North Sea circulation: Atlantic inflow and its destination

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Abstract.

This study investigates the Atlantic inflow to the North Sea; its variability, pathways and destination. Results from a numerical model show that the variability of Atlantic inflow is dependent on the inflow location. The inflow between Orkneys and Shetland and in the Shetland shelf area show a strong connection to the strength in westerly winds in winter and spring on a weekly time scale, while the inflow in the Norwegian Trench has a longer response time to the large scale wind pattern. About 50% of the Atlantic water that enters the North Sea is mixed with fresher water before it leaves the North Sea as the Norwegian Coastal Current. This illustrates the important role of estuarine processes within the North Sea and Skagerrak area, and their interaction with the Atlantic water.

1. Introduction

The pathways of the North Atlantic Current are one of the key factors in the climate system, because it brings warm subtropical water much further north than any other current of the Northern Hemisphere. The warm Atlantic water is high on nutrients and keeps the Norwegian Sea and parts of the Barents Sea free from ice. Hence, it is important for biological production and fishery industries.

In the eastern North Atlantic the North Atlantic Current splits into two branches, and follows different pathways towards the Norwegian Sea [see e.g. *Orvik and Niiler*, 2002]. We know that a part of the North Atlantic Current branches into the North Sea on its way northwards, but the destination of the Atlantic water within the North Sea is not clear.

The North Sea is a shelf sea that lies between Norway, the British Isles and the European Continent (Figure 1). It is a shallow sea, and two thirds of the region have depths shallower than 100 m. An exception is the Norwegian Trench, which has depths exceeding 700 m. This special topography influences the circulation to a great extent.

The warm and saline Atlantic water enters the North Sea through the English channel and at the northern boundary. The northern boundary inflow is usually divided into three different inflow sites; the Orkneys-Shetland section, the Shetland shelf area and the western part of the Norwegian Trench.

The general circulation pattern in the North Sea and Skagerrak is mainly cyclonic. We know that the Atlantic water flows mainly southwards, and is influenced by the topography. In the coastal areas of the British Isles and the European continent it is mixed with fresher water from rivers. The flow continues eastwards, and when it reaches the inner part of Skagerrak, the area between Denmark, Sweden and Norway, it meets brackish water from the Baltic and turns northward. It follows the Norwegian coast westwards and becomes the Norwegian Coastal Current (NCC). The reader is referred to *Sætre and Mork* [1981]; *Hackett* [1981]; *Aure and Sætre* [1981]; *Otto et al.* [1990]; *Rodhe* [1996, 1998] for studies about the North Sea, and to *Svansson* [1975]; *Rodhe* [1987, 1998]; *Gustafsson and Stigebrandt* [1996]; *Danielssen et al.* [1997]; *Gustafsson* [1999] for studies about the Skagerrak.

The common perception about the North Sea is that the main Atlantic inflow to the area is at the western slope of the Norwegian Trench, and that the NCC outflow is mainly compensated by the Norwegian Trench inflow [see e.g. *Furnes*, 1980; *Rodhe*, 1998]. The role of the different inflow sites, and the amount of Atlantic water that is mixed with fresher water before it leaves the North Sea is not clear.

The objective of this study is therefore to do a thorough evaluation of the Atlantic inflow to the North Sea, and to examine its variability and interaction with estuarine processes in the area. The basis of the analysis is a one year simulation of a high resolution, numerical model covering the North Sea and Skagerrak.

Several earlier studies have used a fully baroclinic/barotropic, three-dimensional numerical ocean model to investigate the North Sea and Skagerrak dynamics, see e.g. *Svendsen et al.* [1996]; *Skogen et al.* [1998]; *Berntsen and Svendsen* [1999]; *Røed and Fossum* [2004]. But none of these studies have investigated the destination of the Atlantic water.

The main estuarine process in the area is the mixing between the brackish water of Baltic origin and water from the North Sea that occurs in Kattegat, the area between the east coast of Denmark and west coast of Sweden. For details about the dynamics in this area see *Rodhe* [1996]. The high-saline Atlantic water is also mixed with fresher water from rivers along the coastal boundaries.

Other studies have shown that the Atlantic inflow to the Norwegian Sea is strongly influenced by the North Atlantic Oscillation (NAO) index [*Blindheim et al.*, 2000; *Mork and Blindheim*, 2000; *Orvik et al.*, 2001]. We also know that there is a connection between the circulation pattern in the North Sea and changing wind regimes [*Furnes*, 1980; *Dooley and Furnes*, 1981; *Sætre et al.*, 1988], but it is unclear if it is the wind stress over the North Sea as a whole or local wind forcing that mainly determines the circulation. Hence, this study also includes an analysis of the large scale wind system in connection with the North Sea circulation.

Section 2 describes the model system, and Section 3 presents and evaluates the model results. Finally, Section 4 presents conclusions.

2. Model system

The numerical ocean model used in this study is the Hybrid Coordinate Ocean Model (HYCOM) by *Bleck* [2002], and is an outgrowth of the Miami Isopycnal Coordinate Ocean Model [MICOM; *Bleck and Smith*, 1990]. The major improvements in HYCOM relative to MICOM is the introduction of a hybrid vertical coordinate, which allows for the use of coordinate formulations suitable for different ocean regimes. The hybrid coordinate is typically isopycnal in the open, stratified ocean, but there is a smooth transition to z-level coordinates in the mixed layer and a transition to sigma coordinates in shallow coastal regions. This approach allows for high vertical resolution close to the surface and in shallow regions.

The overall model system consists of a two-level nested system where a large scale model feeds an intermediate resolution model with boundary conditions. This intermediate model provides boundary conditions needed by the high resolution model covering the North Sea and Skagerrak (Figure 2).

Boundary conditions are treated differently depending on whether the variables are barotropic or baroclinic. For the slowly varying variables, i.e. baroclinic velocities, temperature, salinity and layer interfaces, the boundary conditions are based on the flow relaxation scheme [FRS; *Davies*, 1983]. This means that we use a one way nesting scheme where the boundary conditions of the regional model are relaxed towards the output from the coarser large scale model. For the barotropic variables the relaxation approach requires careful treatment to avoid reflection of waves at the open model boundaries. In HYCOM the barotropic model is a hyperbolic wave equation for pressure and vertically integrated velocities. Following an approach outlined by *Browning and Kreiss* [1982, 1986], it is possible to compute the barotropic boundary conditions exactly while taking into consideration both the waves propagating into the regional model from the external solution and the waves propagating out through the boundary from the regional model.

The large scale model has a variable resolution with approximately 15-30 km grid cells, and this model ensures that the overall general circulation and water masses in the North Atlantic and its seasonal variability are properly represented. The intermediate model covers all of the North Sea and the Atlantic Margin including the deep waters between Spain, Iceland and Norway. This model has about 7 km resolution, which is sufficient to provide realistic and fairly detailed circulation pattern along the Atlantic Margin. A higher resolution model is needed to ensure good representation of the mesoscale variability and its energetics. Thus, a resolution of 4 km is used for the regional model covering the North Sea and Skagerrak.

Note that 4 km is normally too coarse to properly represent the mesoscale dynamics of the NCC, see e.g. *Johannessen et al.* [1989]; *Ikeda et al.* [1989]; *Haugan et al.* [1991]; *Oey and Chen* [1992] which indicated that a model of 2 km resolution is needed. However, we have compensated for resolution by implementing a fourth order numerical scheme for the advection terms in the momentum equation which improves the dynamical representation of potential vorticity. In practical applications this leads to similar results with half the resolution compared to the original version of HYCOM as shown by *Winther et al.* [2006].

The synoptic forcing fields are temperature, wind and humidity (determined from dew-point temperatures) fields from the European Center for Medium-Range Weather Fore-casting (ECMWF). Clouds are based on climatologies from the Comprehensive Ocean and Atmosphere Dataset [COADS; *Slutz et al.*, 1985], while precipitation is based on the climatology of *Legates and Willmott* [1990]. River input is modeled as negative salinity flux, and tides are specified as barotropic forcing at the open boundaries.

