Evaluation of the heat balance components over the Baltic Sea using four gridded meteorological databases and direct observations*

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Abstract In this paper, which reports on part of the BALTEX project, various components of the heat balance over the Baltic Sea are calculated using a number of gridded meteorological databases. It is the heat exchange between the Baltic Sea surface and the atmosphere that is of interest. The databases have different origins, comprising synoptic data, data re-analysed with a 3D assimilation system, an ocean model forced with gridded synoptic data, ship data and satellite data. We compared the databases and found that the greatest variation between them is in the long- and short-wave radiation values. However, considerable upward long-wave radiation is followed by considerable downward short-wave radiation, so the total radiation component is partly compensated for in the total budget. The variation in the total heat transport in the databases therefore appears smaller ($1.5 \pm 3\,\mathrm{W\,m^{-2}}$) as the average and one standard deviation. The turbulent heat fluxes estimated from satellite data have very low values; this can largely be explained by the method of calculating air temperature, which also produces an unrealistic stratification over the Baltic Sea. The ERA40 data was compared with measured values: there, we found a certain land influence even in the centre of the Baltic proper. The indicated turbulent heat fluxes were too large, mainly in the fall and winter, and the sensible heat flux was too large in a downward direction in spring and summer.

Keywords Air–sea exchange; Baltic Sea; ERA40; gridded databases; heat budget; turbulent heat fluxes

Introduction

Investigating heat fluxes over the Baltic Sea is of interest for a variety of reasons and is a major research focus of the Baltic Sea Experiment (BALTEX). The heat balance of the Baltic Sea water body is controlled by turbulent heat fluxes (sensible and latent), outgoing and incoming long-wave radiation, incoming short-wave radiation and heat flux between water and ice (Omstedt and Rutgersson, 2000). Other possible heat fluxes between the atmosphere/land and the ocean (from river runoff, precipitation, etc) are small and often negligible. The net heat exchange over decadal time periods has been analysed in various papers using various methods (Lindau, 2002; Meier and Döscher, 2002; Omstedt and Rutgersson, 2000; Omstedt and Nohr, 2004) and has been shown to be small, indicating that the Baltic Sea behaves as a closed marine system with regards to heat.

A major problem in investigating heat fluxes is the sparseness of traditional measurements made over the sea; in general, most of our knowledge is based on measurements made on land and at coastal synoptic stations. Types of measurements other than those made at traditional synoptic meteorological stations, such as satellite and ship

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data, can yield new independent information about the fluxes over ocean areas. One problem with the turbulent heat fluxes and the radiation components is that all available gridded data sources include fluxes calculated from other parameters, and thus include the uncertainties of those parameters (temperatures, humidity, cloudiness and wind speed) as well as the uncertainties of the methods used for calculating the heat parameters.

This investigation uses a number of gridded meteorological databases to evaluate differences in surface heat fluxes and to produce error bars in determining the net heat budget of the Baltic Sea and of its various components. We are using re-analysis data (ERA40) from the European Centre for Medium-Range Weather Forecasts (ECMWF) covering the past 43 years. We are also using the Swedish Meteorological and Hydrological Institute (SMHI) 1° × 1° gridded database, available from the BALTEX Hydrological Data Centre, in combination with the PROBE-Baltic ocean model (Omstedt and Axell 2003). The SMHI data have previously been evaluated for limited periods by comparing them with *in situ* measurements from the island of Östergarnsholm in the Baltic Sea as well as with modelled data based on Baltic Sea modelling. Using decadal long term modelling, Omstedt and Nohr (2004) estimated the net heat loss from the Baltic Sea with an accuracy better than 3 $\mathrm{W\,m^{-2}}$ in comparison with measurements.

The SMHI 1° × 1° and the ERA40 data sets have been compared for the Baltic Sea region and analysed for the purposes of Baltic Sea modelling by Omstedt *et al.* (2005). The meteorological parameters considered in that analysis were air temperature, wind, total cloudiness, relative humidity and precipitation. In the Baltic Sea modelling the maximum ice extent, water temperature, salinity and calculations of net precipitation were examined. The two gridded meteorological data sets showed many similarities and it was concluded that they both could be used in Baltic Sea modelling. However, the horizontal resolution of the two data sets is too coarse for resolving marine conditions over the Baltic Sea. This implies, for example, that the surface winds determined by ERA40 may be too low in some Baltic Sea regions. The ERA40 precipitation fields are also too low compared with those of the SMHI data and other available data.

Additional gridded fluxes from the satellite-derived data set, Hamburg Ocean–Atmosphere Parameters and Fluxes from Satellite Data (HOAPS), are also used. This climatological atlas of satellite-derived, air–sea interaction parameters presents seasonal, annual and monthly fields. In the present study data from 1988 to 1994 are used. Synoptic measurements made over the sea (mainly from ships) are collected in the Comprehensive Ocean–Atmosphere Data Set (COADS). These data are contained in the "daSilva database" (da Silva *et al.*, 1994), which extends and improves on the COADS data to enable the calculation of heat fluxes, for example, with new analysis giving finer resolution than that of the original COADS data. We use monthly fields from 1988 to 1994.

The present paper focuses on the components of the heat budget in the interface between the air and ocean surface. The various databases are briefly described (for detailed information see the relevant papers and websites). In the results section two of the databases are compared *vis-à-vis* turbulent heat fluxes at one site in the Baltic proper. All four databases are compared for a six-year period. The focus is on the terms in the heat budget, but the mean parameters are also analysed.

Gridded databases and direct measurements

The ECMWF 40-year analysis (in the following text denoted ERA40)

In the ECMWF Re-Analysis project, observational data are assimilated using the ECMWF operational global model (see http://www.ecmwf.int/research/era for detailed information). For this project all available observational data are used, including satellite data, synoptic data, ship data and buoy data, to produce a globally gridded database. The ERA40 database covers the period from mid-1957 to August 2002. The data can be divided into three periods depending on the data used: 1957–1972, only conventional data; 1972–1978, conventional and poorly reliable satellite data; and 1979–2002, conventional data including an increasing amount of reliable satellite data. The advent of satellite data could possibly affect trends in a number of parameters. It is, however, expected mainly to affect the stratosphere and southern hemisphere, where data from other sources are sparse and of poor quality. The ERA40 uses the 3D variational data assimilation system from the operational model at the ECMWF. The turbulent surface fluxes are calculated according to formulations presented in Beljaars (1995, 1997), which are based on the Monin–Obukhov similarity and use different roughness lengths for momentum, heat and humidity. Short- and long-wave radiation is described and evaluated in Morcrette (2002a, b).

