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Evaporation over a heterogeneous land surface: EVA_GRIPS and the LITFASS-2003 experiment—an overview

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Abstract The Evaporation at Grid/Pixel Scale (EVA_GRIPS) project was realised in order to determine the area-averaged evaporation over a heterogeneous land surface at the scale of a grid box of a regional numerical weather prediction or climate model, and at the scale of a pixel of a satellite image. EVA_GRIPS combined surface-based and airborne measurements, satellite data analysis, and numerical modelling activities. A mesoscale field experiment, LITFASS-2003, was carried out in the heterogeneous landscape around the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service in May and June, 2003. The experiment was embedded in the comprehensive, operational measurement program of the MOL. Experimental determination of surface fluxes on a variety of spatial scales was achieved by employing micrometeorological flux stations, scintillometers, a combination of ground-based remote sensing instruments, and the Helipod, a turbulence probe carried by a helicopter. Surface energy fluxes were also derived from satellite data. Modelling work included the use of different Soil–Vegetation–Atmosphere Transfer schemes, a large-eddy simulation model and three mesoscale atmospheric models. The paper gives an overview on the background of EVA_GRIPS, and on the measurements and meteorological conditions during LITFASS-2003. A few general results are discussed.

Keywords Area-averaging · Evaporation · Heterogeneous land surface · LITFASS · Turbulent fluxes

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1 Introduction

Land surface–atmosphere interaction processes play an important role in the energy and water cycle over a wide range of scales and exhibit a major influence on the diurnal cycle of near-surface values of temperature, humidity, wind, and associated phenomena (e.g., dew or fog) as well as on the spatial distribution of clouds and precipitation. Among these processes, the vertical turbulent fluxes of momentum, heat and water vapour represent the fundamental link between the soil–vegetation system and the overlying atmosphere. The turbulent transport of water vapour is of special interest since it connects the energy and water cycles. Water availability at the soil/vegetation–atmosphere interface determines the consumption and redistribution of energy at the surface and hence controls the evolution of the atmospheric boundary layer (ABL, see, e.g., Betts et al. 1996; Ek and Holtslag 2004) with effects on the state of the atmosphere in general. The effect of land-surface heterogeneity combined with the heterogeneity of incoming radiation and precipitation at the surface can result in large spatial variations of the surface energy fluxes (e.g., Doran et al. 1992; Avissar and Schmidt 1998; Lyons and Halldin 2004).

An adequate description of the surface–atmosphere exchange processes in numerical weather prediction (NWP) and climate models is therefore fundamental for a reliable simulation of weather and climate conditions both at the surface and in the free atmosphere. However, considerable deficits still have to be acknowledged concerning our understanding and ability to properly describe these processes consistently over a variety of scales ranging from the local patch to the regional landscape scale. This holds in particular for heterogeneous land surfaces that are typical for most regions in Central Europe.

Contemporary regional weather and climate prediction models have a typical grid resolution of the order of 10 km in the horizontal dimension and consist of 30–50 atmospheric layers resulting in a vertical resolution of a few decametres close to the ground. The tendency is towards even finer grids. Grid size reduction makes the grid point model output more sensitive to a proper description of the surface characteristics and of the surface–atmosphere interaction processes. However, many flux parameterisation schemes currently used in NWP and climate models have been derived for models with a much coarser grid resolution assuming homogeneous surface cover within one grid cell. Over the last 15 years increasing efforts have been therefore devoted to the problem of taking into account the subgrid-scale land-surface heterogeneity by an appropriate averaging concept. Strategies suggested include, e.g., the use of effective parameters, the mosaic and tile approaches, or explicit subgrid schemes (e.g. Avissar and Pielke 1989; Avissar 1991; Lhomme et al. 1994; Mahrt 1996; Mölders et al. 1996; Giorgi and Avissar 1997; Schlünzen and Katzfey 2003).

In 1995, the German Meteorological Service (Deutscher Wetterdienst, DWD) initiated the LITFASS project (LITFASS, 'Lindenberg Inhomogeneous Terrain—Fluxes between Atmosphere and Surface: a long-term Study') in order to develop and test a strategy for the operational determination of the area-averaged turbulent fluxes of heat, momentum, and water vapour over a heterogeneous landscape at the meso-γ scale (2–20 km). LITFASS combined measurements in the heterogeneous landscape around the Meteorological Observatory Lindenberg (MOL) with numerical model simulations using a large-eddy-simulation (LES) type high-resolution model (Beyrich et al. 2002a; Herzog et al. 2002). A first field campaign, LITFASS-98, was carried out in the region around the MOL in May and June, 1998. LITFASS-98 added to a sequence of field experiments performed in the 1980s and 1990s over heterogeneous land surfaces in different geographical and climate regions, and which were devoted to the question of flux averaging (e.g., HAPEX-MOBILHY—André et al. 1988; FIFE—Sellers and Hall 1992; EFEDA—Bolle et al., 1993; BOREAS—Sellers et al. 1997; NOPEX—Halldin et al. 1998).

In general, field experiments of limited duration can provide valuable and comprehensive datasets for process studies but usually represent a limited spectrum of meteorological situations. This resulted in a general need for reliable, high-quality long-term datasets on land-surface atmosphere interaction processes for model development and testing (e.g. ECMWF 1999; Gustafsson 2000). The LITFASS measurement facilities established at MOL have therefore been set into continuous operation since summer 2001. These include

- a boundary-layer field site (in German: Grenzschicht-Messfeld, GM) close to the village of Falkenberg equipped with a 99-m meteorological tower, a 10-m profile mast, a sodar/RASS, and measurement systems for the determination of soil, radiation and turbulence parameters (e.g., Neisser et al. 2002),
- a network of micrometeorological (flux) stations operated over different land-use classes in the LITFASS area (grassland, farmland, forest, water, e.g., Weisensee et al. 2001),
- networks of automatically recording rain gauges and global radiation sensors to characterise the spatial variability of the main meteorological forcing variables (insolation, and precipitation), and
- a large-aperture scintillometer (LAS) over a path length of 4.7 km for the estimation of area-representative sensible heat fluxes (Beyrich et al. 2002c).

The synthesis of local measurements with modelling work and satellite data analysis (e.g. Hasager and Jensen, 1999; Braun et al., 2001) seems to have the highest potential for successfully solving the area-averaging problem (from local in situ measurements to path- and area-integrated information), and appears to be suited to the generation of the long-term datasets, requested by the NWP and climate modelling communities. This strategy is in line with the conclusion formulated by Parlange et al. (1995): *'The combination of field measurements, ABL similarity modelling, and numerical simulations is providing a timely advancement of our understanding of land surface fluxes and the ABL'*.

2 The EVA_GRIPS project

Motivated by the existing deficits of NWP and climate models in properly representing the land–atmosphere exchange processes over heterogeneous terrain, the Evaporation at Grid/Pixel Scale (EVA_GRIPS) project was realised with the primary goal of determining the area-averaged evaporation over a heterogeneous land surface at the scale of a grid box of a regional atmospheric circulation model, and at the scale of a pixel of a satellite image both from measurements and model simulations. In order to achieve this, the following detailed tasks were defined:

- to assess the sensitivity of modelled surface fluxes and ABL variables on model grid resolution, on the description of external model parameters and forcing variables, on the representation of turbulence, clouds and precipitation, and on flux averaging strategies,

- to characterise model uncertainty in determining area-averaged evaporation fluxes by controlled intercomparison experiments between different models,
- to provide a long-term dataset of model forcing variables and fluxes from the operational LITFASS measurement facilities at the MOL,
- to perform a mesoscale field experiment in the area around the MOL in order to collect a comprehensive dataset on local and regional scale surface fluxes over a heterogeneous landscape,
- to assess the consistency of area-averaged surface flux values derived from experimental data using a suite of measurement systems from the local to the regional scale and from the surface layer across the whole atmospheric boundary layer,
- to study the relevance of mesoscale circulations and advective transports for the exchange of energy and water vapour over a heterogeneous land surface, and
- to validate surface energy fluxes derived from satellite data.

Two research programs based on comparable arguments and ideas have been established in Scandinavia and in the U.S.A. over the last decade, namely the NOPEX and ABLE/CASES activities (see, e.g., Halldin et al. 1999; LeMone et al. 2000; Poulos et al. 2002). When compared to these programs, EVA_GRIPS differs in scale (meso-γ vs. meso-β), areal coverage (grid cell or satellite pixel vs. watershed), degree of land-surface heterogeneity, and regional climate. Moreover, the activities in EVA_GRIPS attempted to fill gaps recognised from previous experimental and modelling work on the area-averaging of fluxes and to take advantage of recent developments in experimental techniques. This concerns in particular

- the performance of model studies (especially with LES) using real land-surface characteristics (orography, land use, soil types) as a lower atmospheric boundary condition instead of synthetic land-use patterns, as has been frequently done in the past (e.g. Mölders and Raabe 1996; Avissar and Schmidt 1998; Friedrich et al. 2000),
- the investigation of exchange processes at the surface in connection with atmospheric boundary-layer processes—both are strongly coupled to each other; this coupling has often not found proper attention in previous field programs by either concentrating on the ABL or the surface processes,
- the employment of modern techniques for (quasi-) continuous operation allowing for a comprehensive characterisation of surface and boundary-layer processes (reliable fast response humidity sensors, scintillometers, combination of Doppler and differential absorption lidars).

