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SST Anomalies in the North Sea in Relation to the North Atlantic Oscillation and the Influence on the Theoretical Spawning Time of Fish

JOACHIM W. DIPPNER

Summary

The weekly sea surface temperature (SST) data of the whole North Sea and selected areas are analyzed using empirical orthogonal functions (EOF's) and related to the North Atlantic Oscillation (NAO) index. With the exception of the inflow area of the Fair Isle current, the SST anomalies of the whole North Sea and the selected areas show a good correlation to the NAO index, which indicates that the North Sea SST is mainly controlled by direct atmospheric forcing. In the Fair Isle current or the Fladenground area the SST seems to be influenced by advection. The strong anomalies of the EOF pattern in shallow water close to the continental coast, especially in the German Bight, and the strong seasonality during winter time suggest that these areas could be very sensitive with respect to climate change. A theoretical computation shows that climate variability influences the spawning time of fish up to two month in the near coastal area.

SST-Anomalien in der Nordsee, ihr Bezug zur Nordatlantischen Oszillation und der Einfluß auf die theoretische Laichzeit von Fischen (Zusammenfassung)

Die wöchentlichen Oberflächentemperaturdaten (SST) der gesamten Nordsee und ausgewählter Gebiete werden mit empirischen Orthogonalfunktionen (EOFs) analysiert und in Beziehung zum nordatlantischen Oszillationsindex (NAO) gesetzt. Die SST Anomalien der gesamten Nordsee und der ausgewählten Gebiete zeigen gute Korrelation zum NAO-Index mit Ausnahme im Bereich des Fair Isle Einstromes. Dies deutet darauf hin, daß die Oberflächentemperaturen der Nordsee hauptsächlich durch den direkten atmosphärischen Antrieb kontrolliert werden. Im Bereich des Fair Isle Einstromes sowie im Fladengrund scheint hingegen die Advektion der kontrollierende Mechanismus zu sein. Die starken Anomalien in den EOF Mustern im küstennahen Flachwasser, besonders in der Deutschen Bucht, und die starke Saisonalität im Winter deuten darauf hin, daß diese Gebiete besonders empfindlich sind hinsichtlich möglicher Klimaänderungen. Die interannuale Klimavariabilität kann im Küstenvorfeld die Laichzeit von Fischen um zwei Monate verzögern.

Introduction

Interannual and interdecadal variability in the North Sea has been observed in hydrography as well as in biology. One of the strongest signal in interdecadal variability was the appearance of the Great Salinity Anomaly (GSA) between 1977 and 1978 in the northern North Sea (DICKSON et al. [1988]) which had some ecological consequences (AEBISCHER et al. [1990], LINDEBOOM et al. [1995]). In the northern North Sea the phytoplankton and herring data show a continuous decrease with a distinct minimum in the late 70's (COLEBROOK [1986], DAAN et al. [1990]). Observations of phytoplankton and zooplankton data collected in the North Sea with the continuous plankton recorder (CPR) (COLEBROOK [1986]) show in 1978 a strong decrease in zooplankton abundance followed by an increase in 1982.

In contrast, synchronously to the appearance of the GSA in the northern North Sea, changes have also been observed in the southern North Sea and the Wadden Sea. Flagellates abundances in the German Bight increase in 1979 (HICKEL et al. [1992]). In the Wadden Sea also changes between 1977 and 1981 have been observed. Data on macrozoobenthos indicate a sudden increase of biomass between 1979 and 1981 (BEUKEMA [1991]), whereas phytoplankton data indicate a doubling of chlorophyll-a between 1976 and 1978 (CADÉE AND HEGEMANN [1991]). In 1977 only nine eider chicks fledged in the western Wadden Sea, whereas in 1978 more than 1000 successful fledglings were reported (SWENNEN [1991]).

