Papers

A model-measurements comparison of atmospheric forcing and surface fluxes of the Baltic Sea

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Abstract

Observed basic meteorological quantities, heat and radiation fluxes from three different measurement stations in the Baltic Sea are compared with model data of the coupled sea-ice-ocean model BSIOM in order to evaluate the atmospheric forcing, corresponding surface fluxes and the sea surface response. Observational data were made available from the BASIS winter campaigns in 1998 and 2001 as well as from the r/v 'Alkor' cruise in June 2001. Simulated fluxes were calculated from prescribed atmospheric forcing provided from the SMHI meteorological database and modelled sea surface temperatures. The comparison of these fluxes with observations demonstrates a strong correlation, even though mean differences in sensible heat fluxes range from 4 to 12 W m^{-2} in winter and -25 W m^{-2} in the June experiment. Differences in latent heat fluxes range from -10 to 23 W m^{-2}. The short-wave radiation flux used as model forcing is on average 15 W m^{-2} less than the corresponding observations for the winter experiments and 40 W m^{-2} for the June experiment. Differences in net long-wave radiation fluxes range from -5 to 12 W m^{-2} in winter and -62 W m^{-2} for the June experiment. The correspondence between measured and calculated momentum fluxes is very high, which confirms the usability of our model component for calculating surface winds and wind stresses from the atmospheric surface pressure.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

The interaction between the atmosphere and the ocean is driven largely by the energy and water cycle, which in turn is determined by the development and energetics of clouds, water vapour and precipitation. Forming these cycles within and among the components of the climate system, water in all of its three phases causes much of the complexity and variability of weather and climate. The quantification of the water and energy budget of the Baltic Sea area is the central aim of the BALTEX (Baltic Sea Experiment) research programme (BALTEX 1995, 2004, 2006). Furthermore, the correct simulation of the energy and water budget is an important requirement for the quality of numerical models, which can be used later for studies of extreme events and climate change in the Baltic area. On the other hand, improved knowledge of energy and water budgets can only be obtained by sophisticated numerical models, including data assimilation. Thus, for a better understanding of the energy and water cycles in the Baltic Sea area, a more detailed validation of model components and a more extensive use of already available observations and satellite measurements are required. The detailed evaluation must therefore include not only the standard parameters but also fluxes; in other words, it will involve a detailed analysis of coupling mechanisms and forcing functions.

Generally speaking, models for the Baltic Sea area show that most of the characteristics of the Baltic Sea and the overlying atmosphere can be described realistically (e.g. Schrum & Backhaus 1999, Omstedt & Rutgersson 2000, Gustafsson 2000a,b, Lehmann & Hinrichsen 2000b, Jacob 2001, Rummukainen et al. 2001, Meier & Döscher 2002). However, the representation of physical exchange processes between ocean and atmosphere still suffers from inadequately resolved processes. Modelling in large and small scales requires a better knowledge of surface fluxes, which are difficult to measure directly on these scales. In general, vertical fluxes of momentum, sensible and latent heat are parameterised by bulk aerodynamic formulas. However, for Baltic Sea modelling purposes, no preference for a specific form of these formulas can be found in the literature. Thus, comparing estimates of the energy and water budget from different models that employ different parameterisations of the exchange fluxes may well exhibit greater differences. How can the reliability of the models be increased and how can uncertainties be reduced?

We believe that atmosphere-ocean or land-atmosphere fluxes are the key to the different behaviour of the models. Uncoupled versions of sophisticated models (e.g. atmosphere only, sea-ice-ocean only) often perform even better than in the coupled mode. This is a clear indicator of the important role of fluxes. In an atmospheric model the ocean surface temperatures and the extent of sea-ice are prescribed; such a model is thus controlled by ocean parameters. In a sea-ice-ocean model, surface fluxes between atmosphere and ocean drive the ocean model.

Comprehensive data sets suitable for validating coupled model systems, and hence, the corresponding parameterisations of fluxes are few in number. However, within the BALTIMOS project, eight field campaigns over the open and ice-covered Baltic Sea were conducted during the period 1998–2001 (Brümmer et al. 2003). The observations focused mainly on:

- the atmospheric boundary layer structure and processes, and the air-sea-ice interaction over areas with inhomogeneous sea-ice cover;
- the atmospheric boundary layer structure over open water under different synoptic conditions such as cold- and warm-air advection and frontal passages.

Gathered systematically during all four seasons and over the open water and sea-ice of the Baltic Sea, these data sets are ideally suited for the validation of coupled model systems. Brümmer et al. (2003) explicitly encouraged potential users to use such data sets.

We used this data to carefully evaluate the atmospheric forcing, corresponding surface fluxes and surface response of our three-dimensional coupled sea-ice-ocean model BSIOM (Lehmann & Hinrichsen 2000a, 2002). The paper is organised as follows: section 2 describes the Baltic Sea-Ice-Ocean Model (BSIOM) and gives the corresponding parameterisations of the fluxes. Section 3 compares meteorological conditions, radiation fluxes and heat fluxes with observations. Section 4 comprises a statistical comparison; it is followed in section 5 by a discussion. The paper ends with a summary and conclusions.

2. Baltic Sea–Ice–Ocean Model (BSIOM)

The numerical model used in this study is a general three-dimensional coupled sea-ice-ocean model of the Baltic Sea (BSIOM; Lehmann & Hinrichsen 2000a, 2002). The horizontal resolution of the coupled sea-ice ocean model is 5 km (eddies permitting), and in the vertical 60 levels are specified, which enable the upper 100 m to be resolved with levels of 3 m thickness. The model domain comprises the Baltic Sea, including the Kattegat and Skagerrak. At the western boundary, a simplified North Sea basin is connected to the Skagerrak to take up sea level elevations and to provide the characteristic North Sea water masses which result from different forcing conditions (Lehmann 1995, Novotny et al. 2005).

The coupled sea-ice-ocean model is forced by realistic atmospheric conditions taken from the Swedish Meteorological and Hydrological Institute's

(SMHI Norrköping, Sweden) meteorological database (L. Meuller, pers. comm.) which covers the whole Baltic drainage basin on a regular grid of $1 \times 1°$ with a temporal increment of 3 hours. The database consists of synoptic measurements interpolated on the regular grid by using a two-dimensional univariate optimum interpolation scheme. This database, which for modelling purposes is further interpolated onto the model grid, includes the surface pressure, precipitation, cloudiness, air temperature and water vapour mixing ratio at 2 m height and the geostrophic wind. Wind speed and direction at 10 m height are calculated from geostrophic winds with respect to different degrees of roughness on the open sea and in coastal waters (Bumke et al. 1998).

The calculation of the ocean-atmosphere energy exchange is based on the following simplified surface heat balance equation for open and ice-covered water:

$$Q_{net} = H + E + (1 - \alpha)S(o) + Lw(o) - Lw(u), \tag{1}$$

where Q_{net} is the net heat flux entering the oceanic mixed layer, H and E are the sensible and latent heat fluxes, respectively, $(1 - \alpha)S(o)$ is the absorbed short-wave radiation, $Lw(o)$ is the incoming atmospheric long-wave radiation and $Lw(u)$ is the long-wave radiation leaving the sea surface.

Surface fluxes are calculated from atmospheric data and modelled SSTs with the aid of bulk aerodynamic formulas. Wind stress on the ocean surface is calculated from the 10 m wind, with the drag coefficient according to Large & Pond (1981). The drag coefficient over sea-ice is chosen to be constant (Joffre 1982). The combined wind stress on ice and ocean surfaces is formulated as

$$\tau = \rho {U_{10}}^2((1 - A)C_{dao} + AC_{dai}). \tag{2}$$

Here, $C_{dai} = 1.5 \times 10^{-3}$ and C_{dao} – the drag coefficients for the atmosphere-ice and atmosphere-ocean interface, ρ – the air density, A – the ice fraction and U_{10} – the wind speed at 10 m height.

