations.

order as those found by Wardle et al. (1996):

$$Z_G = 0.046 \cdot V_{NL} + 0.0055$$

(mV; based on dataset E in Table 5) and

$$Z_D = 0.0492 \cdot V_{NL} + 0.0002$$

(mV; based on dataset D in Table 5). The uptime for shortwave radiation measurements has been improved by a system that flags unexpected values and automatically issues e-mail messages to the personnel on-duty. One flag, based on BSRN recommendations (McArthur, 1998), is the quotient of measured (R_{SG}) and calculated (R_{SG0}) global shortwave radiation, where

$$R_{SG0} = R_{SDIR} \cdot \sin(h) + R_{SDIFF}$$

R_{SDIR} is direct solar radiation and h is sun elevation. This quotient was analysed in two ways. The first was to determine a lowest threshold for sun elevation above which the quotient could be used as a quality flag (no pyranometers are very reliable close to zero sun elevation). The other was to select limits of acceptance for data to be automatically entered into SINOP. The analysis was done with data from the roof subsite from January to June 1997. Hourly averages of the 5 min data were used for the calculations. The lowest sun elevation for which stable quotients could be found was 12° (Fig. 9). This means that the quotient cannot be used as a quality flag in December when the sun does not rise above 8.5° at MMO. Based on the minimum and maximum quotients, subjectively assessed as 'acceptable' (Table 6), acceptance limits were taken to be 0.95–1.10 for sun elevations between 12–17°, and 0.95–1.08 for elevations greater than 17°.

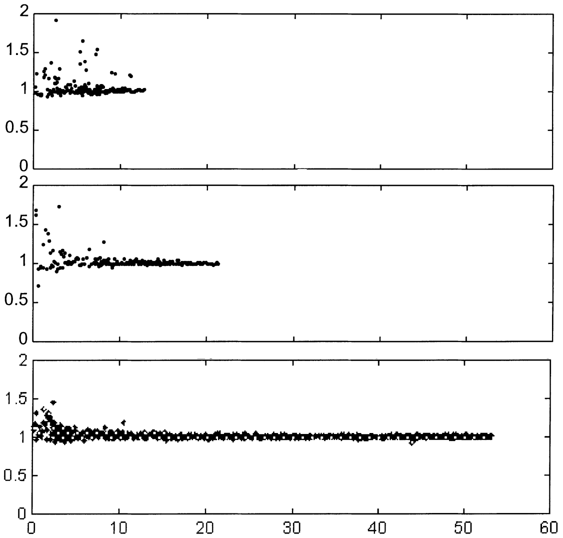

Fig. 9. Quotients of global shortwave radiation, measured and calculated from measurements of diffuse and direct radiation, as a function of solar elevation (degrees). Top, middle and bottom graphs show data from Marsta in January, February, and May–June 1997.

Table 6
Limits for quotients of global shortwave radiation, measured (R_{SG}) and calculated (R_{SG0}) from direct and diffuse shortwave radiation measurements at the Marsta Meteorological Observatory in 1997 at two sun-elevation (h) classes

Period	R_{SG}/R_{SG0}			
	$12° < h \leq 17°$		$h > 17°$	
	Minimum	Maximum	Minimum	Maximum
January	1.010	1.037	–	–
February	0.986	1.070	0.989	1.023
March–April	0.950	1.092	0.977	1.076
May–June	0.959	1.067	0.957	1.044

Data from MMO (Bergström, 1999; Smedman et al., 1999) has not only been used to evaluate equipment but also served to shed light on exchange processes. According to the Monin–Obukhov similarity theory, the non-dimensional wind gradient, Φ_m, depends on the stability parameter z/L, where z is height above ground and L is the Monin–Obukhov length. Based on MMO data, Johansson et al. (1999, 2000) found a clear ordering of Φ_m with the stability parameter $-z_i/L$ during convective conditions, where z_i is the height of the convective boundary layer (Fig. 10). This supports results on convective boundary-layer characteristics found with large-eddy-simulation technique (Khanna and Brasseur, 1997).

