A study of the climatic system in the Barents Sea

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The climatic conditions in the Barents Sea are mainly determined by the influx of Atlantic Water. A homogeneous wind-driven numerical current model was used to calculate the fluctuations in the volume flux of Atlantic Water to the Barents Sea which are caused by local wind forcing. The study period is from 1970 to 86. When compared with observed variations in temperature, ice coverage, and air pressure, the results show remarkably good agreement between all three parameters. The climate system of the Barents Sea is discussed with emphasis on the interrelations and feedback mechanisms between air, sea, and ice.

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Introduction

Variations in the climatic conditions of the Barents Sea have been described by several authors. At first, attention was paid to variations in ice coverage (Chavanne 1875), but changes in hydrographical conditions soon came into focus. One of the first more detailed analyses of climatic fluctuations in the Barents Sea was performed by Helland-Hansen & Nansen (1909). During the past 30 years the climatic conditions have been analysed by Kislyakov (1964), Midttun (1969), Bochkov (1976, 1982), Blindheim & Loeng (1981), Dickson & Blindheim (1984), and Midttun & Loeng (1987).

A general conclusion is that climatic variations in the Barents Sea depend mainly on the activity and properties of inflowing Atlantic Water. Helland-Hansen & Nansen (1909) suggested that climatic variations in the Barents Sea probably are of an advective nature. This has later been confirmed by several authors, but the most clear demonstration of advection of water masses properties has been given by Dickson et al. (1988).

During recent years, the importance of understanding the physical causes behind the variations observed in the inflowing water masses has come into focus. Bochkov (1976) indicated that variations in temperature and ice conditions coincided with the solar activity cycle, but the verification was not convincing. The formation of dense bottom water and the outflow of bottom water to adjacent seas has been proposed by Midttun (1985) and Midttun & Loeng (1987) as one cause.

Using results from the wind-driven model for the Barents Sea presented by Ådlandsvik (1989), this paper concentrates on the influence of local wind conditions on variations in the Atlantic inflow to the Barents Sea. It must be pointed out, however, that the authors do not consider local atmospheric forcing to be the only important factor in influencing the variability of the Atlantic inflow.

The model

The model equations are linear shallow water equations with vertical eddy vioscosity, that is the continuity equation

$$\frac{\partial \eta}{\partial t} = -\nabla \cdot \int_{-H}^{0} \mathbf{u}\,dz \tag{1}$$

and the momentum equation

$$\frac{\partial \mathbf{u}}{\partial t} + f\mathbf{k} \times \mathbf{u} = -g\nabla\eta - \frac{1}{\rho}\nabla p_a + \frac{\partial}{\partial z}\left(\nu \frac{\partial \mathbf{u}}{\partial z}\right). \tag{2}$$

These equations are transformed to bottom following "σ-coordinates", $\sigma = -z/H$, in the vertical and solved for the horizontal velocity field $\mathbf{u}$ and the surface elevation η. The driving forces are atmospheric pressure p_a and wind stress. The last term is not visible in the equations but enters through the sea surface boundary condition. The vertical eddy viscosity term ν is prescribed. The constant density is ρ; H is the depth, and f is the Coriolis parameter.

The model is a three-dimensional level model. The equations are discretised by finite differences using the Arakawa-C grid. The numerical methods are similar to those applied by Davies (1985); in particular, the scheme is explicit and uses a time splitting technique. The model was not constructed for flux calculations only. A two dimensional baroclinic model would use less computer time and give nearly identical results. Details of the model are described by Ådlandsvik (1989).

The model is implemented for the Barents Sea. The model domain is shown in Fig. 1. The horizontal grid size is approximately 20 km. The atmospheric forcing is taken from the Hindcast Archive of the Norwegian Meteorological Institute (Eide et al. 1985). This archive contains six-hourly values on a 75 km grid covering all seas surrounding Norway. At the open boundaries a radiation condition with no prescribed in/outflow is used.