EVA_GRIPS was also realised as a contribution to the international Baltic Sea Experiment BALTEX (see, e.g., Raschke et al. 2001), the European Continental Scale Experiment within the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Programme (WCRP) of the World Meteorological Organisation. Within BALTEX the area around Lindenberg was selected as a reference site for land–air interaction studies (together with Sodankylä in northern Finland, Marsta / Norunda in central Sweden, and Cabauw in The Netherlands). Equally, Lindenberg is one of the European reference sites for the Co-ordinated Enhanced Observation Period (CEOP) project in GEWEX (e.g., Lawford et al. 2004).

3 The LITFASS-2003 experiment: goals, study region and experimental set-up

Based on the central goal of the EVA_GRIPS project, the LITFASS-2003 field experiment focused on the collection of a comprehensive dataset suited for the validation of different types of numerical simulation models and of strategies to derive land-surface parameters and fluxes from satellite data taking into account area-averaging and scale-aggregation issues. To achieve this general objective, the experiment strategy had to meet the following specific requirements:

- Performance of direct measurements of the local water vapour and energy fluxes using eddy-covariance techniques at a number of sites considering the surface properties (representation of all major land-use and soil classes) and the spatial variation of precipitation, cloudiness, and radiation (i.e., the water and energy input) across the study area,
- use of spatially integrating measurement and analysis techniques (scintillometry, airborne measurements) for the experimental determination of the area-averaged turbulent fluxes both at the surface and inside the ABL,
- performance of profile measurements of mean and turbulent variables (with airborne and ground-based remote sensing techniques) in order both to characterise the vertical structure of the ABL and its spatial and temporal variability, and to link the near-surface observations to the area-averaging measurements,
- realisation of a thorough quality assurance and quality control for the measurements from all systems in order to ensure their comparability and to allow profound assessment of the flux uncertainties.

Although the focus of EVA_GRIPS was on evaporation, other processes and variables such as precipitation, soil moisture, radiation fluxes, ground and sensible heat fluxes had to be considered, as well as taking into account the central role of evaporation as a link between the energy and water cycle at various scales.

The study region of the EVA_GRIPS project was a $20 \times 20\,\mathrm{km}^2$ area (the so-called LITFASS area, Beyrich et al. 2002a) around the MOL. The boundaries of the LITFASS area are given by the following co-ordinates: 52°05′30″ N, 13°54′00″ E (lower left corner) and 52°16′30″ N, 14°12′00″ E (upper right corner).

The landscape in this area has been formed by the inland glaciers during the last ice age exhibiting a slightly undulating surface with height differences of about 80–100 m over distances of about 10 to 15 km. The land use in the LITFASS area is dominated by forest and agricultural fields (more than 40% each), lakes represent 6–7% while villages and traffic roads cover less than 5% (compare Figs. 1–4). This mixture of surface types is typical of the region and also for larger parts of northern Central Europe south of the Baltic Sea. The forest is mainly situated in the western part of the area, while agriculture is dominant in the eastern part (see Fig. 2). For the farmland, cereals (triticale, rye, and to a smaller extent barley and wheat) are the main type of crops; significant parts of the agricultural fields are also covered by grass, rape, and maize. The overall percentages of the basic land-use types in the area are indicated in Fig. 3. The fractions of the different types of agricultural crops may slightly change from year to year. During the last 5 years, however, they differed by not more than 2% from the values given in Fig. 3. The soil type distribution is dominated by sandy soils. In the forested western part of the area, the sand reaches a depth of several metres. At the GM Falkenberg, sandy soils (pale soil—*Eutric Podzoluvisol*, brown soil—*Cambic*

Fig. 1 Aerial view towards north-west of the landscape around Lindenberg (the LITFASS area) with the GM Falkenberg (marked by the arrow) in the centre (photo: F. Beyrich, DWD-MOL, 2002)

Arenosol) cover a layer of loam, which can be typically found at a depth of 0.5–0.8 m, locally even deeper.

At the MOL a comprehensive operational measurement program is performed in order to characterise the vertical structure of the atmosphere. Measurements include the operation of the LITFASS boundary-layer measurement facilities (see Section 1), a radiation station of the global Baseline Surface Radiation Network (e.g., Ohmura et al. 1998), a complex of ground-based remote sensing systems (two wind profiler radar, WPR/RASS, a sodar/RASS, a microwave radiometer profiler (MWRP), a cloud radar—e.g., Engelbart and Steinhagen 2001), and the execution of four regular radiosoundings per day (e.g., Leiterer et al. 2005). These operational measurements along with the available infrastructure and logistics represent an ideal basis to carry out a mesoscale field experiment embedded into a long-term background measurement program.

Linked to the operational measurements of the MOL, additional systems and instruments were set-up for the LITFASS-2003 experiment. The experiment measurement program comprised:

- fourteen micrometeorological and flux stations operated over different surfaces representing the major land-use types in the area, and laser scintillometers at five of the sites,
- three large-aperture optical scintillometers (LAS) and a microwave scintillometer (MWS) set-up along three different paths over distances of 3–10 km (see also Meijninger et al. 2006; Kohsiek et al. 2006),

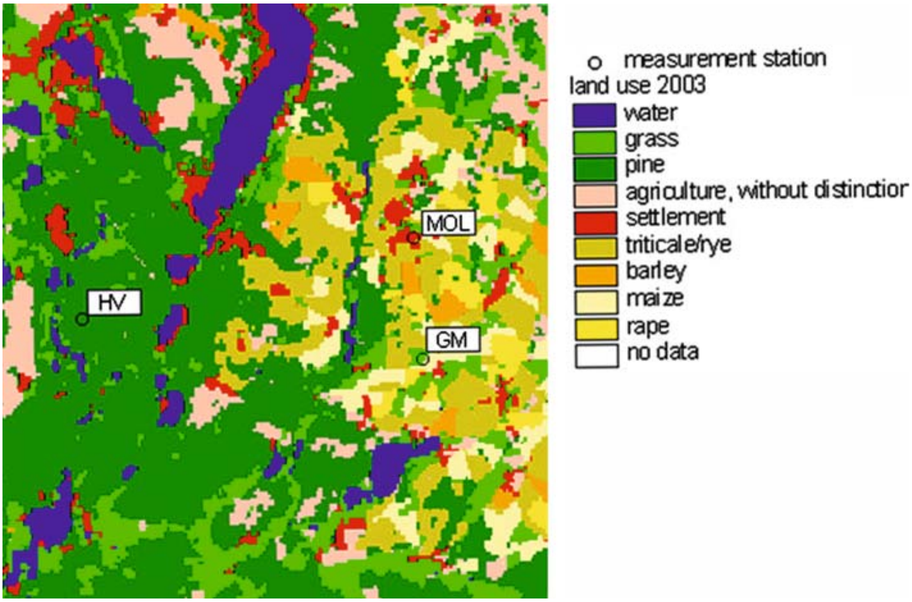

Fig. 2 Land-use map of the LITFASS area during the period of the LITFASS-2003 experiment (this figure was prepared by C. Heret, TU Dresden, and J. Uhlenbrock, University of Hannover)

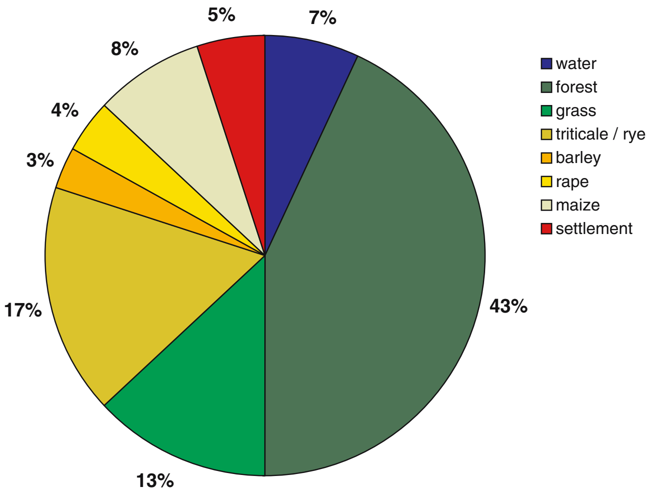

Fig. 3 Relative frequency of occurrence of the major land use classes in the LITFASS area

- synchronised high-resolution (10 s sampling rate) measurements of water vapour and vertical velocity profiles by a DIAL/RASS combination and by a DIAL/Doppler lidar combination,
- more than 60 flight hours with the Helipod, a turbulence probe hanging well below a helicopter, (see also Bange et al. 2006),

For 4 days, mapping of the surface temperature distribution in the LITFASS area with an infrared camera on board of a Tornado aircraft of the Deutsche Bundeswehr