The ERA40 data are archived at a number of horizontal grid resolutions, of which the regular latitude–longitude grid is the simplest type. The highest resolution available is 1° × 1°, which is the resolution of the data used in this study. This grid is a result of an interpolation of the grid of the model. One representative grid point is selected for each of the major basins representing the Baltic Sea. For all of the selected grid points the fraction of sea + ice is either 0 or 1 (see Figure 1 for the distribution of land and sea points).

In the ERA40 data the fluxes are integrated over the grid square and can thus include both open sea and ice fluxes. It is not, however, possible to separate ice fluxes and open ocean fluxes for a partly ice-covered grid square. We have only used data where there is no ice in the grid when investigating open ocean conditions.

Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data (HOAPS)

The Hamburg Ocean–Atmosphere Parameters and Fluxes from Satellite Data (HOAPS) is a climatological atlas of satellite-derived, air–sea interaction parameters for oceans around the world (http://sop.dkrz.de/HOAPS). It presents seasonal, annual and monthly fields of air–sea interaction parameters for the period from July 1987 to December 1998. The present

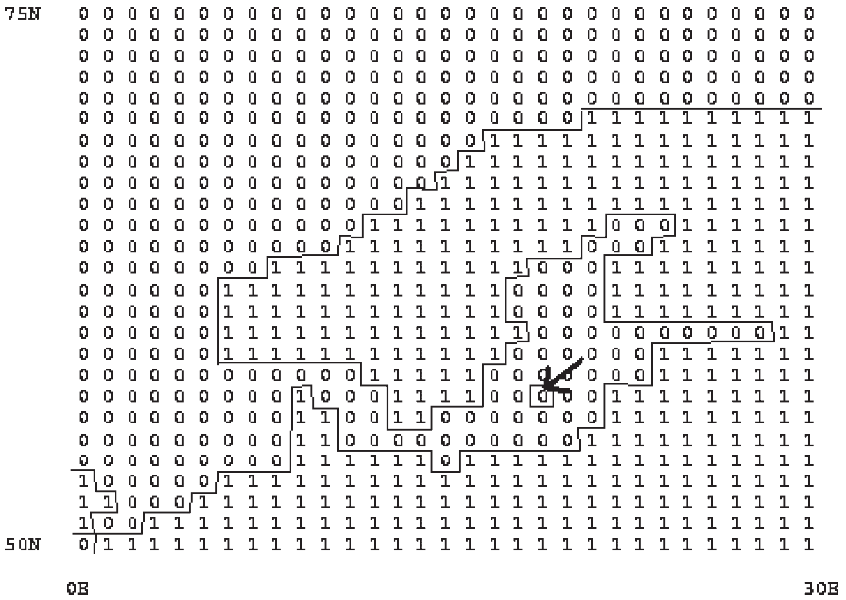

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Figure 1 Map showing the grid in ERA40 data. Zeros are ocean grid points and ones land surface points. The square in the Baltic Sea shows the grid used for comparison with the Östergarnsholm measurements and the arrow shows the position of the measuring site study uses data from 1988 to 1994 with the highest available horizontal resolution (0.5°). The meteorological information is mainly based on data from the Special Sensor Microwave/Imager (SSM/I) aboard a number of satellites. The SSM/I is a passive microwave radiometer measuring radiation emitted and reflected from the Earth's surface and atmosphere at a number of frequencies. The satellites in this system cover the entire globe every three days. For sea surface temperature (SST) information, data from the Advanced Very High Resolution Radiometer (AVHRR) from NOAA/NASA are used. For the fluxes, maps of calculated SST averaged over one week have been used. More detailed information on the satellites and retrieval systems as well as parametrisations are given in Graßl *et al.* (2000).

Sensible and latent heat fluxes are calculated using bulk formulations, while the transfer coefficients are computed following the approach of Smith (1988). The transfer coefficients for heat and humidity are stability dependent, with constant neutral values. Air temperature is calculated from the near-surface atmospheric specific humidity as measured by satellite. A constant relative humidity of 80% is assumed – a rather coarse assumption – and for a stably stratified atmosphere this may lead to totally erroneous values for the sensible heat fluxes (Graßl *et al.*, 2000). Errors in air temperature affect the calculation of sensible heat fluxes both directly through the calculation of the temperature difference and indirectly due to the stability dependence of the exchange coefficient. The latent heat fluxes may also thus be influenced. The long-wave net flux is calculated from the SST and atmospheric back-radiation using constants from Gardashov *et al.* (1988). The retrieval schemes used in the atlas only work over open ocean areas; land and ice surfaces are excluded from the analysis.

The SMHI 1° × 1° database in combination with the PROBE-Baltic ocean model (SMHI-PB)

The SMHI 1° × 1° database is used as the meteorological input into a process-oriented ocean model of the Baltic Sea (PROBE-Baltic). The database covers the Baltic Sea drainage basin with a grid of 1° × 1° squares and incorporates data from all available synoptic weather stations in the area. In general, 700–800 observations are made every three hours (for most parameters). These are interpolated in space using a two-dimensional optimum interpolation scheme. The database covers the 1970–2003 period and includes meteorological parameters such as geostrophic wind speed and direction (calculated from pressure observations), surface temperature, surface humidity, precipitation and cloudiness.

The ocean model divides the Baltic Sea into 13 separate basins based on data for the bottom topography (Omstedt and Axell, 2003). Each basin is coupled to the surrounding basins via horizontal flows. The model calculates the horizontal mean properties of sea surface temperature, ice concentration and thickness, and vertical profiles of temperature and salinity in each basin. The model has been extensively verified and shows good agreement with observed sea surface temperatures and ice cover as well as the vertical structure of temperature and salinity. Turbulent heat fluxes are calculated using bulk formulation with constant neutral transfer coefficients and a certain amount of stability dependence (Rutgersson *et al.*, 2001a). For long- and short-wave radiation, formulae from Bodin (1979) are applied. All equations and constants are given in Omstedt and Axell (2003).

For the open ocean part of each basin, turbulent fluxes and radiation from the atmosphere to the ocean are calculated. For the ice-covered parts, fluxes from the ice to the ocean are calculated.