The mean current pattern in the Barents Sea is dominated by density driven currents and the 'background' Atlantic inflow. These forces are not included in the model. The changing weather conditions induce variations in the current pattern. These variations are, however, captured by the model.

Model results

The model was run for a period of seventeen years, 1970–86. The output data is the integrated volume flux through the section from Fugløya (70°30'N, 20°E) to Bjørnøya (74°15'N, 19°10'E) (Fig. 1). Since the mean Atlantic inflow is not included in the model, the model results should be viewed as fluctuations from this mean due to local wind conditions. Negative values represent a decreased Atlantic inflow to the Barents Sea and positive values correspond to an increased inflow.

Fig. 1. The model domain with bathymetry. The equidistance is 100 m down to 2300 m. The Fugløya-Bjørnøya section is marked with an "F" and the Kola section by a "K".

The mean values for each month are presented as the thin line in Fig. 2. Even though the large variations within each month are removed, the picture gives a chaotic impression. The values vary from -1.3 Sv (1 Sv(erdrup) = $10^6\ m^3s^{-1}$) in March 1979 to $+1.6$ Sv in February 1983. For the whole period the mean is 0.06 Sv and the standard deviation is 0.56 Sv. Compared with the standard value of 2 Sv for the inflow (Blindheim 1989), the net effect of the local atmospheric forcing is very small. A two-dimensional version of this model has been rerun on a model domain also covering the Norwegian Sea. Unpublished results from this model give consistently more water into the Barents Sea, with a mean inflow of 0.38 Sv. The variations are, however, very similar.

The monthly data have been filtered by a moving one-year average. The smoothed data are given by the thick line in Fig. 2 and a blown up version in Fig. 3. This time series shows an increased inflow in the early 1970s, a decrease from 1977 to 1978 and a peak inflow in the period

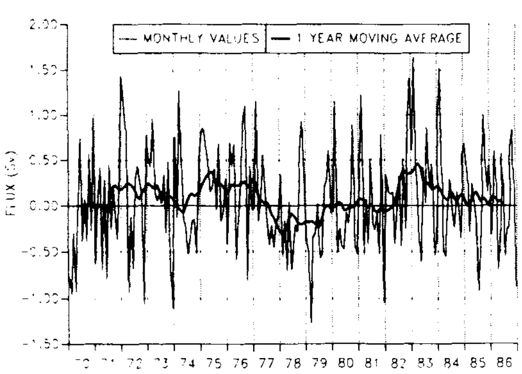

Fig. 2. Computed atmospherically drive volume flux through the Fugløya-Bjørnøya section in the period 1970–1986. The thin curve gives monthly mean values and the heavy curve is a moving one-year average.

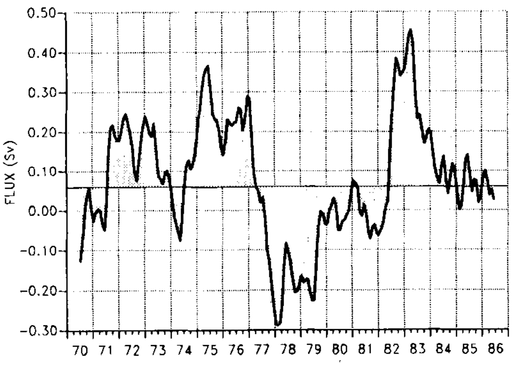

Fig. 3. The moving one-year average of monthly values of computed atmospherically driven volume flux through the Fugløya-Bjørnøya, section, 1970–1986.

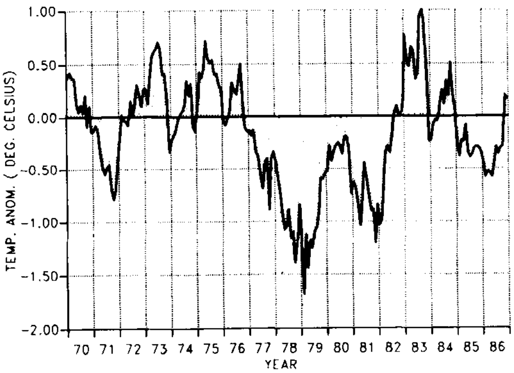

Fig. 5. Monthly temperature anomalies from the Kola section, 1970–1986.