Soil-temperature measurements in the arable field and in the grassland (Figs. 11 and 12) show the importance of the vegetation cover for the surface energy balance. Except for a short period in the spring, soil temperatures are consistently higher in the grassland soil than in the soil of the neighbouring arable field. Since the thermal and radiative properties of the MMO grassland grounds deviate from those of the surrounding fields, this must be taken into account when measurements from different subsites are compared. It is, e.g., not obvious that one can directly combine net-radiation measurements from the lawn

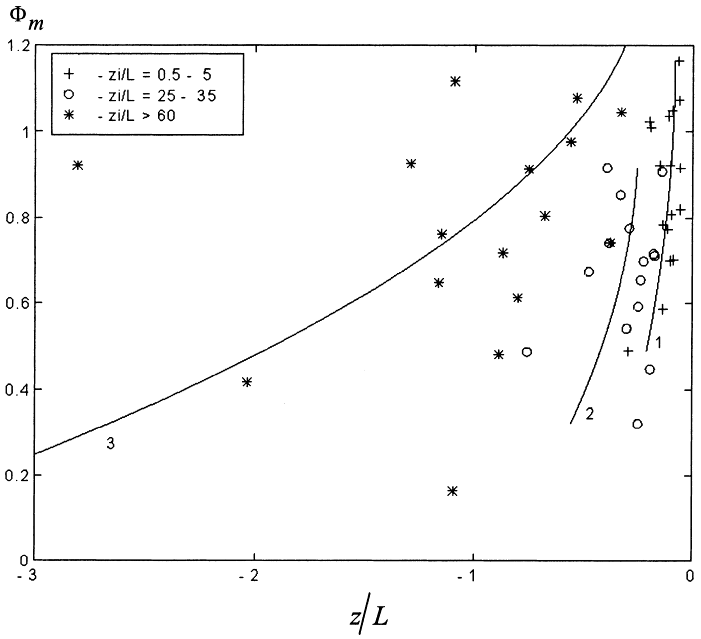

Fig. 10. Dimensionless wind gradient Φ_m against z/L for measurements in the three z_i/L-ranges at Marsta from 14 days of radiosonde data during CFE1 and CFE2. Lines are manually fitted to measurements for each stability range.

subsite and flux measurements showing the footprints of the arable fields surrounding MMO.

5. Discussion

After more than 5 years of operation of the CCM programme at the Marsta Meteorological Observatory we can conclude that it was possible to set up and successfully operate a continuous, long-term monitoring of a surface–atmosphere exchange-process system. MMO 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 agricultural flux data from MMO and forest flux data from the Central Tower Site at Norunda Common can be weighted to give representative fluxes from the whole NOPEX region during spring and summer conditions.

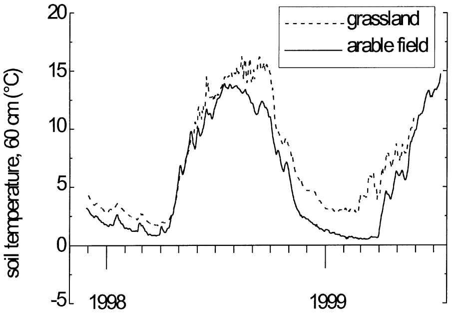

Fig. 11. Soil temperature at 60 cm depth in the arable field (solid line) and in the grassland (dashed line) at Marsta Meteorological Observatory November 1997–July 1999