The opposite effect of the GSA has been observed between 1989 and 1991: a positive salinity anomaly in the southern North Sea (BECKER et al. [1992], BECKER AND DOOLEY [1995]). This positive anomaly was connected with a strong inflow of Atlantic water masses through the English Channel. Similar events have been observed in salinity measurements of German light vessels in November 1934, from Februar to April 1973 and in November 1977 during the GSA event (DEUTSCHES HYDROGRAPHISCHES INSTITUT [1984]). In addition, an analysis using empirical orthogonal functions (EOF) shows that 96% of the variability in surface salinity can be explained with two EOFs and the first EOF which explains 85% of the variance is strongly correlated to the river runoff with a time lag of six month (HEYEN AND DIPPNER [1996]). Connected with the strong inflow of Atlantic water masses in 1989 into the southern North Sea is the observed recolonization of the flagellate *Gymnodinium catenatum* (NEHRING [1994]) or the appearance of *Lepidodinium viride* in the German Bight. The strong inflow of Atlantic water masses in 1989 into the southern North Sea shows also a signal in benthic macrofauna. A distinct increase in total biomass of benthic macrofauna occurs since 1989. In 1989 the biomass of *Echinocardium cordatum* and of *Lanice conchilega* abrupt increases (ZEISS AND KRÖNCKE [1998]). A detailed statistical analysis on interannual variability in benthic macrofauna in relation to climate variability is given by KRÖNCKE et al. [1998].

In this paper the physical variability of the North Sea is investigated with respect to large-scale climate variability. The central question is, how much of the observed variability of the SST in the North Sea can be attributed to the interannual variability of the atmospheric pressure fields.

Data and Method

NAO data

The dominant signal of interannual variability in the atmospheric circulation is the North Atlantic Oscillation (NAO) (WALKER AND BLISS [1932], BARNSTON AND LIVEZEY [1987], LAMB AND PEPPLER [1987], KUSHNIR AND WALLACE [1989], HURRELL [1995]). An EOF analysis of the mean sea level pressure fields from December to March over the region from 20° N to 80° N and 90° W to 40° E reveals that the NAO is the dominant mode of the atmospheric variability with an amount of explained variance of more than 36%. BARNSTON AND LIVEZEY [1987] showed that the NAO is evident in monthly mean data throughout the year but that it is most pronounced during wintertime. An index of the NAO (Figure 1) shows its variability since 1864 (HURRELL [1995]). According

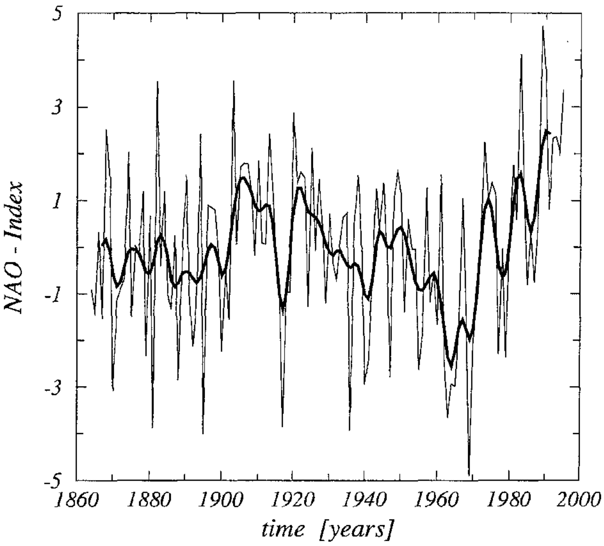

Fig. 1: NAO winter index after HURRELL [1995]. The heavy solid line represents the low-pass filtered time series.

to HURRELL [1995] the NAO index is defined as the difference between the normalized sea level pressure anomalies during wintertime at Lisbon and Stykkisholmur. Different equivalent definitions exist such as the spatial difference between Ponta Delgada and Akureyri used by LAMB AND PEPPLER [1987]. A high index is associated with strong westerly winds and a low index represents low westerly winds. During high NAO winters the westerly winds onto Europe are over 8 ms^{-1} stronger than during low NAO winters and consequently during high NAO winters the moderating influence of the ocean results in warmer than normal winter temperatures in Europe (HURRELL [1995]). For the present paper the NAO index data have been provided by James Hurrell from NCAR which is greatly acknowledged.

