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The BALTIMOS (BALTEX Integrated Model System) field experiments: A comprehensive atmospheric boundary layer data set for model validation over the open and ice-covered Baltic Sea

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A comprehensive atmospheric boundary layer (ABL) data set was collected in eight field experiments (two during each season) over open water and sea ice in the Baltic Sea during 1998–2001 with the primary objective to validate the coupled atmospheric-ice-ocean-land surface model BALTIMOS (BALTEX Integrated Model System). Measurements were taken by aircraft, ships and surface stations and cover the mean and turbulent structure of the ABL including turbulent fluxes, radiation fluxes, and cloud conditions. Measurement examples of the spatial variability of the ABL over the ice edge zone and of the stable ABL over open water demonstrate the wide range of ABL conditions collected and the strength of the data set which can also be used to validate other regional models.

Introduction

The main objective of the BALTEX research programme is the understanding and realistic modelling of the water and energy budgets of the Baltic Sea and its catchment area. A powerful tool to reach this objective is an integrated model in which the relevant components of the system, namely atmosphere, ocean, sea ice, hydrology and vegetation, are coupled. An integrated model system is able to deliver a consistent view of the processes involved in the water and energy cycles to such a degree of completeness which can never be reached by observations. However,

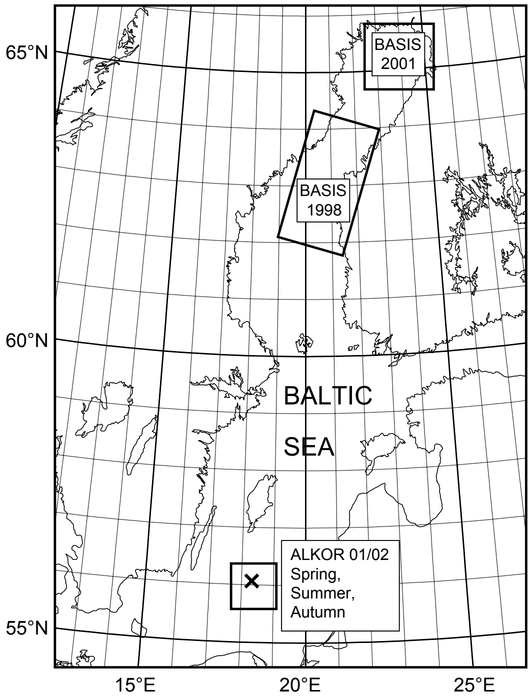

Fig. 1. Locations of the eight BALTIMOS field campaigns: two BASIS winter experiments in 1998 and 2001 and six *Alkor* cruises in spring, summer, and autumn 2000 and 2001.

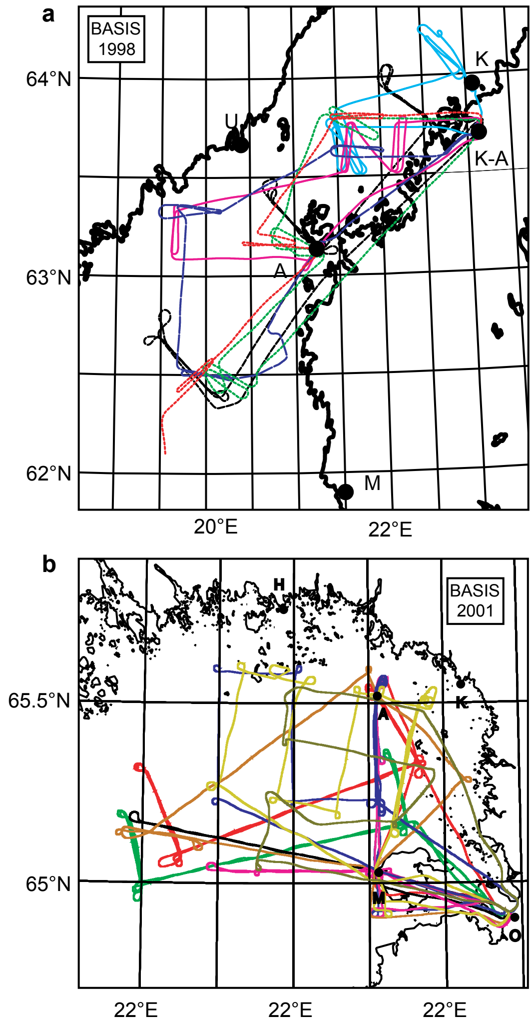

Fig. 2. — **a**: BASIS 1998: Locations of r/v *Aranda* (A), radiosonde stations Kokkola (K), Umeå (U), Merikarvia (M), the six flight missions of research aircraft Falcon operating from airfield Kokkola (K-A). — **b**: BASIS 2001: Locations of r/v *Aranda* (A), surface station Marjaniemi (M), automatic Argos surfaces stations Kuivaniemi (K) and Haparanda (H), and the ten flight missions of research aircraft Dornier-128 operating from airfield Oulu (O).

without validation against observations the model results are of limited use.

