A comparison between the ERA40 and the SMHI gridded meteorological databases as applied to Baltic Sea modelling*

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Abstract Two gridded meteorological data sets for the Baltic Sea region, both having 1° × 1° horizontal resolution, were compared and analysed for use in Baltic Sea modelling. The SMHI 1° × 1° data set covers surface parameters with a three-hour time resolution over the 1970–2004 period. The ERA40 data cover analysed and modelled parameters for several atmospheric layers with a six-hour time resolution over the 1957–2002 period. Meteorological variables considered in this analysis were air temperature, wind speed, total cloud cover, relative humidity and precipitation. In considering Baltic Sea modelling, we examined maximum ice extent, water temperature, salinity and net precipitation calculations.

The two data sets are largely similar and can both be used in Baltic Sea modelling. However, their horizontal resolution is too coarse for resolving marine conditions over the Baltic Sea. This implies, for example, that the ERA40 original surface winds are too low for some Baltic Sea regions. The ERA40 precipitation values are also too low compared with those of the SMHI and other available data.
Keywords Baltic Sea; evaporation; meteorological data; modelling; precipitation; sea ice

Introduction

The possibility of obtaining forcing data for modelling and process studies has considerably increased over the last few decades. For the meteorological forcing of ocean models, synoptic station values without horizontal interpolations are available from various national weather services. Gridded data sets are also produced by these services. For the Baltic Sea, the BALTEX data centres provide station data as well as one gridded data set. This meteorological data set, the SMHI 1° × 1° data set, has played an important role in the BALTEX project, being used for both process studies and ocean and hydrological modelling (e.g. Omstedt *et al.* 1997; Graham 1999; Lehmann and Hinrichsen 2001; Rutgersson *et al.* 2001; Meier and Döscher 2002; Hennemuth *et al.* 2003; Omstedt and Axell 2003). Meteorological gridded data sets are also available from other sources: ERA40 from the European Centre for Medium-Range Weather Forecasts and NCEP/NCAR from the US National Oceanic and Atmospheric Administration. The NCEP/NCAR data for the Baltic drainage basin was recently analysed by Ruprecht and Kahl (2003), who illustrated the problems in using this data set for basic water balance studies.

The aim of this study is to compare two gridded meteorological data sets, the SMHI 1° × 1° and the ERA40 data sets, for the Baltic Sea and determine which is more reliable for use in Baltic Sea modelling. We have investigated various surface meteorological variables and also used Baltic Sea modelling and independent marine observations to evaluate these meteorological data sets.

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The outline of the paper is as follows. The next section provides the data used and some statistical properties of the data. Then the various variables of the two data sets are compared one by one. The variables discussed are air temperature, wind speed, total cloud cover, relative humidity and precipitation. Then in the next section results from Baltic Sea modelling are presented and the last section provides a summary and some conclusions.

Material and statistics

The gridded data set from SMHI (SMHI $1^\circ \times 1^\circ$) covers the 1970–2004 period using mainly meteorological surface parameters. This data set is available from the BALTEX Hydrological Data Centre (BHDC, http://www.gkss.de/baltex/) and is briefly described in Omstedt *et al.* (1997). The data set is continuously updated with a delay of about half a year, and has been used in several ocean and hydrological projects. For example, Rutgersson *et al.* (2001) analysed precipitation over the Baltic Sea using this database and other methods. Rutgersson *et al.* (2002) and Omstedt *et al.* (1997) examined net precipitation rates over the Baltic Sea. Hennemuth *et al.* (2003) analysed various methods for calculating turbulent fluxes over the Baltic Sea, with one method using ocean modelling and the SMHI database. Lehmann and Hinrichsen (2001), Meier and Döscher (2002) and Omstedt and Axell (2003) applied the same database in modelling the Baltic Sea; Graham (1999) applied the same data in large-scale hydrological modelling.

The ERA40 reanalysis project (http://www.ecmwf.int/research/era/), covering the 1957–2002 period, has been a major undertaking of the ECMWF. Through combining a large number of observations of various origins and numerical modelling, several different meteorological variables have been calculated and made available to the research community. The ERA40 data have already been analysed in some other studies. For example, Karlsson (2003) has found good agreement between ERA40 data and NOAA AVHRR satellite data.