Weekly SST data

Since autumn 1968 the German Hydrographic Institute (now Federal Maritime and Hydrographic Agency, BSH) is analyzing and distributing weekly SST charts of the North Sea. These SST maps are based on near surface temperature observations from ship of opportunity programs, commercial vessels, light vessels, fixed stations and buoys, regular measurements from coastal stations and observations from research vessels and monitoring programs (MITTELSTAEDT [1969], BECKER et al. [1986], BECKER AND PAULY [1996]). In this paper the weekly SST charts from 1969 to 1995 are used for the selected areas of the North Sea and from 1971 to 1995 for the whole North Sea. The reasons for starting in 1971 for the whole North Sea are some changes between 1968 and 1971 in the land-sea mask of the North Sea SST data set. The North Sea is separated into six different areas, namely: the inflow of the Fair Isle current in the Fladenground (FLA) area 58–59° N, 0–2° W, the central North Sea (CNS) area 56–57° N, 3–5° E, the Norwegian Coastal Current (NCC) area 59–60° N, 3–5° E, the Skagerrak and Baltic outflow area 58–59° N, 9–10° E, the German Bight (GB) 54–55° N, 7–9° E and the northern part of the English Channel (CHA) 52–53° N, 2-4° E. For each subarea and for the whole North Sea (TNS) time series of SST anomalies are constructed by subtracting the long-term seasonal mean temperature from the area averaged SST. The anomalies of these long term data sets are analyzed with EOFs using the 52 weeks of the year as EOF pattern and the years as time series of coefficients. For the whole North Sea each SST map serves as EOF pattern and the weeks as time series of coefficients. Formally the coefficients carry the physical dimension while the fixed patterns are dimensionless. For practical situations, e. g. to make the time series of coefficients comparable to other time series, it is convenient to renormalize the patterns and the coefficients with the squareroot of the eigenvalues (VON STORCH AND ZWIERS [1995]). Then, the renormalized pattern carries the physical units and the coefficients are dimensionless. The renormalized time series of the first EOF of the SST anomalies is related to the NAO index (HURRELL [1995]).

Table 1 displays the explained variance of first and second EOF of the SST anomaly, the correlation to NAO index, the degree of freedom and the confidence level of correlation for the different areas in the North Sea and the whole North Sea. Figure 2 shows the first EOF pattern of the North Sea SST and Figure 3 the time series of coefficients averaged over the winter months and the corresponding winter NAO index.

Discussion

The first EOF pattern of the North Sea SST (Fig. 2) shows a clear gradient in SST anomaly from the northwest to the southeast with an amplitude of less than 0.4 °C in the northwestern inflow region up to an amplitude of more than 1.2 °C in the German Bight. The strong influence of the Dogger Bank which separates the North Sea into two different hydrographic regimes is clearly visible in the contour of the 0.9 isothermal. The amount of the explained variance for the first EOF pattern is 60.4%. The corresponding time series of coefficients for the first EOF averaged over the winter months and the corresponding winter NAO index are shown in Figure 3. The correlation coefficient between the time series is $r = 0.71$ with a confidence level of 97.9%. The time series clearly indicates the warm winter periods at 1989 and 1990 as well as the influence of the GSA to the North Sea during the mid 70s where negative anomalies in salinity appeared in addition to negative anomalies in SST. From this result it is obvious that more than 60% of the interannual variability of the SST in the North Sea can be addressed to the direct atmospheric forcing of the interannual variability of the large scale atmospheric pressure fields.

Table 1

Explained variance of the SST anomaly, the correlation to NAO index, the degree of freedom and the confidence level of correlation for different areas in the North Sea and the whole North Sea. Baltic outflow (BAL), English Channel (CHA), Central North Sea (CNS), Fladenground (FLA), German Bight with nearcoastal points (GB1), German Bight without nearcoastal points (GB2), Norwegian Coastal Current (NCC), and total North Sea (TNS)

Area	Explained variance 1. EOF (2. EOF)	Correlation r (NAO, 1. EOF)	Degree of freedom	Confidence level
BAL	35.0% (11.9%)	0.63	9	96.2%
CHA	40.9% (18.9%)	0.63	9	96.2%
CNS	34.6% (17.9%)	0.64	9	96.6%
FLA	26.6% (15.5%)	0.42	13	88.1%
GB1	43.3% (10.5%)	0.72	9	98.7%
GB2	46.7% (10.3%)	0.68	9	97.9%
NCC	30.0% (16.8%)	0.64	9	96.6%
TNS	60.4% (6.0%)	0.71	8	97.9%

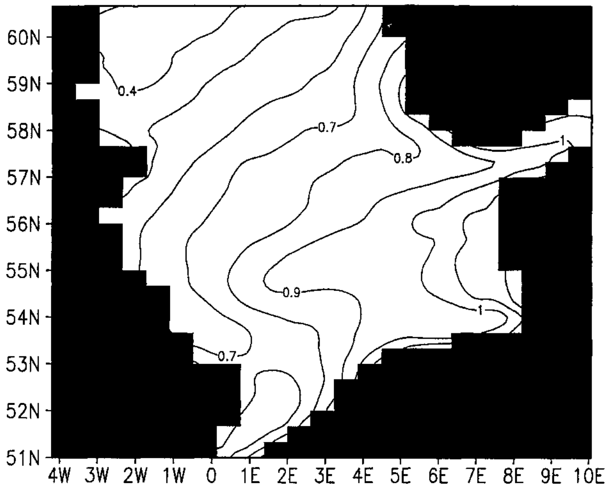

Fig. 2: First EOF pattern of North Sea SST. The explained variance is 60.4%.

