INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA

ICES CM 2006/C:14
Use of isopycnal water mass to distinguish between variability due to the heaving of, and property change on density surfaces
.

Isopycnal Analysis of Near-surface Waters in the Norwegian-Barents Sea Region

by Tom Rossby, Vladimir Ozhigin, Victor Ivshin, and Sheldon Bacon

Abstract

The waters of the Nordic and Barents Seas exhibit very large variations in temperature and salinity. In order to distinguish between dynamical and thermodynamical effects we use isopycnal analysis to map the depths of these surfaces on the one hand, and property change along these surfaces on the other. Analysis of the 27.7 to 27.9 isopycnal surfaces show that these generally shoal to the north as expected, towards the Greenland Sea in the west and the Barents Sea in the east. However, geostrophically speaking this bowl-like shoaling pattern implies a retroflection and anticyclonic circulation in the Lofoten Basin. Identifying the processes responsible for this pattern is of fundamental importance to a proper understanding of the dynamics of the region as well as to identify transport pathways of physical, chemical and biological properties. The isopycnal analysis also reveals a conspicuous T/S-anomaly maximum in the Lofoten Basin, which appears to result from convective heat losses and downward mixing of saline waters to deeper isopycnal surfaces where they then appear as warm salty water.

We also show that temporal variations in isopycnal layer depth and water properties can persist and/or propagate around the Nordic Seas for several years. Depth variations likely reflect variations in Ekman pumping while T/S-anomalies probably result from the subduction of surface waters, and varying fluxes from the Arctic and Barents Seas. This isopycnal approach may help us better understand the roles of mechanical and thermodynamic forcing of upper ocean conditions in the Nordic Seas.

Keywords: Nordic Seas, transport pathways, isopycnal analysis, water mass modification.

Thomas Rossby: Graduate School of Oceanography, University of Rhode Island, Kingston, RI 02881, USA [tel: +1 401-874-6521, fax: +1 401-874-6728, e-mail: trossby@gso.uri.edu]

Vladimir Ozhigin: Knipovich Polar Research Institute of Fisheries and Oceanography (PINRO), 6 Knipovich Street, Murmansk, 183038 Russia [tel: + 7 8152 47 32 80, fax: + 7 8152 47 33 31, email: ozhigin@pinro.ru]

Victor Ivshin: Knipovich Polar Research Institute of Fisheries and Oceanography (PINRO), 6 Knipovich Street, Murmansk, 183038 Russia [tel: + 7 8152 47 30 64, fax: + 7 8152 47 33 31, email: ivshin@pinro.ru]

Sheldon Bacon: National Oceanography Centre, Southampton Empress Dock, Southampton SO14 3ZH, U.K. [tel: +44 23 8059 6441, fax: +44 23 8059 6204, e-mail: shb@noc.soton.ac.uk]

Introduction

No ocean region has been studied for as along or as thoroughly as the Nordic Seas. Already in 1887 Mohn published a chart of the circulation of the Norwegian Sea clearly indicating the inflow of warm North Atlantic waters on the eastern side and flow south of Arctic waters in the west. This study was followed a couple of decades later by the groundbreaking Helland-Hansen and Nansen (1909) study of the hydrography of these northern waters. Using both water mass analysis (reversing thermometers and accurate salinity titrations) and the dynamic method the circulation patterns they published have stood the test of time impressively well. Even today their figure of salinity in the southern Norwegian Sea and across the Iceland-Faroe Ridge stands out as an extraordinarily prescient synthesis of circulation in the region. They detailed the route by which warm North Atlantic waters flowed north through the Norwegian Sea and beyond towards the Barents Sea and Spitsbergen. A striking aspect about the Helland-Hansen and Nansen study was their emphasis on the horizontal structure of the density field. They could do this thanks to the systematic hydrographic surveys throughout the Norwegian and Greenland Seas. For a nice, up-to-date overview of our knowledge of the Nordic Seas, please see the paper by Blindheim and Østerhus, 2005.

Many hydrographic surveys have been conducted throughout the region. Some focused on the hydrographic properties and how these vary spatially and temporally, but the majority of the surveys have taken place as part of fish stock assessment studies in particular areas such as around the Iceland-Faroe Ridge, the Lofoten region and throughout the Barents Sea. While these surveys concentrate on the upper ocean with limited coverage of deeper waters, they constitute an enormous resource for examining the mean fields of the upper ocean and how they vary with time.

In this note we explore and develop the use isopycnal analysis to more clearly separate out dynamical variations from changes in T/S-properties along isopycnal surfaces. The latter are typically quantified through T/S analysis on a regional basis. But with a large enough database, one can look at the isopycnal surfaces directly, their depths and their physical properties. This way one retains the full spatial context in which these variations are taking place. A change in depth of an isopycnal implies a change in the density and hence pressure field, a change of dynamical consequence, whereas a change in temperature/salinity make-up or spiciness on an isopycnal implies water characteristics. The latter does not impact the pressure field although it contains much information regarding the prior history of the waters.

