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Circulation of the Baltic Sea and its connection to the Pan-Arctic region — a large scale and high-resolution modeling approach

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The Baltic Sea has traditionally been considered as a semi-enclosed marginal sea with little or no influence on the adjacent oceans. We employ an eddy-permitting, coupled ice-ocean model of the Pan-Arctic region to study the Baltic Sea, especially its circulation and property exchanges with the North Sea and other regions. Using this high-resolution and large scale model we focus here on the freshwater export from the Baltic Sea and its transport by the Norwegian Coastal Current (NCC) into the Norwegian and Barents Sea. We hypothesize that the freshwater outflow from the Baltic Sea plays a significant role in modification of Atlantic Water properties along its northern pathway from the North Atlantic, through the Nordic Seas, and into the Arctic Ocean. Recommendations are made for more realistic model representation of the Baltic Sea circulation to advance understanding of this region's influence on the large-scale northern polar ocean circulation and climate change.

Introduction

General ocean circulation models (GCMs) have become a powerful tool for investigating local, basin-wide, and global ocean dynamics and their contribution to climate variability. These models can be used as a component of a climate model or separately with prescribed atmospheric forcing to study wind and thermohaline driven ocean circulation. Over the last few decades GCMs have made significant advancements in representation of physical processes controlling the ocean dynamics and its variability at a wide range of spatial and temporal scales, and in use of modern high performance computers to solve complex oceanographic problems (Semtner 1995). Limited-domain or regional models have increased their spatial resolution from order of 0(100 km) to order of 0(10 km) or less. This has allowed for more adequate representation of marginal or semi-enclosed seas, such as the Baltic Sea. In addition, higher resolution provides means

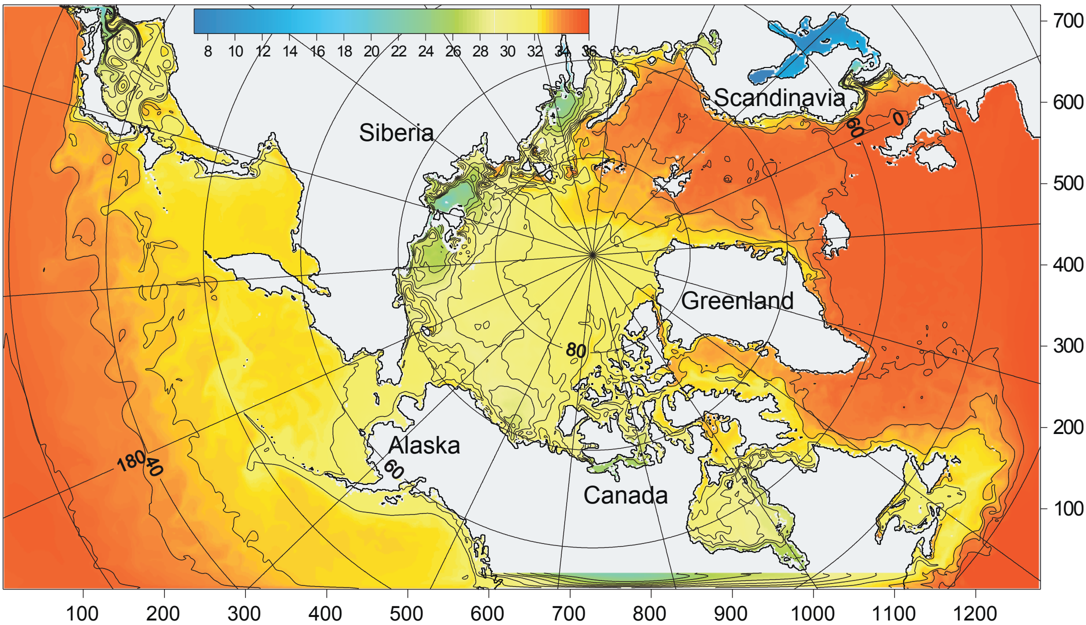

Fig. 1. The November 1979 monthly-mean salinity (ppt) distribution at depth 5–10 m. The full model domain of the 1/12° Pan-Arctic coupled ice-ocean model is shown.

to study processes controlling communications between such regions and the large-scale ocean circulation. With such tools at hand we address below one of the outstanding questions of the BALTEX program about the role of the Baltic Sea in large scale ocean circulation and climate change.

