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Direct measurements of the mean flow and eddy kinetic energy structure of the upper ocean circulation in the NE Atlantic

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[1] The upper ocean circulation in the sub-polar northeast Atlantic has been a challenge to quantify due to strong and variable wind-forcing, and strong and variable deep currents that lead to large uncertainties in the use of the standard dynamical method. Since 1999 we have been operating an acoustical Doppler current profiler on a container vessel that operates between Denmark and Greenland to repeatedly sample upper ocean currents across the northeast Atlantic. Individual transects exhibit a highly energetic mesoscale variability, but ensemble-averaging of the sections reveals a striking organization of the mean field along the Reykjanes Ridge: a distinct southward flow along its eastern slope and two clearly defined peaks with seasonal modulation flowing to the north along its western slope. Higher values of eddy kinetic energy (about 150–600 cm^2 s^{-2}) are observed along the transect, O(1.5) greater than surface drifter estimates.

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1. Introduction

[2] The advection of warm subtropical waters east- and northward along the Subpolar Front plays a central role in moderating the climate of the European subcontinent. Further, it is known that there exist low frequency (seasonal to decadal) variations in the circulation and hence poleward transport of mass and heat [*Bersch et al.*, 1999]. Unfortunately, the lack of accurate information on currents (currents and transports are rarely measured, they are inferred from the density field) has made this variability difficult to define and quantify.

[3] The literature on the North Atlantic circulation has a long history and many studies have been conducted of the hydrography of this ocean. The International Geophysical Year (IGY) program in the late 1950s with extensive surveys was probably the most ambitious effort ever [e.g., *Dietrich et al.*, 1980; *Ivers*, 1975]. Out of these earlier efforts other programs have sought to improve our knowledge of the circulation [*Krauss*, 1986, 1995; *Poulain et al.*, 1996; *Hansen and Østerhus*, 2000; *Lavender et al.*, 2000; *Cuny et al.*, 2002; *Fratantoni*, 2001; *Jakobsen et al.*, 2003], but it is an interesting fact that even today this knowledge tends to be communicated in terms of sketches about how warm waters are transmitted north rather than as quantitative statements about the mean circulation and its variability. The reasons for this can be traced to data uncertainties, perhaps change over time, and/or to the dynamic or geostrophic method, which depends upon assumptions about the velocity field at some depth. There are ways to work around this limitation using inverse methods, data assimilation into dynamical models, or by integrating the equations of motion given the mean density field, and average forcing at the surface [*Greatbatch et al.*, 1991; *Bogden et al.*, 1993; *Bacon*, 1997]. However, these estimates differ by quite a bit, and depend upon assumptions about forcing, the relative roles of advection, diffusion, baroclinicity and bathymetry.

[4] In order to understand the total velocity field and its variability, direct measurements of currents are necessary. Since the eddy field is far more energetic than the mean, many repeat observations are needed in order to construct accurate ensemble averages of the mean field and eddy fluxes of heat, salt and other tracers. Out of these needs, a project to measure currents directly was started in late 1999. The approach was to instrument a container vessel that operates between Denmark and Greenland with a hull-mounted ADCP to measure directly upper ocean currents. This vessel, 'Nuka Arctica', operates on a three-week schedule (see Figure 1). Since late 1999, the 'Nuka Arctica' has collected velocity data from nearly 50 transects to the end of 2002.

2. Instrument and Methods

[5] The instrument is a RD Instruments Narrowband 150 kHz ADCP transducer mounted in a sea chest. In the Atlantic Ocean the ADCP is configured to sample the vertical structure of currents in 8 m bins to achieve reliable data to about 400 m depths.

[6] The measured current is relative to the ship, and the motion of the ship has to be determined from the GPS. The accuracy of the ship's speed from GPS is typically 0.05 m/s [*Rossby and Gottlieb*, 1998], and the ship's service speed is 16.5 knots. The ADCP records data which are averaged in

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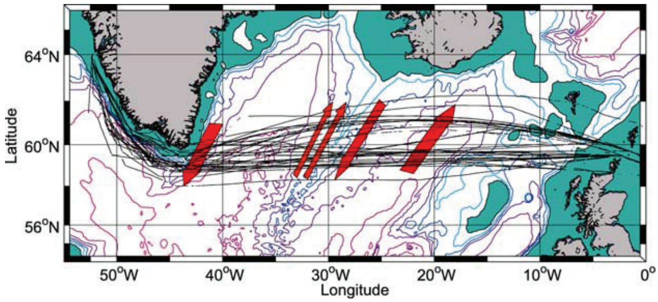

Figure 1. Ensemble of the transects between Denmark and Greenland collected by the Nuka Arctica. Additional transects that fall out outside acceptable limits either due to transits to Reykjavik or bad weather are not shown. The green areas are shallower than 500 m, and the depth contours range from 500 m to 3500 m in 500 m steps. The arrows schematically represent from west to east: EGC, twin-peaks IC, southward flow on the eastern side of the Reykjanes Ridge, and NAC.

five minute intervals, resulting in a spatial resolution of about 2.5 km for the velocity profiles.

