Wind-Driven Variability of the Large-Scale Recirculating Flow in the Nordic Seas and Arctic Ocean

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ABSTRACT

The varying depth-integrated currents in the Nordic seas and Arctic Ocean are modeled using an integral equation derived from the shallow-water equations. This equation assumes that mass divergence in the surface Ekman layer is balanced by convergence in the bottom Ekman layer. The primary flow component follows contours of f/H. The model employs observed winds and realistic bottom topography and has one free parameter, the coefficient of the (linear) bottom drag. The data used for comparison are derived from in situ current meters, satellite altimetry, and a primitive equation model. The current-meter data come from a 4-yr record at 75°N in the Greenland Sea. The currents here are primarily barotropic, and the model does well at simulating the variability. The ''best'' bottom friction parameter corresponds to a spindown time of 30–60 days. A further comparison with bottom currents from a mooring on the Norwegian continental slope, deployed over one winter period, also shows reasonable correspondence. The principal empirical orthogonal function obtained from satellite altimetry data in the Nordic seas has a spatial structure that closely resembles f/H. A direct comparison of this mode's fluctuations with those predicted by the theoretical model yields linear correlation coefficients in the range 0.75–0.85. The primitive equation model is a coupled ocean–ice version of the Princeton Ocean Model for the North Atlantic and Arctic. Monthly mean depth-averaged velocities are calculated from a 42-yr integration and then compared with velocities predicted from an idealized model driven by the same reanalyzed atmospheric winds. In the largely ice-free Norwegian Sea, the coherences between the primitive equation and idealized model velocities are as high as 0.9 on timescales of a few months to a few years. They are lower in the remaining partially or fully ice-covered basins of the Greenland Sea and the Arctic Ocean, presumably because ice alters the momentum transferred to the ocean by the wind. The coherence in the Canadian Basin of the Arctic can be increased substantially by forcing the idealized model with ice velocities rather than the wind. Estimates of the depth-integrated vorticity budget in the primitive equation model suggest that bottom friction is important but that lateral diffusion is of equal or greater importance in compensating surface Ekman pumping.

1. Introduction

The Nordic seas and the Arctic Ocean can be thought of as the northernmost limb of the meridional overturning circulation: warm water is brought northward, entering the domain primarily on the eastern side, and cold, dense water is exported to the North Atlantic across the Greenland–Scotland Ridge east and west of Iceland.

The significance of topography on the large-scale circulation within the Nordic seas and the Arctic Ocean has long been recognized. In their monumental treatise of the Nordic seas, Helland-Hansen and Nansen (1909) give a careful description of the bathymetric features as they were known at the time, and infer cyclonic circulations associated with the major basins (the Greenland, Norwegian, Lofoten, and Iceland Basins). They note that topographic features, in particular ridges and elevations projecting seaward from the continental slope, probably are of special importance for the division of the cyclonic systems. They also remark

> As the configuration of the sea-bottom, even at great depths, has a very great influence upon the directions of currents and the circulation of the sea, even near its surface, it is much to be regretted that a more detailed knowledge of the topography of the bottom of the Norwegian Sea has not been acquired, as such knowledge would have been most desirable in discussing the circulation of this sea. It would be reasonable to suppose that many features of this circulation which may now seem puzzling, would then have been easily explained.

One of the topographically steered circulation features described by Helland-Hansen and Nansen is the inflow of Atlantic water in the southern Norwegian Sea.