In the research project BALTIMOS (**BALT**EX **I**ntegrated **Mo**del **S**ystem) funded by the German Ministry of Research an integrated model system linking existing model components for the atmosphere (model REMO), for the ocean including sea ice (model BSIOM), for the hydrology (model LARSIM) as well as for lakes and vegetation, is to be established and validated against various measurements. One set of data for this validation are the atmospheric boundary layer (ABL) measurements taken during eight field experiments (termed here as BALTIMOS field experiments) over the open and ice-covered water of the Baltic Sea during the period 1998–2001.

The Baltic Sea itself is a large data-sparse area. Following the recommendations of the BALTEX/BRIDGE Strategic Plan (1997) the eight BALTIMOS field experiments were conducted systematically during all four seasons (two during each season) and over water and sea ice of the Baltic Sea where otherwise no data are available. Aircraft, ships, and surface stations were applied. The winter experiments were conducted as cooperative efforts of the Finnish Institute of Marine Research (FIMR), Helsinki, and the University of Hamburg. The experiments during the other seasons were conducted by the University of Hamburg, only.

The purpose of this paper is to introduce the field experiments and the comprehensive data set sampled to the BALTEX scientific community and beyond. The focus is on the ABL, i.e. its mean thermodynamic and kinematic vertical structure and the turbulent fluxes under different large-scale flow conditions.

The experiments: locations, times, platforms and measurements (overview)

The locations of the experiments are shown in Fig. 1. The two winter experiments, called BASIS (**B**altic **A**ir **S**ea **I**ce **S**tudy) 1998 and BASIS 2001, took place over the ice-covered part of the Gulf of Bothnia whereas the non-winter experiments, called Alkor XX after the r/v *Alkor* involved, were conducted in the middle of the Baltic Sea proper where coastal distances are largest. A detailed description of the BASIS 1998 field measurements is given in Launiainen (1999) and scientific results are presented in Launiainen and Vihma (2001).

The experiment times, the platforms involved and a brief overview of the measurements taken are given in Table 1. The experimental strategy was a different one in the winter and non-winter experiments. In the winter experiments, when surface conditions were inhomogeneous (land-fast ice, drifting sea ice, and open water) measurements were made within a mesoscale area (Fig. 2). Research vessel *Aranda* was placed in the land-fast ice. Radiosonde and surface measurements were made by stations installed at the ice-covered coast either some hundred meters on the ice (as for Kokkola in BASIS 1998 or Marjaniemi in BASIS 2001) or on the shore (as for Umeå and Merikarvia in BASIS 1998 or for Kuivaniemi and Haparanda in BASIS 2001). The spatial variability was measured by the research aircraft Falcon during six flight missions in BASIS 1998 and by the research aircraft Dornier-128 during 10 flight missions in BASIS 2001 (Fig. 2). The aircraft flow horizontal legs and vertical profiles within boxes of up to 50 km × 100 km side length and between 10 m and 3 km height to document the mesoscale variability of the mean ABL structure and the turbulent and radiation fluxes over sea ice and open water.

In the non-winter experiments in the middle of the Baltic Sea proper where the sea surface temperature is rather homogeneous measurements were made at one location only. Research vessel *Alkor* was used as platform for the radio-

Table 1. The eight BALTIMOS field experiments: names, times, involved platforms and measurements (overview).

BASIS 1998: 17 February–06 March
- Ship in land-fast sea ice (*Aranda*): 6-hourly radiosounding (0–15 km). Continuous surface measurements including turbulent and radiation fluxes. Sea ice measurements.
- Radiosonde and surface stations at ice-covered shore (Kokkola, Umeå, Merikarvia): Measurements as at *Aranda* except sea ice measurements.
- Aircraft (Falcon-20 operating from air base Kokkola): 6 flight missions in mesoscale box (appr. 100 km × 50 km × 3 km) over sea ice and open water with vertical profiles and horizontal flight legs including turbulent and radiation fluxes.