The time period from 1 January 1971 to 31 December 2000 was used in the comparison. The two data sets both have a resolution of $1^\circ \times 1^\circ$, a resolution that does not resolve the complex geometry of the Baltic Sea. The land influence arising from this coarse resolution has been analysed in the SMHI $1^\circ \times 1^\circ$ data by Rutgersson *et al.* (2001), and Omstedt and Axell (2003) have introduced some correction methods.

The various variables studied are temperature, wind, total cloud cover, relative humidity and precipitation. The data were selected from several regions in the Baltic Sea (see Figure 1 and Table 1). To avoid land influence as much as possible, the strategy has been to select grid cells in the central part of the various sub-basins. Tables 2 and 3 present summary statistics pertaining to the two data sets. The comparison will be discussed in the next section.

Comparison of the two data sets

Air temperature

The comparison of air temperatures from the Eastern Gotland Basin is illustrated in Figure 2 as an example of what was done in the study. Both the 30-year daily mean temperatures and standard deviations show a clear yearly cycle, with the highest standard deviation occurring in the winter. The SMHI $1^\circ \times 1^\circ$ data is slightly 'colder' and has a greater standard deviation. However, the two temperature data sets are largely similar. Looking at other regions of the Baltic Sea, the results are similar. In some regions the SMHI $1^\circ \times 1^\circ$ data is slightly colder/warmer, with greater/less standard deviation than the ERA40 data set. This is also reflected in Tables 2 and 3, where the difference in mean temperatures between the two data sets is less than 0.7 °C.

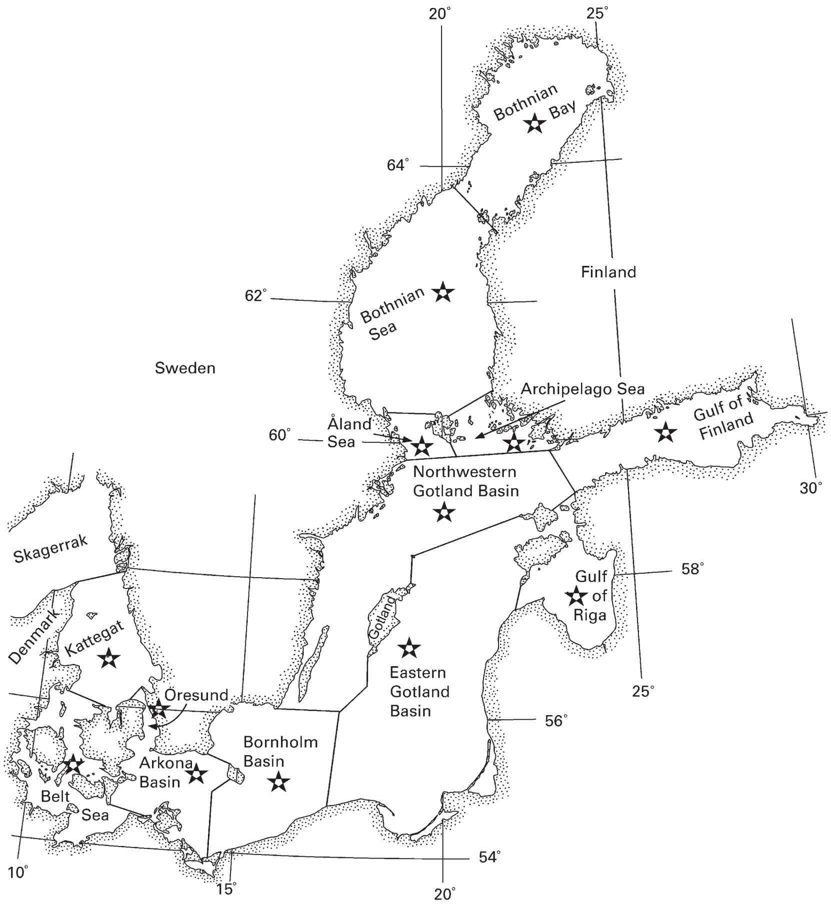

Figure 1 The Baltic Sea with sub-basins defined according to the ocean modelling. The stars indicate where data from the different meteorological data sets were extracted

Table 1 Positions in the two analysed data sets with latitude and longitude given for the ERA40 data. The corresponding values for the SMHI database are equal to those of the ERA40 minus 0.5° in both longitude and latitude