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-monitor-

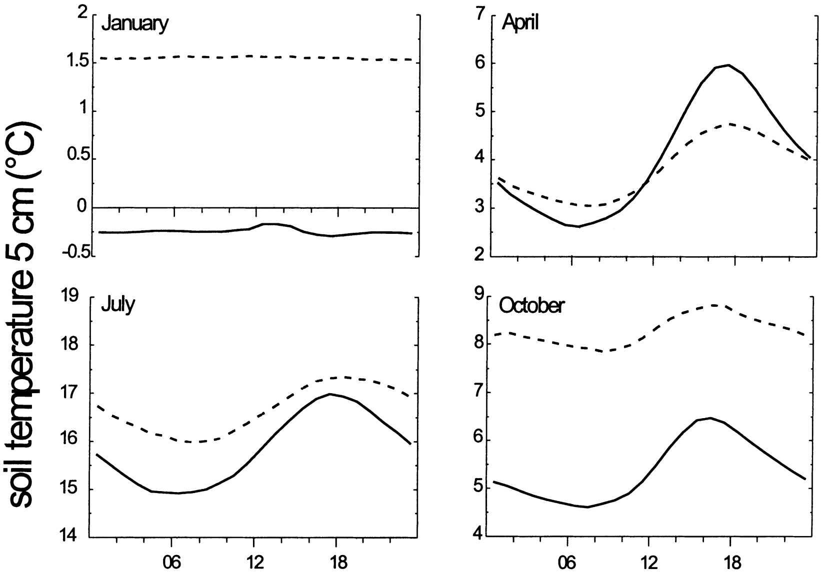

Fig. 12. Average diurnal courses of soil temperature at 5 cm depths in the arable field (solid line) and in the grassland (dashed line) at Marsta Meteorological Observatory during winter, spring, summer, and autumn of 1998.

ing system. Many of the new systems now being set up in the framework of the global FLUXNET (Valentini et al., 1996) belong to the SVAT-monitoring category. The unique feature of the MMO, in combination with the Central Tower Site, is that it qualifies to both ABL and SVAT labels.

Many sites worldwide are now labelled 'continuous'. Our experience from more than 5 years of operation is that we can obtain long-term data sets 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 carefully document the percentage of downtime. Since the 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 possible 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 MMO on a 24 h basis. Such intensive maintenance and control can possibly 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). Jones et al. (1999), who provide some of the most authoritative compilations of earth-surface temperatures in the last 150 years, also stress the importance of such changes.

5.1. Instrumentation and data collection

The data-collection systems have been operating smoothly and without large problems, despite the fact that several persons have used common data loggers for their measurement systems. The logger system for the grassland subsite proved vulnerable for theft of the PC it was connected to. Before security measures were implemented, old low-value PCs were utilised and they were not always reliable.

The need for synchronisation of various computers and logger systems was identified as important. This is especially crucial if local daylight-savings time is used in some parts of the system and local time in other parts. The use of a common time that does not need to be reset twice a year, preferably 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. An integrated data-collection, communication, and storage system for all subsites and individual instruments would be valuable as a future development of MMO.

5.2. Maintenance and operational issues

The planning phase of the NOPEX MMO project started in 1993 and involved a large number of persons. Experienced personnel at the Department of Meteorology, Uppsala University established the grassland subsite and made use of well-established sensors whereas the data-collection system was new. The erection of the tower and installation of the sensors were completed within 1 month in the spring of 1994. The installation of the two radiometric subsites was a more cumbersome affair. The building of the roof platform and installation of suntrackers and sensors were initiated in early 1994 but not fully completed until late 1995. The installations of the rigid lawn scaffold had to wait for the establishment of the lawn, which was initiated in 1993. Final levelling of the ground and maintenance of the grass could only be done after soil freezing had established a permanent soil structure. The scaffold required a previously untested construction that fulfilled requirements of rigidity and minimal radiative disturbances. Selection of material, construction of support arms, painting of the scaffold surface, and establishment of the lawn required work that was finished in August 1994. This work was done by a combination of Ph.D. students and technical personnel. The installations at the arable-field subsite were undertaken in three steps in 1997 as a result of CFE3 studies of wintertime processes. The flux station was installed during the last two weeks of March 1997 and has delivered data since then. Two soil profiles with thermocouples and TDR probes and the four ground water level tubes, were installed in early November 1997. Soil cores for estimation of hydraulic properties were collected at the same time. Two additional TDR profiles and a snow-depth sensor were installed in early December. The ground-based equipment at the arable-field subsite were unearthed the first time in July 1999 and reinstalled in early September the same year.

A combination of students and technical personnel could be utilised during the initial phases but 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 ventilators and fans that are not working, cup anemometers that need service, and humidity in junction boxes. Birds have been a major nuisance at MMO. Birds have attacked and destroyed radiometer domes and put spilling on them. Birds have been sitting on the thin-wire thermometer of the arable-field flux station and forced replacement of it at an accelerated rate. They have pecked at the radiation shielding of the psychrometers and the cover of the raingauge windshield. Special action is needed to get rid of, or minimise, this problem in order to keep long-term measurements within a reasonable budget.

