Decadal variations in the stratification and circulation patterns of the North Sea. Are the 1990s unusual?

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The variability of transport processes and stratification in the North Sea is investigated using the results of a 40-year simulation with the 3-D hydrodynamic model HAMSOM (HAMburg Shelf Ocean Model). The results show that there is considerable variability of physical processes potentially impacting on ecosystem dynamics. Stratification and transport processes are characterized by year-to-year variability. However, resolution of decadal variability is possible. Long periods with similar stratification as well as transport conditions have been resolved and the 1990s have been identified as having been an outstanding period with respect to two key biologically relevant physical parameters both potentially impacting on the ecosystem dynamics: the exchange flow into the North Sea and Skagerrak in February/March and the timing of the onset of stratification in spring. There is pronounced interannual variability and a comparison of variability in different seasons indicates that the between-season correlations are small for water transports as well as for stratification conditions.

Keywords: circulation, decadal variability, North Sea, stratification.

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Introduction

The influence of environmental conditions on the marine ecosystem has been the subject of discussion over the past 5–10 years. International research programmes such as GLOBEC have been established to investigate the linkage between environmental conditions and ecosystem dynamics. Furthermore, national and international projects (LIFECO, GLOBEC related projects) and international workshops (e.g. ICES Backward-Facing Workshops) have been initiated in order to improve the understanding of environmental variability and its impact on higher trophic levels in the marine ecosystem. The first natural step towards a comprehensive understanding of ecosystem variability is the investigation of the effects of climate variability on the physical environment, i.e. on the physical features that control the ecosystem dynamics.

Recently, many attempts have been made to investigate the climatically induced long-term variability in the North Sea. A couple of investigations have been based on the analysis of observational data focused, in particular, on quasi-synoptic surface data (e.g. Becker and Pauly, 1996; Dippner, 1997) and on long-term hydrographic time-series (e.g. within the NOWESP project; Sündermann et al., 1996). Although valuable understanding was achieved, e.g. on the connection between winter North Atlantic Oscillation (NAO) and sea surface temperature (SST) in the North Sea, observational data are sketchy in time and space and thus investigation of variability based on field data is strongly limited. In particular, field-based studies on the variability of subsurface conditions such as water column stability and intensity and duration of thermal stratification, key to resolving the timing of the spring bloom as well as transport of nutrients into the euphotic zone, are rare. Furthermore, studies examining intra-annual and interannual variations in transport, impacting on the invasion of *Calanus finmarchicus* into the North Sea as well as on the
transport of fish eggs and larvae from spawning to nursery areas, are limited. Both of these transport processes have been proposed to impact on North Sea fish stocks (e.g. Heath and Gallego, 1998; Heath et al., 1999; ICES, 2001).

Realistic hindcast simulations provided by complex numerical models are valuable tools to fill this gap and to provide more information on the variability in the physical marine environment. Deterministic numerical models can be used to interpolate dynamically in space and time, depending on the prescribed boundary forcing and initial conditions. This has been done in the past in the North Sea by several authors (e.g. Kauker, 1999; Langenberg et al., 1999; Pohlmann, 1996; Smith et al., 1996). These models have been integrated for different periods, and describe the hydrodynamic state of the North Sea on different levels of spatial and temporal resolution.

A similar model, the HAMburg Shelf Ocean Model (HAMSOM), has been utilized to examine the dynamics of the coupled system of North Sea and Baltic Sea (Schrum, 1997a) to provide a more realistic description of the exchange flow between both seas. In particular, it has been used to study two different periods, namely 1979–1993 and 1958–1997. In the following, results of the latter longer run will be used to investigate the decadal and interannual variability of stratification and circulation in the North Sea in order to relate the 1990s to trends over previous decades. As the variability of stratification and circulation in the North Sea is closely connected with the atmospheric variability, in particular the windfield variability, the discussion of oceanic conditions (model results) will not be separated from the discussion of forcing wind conditions.