BASIS 2001: 12–23 February
- Ship in land-fast sea ice (*Aranda*): Measurements as in BASIS 1998.
- Sfc station on land-fast ice (Marjaniemi): Continuous surface measurements including turbulent and radiation fluxes, clouds (base, coverage), and precipitation.
- Automatic Argos surface station at ice-covered shore (Kuivaniemi, Haparanda): Hourly meteorological surface measurements.
- Aircraft (Dornier-128 operating from air base Oulu): 10 flight missions in mesoscale box (appr. 60 km × 60 km × 3 km) over sea ice and open water. Measurements as Falcon-20 (*see* above).

Six *Alkor* cruises: Year 2000: 05–11 April, 14–20 June, 25–31 October. Year: 2001: 01–11 April, 12–20 June, 29 October–07 November
- Ship in Baltic Sea Proper (*Alkor*): 3–6 hourly radiosoundings (0–15 km). Continuous meteorological surface measurements including radiation fluxes, clouds (base, coverage), and precipitation.

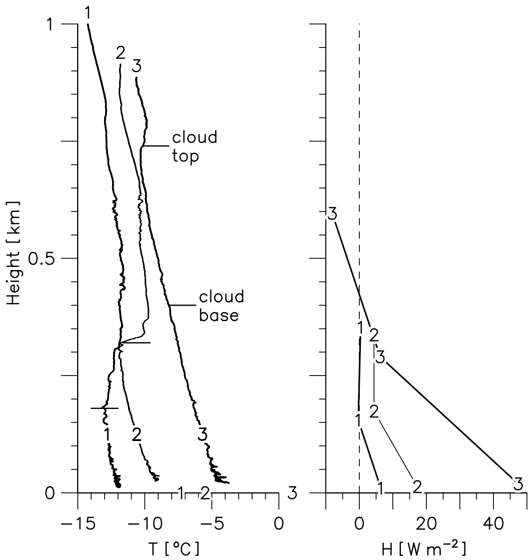

Fig. 3. Vertical profiles of temperature (*T*) and sensible heat flux (*H*) over sea ice at Δx = –130 km (1) and Δx = –40 km (2) distance from the ice edge and over water at Δx = 40 km (3). Surface temperatures are marked by respective numbers. There were no clouds at (1) and (2) and 6–8 octas stratocumulus between 400 and 750 m at (3). Horizontal bars indicate boundary layer top or cloud layer boundaries, respectively.

sonde and various ship-based surface measurements (Table 1).

Concerning its volume, an unpreceeded data set of ABL data over the Baltic Sea was sampled during the BALTIMOS experiments. Only to mention the radiosoundings, about 450 ascents were performed. In the following two sections, measurement examples of the spatial and temporal variability of the atmospheric boundary layer over sea ice and open water are presented. It will be of primary interest to test if these features are simulated realistically by the BALTIMOS model.

The spatial ABL variability in a cold off-ice air flow

As an example of the spatial variability of the ABL over sea ice during the BASIS winter campaigns the conditions as measured by the research aircraft Falcon during a cold off-ice flow on 6 March 1998 are presented below. Figure 3 shows the vertical profiles of temperature T and sensible heat flux H at different distances Δx from the ice edge: (1) Δx = –130 km over white sea ice, (2) Δx = –40 km over white and new grew ice, and (3) Δx = 40 km over open water. The depth of the ABL increased from 150 m (1) to 300 m (2) and 750 m (3) together with a continuous increase in ABL temperature and surface (ice or water) temperature. Growth and warming of the ABL were the result of the convergent upward heat flux H which increased also from 1 to 3. A similar result was presented by Vihma and Brümmer (2001).

Horizontal mesoscale distributions of wind vector, surface temperature T_s, sensible heat flux H and net radiation flux R_N on the same day are shown in Fig. 4 which is based only on flight sections flown below 20 m height. The numbers and the large red wind vectors represent averages over 4 km length. The colored areas and the small blue arrows are values inter- and extrapolated on a regular 11 km grid using the method of Cressman (1959) to give a coherent view of the mesoscale distribution. T_s increases from –11 °C for the closed white ice in the northeast to warmer values (–8 to –2 °C) for the newly formed ice further southwest and to 0–1.3 °C for the open water. Roughly the same spatial distribution holds for H and R_N. R_N is small over ice inspite of the cloudless sky and is clearly larger over open water inspite of the overcast sky (positive R_N is a flux to the surface, in contrast to the convention for H).

