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THE FORMATION OF GREENLAND SEA DEEP WATER

by

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ABSTRACT

An analysis of the hydrographic and tracer data set collected in the Greenland Sea by C.S.S. Hudson in March, 1982, suggests that if the winter of 1981/82 had been more severe or longer, convection would have taken place to the bottom in the central Greenland Sea. Because of the presence of a low salinity surface layer, sea ice is formed as the sea surface is cooled; however, brine rejection during freezing causes mixed layer deepening, vertical transfer of heat from deeper layers and subsequent ice melt. The deep convection mechanism, in conjunction with formation and melting of sea ice, is also consistent with the significantly under-saturated oxygen concentrations seen in the upper layers of the Greenland Sea.

Other possible mechanisms for deep water formation, such as caballing and double diffusion, are discussed in light of the high precision CTD data available from March, 1982. It is clear, however, that the formation of Greenland Sea Deep Water has not yet been directly observed.

Introduction

Open ocean deep water convection leading to the formation of water types has been observed both in the western Mediterranean Sea (MEDOC Group, 1970, Gascard, 1978) and in the western Labrador Sea (Clarke & Gascard, 1983). Both these regions share the three following characteristics: i) a large scale cyclonic circulation, ii) a subsurface source of heat and salt, and iii) a region of enhanced air/sea exchange. These three characteristics have been argued to be prerequisites for open ocean deep convection. Because the Greenland Sea shares all three of these characteristics, it was felt that it was likely that deep convection leading to renewal of Greenland Sea Bottom Water occurs there. Consequently, preparations were made to conduct a pilot study of the formation processes should indications be seen during a winter hydrographic cruise to the area on C.S.S. Hudson during February/March, 1986.

While a rather complete station coverage of the Greenland Sea was obtained during the course of the cruise, no evidence of deep convection processes was seen and, therefore, no studies of these processes could be carried out. We can, however, use this hydrographic data set to look at why deep convection did not happen during winter 1981/82 and also what might have happened if convection had taken place.

In the following paper, I will first demonstrate that among the various basins that make up the Nordic Seas, it is the Greenland Sea Basin that has the deep cyclonic circulation that makes it most susceptible to deep water renewal via deep convection. The deep salinity maximum extending from the Norwegian into the Greenland Basin will be described, and its possible roles as either a subsurface source of salt to deep convection or as a forcing mechanism for deep water renewal via double diffusion is discussed. It will then be shown that the winter of 1981/82 was somewhat colder than normal and argued that the lack of observable deep water renewal must be attributed to increased stability in the water column due to excess fresh water in the upper layer. Finally, a simple model will be used to demonstrate how easily the Greenland Sea could have proceeded to overturn via deep convection and the consequences of such an overturn on the properties of the Greenland Sea Deep Water.

Circulation of the Greenland Sea

The upper level circulation of the various basins of the Nordic seas can probably best be inferred from the distribution of density, σ_θ, at 100 dbars (fig. 1). The Norwegian Atlantic Current associated with the gradient towards lower density as one moves up the Norwegian continental slope carries the warm salty Atlantic inflow from the Faroes-Shetland Channel northeasterly toward the Barents Sea. The West Spitsbergen Current is seen in the gradient that lies across the West Spitsbergen continental slope. The nearly closed isopycnals in the Greenland Sea are in response to the cyclonic circulation around the sea; a cyclonic circulation that seems to follow the bathymetry of the basins very closely. This cyclonic circulation is the first prerequisite for a deep convection area.

If we were to look at the depth of a deeper density layer such as $\sigma_1 = 32.81$ (fig. 2), we see that this surface bowls downward in the Norwegian Sea and upwards in the Greenland Sea. This suggests that the deep circulation in the Norwegian Sea is separated from the surface circulation by some intermediate level of minimum motion. The Greenland Sea circulation remains cyclonic at depths of the order of 1000 m; however, the circulation has fairly unambiguously split into separate circulations within the Greenland and the Boreas Basins. It is also clear that this density layer is shallowest in the centre of the Greenland gyre; therefore, it is here that renewal of this and deeper layers by deep convection is most probable.