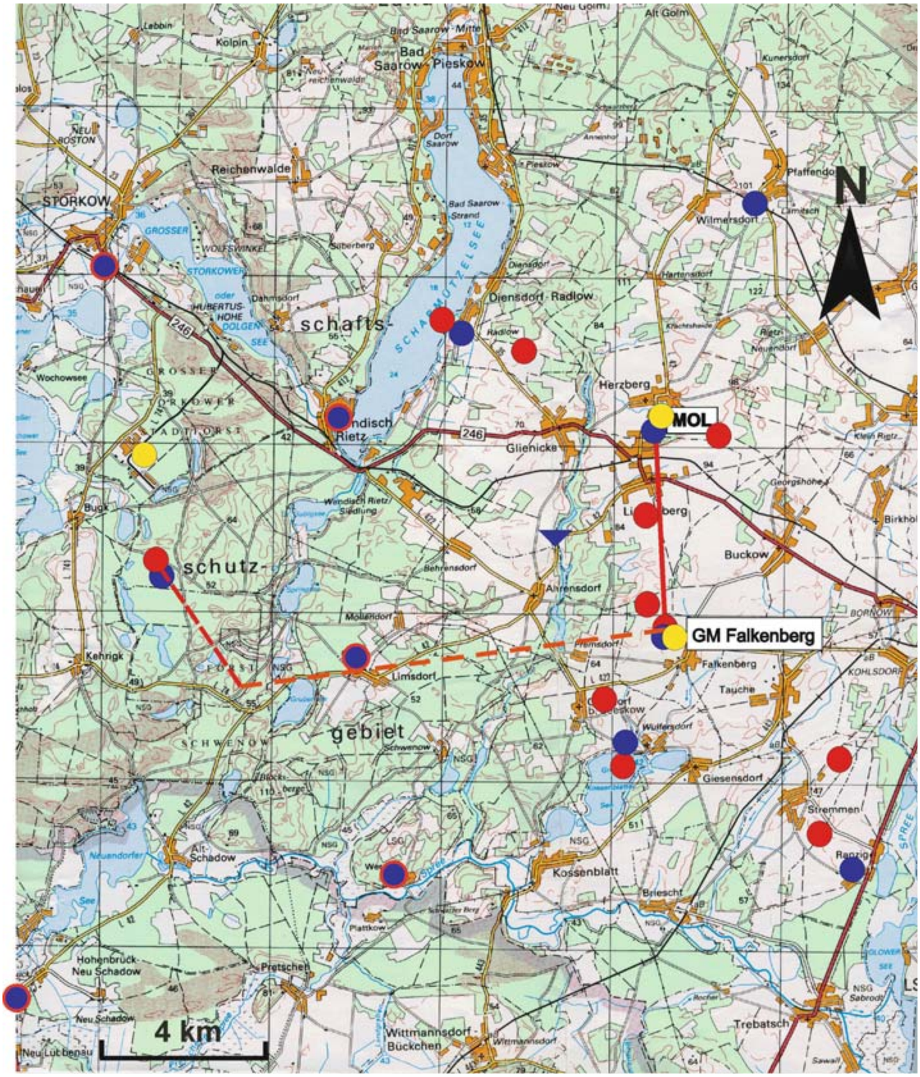

Fig. 4 The experimental set-up and measuring strategy of the LITFASS-2003 experiment. Red circle: micrometeorological station, yellow circle: remote sensing site, blue circle: rain gauge, blue circle with red ring: rain gauge with global radiation sensor, blue triangle: water table measurement, red solid/dashed line: long-distance scintillometer path. This figure is based on a topographic map TK100 issued by the Landesvermessungsamt Brandenburg, reproduction has been kindly permitted under Ref.-No. GB 57/01

(German Air Force) was performed. Moreover, monitoring activities included the collection of information on soil and vegetation parameters and on the spatial distribution of precipitation and radiation across the study region. A detailed list of the different measurement systems is given in Table 1, and the set-up of the instrumentation during LITFASS-2003 is shown in Fig. 4.

Table 1 Measurement systems operated during the LITFASS-2003 experiment

Measurement complex	Operator [a]	Number of Systems	Site(s)	Status of operation[b]	References
Basic measurements					
Synoptic weather station	DWD	1	MOL	op	
Routine radiosoundings	DWD	1	MOL	op	Leiterer et al. (2005)
Additional radiosoundings	DWD	1	MOL	sel	Leiterer et al. (2005)
BSRN station	DWD	1	MOL	op	Ohmura et al. (1998), http://www.bsrn.ethz.ch
GM Falkenberg	DWD	1	GM	op	Neisser et al. (2002)
Ground-based remote sensing					
Sodar/RASS	DWD	1	GM	op	Engelbart and Steinhagen (2001)
1290 MHz WPR/RASS	DWD	1	MOL	op	Engelbart and Steinhagen (2001)
492 MHz WPR/RASS	DWD	1	MOL	op	Engelbart and Steinhagen (2001)
MWRP	DWD	1	MOL	op	Engelbart and Steinhagen (2001)
Cloud radar	METEK	1	MOL	cont	http://www.metek.de
Micro rain radar	DWD	1	MOL	op	Peters et al. (2002)
Wind/temperature radar	MPI	1	GM	cont	Hirsch (2000)
DIAL	MPI	2	GM	sel	Wulfmeyer and Bösenberg (1998)
Wind lidar	MPI	1	GM	sel	Bösenberg and Linné (2002)
Raman lidar	AWI	1	MOL	sel	Schäfer et al. (1995)
Sodar	ALUF	1	BW	cont	http://www.scintec.com
Laser ceilometer	DWD/MPI	3	MOL/GM/Bw	op/cont	Münkel et al. (2001)
Micrometeorological measurements					
Micrometeorological stations over all relevant land use classes	DWD, GKSS, TUDD, UBT, WUR, MPI	14(13 sites)	see Fig. 4	op/cont	Weisensee et al. (2001) Beyrich et al. (2002b) Beyrich et al. (2006)

Table 1 continued

Measurement complex	Operator [a]	Number of Systems	Site(s)	Status of operation[b]	References
Turbulence measurements at the 99 m tower	DWD	2	GM	cont	
Scintillometer measurements					
Laser scintillometer SLS-20/40	DWD, GKSS, WUR, LIM	7	see Fig. 4	op/cont	De Bruin et al. (2002), Hartogensis et al. (2002) http://www.scintec.com
LAS	DWD, WUR	2	see Fig. 4	op/cont	Beyrich et al. (2002c)
XLAS	KNMI/WUR	1	see Fig. 4	cont	Kohsiek et al. (2002)
Microwave scintillometer	DWD/Ubern	1	GM → MOL	cont	Lüdi et al. (2005), Martin et al. (2002)
Airborne Measurements					
Helipod sonde	TUBS	1	-	sel	Bange and Roth (1999), Bange et al. (2002)
Tornado	Bundeswehr	1	-	sel	
Monitoring in the LITFASS area					
Registr. precipitation gauges	DWD	14	see Fig. 4	op	Beyrich et al. (2002a)
Global radiation	DWD	5	see Fig. 4	op	
Soil moisture monitoring	DWD	2	GM/HV	sel	
LAI-measurements	DWD	9	see Fig. 4 (A1-A9)	sel	For details regarding the A1-A9, FS, and SS sites see
Water temperature	DWD/BTU	8	see Fig. 4 (FS, SS)	op/sel	Beyrich et al. (2006)

[a]Short names of the operators are explained in the Appendix

[b]op—Operational at MOL, cont—continuously during LITFASS-2003, sel—selected days only

Table 2 Sampling characteristics of the flux measurement systems operated during the LITFASS-2003 experiment

Measurement system	Sampling scale (m)	Sampling domain (m)	Footprint scale (m)
Sonic/hygrometer	10^{-1}	10^{-1}	10^{1}–10^{2}
(~ at tower)	10^{-1}	10^{-1}	10^{2}–10^{3}
Laser scintillometer	10^{2}	10^{2}	10^{2}–10^{3}
Remote sensing	10^{2}	10^{1}	10^{3}–10^{4}
LAS/MWS	10^{3}	10^{3}	10^{3}–10^{4}
XLAS	10^{4}	10^{4}	10^{3}–10^{4}
Helipod	10^{0}	10^{4}	10^{3}–10^{4}

The MOL site and the GM Falkenberg formed the two central measurement sites of the experiment (see Fig. 4). An additional remote sensing site, equipped with a sodar and a ceilometer, was set-up in the western (forested) part of the area (BW). The micrometeorological measurements were concentrated in the eastern part of the study region, and covered all major agricultural crops (triticale, rye, barley, rape, maize and grassland), forest and water. The long-distance scintillometer paths represented three different distributions of major land-use classes with forest-to-farmland ratios of about 20, 2, and 0.1, respectively, in the footprint area of the paths.

Different flight patterns were designed for the Helipod flights. Flight strategies used for flux measurements included the “grid”, “box” and “catalogue” pattern, respectively. They all consisted of straight flight legs of 10–20 km length flown at different altitudes where the lowest measurement level typically was at about 85 m above ground (for details, see Bange et al. 2006).

With respect to the experimental determination of the turbulent fluxes, several orders of scales in the magnitudes of sampling domains and footprint area sizes were covered by this combination of measurement systems (see Table 2).

The LITFASS-2003 field experiment was performed in the LITFASS area from 19 May to 17 June 2003, i.e., during the main growing season. A list of the participating institutions is given in the Appendix.

4 QA/QC activities

Special attention within the EVA_GRIPS project and, in particular, in connection with the LITFASS-2003 experiment, was given to quality assurance and quality control issues of the measurements (see also Mauder et al. 2006). This included the performance of a pre-experiment in May and June 2002 at the GM Falkenberg in order to perform an intercomparison of the different types of turbulence measurement systems as well as of radiation and soil sensors operated by the different groups. In addition, the different Helipod flight patterns were tested during this pre-experiment in order to define and to adopt the data analysis and interpretation strategy to the goals of the project, and to obtain a first insight into the representation of the heterogeneous landscape in the measurements. During a second campaign in September 2002, the synergy of systems for the flux-profile measurements was tested: eddy-covariance measurements at the surface and at the 90-m level of the Falkenberg tower were performed along with water vapour DIAL and wind profiler/RASS soundings over a period of 2 weeks, and the Helipod was flown on 4 days to assess the suitability of the vertical grid, catalogue and box flight patterns in comparison with the lidar/RASS profile measurements.