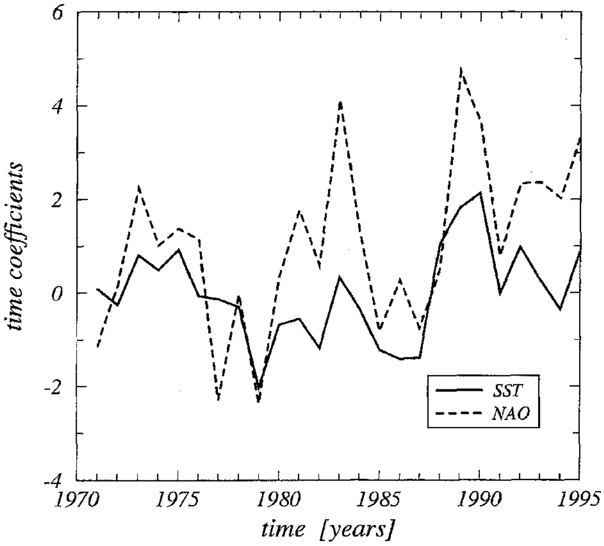

Fig. 3: Time series of the coefficients for the 1st SST EOF of the whole North Sea averaged over the winter months and the NAO winter index. The correlation is r = 0.71.

Concerning the six different areas, a similar structure from northwest to southeast appears in the amount of explained variance (Tab. 1). The minimum of explained variance is in the Fladengound area with an amount of explained variance of 26.6% in the first EOF pattern and a maximum of 46.7% in the German Bight. The correlation between the time series of coefficients of the first EOF and the NAO index is everywhere larger than 0.63 except the Fladenground area where the correlation is 0.42 only. The maximum of correlation appears in the German Bight with r=0.72. In all areas the autocorrelation time is three years, except the Fladenground area. There the time series of coefficients has an autocorrelation time of two years. The reason for the different correlation times is not clear and should be subject of further investigations. In all areas, except the Fladenground area, the confidence level (Tab.1) is higher than 95%. This indicates that the heat budget of the whole North Sea is controlled by direct atmospheric forcing whereas the Fladenground area seems to be more controlled by advection of the circulation field. Similar to the analysis of the whole North Sea the influence of the Dogger Bank appears in the seasonality of the local EOF pattern. With the exception of the Fladenground area, the time series of coefficients are in good correlation to the NAO index and very similar which can be seen from the cross correlation of the six different areas (Tab. 2). All correlations have a confidence level higher than 95%. In the EOF patterns of the six areas two different seasonal patterns exist which are connected to the Dogger Bank. As examples Figures 4 and 5 show the patterns and time series of the first EOF for the Fladenground area and the German Bight, respectively. The Dogger Bank separates the North Sea into two areas which are different with respect to the seasonal signal. North and northwest of the Dogger Bank the seasonal pattern of the first EOF is more or less a noisy signal over the whole year which appear in the Fladengroud area, in front of the Norwegian coast and in the central North Sea. In contrast, south and southeast of the Dogger Bank a strong signal in the SST anomalies appears in the first 15 weeks of the year. This general structure is observed in the Skagerrak, the German Bight and the English Channel. From these results can be concluded, that the strong anomalies of the EOF pattern in shallow water close to the continental coast, especially in the German Bight, and the strong seasonality during winter time suggest that these areas could be very sensitive with respect to climate change.