Deep Salinity Maximum

This density surface is also close to the one on which a deep salinity maximum is found in the Norwegian Sea. This same salinity maximum extends throughout the Greenland Sea, although at a somewhat greater density, $\sigma_1 > 32.82$. The salinity on this surface (fig. 3) is quite constant within the Norwegian Sea within values close to 34.913 P.S.U. and drops to values less than 34.89 P.S.U. in the central Greenland Sea. The isohalines parallel closely the bathymetric boundaries of the Greenland Basin. Oxygen concentrations on the same surface rise from values near 6.9 ml/l in the Norwegian Basin to values greater than 7.2 ml/l in the central Greenland Basin (Figure 4). In the absence of actual observed renewal of deep waters in these basins by surface processes, Carmack and Aagaard (1973) and McDougall (1983) have argued that renewal takes place by subsurface mixing of water masses and the formation of mixed waters through such processes that are denser than their parent waters. It is also possible that a salinity maximum structure like this does provide a valuable source of salt to the deep water, but the ultimate conversion to new deep water occurs when convection from the surface incorporates this salinity maximum into a deep homogeneous mixed layer extending from the surface.

$\frac{\partial^2 S}{\partial z^2}$ evaluated over the entire depth range of the salinity maximum is about 10 times smaller than $\frac{\partial^2 O_x}{\partial z^2}$. Since the range of variation of oxygen concentration along the axis of the salinity maximum is some 7 times that of salinity, this suggests that the shape of the salinity maximum and the corresponding oxygen minimum might both be maintained by similar vertical mixing processes that can be modelled by the traditional vertical eddy diffusivity formulation. Others have suggested that these vertical mixing processes can account for the renewal of the Greenland Sea Deep Water; however, at none of our stations had the deep salinity maximum/oxygen minimum disappeared or had it attained the salinity/oxygen characteristics of the GSDW seen beneath it in the centre of the Greenland Basin. It may be possible that such a subsurface mechanism for deep water renewal is, like the deep convection mechanism, dependent on intense air-sea forcing to cool the low salinity upper layer, which in turn cools the deeper layers through double diffusion. Hence, one can argue, as I will for deep convection, that the process would operate during a winter more intense than 1981/82.

Severity of the Winter

There is the question of how intense a winter the winter of 1981/82 was. We certainly left Halifax in February, 1982, expecting the worst, yet other than a problem of high winds and icing conditions as we tried to exit Denmark Strait, we experienced weather conditions that seemed mild in comparison to our earlier winter voyages in the Labrador and Irminger Seas and Denmark Strait. At sea, therefore, we attributed the lack of evidence of ongoing deep water renewal to the mildness of the winter. A closer study, however, suggests that the winter was somewhat colder than average. Table I summarizes the air temperatures observed at various stations around the Greenland/Norwegian Sea during the winter. One can see, without exception, that all stations were colder than normal. One also sees that March was somewhat milder than normal, which accounts for our experiences at sea. The ice cover, as summarized by the Marine Observer, was somewhat heavier than normal earlier in the winter, somewhat lighter at the end. The Marine Observer also evaluates the marine winds. During December 1981, there was a anamoly for northeasterly winds over the Norwegian Sea driven by a +8mb pressure anamoly over Greenland and the Greenland Sea. This pattern disappeared in January, 1982, and by February, a stronger anamoly for southerly winds had developed over the southern Norwegian Sea. This pattern continued into March, weakening somewhat, but extending northward over all of the Nordic Basins. These winds were probably largely responsible for the ice edges being displaced to the NNW of their normal positions.

If the air temperatures and winds were somewhat more severe than normal then why did deep water renewal not seem to occur during this winter? One answer may be because of the presence of a low salinity surface layer over all of the Greenland Sea. This surface layer does not appear in the winter data collected in the 1950's and 1960's. It is possible that there is sufficient additional fresh water in this layer, so that cooling the Greenland Sea will only result in large amounts of ice formation rather than deep overturn of dense, warm and salty subsurface layers. A modified mixed layer model, first used to look at the deep convection in the Labrador Sea (Clarke and Gascard, 1983), was used to look, in some detail, at this question of the effect of ice formation on deep water renewal.