Sensible and latent heat fluxes are caused by temperature and moisture differences between ocean/ice and atmosphere. Their parameterisations can be written as

$$H = \rho c_p C_H U_z((1 - A)(T - T_s) + A(T - T_{ice})), \tag{3}$$

$$E = \rho C_E U_z((1 - A)L_z(q_{10\,m} - q_s) + AL_{zi}(q_{ai} - q_{si})), \tag{4}$$

where c_p is the specific heat of air at constant pressure, C_H stands for the Stanton number, and $T - T_s$ is the temperature difference between the atmosphere and the sea surface; E represents the latent heat flux between the atmosphere/ocean and the atmosphere/ice (C_E is the Dalton number), $q_{10\,m} - q_s$ is the difference in specific humidity between the atmosphere and the ocean, and $q_{ai} - q_{si}$ is the difference in specific humidity between the atmosphere and the ice. L_z and L_{zi} are the respective latent heats of evaporation over open water and ice. The transfer coefficients (C_H and C_E) are determined according to Large & Pond (1982). The short-wave radiation R_{sw} is approximated by the empirical Zillman equation for clear skies (Zillman 1972). The short-wave radiation flux absorbed at the ocean surface, together with the modification due to cloudy skies, is parameterised by:

$$(1-\alpha)\,S(o) = (1-\alpha)R_{sw}(1-0.75\,cl), \tag{5}$$

where α is the albedo at the ocean/sea-ice/snow surface (0.03 for the open sea, 0.7 for frozen ice, 0.6 for melting ice, 0.87 for frozen snow and 0.77 for melting snow) and cl is the fractional cloud coverage. The net long-wave radiation is due to atmospheric ($Lw(o)$) and water surface radiation ($Lw(u)$).

$$\begin{aligned} Q_l &= Lw(o) - Lw(u) \\ &= \varepsilon\sigma_s[{T_s}^4 - T^4(a_1 + a_2 e^{1/2})(1 + a_3 cl^2)], \end{aligned} \tag{6}$$

where $\varepsilon = 0.97$ is the emissivity of surface water, σ_s the Stefan-Boltzmann constant, T_s the sea surface temperature and T the air temperature, e the water vapour pressure, and a_1, a_2, a_3 are constants equal to 0.68, 0.0036 and 0.18, respectively (Hagedorn et al. 2000, Lehmann & Hinrichsen 2000a).

Additionally, river runoff is prescribed from a monthly mean runoff data set (Bergström & Carlsson 1994). Runoff data are specified for 42 separate rivers discharging into the Baltic Sea and the Kattegat. The prognostic variables of the coupled sea-ice-ocean model are sea-ice thickness and compactness, sea-ice drift, the oceanic baroclinic current field, the 3-D temperature, salinity and oxygen distributions, the 2-D surface elevation, and barotropic transport. These prognostic variables were extracted from the model every 6 hours. The model was run for the period 1979–2004 including three field campaigns: February to March 1998, February 2001 and June 2001. Model data were extracted at three different positions in the Baltic Sea in order to allow a minutely detailed comparison with the corresponding observations.

3. BALTIMOS field experiments

During the period 1998–2001 over the open and ice-covered water of the Baltic Sea eight experiments were performed with the overall objective of collecting a comprehensive data set suitable for validating the BALTIMOS coupled model system (**BALT**ic Sea **I**ntegrated **MO**del **S**ystem, Brümmer et al. 2003) for the Baltic Sea region. BALTIMOS was developed within the framework of BALTEX/DEKLIM (German Climate Research Programme

2001–06) by linking existing model components for the atmosphere (REMO model), for the ocean including sea-ice (BSIOM model), for the hydrology (LARSIM model) as well as for lakes.

Of the eight field campaigns, we consider only three experiments here:

BASIS 1998:	17 February–6 March 1998
BASIS 2001:	12–23 February 2001
Alkor 6/2001:	12–20 June 2001.

The winter experiments were conducted within BASIS (Baltic Air Sea-ice Study, Brümmer et al. 2003) over sea-ice, and the third experiment was performed over the open Baltic Sea during spring.

3.1. BASIS (Baltic Air Sea – Ice Study) 1998

During the first BASIS field experiment, lasting from 16 February to 6 March 1998, turbulent heat, moisture and momentum fluxes as well as radiation fluxes were measured over ice and water in the northern Baltic Sea (Brümmer et al. 2002). The locations of the ice measurement stations Kokkola and r/v 'Aranda', situated about 80 km apart, are shown in Fig. 1a. The Kokkola ice station was placed on land-fast ice about 4 km south of

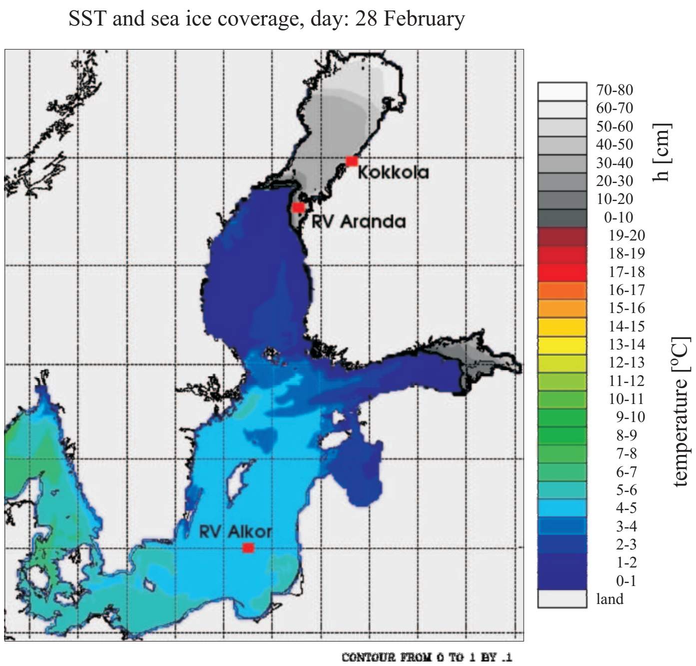

Fig. 1a. Simulated SST and sea-ice extent (grey colours – sea ice thickness; contour lines – sea ice concentration) on 28 February 1998 with positions of the ice stations Kokkola and r/v 'Aranda', as well as r/v 'Alkor'

the island of Vallgrund and at a distance of about 30 km from the ice edge. The time interval of the measurements at the two stations was 10 minutes, whereas calculated values are given at 6-hour intervals.

The 1997–98 sea-ice season was generally normal, except in the northern Bay of Bothnia and the eastern Gulf of Finland, where ice began to form about a week earlier than usual. The ice cover reached its largest extent – 129 000 km^2 – on 11 March (Kalliosaari 2002a).

During the experiment, sea-ice conditions with respect to the sea-ice extent varied only slightly. The sea-ice extent on 28 February 1998 (Fig. 1a) can therefore be taken as representative of the sea-ice situation during this period. The simulated sea-ice extent agrees well with field observations (see Fig. 1 in Brümmer et al. 2002) and the satellite analysis of sea-ice (Fig. 1b), but in the Gulf of Finland and the Gulf of Riga the ice extent was somewhat underestimated.