The advantage of using the ocean model is that realistic sea surface temperatures and ice cover are calculated at a high temporal resolution. This system has been used for previous investigations of the heat budget and water cycles of the Baltic Sea region (Omstedt and Rutgersson, 2000; Rutgersson *et al.*, 2002; Hennemuth *et al.*, 2003; Omstedt and Nohr, 2004).

Atlas derived from the Comprehensive Ocean-Atmosphere Data Set, COADS (DASILVA)

An atlas and database presenting objectively analysed mean anomalies and climatologies using ship data is available in the daSilva database (da Silva *et al.*, 1994). This database is based on data from the Comprehensive Ocean–Atmosphere Data Set (COADS) (Slutz *et al.*, 1985; Woodruff *et al.*, 1987, 1998). COADS data use synoptic measurements made over the sea, comprising mainly ship observations of wind speed and direction, air and sea surface temperatures, sea-level pressure, dew-point temperatures, cloudiness and present weather, to compile direct meteorological information over the oceans; it provides one of the most complete records of surface marine climate.

The COADS project has unified several historical data sets in a single, consistent format, and subjects the ship reports to the same quality control procedure as would be applied to a homogenised data set. This data set is available as monthly mean values summarised in $2^\circ \times 2^\circ$ grid squares covering the Earth's oceans and as raw individual observations. The daSilva database was generated to extend and improve the oceanic fluxes obtained from the COADS database. High-resolution $1^\circ \times 1^\circ$ stability-dependent heat and momentum fluxes, as well as evaporation, precipitation and radiational fluxes, are generated on a monthly basis. Raw data are available as monthly mean fields from 1945–1994 (http://ingrid.ldgo.columbia.edu/SOURCES/.DASILVA/.SMD94/); this material has been objectively analysed with the successive correction scheme used by Levitus (1982).

The turbulent heat fluxes are calculated using bulk formulation; transfer coefficients from Large and Pond (1982) are applied, where different constant values are used for stable and unstable conditions, respectively. The net long-wave radiation calculations are based on an empirical formula that includes the effect of the air–sea temperature difference (Rosati and Miyakoda, 1988). The short-wave radiation is calculated as a function of the clear-sky incident radiation, including the effect of clouds, using monthly means of the cloudiness (Rosati and Miyakoda 1988). The ocean surface albedo is taken from Payne (1972). Only data representing ocean conditions are included in the database.

The Östergarnsholm measuring site

The Östergarnsholm measuring site is situated on a small very flat island, 4 km east of Gotland in the Baltic Sea (57.43°N, 19.0°E). A 30 m tower is situated at the southern tip of the island, the tower base being approximately 1 m above the sea surface. Slow- as well as fast-response sensors for the turbulent fluctuations are placed at several levels on the tower. Wave information and sea surface temperature are measured by a wave-rider buoy located approximately 5 km south-east of the tower. Careful analysis of the flux footprint has shown that, for wind directions of approximately 80–220°, the site can be considered to represent undisturbed ocean conditions. A more detailed description of this measurement site and analysis of the limited water depth and footprint analysis made there is found in Smedman *et al.* (1999).

Turbulent sensible heat fluxes are measured directly, but the number of direct latent heat flux data is very limited. Thus latent heat fluxes are calculated using bulk formulation (see also Rutgersson *et al.*, 2001a). The transfer coefficients are stability-dependent with constant neutral values. Analysis of bulk formulation for sensible heat fluxes shows that the bulk-calculated sensible *upward* heat fluxes are underestimated during winter and fall (the very large fluxes are underestimated more than the smaller fluxes), while *downward* fluxes are overestimated during spring and summer. These differences can be explained by problems with the bulk formulations regarding stable stratification (Rutgersson *et al.*, 2001a; Oost *et al.*, 2000). The presence of swell also exposes the lower validity of bulk formulation (Rutgersson *et al.*, 2001b; Smedman *et al.*, 1994). This should be kept in mind when comparing model and bulk-calculated measured latent heat fluxes, as similar biases are likely. The correlation coefficient for measured and bulk-calculated sensible heat fluxes is 0.78.

Results

Evaluation of gridded data using direct measurements from one point in the Baltic proper

The data from every sixth hour from ERA40 and SMHI-PB are compared with high-quality measurements from the Östergarnsholm measuring site. Only data with wind direction representing open-ocean conditions in the 1995–2001 period are used. For DASILVA as well as HOAPS data only monthly mean values are available, so it is thus not possible to compare those data with the direct measurements. Table 1 shows the accuracy of the mean meteorological parameters (wind-speed, U, air temperature, T, and air humidity, q) and turbulent heat fluxes (H and λE for sensible and latent heat flux, respectively) for the SMHI-PB data. Air temperature and SST data from SMHI-PB generally agree very well with the measured data. The values of SMHI-PB 2 m humidity data are too low, indicating excessive dryness and land influence. For the wind speed there is a very small mean difference (bias), but with a larger scatter. There are also seasonal differences. In summer the SMHI-PB data indicate conditions that are too dry and cold, while the air temperature was shown to be too high in spring and the water temperature too high in winter. The sensible heat fluxes are too low according to the SMHI-PB system. The latent heat flux according to the SMHI-PB data is too high by almost the same amount as the bulk-calculated latent heat fluxes. The agreement of the fluxes (i.e. the correlation) is highest in winter and lowest in spring. Spring is a season with dominantly stable stratification, which is generally more difficult to describe. Rutgersson *et al.* (2001a) used data from two Baltic Sea sites to evaluate the accuracy of various parameters for eight months of 1998, applying a system similar to the present SMHI-PB system. That the results are somewhat different from the present could be explained by differences in the model system, but also indicates the importance of including a large amount of data covering all seasons when making such comparisons.