To ensure a proper representation of the Baltic inflow to the North Sea model, a barotropic volume flux (net transport from Baltic) is included at the eastern bound-ary. Values used to specify the volume flux are monthly climatology data and the Baltic water has been given a salinity of 8 psu.

This configuration of HYCOM has been thoroughly evaluated in a recent study by *Winther and Evensen* [2006]. This paper shows that the different water masses in the North Sea ands Skagerrak are well represented in the simulations, and that the general circulation is well reproduced. In addition they found that the dynamics of the chaotic

NCC was well simulated in the model. The main problem in the model simulations was too smooth stratification between the NCC and the Atlantic water. This problem is related to properties of the vertical mixing scheme in combination with the setup of isopycnal coordinates. For details we refer to *Winther and Evensen* [2006], and model results used in this study are from Exp. 2 in the paper.

3. Results

3.1. General model circulation

Figure 3 (upper panels) shows the annual mean surface velocity and annual mean barotropic (i.e. depth averaged) velocity (average over a period from July 1997 to July 1998). The clearest Atlantic inflow sites at the northern boundary are between Orkneys and Shetland, and in the western part of the Norwegian Trench. There is also a considerable inflow at the Shetland shelf, but this inflow is more diffuse. The Shetland shelf is here defined as the area from the northeast coast of Shetland to the Norwegian Trench (see Figure 1).

The Atlantic water that enters through the Orkneys-Shetland section can follow two different pathways. The main part follows the 100 m isobath and crosses the central North Sea from west to east. This current is known as the Dooley current, already described by *Dooley* [1974] and later analysed by *Svendsen et al.* [1991]. The other possible pathway is to follow the east coast of the British Isles, where it eventually meets the Atlantic inflow through the English channel. The Atlantic water continues along the coast of the European Continent, and all along the coast it is mixed with fresher water from rivers. The Atlantic inflow between Orkneys and Shetland eventually ends up in Skagerrak, irrespective of what path it follows.

The water that enters in the western part of the Norwegian trench follows the 200 m isobath southwards, mainly underneath the NCC. Part of this flow does not travel far before it turns eastwards and then northwards and flows out of the area. This retroflection process, first described by *Furnes et al.* [1986], will be further discussed later on.

The Shetland shelf inflow is a more diffuse transport, and can turn both west or east before it eventually joins the other transport routes. Although this is a more diffuse flow, we will see later on that it amounts to a considerable part of the total Atlantic inflow.

The Atlantic water that enters Skagerrak is a composite of inflow both through the English channel and at the northern boundary. The annual mean velocity (Figure 3) show a clear cyclonic circulation in Skagerrak and the flow continues northwards as the NCC. At about 58°N, where the Norwegian Trench becomes wider, the NCC splits into two parts, which eventually meet again at about 59°N. When the NCC reaches about 62°N, the area where the shelf becomes wider, it splits into two parts again; a narrow coastal branch and a branch that follows the shelf break.

In shallow regions the surface and barotropic velocities show similar current pattern. Differences are mainly seen in the Norwegian Trench, where the current system is clearly baroclinic with a northward flowing NCC and the southward flowing Atlantic water.

Monthly mean velocities of surface currents (Figure 3, lower panels) reveal clear deviations from this circulation pattern throughout the year. In February the inflow at the northern boundary is very strong, resulting in high velocities in the entire central North Sea and a narrow NCC. In June the situation is quite different. The Atlantic inflow takes place mainly along the western part of the Norwegian Trench, the Dooley current is almost absent and the NCC is much wider than in February.

The English channel inflow is very weak in February and strong in June. This indicates that strong inflow at the northern boundary may act as an obstacle for the English channel inflow.

3.2. Transports

Otto et al. [1990] reviewed the physical oceanography of the North Sea and summarized fresh- and sea-water fluxes from both measurements and modeling studies (Table 1-II in *Otto et al.* [1990]). The transport estimates based on measurements from *Otto et al.* [1990], together with more recent transport estimates [*Rodhe*, 1996; *Rydberg et al.*, 1996; *Danielssen et al.*, 1997], were used to evaluate the general circulation in the model. Table 1 summarizes the mean transports together with minimum and maximum transport values from the model to illustrate the large variability in the circulation pattern. The location of sections where transports were calculated is illustrated in Figure 1.

In general the model mean transport estimates agrees well with estimates from measurements, a surprising result considering the large variability seen in all transports and also the fact that the measurement estimates are based on either moored current meter stations or scientific cruises for a certain time period.

The transport estimate that deviates most from observations is the Norwegian channel outflow. For this particular outflow the transport estimate is based on four stations in the eastern part of Norwegian Trench during a measurement program that took place from March to June in 1976. The rigs located at the western part of the Norwegian Trench were lost, and this will influence the transport estimates. Hence, it is not certain that this time period is a good measure of the mean transport or that these four stations captures the total flow.

The comparison in Table 1 illustrates that the numerical model system used in this study represents the general circulation features in the North Sea. Also this HYCOM configuration was evaluated in *Winther and Evensen* [2006], and proven to give good results. This gives us confidence in the model and allows us to do further analysis of the model results.

The total mean inflow at the northern boundary is 2.22 Sv, but the variability is large, and the daily mean values varies from 0.85 to 6.09 Sv. All transports show high variability throughout the year, and to further investigate the variability, we first examine the timeseries of Atlantic inflow (northern boundary), NCC outflow and Skagerrak outflow. (Skagerrak outflow is total transport from Skagerrak to the central North Sea, see black line in Figure 1.) The different transports are distinguished by their water mass properties, i.e. Atlantic inflow is water with salinity above 35 psu, NCC outflow is water fresher that 35 psu. The exception is the Orkneys-Shetland inflow, where water with salinity down to 34.5 psu is seen, because of some mixing with continental shelf water. Nevertheless, the total inflow between Orkneys and Shetland is included in the Atlantic inflow.

Weekly filtered timeseries (Figure 4, upper panel) show that the Atlantic inflow and the NCC outflow have the same annual cycle, with maximum transport in February 1998 and minimum transport in June 1998. (This is seen more clearly in monthly filtered timeseries, not shown here.)

Orvik et al. [2001] showed that the Norwegian Atlantic Current through the Svinøy section (see Figure 1) has a systematic annual cycle with a February maximum that is twice the size of the June/July minimum. This is the same variation in transport that we see in both the Atlantic inflow and NCC outflow in our model simulations for 1997 and 1998. *Orvik et al.* [2001] also showed that there is a strong connection between the Atlantic transport through the Svinøy section and the seasonal NAO index. Hence, a natural question is how strongly the North Sea fluxes is coupled to the NAO index. This is further addressed in Section 3.3.

Results from HYCOM are also in agreement with *Riepma* [1978] and *Dooley and Furnes* [1981], who showed that the inflow at the northern boundary is highly correlated with NCC outflow. The model results show a high correlation both on weekly and even on daily time scales (Table 2), and this result is valid both for total transports and when we distinguish between different water masses.

The largest Atlantic inflow occurs at the western part of the Norwegian Trench with a mean transport of 1.23 Sv, while the mean inflow at the two other sites, Orkneys-Shetland section and Shetland shelf area, are of equal size and about 0.50 Sv each (Table 1). This means that the amount of Atlantic water that enters the North Sea in the relatively shallow area from Orkneys to Shetland including the Shetland shelf is on the same order as the Atlantic inflow in the Norwegian Trench.

Furnes et al. [1986] showed that a large part of the Atlantic inflow that enters the North Sea in the Norwegian Trench is retroflected in the northwestern part of the trench and does not reach Skagerrak. *Furnes et al.* [1986] proposed two possible mechanisms to explain the retroflection; topographic steering (the trench gets shallower towards south) and bottom Ekman transport.