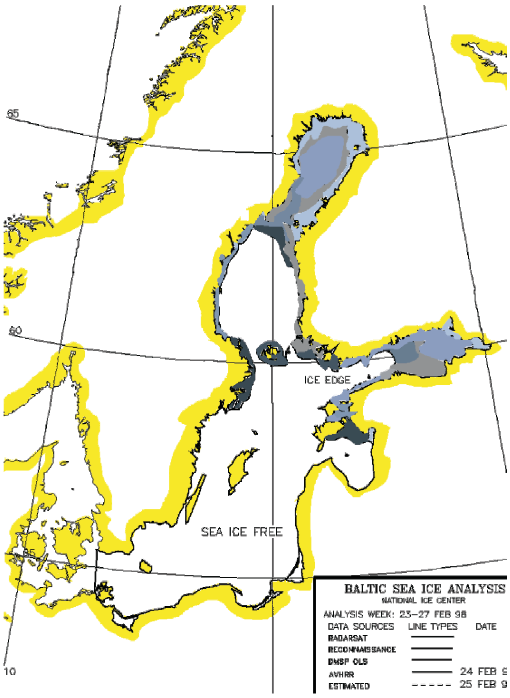

Fig. 1b. Baltic Sea-ice analysis (sea-ice concentration) by the US National Ice Center for 24 February 1998

3.1.1. Evolution of meteorological quantities

During BASIS 1998, meteorological conditions in the experimental area were characterised by a rapid sequence of high and low pressure systems

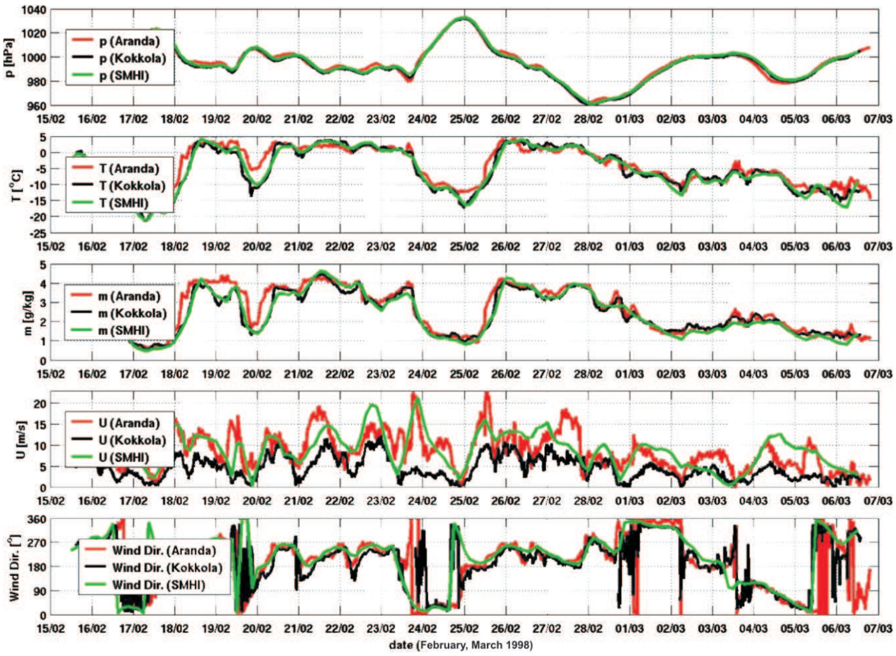

Fig. 2. Time series of pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* at Kokkola and r/v 'Aranda' in comparison with observed atmospheric data (SMHI meteorological database) at Kokkola

and passing atmospheric fronts. Fig. 2 shows time series of the basic meteorological quantities pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* at Kokkola and r/v 'Aranda'. Steady weather conditions lasted no longer than one day. In the rear of lows, passing close to or directly over the experimental area, air temperatures decreased rapidly to below 0°C (17, 19, 24 February). These three cold episodes lasted only one or two days and were brought to an end by approaching warm fronts. Extracted atmospheric (SMHI forcing) data at Kokkola compare well with the corresponding measurements. However, wind velocities agree better with the r/v 'Aranda' measurements owing to the different measurement heights (Kokkola 2 m, r/v 'Aranda' 19 m).

3.1.2. Radiation fluxes

The temporal evolution of surface fluxes measured at Kokkola and on r/v 'Aranda' is presented in Fig. 3. Although these two stations were only 80 km apart from each other, there are obvious differences, which might have been due to differences in cloud cover. Differences in cloud cover could

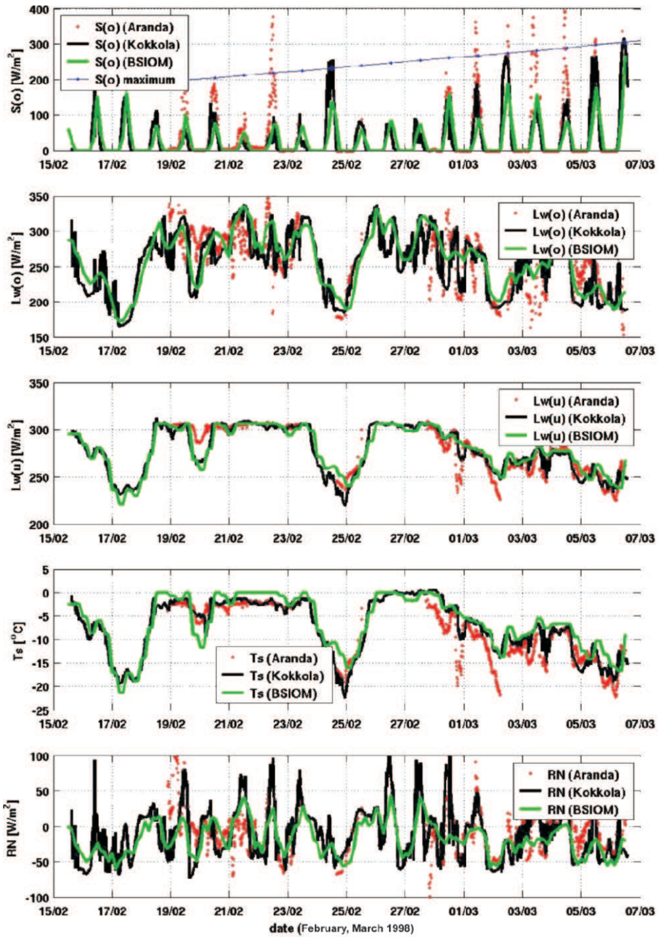

Fig. 3. Time series of short-wave radiation $S(o)$ (the blue line represents the daily clear sky $S(o)$ maximum at Kokkola), downwelling long-wave radiation $Lw(o)$, upwelling long-wave radiation $Lw(u)$, surface temperature T_s and net radiation RN at Kokkola and r/v 'Aranda' in comparison with model data at Kokkola

also have caused the discrepancies between the calculated (BSIOM) and measured values.

The downwelling long-wave radiation flux $Lw(o)$ is closely related to the varying cloud conditions. During warm periods with low-level clouds (e.g. about 325 W m^{-2} on 21 February) and during cold air periods with clear skies (e.g. about 175 W m^{-2} on 25 February) $Lw(o)$ exhibits extreme values. Calculated (BSIOM) long-wave radiation fluxes agree well with local observations. Compared to $Lw(o)$, the variability of the upwelling long-wave radiation flux $Lw(u)$ is smaller, although extreme values also occur at the same time in relation to the changing weather conditions. The surface temperature T_s shows approximately the same structure as the air temperature (Fig. 2). Calculated sea-ice surface temperatures compare extremely well with observations. The net radiation flux, $RN = S(o) - S(u) + Lw(o) - Lw(u)$, varies with the daily cycle and clouds. Day values were positive (e.g. 22 February at Kokkola), whereas night values were predominately negative (e.g. 25, 27 February at Kokkola). The comparison of net radiation fluxes reveals the largest deviations, because small differences in short-wave radiation and downwelling long-wave radiation lead to larger discrepancies, although the overall structure is well covered.