Model description

A coupled ice-ocean model configured on a rotated spherical grid with horizontal nodes distributed every 1/12° (or ~9 km) and with 45 vertical levels (Fig. 1) has been developed at the Naval Postgraduate School (NPS) in Monterey, California (www.oc.nps.navy/mil/~pips3). It consists of a regional adaptation of the Parallel Ocean Program (POP) developed at the Los Alamos National Laboratory (LANL) (Maltrud *et al*. 1998) coupled to a parallel version of the original Hibler dynamic-thermodynamic model with a viscous-plastic rheology (Maslowski *et al*. 2000). At the surface and along the model lateral boundaries monthly mean temperature and salinity fields are used with the restoring time scale of 30 and 10 days, respectively. In addition, the European Centre for Medium-range Weather Forecast (ECMWF) daily-averaged reanalyzed data for 1979–1993, including the surface incoming long wave and short wave radiation, 2-m air temperature and dew point temperature, and 10-m winds, are used. The model incorporates the 2.5-km bathymetry field developed by the International Bathymetry Charting of the Arctic Ocean (IBCAO) project (Jakobsson *et al*. 2000) interpolated to the 9-km grid. The free-surface approach allows use of the unsmoothed bottom topography, which is critical for realistic representation of marginal seas, narrow straits and passages, and submarine troughs and ridges. The model was initially integrated for 27 years using the repeated ECMWF-derived annual cycle climatology forcing. An additional 15-year run was completed, consisting of a 6-year integration with the realistic 1979 daily-averaged ECMWF forcing, followed by a 9-year integration using the 1979–1981 realistic forcing repeated 3 times. Results from the last 3 years of this ongoing integration are presented here.

Results

Circulation of the Baltic Sea

The modeled circulation of the Baltic Sea consists of several bathymetry-controlled and mostly cyclonic gyres. The surface circulation pattern varies over the annual cycle. During the period from October to March currents are relatively strong. A cyclonic circulation around the Proper Baltic exists with the mean current velocities along the coast up to 6 cm s^{-1}. A strong velocity shear region is modeled between the coastal zone and the open sea. An intensive recirculation and mixing occurs in the outer Bay of Gdansk and Gulf of Riga in autumn (Fig. 2). The main flow in the upper 33 m continues to the north along the eastern side of the Proper Baltic towards the southwestern coast of Finland. Portions of this flow enter the Gulf of Finland to the east and the Gulf of Bothnia to the north but its major part recirculates to the south towards Gotland. During winter the circulation there evolves into a 200-km diameter mesoscale cyclonic gyre occupying the northern part of the Proper Baltic. The southward current splits north of Gotland into a western branch following the coast of Sweden and into an eastern branch along the eastern side of Gotland. To the north, a semi-enclosed cyclonic gyre occupies the entire Bothnian Sea. In the Gulf of Bothnia and Golf of Finland weaker cyclonic circulations are also present. In spring the upper ocean circulation is less organized and it weakens and becomes less defined during summer.

The mid-depth circulation (Fig. 3) is also divided into several separate cyclonic and anticyclonic gyres occupying main deeps. The circulation in these gyres varies somewhat throughout the year, but they stay well organized with the prevailing cyclonic sense of rotation. There are two regions (Fig. 3) where circulation reverses from cyclonic in November to anticyclonic in February: one in the northern Gulf of Bothnia and another one in the northernmost part of the Proper Baltic. The Slupsk Furrow is the only deep connection between the Bornholm and Gotland Basins and it appears to play an important role in the deep-water exchange. The Gdansk Deep is seen as a buffer zone for the advection of saline water from the Bornholm Basin into the Gotland Deep. The local circulation patterns modeled in the Slupsk Farrow suggest high temporal variability of the mass transport.