Model configuration

The model is based on the HAMSOM, which has been described in detail by Schrum and Backhaus (1999). The model region, the North Sea from 49° to 59°N and the Baltic Sea, is resolved with a horizontal resolution of 10 km ($\Delta\varphi = 6'$ and $\Delta\lambda = 10'$) and by a maximum of 20 vertical levels. The vertical resolution is 5 m from surface to 40 m, 8 m from 40 to 88 m with subsequent depth layers at 100, 125, 150, 200, 400, and 630 m.

To investigate the impact of climatic induced variability, the model employs forcing from consistent atmospheric gridded data sets. Typically these atmospheric data sets are provided by weather services, using an analysis model to interpolate the sketchy meteorological observations in time and space. Since the analysis and forecast models have been changed many times from the beginning of the operational analysis, the resulting long-term data sets are highly heterogeneous and thus not suitable for describing climate variability of the atmosphere. This was the motivation to set up independent re-analysis projects by the European Center of Medium-Range Weather Forecast (ECMWF) and by the NCEP/NCAR to provide consistent global 3-D atmospheric data sets. The re-analysis has been carried out with a ‘frozen’ version of the data assimilation system for the respective hindcast periods ECWMF: 1979–1993 (ERA-15); NCEP: 1958–1997 (NCEP-40)). The main features of the assimilation schemes can be characterized as follows: The horizontal resolution corresponds to the spectral wave number T106 (ECMWF, about 1.1°) and T62 (NCEP, about 2°); the time stepping of the models output corresponds to 6 h, i.e. 4 times daily. More details about the re-analysis project of the ECMWF have been given by Gibson et al. (1996), while for the NCEP/NCAR re-analysis project a detailed description is presented in Kalnay et al. (1996).

The HAMSOM has been integrated for both re-analysis periods. The initial conditions for the respective runs are provided by the climatology for temperature and salinity as presented by Janssen et al. (1999), with additional corrections in the initial state for 1958 and 1979 (based on the ICES database that was also used for the climatology). At the open boundaries, sea surface elevation was taken from a coarser shelf sea model (for details, see Schrum et al., 2000). Boundary conditions for temperature and salinity were prescribed based on climatological temperature and salinity data from Janssen et al. (1999), with an additional annual correction calculated from the ICES database. More information regarding the incorporation of freshwater run-off boundary forcing and validation of the model sensitivity is given by Schrum et al. (2000). Detailed analysis of the skill of the model using ECMWF atmospheric forcing data are presented by Schrum et al. (2000) and Janssen et al. (2001). In these studies it was shown by comparisons to tide gauges, in situ and satellite data that sea surface elevation, sea surface temperature, salinity and sea ice were described with considerable accuracy. Correlations of observed and modelled sea surface elevation, which is a measure for the quality of modelled volume transports, are in the order of 0.9 for different tide gauges in the Baltic and along the continental coast of the North Sea. Correlations along the British coast are slightly lower (about 0.8). It should be recognized that a detailed validation has not yet been carried out using the NCEP-40 generated estimates. However, the overlapping period of both runs will be used to compare the estimates of both model realizations and thereby compare the behaviour of the latter model configuration with respect to the description of variability.
Figure 1. Calculated monthly mean stratification pattern for the period 1958–1997. The contour lines give the maximum temperature difference across the modelled thermocline. Contour levels are 0.25°C. The shading indicates the depth level (m) of the maximum gradient.
Stratification

Methods and general remarks

The monthly mean stratification pattern calculated by the model in response to the NCEP-40 forcing is presented in Figure 1 in terms of temperature difference across the thermocline. Here, the thermocline is assumed to be located at the depth of the strongest temperature difference between the vertical levels. Furthermore, we assume that the critical level for defining stratified conditions is a temperature difference of at least 0.5°C between the levels. Information on the depth of the thermocline is provided by contouring. Additional information about the depth of the thermocline is given by the shaded area. However, it should be noted that these estimates are strongly limited by the coarse vertical resolution of the model, as the estimates are based on a 5-m integrated value in the surface layers.

