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The development of the regional coupled ocean-atmosphere model RCAO

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A regional coupled ocean-atmosphere-ice general circulation model for northern Europe is introduced for climate study purposes. The Baltic Sea is interactively coupled. The coupled model is validated in a 5-year hind-cast experiment with a focus on surface quantities and atmosphere-ocean heat fluxes. The coupled sea surface temperature matches observations well. The system is free of drift, does not need flux corrections and is suitable for multi-year climate runs. With flux forcing from the atmospheric model the regional ocean model gives sea surface temperatures statistically equivalent to the uncoupled ocean model forced by observations. Other oceanic surface quantities do not reach this quality in combination with the current atmosphere model. A strong dependence of sea ice extent on details of the atmospheric radiation scheme is found. Our standard scheme leads to an overestimation of ice, most likely due to a negative bias of long-wave radiation. There is indication that a latent heat flux bias in fall contributes to the ice problem. Other atmosphere-ocean heat fluxes are generally realistic in the long term mean.

Introduction

Regional coupled ocean-atmosphere-ice models represent a major element in the BALTEX strategy of assessing the energy budget and water cycle over the Baltic Sea catchment area. To approach that goal, coupled models need to be developed and verified. That is precisely the scope of this paper.

The history of coupled models for the Baltic Sea area started with Gustafsson *et al*. (1998) where a regional atmospheric model HIRLAM was coupled to an ocean basin model. Non-interactive coupling resulted in an ocean drift detectable after a few months. Flux corrections were necessary to provide realistic results. As a next step, Hagedorn *et al*. (2000) coupled the regional atmosphere model REMO with the 3D Kiel ocean model for the Baltic Sea. This flux coupled model gave realistic results during summer months. Its major limitation was a missing ice component. Hagedorn *et al*. (2000) showed that significant differences between coupled and uncoupled sea level pressure are connected to weak winds in meridional direction. During such periods, the coupled system appears to be more free to develop local dynamics. Rummukainen *et al.* (2001) utilized a vertically resolved, box-like ocean model representing 13 Baltic basins according to the approach of Omstedt and Nyberg (1996). That model was coupled via state variables (i.e. no fluxes were passed) to a regional atmosphere model in order to run regional climate scenarios. Schrum *et al.* (2001) did a full flux coupling of REMO with the 3D Hamburg Ocean Model HAMSOM. Their model was shown to run stable over a full seasonal cycle with generally satisfying sea surface temperature. The interactively coupled ocean performed distinctly better than a one-way flux coupled ocean without feedback of SST to atmospheric fluxes.

The next logical step is a multi-year run with interactive coupling of 3D models. Therefore, the Rossby Centre regional Atmosphere Ocean model RCAO has been developed within the framework of the Swedish Climate Modelling Program SWECLIM. Our coupled system aims at regional coupled climate scenarios. Moreover, we intend to examine the interaction of sub-basin scale ocean processes with ocean-atmosphere fluxes and Baltic Sea water and energy budgets. The latter point is addressed by Meier and Döscher (2002).

In this paper, we introduce RCAO by a description of the model set-up and a validation focused on the ocean part and atmosphere-ocean fluxes. The major questions are: (1) What is the degree of realism in multi-year coupled hind-cast runs? (2) Does the coupled system drift? (3) How do the ocean results differ between applying atmosphere forcing, provided by the coupled atmosphere model, compared to observation-based forcing?

These questions are addressed by comparing 5-year long hind-cast runs with observations and ocean stand-alone runs.

The coupled model

Our current coupled regional model system, the Rossby Centre Atmosphere Ocean model RCAO has been set up for climate studies in northern Europe. Besides the European continent, the model domain covers parts of the North Atlantic, the Nordic seas and the Arctic (*see* Fig. 1). The interactively coupled ocean is limited to the Baltic Sea. The remaining ocean areas are represented by a one-way data transfer of sea surface temperature (SST) and fractional ice cover to the atmosphere.

The component models of RCAO are the Rossby Centre Ocean model RCO and the Rossby Centre Atmosphere model RCA. The version 1 of RCA is described in detail by Rummukainen *et al.* (2001). RCA builds on the parallel coding of the operational High Resolution Limited Area Model HIRLAM, version 2.5. Newer improvements include semi-lagrangian advection, modification of the radiation scheme (Räisänen *et al.* 2000), Kain-Fritsch mesoscale convection and a new vertical mixing scheme based on turbulent kinetic energy in the present set-up, RCA (version 2). Here we use a rotated latitude–longitude grid with a resolution of 44 km and with 24 hybrid levels between the surface and 10 hPa. The timestep is 30 minutes. RCA is forced at its lateral boundaries by relaxation within a 8 grid point wide boundary zone. An additional forcing is applied by a weak relaxation of deep soil temperature. In our case, ECMWF reanalysis data (ERA15) is used at the lateral boundaries, for the deep soil temperature and for the non-Baltic sea surface quantities.