This retroflection process is indeed present in our model. If we follow the southward transport of Atlantic water (>35 psu) within the Norwegian Trench from section A to B to C in Figure 1 there is a clear reduction in the inflow. At section A the Atlantic inflow is 0.90 Sv, at B it is reduced to 0.42 Sv and at section C it is further reduced to 0.20 Sv. This reduction can partly be explained by mixing with the NCC (about 20%), which means that this water is not retroflected, but becomes fresher on its way southwards. The remaining part, about 0.5 Sv, is retroflected before it reaches 59°N.

Another interesting feature is that the Orkneys-Shetland and Shetland shelf inflows show similar variability (Figure 4, lower panel), with a correlation coefficient of r=0.73 on a daily time scale (Table 2). The Norwegian Trench inflow does not show similar variability at all, and the correlation with the Okneys-Shetland inflow is only r=-0.25. Possible forcing mechanisms to explain these differences will be discussed later on.

Table 2 also shows the correlation between the NCC outflow and inflow at different locations. There is a strong correlation between total Atlantic inflow at the northern boundary and the NCC outflow, but the correlation between the inflow and outflow within the Norwegian Trench is much weaker. This indicates that the NCC outflow is highly influenced by Atlantic inflow outside the trench.

These points contradicts two common perceptions about the North Sea circulation; that the main Atlantic inflow to the North Sea and Skagerrak is along the western slope of the Norwegian Trench, and that the NCC outflow is mainly compensated by the Norwegian Trench inflow. (See *Furnes* [1980]; *Rodhe* [1998].)

If we focus only on the circulation of Atlantic water within the North Sea, the total inflow of water with salinity above 35 psu is 1.90 Sv, while the outflow is only 0.88 Sv. This means that about 50% of the water of Atlantic origin that enters the North Sea is mixed with fresher water before it leaves through the Norwegian Trench. This is a higher estimate than earlier reported, *Rodhe* [1998] estimated that about one third of the

Atlantic water is mixed with fresher water, and illustrates the importance of estuarine processes in the North Sea.

Winther and Evensen [2006] showed that the main problem with this model configuration is too smooth stratification between the NCC and the Atlantic water. This issue will influence the estimate above, but it is difficult to say how uncertain this estimate is. One could argue that too much Atlantic water is mixed with fresher water on its way southwards, but a counter-argument is that the model gives a good estimate of Atlantic inflow to Skagerrak.

The correlation between Skagerrak in- and outflow is $r = 0.98$ on a daily timescale, so increased inflow to Skagerrak results in a direct response in the outflow from Skagerrak. The correlation between Skagerrak outflow and NCC outflow is not that strong, and the strongest correlation is found with a timelag of 5 days.

Due to freshwater supply to Baltic, there is a net inflow of Baltic water to Skagerrak of 0.015 Sv; a result already reported by *Knudsen* [1899]. The model has a mean net transport of Baltic water of 0.014 Sv, which is not to bad considering that we use monthly climatology values to represent the Baltic inflow.

The mean transports through the English channel (Straits of Dover) is 0.16 Sv, which is only 7% of the total Atlantic inflow to the North Sea. But because of the large variability (up to 1 Sv), this inflow cannot be entirely ignored.

3.3. Atmospheric forcing

The North Atlantic Oscillation [NAO; *Hurrell*, 1995] index is the sea level pressure difference between Lisbon and Iceland, and is a measure of the strength of westerly winds. Other studies have shown that the Atlantic inflow to the Nordic seas (Greenland, Iceland, Norwegian and Barents Seas) is strongly influenced by the NAO index [*Blindheim et al.*, 2000; *Mork and Blindheim*, 2000; *Orvik et al.*, 2001], both on interannual and annual timescales. In this section we want to examine if there is a connection between North Sea fluxes and the NAO index. Our focus is variability within one year, and we therefore use the daily NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA [*Hurrell*, 1995]. These data were run through weekly and monthly low-passed filters, in the same manner as the model transports.

Results show that the maximum Atlantic inflow at the northern boundary in February 1998 coincides with a local maximum in the NAO index, while the minimum Atlantic inflow in June 1998 coincides with a local minimum in the NAO index. These results indicate that the annual cycle of Atlantic inflow to the North Sea is strongly influenced by westerly winds.

A correlation analysis was performed for weekly filtered timeseries, to examine the relation between transports and the NAO index on shorter time scales. Weekly filtered timeseries of Atlantic inflow at the northern boundary and the NAO index reveal a strong connection between these two in winter and spring of 1998, but a rather poor connection in fall 1997 (Figure 5).

These results are further emphasized by the correlation analysis in Table 3. The correlation coefficient for the entire time series is not very strong, $r = 0.30$, although it is above the 99% significance level. The strongest correlation is found from December 1997 to July 1998, when the correlation coefficient increases to $r = 0.61$. This indicates that in the winter and spring season the westerlies strongly influences the inflow of Atlantic water to the North Sea from week to week, at least for the period studied here.

The Atlantic inflow is closely related to the NCC outflow (Section 3.2), hence the strength in westerly winds also affects the NCC outflow.

Having in mind other studies already cited on the NAO index and Atlantic flow it might not be surprising that there is a connection between NAO index and the inflow to the North Sea. But as a first result it is surprising to see such a strong connection on a weekly time scale.

A interesting result is that the inflow through the three different inflow sites show different response to the strength of westerlies on different time scale. For the weekly time series the inflow between Orkneys and Shetland and at the Shetland shelf have correlations of $r = 0.62$ and $r = 0.55$, respectively, with the NAO index, while the inflow in the Norwegian Trench only shows a very weak correlation to the weekly NAO index, $r = 0.22$ (Table 3). If we repeat the same analysis with monthly filtered time series, the Norwegian Trench inflow shows a stronger connection to the NAO index. Also the same correlation analysis was repeated for the Atlantic inflow in the boundary conditions of the inner model, which includes the Faroe-Shetland ridge, and we found no significant correlation on a weekly scale.

To summarize, the relatively shallow Atlantic inflow sites show a strong connection to weekly changes in the strength of westerly winds, while the Norwegian Trench inflow has a longer response time to the large scale wind pattern. This connection on a weekly time scale is not seen in the deeper Atlantic inflow sites, i.e. the Faroe-Shetland ridge and the Norwegian Trench. Possible forcing mechanisms to explain this difference will be given in the next chapter.

There is some indication that other processes than the strength of westerly winds influences the Norwegian Trench inflow. The wind pattern used to force the numerical model were plotted for last week in February 1998 and the second week in April 1998, together with surface currents from the same two weeks (Figure 6).

In February 1998 the NAO index is high, the wind field reveals strong westerlies and the inflow to the North Sea is high at all three inflow sites at the northern boundary. In April 1998 the NAO index is low, the wind is mainly from north - northeast and the Atlantic inflow is weak except in the Norwegian Trench where we see a maximum in the transport (see Figure 4, lower panel). Also notice how the surface circulation changes with different wind regimes. A dynamical explanation for this change will be given in the next chapter.

Furnes [1980] based his analysis on observations and theoretical considerations and showed that winds between west and north favor inflow on the North Sea plateau and outflow in the Norwegian Trench. This is a combined effect of wind-induced currents and the depth variations between the Norwegian Trench and the North Sea plateau. The results of *Furnes* [1980] are in agreement with the results of this study. Strong westerly winds, i.e. high NAO, gives high inflow between Orkneys and Shetland and in the Shetland shelf area. We also see strong inflow in the Norwegian Trench, which is connected to high NCC outflow.

These results disagree to some extent to the work of *Dooley and Furnes* [1981]. They first pointed out that North Sea outflow occurs in the Norwegian Trench, and that the contributions to the inflow were made up of components from both the west and east side of the northern North Sea. They also concluded that winds from the west enhanced the circulation, whereas wind from the east weaken the circulation. These points are in agreement with the results in this study. But *Dooley and Furnes* [1981] also pointed out that the situation changed during very high transport periods. They claim that at these times most of the inflow occurs in the east and this inflow approximately balances the outflow. This contradicts the results in this study, were we found that at the highest in- and outflow periods, which coincides with high NAO index, the transport is high at all inflow locations.