It is possible that the stratified area identified by the pattern of temperature difference is larger than the shaded area estimated from mean thermocline depth. This could be explained as follows: the temperature difference is to be interpreted as a monthly mean difference, unstratified situations included as zero temperature difference. It is thus possible that, after averaging, the monthly mean temperature difference at a respective grid point is less than the critical temperature difference of about 0.5°C. Hence, the respective grid point appears as unstratified in the contouring of Figure 1. The mean thermocline depth is estimated slightly differently, i.e. only the stratified conditions are taken into account. It is therefore possible that an estimate of the thermocline depth is based on only a few (or possibly only one) stratified days. This implies that the mismatch between the two respective patterns is also a measure of variability in the respective averaging period.

Seasonal cycles and extreme situations

Comparison of the modelled stratification pattern to estimates based on climatological data analysis (Janssen et al., 1999) shows that seasonal extension and intensity of stratification are similar for model results and observations. The onset of stratification occurs in May with thermocline depths between 10 and 20 m. Strongest mismatches between the pattern of thermocline intensity and thermocline depth are found at the beginning and end of the stratified period, i.e. in May and October. The onset and breakdown of stratification are subject to strong interannual variability. Thus, the resulting climatological mean temperature difference in May and October is below 0.5°C for almost the whole area, indicating climatologically unstratified conditions. However, occasionally stratification has developed in May, as shown in the monthly mean pattern for May 1993 (Figure 2), and can persist in a diagonal band across the northern North Sea until October.

The maximum temperature gradient increases continuously during the summer, reaching its maximum values in August. Local maxima up to 5°C can be found in the eastern North Sea, off the Jutland coast. Significant deepening of the thermocline occurs from July onwards caused by increasing windspeed (not shown here) and decreasing heating from short wave radiation, resulting in increasing vertical mixing due to wind induced turbulence and thermal convection. This process is connected with a decrease in the stratified area.

Variability of stratified conditions can be also be detected from the monthly mean model data. In the summer months, variability occurs roughly in a band of 100 km extension (June, July), which expands until the breakdown of stratification, starting in the region of the shallower southeastern North Sea in August. The variability here is strongly...
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connected to windspeed and wind direction changes, with tidal and wind-induced turbulent mixing limiting stratification. Along the continental coast, offshore wind-induced transport of less saline surface water has a stabilizing effect on the water column and allows the development of thermal stratification even very near the coast, where tidal mixing is high. The near surface advection of less saline coastal waters offshore, connected to more easterly and northerly wind forcing, is responsible for a stabilization of the water column and counteracts the strong tidal and wind induced stirring. This was earlier investigated for the region of the German Bight by Schrum, 1997b and it was found that a necessary pre-condition for near-coastal stratification was the wind-induced haline stratification.

To answer the question whether the variability results in coherent patterns of monthly distribution, i.e. to estimate whether the variability occurs on interannual rather than on intra-monthly time scales, two extreme conditions are presented in Figure 3: The August 1997 situation shows high temperature differences between layers of up to 6.5°C and an extended near coastal stratification towards the Danish and German coasts. A contrasting situation was seen in August 1985, when stratification was at a minimum. The maximum temperature difference across the thermocline was 1.5°C less than maximum values reached in August 1997. In August 1985 the near coastal region is unstratified, with stratification found only west of 7°E. The pattern was coherent for the whole month, with the variability below the monthly time scale being small, as indicated by a good correspondence of the shaded region (estimated only for the stratified cases) and the contoured area (averaged over all cases).