In order to minimise differences in the estimates of the turbulent surface fluxes from the eddy-covariance measurements caused by different sensor and system characteristics, only two types of ultrasonic anemometer-thermometers and fast response hygrometers were used during the LITFASS-2003 experiment (see Beyrich et al. 2006). A laboratory calibration procedure for the fast response hygrometers was established and tested at MOL during the pre-experiment in 2002 (Weisensee et al. 2003). Prior to and after LITFASS-2003, all KH20 and LI-7500 instruments from the different groups were calibrated with this unified procedure. The calculation and quality assessment of the turbulent surface fluxes for LITFASS-2003 was realised with one unique program module applied to the eddy-covariance measurements of the different groups (see Mauder et al. 2006). This ensured comparability of the computed fluxes with respect to data treatment and correction algorithms. The uncertainty of the resulting flux values (half-hour averages) was estimated as 10% (or $10\,\mathrm{W\,m^{-2}}$, whatever is larger) for the sensible heat flux, and 15% (or $15\,\mathrm{W\,m^{-2}}$) for the latent heat flux (see Beyrich et al. 2006).

In addition, post-field consistency checks were performed between the data from the different sites and/or instruments collected during LITFASS-2003. This included a thorough comparison of the downward radiation flux measurements under clear-sky conditions, a plausibility control for the temperature, humidity, wind and soil data, and the intercomparison of the humidity profile data from the DIAL, radiosonde, and MWRP systems.

5 Meteorological conditions

In the experimental region, the first half of the year 2003 was characterised by a rather cold and long winter with little snow, followed by a very warm and dry late spring and early summer period. With the exception of January 2003, all the other months were too dry and had an excess of sunshine compared to the long-term (30 years) mean. Some selected climate data for this period are summarised in Table 3. The first half of the year 2003 was one of the driest since the beginning of the Lindenberg record in 1905: from January to June 2003, 165.4 mm of precipitation was measured representing only 60% of the normal amount.

These atypical observations were the result of an unusual circulation pattern with east-south-east being the most frequent wind direction, while during "normal" years winds from the south-west are dominant. The precipitation deficit between February and May 2003 resulted in a rapid and early consumption of the soil water storage already at the beginning of the vegetation period. This is illustrated in Fig. 5 showing the time series of soil moisture and daily precipitation sum from March 2003 till the end of June 2003. Continuous time-domain reflectometry measurements of soil moisture were supported by regular probing with the gravimetric method and by measurements with the Lumbricus sonde (profile measurements of the dielectric constant of the soil). Although differences up to 3–5% of volume may be noticed for single measurements, the general evolution of estimated soil moisture is in good agreement between the different measurements. At the beginning of the LITFASS-2003 experiment, soil moisture was already quite low (between 5% and 8% of volume

Table 3 Selected climatological data of the synoptic weather station at the MOL during the period December, 2002 till June, 2003 in comparison with the long-term climatological mean (1961–1990, comparison denoted "versus climate")

Month	Air temperature		Precipitation		Sunshine duration		Days with frost ($T_{min} < 0°C$)		Summer days ($T_{max} > 25°C$)	
	Mean (°C)	Versus climate (K)	Sum (mm)	Versus climate (%)	Sum (h)	Versus climate (%)	Number	Versus climate	Number	Versus climate
Dec 02	−2.5	−2.9	14.6	29	64.9	173	27	+8	–	–
Jan 03	−1.0	+0.2	49.4	128	44.3	96	18	−5	–	–
Feb 03	−1.9	−1.8	4.7	14	121.7	174	28	+9	–	–
Mar 03	4.1	+0.7	25.8	72	167.8	136	20	+4	–	–
Apr 03	8.7	+0.8	31.5	77	212.8	129	10	+5	–	–
May 03	15.7	+2.6	14.1	24	254.4	113	–	–	8	+5
Jun 03	19.4	+2.9	39.9	62	294.6	129	–	–	14	+5

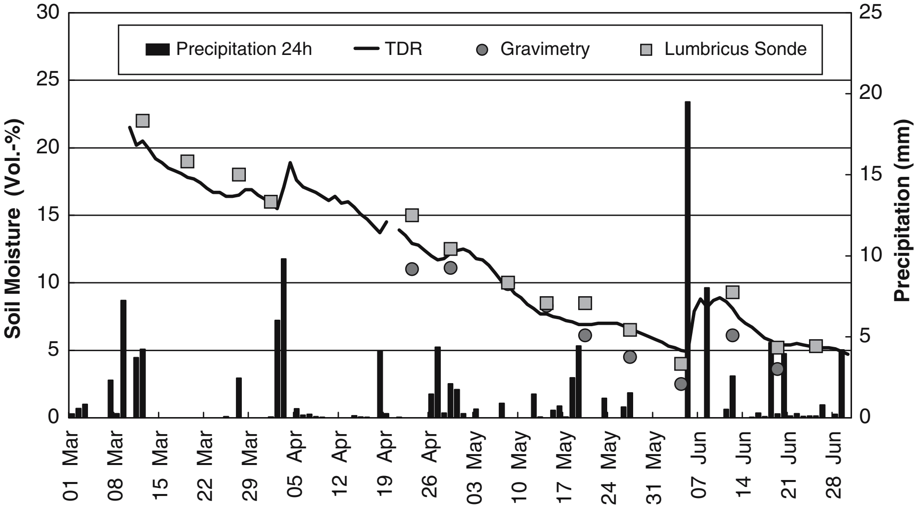

Fig. 5 Daily precipitation and soil moisture (measured with three independent techniques at a depth of 0.15 m) at the GM Falkenberg during the period March to June 2003

typically), and it further decreased towards the wilting point during LITFASS-2003 in some parts of the region.

At the beginning of the experiment, the region was influenced by a cyclonic south-westerly to westerly flow with several frontal passages and embedded high pressure ridges. After the first week, the meteorological situation was dominated by the anticyclonic influence of an upper level ridge extending from central Europe to Scandinavia. At the surface this caused high-pressure influence as well, which was only temporarily interrupted by the passage of shallow low-pressure zones (depressions) with embedded showers or thunderstorms. During the last week, the study region again came under the influence of the frontal zone, but it was influenced mainly by subtropical air masses. The weather was thus characterised by high insolation and a few days only with significant precipitation. Nighttime temperatures were mostly above 10°C except for two nights during the first week. Daytime maximum temperatures exceeded 30°C on several days, in particular during the first week of June. Winds were generally weak

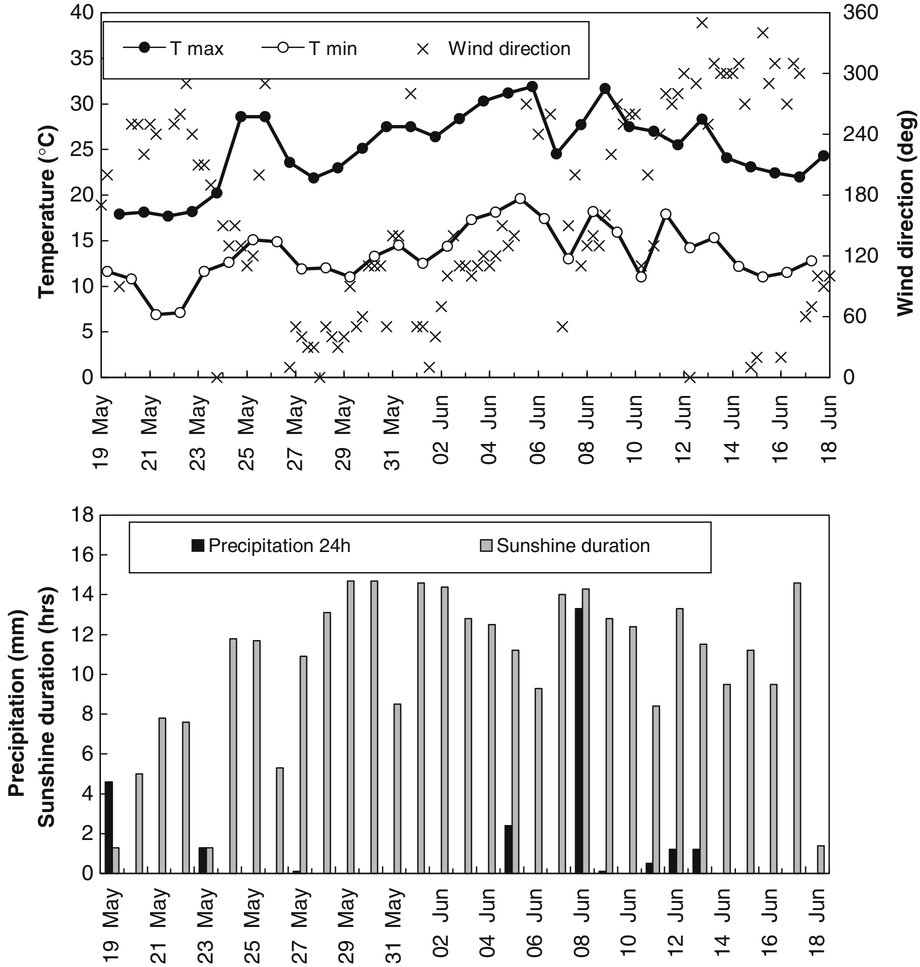

Fig. 6 Time series of basic meteorological parameters measured at the MOL for the period of the LITFASS-2003 experiment: daily maximum/minimum temperatures and wind direction (upper panel), daily precipitation and sunshine duration (lower panel)

to moderate, frequently from the easterly direction; the 10-m wind speed was mostly less than 6 m s^{-1}. Time series of some basic meteorological variables for the period of the LITFASS-2003 experiment are shown in Fig. 6.