The interactively coupled ocean component RCO is described in detail in Meier *et al.* (1999) and Meier *et al.* (2002). RCO is a parallel code based on the OCCAM model (Webb *et al.* 1997, 1998b). Here we use RCO in a horizontal resolution of 6 nautical miles with 41 vertical levels (3 m–12 m level thickness). The baroclinic timestep is 10 minutes. From the OCCAM model, RCO inherits a free surface (Killworth *et al.* 1991), and low dispersion advection (Webb *et al.* 1998a). The adjustment to Baltic Sea conditions include a k-ε mixed layer, open boundary conditions and river runoff. Moreover, a dynamic-thermodynamic sea ice model based on EVP (elastic-viscous-plastic) rheology and a Semtner-type thermodynamics is included. Both RCO and RCA are efficiently parallelized.

In stand-alone mode, i.e. not coupled to an atmosphere model, the ocean model RCO is

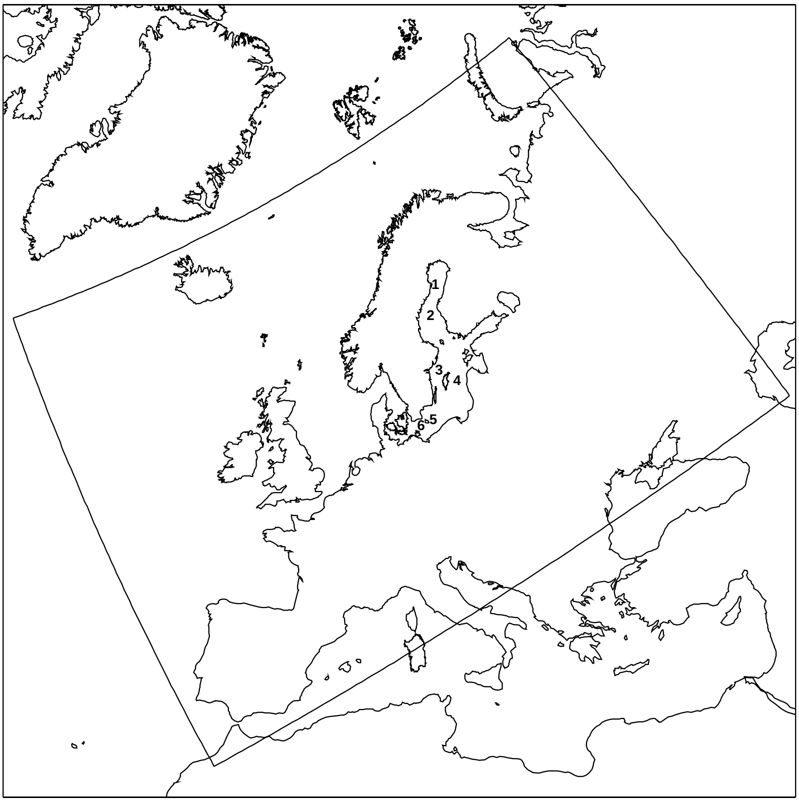

Fig. 1. RCAO model domain for hindcast runs, covering most of Europe and parts of the North Atlantic Ocean and Nordic Seas. Only the Baltic Sea is interactively coupled. Positions for sea surface temperature observations are indicated by numbers. **1**: Bothnian Bay, **2**: Bothnian Sea, **3**: Landscort, **4**: East Gotland Basin, **5**: Bornholm Basin, **6**: Arkona.

forced by observations from the SMHI database via standard bulk formulae as described by Meier (2002). 10-m wind speed is parameterized according to Bumke *et al.* (1998), resulting in a geostrophic wind with coastal and directional corrections. Heat, freshwater and momentum enter the model as fluxes based on standard bulk formulas. No restoring of sea surface values is used.