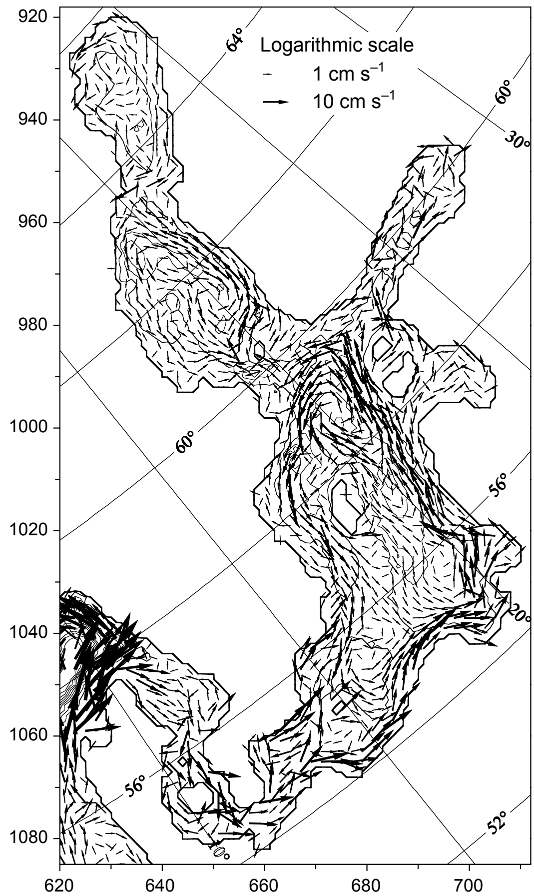

Fig. 2. The three-year (1979–1981) November mean velocities averaged over the upper 33 m.

Communication between the Baltic and North Sea.

As noted earlier the model horizontal resolution of ~9 km is not adequate to resolve details of passages in the Belt Sea. The Sound separating Zealand Island from Sweden is closed in the model, what may significantly affect the outflow of fresh water from the Baltic Sea. At the same time results show quite strong water mass exchange in the Skagerrak (Fig. 3). The cyclonic

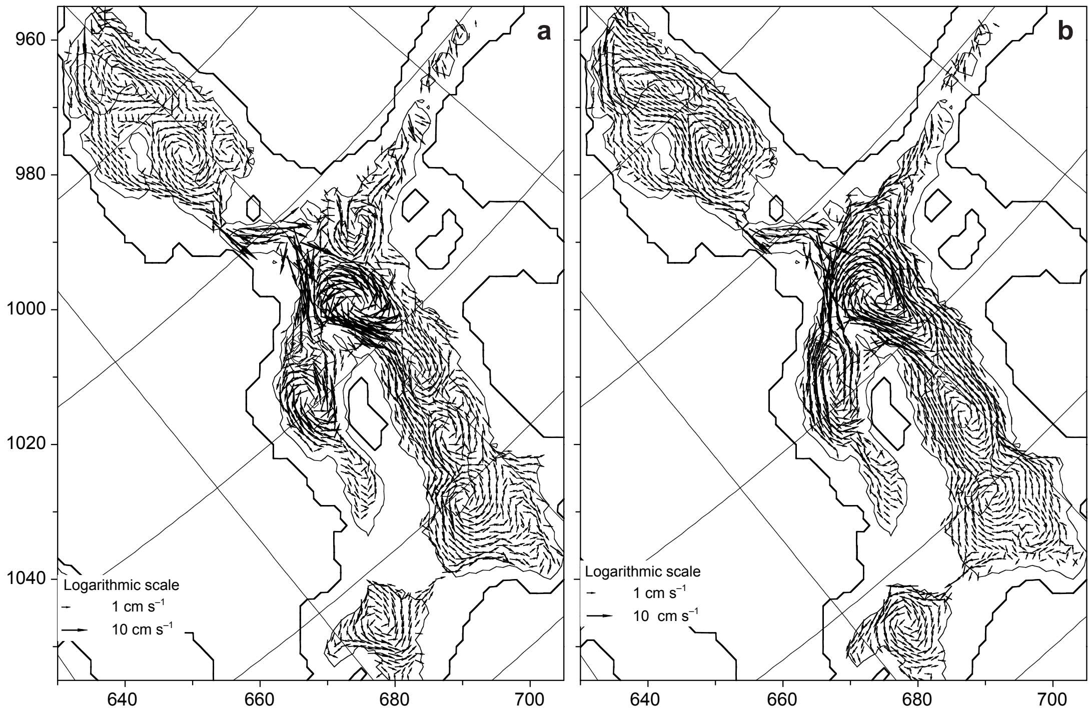

Fig. 3. The mean velocity fields at depth 42–53 m in (**a**) February, and (**b**) November of 1981.