In Figure 4, the respective wind density distributions are presented for the region of the eastern North Sea (2.5°E–10°E). The wind density is calculated from the 6-hourly values of the NCEP re-analysis by division of the wind rose into 36 classes, i.e. 10° steps were chosen. The angle of 0° corresponds to wind blowing from the East. Within the respective classes, the wind speeds \( v'_{ij} \) (i and j indicate the position of the respective event in time and space) were summed and normalized by the total number of events. The normalized wind density function for a respective class \( k \) is defined as:

\[
w_k = \frac{\sum_{(i,j)=k} v'_{ij}}{\text{number of classes}} \frac{\text{total number of events}}{}
\]

Figure 3. Calculated stratification for two extreme situations in August: extended stratification in August 1997 (right) and less extended stratification in August 1985 (left). Contour lines give the maximum temperature difference across the modelled thermocline; the shading indicates the depth level (m) of the maximum gradient. Contour levels are 0.25°C.
Figure 4. Normalized wind density distribution for August 1984 (stable stratification occurred), August 1985 and August 1997. The wind density function for class k is defined as

\[ w_k = \frac{\text{number of classes}}{\text{total number of events}} \]

According to the definition of the wind density function, high values indicate high frequency of winds blowing from a respective direction or result from high windspeeds. Increasing total area of the wind density function (over all classes) indicates an overall increase in windspeed. Further details about the calculation of the wind density function are given by Siegismund and Schrum (2001). Comparing the forcing wind field for the two years 1985 and 1997, and for 1984, which is also an example of an intensively stratified situation, the reason for the different stratification pattern is understandable: For the extreme stratified situations, the August wind distribution show only weak winds. Prevailing wind directions are east (1997) and northwest (1984), favouring stratification by offshore advection of fresher coastal waters. Contrasting wind forcing can be found for August 1985. Here, the prevailing wind direction was southwest, resulting in near-coastal northward advection of the coastal waters and no haline stratification. The larger area covered by the wind density pattern in August 1985 indicates higher windspeeds compared to 1984 and 1997, which results in increasing wind mixing and thus faster stratification breakdown.

Interannual and decadal variability

Investigation of interannual and decadal stratification variability was focused on the southeastern North Sea in a coastal band from 3°E to the continental coast for latitudes between 52.5°N and 56.5°N, an area found to be representative of the changes in the whole North Sea system and, furthermore, a key habitat for juvenile cod (e.g. St. John and Lund, 1996). Stratified grid points were identified by the critical temperature difference of 0.5°C, to be reached in monthly mean values. The onset of stratification differs strongly from year to year, as can be seen in Figure 5, where the stratified area in terms of stratified grid points (each corresponding to an approximate area of about 100 km²) are shown. A 5-year running mean shows that more stratified periods and periods with less stratification (caused by frequent unstratified years) can be distinguished on longer time scales. It is obvious from Figure 5 that a long period with less unstratified conditions in May exists from 1967 to 1985. Contrastingly, from the mid-1980s to the end of the investigation period, the North Sea tends to be stratified again earlier in the year, with only 2 exceptions in 1992 and 1997. Most of the years with highest extent of stratification can be found within this latter period, at the end of the 1980s and the 1990s from 1986–1991 and 1993–1996.

A similar outstanding period can be found by analysing the distribution of stratification in August. The modelled extent of stratification is significantly higher during August from 1963 to 1984. This is followed by a period with low stratification from 1985–1994 with increasing stratification for the last years of the investigation period.

The year-to-year variability late in the year is less compared to the decadal trends for this period. The higher frequency variability, which is dominant at the beginning of the stratified period, is damped during the summer. The respective curves for June and July are given in Figure 5. In principle, they confirm this with higher frequency variability (i.e. the year-to-year variability) stronger earlier in the year. The variability in July is similar to that in August, whereby stratification in June is only weakly correlated to pattern earlier and later in the year. This is the case for the year-to-year variability as well as for the filtered time-series. The only coherent signal in June, July, and August is found for the year 1962 when stratification shows a significant minimum after relatively strong stratification in May 1962.