Area	Position
Kattegat	N 57 E 12
Öresund	N 56 E 13
Belt Sea	N 55 E 11
Arkona Basin	N 55 E 14
Bornholm Basin	N 55 E 16
Eastern Gotland Basin	N 57 E 19
NW Gotland Basin	N 59 E 20
Gulf of Riga	N 58 E 24
Gulf of Finland	N 60 E 26
Archipelago Sea	N 60 E 22
Åland Sea	N 60 E 19
Bothnian Sea	N 63 E 20
Bothnian Bay	N 65 E 23

Table 2 Basic statistics pertaining to the meteorological variables in the SMHI database where *Ta* denotes air temperature, *W* wind speed, W^3 wind speed cubed, *Cl* total cloud cover, *Rh* relative humidity and *P* precipitation rate

SMHI	Attribute	*Ta* (°C)	*W* (m s^{-1})	W^3 (m^3 s^{-3})	*Cl*	*Rh*	*P* (mm/d)
Kattegat	Mean	8.17	7.55	647.90	0.64	0.84	1.85
Kattegat	STD	2.68	2.38	689.44	0.24	0.07	3.22
Arkona Basin	Mean	8.06	7.79	719.54	0.65	0.82	1.78
Arkona Basin	STD	2.70	2.47	785.40	0.24	0.07	3.28
Bornholm Basin	Mean	7.92	7.79	735.95	0.64	0.84	1.61
Bornholm Basin	STD	2.49	2.54	825.44	0.24	0.07	2.98
Eastern Gotland Basin	Mean	7.46	7.47	628.13	0.63	0.81	1.58
Eastern Gotland Basin	STD	2.60	2.30	660.78	0.23	0.08	2.82
NW Gotland Basin	Mean	6.95	7.60	660.62	0.63	0.81	1.53
NW Gotland Basin	STD	2.57	2.29	662.45	0.24	0.08	2.85
Bothnian Sea	Mean	4.16	6.83	473.99	0.64	0.81	1.69
Bothnian Sea	STD	3.57	1.93	455.98	0.23	0.09	3.10
Bothnian Bay	Mean	2.94	7.37	632.16	0.63	0.81	1.54
Bothnian Bay	STD	4.11	2.19	676.91	0.24	0.08	2.67

Table 3 Basic statistics pertaining to the meteorological variables in the ERA40 database where *Ta* denotes air temperature, *Cl* total cloud cover, *Rh* relative humidity, *W* wind speed, W^3 wind speed cubed and *P* precipitation rate

ERA40	Attribute	*Ta* (°C)	*W* (m s^{-1})	W^3 (m^3 s^{-3})	*Cl*	*Rh*	*P* (mm/d)
Kattegat	Mean	8.03	6.20	421.93	0.66	0.83	1.94
Kattegat	STD	2.57	2.45	463.10	0.24	0.07	2.83
Arkona Basin	Mean	7.41	4.49	168.54	0.67	0.82	1.47
Arkona Basin	STD	2.99	1.87	207.58	0.24	0.08	2.37
Bornholm Basin	Mean	7.85	5.65	321.25	0.66	0.81	1.33
Bornholm Basin	STD	2.55	2.27	369.93	0.24	0.07	2.31
Eastern Gotland Basin	Mean	7.78	6.86	554.14	0.64	0.82	1.48
Eastern Gotland Basin	STD	2.35	2.57	576.23	0.24	0.07	2.36
NW Gotland Basin	Mean	6.82	6.81	547.82	0.63	0.82	1.36
NW Gotland Basin	STD	2.47	2.54	567.35	0.25	0.07	2.27
Bothnian Sea	Mean	4.43	5.37	283.36	0.63	0.82	1.40
Bothnian Sea	STD	3.33	2.11	320.02	0.26	0.08	2.51
Bothnian Bay	Mean	2.66	4.66	186.30	0.67	0.82	1.27
Bothnian Bay	STD	3.97	1.87	220.37	0.25	0.07	2.18

Wind

Winds are calculated as geostrophic winds in the SMHI database and at various levels in the ERA40 data. Geostrophic winds are not, however, directly captured in the ERA40 database and therefore need to be calculated from the surface air-pressure field. We have done this and compared the results with the corresponding values in the SMHI database (see Figure 3). In general, both sets of values for the geostrophic winds are in excellent agreement. The mean wind speeds and standard deviations indicate a clear yearly cycle, with the highest winds and greatest standard deviation occurring in the winter.