A lateral open boundary is situated in the Kattegat. The method of Stevens (1991) is applied to the baroclinic fields. Temperature and salinity are relaxed towards prescribed values in case of inflow, while a radiation condition is used for outflow. The sea surface height is prescribed according to coastal observations. (A parameterization relating the large scale wind field to sea surface height in Kattegat can be applied for climate runs). In stand-alone mode, RCO has been proven to preserve the stratification realistically for more than a decade (Meier *et al.* 2002).

The ocean and atmosphere models are coupled via the OASIS coupler (Terray *et al.* 1999, Valcke *et al.* 2000). Both components run as individual executables synchronized by the third executable OASIS. This coupler handles all the data communication and performs interpolations between different grids. Differences between the coupled and uncoupled versions of RCO and RCA are limited to certain interface routines and additional internal communication between master and slave processors of the component models. By using OASIS, we avoid complex technical problems arising from an all-in-one code. Instead we can keep independent codes. This is of great advantage for the flexibility of the system.

In general, ocean surface quantities are passed to the atmosphere and atmosphere-ocean fluxes are returned to the ocean (longwave upward radiation is an exception, *see* next paragraph). The scheme of energy exchange is not conservative over the complete interactively coupled region (no “global conservation”) due to different coast line geography in the current ocean and atmosphere models. Momentum is

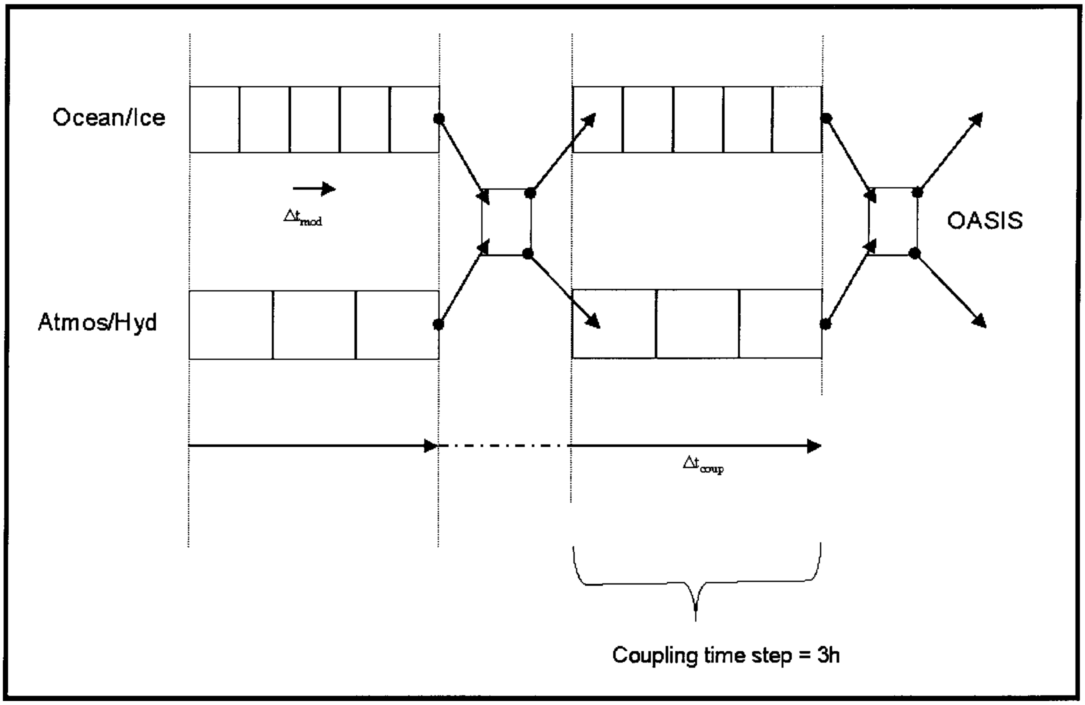

Fig. 2. The coupling scheme of RCAO. Atmosphere and ocean run in parallel.

not yet fully flux coupled. Instead, 10-m wind velocities are passed and momentum fluxes are calculated in RCO.

The fluxes are calculated within the atmosphere on the atmospheric grid (44 km), which is coarser than the ocean grid (11.1 km). This set-up neglects sub-atmosphere-grid scale variability of the sea surface. This can be accepted for fluxes moderately dependent on SST, but clearly not for longwave upward radiation with its 4th order dependency on SST. Isolated ocean points such as small shallow bays, which heat up rapidly in spring, cannot radiate sufficient heat to cool down. As this problem cannot be tolerated for our purposes, the longwave upward radiation is the only flux calculated within the ocean. The fluxes undergo a Gaussian interpolation with a variance of the order of the target grid scale. Flux calculation on the finest grid for all variables is planned for the next evolution step of RCAO.