Table 2

Cross correlation coefficient for different areas in the North Sea. The confidence level is higher than 95%, in some cases higher than 99%

Area	BAL	CHA	CNS	GB1	FLA	NCC
BAL	1.00	0.87	0.87	0.94	0.66	0.88
CHA		1.00	0.89	0.92	0.69	0.81
CNS			1.00	0.90	0.83	0.89
GB1				1.00	0.66	0.85
FLA					1.00	0.76
NCC						1.00

A similar analysis has been performed by Becker and Pauly [1996]. Becker and Pauly [1996] have computed from the North Sea SST data set annual means of SST anomalies and have correlated these time series to the NAO index. A surprising result in comparing both methods is that in the area north and northwest of Dogger Bank where the EOF patterns show no seasonal signal, the correlation coefficients are identical. In contrast, south and southeast of the Dogger Bank, where the EOF patterns show a seasonal signal during wintertime, the correlation between the time series of coefficients of the first EOF and the NAO index is much higher than in the computation of Becker and Pauly [1996]. They conclude that the North Sea SST anomaly changes are explained mainly by local air-sea exchange processes which depend on the North Atlantic atmospheric circulation. From their poor correlation of annual mean SST anomalies to the NAO index in the Fair Isle current area and the English Channel as well as from their low cross correlation, Becker and Pauly [1996] conclude that these areas are controlled more by advection from the Atlantic than by direct atmospheric forcing. The last hypothesis cannot be supported from the results of the presented EOF analysis. The significant correlation between the NAO index and the EOF time series in the English Channel indicates that also this area is controlled more by direct atmospheric forcing than by advection.

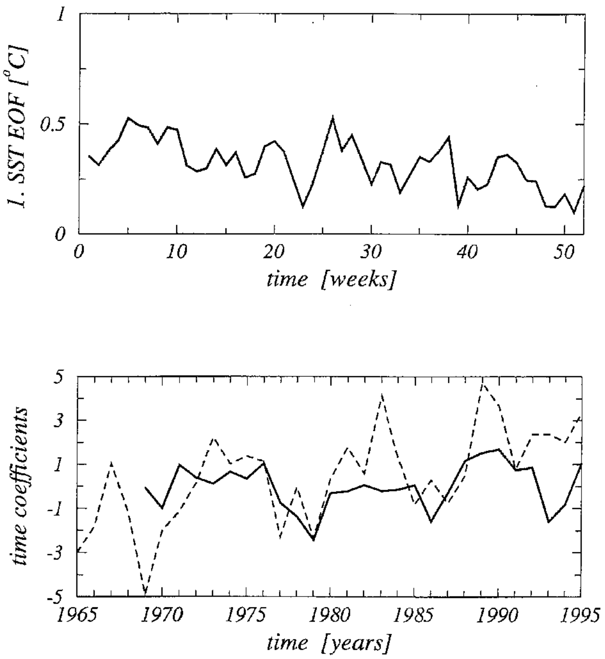

Fig. 4: EOF pattern (upper panel) and time series of the 1st SST EOF (soli line) for the Fladengrund area and NAO index (dashed line). The explained variance is 26.6%, the correlation to the NAO index is r = 0.42.

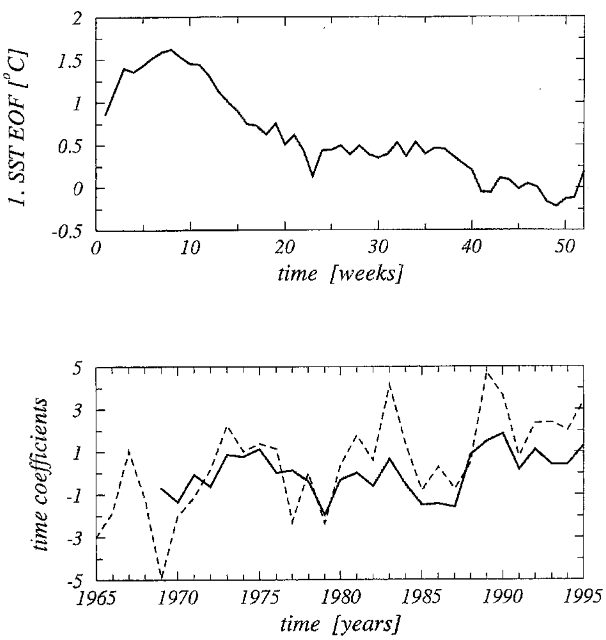

Fig. 5: EOF pattern (upper panel), time series of the 1st SST EOF (solid line) for the German Bight area and NAO index (dashed line). The explained variance 43.3%, the correlation to the NAO index is r = 0.72.