[7] Figure 1 show the ensemble of Nuka Arctica ADCP transects to date between Denmark and Greenland. The transects fall into two sub-groups, the largest of which is the eastbound section along 60°N from Cape Farewell to Shetland. The other group is a westbound great circle section that goes farther to the north, about 62°N. All transects were subject to various forms of quality control leaving us with 33 good sections, 20 in the southern group and 13 in the northern group. Anticipating that the Reykjanes Ridge topography may play a significant role in structuring the flow in the area, we define a coordinate system that has one axis parallel to the Reykjanes Ridge and one axis in the east-west direction. The data are then grouped into 9–17 km boxes along latitude.

3. Results

[8] We focus on the circulation in the Iceland and Irminger Basins where the effect of aliasing by tides is minimal. Figure 2 shows the mean statistics based on all data from the first four years of operation. The top panel, Figure 2a, show the Eulerian mean velocity vectors and the corresponding velocity variance ellipses along the track, calculated for boxes of 45 km in the east-west direction. The ellipses correspond to one standard deviation and their shapes indicate the coupling between u' and v', where u' and v' represent the difference between the velocity component and its local mean. In the East Greenland Current (EGC) there is a strong coupling between them, somewhat less in the Irminger Current and North Atlantic Current (NAC), and for the rest of the transect the eddy field is nearly isotropic. The vectors are enlarged four times to more easily see their direction and variation in strength of the flow along the section. Without this enlargement it is clear that the mean flow vectors are small compared to the size of the ellipses.

[9] The mean flow shown in Figures 2b and 2c with 9 km box width is vertically averaged for the upper 200 m due to small vertical shear below in the range of the ADCP. All the 33 sections are averaged to one mean field in Figure 2b. The velocity is along and normal to the Reykjanes Ridge, positive to the northeast and southeast, respectively. The x-axis indicates distance in the east-west direction, where $x = 0$ is the middle of the ridge. To the extreme left the panel shows the East Greenland Current (EGC) flowing southwest, which is the most powerful signal in the dataset. Immediately to the east of the EGC in the central Irminger Basin both the velocities and eddy kinetic energies reach their lowest levels along the entire section. Within about ±150 km spanning the Reykjanes Ridge, Figure 2b reveals a striking northward flow on the western side of the Reykjanes Ridge ($x < 0$) in the form of a double peak whereas the southward flow on the eastern flank of the ridge ($x > 0$) has only a single peak. The velocity along the ridge is significantly higher than the component normal to the ridge out to about 200 km away from the ridge crest. Farther east, in the central parts of the Icelandic Basin the NAC with its northeastward transport stands out clearly.

[10] To underscore the robustness of the double peak of the Irminger Current (IC) and the southward flow on the eastern flank of the Reykjanes Ridge, Figure 2c shows that flow patterns are quite similar for both the northern and southern groups which cross the ridge about 190–200 km apart.

[11] The EKE panel, Figure 2d, reveals patterns similar to what has been observed in the past with maxima in the Iceland Basin, over the western slope of the Reykjanes Ridge and in the EGC, but thanks to the high-resolution repeat sampling, Figure 2d gives a more accurate reading of the structure and amplitudes of the maxima, features that previously have eluded quantification. The minimum in the Irminger Sea, the maximum in the Iceland Basin, and the asymmetry of the EKE between the eastern and western slopes of the Reykjanes Ridge are particularly striking features that emerge from the repeat sampling program. Curiously, the EKE maximum in the Iceland Basin coincides with the eastern part of the NAC, it is much less on the western side of the current (Figures 2b and 2d).