The river runoff to the Baltic Sea is represented by a river routing scheme connecting the land runoff with river mouths.

The coupling scheme in Fig. 2 describes the time sequence of interaction between atmosphere and ocean. Ocean and atmosphere run in parallel. After running through a coupling timestep of 3 h, information is exchanged via the OASIS coupler. With this choice of the coupling timestep, diurnal cycles are represented. Ocean and atmosphere are forced with fields from the preceding coupling timestep. All fluxes are averaged. Therefore, it is important to calculate the shortwave downward radiation as net flux including a time-dependent surface albedo. Applying the albedo in the ocean according to the time of the day would result in too little daily radiation due to not synchronous cycles of radiation and albedo.

The coupled integration starts on 2 September 1988 and runs for 5 years. The atmosphere is initialized with ERA data and zero velocities from that date. The ocean is initialized with observed temperature and salinity profiles for each Baltic basin in May 1980 and then integrated in stand-alone mode towards 2 September 1988, forced with observations for more than 8 years. This period is well validated (Meier *et al.* 2002) and the stand-alone run provides a realistic field in dynamical balance with observed forcing at the starting time of the coupled integration.

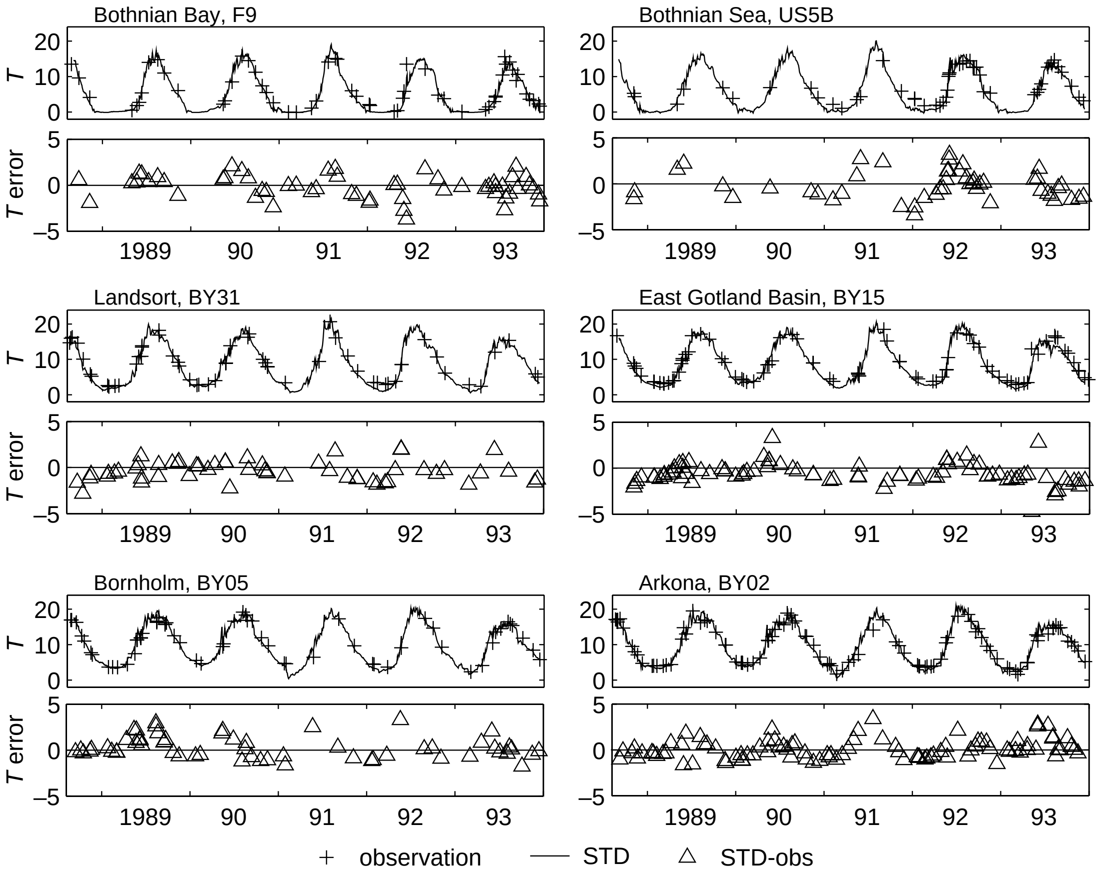

Fig. 3. SST in °C for the coupled standard case STD and observations (upper panels), and SST error (lower panels).