The approach taken here is to first construct the mean hydrographic state of the upper ocean. The resulting climatologies of these upper ocean density surfaces provide a wealth of information about the basic state of the Nordic Seas. For example, as one proceeds north, surface waters lose heat such that the lighter isopycnals disappear and underlying isopycnals shoal and eventually outcrop, more specifically we can see more clearly where and how this shoaling takes place. Next these mean fields can be subdivided to look at seasonal variations. And finally, one can use the climatologies to examine how the Nordic Seas vary spatially from year-to-year, but now considering separately changes due to depth variability and changes in spiciness.

Data preparation

The data used here combine data (1946-2004) in the ICES archives and Russian data at PINRO in Murmansk, Russia. The database comprises some 364,000 stations throughout the Nordic Seas from the Iceland-Faroe Ridge in the southwest to the Barents Sea in the northeast. Each station was used to calculate depth, temperature and salinity of three sigma-t surfaces, namely 27.7, 27.8 and 27.9 kgm^{-3}. Given pairs of temperature and salinity (T and S), sigma-t values were calculated for each measurement depth for each hydrographic station. Based on adjacent sigma-t values, density inversions were checked for each hydrographic station. Stations with a density decrease (inversion) of more than 0.005 $kg/m^3/m$ were eliminated (deleted). Temperature, salinity and sigma-t were linearly interpolated between adjacent measurement depths to the set of sigma-t values 27.7, 27.8 and 27.9 kgm^{-3} to yield the following parameters for each station in the data set: (D-27.7, T-27.7, S-27.7); (D-27.8, T-27.8, S-27.8); (D-27.9, T-27.9, S-27.9). **Figure 1** shows the seasonal distribution of hydrographic stations used in this study. Clearly the summer months have the best coverage and the winter months the least. This is particularly true of the open waters of the Norwegian and Greenland Seas. The Barents Sea and all coastal waters appear to be well-sampled all-year round.

For each month in 1946-2004, D, T and S values for the corresponding isopycnals were interpolated into grid nodes. Grid spacing was 30’ along parallels (30°W to 30°E) and 15’ along meridians (50°N to 80°N). The surface mapping system SURFER 8.01 (Golden Software, Inc) was used with the *Triangulation with Linear Interpolation* method applied for gridding D, T and S. This method is an exact interpolator (honors data points exactly when the point coincides with the grid node, meaning a coincident point carries a weight of 1.0). It creates a good representation of moderate-sized data sets (250-1000 observations) and does not extrapolate values beyond the range of data. The result of this stage is a set of more than 6 000 contour maps (12 months, 59 years, 3 parameters, 3 isopycnals).

The contour maps plotted at the previous stage were rather “patchy” reflecting station availability in a particular month of a particular year. To get climatic fields of D, T and S, the contour maps (of corresponding parameters) were arranged into 12 groups (for January through December). Each group consisted of 59 maps (1946-2004) that could be considered as “layers”. To average contour maps within a group, a number of “layers” (or years) with an interpolated value was calculated for each grid node. This process has the advantage of giving equal weight to all years where data are available. To plot reliable climatic fields, interpolated values were averaged, but only for corresponding grid nodes having 10 and more values. The result of this stage is a set of 108 climatic maps (12 months, 3 parameters, and 3 isopycnals).

The mean state and annual cycle

This discussion will consist of two sections: the overall means of depth, temperature and salinity of all data. We then proceed to discuss the seasonal cycle, and lastly we give a preliminary report on interannual variability, patterns and causes.

We begin by showing in **Figure 2** the mean field of depth, temperature and salinity on one density surface, $\sigma_t = 27.9$. This is the shallowest surface that exists all year in both the Norwegian and Greenland Seas. (Depending upon the particular conditions in winter this surface may on occasion outcrop in the Greenland Sea, i.e. for a small subset stations the surface waters have a $\sigma_t > 27.9$. These are ignored). The three panels show depth (meters), temperature (°C) and salinity (PSU), left to right. The depth of the isopycnal shows clearly the baroclinic inflow from the Iceland-Faroe Front, turning straight north and away from the Norwegian coast towards the western Lofoten Basin where the isopleths turn almost east and northeast and north towards the Fram Strait. This would be the pathway of North Atlantic waters that have entered the Nordic Seas between Iceland and the Faroes. This pattern accords well with the sketch of the North Atlantic inflows in Orvik (2004).

The panels of temperature and salinity show clearly the warm salty waters of the North Atlantic on the eastern side and the cold fresh waters from the Arctic in the Greenland and Iceland Seas. We further see a very sharp gradient in water properties (which we will call spiciness for short) along the Jan Mayen Mohn and Knipovich Ridges. This is a very fundamental result: the mid-atlantic Ridges serve as barriers to mixing between these two major water masses from the North Atlantic and Arctic, respectively. Without this barrier, the fresh waters from the Arctic could reduce the salinity of the North Atlantic waters to the point that they could not sink in wintertime and produce the dense waters that spill back out into the Atlantic and beyond.

It is interesting to note that the high gradients of spiciness do not coincide with gradients in depth, or what we will refer to as baroclinity from now on. The latter indicates a velocity shear, whereas the former indicates a transition from one water mass type to another. A property gradient may imply a lack of mixing or exchange of waters. The fact that the two do not generally coincide anywhere other than over the Mohn Ridge suggests that different physical mechanisms are controlling currents and mixing.