Based on surface wind observations at Östergarnsholm, Omstedt and Axell (2003) developed a statistical model of how geostrophic winds are related to surface winds. In Figure 3 we also compare the reduced geostrophic winds with the orginal surface winds as captured in ERA40. The reduced geostrophic winds are close to the ERA40 winds in Eastern

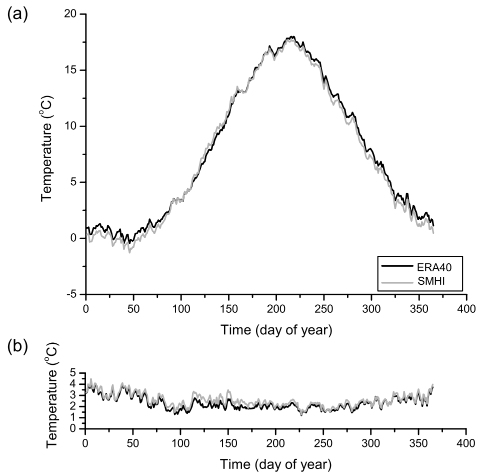

Figure 2 Mean temperature (a) and standard deviation of temperature (b) for the Eastern Gotland Basin

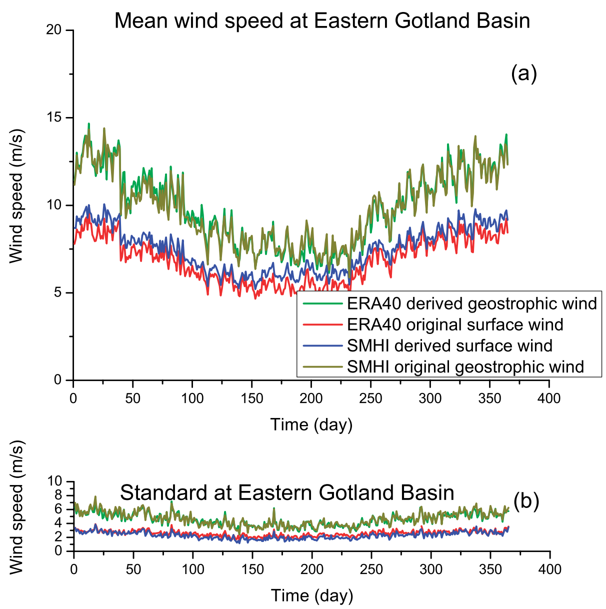

Figure 3 Mean wind speed (a) and standard deviation of wind speed (b) over the Eastern Gotland Basin. The different curves illustrate geostrophic winds according to the two databases, reduced geostrophic winds with reductions according to Omstedt and Axell (2003) and original surface winds according to the ERA40 data

Gotland Basin. However, in the case of a smaller sub-basin, such as the Arkona Basin (Figure 4), the reduced geostrophic winds are larger than is suggested by the ERA40 data (see also Tables 2 and 3). This indicates that the ERA40 winds are influenced by land, which increases surface friction and thus reduces surface winds. Gridded surface wind data obtained using a $1^\circ \times 1^\circ$ resolution are thus too coarse in some of the sub-basins of the Baltic Sea, and higher horizontal resolution is needed to resolve the wind field properly. The development of meteorological data sets with high horizontal resolution (11–22 km) has begun in BALTEX, but test results are only currently available for certain shorter periods (Fortelius *et al.* 2002). The need for high-resolution meteorological data can easily be illustrated by studying cloud climatology based on NOAA AVHRR satellite data (Karlsson 2003) or precipitation data (Rutgersson *et al.* 2001). An alternative for the ERA40 database