3.4. Possible forcing mechanisms

Building on the results in the previous sections, we will now consider possible forcing mechanisms in explanation for the different correlations between atmospheric fields and model transport estimates. The previous chapters have shown that the averaged wind field and inflow patterns are quite different in February and in April (see Figure 6). The question is therefore how these distinctly different wind regimes impact on the dynamics of the inflow circulation. The analysis that follows is based on the simple relationship between the wind field and Ekman transport, see e.g. *Gill* [1982]. A wind field acting on the ocean surface will produce a volume transport in the upper waters given by

$$\mathbf{U}_E = -\frac{1}{\rho_0 f}\mathbf{k} \times \boldsymbol{\tau}. \tag{1}$$

$\mathbf{U}_E$ is the Ekman volume transport per unit length (m^2/s), ρ_0 is the mean density, f is the Coriolis parameter, $\mathbf{k}$ is the vertical unit vector and $\boldsymbol{\tau}$ is the wind stress. The horizontal variability of a wind field acting on the sea surface leads to horizontal variability of the Ekman transports, which again leads to a vertical velocity in the upper boundary layer of the ocean, a process called Ekman pumping. The strength of this vertical motion is given by

$$w_E = \frac{1}{\rho_0 f}\mathbf{k} \cdot \nabla \times \boldsymbol{\tau}. \tag{2}$$

Both the Ekman transports and pumping were calculated based on the ECMWF forcing fields for the last week in February and the second week in April 1998 (see Figure 7).

The response of the westerly wind field in February with a weekly mean of about 10 m/s is Ekman transport towards south accompanied by negative Ekman pumping (downwelling) in most of the North Sea (see Figure 7, a and c). Hence, the direct response of this atmospheric forcing is southward directed Ekman transport at all three inflow sites to the North Sea.

The correlation analysis in the previous section emphasized that the shallow and deep inflow sites had different response to the large scale wind pattern, i.e. the NAO index, on different time scales. This is mainly a manifestation of the relative importance of the difference in depth at the three inflow sites, combined with the strength of the vertical stratification. At the entrance of the North Sea the mixed layer depth varies from about 30 m in summer to about 120 m in winter [*Nilsen and Falck*, 2006]. Consequently the Ekman transport will become more effective in the weakly stratified shallow water regions (about 100 m depth) between Shetland and Orkneys and the Shetland shelf. For the deeper Norwegian Trench (about 300 m depth), where the water is more stratified, a longer (monthly) persistent westerly wind field is needed to allow for a similar response.

In April the mean weekly wind field is mainly from northeast, with a magnitude ranging from 6-10 m/s over the North Sea. This results in a westward, offshore Ekman transport accompanied by upwelling along the west coast of Norway (Figure 7, b and d). The upwelling along the Norwegian Coast will draw water from the deeper parts of the Norwegian

Trench towards shallower depths near the coast, leaving more space for the Atlantic water in the trench. The result is increased inflow in the Norwegian Trench for the April regime (see Figure 4). In contrast, the inflow through the shallow water sites around and between Shetland and Orkneys vanish and becomes replaced by an Ekman transport towards west, and out of the northern North Sea. This can, in turn, also magnify the inflow of Atlantic water in the deeper Norwegian Trench through water mass conservation. In summary, weekly persistent north-easterly wind field creates a dynamical response and inflow circulation in the Norwegian Trench and over the shallow inflow sites, that are distinctly different from the dynamical regime encountered under persistently westerly winds.

4. Conclusions

In this study we have used the numerical ocean model HYCOM to simulate the circulation in the North Sea and Skagerrak. Our objective was to study the Atlantic inflow to the North Sea, its variability and destination.

Results show that both the in- and outflows of the North Sea show great variability from day to day, but the mean annual transport estimates compares well with transport estimates based on measurements.

The inflow at the northern boundary can enter at three different locations; between Orkneys and Shetland, Shetland shelf area and the Norwegian Trench. The two first locations both have a mean inflow of about 0.5 Sv, and combined they are on the same order as the the Norwegian Trench inflow, 1.23 Sv.

The relatively shallow Atlantic inflow sites around Shetland and between Shetland and Orkneys have the same variability throughout the year and show a strong connection to weekly changes in the strength of westerly winds, while the Norwegian Trench inflow has a longer response time to the large scale wind pattern.

In the introduction we stated that it is unclear if it is the wind stress over the North Sea as a whole or local wind forcing that mainly determines the circulation. From the results in this study we would argue that the answer is that both the large scale wind field as well as coastal wind effects over the Norwegian Trench have important impacts on the North Sea dynamics.

The results in this study show distinct differences in inflow circulation pattern between the three inflow sites, although they are all important for the overall circulation in the North Sea. The Atlantic inflow in the shallow water region between Orkneys and Shetland and in the Shetland shelf area is strongly modified by the wind driven Ekman transport, and on a weekly time scale this transport is in phase with the large scale wind field pattern. The southward inflow in the deeper water of the Norwegian Trench, on the other hand, shows that other processes, like wind driven upwelling along the west coast of Norway, can also modify the inflow. The connection to the large scale wind field also seems to favour longer monthly time scales. Moreover, interaction of the inflowing Atlantic water with the northward flowing NCC, through mixing, frontal instabilities and eddy formation, is also expected to modify the Atlantic water inflow in the Norwegian Trench.

We found that about 50% of the Atlantic water that enters the North Sea is mixed with fresher water, before it leaves the area as the NCC. This mixing occurs mainly in the inner part of Skagerrak, where the Atlantic water meets brackish water from the Baltic. The Atlantic water is also mixed with fresh water from rivers. This illustrates the important role of estuarine processes within the North Sea and Skagerrak area, and their interaction with and gradual modification of the Atlantic water.

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References

Aure, J., and R. Sætre, Wind effects on the Skagerrak outflow, in *The Norwegian Coastal Current*, edited by R. Sætre and M. Mork, pp. 263–293, proceedings from the Norwegian Coastal Current Symposium, Geilo, 9-12 September, 1980, University of Bergen, Bergen, Norway, 1981.

Berntsen, J., and E. Svendsen, Using the SKAGEX dataset for evaluation of ocean model skill, *J. Marine. Sys.*, *18*, 313–331, 1999.

Bleck, R., An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates, *Ocean. Mod.*, *4*, 55–88, 2002.

Bleck, R., and L. T. Smith, A wind-driven isopycnic coordinate model of the North and Equatorial Atlantic Ocean. 1. Model development and supporting experiments, *J. Geophys. Res.*, *95*, 3273–3285, 1990.

Blindheim, J., V. Borovkov, B. Hansen, S. A. Malmberg, W. R. Turrell, and S. Østerhus, Upper layer cooling and freshening in the Norwegian Seas in relation to atmospheric forcing, *Deep-Sea Res.*, *47*, 655–680, 2000.

Browning, G. L., and H.-O. Kreiss, Initialization of the shallow water equations with open boundaries by the bounded derivative method, *Tellus*, *34*, 334–351, 1982.

Browning, G. L., and H.-O. Kreiss, Scaling and computation of smooth atmospheric motions, *Tellus, Ser. A*, *38*, 295–313, 1986.

Danielssen, D. S., L. Edler, S. Fonselius, L. Hernroth, M. Ostrowski, E. Svendsen, and L. Talpsepp, Oceanographic variability in the Skagerrak and Northern Kattegat, May-June, 1990, *J. Marine Science*, *54*, 753–773, 1997.

Davies, H. C., Limitations of some common lateral boundary schemes used in regional NWP models, *Mon. Weather Rev.*, *111*, 1002–1012, 1983.

Dooley, H. D., Hypotheses concerning the circulation of the northern North Sea, *J. Conseil*, *36*, 54–61, 1974.

Dooley, H. D., and G. K. Furnes, Influence of the wind field on the transport of the northern North Sea, in *The Norwegian Coastal Current*, edited by R. Sætre and M. Mork, pp. 57–71, proceedings from the Norwegian Coastal Current Symposium, Geilo, 9-12 September, 1980, University of Bergen, Bergen, Norway, 1981.