Deep Convection Model

The mixed layer model simply evaluates the static stability at the bottom of the mixed layer after a user prescribed amount of heat and fresh water is removed from it. If the mixed layer is statically unstable then the mixed layer is allowed to deepen by fully mixing the water below into it until static stability is finally reached. This model gives a lowest estimate of the rate of mixed layer deepening as it neglects completely the effects of entrainment driven by shear at the bottom and edges of the deepening mixed layer. The model also allows the processes of mixing along isopycnal surfaces to be evaluated by allowing water at the same density to be exchanged between neighbouring stations. In the simulations that will be discussed here, this mixing was set to zero. For the Greenland Sea simulations, the processes of ice formation and melting had to be incorporated into the model. After the heat and fresh water has been removed from the mixed layer, if the layer is below the freezing point, just enough ice of salinity 10 P.S.U. is formed so that after the heat of fusion and excess salt is mixed into the mixed layer, the mixed layer is at the freezing point. Then the test for stability is done and the layer is deepened if necessary. This deepening generally raises the temperature of the mixed layer above the freezing point, consequently, ice is melted too for a new low salinity mixed layer some 10 metres thick.

This model was applied to our station data from the Greenland, Boreas and Norwegian Basins. If the time step used is considered to be equivalent to one day then the heat and fresh water losses for each time step are equivalent to a heat loss of 150 watts/m and an evaporative loss of 0.002 m/day. These values are, perhaps, as much as a factor of two lower than actual values for this region. The model was run for 100 time steps, the resulting mixed layer depths and ice thickness are given in Table II. One sees in this table that in the Greenland Sea stations, convection takes place to the bottom in 40 to 100 time steps accompanied with the formation and subsequent melting of less than 20 cm of ice. It is clear from this that some stations, such as station 35, were very close to full depth convection. For the stations in the Boreas Basin and those over the ridges bounding the Greenland Basin, convection after 100 time steps was generally limited to less than 1000 m and .3 m or more ice often was formed. In the Norwegian Sea, mixed layers deepened to depths of only 500-700 m with no ice formation.

Oxygen Concentration

The same mixed layer model can also be used to model the evolution of oxygen concentration in a deepening mixed layer. Station 35 has oxygen concentrations of 7.68 - 7.75 ml/l in the upper 202 m (91.3 - 91.7% saturated) dropping to values of 7.22 - 7.23 ml/l (86.9% saturated) at the deep salinity maximum and rising again to values of 7.29 - 7.31 ml/l (87.5 - 87.7% saturated) in the deep water. The oxygen concentration averaged over the entire depth for station 35 is 7.31 ml/l; that is the same oxygen concentration as the existing deep water.

The flux of oxygen through the sea surface can be parameterized through the equation

$$F = K_w(C_a - C_w) \qquad (1)$$

where C_a, C_w are the oxygen concentrations in the atmosphere and the ocean respectively, K_w is a parameter referred to as the piston velocity and F is the oxygen flux. Field studies in which the oxygen concentrations of semi-enclosed basins have been monitored over the course of a winter season suggest that $K_w \sim 50$ cm hr^{-1}. Wind tunnel tests suggest values of 50 cm hr^{-1} at wind speeds of 10 ms^{-1}, 100 cm hr^{-1} at winds of 15 ms^{-1} (Broecker & Peng, 1982). Using the value of $K_w = 50$ cm hr^{-1}, the surface oxygen concentration and water depth for station 35, the increase of depth averaged oxygen concentration is the order of 0.002 ml/l/day, or an increase of 0.10 ml/l over the 45 days that the mixed layer model computation required for convection to the full depth. It was suggested in the discussion of the mixed layer model that the cooling and evaporation rates used were perhaps too small by a factor of two or more; hence, the increase in oxygen concentration of the water column, if deep convection had occurred, would have been 0.05 ml/l or less. Since the residence time of the deep water in the Greenland Sea is longer than 10 years, only some small fraction of its total volume can be replaced in a given year, and this calculation would suggest that the increase in the mean oxygen concentration due to such a renewal would be the order of 0.01 ml/l or less; much below the detection limit of the data.