An interesting feature to emerge from these analyses is the field of warm salty water in the Lofoten Basin west of northern Norway. It appears that this local excess spiciness results from the loss of heat and ‘densification’ of the salty surface waters. As these waters sink to a deeper isopycnal, they are saltier than the preexisting waters on the deeper surfaces, and thus appear as warm salty water. The actual mechanism by which this vertical flux takes place needs much more study, but most likely it is through saltfingering (Pereskokov, 1999).

If we look at the 27.7 surface (which does outcrop in the Greenland Sea in winter), we notice that the baroclinic shear from the Iceland-Faroe Front does not continue north to the Mohn Ridge but curls around the Vøring Plateau and continues northeast much more closely to the Lofoten Islands and beyond, **Figure 3**. The spiciness gradients, on the other hand, continue north to the Mohn Ridge and beyond, very much the same as for the 27.9 surface. We find thus that the density field and the property fields exhibit different patterns in the vertical. Intuitively, one might have expected the density field to be more locked in the vertical, i.e. strong tilts are lined up in the vertical such as in major currents, for example, with the property fields exhibiting more depth dependence, but here it is the other way around, the spiciness patterns are lined up while the flow patterns differ.

The quarterly mean fields in **Figures 4 and 5** show rather little change over the year. Temperatures are lower in winter in the Greenland Sea reflecting the fact that the isopycnal is very close to the surface. In the Norwegian Sea the depth of the 27.9 surface shows a hint of deepening in winter but its significance remains to be determined. The main point is that the seasonal cycle is quite muted in depth and no T/S variability other than at the surface in the Greenland Sea. Knowing this makes studies of longer-term variations easier to explore.

Interannual variations

With the mean state now well-known, and given that the annual cycle evidently has little signal, we can use the extensive data set to explore variations from year to year. What immediately becomes apparent is that these anomalies, however they are induced, can be quite substantial, as large as ±200 m. We consider depth changes first. We see a significant deepening of the 27.8 isopycnal taking place in the 1987-1989 timeframe, a state that persists until 1996-1997, a period during which the isopycnal is much shallower. By 1999 the surface has deepened noticeably. In 2001 and 2002 the surface is conspicuously deeper in the Lofoten Basin but nearly average in the Greenland Sea. The fact that deviations appear for consecutive years - such as deepening in the Lofoten Basin and in the Barents Sea clearly indicates that these anomalies can persist for considerable periods of time. The corresponding temperature anomalies have a range in excess of ±1°C, and these can show patterns of persistence. But the variability is conspicuously greater on the Greenland Sea side and in the northern Barents Sea. Along the Atlantic inflow including the southern Barents Sea the anomaly of temperature on the isopycnal rarely deviates more than ±0.5°C, but large variations in the Iceland Sea can get advected into the southern Norwegian Sea and continue northwards. These are examples of advection and mixing along isopycnals, and not due to local outcropping. For the purposes of this note, we show a set of four summer plots of isopycnal depth and salinity anomaly for the years 1986-1989 in **Figures 6 and 7.**

Variations in depth very likely reflect changes in atmospheric forcing, particularly Ekman pumping (Jonsson, 1991). Winds can also come into play through differential forcing of the NE Atlantic and the Nordic Seas (Orvik and Skagseth, 2003). The fact that the variations in water properties are larger in the Greenland and northern Barents Seas no doubt reflects outcropping in winter. As these waters subduct and move cyclonically around the Nordic Seas they carry memory of this previous exposure. If the surface remains covered the following winter (farther south), then the anomaly can remain for a longer period, and which might account for the progression of anomalies from the Greenland Sea, into the Iceland Sea and then the southern Norwegian Sea. Shifting circulation patterns can contribute too. We see some evidence of variability in the vicinity of the mid-Atlantic ridges (Mohn and Knipovich Ridges) suggesting mixing effects across topography.

Summary

The isopycnal analyses shown here seek to distinguish between dynamical change as measured by changes in depth and property change due to T/S variations *on* an isopycnal. In conventional x-y-depth displays it is difficult to distinguish between the two due to the basic stratification of the water column. This is, of course, well-known, but the large volume of stations in the Nordic Seas allows one to explore the spatial structure of the density field and how it varies, not at merely at prescribed depths or on T/S diagrams, but on selected *isopycnal surfaces.* A central result here is that the mean fields of depth and property have distinctly different patterns. We find that the mid-Atlantic ridges serve as a dynamical (in the sense that the ridges are much deeper but are felt throughout the entire water column) barrier to interbasin exchange. But property fronts need not and typically do not coincide with dynamical fronts, i.e. currents. This is not so obvious when we examine fields as a function of depth because what looks like a large property change across a front, may actually result from water of the same property appearing at different depths.