Furnes, G. K., Wind effects in the North Sea, *J. Phys. Oceanogr.*, *10*, 978–984, 1980.

Furnes, G. K., B. Hackett, and R. Sætre, Retroflection of Atlantic water in the Norwegian Trench, *Deep-Sea Res.*, *33*, 247–265, 1986.

Gill, A. E., *Atmosphere-Ocean Dynamics*, 662 pp., Academic Press, London, 1982.

Gustafsson, B., High frequency variability of the surface layers in in the Skagerrak during SKAGEX, *Cont. Shelf Res.*, *19*, 1021–1047, 1999.

Gustafsson, B., and A. Stigebrandt, Dynamics of the freshwater-influenced surface layers in Skagerrak, *J. Sea Res.*, *35*, 39–53, 1996.

Hackett, B., The Feie-Shetland section: A Hydrographic Atlas, *Norwegian Coastal Current Project, Report No. 3/81*, University of Bergen, Bergen, Norway, 1981.

Haugan, P. M., G. Evensen, J. A. Johannessen, O. M. Johannessen, and L. Pettersson, Modelled and observed mesoscale circulation and wave-current refraction during the 1988 Norwegian continental shelf experiment, *J. Geophys. Res.*, *96*(C6), 10,487–10,506, 1991.

Hurrell, J., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.

Ikeda, M., J. A. Johannessen, K. Lygre, and S. Sandven, A process study of mesoscale meanders and eddies in the Norwegian coastal current, *J. Phys. Oceanogr.*, *19*, 20–35, 1989.

Johannessen, J. A., E. Svendsen, S. Sandven, O. M. Johannessen, and K. Lygre, Three-dimensional structure of mesoscale eddies in the Norwegian Coastal Current, *J. Phys. Oceanogr.*, *19*, 3–19, 1989.

Knudsen, M., De hydrografiske forhold i de danske farvan de indenfor skagen i 1894-1898, *Beretning fra Kommisionen for videnskabelig undersøgelse av de danske Farvande, Copenhagen*, *2*, 19–79, 1899.

Legates, D., and C. Willmott, Mean seasonal and spatial variability in gauge-corrected global precipitation, *Int J. Climatol*, *10*, 110–127, 1990.

Mork, K. A., and J. Blindheim, Variation in the Atlantic inflow to the Nordic Seas, 1955-1996, *Deep-Sea Res.*, *47*(6), 1035–1057, doi:10.1016/S0967-0637(99)00091-6, 2000.

Nilsen, J., and E. Falck, Variations of mixed layer depth and water properties in the Norwegian Sea for the period 1949-1999, *Progress in Oceanography*, doi:

10.1016/j.pocean.2006.03.014, 2006.

Oey, L.-Y., and P. Chen, A nested grid model: With application to the simulation of meanders and eddies in the Norwegian Coastal Current, *J. Geophys. Res.*, *97*(12), 20,063–20,086, 1992.

Orvik, K. A., and P. Niiler, Major pathways of Atlantic water in the northern North Atlantic and Nordic Seas toward Arctic, *Geophysical Research Letters*, *29*(19), 1896, doi:10.1029/2002GL015002, 2002.

Orvik, K. A., Ø. Skagseth, and M. Mork, Atlantic inflow to the Nordic Seas: current structure and volume fluxes from moored current meters, VM-ADCP and SeaSoar-CTD observations, 1995-1999, *Deep-Sea Res.*, *48*, 937–957, 2001.

Otto, L., J. T. F. Zimmerman, G. K. Furnes, M. Mork, R. Sætre, and G. Becker, Review of the physical oceanography of the North Sea, *Netherlands J. Sea Res.*, *26*, 161–238, 1990.

Riepma, H. W., Residual current in the North Sea during the IN/OUT phase of JONSDAP'76, *Int. Coun. Explor. Sea*, rep. CM 1978/C:42, 1978.

Rodhe, J., The large-scale circulation in the Skagerrak, interpretation of some observations, *Tellus*, *39A*, 245–253, 1987.

Rodhe, J., On the dynamics of the large-scale circulation of the Skagerrak, *J. Sea Research*, *35*(1-3), 9–21, 1996.

Rodhe, J., The Baltic and North Seas: A process-oriented review of the physical oceanography, in *The Sea*, vol. 11, edited by A. R. Robinson and K. H. Brink, pp. 699–732, John Wiley & Sons, Inc., 1998.

Røed, L. P., and I. Fossum, Mean and eddy motion in the Skagerrak/northern North Sea: insight from a numerical model, *Ocean Dynamics*, *54*(2), 197–220, doi:10.1007/s10236-003-0076-1, 2004.

Rydberg, L., J. Haamer, and O. Liungman, Fluxes of water and nutrients within and into the Skagerrak, *J. Sea Research*, *35*, 23–38, 1996.

Sætre, R., and M. Mork (Eds.), *The Norwegian Coastal Current*, University of Bergen, Proceedings from the Norwegian Coastal Current Symposium, Geilo, Norway, 9-12 September 1980, 1981.

Sætre, R., J. Aure, and R. Ljøen, Wind effects on the lateral extension of the Norwegian Coastal Water, *Cont. Shelf Res.*, *8*(3), 239–253, 1988.

Skogen, M. D., E. Svendsen, and M. Ostrowski, Quantifying volume transports during SKAGEX with the Norwegian Ecological Model system, *Cont. Shelf Res.*, *17*(15), 1817–1837, 1998.

Slutz, R., S. L. J. Hiscox, S. Woodruff, R. Jenne, D. Joseph, P. Steurer, and J. Elms, Comprehensive ocean-atmosphere dataset; release 1, *Tech. Rep. NTIS PB86-105723*, NOAA Environmental Research Laboratories, Climate Research Program, Boulder, CO, 1985.

Svansson, A., Physical and chemical oceanography of the Skagerrak and the Kattegat, *Report 1*, Fishery Board of Sweden, Marine Research Institute, pp. 1-88, 1975.

Svendsen, E., R. Sætre, and M. Mork, Features of the northern North Sea circulation, *Cont. Shelf Res.*, *11*(5), 493–506, 1991.

Svendsen, E., J. Berntsen, M. Skogen, B. Ådlandsvik, and E. Martinsen, Model simulation of the Skagerrak circulation and hydrography during SKAGEX, *J. Marine. Sys.*, *8*, 219–

236, 1996.

Winther, N. G., and G. Evensen, A hybrid coordinate ocean model for shelf simulation, *Ocean Modelling*, *13*(3-4), 221–237, doi:10.1016/j.ocemod.2006.01.004, 2006.

Winther, N. G., Y. Morel, and G. Evensen, Efficiency of high order numerical schemes for momentum advection, submitted to J. Marine Sys., 2006.