It is possible that the presence of ice will further reduce the transfer of oxygen across the sea surface; however, it is not necessary to hypothesize such a reduction in order to account for the under saturated waters of the Greenland Sea. Deep convection penetrating into under saturated subsurface layers results in under saturated mixed layers in both the Labrador Sea (93 - 94%) and the Mediterranean Sea (78.6 - 80.6%) (Tchernia & Fieux, 1971). It is likely that the same processes are operating in the Greenland Sea.

Discussion

It is clear from the data collected during March/April, 1982, that the central Greenland Sea was very close to overturning via deep convection. There is still a question on whether overturning did, in fact, take place during that winter. In the case of formation of Labrador Sea water, the eddies containing the deep homogeneous mixed layers of new Labrador Sea water were long lived (>10 days). If such features were present in the Greenland Sea during our observational period, it is difficult to see how we would have failed to detect one. On the other hand, in the MEDOC region, once convection extends to the bottom, the new bottom water spreads away from the formation region and the surface evidence of the convection disappears quickly. In this case, it is possible to arrive too late to observe the eddies. In the Greenland Sea, an additional mechanism due to ice movement and melting is available to cap the top of a deep mixed layer with a new low salinity melt layer and hence obscure the evidence of convection. It is still an open question of how Greenland Sea Deep Water is renewed.

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TABLE I

Monthly Mean Air Temperature

Stations	Jan Mayan		Bear Island		Svalbard	
	81/82	Mean	81/82	Mean	81/82	Mean
Month						
August	4.6	5.4	4.4	5.0	5.4	4.9
September	2.1	3.9	3.1	3.0	1.3	0.7
October	-1.0	0.9	-0.1	0.4	-3.7	(-3.3)*
November	-2.8	-4.4	-1.4	-2.0	-7.4	-7.6
December	-6.0	-3.0	-10.9	-3.9	-15.0	-9.9
January	-9.0	-4.0	-12.0	-5.7	-19.7	-12.4
February	-3.5	-5.2	-7.1	-6.9	-15.6	-14.3
March	-4.6	-4.8	-3.7	-7.2	-8.6	-15.2
Total ° Days	-615	-331	-839	-516	-1909	-1720

* estimated

TABLE II

Mixed Layer Model - Winter 1982

150 watts m^{-2}, 0.002 m evap

Mixed Layer

Stn. No.	Location	Depth	σ	Cycle No.	Ice Formed
		Boreas Basin			
32	South	1065	28.071	100	None
64	South-east	143	27.993	100	0.46 heavy
		Greenland Basin			
14	East	3001^b	28.076	75	None
15	East-ridge	1559	28.075	100	0.2
34	North	3733^b	28.075	81	0.03 to 0.14
35	Centre/north	3715^b	28.075	45	0.06 to 0.12
57	Centre	3660^b	28.075	70	0.0 to 0.11
58	Centre/west	3573^b	28.076	64	0.01 to 0.08
59	Centre/south	3652^b	28.076	75	0.04 to 0.19
61	Centre/east	323*	28.057	100	0.54 heavy
62	East	3760^b	28.076	66	0.03 to 0.18
		Norwegian Basin			
65	West	505	28.030	100	None
66	West	507	28.033	100	None
67	West	539	28.028	100	None
50	North	709	28.066	100	None

b Convection to the bottom.

* Computation began with 0.5 m of ice - if ice not initially present; convects to bottom after 74 cycles forming 0.00 to 0.10 m of ice.