Table 2 presents statistics pertaining to the comparison between the measured mean parameters as well as measured and modelled turbulent heat fluxes and the ERA40 data. Annual and seasonal mean values are calculated. ERA40 slightly overestimates the

Table 1 Statistics for comparison between SMHI-PB and measurements of the mean parameters and turbulent heat fluxes at Östergarnsholm. Statistical parameters include the correlation coefficient, r_0, the mean difference and bias (SMHI-PB minus Östergarnsholm data). As measurements of latent heat fluxes bulk-calculated data are used. Winter refers to December to February, spring is March to May, summer is June to August and autumn September to November. About 700 data points are used for the statistics of the fluxes, with almost 300 data ponts for spring and autumn and 95 and 130 for winter and summer, respectively. The statistics for the mean parameters include about twice as much data as for the fluxes

	U (m s^{-1})	T (°C)	q (g kg^{-1})	SST (°C)	H (W m^{-2})	λE (W m^{-2})
Annual	$r_0 = 0.77$	$r_0 = 0.98$	$r_0 = 0.92$	$r_0 = 0.98$	$r_0 = 0.71$	$r_0 = 0.77$
	bias = −0.18	bias = −0.02	bias = −0.67	bias = −0.15	bias = −11.83	bias = 7.72
Winter	$r_0 = 0.72$	$r_0 = 0.93$	$r_0 = 0.88$	$r_0 = 0.95$	$r_0 = 0.77$	$r_0 = 0.88$
	Bias = −0.09	bias = −0.12	bias = −0.19	bias = 0.43	bias = −7.38	bias = 8.44
Spring	$r_0 = 0.73$	$r_0 = 0.95$	$r_0 = 0.78$	$r_0 = 0.94$	$r_0 = 0.46$	$r_0 = 0.49$
	Bias = −0.03	bias = 0.39	bias = −0.54	bias = −0.35	bias = −15.89	bias = 6.18
Summer	$r_0 = 0.64$	$r_0 = 0.90$	$r_0 = 0.79$	$r_0 = 0.98$	$r_0 = 0.52$	$r_0 = 0.78$
	Bias = −0.46	bias = −0.26	bias = −1.82	bias = −0.70	bias = −11.45	bias = 6.46
Autumn	$r_0 = 0.80$	$r_0 = 0.97$	$r_0 = 0.94$	$r_0 = 0.96$	$r_0 = 0.68$	$r_0 = 0.69$
	Bias = −0.16	bias = −0.16	bias = −0.36	bias = 0.11	bias = −10.24	bias = 9.35

Table 2 Statistics for comparison between ERA40 and measurements of the mean parameters at Östergarnsholm. Parameters are the correlation coefficient, r_0, and the mean difference (ERA40 minus Östergarnsholm data)

	U (m s^{-1})	T (°C)	q (g kg^{-1})	SST (°C)	H (W m^{-2})	λE (W m^{-2})
Annual	$r_0 = 0.82$	$r_0 = 0.96$	$r_0 = 0.95$	$r_0 = 0.98$	$r_0 = 0.74$	$r_0 = 0.77$
	bias $= -0.63$	bias $= 0.18$	bias $= -0.2$	bias $= 0.81$	bias $= -3.76$	bias $= 11.91$
Winter	$r_0 = 0.80$	$r_0 = 0.86$	$r_0 = 0.87$	$r_0 = 0.93$	$r_0 = 0.80$	$r_0 = 0.89$
	bias $= -0.40$	bias $= -0.73$	bias $= -0.40$	bias $= 0.88$	bias $= 5.78$	bias $= 25.07$
Spring	$r_0 = 0.76$	$r_0 = 0.94$	$r_0 = 0.82$	$r_0 = 0.93$	$r_0 = 0.51$	$r_0 = 0.47$
	bias $= -0.76$	bias $= 1.33$	bias $= 0.20$	bias $= 0.87$	bias $= -12.75$	bias $= 2.03$
Summer	$r_0 = 0.72$	$r_0 = 0.85$	$r_0 = 0.84$	$r_0 = 0.95$	$r_0 = 0.42$	$r_0 = 0.74$
	bias $= -0.88$	bias $= 0.58$	bias $= -0.50$	bias $= 0.70$	bias $= -9.47$	bias $= 2.98$
Autumn	$r_0 = 0.86$	$r_0 = 0.96$	$r_0 = 0.94$	$r_0 = 0.96$	$r_0 = 0.68$	$r_0 = 0.74$
	bias $= -0.46$	bias $= -0.50$	bias $= -0.28$	bias $= 0.81$	bias $= 2.44$	bias $= 18.63$

near-surface air temperature, mainly due to overestimation during spring and summer (over 1° of overestimation of the spring seasonal average) and underestimation of low temperatures in fall and winter. SSTs are almost one degree too high according to the ERA40 data in all seasons. ERA40 underestimates the summer seasonal average wind speed by nearly 1 m/s. The specific humidity values of the two data sets agree relatively well; the difference is greatest in spring when conditions as indicated by ERA40 are 0.5 g kg^{-1} too dry. ERA40 also indicates that the annual temperature cycle is too large and that wind speed is slightly too low, indicating that the land influence is excessive. This can also be seen in the pronounced daily cycle in temperature and relative humidity in ERA40 data, which is not present in the direct measurements (Figure 2 shows air temperature for September 1998). The problem with low data coverage over the oceans (and thus too large a land influence) was also experienced in the predecessor, ERA15 (Kållberg, 1997; Stendel and Arpe, 1997).

Figures 3 and 4 present the sensible and latent heat fluxes, respectively. Some interesting features can be seen in Figure 3. The negative (downward) sensible heat fluxes are significantly too large in the ERA40 data. This explains the large negative bias in spring and summer when negative sensible heat fluxes are most common. The scatter is also larger in spring and summer. The bias is much smaller in winter and fall. Annual average sensible heat fluxes are slightly underestimated by 4 W m^{-2}, while positive data for autumn and winter are larger and negative data for spring and summer are larger according to the ERA40 data.

Latent heat fluxes (Figure 4) are overestimated by ERA40 in winter and autumn and there is a small bias in spring and summer. The accuracy of the databases is thus strongly seasonal dependent, probably due to the effects of stratification and the variability of the accuracy of

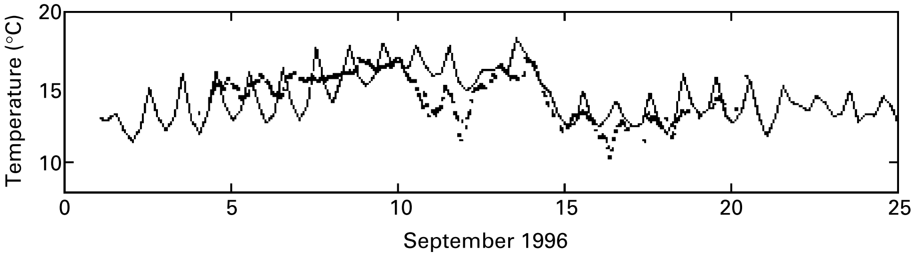

Figure 2 Air temperature from September 1998. Solid line is data from the ERA40 database for one point and dots measurements from the Östergarnsholm site