The horizontal variations on an even smaller scale are shown in Fig. 5 for a 40 km long flight leg at about 15 m height flown from the sea ice to the open water. The small-scale variability of the sea ice conditions is given by T_s and the albedo. There are different types of sea ice: white ice with high albedo and cold T_s and new thin ice which is grey and has a higher T_s. The heat flux in Fig. 5 clearly reflects the different sea ice conditions. In order to show the effect of the choice of the horizontal length interval L for the flux computation, fluxes computed for L = 1, 2, 4, and 8 km are presented. The results for the longer intervals appear like averages of the results for the shorter intervals (as also shown in Brümmer *et al*. 2002). L = 4 km was chosen in Fig. 4.

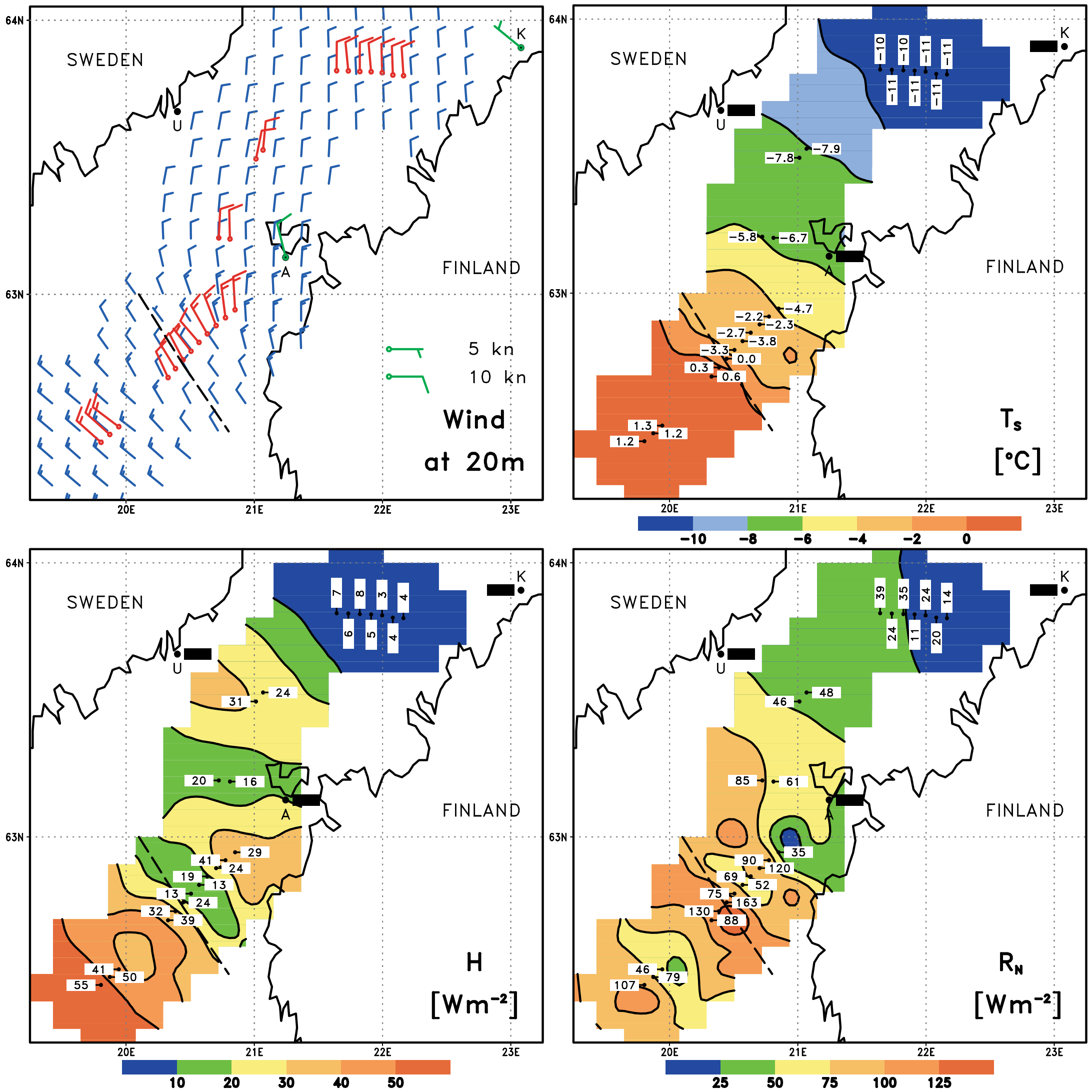

Fig. 4. Horizontal fields of wind, surface temperature T_s, sensible heat flux *H*, and net radiation R_N on 6 March 1998 between 08.45 and 09.50 UTC. Numbers and thick wind arrows represent 4 km averages of Falcon measurements. Colored areas and thin arrows represent inter- and extrapolations on a regular 11 km grid. A, K, U mark values measured at the same time at surface stations Aranda, Kokkola, and Umeå.