3.1.3. Turbulent fluxes

Turbulent fluxes of heat and momentum are presented in Fig. 4. Sensible heat fluxes reflect the advection of warm and cold air masses due to moving lows and passing fronts. The sensible heat flux H varies approximately between -110 W m^{-2} and 100 W m^{-2}. Positive values were the result of melting weather conditions (e.g. 20/21, 22 and 25/26 February) with high wind speeds, and negative values occurred when the air temperature dropped rapidly below 0°C in the rear of passing lows. The latent heat flux E was not measured, so only the calculated latent heat fluxes are displayed. The latent heat flux E at Kokkola was calculated by the same bulk formula as in BSIOM (eq. (4)). At r/v 'Aranda', however, E was calculated by the bulk aerodynamic method presented by Launiainen & Vihma (1990). Latent heat fluxes varied mostly between -80 W m^{-2} and 130 W m^{-2}. Negative

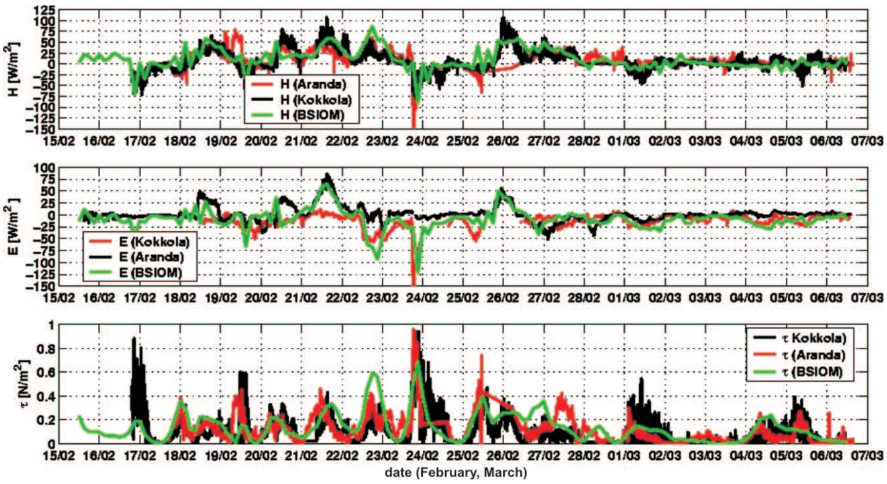

Fig. 4. Time series of sensible heat flux H, latent heat flux E and momentum flux τ at Kokkola and r/v 'Aranda' in comparison with model data at Kokkola

values occurred when the air temperatures were above freezing (e.g. 19, 21 and 26 February), causing snow to melt and leaving patches of melt water on the sea-ice. The momentum flux reflects the wind speed variations caused by synoptic variability. Extreme values occurred on 24 February during the passage of a cold front. Surprisingly, the measured values are much higher compared with calculated values, although the wind speeds on 24 February are in relatively close agreement (wind measurements at Kokkola did not show a maximum at all – Fig. 2).

3.2. BASIS (Baltic Air Sea – Ice Study) 2001

The BASIS field experiment 2001 lasted from 12 February to 23 February 2001. The ice season 2000–01 was mild and shorter than average. The maximum ice extent reached 128 000 km^2 (Kalliosaari 2002b). Figs 5a and b show a comparison of the ice situation on 19 February 2001 between the simulated SST (Fig. 5a) and the Baltic Sea-ice analysis of the US National Ice Center (Fig. 5b). Simulated and observed ice extent agree reasonably well, but in

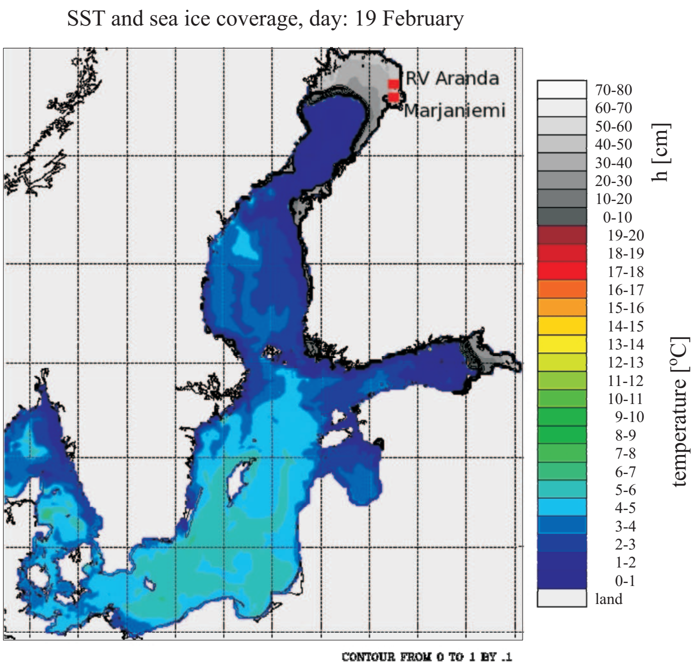

Fig. 5a. Simulated SST and sea-ice extent (grey colours – sea ice thickness; contour lines – sea ice concentration) on 19 February 2001 with positions of the ice stations Marjaniemi and r/v 'Aranda'

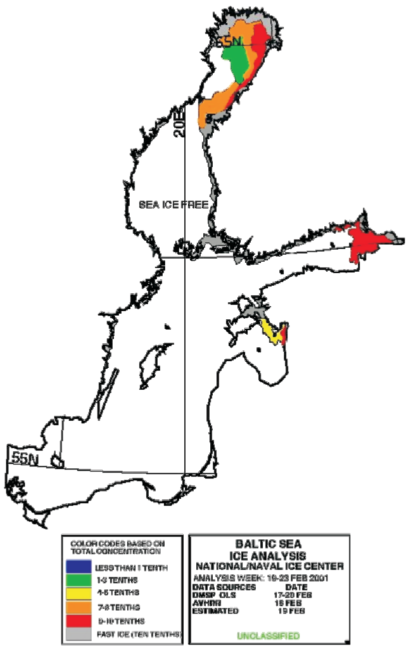

Fig. 5b. Baltic Sea-ice analysis (sea-ice concentration) of the US National Ice Center for 19 February 2001

the simulation no ice is present in the Gulf of Riga and the ice extent in the Gulf of Finland is somewhat underestimated (Fig. 5a).

The Marjaniemi Station was located on the west side of the island of Haparanda Hamn on 30–40 cm thick land-fast ice at a distance of about 100 m from the shoreline. The Finnish r/v 'Aranda' was placed in the ice-covered Bay of Bothnia inside the land-fast ice 15 km from the nearest coast (Brümmer et al. 2003). Turbulent heat, radiation fluxes, moisture and momentum fluxes were measured as in BASIS 1998. The time interval of the measurements was 10 minutes at r/v 'Aranda', 1 minute at Marjaniemi, and calculated values are again given at 6 hourly intervals.

3.2.1. Evolution of meteorological quantities

During BASIS 2001, the weather conditions were characterised by a rapid sequence of high- and low-pressure systems and passing atmospheric fronts. The time series of the meteorological data pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* at Marjaniemi and r/v 'Aranda' are shown in Fig. 6. At the beginning of the experiment the weather was mild, but with the passage of a low on 21 February the wind backed from east to north, and the air temperature dropped to -20°C. Correspondingly, the water vapour mixing ratio fell

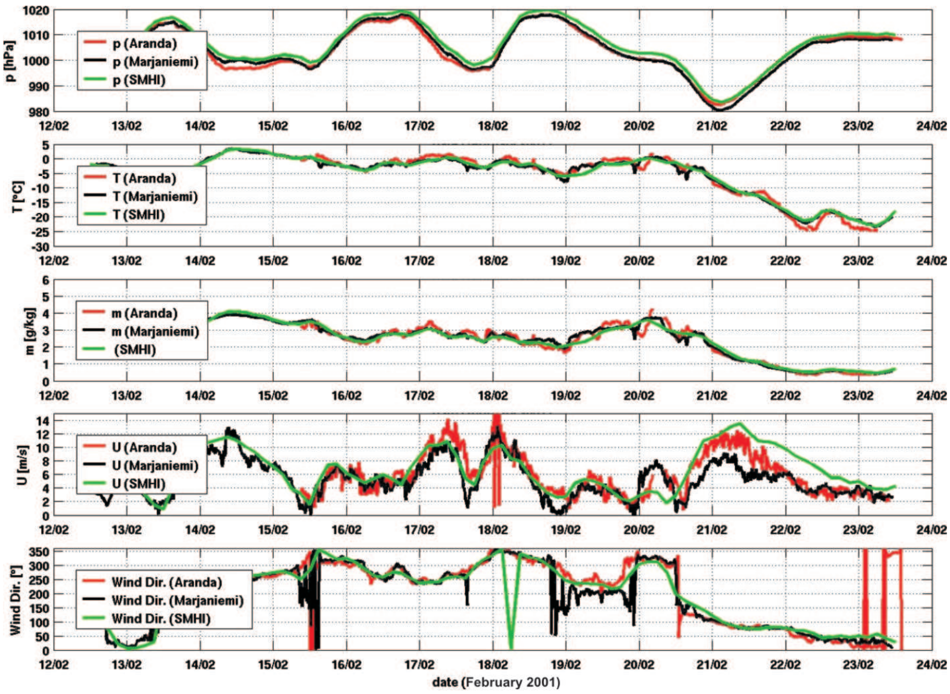

Fig. 6. Time series of pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* at Marjaniemi and r/v 'Aranda' in comparison with observed atmospheric data at Marjaniemi

to less than 1 g kg^{-1}. Generally, the comparison of measurements with extracted atmospheric (SMHI forcing) data at position Marjaniemi shows good agreement.