[12] The double peak appears to be a seasonal feature as indicated in Figure 3, with two peaks clearly present in the spring (black) and in somewhat reduced form in the

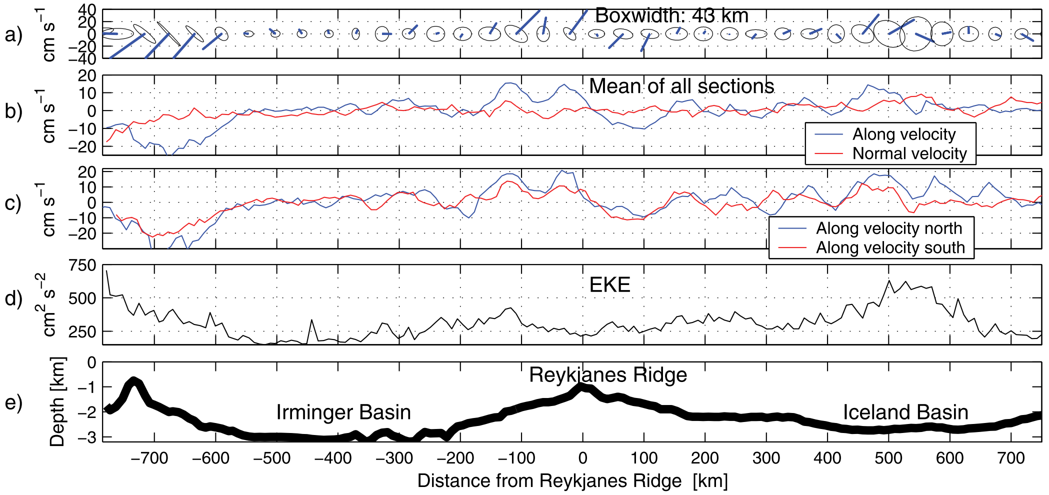

Figure 2. (a) Mean velocity vectors and variance ellipses (100 units on an axis = 25 cm/s and 100 $cm^2\ s^{-2}$) for the upper 200 m. (b) Mean flow along the Reykjanes Ridge (blue line) and normal to (red line). The red arrows in Figure 1 indicate the locations of the 5 major peaks. (c) Mean flow along the ridge, 13 from the northern (blue line) and 20 from the southern main route (red line). (d) Eddy kinetic energy. (e) Topography along the average section. The x-axis show distance in km east ($x > 0$) or west ($x < 0$) of the Reykjanes Ridge. Distance normal to the ridge is about 0.6 times the distance in the east-west direction.

summer (red), and apparently merging into one broad current in the autumn (blue). This seasonal pattern in the northward current on the western side of the ridge is also evident when averaging sections within each year. Our data also show a tendency, although less pronounced, to this seasonal "double peak" for the northeastward transport in the mid-Icelandic Basin about 300–550 km east of the Reykjanes Ridge. In this case the phenomenon also decreases in the summer and is nearly absent in the autumn. The NAC in the Icelandic Basin also exhibits a seasonal pattern with a minimum in the summer. Deeper down to below 400 m the currents are surprisingly similar with only somewhat reduced amplitude, especially the component normal to the ridge. Continued sampling should clarify the robustness of these observations. The distribution of the transects within the seasons are as follows: Spring: 9 sections, summer: 17 sections and autumn: 7 sections.

4. Discussion

4.1. The Mean Field

[13] To illustrate in more concrete terms the significance of these Nuka Arctica results, we recall some problematic uncertainties of the upper ocean circulation, particularly with respect to the pathways by which the warm waters reach the Nordic Seas. From a hydrographic section and the deployment of 20 drifters along 62°N *Krauss* [1995] suggested that the northward flow NE along the Reykjanes Ridge splits into two branches, one that turns west towards the Irminger Sea and one that turns east towards the Iceland-Faroe Ridge with a significant fraction of the transport entering the Nordic Seas to the northwest of the Faroe Islands. On the one hand this was an important contribution for it highlighted what seemed to have been ignored for a long time, namely that a significant part of the Nordic Sea inflow enters between Iceland and the Faroe Islands [*Østerhus et al.*, 2001; *Jakobsen et al.*, 2003]. On the other hand, his northward flow along the Reykjanes ridge was appeared to be at variance with an earlier study (mostly based on the IGY data set) that suggested a southward flow along its eastern flank [*Ivers*, 1975]. *Krauss* [1995, Figure 7] showed a double-peak similar to our findings on the western side of the ridge in his drifter data, but he does not comment on it in the text. His results showing almost no southward transport on the eastern side of the ridge, is similar to a few of our