Notable precipitation was recorded during the 1-month period of the experiment on 8 days only. Significant amounts of rain occurred in connection with two frontal systems at the beginning of the experiment (18–19 May, 4–13 mm) and during the passage of low-pressure zones with embedded showers and thunderstorms on 5 June (1–45 mm), 8 June (8–20 mm), and 12 June (2–9 mm). In particular the precipitation event on 5 June produced an extremely heterogeneous distribution of rain across the study region, which caused a rather complex spatial pattern of evaporation during the following days. The second thunderstorm situation 3 days later resulted in a smoother precipitation distribution (the precipitation occurred in the late evening after a calm sunny day). The spatial pattern of rain during these two events compiled from the

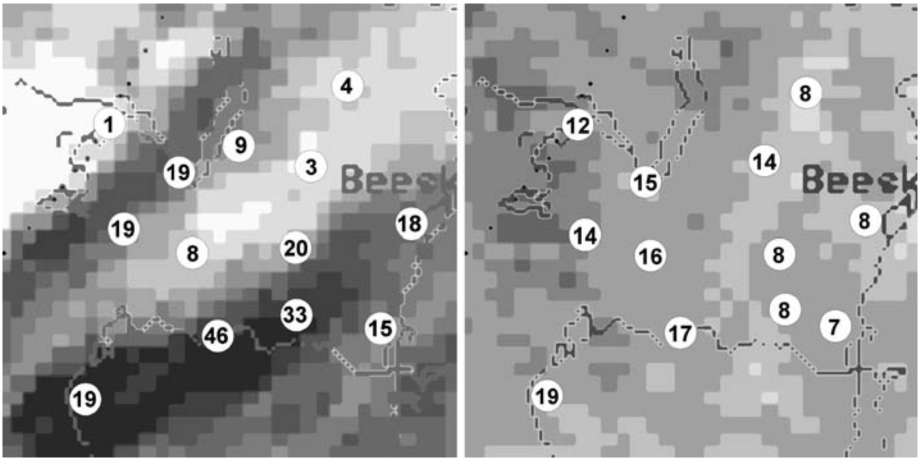

Fig. 7 Spatial distribution of rain in the LITFASS area on 5 June (left) and 8 June (right) based on measurements with the Berlin weather radar and with a regional raingauge network (numbers in circles indicate the precipitation measured at the gauge sites, this figure was prepared by J.-P. Leps, DWD-MOL)

measurements of the Berlin weather radar (precipitation scan mode) and the regional LITFASS raingauge network is illustrated in Fig. 7.

Figure 8 depicts the moisture content of the ABL during daytime for the individual days of the experiment as derived from measurements with the water vapour DIAL, with the MWRP, and from the 1200 UTC radiosonde ascent. Data from all three systems were averaged over the height range between 500 m and 1000 m above ground representing the central part of the ABL in most cases, and the upper half of the ABL for a few days when ABL growth was slow. Error bars indicate the variability of humidity within this height range. The humidity values derived from the three different systems are in reasonable agreement taking into account the site separation and the different principles of measurement. While the DIAL was operated at GM Falkenberg, both the MWRP and the radiosonde release point are situated at the MOL site. The radiosonde profile represents a snapshot of the instantaneous structure of the ABL during the time of the ascent, and the height range of interest is traversed by the radiosonde along a slanted path in less than 2 min. The DIAL and MWRP data reflect the characteristics of the ABL directly above the instrument; while the DIAL measurements were performed with a vertical resolution of 60 m and averaged over 10 min, a smoothing of the vertical profile is inherent in the MWRP analysis scheme as is typical for passive remote sensing instruments. From Fig. 8 it is obvious that the ABL humidity was rather low between 20 May and 22 May, but then increased for 4 days in connection with a frontal system that brought moist subtropical air from the south. North-easterly winds produced advection of rather dry air between 27 May and 31 May. At the beginning of June, continental air masses were advected from the south-east and south resulting in maximum humidity values of more than 10 g m^{-3} on 5 June. Minor variations of ABL moisture at an intermediate level occurred for the rest of the experimental period except for 11 June when moist air was present after the passage of a weak cold front.

A central parameter characterising the ABL structure is the ABL height, which also serves as a scaling parameter for the vertical profiles of fluxes, variances and

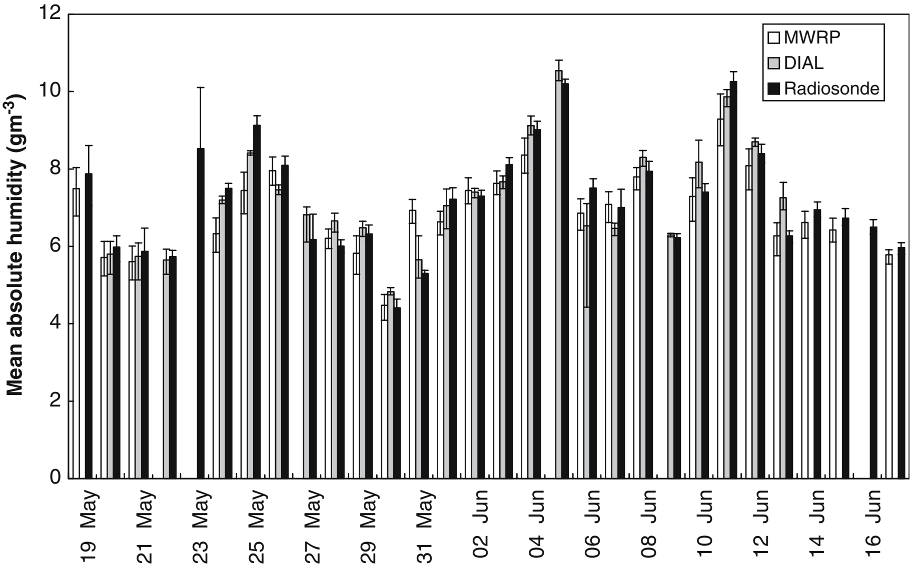

Fig. 8 Mean absolute humidity values in the middle of the ABL (500–1000 m agl) at 1100 UTC for the period of the LITFASS-2003 experiment as derived from radiosoundings, water vapour DIAL and MWRP measurements. (MWRP and DIAL data were provided by J. Güldner, DWD-MOL, and B. Hennemuth, MPI Hamburg)

structure parameters for a well-mixed convective boundary layer. An estimate of the ABL height can be obtained from vertical profile measurements with in-situ and ground-based remote sensing systems (e.g., Seibert et al. 2000). Corresponding estimates for the daytime convective ABL have been derived from the radiosonde, lidar and wind profiler data. The ABL height during the midday radiosonde ascent for the period of the experiment is shown in Fig. 9. The WPR data have been analysed for a local maximum of the backscattered signal that can be expected at the top of a fairly mixed convective ABL (e.g., Beyrich and Görsdorf 1995). Height values displayed are an average of the position of this maximum in the mean reflectivity profiles of the five WPR beams in its standard operation mode. Error bars of ±150 m are given corresponding to the height resolution of the system. The DIAL data were analysed for the occurrence of sharp gradients and local variance maxima both in the backscatter intensity and water vapour profiles averaged over ten minutes (for details, see Lammert and Bösenberg 2006). ABL height values shown in Fig. 9 are averages over six 10-min intervals with the maxima and minima indicated by the error bars. Radiosonde profiles have been analysed according to three different criteria: (i) the height of an elevated inversion base, (ii) the height above which a sudden decrease in moisture occurs, and (iii) the height at which a parcel rising with the temperature measured at the surface becomes neutrally buoyant. The mean, maximum and minimum from the three estimates are presented in Fig. 9. In general, good agreement between the different ABL height estimates from the three systems is apparent; deviations are within the uncertainty range during most of the days. A few exceptions correspond to situations with disturbed ABL structure or an ill-defined ABL top (e.g. 31 May). Early afternoon mixing heights typically varied between 1200 m and 2000 m.

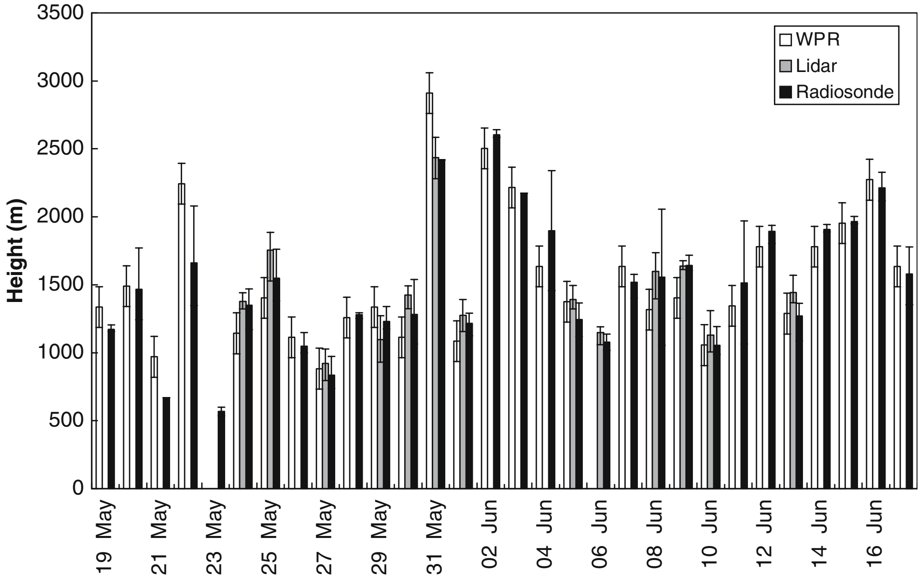

Fig. 9 Daily ABL heights at noontime during the LITFASS-2003 experiment (DIAL data were provided by A. Lammert, MPI Hamburg)

However, there were also a few days with 1100 UTC ABL heights below or around 1000 m. Maximum values between 2500 m and 3000 m occurred on 31 May and 2 June.