1982–1983. The difference between maximum and minimum in the smoothed curve is about 0.75 Sv, which is quite a large value compared with the measured 2 Sv. It is therefore reasonable to assume that variations in the local atmospheric conditions are among the important factors in determining the variability in the Atlantic inflow to the Barents Sea.

Comparison with other data

Fig. 4 gives a moving one-year average on the air pressure of a hindcast grid point between Bjørnøya and Hopen. For comparison, the pressure axis is reversed. The mean pressure for this period is 1008.7 hPa with a standard deviation of 6.5 hPa. These data show low pressures in the early 1970s and in the period 1982–1983. The late 1970s up to 1981 show a high pressure anomaly. There is close agreement between these data and the flux data since the atmospheric data are part of the driving force for the model.

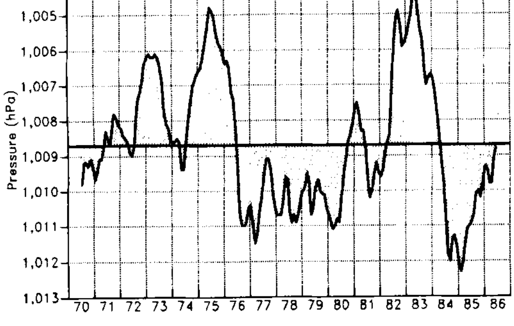

Fig. 4. The moving one-year average of monthly values of air pressure at (22°47′E, 75°02′N), 1970–1986.

Soviet scientists (Bochkov 1982) provide monthly temperature values from the upper 200 m in the Kola section along the 33°30′E meridian from 70°30′N to 72°30′N (Fig. 1). Subtracting a 60-year mean for each month gives the temperature anomalies shown in Fig. 5 for the period 1970–1986. These data show the same overall pattern, a warm period in the early 1970s and then a cold period followed by high temperatures in the period 1983–1984.

Ice coverage is often used as a climatic indicator. The position of the ice border in the Barents Sea varies from year to year. A quantitative measure of these variations is the ice-index introduced by Loeng (1979). A comparison of these values and the temperature data from the Kola section is given in Sætersdal & Loeng (1987). The index is based on the zone between 25°C and 45°E. The winter index is defined by

$$I_w = -\int_{\text{winter}} (\text{ice covered area south of76°N})\,dt. \qquad (3)$$

Note that low index values correspond with much ice. The ice coverage is taken from the ice maps from the Norwegian Meteorological Institute. A histogram of the winter index for the period 1971–1986 is given in Fig. 6. There was little ice up to 1978 followed by a period with more ice until 1983 when a new period with little ice started. This corresponds nicely with the same pattern as the other data.

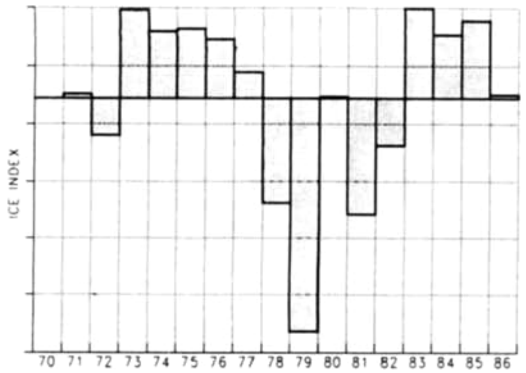

Fig. 6. Histogram of Barents Sea winter ice index, 1971–1986.