Once the basic state has been determined, it can serve very effectively as a basis for exploring anomalies and their behavior in the Nordic Seas. This is where the large data base can be very useful. Looking from one year to the next one can observe very substantial variations in both isopycnal layer depth and properties anomalies, and these can persist for several years. Depth variations most likely reflect variations in Ekman pumping and T/S anomalies subduction and advection of past exposure to surface wintertime conditions. This isopycnal framework allows one to more clearly distinguish between the effects of mechanical and thermodynamic forcing. We plan to start some studies in this direction. But it is also clear that these fields, or reanalyses to borrow a phrase from meteorology, may prove useful for testing and verifying numerical models and simulations of the Nordic Seas circulation.

References:

Blindheim, J. and S. Østerhus, 2005. The Nordic Seas, Main Oceanographic Features. In: 'The Nordic Seas – *An Integrated Perspective*' Helge Drange et al. Editors. AGU Geophysical Monograph 158.

Helland-Hansen, B. and F. Nansen, 1909. The Norwegian Sea: Its Physical Oceanography based on Norwegian Researches 1900-1904. In *Report on Norwegian fishery and marine investigations, vol. 2*. Bergen, Norway, 390 pp + 25 plates.

Jonsson, S., 1991. Seasonal and interannual variability of wind stress curl over the Nordic Seas. Journal of Geophysical Research, 96(C2), 2649-2659.

Orvik, K. A., 2004. The deepening of the Atlantic water in the Lofoten Basin of the Norwegian Sea, demonstrated by using an active reduced gravity model. Geophysical Research Lettters, 31, L01306, doi:10.1029/2003GL018687, 2004.

Pereskokov, A. I., 1999. On the physical nature of the large-scale anticyclonic eddy in the water column of the Norwegian Sea. Doklady Akademii Nauk (Contributions of the Academy of Science, 364(4), 549-552.

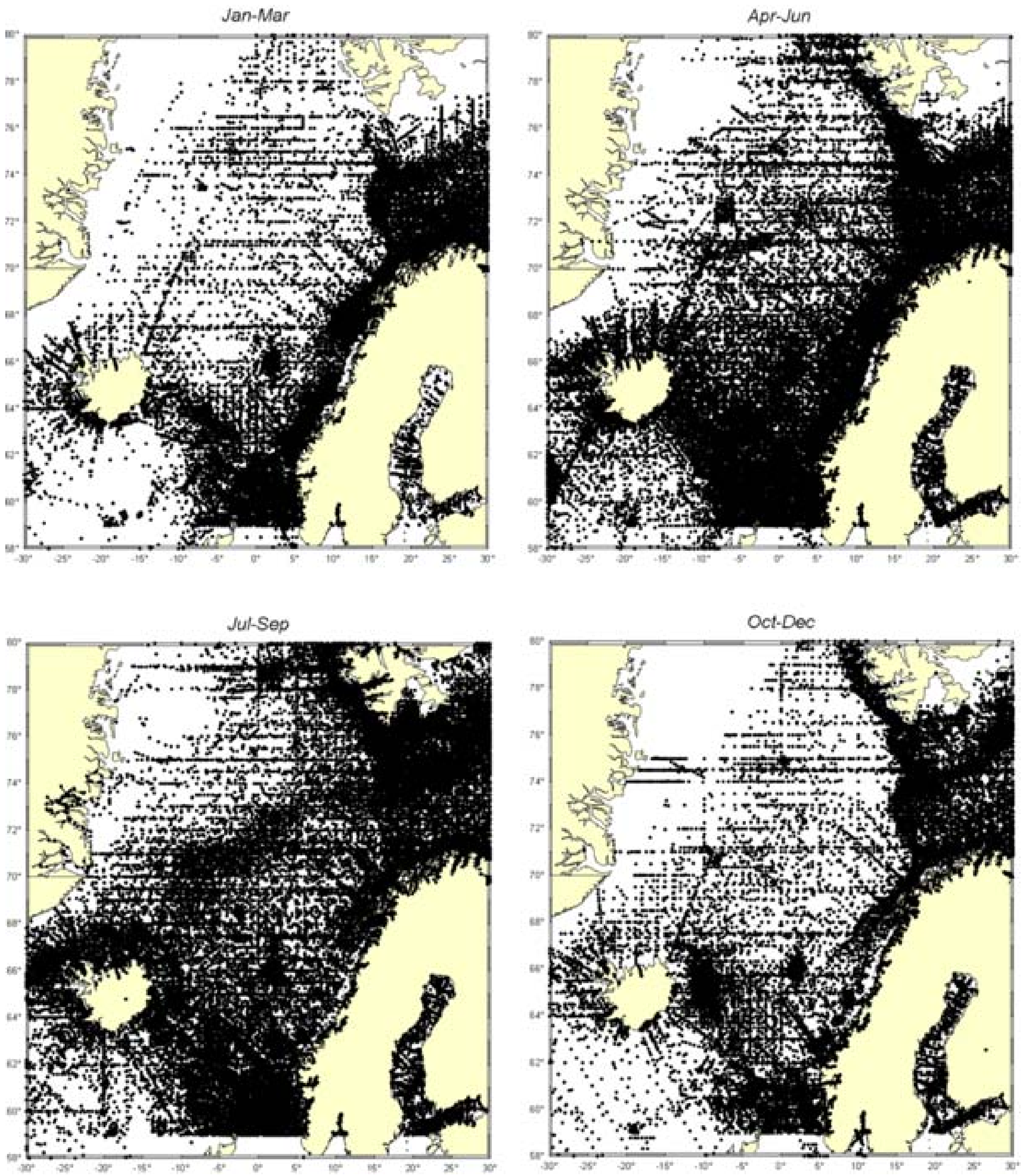

Figure 1: Distribution of hydrographic data available for this study. Many of the stations were obtained as part of fisheries surveys and thus do not go deeper than 1000 m, but for this study that is not a problem.