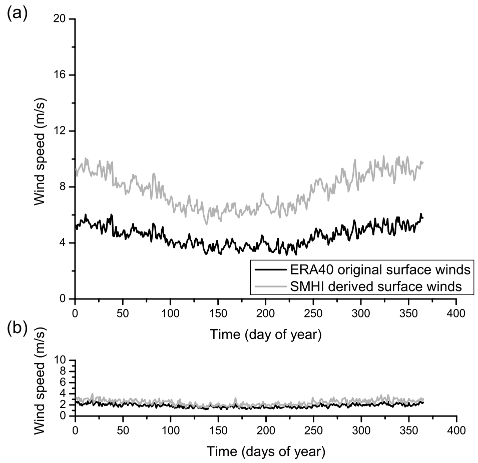

Figure 4 Mean wind speed (a) and standard deviation of wind speed (b) over the Arkona Basin. The different curves illustrate derived surface winds based on SMHI geostrophic data and with reductions according to Omstedt and Axell (2003), and original surface winds according to the ERA40 data

is to use derivate geostrophic winds and use reduction formulae, such as were developed by Omstedt and Axell (2003).

Total cloud cover

The total cloud cover values for the Eastern Gotland Basin as captured in the two data sets are compared in Figure 5. The mean and standard deviation values are quite similar, and indicate a clear yearly cycle. Mean cloudiness is highest in winter, while the standard deviation values are greatest in spring.

Using cloud climatology information obtained from satellite data (NOAA AVHRR) as a reference, Karlsson (2003) analysed the ERA40 data and found good agreement. This is of course a positive result; however, as the gridded data sets are on a rather coarse scale ($1° \times 1°$), cloudiness over the Baltic Sea is probably overestimated due to interpolations of land-based observations. From Tables 2 and 3 we can estimate that the difference in mean cloudiness between the two data sets is less than 0.05.

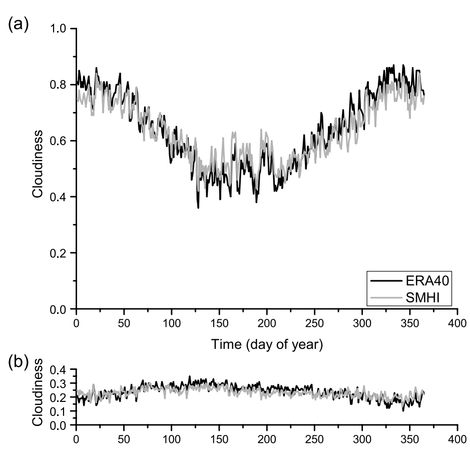

Figure 5 Mean total cloud cover (a) and standard deviation of total cloud cover (b) for the Eastern Gotland Basin

Relative humidity

The relative humidity values for the Eastern Gotland Basin as captured in the two data sets are compared in Figure 6. The mean and standard deviation values indicate a clear yearly cycle. Mean humidity is highest in the winter, while the standard deviation values are greatest in the spring. The relative humidity values captured in the ERA40 data are slightly higher in the spring and early summer, and with slightly less standard deviation. The opposite is true in other sub-basin areas. In general, Tables 2 and 3 show very good correspondence between the values in the two data sets: the difference in humidity values between the two data sets is less than 0.03.

Precipitation

It is well known that precipitation and evaporation are among the parameters causing the greatest problems for weather prediction. This is also true for meteorological reanalysis, such as that of the NCEP/NCAR data (Ruprecht and Kahl 2003). Precipitation data in the BALTEX region has been analysed by many. A review of the recent state of art is given by Rutgersson *et al.* (2001), where various methods are compared. In general, it was found that the differences between most of the studied estimates, when averaged over many years and larger areas, are of the order of 10–20%. The effects of land influence were also analysed, indicating the need to treat areas near the coast with care. In the present work, where gridded data sets with a resolution of $1^\circ \times 1^\circ$ are used we only extract data from the central part of each sub-basin (see Figure 1). For some of the larger sub-basins the land influenced is thus, we hope, reduced; for smaller sub-basins, however, there is probably still a strong land influence in the data. The mean precipitation rate and standard deviation for precipitation in the Eastern Gotland Basin are illustrated in Figure 7. The data indicates a seasonal cycle in terms of both means and standard deviation. The two data sets are similar, but the ERA40 data indicate both less precipitation and less standard deviation.

To analyse this further we compared the two data sets with wind-corrected precipitation data from Rubel and Hantel (1999). These data are probably the most complete data for the region, but are only available for five years (see Table 4). As can been seen, the ERA40 values are smaller than those from the two other data sets. Precipitation rates over the whole Baltic Sea region will be further discussed in the next section where we also analyse net precipitation rates over the Baltic Sea.