6 Selected results

It is beyond the scope of this overview paper to present the major results of the LITFASS-2003 measurements and EVA_GRIPS project achievements here in detail. Instead, selected results will be discussed that illustrate the complexity of the ABL structure and processes over the study area. For details, and for the different aspects of the measurements, data analysis and modelling activities, the reader is referred to companion articles in this special issue.

The heterogeneity in land-use, soil and vegetation characteristics produces a complex heterogeneous pattern of basic aerodynamic, thermal and hydrological characteristics of the land surface across the LITFASS area. As an illustration, the surface temperature distribution around noon on 17 June 2003, both measured from the Helipod during a grid flight and derived from NOAA-16 satellite imagery using the SESAT algorithm (Berger 2001), is shown in Fig. 10. Differences of more than 10 K can be found over rather short distances. The coldest surfaces are the lakes while the highest temperatures were measured over the farmland areas. In the satellite image, a few cold spots at the lateral boundaries of the LITFASS area are due to clouds. The general surface temperature distribution between the forested and farmland areas and the water surfaces shows reasonable agreement, but the detailed structure of the surface temperature pattern for the single patches of land use is much better resolved from the Helipod measurements. Note that the whole Helipod flight took about 2 h, starting with the north-south flight legs in the eastern part of the area and ending

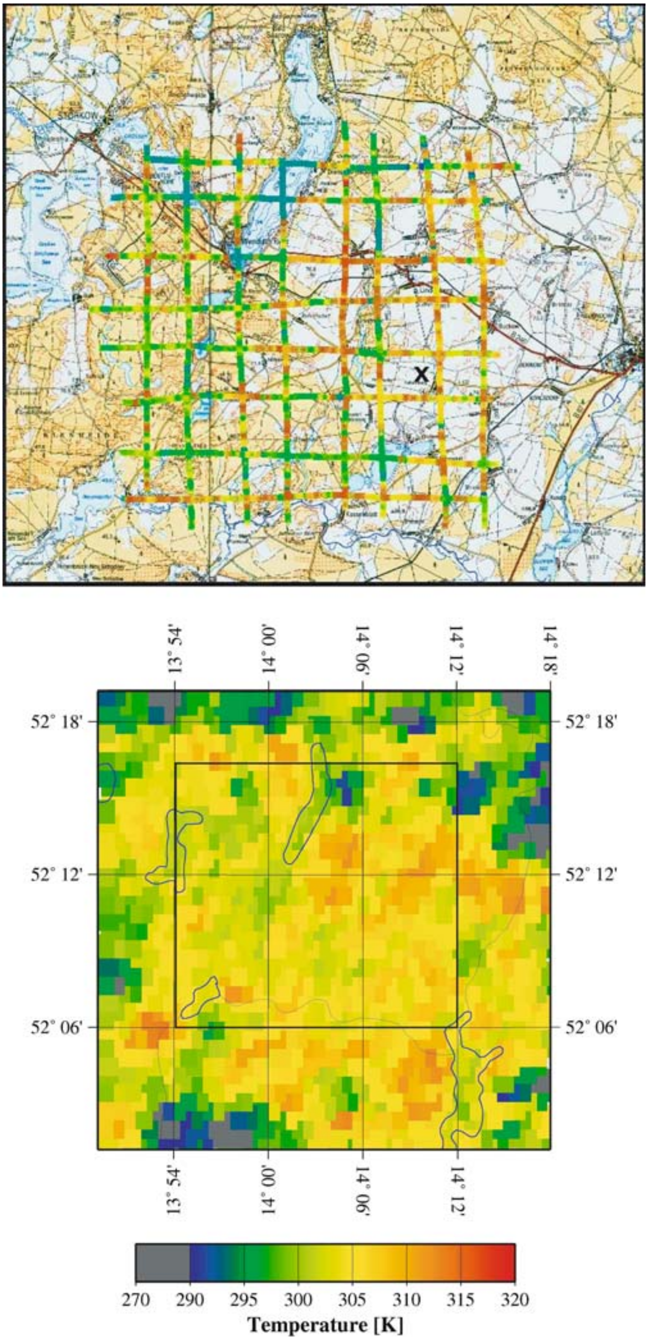

Fig. 10 Areal distribution of surface radiative temperature across the LITFASS area as measured with the Helipod during a grid flight on 17 June 2003, 1132–1333 UTC (upper panel) and as derived from a NOAA-16 satellite image taken at 1202 UTC (lower panel) (these figures were prepared by P. Zittel , Th. Spieß—TU Braunschweig, and A. Tittebrand—TU Dresden, the temperature scale holds for both panels)

with the east-west legs at the southern edge. Hence, effects of different surfaces partly match with non-stationarity effects in the upper panel of Fig. 10. However, this non-stationarity is considered to be of secondary importance during the hours after local noon on a day with dominant clear sky. The changes in local surface temperature during the time of the flight as measured with infrared thermometers at GM Falkenberg, and at the forest and lake sites, respectively, did not exceed 5 K for Falkenberg and 2 K for the other two sites. The SESAT (Strahlungs-und Energieflüsse aus Satellitendaten) algorithm was also used to infer land-surface parameters (e.g., the leaf-area index) and energy fluxes over the LITFASS area from the satellite data. The land-surface parameters were then taken as external parameters at the lower boundary for mesoscale model simulations (see Heret et al. 2006).

As a consequence of the variability of surface characteristics and meteorological forcing conditions, significant differences were found for the surface energy fluxes between the three major land-use classes (forest, farmland, water), but also between the different types of agricultural farmland (see Beyrich et al. 2006). The combined effect of the forcing conditions on the turbulent energy and water vapour fluxes can be illustrated by the Bowen ratio ($Bo = H/\lambda E$) characterising the partitioning of available energy between the sensible and latent heat fluxes. The variability of *Bo* over the period of the LITFASS-2003 experiment for some of the micrometeorological sites is shown in Fig. 11. Highest *Bo* values were always found over the forest. Over the lake, *Bo* was less than one all the time indicating the dominance of evaporation over the free water surface. For most of the other sites, *Bo* was less than one at the beginning of the experiment after rain on 18–19 May, and again after the precipitation events on 5 June and 8 June. During the mostly dry periods (27 May to 5 June and 9 June to 17 June) a gradual increase of *Bo* could be noticed over all land surfaces. A different evolution for the different types of farmland can be attributed to the vegetation development of the various crops. As is obvious from Fig. 11 the highest differences in *Bo* occurred at the end of the dry periods on 4 June and 17 June. The reduced increase in *Bo* between 1 June and 5 June can be attributed to the warm and more humid air masses prevailing in the area during these days (compare Fig. 8) thus reducing the surface–air temperature and moisture differences and also the water stress for the plants. This also illustrates the interrelations between the ABL structure and processes and the surface fluxes.

Different methods were used to determine the area-averaged fluxes of heat and water vapour over the study region. A flux composite was derived from the local micrometeorological measurements at 13 sites by a suitable averaging and aggregation scheme taking into account the data quality of the single flux measurements and the relative frequency of occurrence of the different land-use types across the area (see Beyrich et al. 2006). Area-averaged fluxes over the parts of the area that mainly consist of farmland and forest, respectively, were derived from the long-distance scintillometer measurements (see Meijninger et al. 2006). Profile extrapolation and inverse modelling methods were applied to determine the area-averaged surface fluxes from the Helipod measurements during the "box" and "grid" flights (see Bange et al. 2006) and from the DIAL/wind lidar measurements, respectively. In general, the different estimates of the regionally representative surface fluxes supported each other quite well. The area-averaged fluxes were then used for comparison and validation studies with different mesoscale numerical models (see Ament and Simmer 2006; Heinemann and Kerschgens 2006; Heret et al. 2006). In particular, different flux aggregation strategies and different methods to derive the land-surface parameters