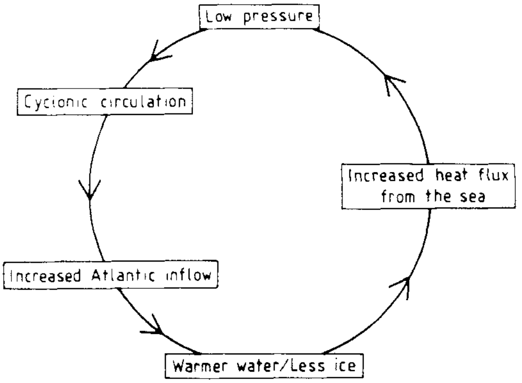

Fig. 7. The feedback cycle during a warm period in the Barents Sea.

Discussion

The close relationship between the calculated inflow (Fig. 3) and the temperature anomalies (Fig. 5) is very interesting. The coupling between these variables can be explained in two ways. Variations in the inflow of warm Atlantic Water is an important factor in determining temperature in the Kola section. On the other hand, differences in the heat content of the Barents Sea have significant influence on the local atmosphere. It seems difficult to decide between cause and action in this case. A search for time lag is complicated by the fact that the temperature correlates with the smoothed flux signal and not the monthly values.

The interrelationship between atmospheric and oceanic circulation complicates the task of identifying the most significant factors influencing the variations of sea ice. During the winter and early spring, the position of the ice edge follows the oceanic Polar Front. It is therefore natural that changes in oceanic circulation cause changes in ice conditions, as claimed by Helland-Hansen & Nansen (1909), Kaminski (1976), and Sætersdal & Loeng (1987).

The conditions are somewhat different during the ablation period, when radiation plays the dominant role by the direct melting of ice and heating of the surface water. In addition, factors such as turbulent transfer of heat, wind drift, and wave effects are inportant (Lunde 1965; Vinje 1984).

The agreement of the fluctuations in all these climatic variables suggests that the climate of the Barents Sea oscillates between two states, a warm and a cold state. The warm state is characterised by high temperatures, low air pressure, cyclonic circulation in the atmosphere, increased Atlantic inflow, and little ice coverage (Fig. 7). The cold state is characterised by low temperatures, high air pressure, anticyclonic air circulation, decreased Atlantic inflow and more severe ice conditions.

Positive feedback mechanisms are required for a state to be maintained. Such a mechanism is proposed in two recent papers by Ikeda (1990a, b). The influence of the atmospheric conditions on the Atlantic inflow is described by the model. Variations in this inflow are important for the position of the Polar Front. This has been demonstrated by a laboratory model (McClimans & Nilsen 1990). Variations in the position of the Polar Front are followed by variations in the winter ice coverage. These variations induce variations in the integrated heat flux from the Barents Sea to the atmosphere and the cycle is closed. The feedback cycle is positive; low pressure leads to cyclonic circulation, increased inflow, less ice, larger heat flux, and lower pressure again, as illustrated in Fig. 7.

The transition from one climatic state to the other is likely to be enforced externally by variations in larger scale oceanic and atmospheric circulation. There is, however, one internal mechanism, the formation of bottom water, which can account for the transition from a cold to a warm state.

Outflow of dense bottom water from the Barents Sea is obviously important for the amount of inflowing Atlantic Water. The formation of bottom water during the winter as a result of cooling and formation of ice is described by Midttun (1985). According to Midttun (1985) and Midttun & Loeng (1987), this bottom water leaves the Barents Sea through the strait between Novaja Zemlja and Frans Josef land. The volume of water which leaves the sea must be replaced by water from the west.

Between 1982 and 1983 there was an extremely large outflow of bottom water from the eastern Barents Sea (Midttun & Loeng 1987) which coincided with the increased Atlantic inflow (Fig. 3). The outflow of bottom water may have taken place due to at least two reasons: firstly, the bottom water, driven by its own density, left the Barents Sea, requiring a compensatory inflow (Midttun 1985); and secondly, an increased inflow of Atlantic Water of high density pushed the bottom water away.

The second explanation is probably most likely. This assumption is consistent with the results from our model. McClimans & Nilsen (1990) also support this conclusion. However, regardless of the cause of the outflow, the replacement of bottom water allows for increased Atlantic inflow and a warmer state of the Barents Sea.

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