3.2.2. Radiation fluxes

Radiation fluxes measured at Marjaniemi and r/v 'Aranda' are compared with calculated fluxes in Fig. 7. This shows that the calculated short-wave radiation is always less than the observed values. However, short-wave measurements overshoot the daily clear-sky maximum short-wave radiation, possibly because of reflection from clouds or snow over or inside the measurement instrument itself. Rapid changes in the incoming long-wave radiation $Lw(o)$ indicate cloudiness. Extreme $Lw(o)$ values were measured during warm air periods with low-level clouds (e.g. about 300 W m^{-2} on 14, 15 and 20 February) and during cold air periods with clear skies (e.g. 150 W m^{-2} on 22 February). The structures of calculated $Lw(o)$, $Lw(u)$, RN and T_s are in good agreement with the measurements, despite the many gaps in the data.

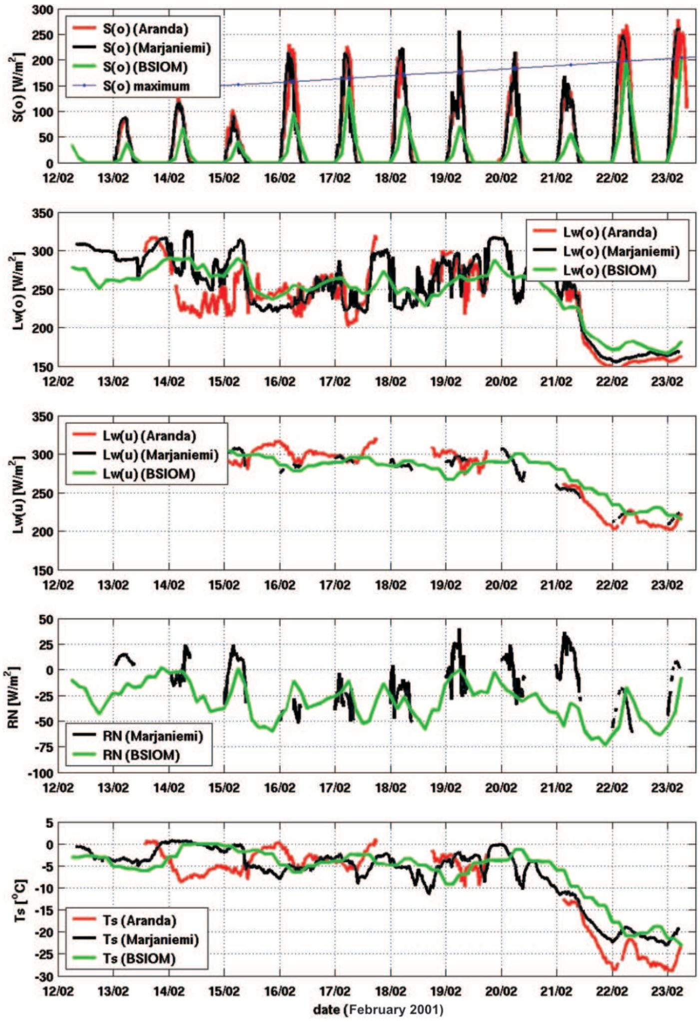

Fig. 7. Time series of downwelling short-wave radiation $S(o)$ (the blue line represents the daily clear sky $S(o)$ maximum at Marjaniemi), downwelling long-wave radiation $Lw(o)$, upwelling long-wave radiation $Lw(u)$, net radiation RN and surface temperature T_s at Marjaniemi and r/v 'Aranda' in comparison with model data at Marjaniemi

3.2.3. Turbulent fluxes

Turbulent surface fluxes are presented in Fig. 8. The larger discrepancies between modelled heat fluxes and the measurements are due primarily to differences in SST and wind velocity (compare with Fig. 6).

The overall agreement of modelled and measured momentum fluxes is excellent, although the observed values tend to be higher.

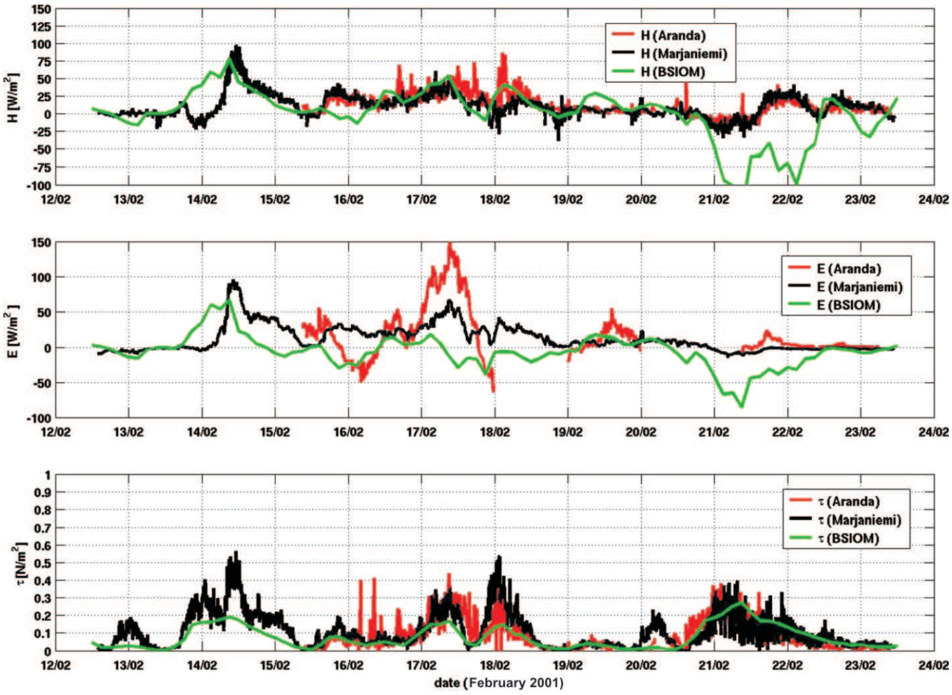

Fig. 8. Time series of sensible heat flux H, latent heat flux E and momentum flux τ at Marjaniemi and r/v 'Aranda' in comparison with model data at Marjaniemi

3.3. Alkor 6/2001

The measurements of the BASIS experiments were performed over sea-ice; in contrast, the Alkor experiments were conducted over the open Baltic Sea. The position in the central Baltic Sea (56.02°N, 18.67°E, Fig. 1a) was chosen to sample data and to study in detail the atmospheric and sea surface boundary layer at a purely marine location. This location is situated at the greatest distance from all coastlines. The nearest coast is the southern point of the island of Gotland at a distance of 110 km. The fetch for SW or NE winds is thus more than 300 km.

The hydrographic survey lasted from 12 to 20 June. Standard meteorological quantities, turbulent heat, radiation and momentum fluxes were measured at the destination point in the central Baltic Sea from 13 to 19 June 2001. Turbulent heat and momentum fluxes were calculated by the same formula used in BSIOM (eqs. (2)–(4)).