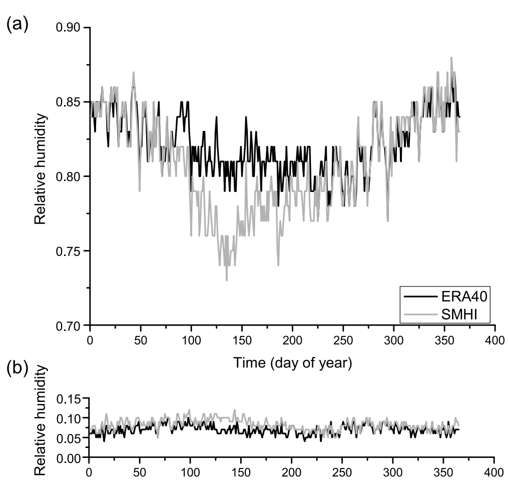

Figure 6 Mean relative humidity (a) and standard deviation of relative humidity (b) for the Eastern Gotland Basin

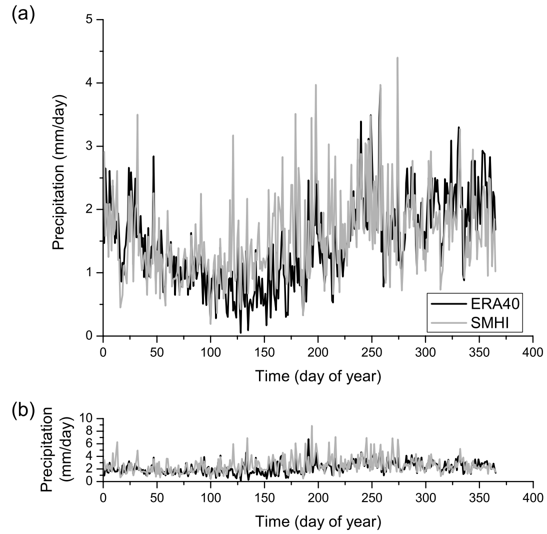

Figure 7 Mean precipitation (a) and standard deviation of precipitation (b) for the Eastern Gotland Basin

Table 4 Annual mean precipitation calculated for the 1997–2001 period based on different data sets. Units: mm/yr

Sub-basin	SMHI 1° × 1°	ERA40	Rubel and Hantel (1999)
Kattegat	683	731	904
Arkona Basin	627	535	780
Bornholm Basin	605	492	728
Eastern Gotland Basin	546	538	663
NW Gotland Basin	538	495	628
Bothnian Sea	617	498	805
Bothnian Bay	571	483	666

Baltic Sea modelling

Baltic Sea modelling is a powerful tool for use when evaluating meteorological data, hydrological data or climate models (Omstedt and Rutgersson 2000; Omstedt *et al.*, 2000; Omstedt and Nohr 2004). In the present study we ran the PROBE-Baltic model (Omstedt and Axell 2003) using the forcing fields from both the SMHI and ERA40 data sets and comparing the simulations with independent ocean observations. We have followed the example of earlier Baltic Sea studies and examined the modelling of sea ice, net precipitation, surface- and deep-water temperatures and salinities, and vertical salinity structure. The results of these validation studies are discussed below.

In Figure 8 the modelling of sea ice extent is examined. The two data sets and the independent observations are all in good agreement. However, the calculations overestimate ice cover during mild winters. This indicates that the two data sets may have a bias towards land influence, which makes their depiction of winter conditions over the Baltic Sea slightly too cold. However, the ERA40 database using geostrophic winds and reduction formulae for both wind and air temperature shows some improvement during mild winters (Figure 8(b)).

The precipitation, evaporation and net precipitation over the Baltic Sea are depicted in Figure 9. The evaporation rates obtained from the two meteorological data sets are in good agreement. However, the values of the ERA40 precipitation data are less than those of the SMHI precipitation data (this was also indicated in the previous section). We conclude that the values of the ERA40 precipitation data are too low.