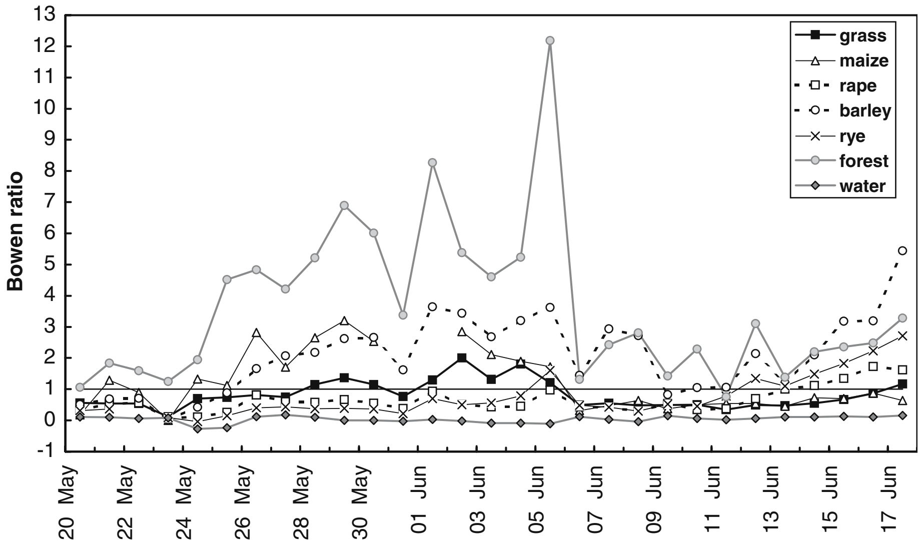

Fig. 11 Mean Bowen ratio during daytime (0800–1400 UTC) over different surface types over the period of the LITFASS-2003 experiment. (data were provided by S. Huneke, GKSS, M. Mauder, University of Bayreuth, W.M.L. Meijninger, Wageningen University, and J.-P. Leps, DWD-MOL)

(including the use of satellite data) were tested with these models. As an example, the mean diurnal cycle of the area-averaged sensible and latent heat fluxes during the LITFASS-2003 period as derived from the eddy-covariance measurements and compared to the output of the DWD NWP model (the "Lokalmodell", LM) is presented in Fig. 12. The results of three types of model runs are shown. The first was the operational run at the time of the experiment, the second one was a modified LM version with improved soil moisture initialisation (based on precipitation measurements prior to the experiment period) and a subgrid-scale land surface parameterisation scheme (mosaic approach, for details see Ament and Simmer 2006), and the third version made use of adapted land-surface parameters (partly derived from NOAA-16 satellite data) and also used measurement-based soil moisture data for initialisation.

The operational LM simulation underestimated the sensible heat flux and considerably overestimated the latent heat flux. Moreover, the model simulation yielded a mean *Bo* ratio smaller than one ($H < \lambda E$) in contrast to the measurements. In addition, the diurnal maximum of the sensible heat flux occurred too early in the model simulations while the maximum of the latent heat flux was modelled too late. These model deficits could be significantly reduced by introducing the above-mentioned modifications to the LM. In particular, the simulated *Bo* ratio obtained with the modified model version was above one during daytime in agreement with the measurements. A remaining difference is the decrease of evaporation in the afternoon that is obvious in the measurements but not properly simulated with LM. This decrease is attributed to the limited water availability during the mostly dry experimental period.

Large-eddy simulations for a number of days from the LITFASS-2003 experiment were performed with the LES model PALM (Raasch and Schröter 2001) at 100-m horizontal resolution. These simulations were used to study the possible contribution

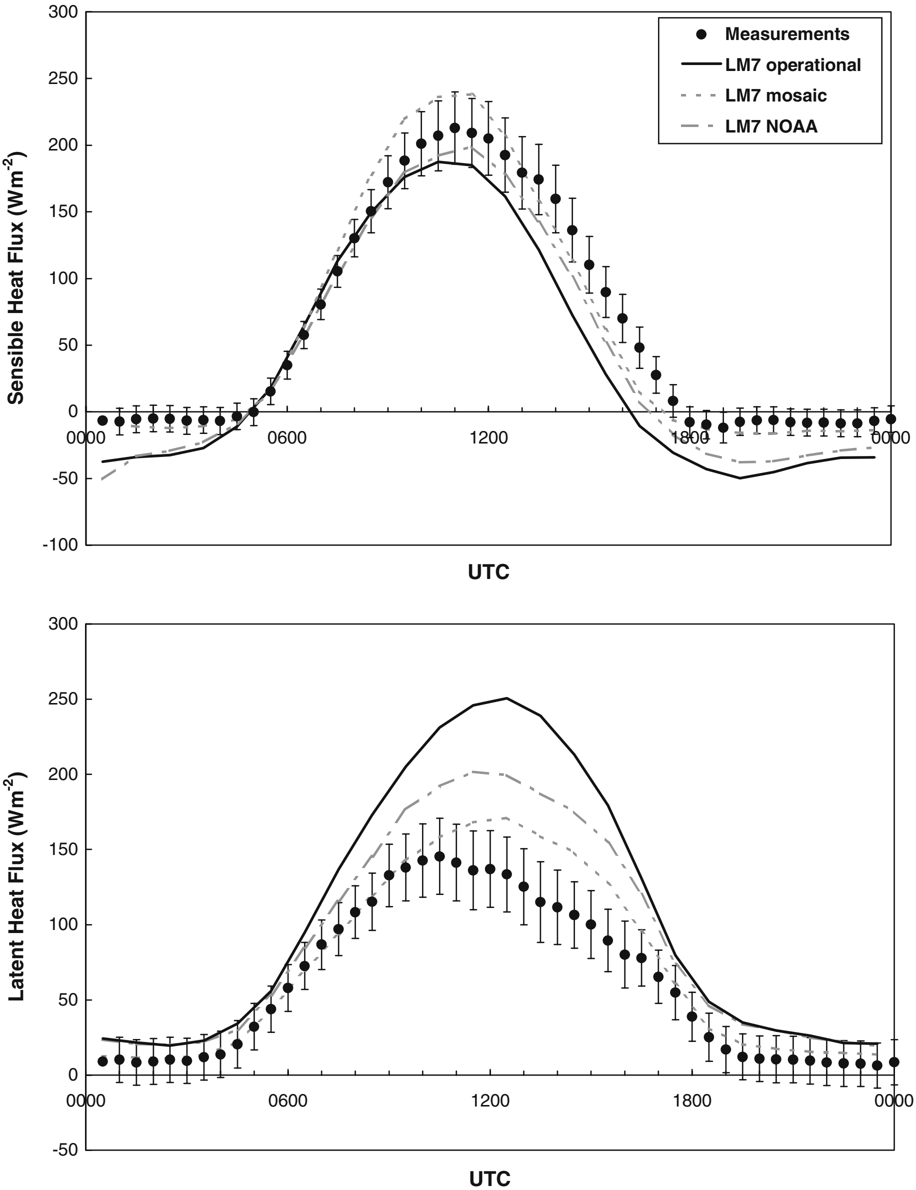

Fig. 12 Mean diurnal cycle of the area-averaged sensible and latent heat fluxes during LITFASS-2003 as derived from the local surface-layer eddy-covariance measurements at the 13 micrometeorological sites compared to the LM output from the standard operational run and from two modified model versions (for details see text) (data were provided by F. Ament, University of Bonn, C. Heret, TU Dresden, and J.-P. Leps, DWD-MOL)

of mesoscale circulations to the area-averaged fluxes within the ABL. Simulations were performed for the daytime hours between 0500 and 1500 UTC, and were initialised with the 0600 UTC radiosonde profiles (time of the sonde ascent at MOL is

0445 UTC) and driven by the composite sensible and latent heat fluxes for the major land-use classes (forest, water, grass, cereals, maize, rape) as derived from the micrometeorological surface measurements. The composite flux values were distributed over the study area according to the detailed land-use pattern. The different days investigated represent cases of different forcing with respect to wind speed and net radiation. For the analysis variables have been decomposed into a large-scale mean, a mesoscale perturbation and a turbulent component, following the method of Chen and Avissar (1994). According to this decomposition, the total vertical flux of a quantity can be split into a mesoscale part, generated by the mesoscale circulation, and a turbulent part caused by the randomly distributed updrafts and downdrafts of the thermal convection.

The contribution of the mesoscale vertical sensible and latent heat fluxes to the respective total fluxes is illustrated for four days in Fig. 13