Circulation

General circulation

The typical circulation pattern in the North Sea shows a prevailing cyclonic circulation with inflow
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Stratification May

Stratification August

Stratification June

Stratification July

Figure 5. Interannual variability of the stratified area in a band from 3°E-10°E and 52.5°N-56.5°N. The stratified area is given in units of grid points, each approximately corresponding to an area of 100 km², annual values (thin line, dashed) and 5-year moving average (thick line). May (upper left) and August (lower left), June (upper right), and July (lower right).

of salty Atlantic Water along the western and central part of the northern boundary (about 1 Sv in annual mean) and outflow of less saline water from the Norwegian Coastal Current (about 1.13 Sv), as presented earlier by a large number of authors (e.g., see the review article by Rodhe, 1998). From the Baltic Sea, typically a net outflow of freshwater occurs, which is potentially compensated on shorter time scales by a wind-induced inflow into the Baltic Sea. The annual mean net exchange between the North Sea and the Skagerrak shows a complicated flow regime with near-surface inflow in the northern Skagerrak and near-surface outflow in the southern part (inflow and outflows are named from the view to the North Sea). Vertically integrated, this picture changes into a net outflow in the northern Skagerrak and a net inflow in the southern part. This typical circulation pattern is reproduced by the model, with results in close correspondence to earlier work (e.g. Rodhe, 1998: Lenhart and Pohlmann, 1997) as the earlier analysis of Schrum et al. (2000) has already indicated.

Transport variability

The volume transports across the boundaries show significant variability on all time scales. It should be noted, however, that below the daily time scale, tidal advection plays the most important role in the variability of the water transports. On longer time scales, the net tidal transports across the open boundaries are negligible, relative to the wind-induced variability; the most important forcing parameter influencing circulation variability. In order to identify seasonal variability we distinguished four different situations: The winter situation with wind forcing mainly dominated by southwesterly winds (Oct–Jan), the late winter (Feb–Mar), characterized by winds from westerly-southerly to easterly directions, April–May with wind forcing from all directions, and finally the summer period (Jun–Sep), which is characterized by less intense wind forcing, mainly from westerly directions. This classification was chosen based on windfield analysis of the monthly mean windfields from the NCEP-40 data set. The criteria for the classification of the seasons were the similarity of the monthly mean windfields.

Significant transport anomalies occur for all investigated seasons on all inflow and outflow sections of the North Sea. First we examined the section Orkney to Norwegian Trench (from 3°W–3°E, 59°20, 5°N), where the main inflow into the North Sea takes place. Figure 6 shows the monthly mean inflow anomalies (positive anomalies indicate higher inflows) during the four periods of interest. The fifth curve in black-dashed is given for validation purposes and
Figure 6. Transport anomalies of North Sea inflows for four respective seasons. The seasons are chosen to be Oct/Nov/Dec/Jan (I, upper solid), Feb/Mar (II, upper dashed-dotted and dashed from ERA-15 forcing), Apr/May (III lower dashed-dotted) and Jun/Jul/Aug/Sep (IV lower solid).

shows the anomalies calculated from the 15-year ECMWF forced run. The two runs came up with almost identical variability and hence support the utility of the NCEP-40 outputs.

The strongest variability on a monthly time scale was found for the North Sea/Skagerrak exchange. Here, the variability at the northern open boundary ranged from 10% to 50% of the annual inflow, depending on the season. Comparing the correlations between the anomalies in different seasons, it is clear that transport anomalies are uncorrelated between the different periods, with a maximum correlation of 0.4 found for period II (Feb/Mar) and III (Apr/May). It cannot therefore be expected that the index of the North Atlantic Oscillation (NAOI; for further details, see Hurrell, 1995), normally calculated from
the winter period December to March, is a measure for transport anomalies in periods other than the winter season. Within the present contribution it is not possible to discuss all details of transport anomalies. Hence, for a first step, only winter (Oct–Mar) and summer anomalies (Apr–Sep) of the inflow are discussed (Figure 7). Two conspicuous features can be identified for the different periods: the winter period shows significant high positive inflows for the last decade compared to the previous decade and could be interpreted as a positive trend, regarding only the past 20 years. However, when examined over the entire time period, resolution of a trend is not possible. The summer period shows a different behaviour: a clear positive trend can be identified for the last three decades. The first decade behaves differently, showing the highest as well as lowest summer inflow anomalies.