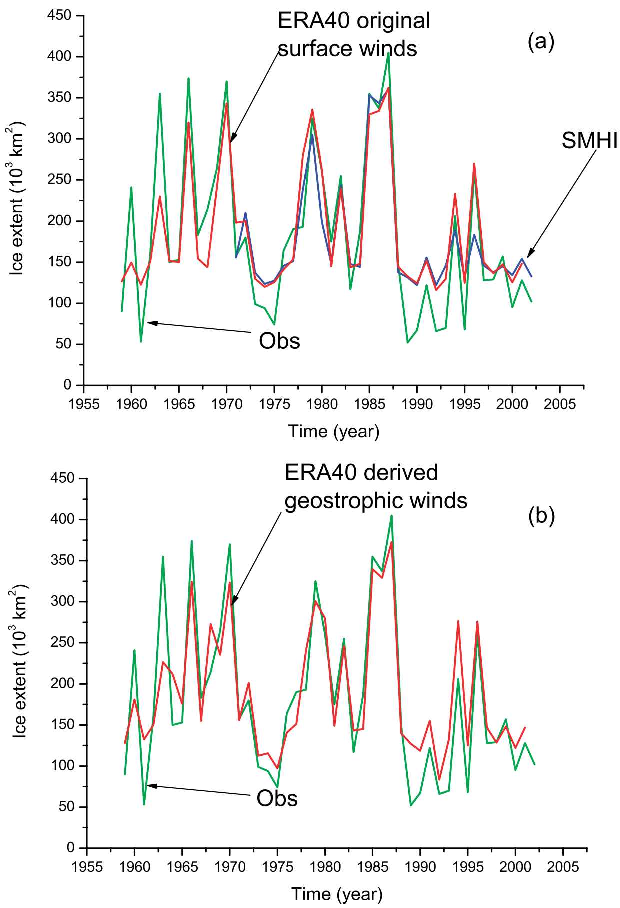

Figure 8 Modelled and observed maximum ice extents in the Baltic Sea. In (a) the ERA40 winds are based on original surface winds and in (b) on geostrophic winds and reductions according to Omstedt and Axell (2003)

The surface- and bottom-water temperatures and salinities are compared and depicted in Table 5. We have evaluated only the sub-basins where the data coverage is good. It is generally difficult to say which data set gives the best results. The ERA40 forcing data give slightly more accurate results for the surface properties than do the SMHI data. However, if the vertical salinity structure is examined, the run using ERA40 data and original surface winds underestimated the thickness of the surface-mixed layers as a result of wind speeds that were calculated too low. The result is improved using derived geostrophic winds in the ERA40 forcing. We therefore recommend that ocean models should use ERA40 data up to 2001, but with surface winds calculated from air pressure data and geostrophic reduction formulae. However, the SMHI $1^\circ \times 1^\circ$ data are continuously updated and could therefore complement ERA40 data from 2002 on. The values of the data pertaining to precipitation over the Baltic Sea seem, however, too low in the ERA40 data and the SMHI data should be used instead.

Summary and conclusions

In the present work we have compared two gridded meteorological data sets, both having a horizontal resolution of $1^\circ \times 1^\circ$. The first one, the SMHI $1^\circ \times 1^\circ$ data set, captures surface parameters using a three-hour time resolution over the 1970–2004 period. This data set is

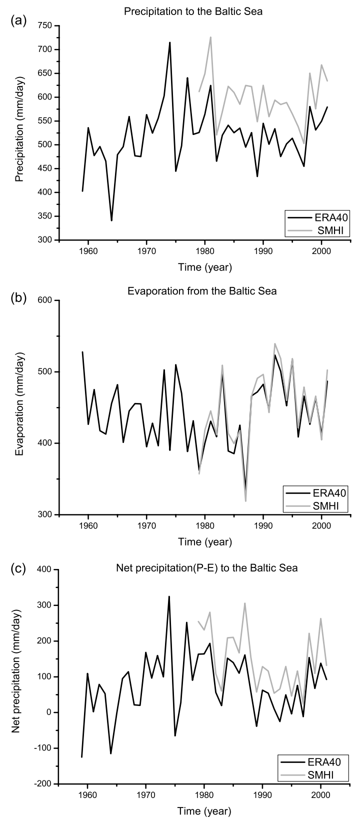

Figure 9 Interannual variation of precipitation (a) evaporation (b) and net precipitation (c) over the Baltic Sea (the Kattegat and Danish Straits are not included). The precipitation data are extracted from the two data sets and the evaporation is calculated using the PROBE Baltic model

continuously updated and is available from the BALTEX Hydrological Data Centre. The second one, the ERA40 data set, includes analysed and modelled parameters for several layers in the atmosphere using a six-hour time resolution over the 1957–2002 period. This data set is available from the ECMWF.