To estimate extreme situations a comparison is made between low or near-normal NAO winters and very high NAO winters using composites of the North Sea SST. For the low or normal NAO composite the winters 1979, 1985, 1986, 1987, and 1988 were used. Only three of these winters have negative index values, resulting in a composited index value of –0.6 ± 0.8. The high NAO composited index is 3.5 ± 0.9 determined from the average of the 1983, 1989, 1990, 1992, and 1993 winter indices. Figure 6 shows the difference in winter SST of the North Sea between the high NAO composite and the low NAO composite. The figure reveals a zonal gradient in SST difference from less than 0.3 °C in front of the Scottish coast up to more than 3 °C in the Skagerrak. The Skandinavian high pressure system and the connected influx of cold continental air masses is the reason for the strong cooling during wintertime in the shallow near-coastal areas of the North Sea. Therefore, figure 6 displays more or less the area of influence of the Skandinavian high pressure system which appears at low NAO index.

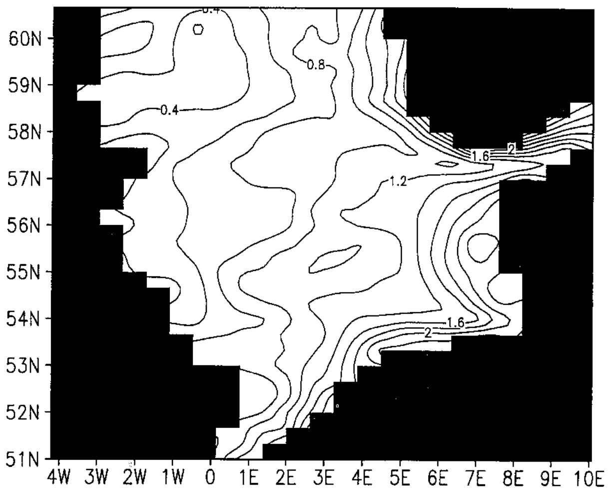

Fig. 6: Difference in winter SST of the North Sea between the high NAO index composite and the low NAO index composite.

Biological consequence

It is well known that interannual and interdecadal variability in SST influences the food chains in the marine ecosystem and has consequences on the interannual variability in the biological system. The 'match/mismatch' hypothesis (Cushing and Dickson [1976]) explains interannual variability by the timing between predator and prey. The overlap between the distribution of larval production and their food – both depend on temperature during winter time – might determine the size of the subsequent year class. The computed differences in winter temperature on the base of a composite analysis have biological consequences and clearly influence quantities such as the spawning time of fish. Lange and Greve [1997] have computed the theoretical spawning time of fish from the monthly mean bottom water temperature (Tomczak and Goedecke [1962]), assuming that gonadal maturation requires a specific growth time at favourable temperature so that the product of both could be identified as the crucial quantity. The required temperature amount TA is:

$$TA = \int_{t = day\,0}^{t = t_{spawn}} T(t)\, dt \qquad (1)$$

This theoretical approach includes three assumptions. The first assumption is the day 0-hypothesis, that gonadal maturation starts at a certain time (*day* 0). The second assumption is that maturation requires a certain amount of temperature *TA*. The last assumption is that the fishes do not migrate. In general, the last assumption is not neccessary. If in the equation $T(t)$ is replaced by $T(\vec{x}, t)$ and the integral is solved in a Lagrangian coordinate system, migration can be considered as well in the computation of spawning time. In the paper of Lange and Greve [1997] and in this paper this assumption is used for convenience only. Lange and Greve [1997] consider as starting time (*day* 0) of gonadal maturation September 1th and the required amount of temperature is TA = 70 mo.°C. The gonadal maturation lasts until the temperature amount (TA) is reached and spawning takes place at time $t = t_{spawn}$.

In this paper a similar computation is carried out from the winter temperature composites during high and low NAO index. The difference to the paper of Lange and Greve [1997] is a higher resolution in time and space. The data set of North Sea temperature of Tomczak and Goedecke [1962] is based on monthly values with a horizontal resolution of 1°. In contrast, in this paper the weekly North Sea SST data set is used which has a resolution of 20 N.m. The assumed starting time of gonadal maturation is the 35th week and the required amount of temperature is TA = 280 weeks °C which is equivalent to the TA = 70 mo.°C approach used by Lange and Greve [1997]. Figure 7 shows the theoretical spawning time in weeks of the year in the North Sea for the high NAO index composite and figure 8 for the low NAO index composite. Figure 9 displays the difference in theoretical spawning time in weeks in the North Sea between the high NAO index composite and the low NAO index composite. The computed theoretical spawning time in the North Sea is in good agreement with the observed band-width of spawning time of dab (*Limanda limanda*) in the English Channel and the southern North Sea (Deniel and Tassel [1986]) and of lemon sole (*Microstomus kitt*) in front of the Scottish coastline (Rae [1965]).