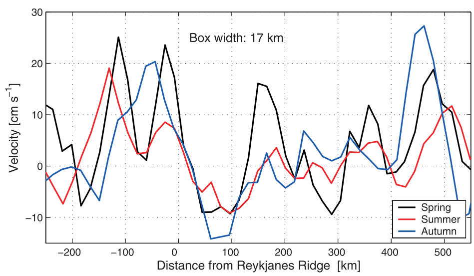

Figure 3. Mean velocity field in the upper 200 m in the vicinity of the Reykjanes Ridge as a function of season: Spring (Apr–June, black), summer (July–Sept, red), autumn (Oct–Dec, blue). X-axis as in Figure 2.

sections, but when averaging over several sections, the current pattern including also the southward transport stands out clearly.

[14] The Nuka Arctica (NA) data show good agreement with the quasi-Eulerian map of current vectors published by *Jakobsen et al.* [2003], although they show a single broader flow on the western side of the Reykjanes Ridge, in contrast to what has been observed here. *Orvik and Niiler* [2002], show drifters with velocity greater than 30 cm/s defining the current pattern in the North Atlantic. This pattern is overall in good accordance with *Jakobsen et al.* [2003] and the NA measurements, but their velocities are somewhat higher due to the fact that they only show the drifters with east- or north velocities higher than 30 cm/s, and such high velocities are smoothed out of the averaging of the NA data.

4.2. Seasonal Variations

[15] A seasonal variability shown in Figure 3 of the NAC is also shown by *Jakobsen et al.* [2003] where a winter (November–April) maximum and a summer (May–October) minimum are reported. However, the NA data do not show as great differences between the seasons as reported by Jakobsen et al., possibly due to the lack of NA-sections in January–March. Unfortunately they did not have enough data [*Jakobsen et al.*, 2003, Figure 7a] to extend their analysis west of about 26°W, thus not reaching the Reykjanes Ridge.

[16] *Bower et al.* [2002] show a map of EKE in the North Atlantic based on subsurface floats on the density surface Sigma-t = 27.5, which shows two local maxima, one in the central Iceland Basin and one on the western slope of the Reykjanes Ridge. Their values in those areas are 200–400 cm^2/s^2, and about 50–200 cm^2/s^2 for the rest of the northeast North Atlantic. Not surprisingly their values are lower because they are at depth. *Fratantoni* [2001] compares EKE based on surface drifters and altimetry, and finds reasonably good agreement between the two, with many similarities in the large-scale structure of the EKE field. The EKE is on the order of 100 cm^2/s^2 lower in the altimeter data than in the drifter data, but both notice local maxima on the Reykjanes Ridge and in the central Iceland Basin. His drifter EKE values are 100–200 cm^2/s^2 for the Irminger Basin, 200–300 cm^2/s^2 for the western side of the Reykjanes Ridge and maximum 300–400 cm^2/s^2 in the Iceland Basin. *Reverdin et al.* [2003] present a slightly more detailed picture of the EKE based on surface drifters, with distribution along the NA section that corresponds well with the NA data, although their minima are around 100 cm^2/s^2. *Jakobsen et al.* [2003] report similar EKE distribution, but their values are often less than half of the NA-data, which reflect the denser sampling and averaging inherent to the NA program. Smoothing our data using 85 km between the boxes, still gives a maximum above 500 cm^2/s^2 in the EGC and NAC and a minimum of 180 cm^2/s^2 in the Irminger Sea. These values are in the range of *Fratantoni* [2001] in the Irminger Basin, over the Reykjanes Ridge and in the westernmost part of the Iceland Basin, but the maximum in the central Iceland Basin is at least 25% higher in the NA-data.

[17] These preliminary results of the Nuka Arctica data analysis reveal a fine structure to the mean field with a superimposed seasonal cycle we had not anticipated. They indicate the existence of a rich mean field that apparently varies seasonally and likely varies from year-to-year in response to interannual variations in atmospheric forcing of the ocean. The NA spans the northeast Atlantic in an area where the north-flowing NAC supplies warm salty water to both the Nordic Seas between Iceland and the Faroes, as well as waters that flow towards Greenland and the Labrador Sea. We hope that by continuing the NA program we will be able to better address to what extent these are apportioned in response to local atmospheric forcing or reflect varying demands from the areas where deep and intermediate waters are formed. In summary, high resolution repeat sampling of the absolute velocity field gives us new and quantitative insights into the structure of flows and their spatial-temporal variability.

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