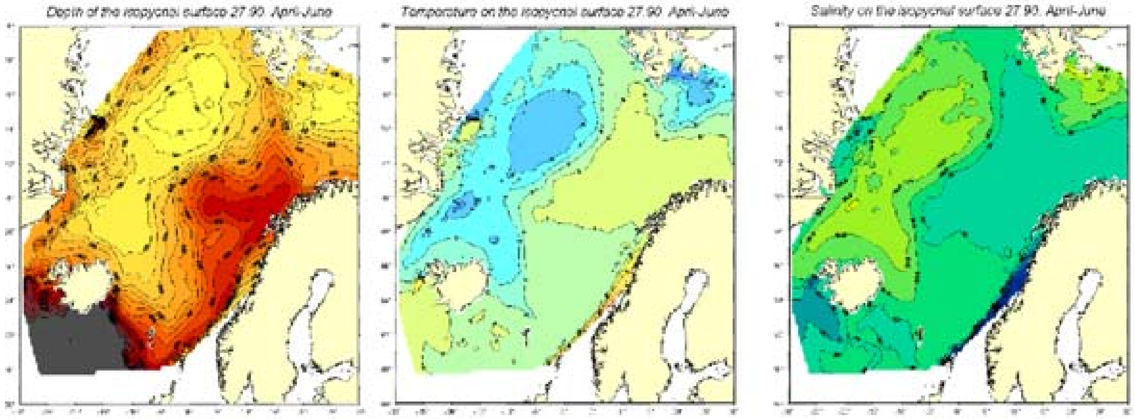

Figure 2: Depth, temperature and salinity of the 27.9 sigma-t surface. Note that the gradient in depth, corresponding to strong vertical shear, does not coincide with the gradient in T/S.

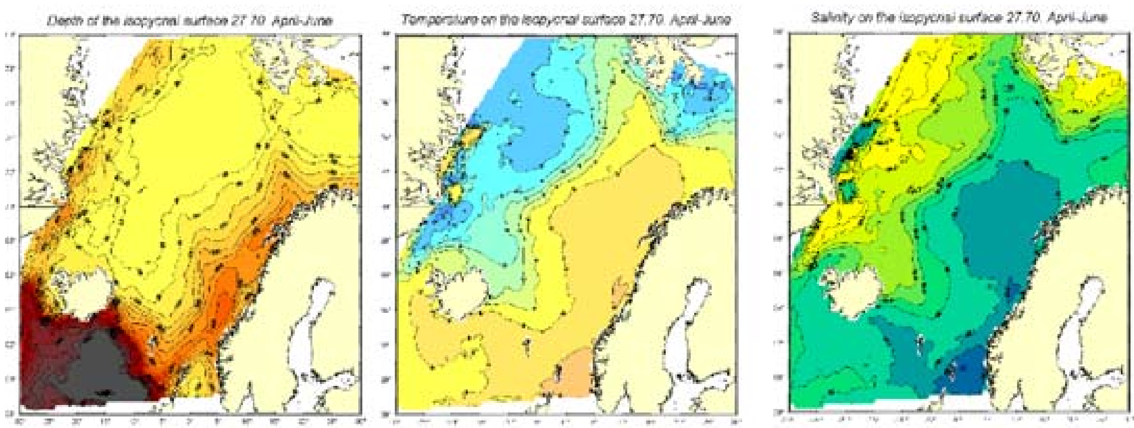

Figure 3: Depth, temperature and salinity of the 27.7 sigma-t surface. Note that the depth contours run much closer to Norway here than on the deeper surface. On the other hand the temperature and salinity contours appear to be much more congruent with the corresponding fields on the deeper surface.