3.3.1. Evolution of meteorological quantities

Synoptic weather conditions, pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* are shown in

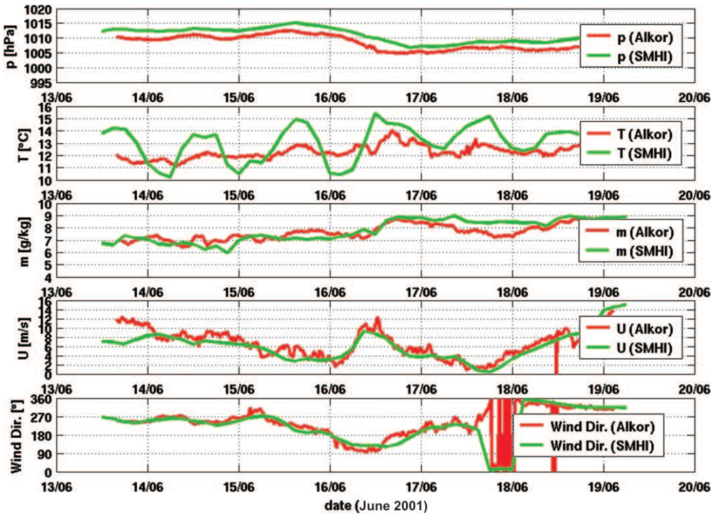

Fig. 9. Time series of pressure p, temperature T, water vapour mixing ratio m, wind speed U and wind direction *Wind Dir* at r/v 'Alkor' in comparison with observed atmospheric data at the position of r/v 'Alkor' (56.02°N, 18.67°E)

Fig. 9. The period was determined by slightly varying the surface pressure and slowly increasing the air temperature and humidity. However, wind speeds varied from strong to calm conditions.

Extracted atmospheric (SMHI forcing) data at the 'Alkor' position (56.02°N, 18.67°E) show a pronounced daily cycle in air temperature T. This clearly demonstrates a shortcoming of the SMHI-data. As mentioned in section 2, the database consists of synoptic measurements made on land. Temperature variations due to the daily cycle are thus extrapolated to the open sea. The air pressure p of the observed atmospheric data (SMHI) compares well with the r/v 'Alkor' measurements. The offset in air pressure results from different measurement heights. The calculated wind direction *Wind Dir* and wind speed U show good agreement with data from r/v 'Alkor'.

3.3.2. Radiation fluxes

The radiation fluxes $S(o)$, $Lw(o)$, $Lw(u)$ as well as sea surface temperatures T_s are presented in Fig. 10. In spite of the generally good agreement of the meteorological parameters, radiation and SST reveal larger discrepancies. The modelled short-wave radiation is generally less compared to the observations.

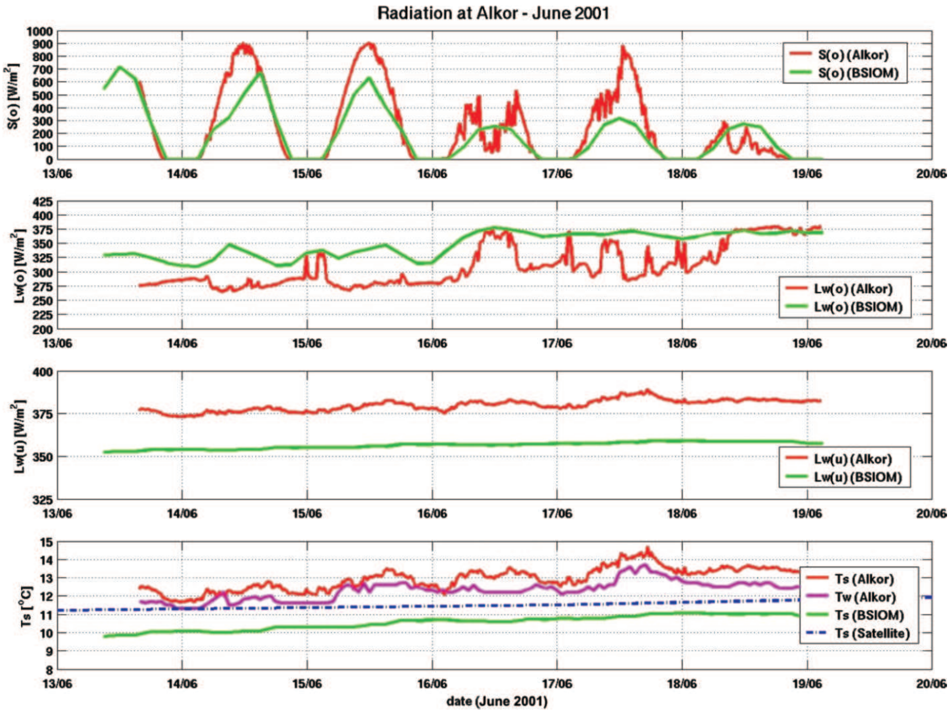

Fig. 10. Time series of downwelling short-wave radiation $S(o)$ (the blue line represents the daily clear sky $S(o)$ maximum), downwelling long-wave radiation $Lw(o)$, upwelling long-wave radiation $Lw(u)$, surface temperature T_s, water temperature T_w at r/v 'Alkor' in comparison with model data at the position of r/v 'Alkor' (56.02°N, 18.67°E) and skin temperature from satellite

3.3.3. Turbulent fluxes

Turbulent fluxes of heat and momentum are shown in Fig. 11. For this experiment, no turbulent flux measurements were conducted; fluxes were therefore calculated by bulk formulas according to eqs. (2)–(4). As a result of the daily cycle of SMHI air temperatures and the differences in SST, the sensible heat flux is mainly negative for the 'measurements' and positive for BSIOM. Latent heat fluxes agree reasonably well, and wind stress calculations are strongly correlated.

4. Statistical comparison of model estimates with measurements

In this section for the three experiments, we present a quantitative assessment of the quality of the atmospheric forcing and corresponding

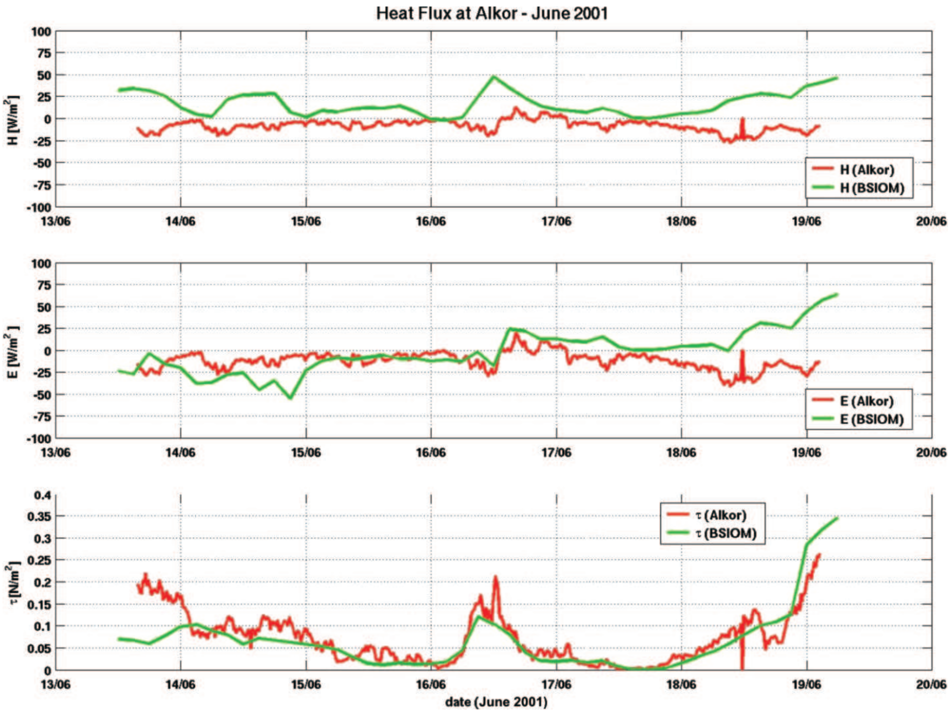

Fig. 11. Time series of sensible heat flux H, latent heat flux E and momentum flux τ at r/v 'Alkor' in comparison with model data at the position of r/v 'Alkor' (56.02°N, 18.67°E)