Variability of late winter conditions

The second focus of the present study is the period February to March. In an earlier wind analysis (Siegismund and Schrum, 2001) it was shown that the 1990s were an outstanding period of wind forcing in the late winter with mean monthly windspeeds increasing in Feb–Mar over the last decade (1988–1997) and the prevailing wind direction changing to a more south–westerly orientation (Figure 8). This has serious implications for the water transports: the exchange across the northern boundary (inflow and outflow, i.e. the cyclonic circulation) is intensified in the period 1988–1997 (Figure 6, also identified in the half year winter mean in Figure 7). Transport anomalies for the 2-month mean of about 0.5 Sv were calculated by the model. These transport changes were found to be in correspondence with the timing and magnitude observed in earlier studies (Iversen et al., 1998; ICES, 2001). These increased inflows in the last decade occurred after a long period with significantly lower inflows from 1974 to 1987. The influence on the exchange flow in the Skagerrak region, which shows high variability, in Feb/Mar is even more pronounced (Figure 9). The wind-forcing fluctuations result in pronounced anomalies in the flow field from 1988 to 1997 (two exceptions being in 1991 and 1996) an exceptional period within the investigated 40-year period. The surface exchange was enhanced, with more surface inflow into the North Sea in the southern part of the Skagerrak (positive anomalies) and more surface outflow in the northern part of the Skagerrak (negative anomalies) with a reduction in deep water exchange. The calculated anomalies are exceptionally high for the near surface inflow (upper 30 m, increasing inflow, negative anomaly) in the southern part of the Skagerrak and for the deep water inflow in the northern part (decreasing inflow, negative anomaly). The calculated transport anomalies are in the order of 0.5 Sv, which is about twice that of anomalies found during the previous 30 years.
Discussion and biological implications

Investigations of the variability of water transports and stratification showed that there is considerable variability in the North Sea hydrodynamic environment. Although the variability is mainly dominated by the year-to-year variability, decadal variability can be identified as well. Longer periods with frequent occurrence of similar conditions were identified for stratification as well as for transport processes.

Yes, regarding the period February and March, the 1990s were unusual with respect to water transports! The anomalous wind forcing found in the 1990s for this period resulted in transport anomalies across the northern boundary and in exceptionally anomalous exchange circulation in the Skagerrak. This potentially impacts on the degree of transport of newly emerged *Calanus finmarchicus* into the Northern North Sea (Heath et al., 1999). A key species whose abundance is linked to variations in recruitment success of North Sea fish stocks (Rothschild, 1998). Furthermore, variations in transport have also been identified as a key issue in the survival success of key fish stocks, impacting on the transport of early life stages of these stocks to optimal larval and juvenile habitats (e.g. ICES, 2001; Heath and Gallego, 1998; Voss et al., 1999).

Similarly, stratification of the North Sea in the 1990s can also be classified as unusual; the years of the most extended stratification in May can be found in the 1990s, with the flux of limiting nutrients into the euphotic zone reduced due to a reduction in turbulent mixing – a situation that reduces the total potential production of the ecosystem by limiting production of lower trophic levels (e.g. Sharpley and Tett, 1994; Nielsen and St. John, 2002). Variations in stratification intensity and its effects on lower trophic level production and phasing (Kiørboe, 1991) is the basis of the so-called ‘bottom-up’ control of higher trophic level production.

In summary, we have identified how the 1990s have varied with respect to two key biologically relevant physical parameters, stratification and transport, both potentially impacting on the ecosystem dynamics. Future research within the European Union-funded LIFECO programme will address the mechanisms by which these parameters impact on the population dynamics of key species in the North Sea.

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