The temporal ABL variability over the Baltic Sea proper

The vertical structure of the ABL is primarily influenced by the temperature difference between air, *T*, and underlying surface, T_s. Figure 6 displays both temperatures as measured during the six *Alkor* cruises in the Baltic Sea proper (56°N, 18.5°E). Besides the annual cycle of *T* and T_s, this figure shows that there is a frequent change in the temperature difference in all seasons. Horizontal *T*-advection is the main reason for this. But also T_s shows variations of up to ±1 K on time scales of a day or even shorter. The relatively high portion of stable $T - T_s$ differences is striking and was also stated by Smedman et al. (1997). The stable ABL is still more difficult to simulate satisfactorily than the unstable one. The BALTIMOS data are thus a valuable set to study model validity.

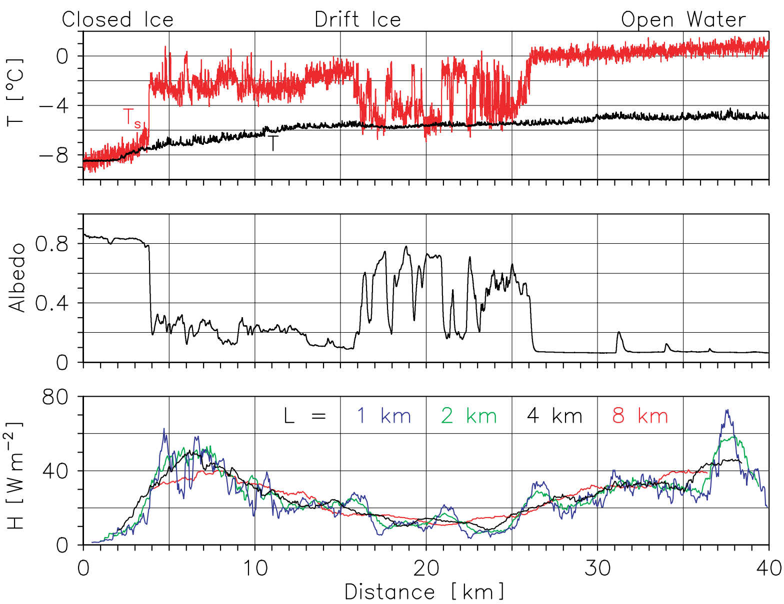

Fig. 5. Air temperature T, surface temperature T_s, albedo, and sensible heat flux H measured by research aircraft Falcon along a 40 km long flight leg at 15 m height across the ice edge zone. Heat flux H was calculated for four interval lengths L = 1, 2, 4, and 8 km.