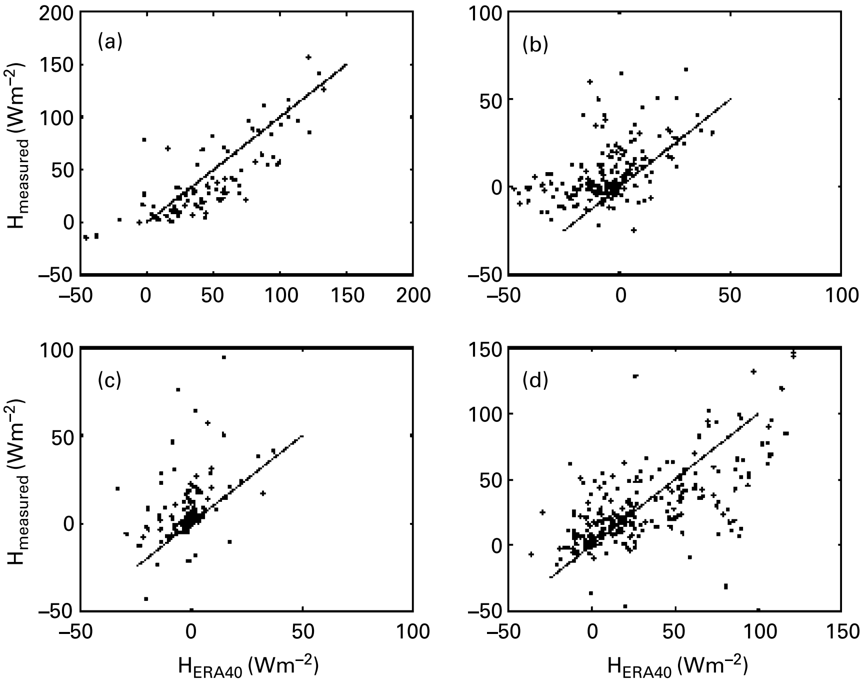

Figure 3 Sensible heat fluxes from the period June 1995 to December 2001 for (a) winter, (b) spring, (c) summer and (d) autumn. Units are W m^{-2}. Solid lines represent a 1:1 relation and dots the comparison between ERA40 and direct measurements

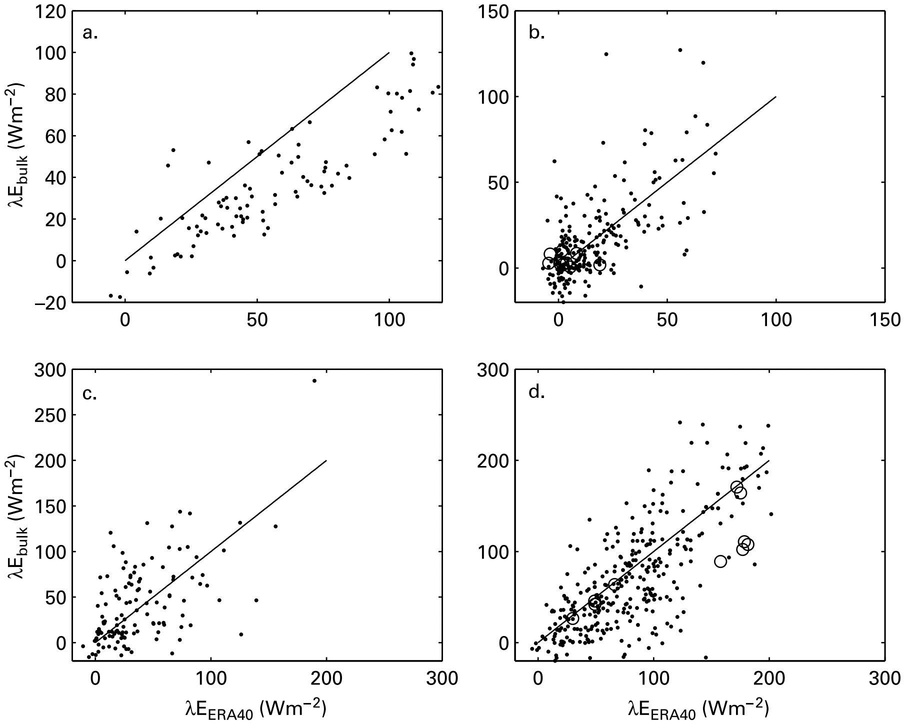

Figure 4 Latent heat fluxes from the period June 1995 to December 2001 for (a) winter, (b) spring, (c) summer and (d) autumn. For the dots measured data are calculated using bulk formulation, circles are directly measured with the MIUU instrument. Units are W m^{-2}. Solid lines are the 1:1 relation

the mean parameters in different seasons. Annual average latent heat fluxes are overestimated by ERA40 by 12 W m^{-2}.

The six-year period 1988–1994

Data from all four databases have been analysed for the January 1988–December 1993 period. For HOAPS and DASILVA data, all data represent the open ocean part of the Baltic Sea; the SMHI-PB system also calculates the heat fluxes for the open ocean part of each basin and ERA40 uses only the ice-free grid squares. Since the different databases can indicate slightly different ice cover in winter, the areas represented may thus differ. However, this has not been found to have any significant influence on the results.

Table 3 shows mean values for the six-year period for turbulent fluxes and radiation parameters (where LW is long-wave and SW is short-wave radiation, respectively) as well as the sum of the upward fluxes ($F_{\mathrm{up}} = \lambda E + H + \mathrm{LW}$) and total heat transport between the atmosphere and open ocean surface ($F_{\mathrm{sum}} = \lambda E + H + \mathrm{LW} + \mathrm{SW}$). Figures 5 and 6 present monthly averages of the terms in the heat budget for this period.

For the turbulent heat fluxes presented in Figure 5, the two methods using mainly land-based surface information (SMHI-PB and ERA40) produce largely similar results. SMHI-PB indicates a more pronounced seasonal cycle and slightly larger mean values for both sensible and latent heat fluxes. The turbulent heat fluxes (especially the sensible heat flux) are larger according to the data in the DASILVA database set than to the other data, and this is especially true for winter and very early spring. The data in the HOAPS database give lower turbulent fluxes than do the other data, and this is most obvious for late summer, fall and winter. The highest six-year averages were calculated from the DASILVA and the lowest from the HOAPS data, and the differences between them are 6 W m^{-2} for latent heat flux and 11 W m^{-2} for the sensible heat flux; for individual months the maximum difference can be up to 46 and 63 W m^{-2}, respectively.