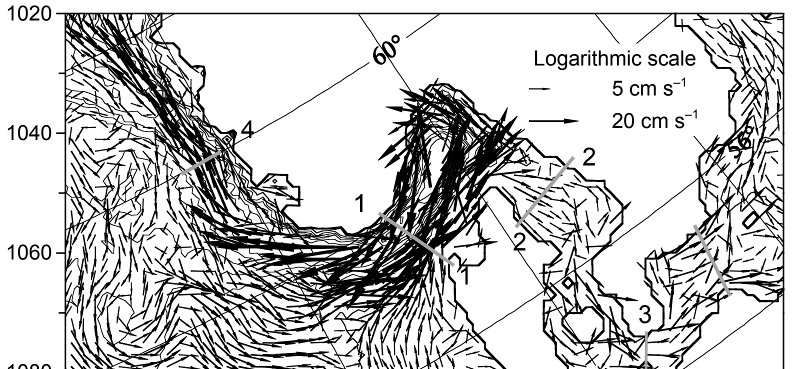

Fig. 4. The three-year (1979–1981) mean November velocity field averaged over depth 0–33 m in the Skagerrak/Kattegat and the Belt Sea region. Locations of Sections 1–4 are shown.

circulation in the area transports water from the North Sea into the strait along its southern side. The returning flow along the northern Skagerrak incorporates the outflow from the Baltic Sea. The resulting outflow, with the three-year mean November velocities up to 90 cm s^{-1}, continues as the well-defined Norwegian Coastal Current (NCC), along the Norwegian inner shelf all the way into the southern Barents Sea (Figs. 1 and 4). The three-year mean volume exchange through the Section 1 across the western Skagerrak (Fig. 4) is 0.87 Sv in each (east and west) direction, with no net transport and with a relatively high month-to-month and year-to-year variability. In contrast, volume exchanges in the Kattegat are about 40 times smaller. Transport across the Section 2 (roughly along 57°N — *see* Fig. 4) is only 21×10^3 m^3 s^{-1} into and out of the Baltic Sea. Volume exchanges between the Kattegat and Proper Baltic are even smaller (i.e. ~6 $\times 10^3$ m^3 s^{-1} each way across the Section 3 in Fig. 4). This means that ~190 km^3/year of salty water enters the Baltic Sea from the North Sea, and the same amount of fresh water is exported from the Baltic Sea. The annual saline water inflow into the Baltic Sea estimated from measurements is ~ 450 km^3/year (Bergström and Carlsson 1994), which translates into the mean volume flux of 14.3×10^3 m^3 s^{-1}. Hence the model estimated flux is more than two times smaller. More realistic exchanges are modeled further to the east, across the section between Sweden and Germany, in the Arkona Basin. The modeled mean volume transport there is ~21×10^3 m^3 s^{-1} in each direction, but 70% of this water recirculates into the Proper Baltic. The main two reasons for this model discrepancy are probably the absence of river runoff and the model horizontal resolution and they are discussed more in the following section.

The Baltic Sea — freshwater source for the Arctic

The modeled NCC volume and freshwater transports vary with latitude. At 60°N, the NCC is defined as a narrow (60–70 km) current with velocities up to 8 cm s^{-1} and a strong horizontal shear (Fig. 4). The three-year mean volume and freshwater transports across the Transect 4 (Fig. 4) is respectively 1.2 Sv and 14×10^3 m^3 s^{-1} (assuming the reference salinity of 34.9 ppt (i.e. part per thousand)). A strong seasonal variability is present (Fig. 5). Generally, the volume transport is smaller in summer, when northerly winds are predominant along the Norwegian coasts (Gade 1986). Further to the north, the NCC meanders, partly merges with the Norwegian-Atlantic Current (NAC), and then separates again. Along the coast to the north of Nordcapp, the NCC becomes again a narrow separated stream with the mean volume and freshwater transports of 1.4 Sv and 5.6×10^3 m^3 s^{-1}, respectively (Fig. 5). There is a positive correlation between the freshwater transport at latitude 60°N and 71–72°N (across the Nordcapp section). The maximum correlation coefficient from the monthly-mean data is 0.47 for the time lag of 3–5 months. Using smoothed data (i.e. 12-month running average), the correlation coefficient reaches 0.82 with the time lag of 6 months. This implies the mean signal propagation speed of 12 cm s^{-1}.