The aim of this study was to compare two gridded meteorological data sets and find out which is more reliable for Baltic Sea modelling. The meteorological variables considered were air temperature, wind speed, total cloud cover, relative humidity and precipitation. In modelling the Baltic Sea we examined the maximum ice extent, water temperature, salinity and net precipitation calculations.

We tested the two data sets using the same Baltic Sea model, the same period and the same validation data. Both data sets can be used to run Baltic Sea models, but the $1^\circ \times 1^\circ$ resolution gridded meteorological data sets for the Baltic Sea are still too coarse; this implies, for example, that the original ERA40 surface winds are often underestimated due to land influence. It is also clear that the precipitation data from the ERA40 reanalysed data set appears to underestimate the amount of precipitation over the Baltic Sea.

There is generally good agreement between the two data sets. The ERA40 data offer much more variables for investigation than do the SMHI $1^\circ \times 1^\circ$ data. However, the SMHI $1^\circ \times 1^\circ$ data are continuously updated and could therefore complement ERA40 data from 2002 on. The ERA40 precipitation data appear to underestimate precipitation over the Baltic Sea, and the horizontal resolution is too coarse, at least in parts of the Baltic Sea region. The conclusions from the paper can be summarised as follows:

Table 5 Statistics based on ocean modelling using the two databases, ERA40 and SMHI 1° × 1° as forcing data. RMS (root mean square) and the mean error are shown. *T* is temperature and *S* is salinity, s*ur* and *bot* stand for surface- and bottom-water values, respectively

Area	Data set	Mean error		RMS		Mean error		RMS	
		T sur	*T bot*	*T sur*	*T bot*	*S sur*	*S bot*	*S sur*	*S bot*
Kattegatt	ERA40	−0.40	−0.65	1.00	2.35	−2.90	0.47	3.75	0.91
Kattegatt	SMHI	−0.72	−0.63	1.04	2.32	−0.99	0.45	2.54	0.90
Arkona Basin	ERA40	−0.09	−1.78	1.16	3.93	−0.22	2.25	0.44	3.60
Arkona Basin	SMHI	−0.36	−1.95	1.04	3.75	0.38	2.04	0.52	3.30
Bornholm Basin	ERA40	0.31	−0.93	1.04	1.75	−0.13	−1.11	0.25	1.55
Bornholm Basin	SMHI	0.32	−1.43	0.94	2.15	0.06	−0.83	0.24	1.38
Eastern Gotland	ERA40	0.16	−0.14	1.31	0.81	−0.28	0.23	0.48	0.42
Eastern Gotland	SMHI	−0.59	−0.43	1.18	0.88	−0.35	0.33	0.51	0.52
Bothnian Sea	ERA40	−0.31	0.37	1.76	0.83	−0.60	−0.26	0.67	0.32
Bothnian Sea	SMHI	−1.54	0.02	1.91	0.74	−0.50	−0.19	0.59	0.26
Bothnian Bay	ERA40	0.14	−0.81	1.65	1.54	0.16	0.19	0.20	0.26
Bothnian Bay	SMHI	−0.94	−0.73	1.47	1.38	0.20	0.21	0.24	0.26

- The two gridded meteorological data sets show many similarities and can both be used in Baltic Sea modelling.
- The horizontal resolution in both data sets is too coarse for resolving marine conditions over the Baltic Sea. This implies, for example, that ERA40 surface wind values are too low.
- The ERA40 precipitation values are too low compared with those in the SMHI data and the data from Rubel and Hantel.

For Baltic Sea modelling we recommend that the ERA40 data be used as they cover the longest time period. SMHI data could be added for years after 2002 for updating the files. However, ERA40 surface wind values are too low; instead, one should use geostrophic wind values and reduction formulae such as those given by Omstedt and Axell (2003). For precipitation, we recommend the pertinent data contained in the SMHI database; further study of precipitation rates at sea are, however, needed.

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