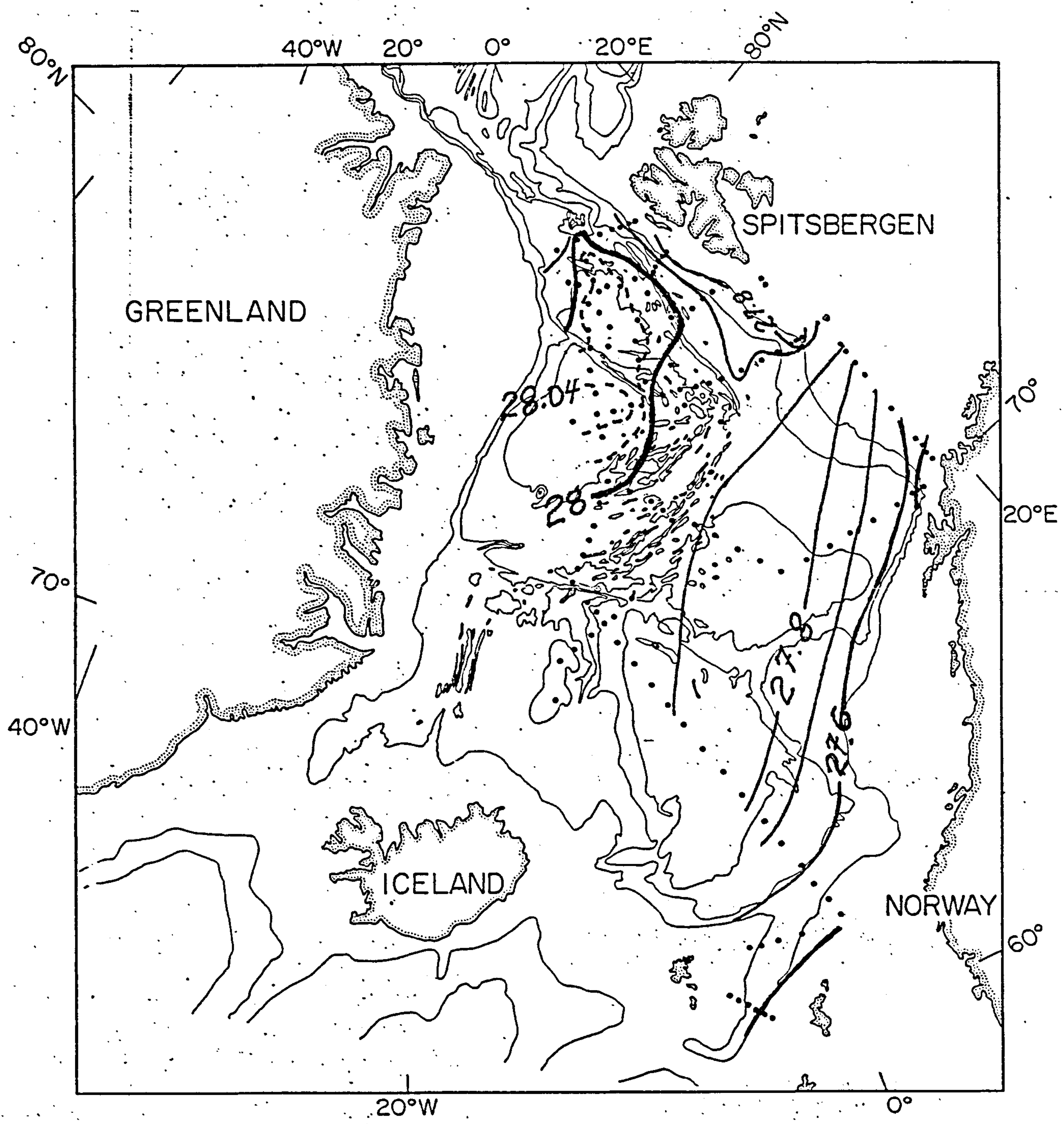

Figure 1 Potential density, σ_0, at 100 dbars for March/April, 1982.