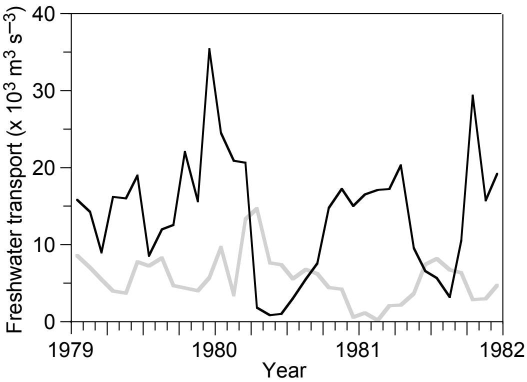

Fig. 5. The freshwater transport (10^3 m^3 s^{-1}) by the Norwegian Coastal Current, at 60°N (black line) and across the section to the north of Nordcapp (gray line).

Figure 6a shows the freshwater layer thickness along the analyzed region. The thickness was calculated from 5 subsurface model layers representing the depth range of 5–33 m. The surface layer was not included to reduce in the analysis the influence of restoration to the climatological surface salinity. The calculated freshwater layer thickness (using the reference salinity of 34.9 ppt) is ~2 m in the southern portion of the NCC and it decreases to ~1m in the northern part. Due to the absence of river runoff into the Baltic Sea in the model, the salinity distribution in the upper ocean is primarily controlled by the surface climatology. However changes in the spatial distribution of freshwater below the surface layer are also a result of the model internal dynamics. In Fig. 6b, the distribution of the difference between the freshwater layer thickness calculated from the model three-year November mean and from the November climatological data is presented. Up to 1-m differences are present in the southern part of the NCC and they decrease to ~25 cm in the northern part. Although the modeled freshwater transport along the NCC is close to the theoretical freshwater supply from the Baltic Sea, most of it originates from the Skagerrak and the southern North Sea instead. An increase of the freshwater layer thickness in the southwestern Baltic Sea up to 3 m is modeled, but majority of this freshwater recirculates inside the Baltic Sea. As noted earlier, the model representation of the freshwater water outflow from the Baltic Sea