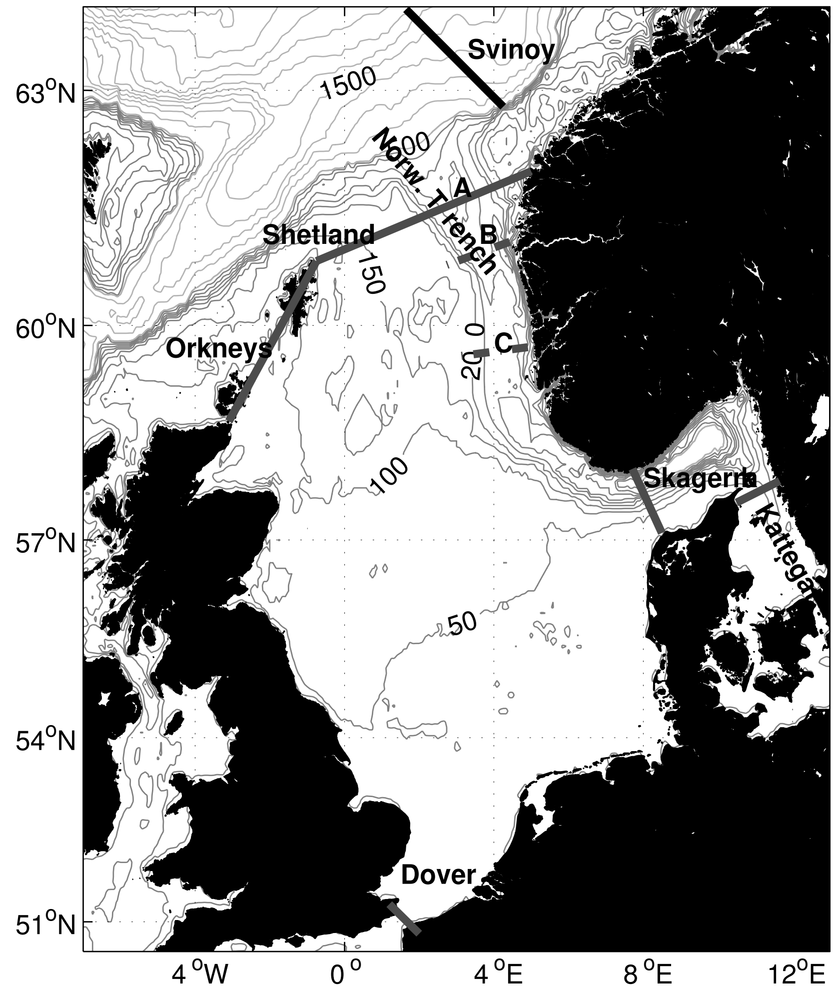

Figure 1. Black lines illustrate the sections where transports are calculated. Isobaths are drawn for every 50 m down to 500 m, then for every 250 m.

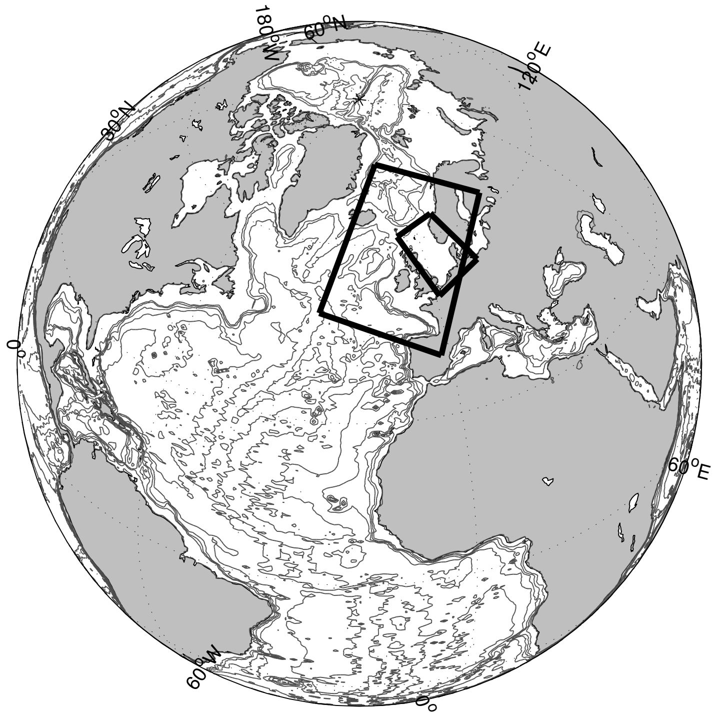

Figure 2. A two-level nested model system, where the large scale model covers the Atlantic and Arctic ocean.

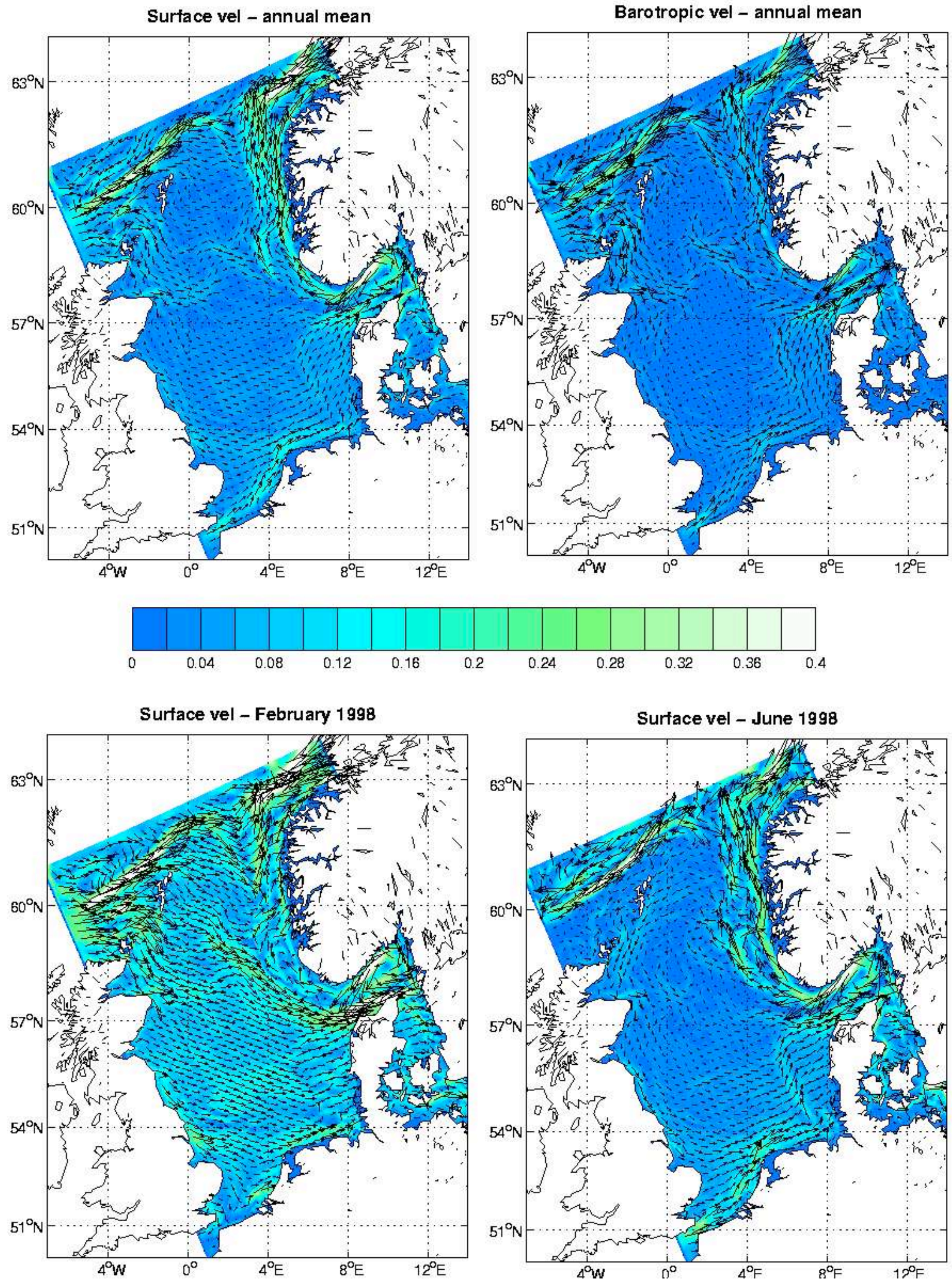

Figure 3. Annual mean surface velocity (upper left) and barotropic velocity (upper right). Monthly mean surface velocity for February 1998 (lower left) and June 1998 (lower right). Velocity arrows are plotted for every 6th grid point, velocity speed in colors.

Table 1. Transport estimates from HYCOM and available measurements.

	Model (mean)	Model (min/max)	Data
Orkneys-Shetland inflow	0.49	0.01/2.36	0.30
Shetland shelf inflow	0.50	0.02/2.04	0.60
Norwegian channel inflow	1.23	0.18/2.91	0.70-1.11
English channel inflow	0.16	0/1.03	0.10-0.17
Skagerrak inflow	1.02	0.44/2.54	0.50-1.50
Skagerrak outflow	1.04	0.42/2.50	0.50-1.50
Norwegian channel outflow (total)	2.33	0.67/5.73	1.80
Norwegian channel outflow (<35 psu)	1.46	0.57/4.85	
Kattegat net inflow	0.014		0.015

[a] Available measurements are summarized from the following studies: *Otto et al.* [1990]; *Rodhe* [1996]; *Rydberg et al.* [1996]; *Danielssen et al.* [1997].