For long-wave radiation (see Figure 5) the seasonal cycle is small and variation between months not very pronounced. There is, however, a great difference between the databases in this regard, the HOAPS data indicating on average over 20 W m^{-2} greater LW than does SMHI-PB; the other databases lie in between. The ERA40 data indicate a seasonal cycle in LW, which is not seen in the other databases.

For upward net heat transport (see Figure 6), the low turbulent heat fluxes indicated by the HOAPS data are compensated for by the very large values indicated for long-wave radiation. DASILVA data indicate the highest upward net heat transport (115 W m^{-2}), greater than that indicated by the other data and mainly so in fall and winter. This is due both to large turbulent heat fluxes and LW radiation. The SMHI-PB data indicate the lowest net heat transport, particularly so in spring and summer (86 W m^{-2}). Variation is almost as great in

Table 3 Mean turbulent and radiation fluxes for the six-year period 1988–1994. Positive fluxes are directed upward. Units are W m^{-2}. $F_{\mathrm{up}} = \lambda E + H + \mathrm{LW}$ and $F_{\mathrm{sum}} = \lambda E + H + \mathrm{LW} + \mathrm{SW}$, where all terms represent the open ocean part of the Baltic Sea. The bottom row represents averaged value of the fluxes from the four databases and ± one standard deviation

Method	λE	H	LW	SW	F_{up}	F_{sum}
SMHI-PB	40.8	8.5	41.9	−93.1	91.2	−1.9
ERA40	38.2	7.2	52.3	−95.1	97.8	2.7
HOAPS	35.1	3.8	62.8		101.7	
DASILVA	40.9	15.5	58.3	−111.7	114.8	3.1
Mean	39 ± 3	9 ± 5	54 ± 9	100 ± 10	101 ± 10	1.5 ± 3

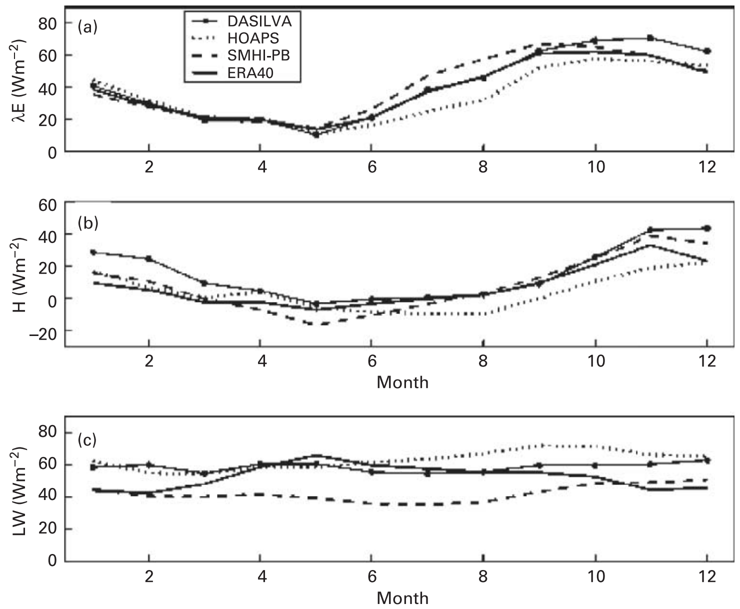

Figure 5 Monthly averages for the period 1988–1994 showing the seasonal cycle. Parameters are: (a) latent heat flux, (b) sensible heat flux and (c) long-wave radiation. Units are W m^{-2}. Solid line with dots represents data from DASILVA, dotted line from HOAPS, dashed line from SMHI-PB and solid line from ERA40 database

the short-wave radiation data, where DASILVA data indicate significantly larger SW than do SMHI-PB or ERA40, especially in summer and early fall. ERA40 and SMHI-PB are more similar in terms of SW data, ERA40 indicating slightly larger values in summer and smaller values in spring. Unfortunately, there is no available SW information from the HOAPS data.

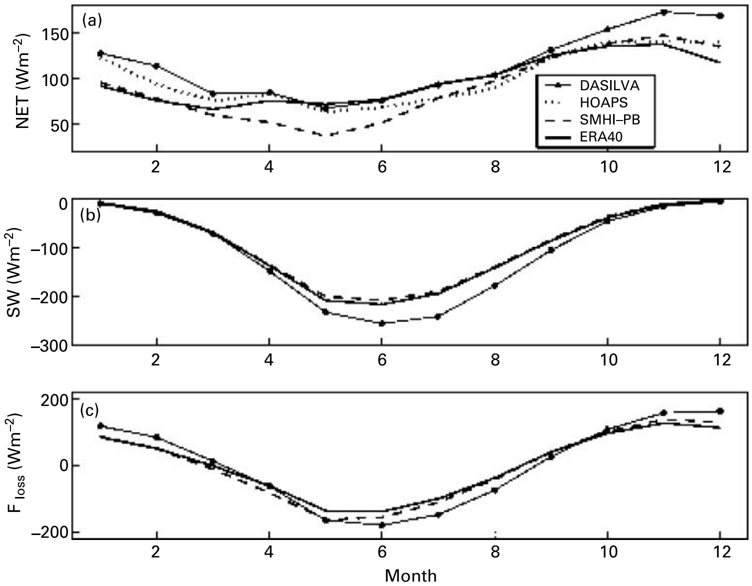

Figure 6 Seasonal cycle for the period 1988–1994 of (a) net upward heat flux ($F_{\mathrm{up}} = \lambda E + H + \mathrm{LW}$), (b) short-wave radiation and (c) sum of all heat fluxes (F_{sum}) over open sea. Units are W m^{-2}, lines as in Figure. 5

The total heat transport between the atmosphere and the open ocean (F_{sum}) is indicated as negative by the SMHI-PB and positive by the ERA40 and DASILVA data, the mean value ranging between -2 and $3\,\mathrm{W\,m^{-2}}$ over these six years. Greater seasonal variations is indicated in the DASILVA data (see Figure 6) and less seasonal variations is indicated in the ERA40 data compared to data in the other databases. The estimated error in the net heat loss based on decadal, long-term modelling and measurements (Omstedt and Nohr, 2004) was estimated to be $-1 \pm 3\,\mathrm{W\,m^{-2}}$.