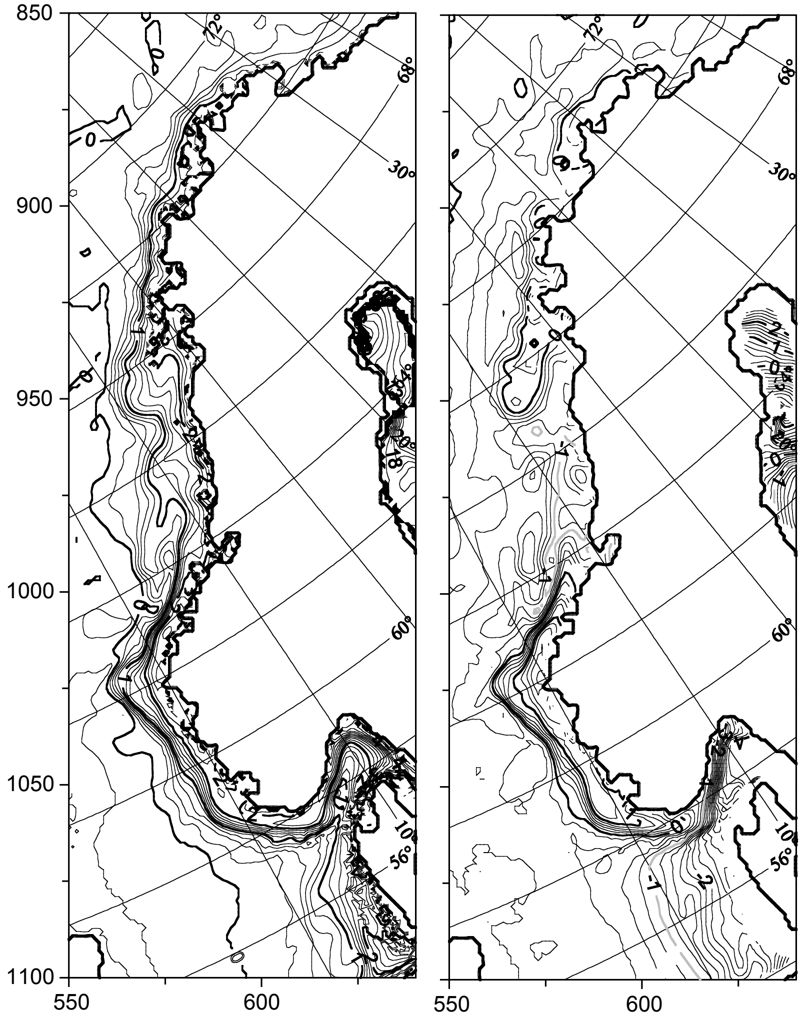

Fig. 6. — **a**: The three-year (1979–1981) November mean thickness (m) of freshwater layer calculated at depth 5–33 m. — **b**: The difference (m) in freshwater layer thickness between the modeled three-year November mean and November climatological data. Contour interval is 25 cm.

is probably mainly limited by the insufficient horizontal resolution to resolve the passages and channels of Danish Straits and by the absence of river runoff (i.e. no net mean volume outflow through the straits).

Discussion

The 9-km horizontal resolution of the model grid cannot resolve eddies with diameter smaller than ~36 km (4 grid points) and some narrow passages of the Danish Straits. It is worth to note that the Baltic Sea region is only a small part of the Pan-Arctic model domain (Fig. 1) as it occupies 1.6% of the total surface and 0.23% of the total volume. On the other hand, the Pan-Arctic domain of this model allows more realistic representation of oceanic conditions outside the Baltic Sea, which cannot be fully accounted in other models of the Baltic Sea. In fact this model is one of the first to include the Baltic Sea in the Pan-Arctic domain at such a high resolution. Such an approach allows considering the Baltic Sea not only as an isolated region but also as a potentially important component of a larger climate system of the northern polar region.

The long-term averaged river discharge into the Baltic Sea is estimated to be ~440 km^3 a^{-1} (Ehlin, 1981). This volume is comparable to the large Siberian river runoffs (e.g. Yenisey ~573 km^3 a^{-1}). Including the effect of precipitation minus evaporation over the Baltic Sea, the total net freshwater supply reaches 15×10^3 m^3 s^{-1}. Since all of this net freshwater flux leaves the Baltic Sea via the Danish Straits into the North Sea, it must have some influence on the larger scale ocean thermohaline circulation in the outflow region. Results of this model suggest that the freshwater exiting the Danish Straits can be tracked as a low salinity signal (Fig. 1) and a well-defined coastal current (i.e. NCC) (Fig. 4) flowing along the coast of Norway to the north into the Norwegian Sea and then to the east into the Barents Sea. In addition to the main outflow of brackish water from the Baltic Sea, other sources of freshwater to the NCC include runoffs from the coasts of Western Europe farther to the south (Johannessen 1986) and from the Norwegian fjords.

A direct connection between the freshwater originating from the Danish Straits and the salinity distribution in the Norwegian and Barents Sea has been demonstrated. Since Atlantic Water is the main source of heat and salt into the Arctic Ocean, any alterations and/or modification of its properties along the path to the north, especially at interannual and longer time scales, might have significant consequences to the regional thermohaline circulation and climate. This fact alone provides a sufficient argument for further and more focused studies of the role of freshwater originating from the Baltic Sea on the northward heat, salt and mass transports into the Arctic Ocean.

Future model improvements should include realistic freshwater discharges into the Baltic Sea. A numerical approach nesting a 1–2-km model of the Baltic Sea in a large-scale pan-Arctic model would allow for more realistic representation of important details of the bathymetry and coastline. Such a nested model should include the Baltic Sea river discharge and the P-E budget. We speculate that the freshwater transport by the NCC into the Norwegian and Barents Sea would significantly increase with those modifications. Such improvements would allow better understanding of the Baltic Sea dynamics and its role in the northern hemisphere ocean thermohaline circulation and climate change.

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