Validation

Sea surface temperature

SST of the coupled ocean is verified by comparison with station data for six stations from SMHI's SHARK data base. The nearest model grid points are used. (stations listed in Fig. 3 with positions indicated in Fig. 1. The model generally shows a good skill. Mean errors are small and RMS error are about the same size for the standard coupled run (henceforth called STD) and the stand-alone case (ocean-only, henceforth called OO). The mean SST error is –0.18 K for the coupled case (0.42 for OO) and the RMS error is 1.43 K (1.67 K for OO). The somewhat negative mean error is due to too cold winter SSTs as seen e.g. for the East Gotland Basin and Bothnian Bay stations in Fig. 3.

Sea ice

Although coupled and uncoupled SST are statistically similar for the complete 5-year period, differences occur, contributing to an overestimation of sea ice extent during several winters in the coupled ocean. Figure 4 (ice data from FIMR and SMHI observations) shows too large ice areas throughout the 5-year period. The ice area is especially overestimated during strong winters. This problem can be related to incorrect fluxes before and during winter. Negative biases are seen in the latent heat fluxes over sea (Fig. 5) and in downward longwave radiation. (Fig. 6b).

A thermal memory for the upper Baltic longer than a seasonal cycle is not observed in nature. Thus, if the fluxes of the coupled model do not deviate by orders of magnitude from reality, we would not expect a longer memory. Indeed we

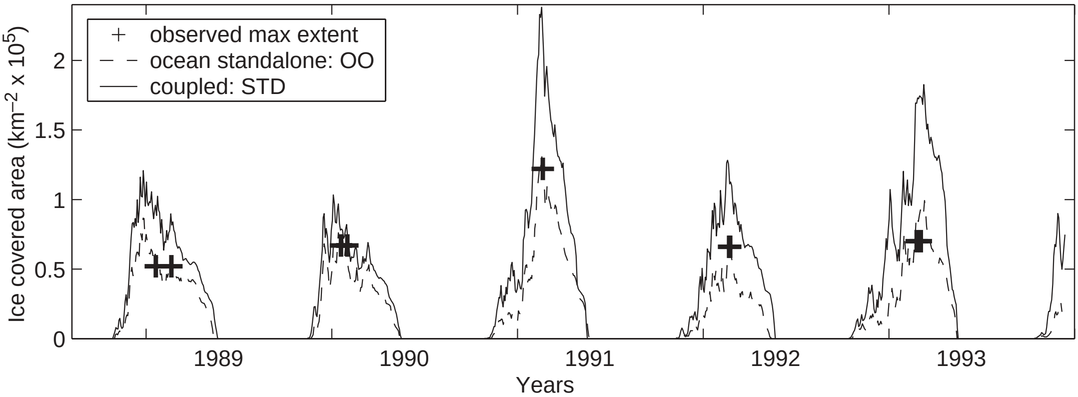

Fig. 4. Ice extent for case STD and OO. Observed maximum annual ice extent is indicated by plus signs. Two observations indicate disagreement between FIMR and SMHI.