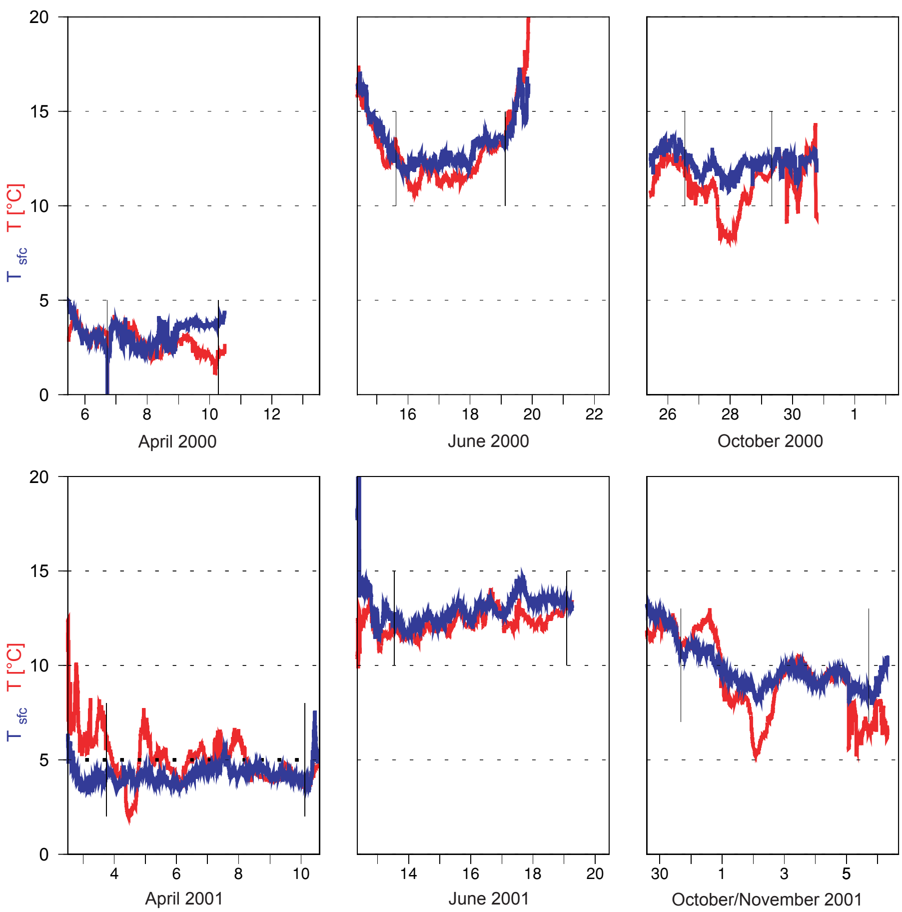

Fig. 6. Air temperature T and sea surface temperature T_s measured during the six *Alkor* cruises in the Baltic Sea proper. Vertical lines mark the period when *Alkor* was on station at 56°N, 18.5°E.

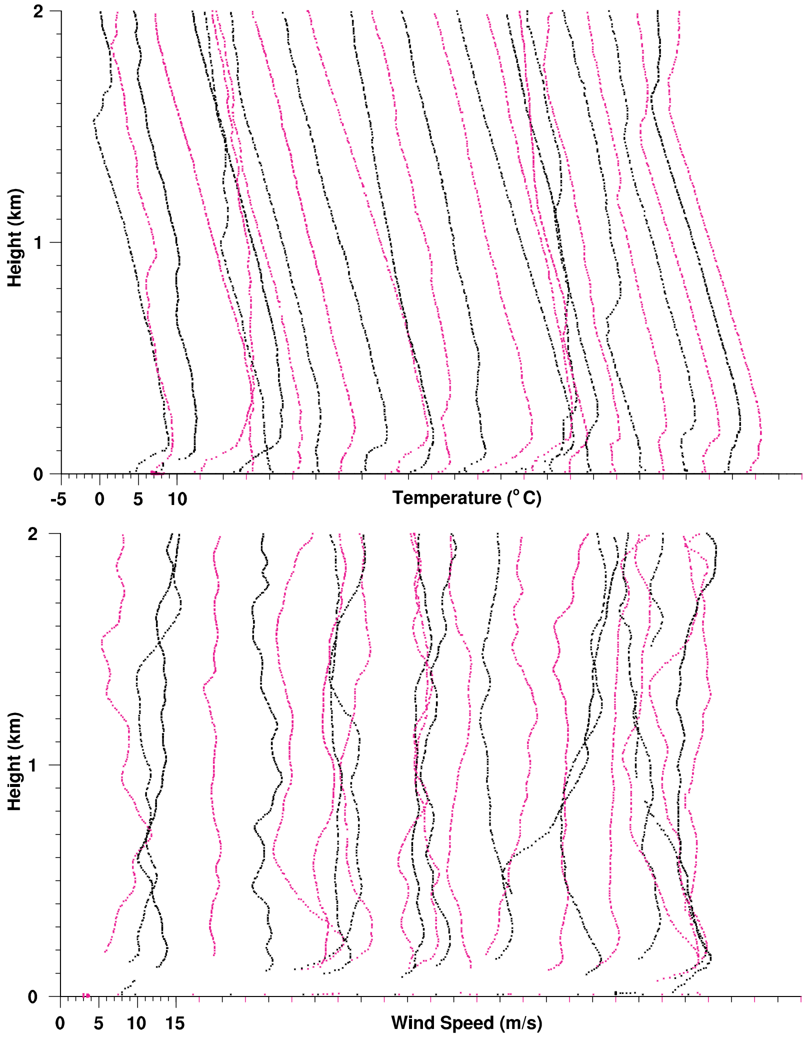

Fig. 7. Six-hourly profiles of temperature (above) and wind speed (below) measured by radiosondes launched on board of *Alkor* at 56°N, 18.5°E during 4 April 00 UTC and 10 April 2001 06 UTC. The running abscissa scale marks the 10 °C temperature value and the 15 m s^{-1} wind speed value, respectively.