The differences between the fluxes indicated by the various databases can, to some extent, be explained by differences in the mean parameters (see Table 4). The wind speed is a very important parameter for calculating turbulent fluxes. The high wind speed indicated by the DASILVA data partly explains the great latent and sensible heat fluxes in winter. The ERA40 data indicate 1–2 m/s lower wind speeds than do the other databases, resulting in lower heat fluxes than would otherwise be the case. The HOAPS data indicate a much higher air temperature than do the other databases; indications of sea surface temperature are, however the same. This result in a positive annual mean air–sea temperature difference. Thus the stratification is stable for much of the year (a positive Ri in Figure 7, where Ri is the stability parameter (Richardson number) $Ri = gz\Delta T/UT$, z is height and g is the acceleration due to gravity). This was not, however, indicated by the other databases and is highly unrealistic. Stable stratification results in lower turbulent heat fluxes and can thus, at least partly, explain the low turbulent heat fluxes indicated by the HOAPS data. The problem with the air temperature data in the HOAPS database, and thus, by extension, with the stratification results, is explained by the very crude method used to estimate air temperature. According to Graßl *et al.* (2000) a known problem arises during stable stratification, which here is shown to be very significant when calculating turbulent heat fluxes in the Baltic Sea region. Errors in air temperature data, arising from the stratification, enter the calculation of sensible heat fluxes both directly in the calculations and indirectly via the transfer coefficients. The other databases indicate a more realistic stratification over the course of the year, the data closest to neutral being the ship data (probably due to the high wind speeds). ERA40 contains the largest stable/unstable values, and this most likely arises from the lower wind speeds. Stratification is stable from April to July and unstable for the rest of the year. The very large negative values for short-wave radiation in the ship data could be related to differences in the degree of cloudiness registered by the different databases. However, in Table 4 the DASILVA data is seen to indicate the highest fraction of clouds as a six-year average. Figure 7(b) reveals that the DASILVA data mainly indicate higher cloudiness in winter and fall. At those times the amount of short-wave radiation is low in any case and the effect of clouds is very small. The cloudiness is also relatively large in the summer, so the differences in amounts of short-wave radiation must arise from a combination of the method of calculation of SW and the differences in cloud cover. In Karlsson (2000) a significant signal of the Baltic Sea was detected in cloudiness using satellite data, and it is thus possible

Table 4 Averaged mean parameters and differences for 1988–1994 from the four databases. Here ΔT = SST-T, q_w is the specific humidity of the water surface, $\Delta q = q_w - q$ and Cl fraction of cloud cover

Method	T (°C)	SST (°C)	ΔT (°C)	q (g kg^{-1})	q_w (g kg^{-1})	Δq (g kg^{-1})	U (m s^{-1})	Cl (frac.)
SMHI-PB	7.0	7.3	0.3	5.3	6.7	1.5	7.5	0.64
ERA40	7.0	7.7	0.7	5.3	6.9	1.5	6.1	0.61
HOAPS	8.8	8.0	−0.8	6.0	7.0	1.0	7.5	
DASILVA	7.5	8.1	0.6	5.8	7.1	1.3	7.9	0.65

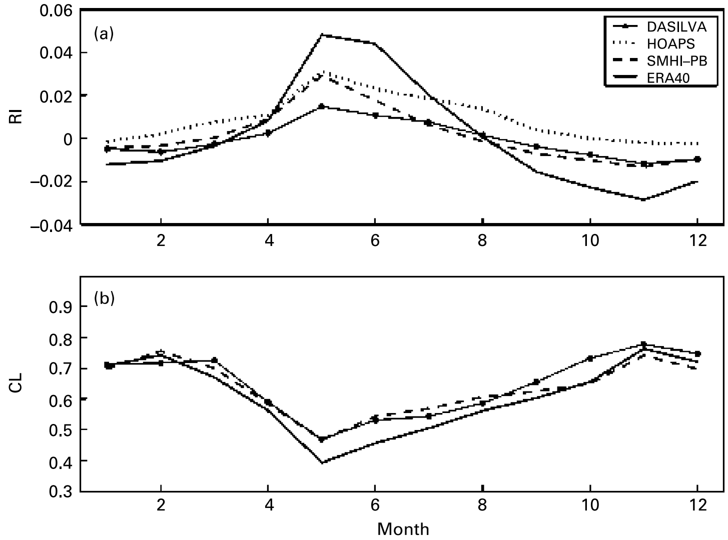

Figure 7 Monthly averages for the period 1988–1994 representing the seasonal cycle. Parameters are: (a) the stability, represented by the dimensionless Richardson number, (b) cloudiness in fraction of cloud cover. Lines as in Figure. 5

that both the ERA40 and SMHI-PB data indicate excessively low short-wave radiation levels due to land influence on the cloudiness data. This problem is not found in the ship data.

The period from 1958 (1971) to 2002

Six years is too short a period over which to investigate climate trends in the Baltic Sea region, and a study of such a short period is mainly useful for the purposes of comparing different databases. Over the past 200 years significant changes have been seen in both the global climate (IPCC, 2001) and in Baltic Sea climate (e.g. Omstedt *et al.*, 2004). The response of the heat budgets and related parameters for the Baltic Sea region are here analysed for the period January 1958 to December 2001 using the ERA40 database. SMHI-PB data are included for the period January 1971 to December 2001 for comparison.

Long-term averages of the various terms in the heat budget are shown in Table 5. Here $F_{\mathrm{sum}}^{\mathrm{tot}}$ is the total heat exchange between the total Baltic Sea surface and the atmosphere (including ice-covered areas). As was also seen in previous analyses, over a six-year period agreement between ERA40 and SMHI-PB data is relatively good for most parameters. The greatest differences are in long- and short-wave radiation, where ERA40 gives larger positive and negative values, respectively.