[b] Minimum and maximum values are extracted from daily average transport values. Inflow is here meant as flow into the North Sea. All values are given in Sv (1 Sv = $10^6 m^3/s$).

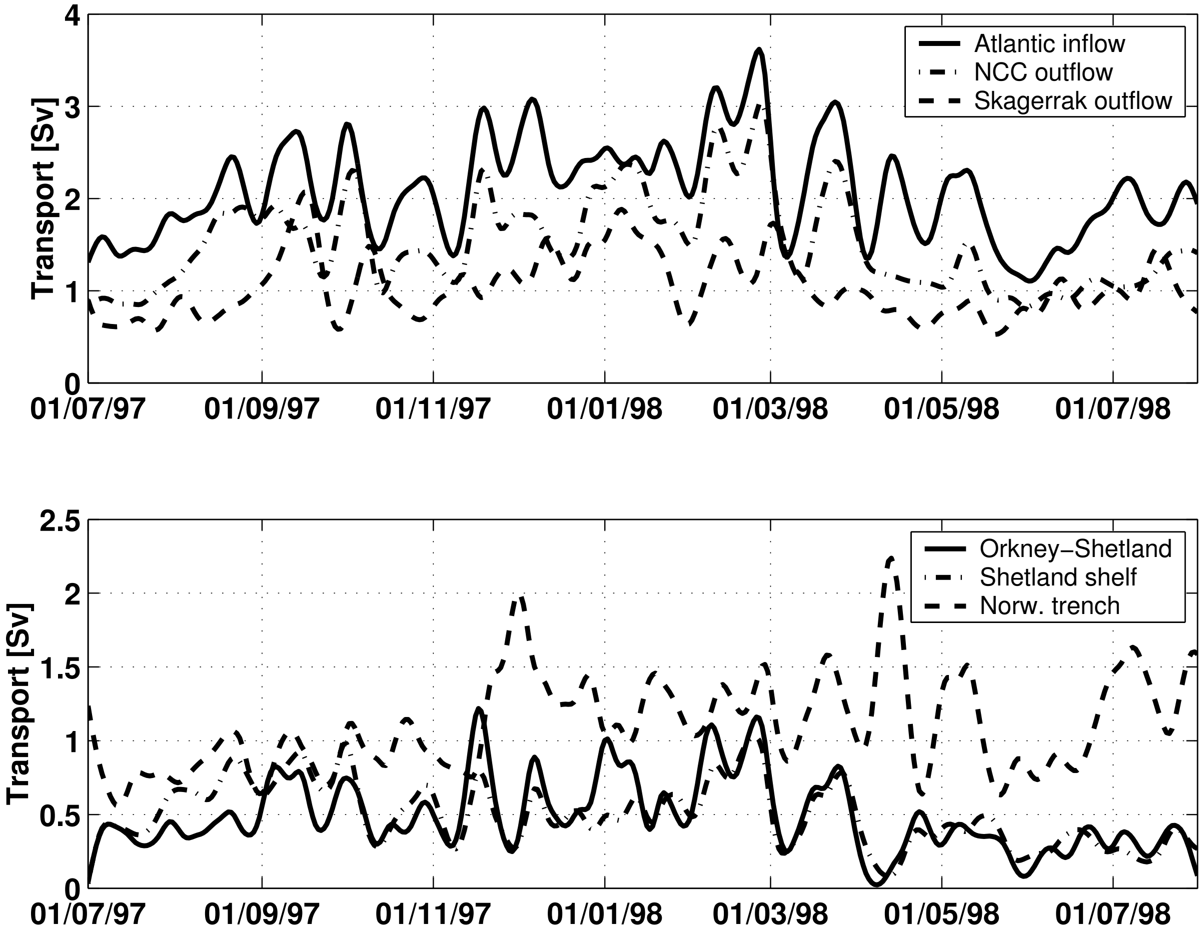

Figure 4. Upper panel: Weekly filtered timeseries of Atlantic inflow at northern boundary (full line), NCC outflow (dash-dot line) and Skagerrak outflow (dashed line). Lower panel: Atlantic inflow at the three different gateways; Orkneys-Shetland (full line), Shetland shelf (dash-dot line) and Norwegian Trench (dashed line).

Table 2. Correlation coefficients between different transports.

	Daily/Weekly	Lag (days)
Inflow and outflow northern boundary	0.78/0.90	
Atlantic inflow and NCC outflow	0.74/0.86	
Norwegian Trench out- and inflow	0.45/0.48	1
Orkneys-Shetland and Shetland shelf inflow	0.73/0.75	
Orkneys-Shetland and Norwegian Trench inflow	-0.25/—	
Norwegian Trench outflow and Skagerrak outflow	0.50/0.68	5
Skagerrak in- and outflow	0.98/1.00	

All values are above the 99% significance level.

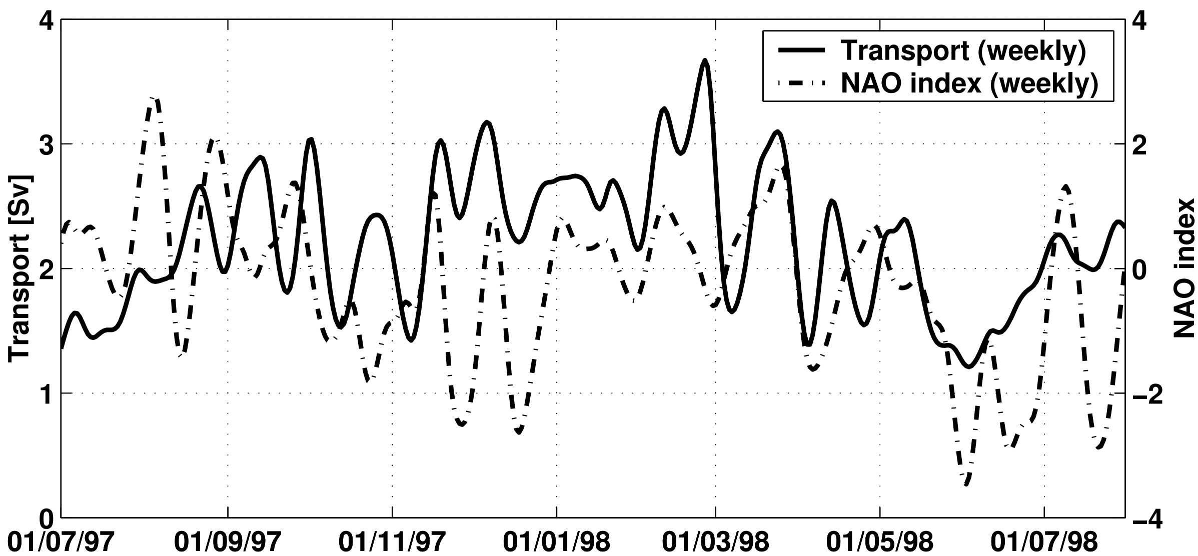

Figure 5. Weekly filtered timeseries of Atlantic inflow at northern boundary and NAO index.

Table 3. Correlation coefficients between weekly transports and NAO index.

	NAO index	
	All year	Dec-Jun
Total northern inflow	0.30	0.61
Orkneys - Shetland inflow	0.40	0.62
Shetland shelf inflow	0.47	0.55
Norwegian Trench inflow	–	0.22

All values given are above the 99% significance level.