Stable $T - T_s$ differences occurred most frequently during the *Alkor* cruise in April 2001. Figure 7 shows the vertical temperature and wind structure in the lowest 2 km during this period based on 6 hourly radiosoundings. With only a few exceptions the ABL shows an inversion below 200–300 m height which was either surface-based or slightly elevated. In many cases a mixed layer was situated on top of the low-level inversion but it was decoupled from the sea surface. Unfortunately, the wind profiles (measured by GPS method) had a gap in the lowest 100 to 200 m above the sea. Nevertheless, the first wind data above the gap often indicate a low-level wind maximum (low-level jet) located in the low-level inversion layer. In this cases, there appears to be a very sensitive balance/imbalance between turbulence generation by wind shear and destruction by stable stratification. A proper model simulation of such ABL conditions requires at least a reasonable vertical grid resolution.

Summary and conclusions

Eight field experiments (two during each season) were conducted over the ice-covered Gulf of Bothnia and the open Baltic Sea proper during the period 1998–2001. Aircraft, ships, and surface stations were applied as experimental platforms. The measurements document the mean and turbulent structure of the ABL including turbulent fluxes, radiation fluxes, and cloud conditions for various large-scale flows situations. The ABL data set will be used to validate the atmospheric model component REMO of the coupled atmosphere-ice-ocean-land surface model BALTIMOS. The usefulness and the quality of the data set was demonstrated by two measurement examples: (a) the spatial variability of the ABL over sea ice during a cold off-ice air flow and (b) the temporal variability of the ABL over the open Baltic Sea proper during warm air advection. The data set is also suited to validate other regional weather forecast models. Beside model validations, the BALTIMOS data set is excellently suited for case studies of the ABL over sea ice and water. During the winter campaigns, the permanent changes from the sea ice from day to day were remarkable. This concerned changes of ice concentration, thickness, roughness, surface temperature, and albedo and had feedback on the ABL. The ABL structure over open water in the central Baltic Sea was also very variable as a consequence of the frequent synoptic changes between warm-air and cold-air advection. The study of the stably stratified ABL with embedded low-level jets will be a special focus of our future analyses as well as the study of the ABL in frontal passages when the winds at ship's level reached 28 m s^{-1}.

The BALTIMOS data are available from the Meteorological Institute of the University of Hamburg and the Finnish Institute of Marine Research in Helsinki.

References

BALTEX 1997. *The main BALTEX experiment 1999–2001: BRIDGE-Strategic Plan*. International BALTEX Secretariat, No. 9, October 1997, 78 pp.

Brümmer B.D. Schröder J. Launiainen T. Vihma A.-S., Smedman & Magnusson M. 2002. Temporal and spatial variability of the surface flux over the ice-edge zone of the northern Baltic Sea. *Journal of Geophysical Research* 107(C8): 3096. (Available on the web at http://www.agu.org/pubs/toc2002/jc/current/; doi: 10. 1029/2001JC000884, 2002)

Cressman G.P. 1959. An operational objective analysis system. *Mon. Wea. Rev.* 87: 367–474.

Launiainen J. (ed.) 1999. BALTEX-BASIS data report 1998. *BALTEX publication series*, Int. BALTEX secretariat, No. 14, March 1999, 94 pp.

Launiainen J. & Vihma T. (eds.) 2001. BALTEX-BASIS final report. *BALTEX publication series*, Int. BALTEX secretariat, No. 19, May 2001, 219 pp.

Smedman A.-S., Bergstöm H. & Grisiogono B. 1997: Evolution of stable internal boundary layers over a cold sea. *Journal of Geophysical Research* 102(C1): 1091–1099.

Vihma T. & Brümmer B. 2001: Observations and modelling of the on-ice and off-ice air flow over the northern Baltic Sea. *Bound. Layer Meteorol.* 103: 1–27.

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