The design of an automated maintenance system has been initiated at the radiometric subsites. The present quality flagging uses only the most obvious interrelations between measured entities. A further development should make use of correlations between other variables than just radiometric ones. Rainfall, e.g., implies clouds and limitations to the direct radiation. Even in the present, limited version, the system allows high-quality measurements to be carried out with a limited amount of manpower. Since the system flags errors within 24 h, quick action can be taken if something fails but other field trips, except for the weekly supervision, are not needed.

The ambitions in 1999 are to operate the MMO continuously for at least another 10 years, assuming that interest from the scientific community and funding agencies pertain. The long time series that such an operation would produce, will include a spectrum of weather events and trends caused both by climate change and crop development and selection. It should be possible to revisit this NOPEX site for another CFE using future generation of sensors and to study their backward 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 at a well-established meteorological observatory in a flat agricultural area. Present-day sensor, computer, and network technology has been combined into a system with an uptime of more than 90% for most of its components.

Enthusiastic PhD students, researchers, and technical personnel from Uppsala University and the Swedish University of Agricultural Sciences built up the system during the initial phase. The organisation of MMO must be changed and long-term, planned issues must come more into focus to guarantee a high-quality operation during a long time period. Questions concerning long-term calibration plans, maintenance of sensors and data-collection system, and continuous development of the computer network to keep it 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 infrastructure at MMO and the easy access to the facilities have been valuable for the performance of intercalibration and testing of various sensors that have subsequently been deployed at various sites in the NOPEX region. Work has started at MMO to develop automated procedures for uninterrupted, troublefree, long-term, and intensive monitoring of fluxes and states in the surface–atmosphere interface.

The MMO 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

ABL	Atmospheric Boundary Layer
BSRN	Baseline Surface Radiation Network; http://bsrn.ethz.ch/
BOREAS	Boreal Ecosystem–Atmosphere Study; http://boreas.gsfc.nasa.gov/
CCM	Continuous Climate Monitoring programme within NOPEX
CFE	Concentrated Field Effort. Time-limited field campaigns within NOPEX
CTS	Central Tower Site. One of the two main CCM sites in NOPEX
FLUXNET	Proposed core project for IGBP/BAHC; http://daacl.ESD.ORNL.Gov/FLUXNET/
GEWEX	Global Energy and Water Cycle Experiment; http://www.cais.com/gewex/gewex.html
GCM	Global Climate/Circulation Model
IEA	International Energy Agency; http://www.iea.org/homechoi.htm
IR	infrared
KNMI	Het Koninklijk Nederlands Meteorologisch Instituut; The Royal Dutch Weather Service; http://www.knmi.nl/indexeng.html
LAN	Local Area Network

Landsat/TM	Land Satellite/Thematic Mapper
MMO	Marsta Meteorological Observatory. One of the two main CCM sites in NOPEX
MIUU	Previously Department of Meteorology, Uppsala University. Presently the chair of Meteorology, Department of Earth Sciences, Uppsala University
NOAA/AVHRR	National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer; http://www.noaa.gov/
NOPEX	Northern Hemisphere Climate-Processes Land-Surface Experiment; http://www.hyd.uu.se/nopex/
SMHI	Swedish Meteorological and Hydrological Institute; http://www.smhi.se/
SINOP	System for Information in NOPEX
SPOT/HRV	Satellite Pour 1'Observation de la Terre/High Resolution Visible; http://www.spotimage.fr/spot-us.htm
SVAT	Soil–Vegetation–Atmosphere Transfer
TDR	Time Domain Reflectometry
UTC	Universal Time Coordinated (in many respects equal to GMT-Greenwich Mean Time)
UV	ultraviolet
WCRP	World Climate Research Programme; http://www.wmo.ch/web/wcrp/wcrp-home.html
WMO	World Meteorological Programme; http://www.wmo.ch/
WRR	World Radiation Reference

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