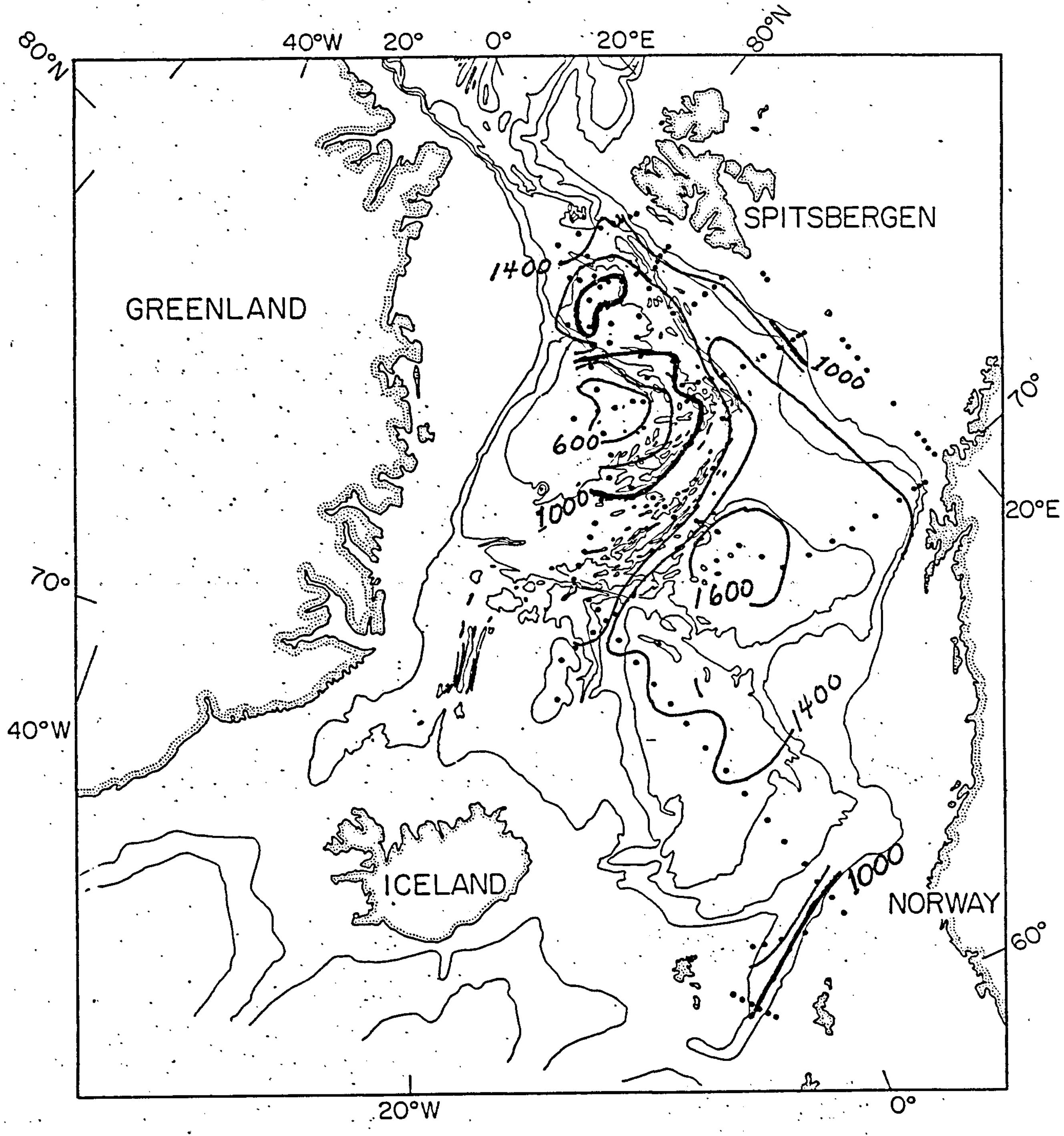

Figure 2 Depth of $\sigma_1 = 32.81$ for March/April, 1982.