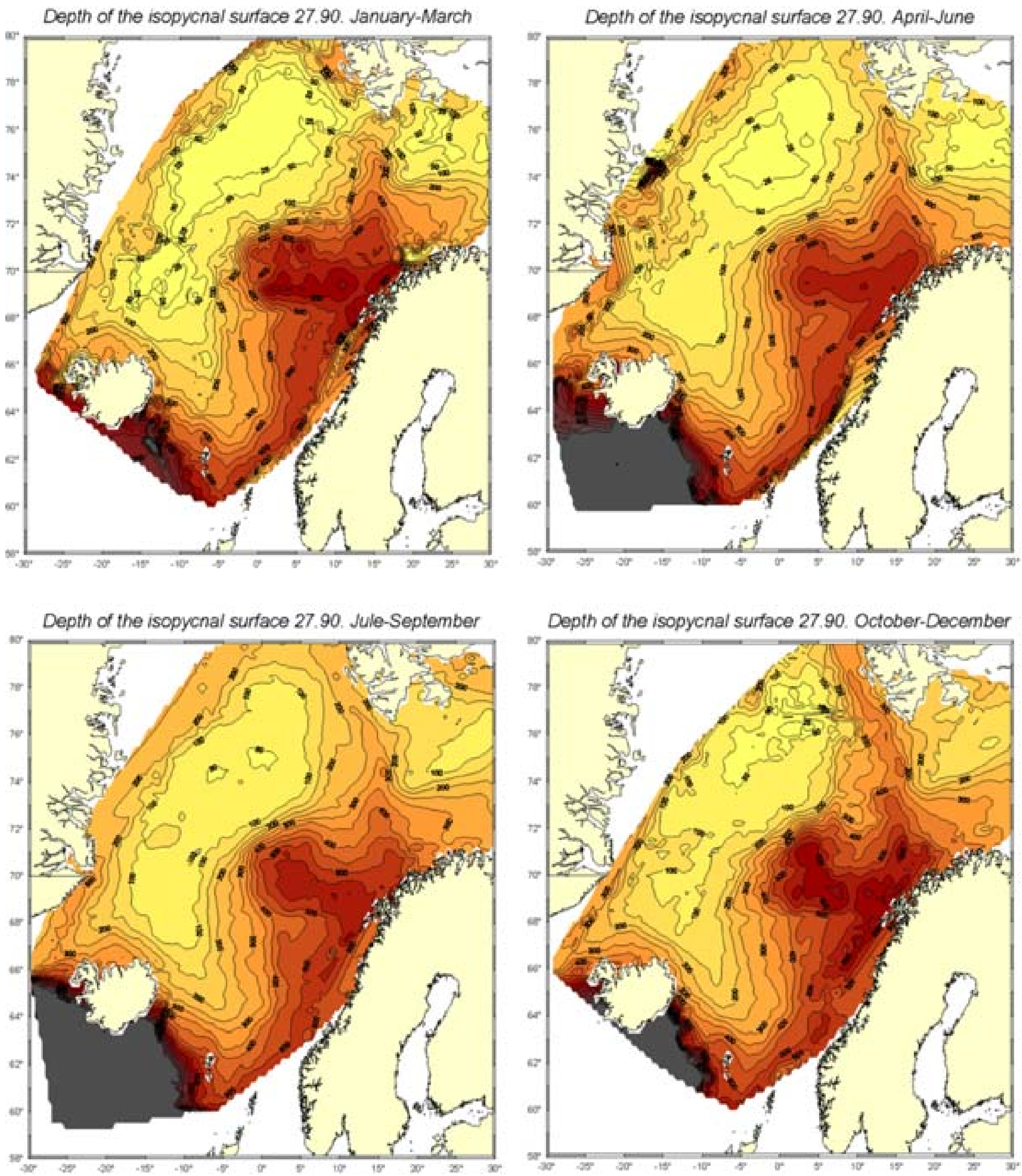

Figure 4: Depth of the 27.9 sigma-t surface for the four seasons. Any seasonal signal is quite slight. There is a hint of greater depth or broadening of the deep field in the Lofoten Basin in winter.