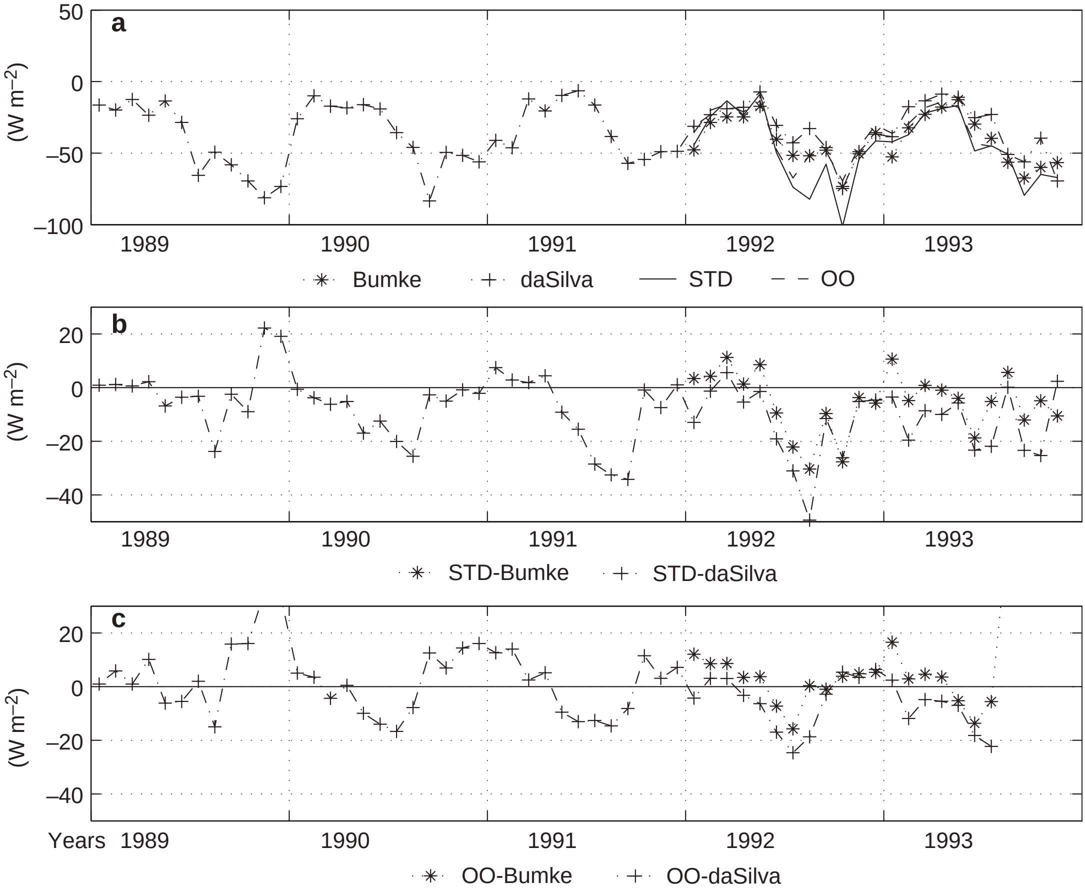

Fig. 5. — **a**: Monthly mean average latent heat flux for the Baltic Sea for the coupled case STD, uncoupled ocean OO, daSilva observations and Bumke observations. — **b**: Difference of latent heat flux for case STD. — **c**: Difference of latent heat for case OO.

find that a misrepresentation of thermal surface fluxes is always compensated by the response of SST and accordingly adjusted fluxes on the seasonal timescale. In the 5-year mean, the total heat content of coupled and uncoupled ocean are similar within 4% (STD compared to OO). The