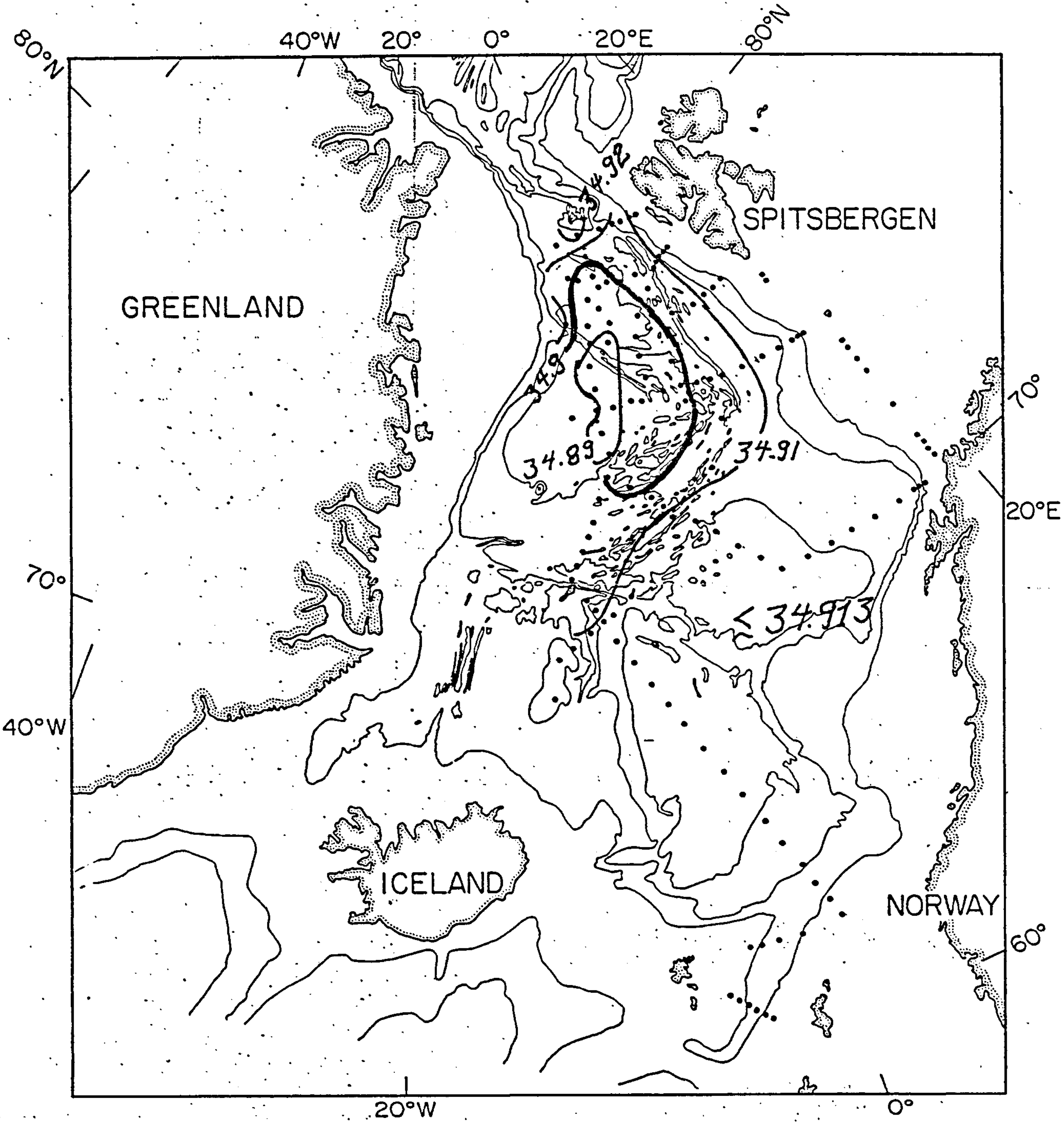

Figure 3 Salinity at $\sigma_1 = 32.81$ for March/April, 1982.