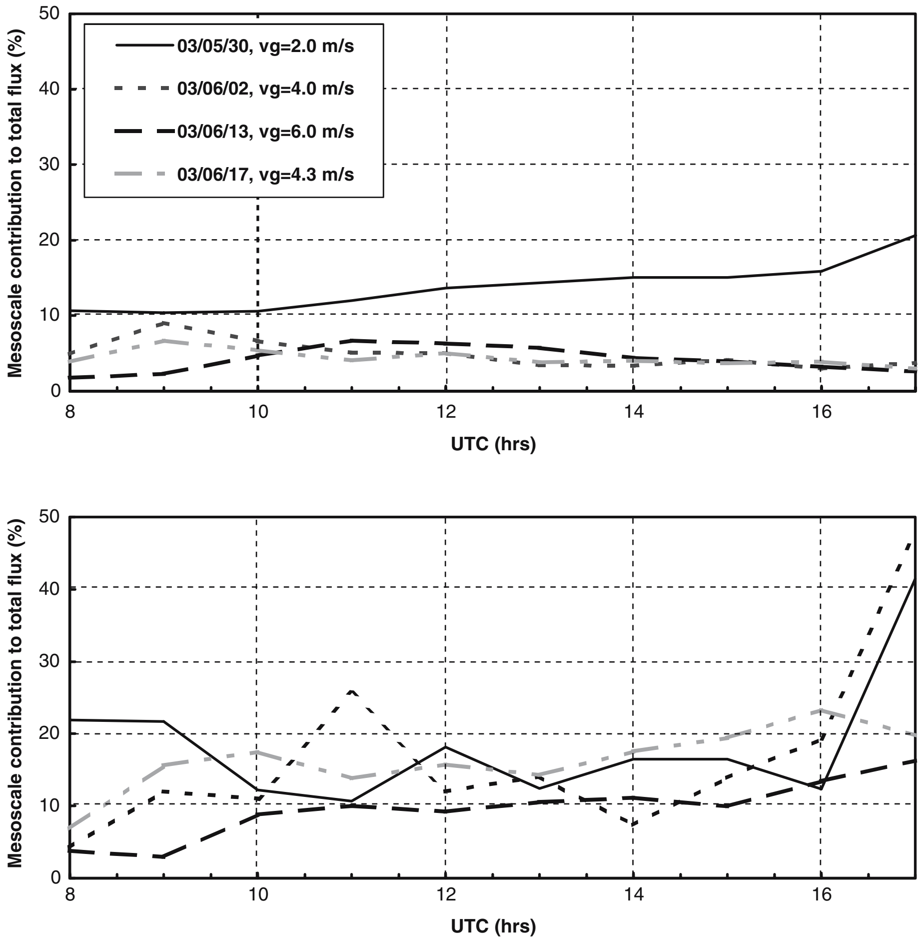

Fig. 13 Relative contribution of the fluxes from mesoscale circulations to the total area-averaged flux over the LITFASS area as determined from LES for 4 days with different forcing conditions: sensible heat flux (upper panel), latent heat flux (lower panel) (data were provided by J. Uhlenbrock and S. Raasch, University of Hannover)

For the sensible heat flux, a significant contribution of the mesoscale to the total flux was found for a case with very weak winds only, it is in the range between 10% and 20%. For wind speeds of 4 m s^{-1} or higher, the mesoscale flux typically amounts to about 5% of the total flux. Results are different for the latent heat flux, where mesoscale circulations contribute 10–20% typically to the total area-averaged flux. There is a weak dependence on wind speed only. These differences are attributed to the structure of the ABL and of the overlying free troposphere. Due to entrainment, warm and dry air is usually transported downward in the ABL, and scalar transport due to mesoscale downward vertical motion thus causes a negative temperature flux but a large positive moisture flux. Consequently, positive fluxes dominate the horizontally-averaged mesoscale latent heat fluxes, while for the averaged temperature flux positive and negative contributions partly cancel and the resulting (mesoscale) flux is small. Figure 13 also reveals a slightly increasing contribution of the mesoscale latent heat fluxes during the course of the day, which is due to the fact that the non-organised convection tends to weaken in the afternoon. Additional "homogeneous" simulations were carried out using the area-averaged surface fluxes calculated from the measurements as boundary conditions. The results show almost no difference in the vertical profiles of the total fluxes to that from the corresponding runs with inhomogeneous surface heating. This implies that mesoscale circulations do not enhance the total vertical transport compared with homogeneous cases for the same mean surface heating. The only effect of these circulations is that they weaken the turbulent transport from the randomly distributed thermal plumes, and this turbulent flux is reduced by just the amount of the mesoscale flux so that the total flux remains unchanged. This relative effect may not have to be regarded in boundary-layer flux parameterisations of large-scale models. Further results from this LES study can be found in Uhlenbrock et al. (2004) and will also be extensively discussed in a forthcoming paper.

7 Summary and final remarks

The LITFASS-2003 experiment was conducted over a $20 \times 20\,km^2$ area of heterogeneous landscape around the MOL of the German Meteorological Service (Deutscher Wetterdienst, DWD). LITFASS-2003 was the central part of the experimental activities of the EVA_GRIPS project that focused on the determination of the area-averaged evaporation over a heterogeneous land surface at the scale of a grid cell in a regional NWP or climate model. Measurements were performed during a 1-month period (19 May to 17 June 2003) and covered the main vegetation growth phase in late spring and early summer. The LITFASS-2003 experiment was embedded into the operational measurement program of the MOL that provided the necessary background data on seasonal and annual time scales.

A hierarchy of instruments and methods was used to derive the fluxes of energy and water vapour from the local to the regional scale including eddy-covariance measurements both at the surface (over all relevant land use classes) and on a 99-m meteorological tower, scintillometry, ground-based remote sensing systems and airborne measurements using the Helipod, a turbulence probe carried by a helicopter. This strategy appeared to be very well suited with respect to the goals of EVA_GRIPS, and met the demand formulated by Parlange et al. (1995): *'To understand transport at the scales of interest in hydrology, it is important to measure evaporative processes at (all) those scales'*.

LITFASS-2003 took place at the end of a warm and dry spring period with low values of the soil water content already at its start. Under these conditions, heterogeneity of the land-surface characteristics was quite pronounced. The synoptic situation during LITFASS-2003 was, except for the first and the last week, dominated by anticyclonic influence causing mostly dry weather with high insolation and weak winds. Two precipitation events at the end of the third week reduced the water stress to the vegetation. The first of these two rain events with a very uneven distribution of precipitation added significant heterogeneity to the meteorological forcing in addition to the heterogeneity caused by land-surface characteristics. This resulted in a quite complex evaporation pattern over the following days.

The LITFASS-2003 experiment provided a comprehensive and unique dataset on land surface/atmosphere interaction processes over a heterogeneous land surface at the meso-γ scale. A complete quality controlled time series of area-averaged surface fluxes from the four-week period of the LITFASS-2003 experiment (with a data coverage of more than 80%) has been created. The accuracy of the area-averaged heat fluxes as determined from the local micrometeorological measurements and from the Helipod data was estimated as 5–10% for the sensible heat flux and about 15% for the latent heat flux, respectively. The data collected during LITFASS-2003 were used either as boundary conditions and forcing data for different kinds of numerical models or as a verification dataset within the EVA_GRIPS project. The modelling activities in EVA_GRIPS comprised one-dimensional models for off-line simulations of the soil–vegetation–atmosphere exchange processes, three-dimensional non-hydrostatic mesoscale models (see Ament and Simmer 2006; Heinemann and Kerschgens 2006; Heret et al. 2006), a hydrostatic mesoscale climate model, and a LES model. Moreover, the data were used to validate retrieval algorithms for the determination of land-surface parameters and energy fluxes from satellite data (see Heret et al. 2006; Tittebrand et al. 2005). The first comparison of measurements and model results showed a systematic overestimation of the latent heat flux by the operational NWP model at DWD up to a factor of about two, which is far beyond the range of the measurements even if their uncertainty is about 15%. Changing the soil moisture model initialisation and introducing a subgrid-scale flux parameterisation considerably reduced the deviations.

Large-eddy simulations were performed for a number of cases with heterogeneous forcing at the surface according to the measured heat fluxes over the different surface types. They revealed the existence of mesoscale circulations in the study region, preferably under weak wind conditions. These may significantly contribute to the total flux especially for the transport of latent heat. This leads to the conclusion that local flux-profile measurements (as performed with the ground-based remote sensing systems in LITFASS-2003) might not necessarily be representative for the mean ABL flux profiles in the study area. It is therefore advisable to perform a model study on mesoscale circulations during the design phase of the measurement strategy in future field experiments.

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Appendix

List of participants in the LITFASS-2003 experiment and in the EVA_GRIPS project

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  W. Kohsiek
- GKSS Research Center, Institute for Coastal Research, Geesthacht, Germany
  S. Huneke, K.-P. Johnsen, H. Lohse, and H.-Th. Mengelkamp
- Max-Planck-Institute for Meteorology (MPI), Hamburg, Germany
  J. Bösenberg, B. Hennemuth, A. Lammert, H. Linné, H. Münster, and G. Peters
- Institute for Tropospheric Research (IfT), Leipzig, Germany
  Th. Conrad
- Alfred-Wegener Institute for Polar and Marine Research (AWI), Bremerhaven/Potsdam, Germany
  F. Immler and R. Neuber
- Wageningen University and Research Center (WUR), Meteorology and Air Quality Group, Wageningen, The Netherlands
  H.A.R. de Bruin and W.M.L. Meijninger
- University of Bern (Ubern), Institute for Applied Physics, Bern, Switzerland
  A. Lüdi and L. Martin
- University of Bayreuth (UBT), Department of Micrometeorology, Bayreuth, Germany
  Th. Foken, M. Göckede, C. Liebethal, M. Mauder, and J. Ruppert
- Technical University Braunschweig (TUBS), Institute for Air and Space Systems, Braunschweig, Germany
  J. Bange, Th. Spiess, and P. Zittel
- University of Technology Dresden (TUDD), Institute for Hydrology and Meteorology, Dresden, Germany
  F.H. Berger, Ch. Bernhofer, Th. Grünwald, C. Heret, R. Queck, and A. Tittebrand
- Albert-Ludwig University of Freiburg (ALUF), Meteorological Institute, Freiburg, Germany
  A. Matzarakis
- University of Leipzig, Institute for Meteorology (LIM), Leipzig, Germany
  K. Arnold

and

- METEK GmbH, Elmshorn, Germany
- FJS Helicopter Service, Damme/Neubrandenburg, Germany
- Deutsche Bundeswehr (Bw, German Air Force), Reconnaissance Squadron Jagel, Germany

Additionally, modelling activities in EVA_GRIPS were performed by

- University of Bonn, Meteorological Institute
  F. Ament and C. Simmer

- University of Cologne, Institute for Meteorology and Geophysics
  G. Heinemann
- University of Hannover; Institute for Meteorology and Climatology
  S. Raasch and J. Uhlenbrock

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