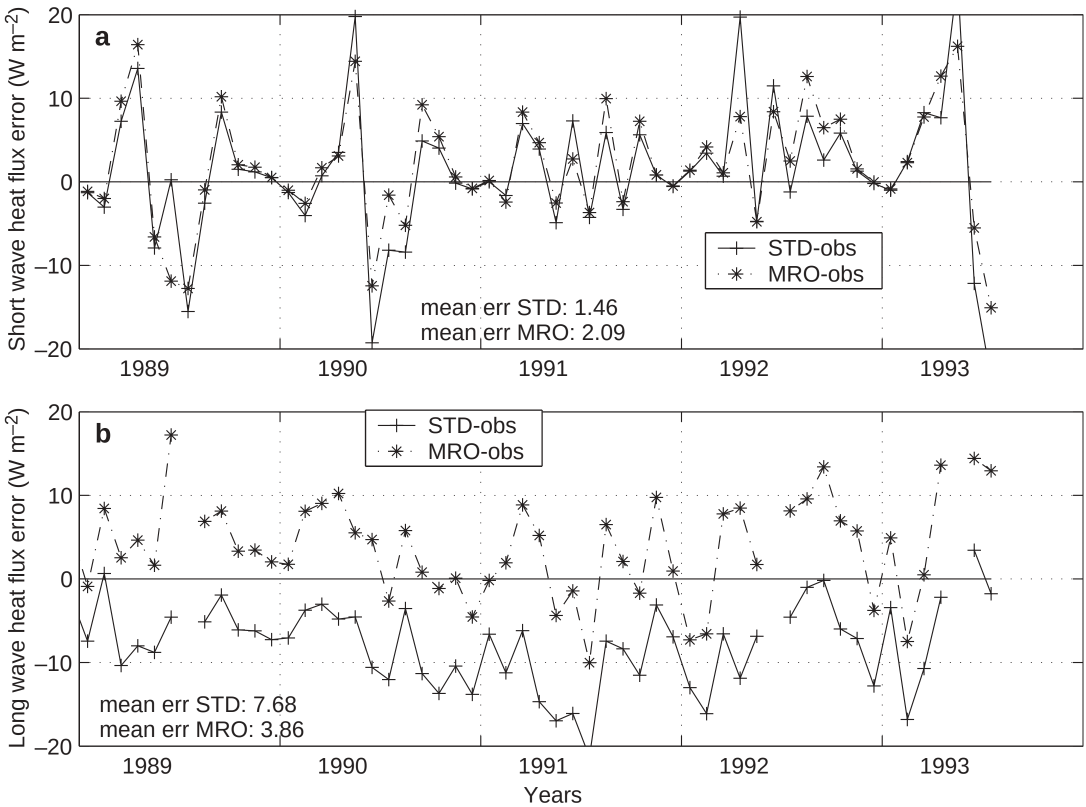

Fig. 6. Monthly mean heat flux error of shortwave (**a**) and longwave radiation (**b**), estimated by comparison with land stations: 11 stations from the SMHI network for shortwave and 3 stations from the SMHI network together with 3 stations from GEBA for longwave radiation. Mean errors over the whole timeseries are given.

mean basin averaged salinity reduces by about 0.08 psu/y in both the coupled and standalone ocean, because most of the simulation time corresponds to a stagnation period (no figure). No significant trend can be identified for the Baltic's heat content.

Heat flux

Sensible and latent heat flux observations for the Baltic Sea are available from daSilva *et al.* (1994). This data represents a refined version of the COADS (Comprehensive Ocean-Atmosphere Data Set) heat fluxes, where the fluxes are calculated from the mean parameters of SST, air temperature and wind given by the synoptic network. In addition, latent heat flux data is given by Bumke *et al.* (1998) who calculate heat fluxes by mean parameters measured on-board ships. Both flux data are averaged over the area of the Baltic Sea.

Nowadays observational accuracy of ocean-atmosphere heat flux is 5–20 W m^{-2} at the best. Often uncertainty is higher for indirect methods. Sensible heat flux of the coupled experiment STD (Fig. 7) fits well with observations within these margins. Maximum difference of up to 15 W m^{-2} are found. Slightly negative differences (too much heat leaving the ocean) occur in fall and winter.

The latent heat flux (Fig. 5) differs from observations by up to 50 W m^{-2} (daSilva) and 30 W m^{-2} (Bumke, Fig. 5b). Largest differences are negative and occur during late summer and fall. Thus, the coupled ocean loses too much heat before the beginning of the ice period. This heat loss is much reduced in the stand-alone ocean case OO (Fig. 5c). This difference contributes to the overestimation of ice during winter. The

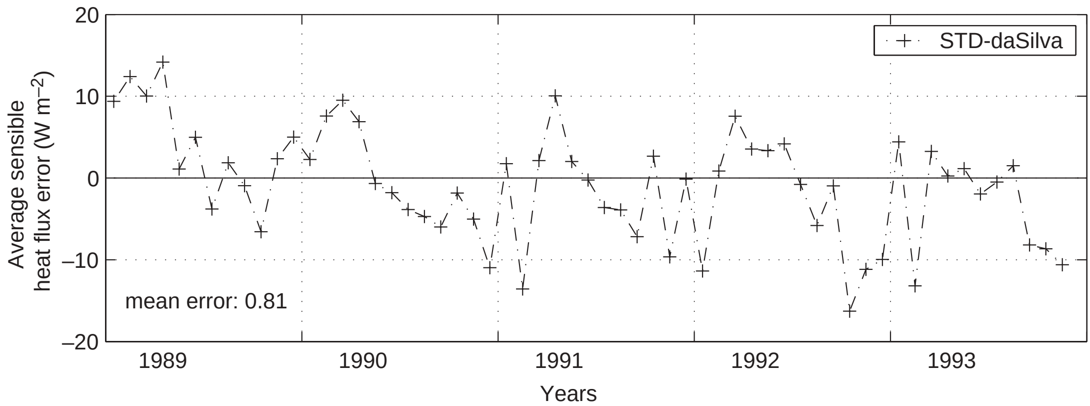

Fig. 7. Monthly mean average sensible heat flux error for the Baltic Sea: difference between the coupled standard case STD and daSilva observation. The mean error over the whole timeseries is given.

surface turbulent fluxes of sensible and latent heat in the RCA-model are calculated using mean model parameters and transfer coefficients. These coefficients are described by Louis *et al.* (1982) and are functions of the stratification in the surface layer and the surface roughness given by the Charnock formula over sea. This scheme has been shown to give too large wind speed dependence for the heat fluxes (Rutgersson *et al.* 2001) and is modified according to Makin and Perov (1997) in order to obtain lower heat fluxes. Our results show that further improvement is needed for the latent heat flux.