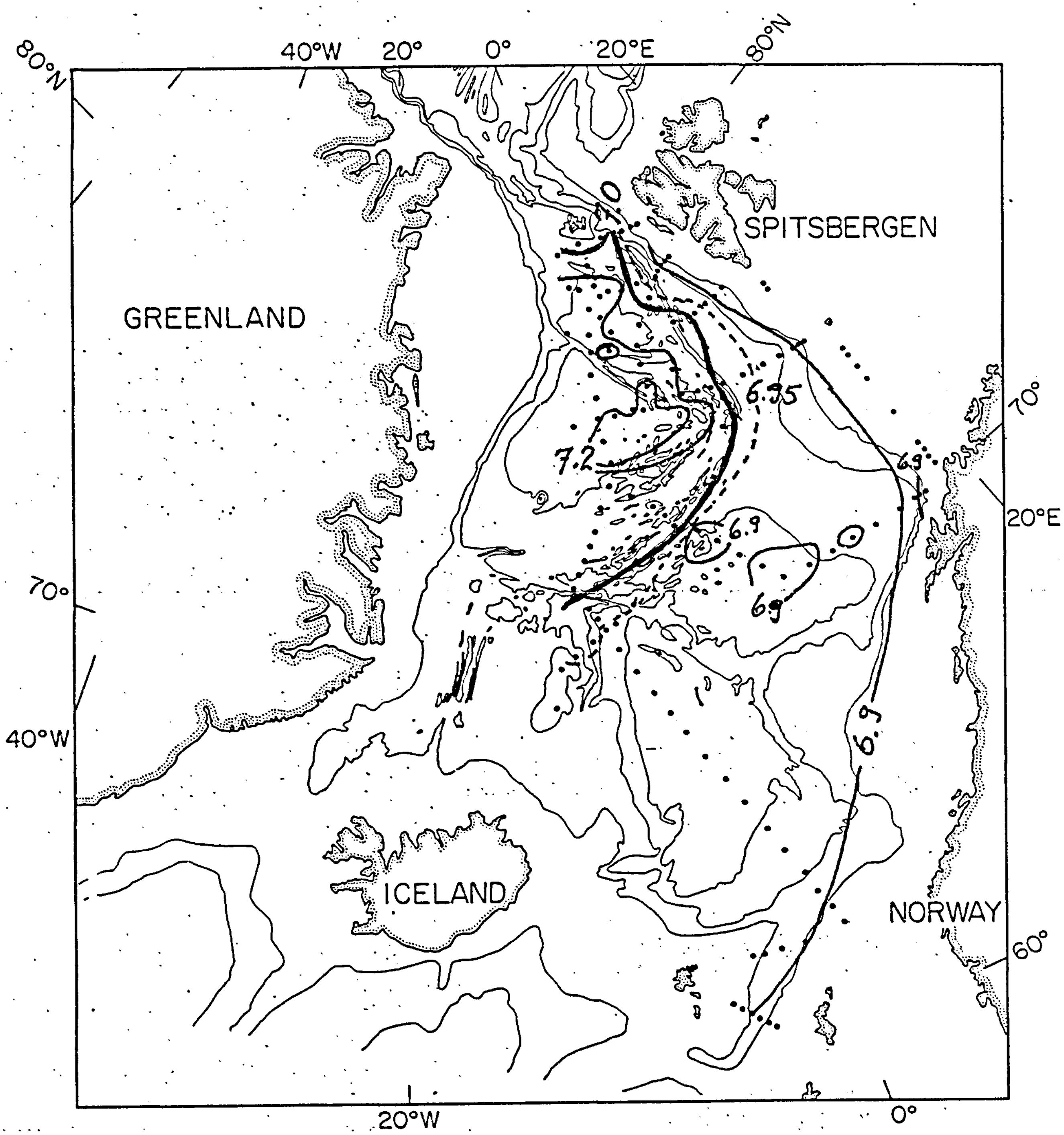

Figure 4 Oxygen at $\sigma_1 = 32.81$ for March/April, 1982.