fluxes used in BSIOM. For the statistical comparison of measurements with model estimates, we used daily mean values (Table 1). Generally, the comparison of measurements with extracted atmospheric (SMHI forcing) data at all positions shows good agreement. In particular, different air pressure estimates show the highest agreement for all experiments. Air temperatures and mixing ratios during the winter experiments agree within less than 0.1°C and 0.05 g kg^{-1}, but for June 2001, the respective differences are about 0.8°C and 0.1 g kg^{-1}, owing to the daily cycle in the SMHI data. Wind velocities agree within 1 m s^{-1} for Marjaniemi and r/v 'Aranda', but for Kokkola the difference is about 4 m s^{-1}. The wind direction corresponds on average within 10°. Surface temperatures agree within 1°C with a correlation coefficient of 0.9 for the winter experiments, and for June, the difference is about 2.4°C, which is probably due to the reduced solar insulation caused by greater cloud coverage. Further, for June 2001, the correlation coefficients of T and m are smaller compared to the coefficients of the winter experiments. In general, simulated short-wave radiation fluxes are about 30 W m^{-2} less than the observations.

Table 1. Statistical comparison of model estimates and observations

BASIS 1998

	Mean			Difference		Standard deviation			Correlation coefficient		
	r/v 'Aranda'	Kokkola	SMHI	Kokkola -SMHI	Aranda -SMHI	r/v 'Aranda'	Kokkola	SMHI	Kokkola -SMHI	Kokkola -Aranda	Aranda -SMHI
p [hPa]	995.12	994.27	995.21	−0.94	−0.09	14.8	14.65	14.56	1	0.99	1
T [°C]	−4.35	−5.31	−5.32	0.01	0.97	5.96	6.48	6.56	0.98	0.93	0.98
m [g kg^{-1}]	2.59	2.41	2.37	0.04	0.22	1.15	1.03	1.12	0.98	0.95	0.99
U [m s^{-1}]	7.71	4.46	8.75	−4.29	−1.04	3.54	2.67	4.14	0.7	0.55	0.78
$Wind\ Dir$ [°]	198.11	196.05	210.1	−14.05	−11.99	94.12	84.75	96.53	0.77	0.64	0.68
	r/v 'Aranda'	Kokkola	BSIOM	Kokkola -BSIOM	Aranda -BSIOM	r/v 'Aranda'	Kokkola	BSIOM	Kokkola -BSIOM	Kokkola -Aranda	Aranda -BSIOM
$S(o)$ [W m^{-2}]	49.82	30.14	26.63	3.51	23.19	94.65	58.11	46.26	0.78	0.68	0.71
$Lw(o)$ [W m^{-2}]	260.34	253.13	257.66	−4.53	2.67	48.55	42.18	39.66	0.86	0.65	0.79
$Lw(u)$ [W m^{-2}]	279.62	278.05	279.49	−1.44	0.12	24.01	24.44	23.43	0.95	0.9	0.92
T_s [°C]	−8.35	−7.36	−6.35	−1.01	−2	5.78	5.93	5.71	0.91	0.91	0.92
H [W m^{-2}]	10.07	6.96	11.08	−4.12	−1.01	19.8	23.51	24.48	0.92	0.6	0.69
E [W m^{-2}]	−13.86	1.09	−9.23	10.32	−4.63	16.36	15.87	22.37	0.65	0.26	0.52
τ [N m^{-2}]	0.11	0.1	0.14	−0.04	−0.03	0.12	0.12	0.13	0.5	0.63	0.84

Table 1. (*continued*)

BASIS 2001

	Mean			Difference		Standard deviation			Correlation coefficient		
	r/v 'Aranda'	Marjaniemi	SMHI	Marjaniemi -SMHI	Aranda -SMHI	r/v 'Aranda'	Marjaniemi	SMHI	Marjaniemi -SMHI	Marjaniemi -Aranda	Aranda -SMHI
p [hPa]	1003.9	1003.8	1005.8	−2	−1.8	8.77	8.97	8.77	1	1	1
T [°C]	−6.31	−5.32	−5.39	0.06	−0.92	7.99	7.1	7.09	0.99	0.99	0.99
m [g kg^{-1}]	2.18	2.41	2.39	0.02	−0.21	0.98	0.99	0.99	0.99	0.98	0.98
U [m s^{-1}]	5.92	5.33	6.5	−1.17	−0.58	3.02	2.75	3.16	0.75	0.83	0.81
$Wind\ Dir$ [°]	213.31	189.83	192.96	−3.13	20.35	105.87	107.15	105.95	0.94	0.92	0.82
	r/v 'Aranda'	Marjaniemi	BSIOM	Marjaniemi -BSIOM	Aranda -BSIOM	r/v 'Aranda'	Marjaniemi	BSIOM	Marjaniemi -BSIOM	Marjaniemi -Aranda	Aranda -BSIOM
$S(o)$ [W m^{-2}]	39.27	34.29	19.32	14.97	19.95	65.26	61.87	39.49	0.71	0.97	0.79
$Lw(o)$ [W m^{-2}]	230.35	252.05	246.1	5.95	−15.75	47.74	46.75	34.59	0.91	0.86	0.86
$Lw(u)$ [W m^{-2}]	275.56	278.92	279.35	−0.43	−3.79	36.78	27.38	23.65	0.9	0.92	0.91
T_s [°C]	−9.61	−6.87	−6.39	−0.48	−3.22	9.32	6.64	5.95	0.89	0.92	0.92
H [W m^{-2}]	12.61	10.4	0.91	9.49	11.7	14.95	16.64	36.82	0.61	0.96	0.63
E [W m^{-2}]	16.42	11.44	−6.23	17.67	22.65	37.79	18.19	23.11	0.58	0.52	0.21
τ [N m^{-2}]	0.08	0.11	0.07	0.04	0.01	0.09	0.1	0.07	0.75	0.83	0.82

Table 1. (*continued*)

Alkor 6/2001

	Mean		Difference	Standard deviation		Correlation coefficient
	r/v 'Alkor'	SMHI	Alkor -SMHI	r/v 'Alkor'	SMHI	Alkor -SMHI
p [hPa]	1008.3	1010.9	−2.6	2.35	2.39	0.97
T [°C]	12.29	13.05	−0.76	0.54	1.38	0.6
m [g kg^{-1}]	7.65	7.77	−0.11	0.62	0.9	0.8
U [m s^{-1}]	6.47	6.1	0.37	2.95	3.19	0.9
$Wind\ Dir$ [°]	233.15	225.09	8.06	75.25	83.16	0.8
	r/v 'Alkor'	BSIOM	Alkor -BSIOM	r/v 'Alkor'	BSIOM	Alkor -BSIOM
$S(o)$ [W m^{-2}]	232.18	193.26	38.92	274.07	211.47	0.59
$Lw(o)$ [W m^{-2}]	309.34	347.57	−38.23	35.68	22.16	0.69
$Lw(u)$ [W m^{-2}]	379.9	356.32	23.58	3.33	1.95	0.76
T_s [°C]	12.94	10.55	2.39	0.63	0.39	0.76
H [W m^{-2}]	−8.19	16.74	−24.93	6.54	13.22	0.32
E [W m^{-2}]	−12.17	−2.24	−9.93	9.83	24.72	0.07
τ [N m^{-2}]	0.07	0.07	0	0.06	0.07	0.89

Long-wave radiation fluxes correspond within a few W m^{-2} for the winter experiments, but for June deviations are higher because of the differences in air and water temperatures.