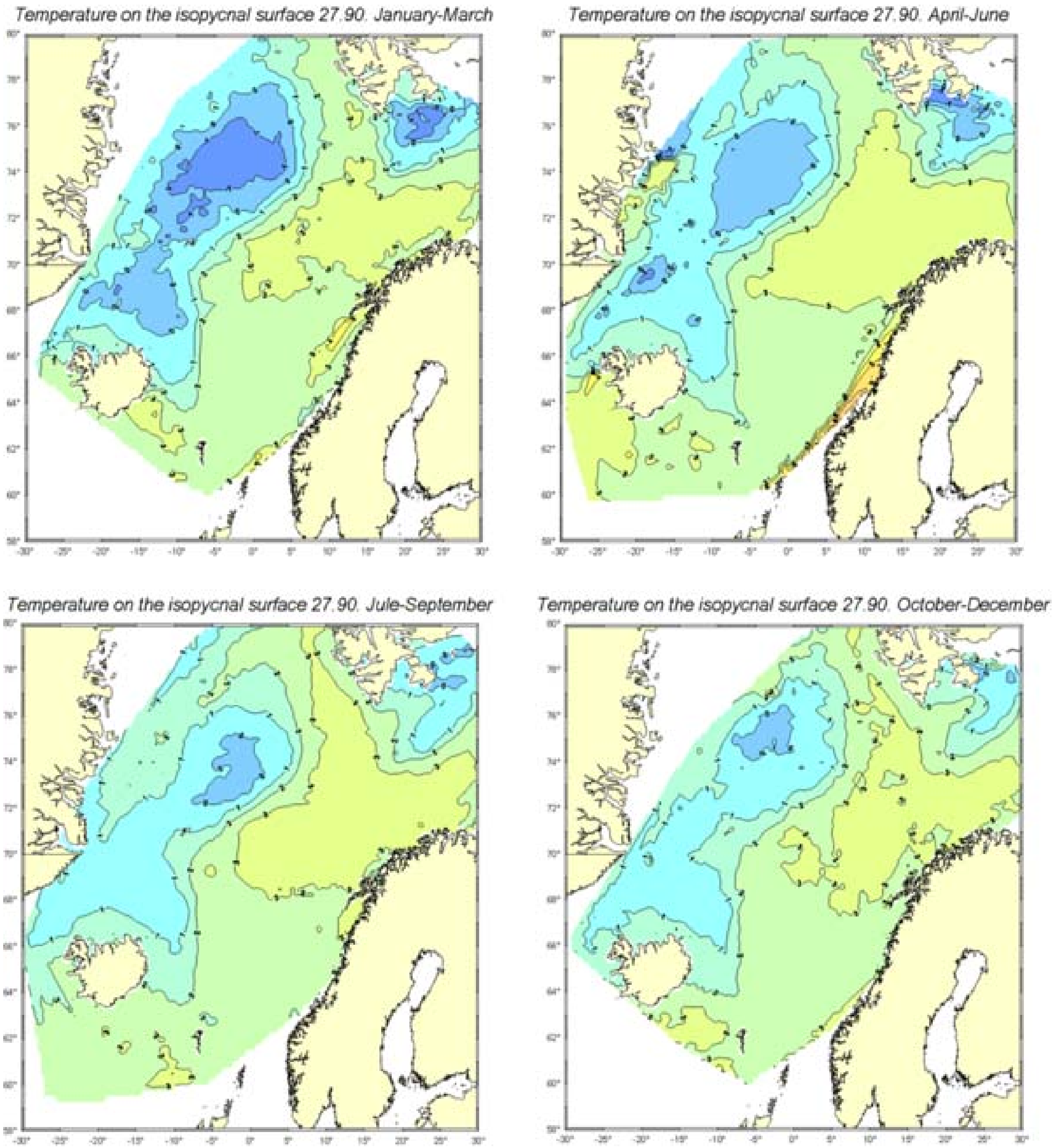

Figure 5: Temperature on the 27.9 sigma-t surface. The pattern shows little seasonal change except in the Greenland Sea where it is very close to the surface.