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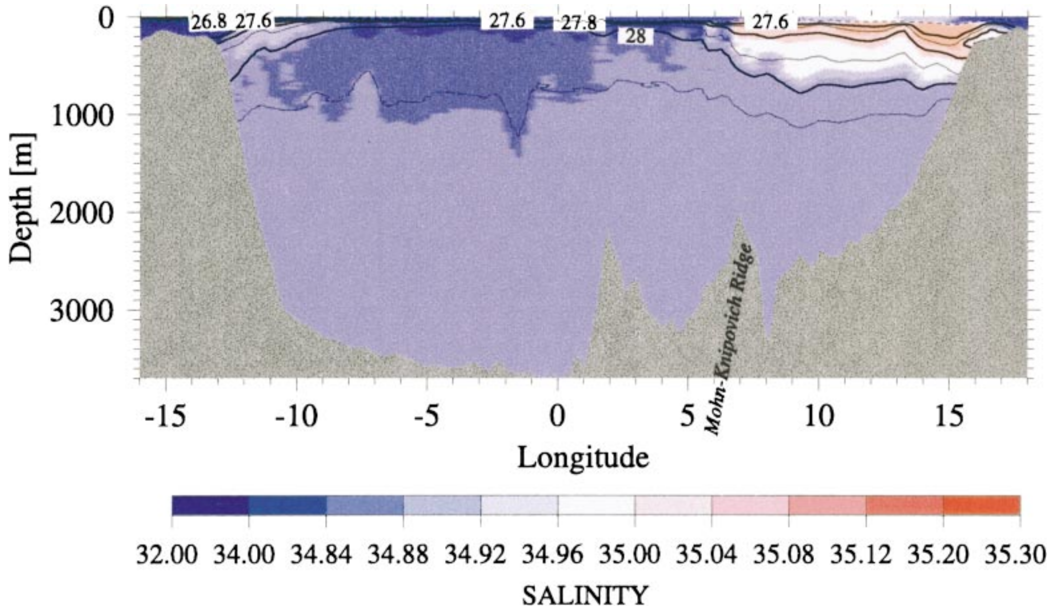

FIG. 1. Salinity (shaded) and potential density (contoured) for a transect crossing from the Norwegian coast via the Lofoten Basin and into the Greenland Sea.

They infer its circulation by interpreting the temperature and salinity fields, and describe an Atlantic inflow that follows the bathymetry along the continental slope of Norway and diverges near 66°N where the current partly is steered westward by the Voering Plateau, and partly continues northward.

This scenario was supported by Poulain et al. (1996) and Orvik and Niiler (2002), who used drifters to study the surface circulation. Three circulation branches, each following isobaths, are evident in the high-velocity trajectory field (their plate 3). Further evidence of cyclonic recirculation gyres, linked to topography and deduced by surface drifters, has been recently presented by Jakobsen et al. (2003).

The ''roof'' of the Voering Plateau has a water depth between 1200 and 1400 m, and the Atlantic water above only reaches to about 60 m, yet the Atlantic water undoubtedly ''feels'' this ''seaward-projecting elevation,'' in Helland-Hansen and Nansen's words.

North of the Voering Plateau the Mohn–Knipowich Ridge clearly influences the flow of the Atlantic water: it creates a barrier between a cold and dense regime to the west (the Greenland Basin) and the warmer domain of the Atlantic water to the east (Fig. 1).

4. Summary and discussion

We have applied an analytical solution to predict depth-averaged currents in the Nordic seas and the Arctic Ocean. This solution assumes a balance between surface and bottom Ekman transports in a region bounded by a closed f/H contour [and is dynamically similar to that of Kamenkovich (1962), and other subsequent models]. It applies to homogeneous fluids, but also to stratified fluids under the conditions that 1) topography dominates f/H and 2) the bottom velocities are significant and related to the depth-averaged velocities. The barotropic solution employs observed winds and real topography and has one free parameter, the bottom Ekman number.

We compared the solution with data from three sources: 1) two current-meter moorings in the Greenland and Norwegian Seas, 2) satellite altimetry, and 3) a primitive equation model. In the first and third cases, the current fluctuations have demonstrably weak vertical shear and significant bottom velocities (of course, the altimeter data give us no information on this). In all three cases there is evidence for flow following f/H. The solution was able to reproduce a large fraction of the variability in all cases, in particular on seasonal to annual timescales (the strong variations on these scales reflect similar variations in the wind). The solution worked better in ice-free regions, presumably because ice alters the momentum transfer at the sea surface. However, we obtained improved predictions against the primitive equation model in one fully ice covered region by ''forcing'' the theoretical model with the observed ice velocities rather than the wind.

These results thus suggest that a significant portion of the variability in the Nordic sea gyres on monthly to yearly timescales is wind-driven, along-f/H, and thus predictable. It is remarkable that in some locations we can produce almost identical transport variations to those found with a (computationally intensive) primitive equation model. The key requirement is that f/H be closed.

As noted earlier, Poulain et al. (1996), Orvik and Niiler (2002), and Jakobsen et al. (2003) have analyzed the surface currents in the Nordic seas using drifting buoy data. These authors observed gyre flows in the Norwegian, Lofoten, and Greenland Basins that were strongly linked to topography and evidently driven by the wind. The gyres were strongest during winter (and, interestingly, during periods of high North Atlantic Oscillation index).