According to Omstedt and Rutgersson (2000) a realistic temperature difference between water in- and outflowing through the Baltic Sea entrance area is less than 1°. This corresponds to a long-term average value of $F_{\mathrm{sum}}^{\mathrm{tot}}$ less than $1\,\mathrm{W\,m^{-2}}$. Thus the SMHI-PB

Table 5 Parameters in heat budget, λE, H, LW and SW, represent values over the open ocean. Units are in W m^{-2}. $F_{\mathrm{sum}}^{\mathrm{tot}}$ is given for the total surface, also including ice-covered areas. Parentheses represent the averaging period

Method	λE	H	LW	SW	$F_{\mathrm{sum}}^{\mathrm{tot}}$
ERA40 (58–02)	36.8	10.1	48.6	−91.7	4.1
ERA40 (71–02)	36.1	9.1	48.0	−90.7	2.9
SMHI-PB (71–02)	35.7	9.7	37.1	−86.3	−0.3

value in Table 5 lies within the realistic range. For the ERA data for both the 1958–2002 and 1971–2002 periods, the $F_{\mathrm{sum}}^{\mathrm{tot}}$ value is probably too large.

Discussion

The scatter is significantly larger for the turbulent heat fluxes than for the mean parameters. This means that the parametrisations do not include all processes of possible significance. More analysis is needed of processes controlling air–sea heat transport. It is of the greatest importance to analyse processes giving rise to systematic errors, such as the effects of waves and sea spray. Differences from coastal areas also warrant investigation. In comparisons between point measurements and gridded databases there is always the problem of the representativity of the data. This cannot fully be solved, but for a measuring station like Östergarnsholm the data represent conditions from the footprint area, which is of the order of kilometres. The horizontal variability over sea is not very large and, since measurements are only used when the wind is from the undisturbed sector, the representativity is not expected to be a great problem.

With several databases it is possible to analyse the uncertainty of the estimates of the heat budget and its components. From Table 3 it can be seen that, in spite of large uncertainties concerning the turbulent heat fluxes, the major terms of uncertainty are the radiation terms, which differ significantly between the databases. There is a compensation between the radiation terms: the small upward LW in the SMHI-PB data is balanced by a small downward SW; likewise, the large upward LW in the DASILVA data is accompanied by a large downward SW. This can be explained by the cloudiness, a too high cloudiness decreases incoming SW and outgoing LW. The sum of the terms is small for all databases. Assuming that the value of F_{sum} calculated from the SMHI-PB data is realistic would indicate that the other databases produce a value of F_{sum} that is too large by an order of $5\,\mathrm{W\,m^{-2}}$. An error of $5\,\mathrm{W\,m^{-2}}$ in the long-term mean value of $F_{\mathrm{sum}}^{\mathrm{tot}}$ results in inaccurate heat budget calculations for the Baltic Sea. This would correspond to a temperature difference between the water in- and outflowing through the Baltic Sea entrance area of 9°, which is not realistic (Omstedt and Rutgersson, 2000). When looking into higher spatial resolution (monthly or seasonal averages), the differences between the databases become greater, both in terms of F_{sum} and the components of the heat budget.

Summary and conclusions

Gridded meteorological databases pertaining to various regions have a number of important applications, such as in numerical model verification, climate investigations of various regions, forcing of meteorological models as well as other types of models, including oceanographic, lake and biological models. It is of great interest to know how accurate the various parameters are in these databases. Traditionally mainly information about mean parameters, such as wind speed, temperature, humidity and cloudiness, was obtained from gridded databases. However, with increased interest in water cycles and heat budgets the various components of these can be obtained as well. The present study analysed various aspects of surface fluxes as indicated by four gridded databases of very different origins. The work was part of the BALTEX project, and the Baltic Sea ocean basin was the area of interest. Two of the databases (SMHI-PB and ERA40) are mainly based on interpolated synoptic surface data, one database is drawn from the COADS database and is thus compiled from synoptic ship observations (DASILVA) and another database is generated from satellite data from the Hamburg Ocean–Atmosphere Parameters and Fluxes from Satellite Data (HOAPS).

Two of the databases have high enough temporal resolution to enable comparison of their direct surface measurements of turbulent heat fluxes from one site, east of Gotland, in the centre of the Baltic proper. This comparison revealed that ERA40 data indicate the upward surface latent and sensible heat fluxes to be too great, especially during fall and winter; however, the scatter is large, probably since not all processes are included in the parametrisations in the databases. It can also be concluded that there is a land influence on the ERA40 data, evident even when investigating a grid point in the centre of the Baltic Sea. This is mainly evident from larger diurnal and seasonal cycles in temperature and humidity than are observed in the direct measurements, and a too low wind speed.

The land influence evident in the ERA40 and SMHI-PB data is not surprising, since both these databases are based mainly on interpolated land-based synoptic data. The type of observational stations used to collect such data are generally situated on land and the Baltic Sea is too small for ocean data obtained from satellites and coastal stations to fully influence the interpolated data. The data pertaining to open sea conditions are thus mainly extrapolated from data obtained from coastal stations.

The six-year intercomparison of the monthly averages obtained from the four databases showed some differences. SW in ERA40 and SMHI-PB is low during summer. Data from SMHI-PB showed significantly lower LW radiation than did the other databases. Most likely the turbulent heat fluxes (especially the sensible heat fluxes) as indicated by the satellite data are too small. This is due to a very crude method of estimating air temperature, a method that also influences the estimation of stratification. The turbulent heat fluxes indicated by the DASILVA data are the largest. Present analyses have shown that both the SMHI-PB and ERA40 data indicate excessive sensible and latent heat fluxes (at least during fall and winter), so it can be assumed that turbulent heat fluxes (especially the sensible heat fluxes), as indicated by the DASILVA data, are also significantly too large. In previous investigations, the sum of the terms in the heat budget (F_{sum}) has been shown to be well described by the SMHI-PB data. For the investigated period, both the ERA40 and DASILVA data indicate an almost 5 W m^{-2} larger F_{sum} than does SMHI-PB. This would imply that data from ERA40 as well as DASILVA and HOAPS databases indicate excessively large transport of heat from the ocean surface to the atmosphere.

This work may be summarised as follows:

- The ERA40 database can be taken to apply to the Baltic Sea if one bears in mind that the database shows a larger land influence than is actually the case for an ocean basin of this size. The seasonal cycle in sensible and latent heat fluxes is overestimated, giving significantly too large heat fluxes in fall and winter. The annual mean value of the latent heat flux is overestimated by approximately 10 W m^{-2}.
- The value of F_{sum} obtained by using the different databases is 1.5 ± 3 W m^{-2}; the various components have an accuracy of ± 10 W m^{-2}, the greatest differences being in the radiation terms. It is likely that F_{sum} is slightly too large according to the ERA40, DASILVA and HOAPS databases. There are some compensating effects in LW and SW, where a small LW value corresponds to a small SW value.

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