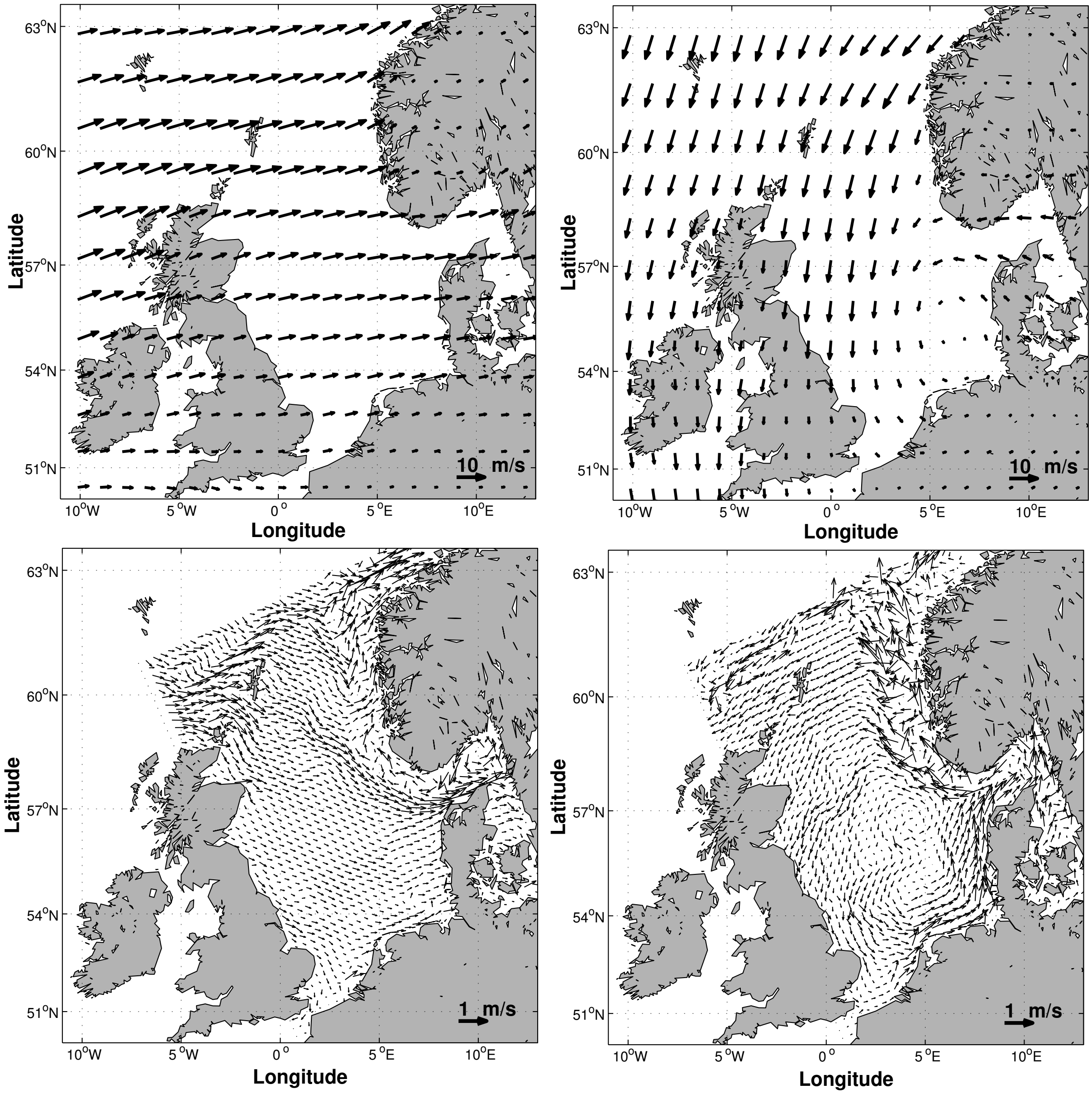

Figure 6. Top: Wind from ECMWF fields, weekly average of last week in February 1998 (left) and second week in April 1998 (right). Bottom: Surface velocity from HYCOM for the same two weeks. Velocity arrows are plotted for every 6th grid point.

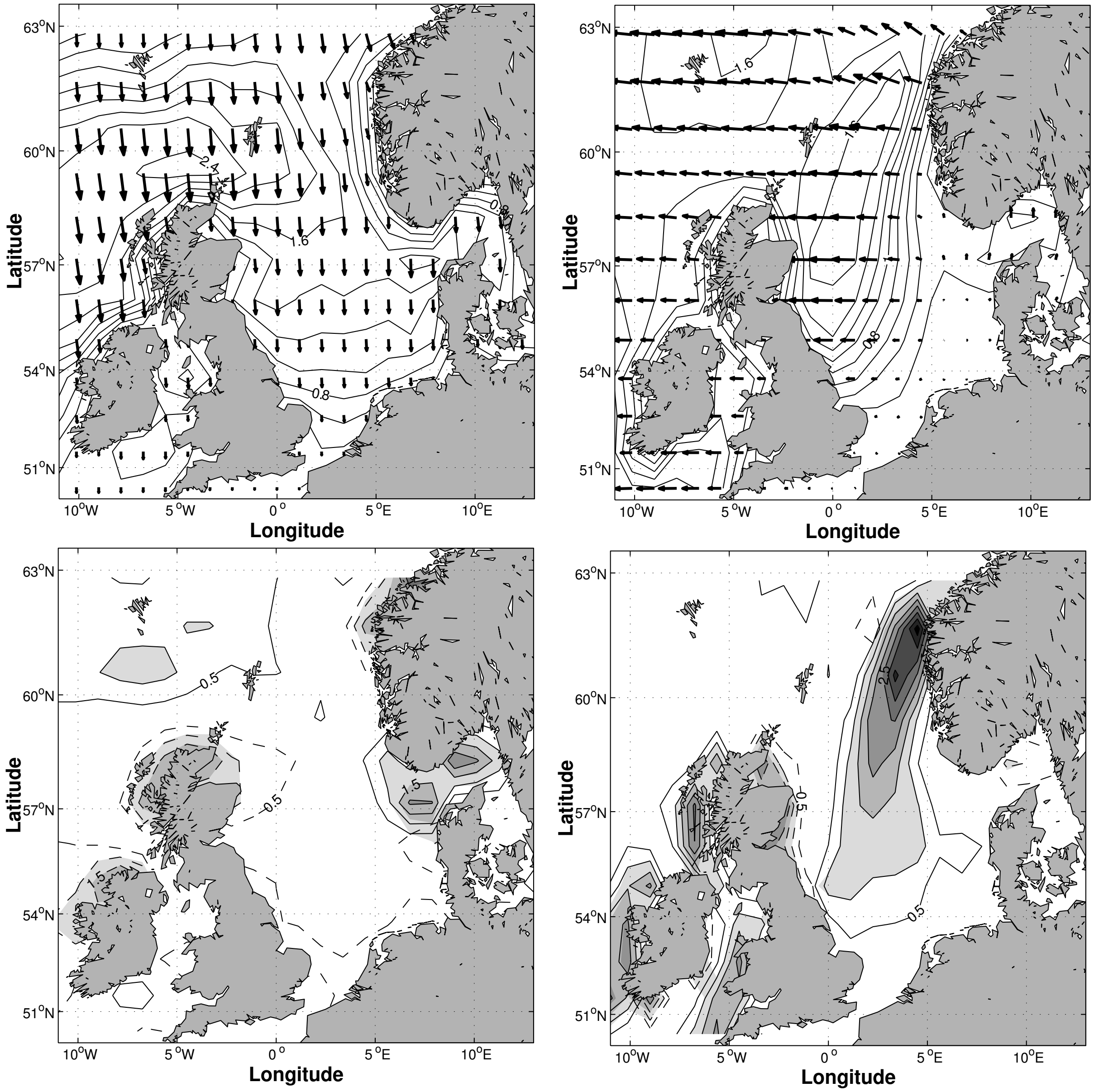

Figure 7. Top: Ekman volume transports per unit length (m^2/s). Weekly average of last week in February 1998 (left) and second week in April 1998 (right). Contour intervals are drawn for every $0.2\,m^2/s$. Bottom: Ekman pumping velocities (m/day) for the same two weeks. Solid lines indicate positive (upwelling) values, dashed lines negative (downwelling) values. Contour intervals drawn for every 0.5 m/day.