The possibility to construct from the weekly SST fields high and low NAO index composites allows a conclusion with respect to fish recruitment. The difference in theoretical spawning time between the high and the low NAO index composite is more than 8 weeks in the German Bight. During low NAO index and the strong cooling of SST due to the connected influx of cold continental air masses, the spawning time has a lag of two month. Hence, interannual variability in winter temperature represents a climatic signal which may control recruitment success or failure for spring spawners.

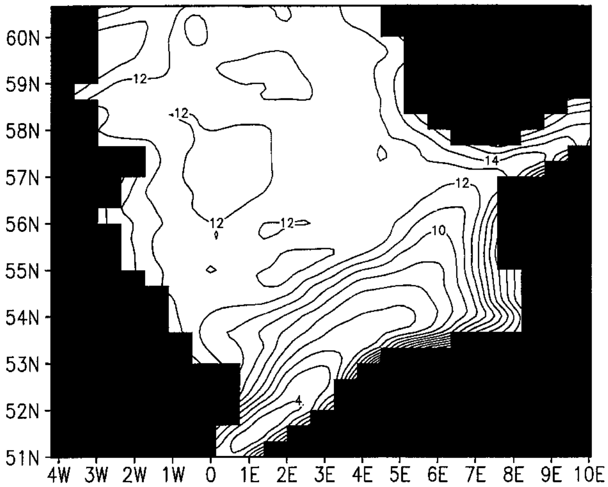

Fig. 7: Theoretical spawning time in weeks of the year in the North Sea at high NAO index.

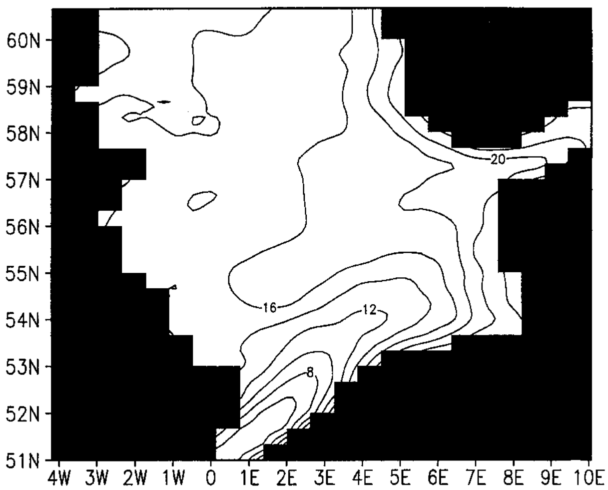

Fig. 8: Theoretical spawning time in weeks of the year in the North Sea at low NAO index.

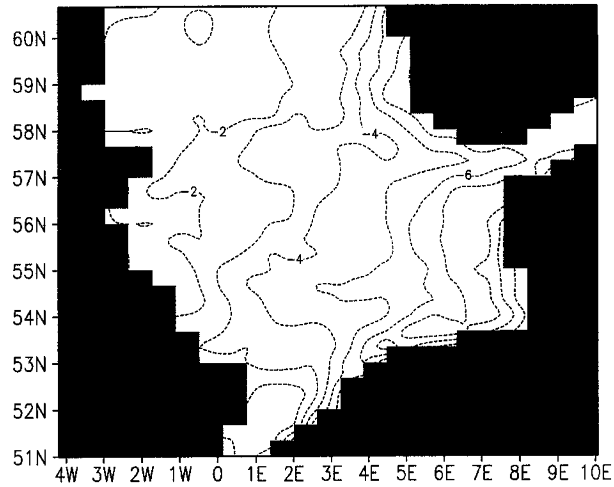

Fig. 9: Difference in theoretical spawning time in weeks in the North Sea between the high NAO index composite and the low NAO index composite.

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Author's address:

Joachim W. Dippner
Max-Planck-Institut für Meteorologie
Bundesstraße 55
D-20146 Hamburg

Present affiliation:
Institut für Ostseeforschung Warnemünde
Seestraße 15
D-18119 Rostock