Observations of radiative fluxes at the ocean-atmosphere boundary are not available for the validation period. Instead, land-based observations can be used as a first approximation. Monthly mean short-wave (SW) and long-wave radiative fluxes are obtained from the SMHI solar radiation network (Persson 2000) and from the GEBA archive (Ohmura and Gilgen 1991). The representativeness of these land based radiation data to the Baltic Sea is not clear. At least during the cold part of the year, the data should be relevant because cloud cover as a major factor for radiation does not generally differ from land to sea. The opposite is true for the summer months. The longwave downward radiation (Fig. 6b) shows a clear negative bias (too little heat into the ocean/ice), thus contributing to the overestimation of sea ice.

The atmospheric formulation of the surface long-wave (LW) downward radiation depends on assumptions about the vertical overlap of clouds in a grid column. Maximum overlap is used in the original formulation (Savijärvi 1990, Sass *et al.* 1994) corresponding to our model run STD. A more physically based assumption, maximum-random overlap (Weare 2001), was introduced and an additional coupled run (MRO) was performed. This run gave better wintertime SSTs and sea-ice (no figure), since the effective cloud cover was increased leading to increased long-wave radiation towards the surface and a reduced LW surface bias. However, the upper atmospheric LW bias was enlarged. The present simplified radiation scheme allows only one vertical loop, making it very sensitive to the overlap formulation. Too little radiation was emitted to space compared with ERBE data, leading to a warming of the upper atmosphere. Therefore, the current maximum overlap formulation will be used, until the present radiation scheme can be replaced by a more elaborated radiation scheme allowing further vertical interactions and other overlap formulations. Figure 6 shows a good agreement of model and observation regarding shortwave radiation for both cases STD and MRO.

Summary and discussion

An interactively widely flux coupled regional atmosphere-ocean-ice model including hydrology for the Baltic Sea area has been developed. The coupled system is fully parallel which enables efficient integrations on climate related timescales.

The model has been demonstrated to run 5 years in a row. This has been achieved without flux corrections. Possible model errors or biases do not add up in the ocean. Possible heat flux anomalies are compensated for by negative feedbacks within the seasonal cycle. No significant artificial trends in heat or salinity can be found. Thus, the coupled model runs stably. Therefore it appears possible to carry out multi-annual simulations.

A 3D Baltic Sea ocean model as such RCO provides high resolution for surface quantities in good quality. Ocean models currently give the most appropriate lower boundary condition for the coupled regional atmosphere in hind-cast mode. Such information in good quality is not available from observations. IR-Satellite observations give better quality for individual snapshots. However they lack continuous data coverage and past (10–100 year) SST/sea ice information. For longterm climate scenarios, sea surface quantities can only be delivered by an ocean model.

The regional ocean model RCO can be forced for hind-cast runs either by calculating surface fluxes from observations with the help of standard bulk formulas ("stand-alone ocean"), or by an interactive flux coupling to the regional atmosphere RCA. We find that both types of forcing give statistically similar results for the SST. However, this statement does not hold for all sea surface quantities. As an example sea ice extent is simulated significantly better for stand-alone ocean runs. Thus, a coupled forcing for the ocean model cannot completely replace observation-based forcing for hind-cast runs. For longer climate scenario runs, of course, the atmosphere model provides the only possible forcing.

Sea ice is found to depend strongly on details of the radiation parameterization within the atmosphere. A "maximum random overlap" scheme (corresponding to model run MRO) for clouds in the parameterization of longwave downward radiation gives a more realistic longwave radiation (more towards the ocean surface), compared to the standard "maximum overlap" scheme (model run STD). The sea ice extent is distinctly better for MRO, which represents the physically desired overlap assumption. However, the maximum random overlap gives too little long-wave radiation to space.

A review of ocean-atmosphere fluxes shows that major uncertainties exist not only in the radiation scheme, but also in the latent heat flux. Both contribute to the overestimation of sea ice. Future work needs to address these issues. A new more sophisticated radiation scheme is needed to fully incorporate the vertical cloud interactions. A more detailed evaluation for longer simulation periods covering times of observational projects like BRIDGE and BASIS is necessary. This will also contribute to a better assessment of atmospheric effects due to different sea surface descriptions.

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