For the comparison of turbulent fluxes, independent measurements exist for H and τ in 1998 and for H in 2001. Thus, any discrepancies between the remaining 'measured' and calculated fluxes depend on differences in the basic quantities; this has already been discussed. Sensible heat fluxes are well correlated with each other, but the differences between measured and calculated heat fluxes are about 4 and 1 W m^{-2} for 1998, and 10 and 12 W m^{-2} for February 2001 (Table 1). Measured and calculated momentum fluxes display only small deviations and are strongly correlated with each other. This confirms the usability of our model for calculating surface winds and corresponding wind stresses from atmospheric surface pressure data (Large & Pond 1981, Bumke et al. 1998).

5. Discussion

Besides temporal and spatial variability, the differences in meteorological quantities result from the different measurement methods with different accuracies, as well as from the distance between measurement stations and the locations of the instrumentation. This is especially evident in BASIS 1998 for the stations Kokkola and r/v 'Aranda', which lay some 80 km apart (Fig. 1a). The accuracy of extracted atmospheric data (SMHI forcing) is determined by the accuracy of the underlying synoptic measurements and of the interpolation method for extrapolating land-based measurements to the open ocean. Independent measurements near the coast generally compare well with extracted atmospheric data (SMHI forcing), but over the open sea, a spurious daily cycle in T is apparent, which is clearly a shortcoming of the SMHI database.

In spite of the generally good agreement of the basic meteorological quantities, larger differences appear in the radiation fluxes. The calculated $S(o)$ is always less than the measured values, but between the stations Kokkola and r/v 'Aranda' (1998) larger differences also occur, which are due to regional distinctions, and differences in cloud cover. Differences in solar radiation could also be the reason for the excessively low simulated sea surface temperatures in June 2001. SSTs derived from satellite data taken from weekly SST maps provided by the BSH (Bundesamt für Seeschifffahrt und Hydrographie in Hamburg, Germany) lie between KT19 skin temperature measurements (Brümmer et al. 2003) and simulated data (Fig. 10). But there may also be other reasons for the differences in surface temperatures. SSTs are the result of the development of the surface energy balance and turbulent mixing in the ocean, so seasonal development has to be taken into account when comparing temperatures. A bias in cloud coverage can thus lead to intermittent and locally greater differences in SST development. Furthermore, modelled T_s represent the water temperature at 1.5 m depth.

The accuracy of the calculated surface fluxes depends on the quality of the observations and on the bulk aerodynamic formulas used to calculate them. The bulk method is a practicable way to estimate surface fluxes, but the determination of the corresponding drag and transfer coefficients introduces an uncertainty to this method. Drag and transfer coefficients depend on the stability of the planetary boundary layer, wind waves and swell. Additionally, the drag coefficient is sensitive to water depth, whereas heat transfer coefficients are not expected to be as sensitive to limitations in water depth (Rutgersson et al. 2001). Generally, the sensitivity with respect to small variations in wind velocity is expected to be small, but slight effects due to high winds cannot be ruled out (De Cosmo et al. 1996, Makin 1998). The validity of transfer coefficients has been investigated in a number of studies (e.g. Large & Pond 1982, Smith 1988, 1989, Rutgersson et al. 2001), which claim that the main uncertainty arises from measurement errors or inaccurate measurements. In particular, the determination of the Stanton number C_H is highly sensitive to surface temperature measurement errors (e.g. Calanca 2001, Schröder et al. 2003). Thus, calculated heat fluxes are always encumbered with systematic errors, and larger discrepancies in measured and calculated data result not only from differences in meteorological quantities, but also from uncertainties in transfer coefficients; Rutgersson et al. (2001), for example, found that a 10% uncertainty in the heat transfer coefficient results in a 10 W m^{-2} uncertainty in heat fluxes. Furthermore, measurement errors in sensible and latent heat fluxes of about 15 and 30 W m^{-2}, respectively, are related to a difference of 1°C in air-sea temperature and humidity of 1 g kg^{-1}. For calculated fluxes this kind of accuracy is hard to achieve.

To assess the validity of the bulk formula used to calculated sensible heat fluxes, we compare 'measured' and calculated heat fluxes, for which measured basic meteorological quantities were used (Table 2). The difference between 'measured' and calculated fluxes are well within the expected range of uncertainty (Rutgersson et al. 2001).

Döscher et al. (2002) compared monthly mean heat fluxes averaged over the Baltic Sea area with heat fluxes obtained from a regional coupled ocean-atmosphere model. They found maximum differences of up to 15 W m^{-2} for sensible heat fluxes, and up to 50 W m^{-2} for latent heat fluxes, which are close to the differences obtained in our study.

Table 2. Comparison of measured and calculated sensible heat fluxes

	Mean		Difference	Standard deviation		Correlation coefficient	
1998	Kokkola (measured)	Kokkola (calculated)	Kokkola (m) -Kokkola (c)	Kokkola (measured)	Kokkola (calculated)	Kokkola (m) -Kokkola (c)	BSIOM -Kokkola (c)
H [W m^{-2}]	6.96	24.2	−17.24	23.51	32.59	0.79	0.65
2001	Marjaniemi (measured)	Marjaniemi (calculated)	Marjaniemi (m) -Marjaniemi (c)	Marjaniemi (measured)	Marjaniemi (calculated)	Marjaniemi (m) -Marjaniemi (m)	BSIOM -Marjaniemi (c)
H [W m^{-2}]	10.4	18.13	−7.73	16.64	19.84	0.77	0.5

6. Summary and conclusions

Observed basic meteorological quantities, heat and radiation fluxes from three different measurement stations in the Baltic Sea are compared with model data of the coupled sea-ice-ocean model BSIOM in order to evaluate the atmospheric forcing, corresponding surface fluxes and the sea surface response. Observational data were made available from the BASIS winter campaigns in 1998 and 2001 as well as from the r/v 'Alkor' cruise in June 2001. Generally, the observed basic meteorological quantities and model data are in good agreement. However, measurements over sea-ice correspond better with the model than the June 2001 observations, mainly because of a spurious daily cycle in the air temperature of the SMHI database. Furthermore, the simulated short wave radiation is generally less than the observed values; this is due to uncertainties in the prescribed cloud coverage, also provided by the SMHI data. Turbulent flux measurements were conducted only for the sensible heat and momentum flux for the winter experiments in 1998 and 2001. Calculated sensible heat fluxes correlate well with observations, even though the mean difference ranges from 4 to 12 W m^{-2}. Comparison of measured fluxes and fluxes, calculated with the bulk method using observed basic meteorological quantities, reveals a high correlation with an uncertainty of 7 to 17 W m^{-2}, which is well within the expected range of uncertainty given by Rutgersson et al. (2001). Hence, the bulk formula used to calculate the sensible heat fluxes provides good estimates in comparison with the measurements. Furthermore, the correspondence between measured and calculated momentum fluxes is very high, which in turn confirms the usability of our model component to calculate surface winds and wind stresses from atmospheric surface pressure. Accordingly, our approach (eqs. (3)–(7)) seems to be well suited to calculate the heat and energy exchange between the ocean, sea-ice and atmosphere.

It has been demonstrated that measurements such as the BALTIMOS field campaigns are extremely useful for the validation of coupled model systems. The time series are relatively short, however; that is to say, the statistical analysis has a somewhat low significance. Additionally, the representativeness of measurements for a larger area needs to be assessed. Döscher et al. (2002) compared heat flux observations averaged over the area of the Baltic Sea with heat fluxes obtained from a regional coupled ocean-atmosphere model. To our knowledge, however, the present study is the first to have validated a sophisticated coupled sea-ice-ocean model with the aid of directly measured atmospheric parameters and fluxes over sea-ice and open water. Further, for a better quantification of the energy and water cycle of the Baltic area a detailed evaluation of sophisticated models must include not only the standard parameters but also the fluxes; this must therefore involve a detailed analysis of coupling mechanisms and forcing functions. Hence, longer flux measurements at the air-sea-ice interface and air-sea interface are needed to improve the understanding of the information exchange between ocean and atmosphere. With such a detailed validation the reliability of coupled model systems will increase and uncertainties will be reduced.

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