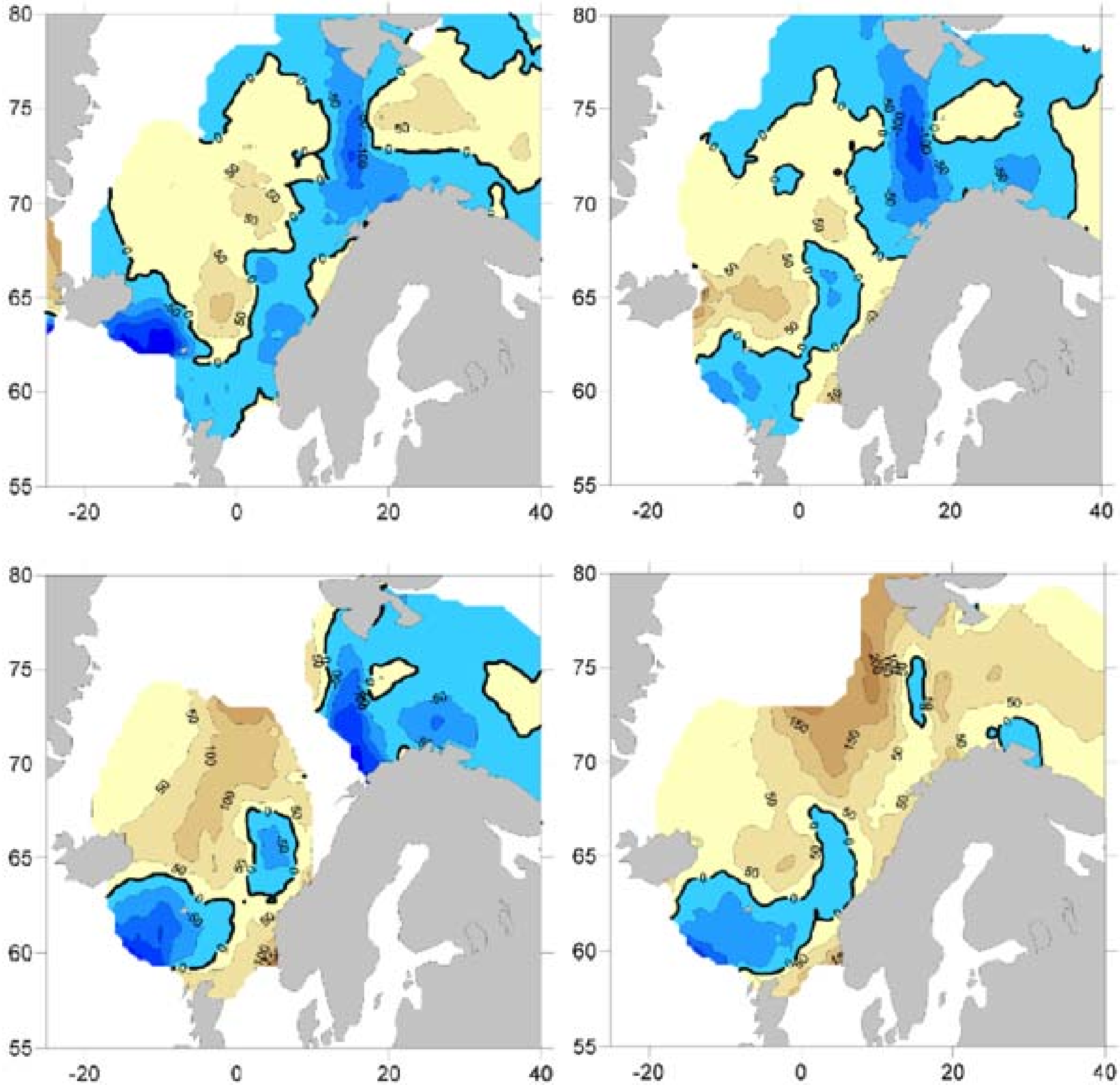

Figure 6: Depth anomaly in m of the 27.8 sigma-t surface in summer 1986, 1987, 1988 and 1989 left to right, top to bottom (positive deeper). Note the general deepening during this period.

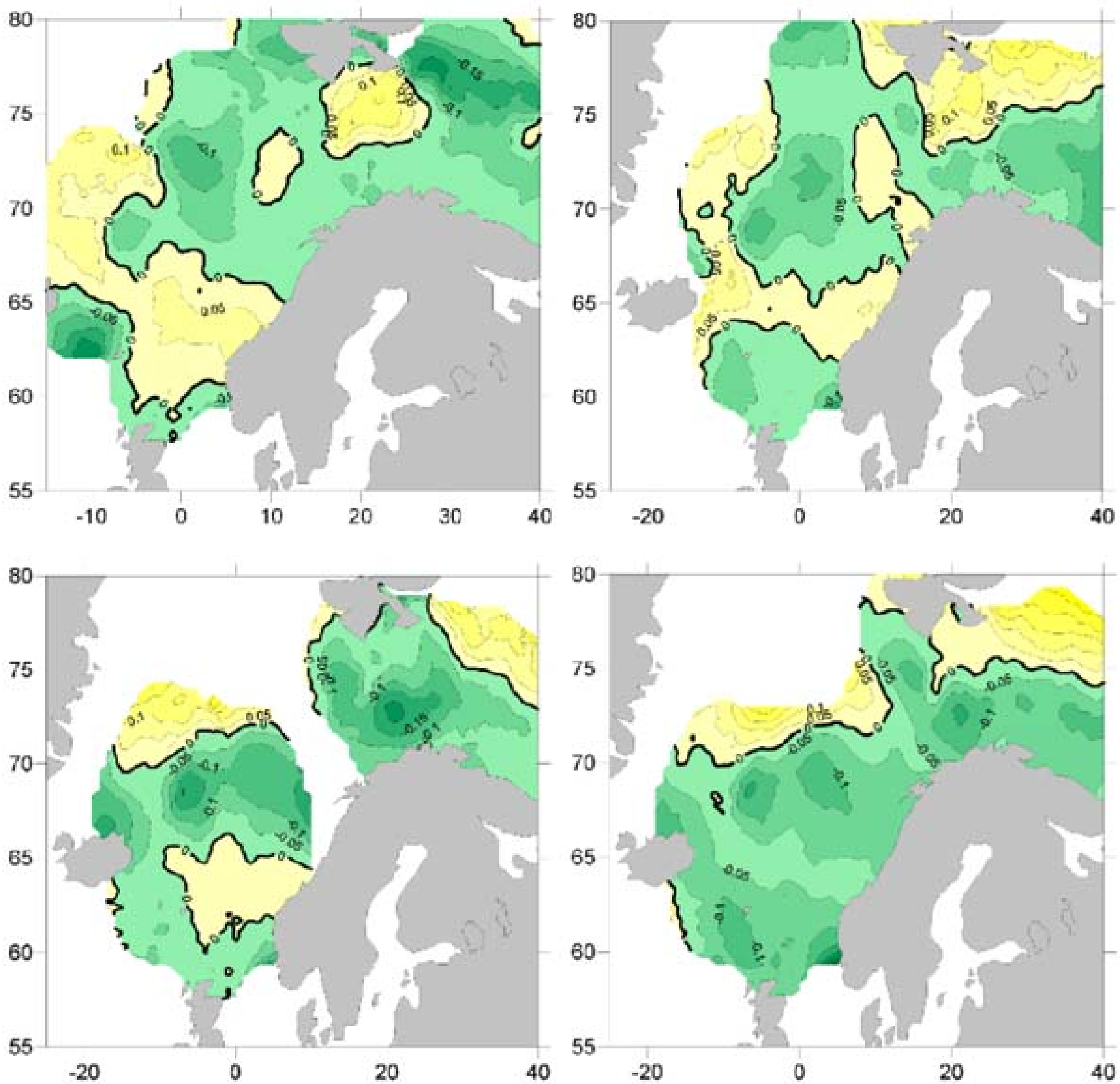

Figure 7: Salinity anomaly (PSU) of the 27.8 sigma-t surface in summer 1986, 1987, 1988, and 1989 (0.05 contour interval, positive saltier).