Directly-measured mid-depth circulation in the Northeastern North Atlantic Ocean

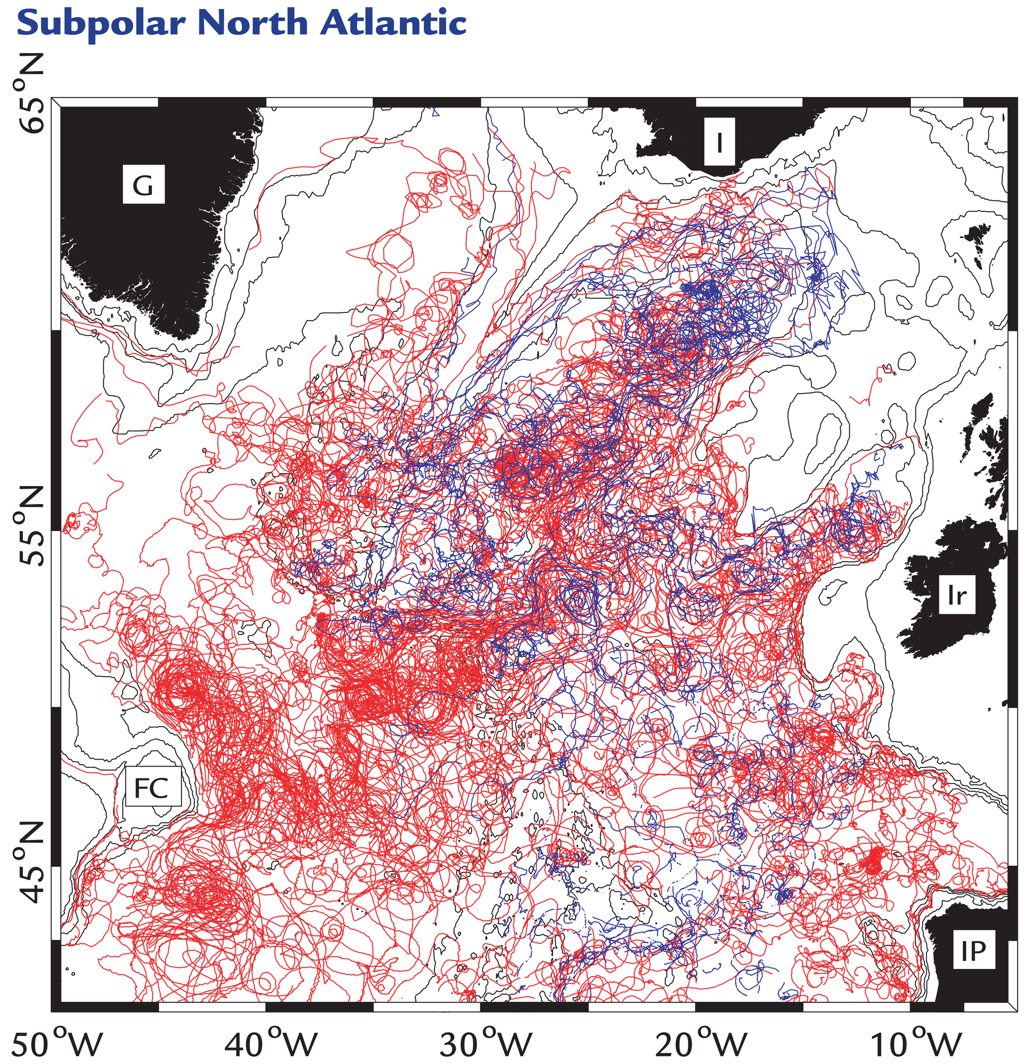
A. S. Bower*, B. Le Cann†, T. Rossby‡, W. Zenk§, J. Gould||, K. Speer¶, P. L. Richardson*, M. D. Prater‡, H-M. Zhang#.

* Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA; † Laboratoire de Physique des Océans, CNRS, UFR Sciences, BP809, 29285 Brest, France ; ‡ Graduate School of Oceanography, University of Rhode Island, Kingston, RI 02881, USA; § Institut für Meereskunde, Christian-Albrechts-Universität, D-24105 Kiel, Germany;
|| Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK; ¶ Department of Oceanography, Florida State University, Tallahassee, FL 32306, USA; # Graduate School of Oceanography, University of Rhode Island. Now at National Climatic Data Center, NOAA, Asheville, NC 28801, USA.

Summary:

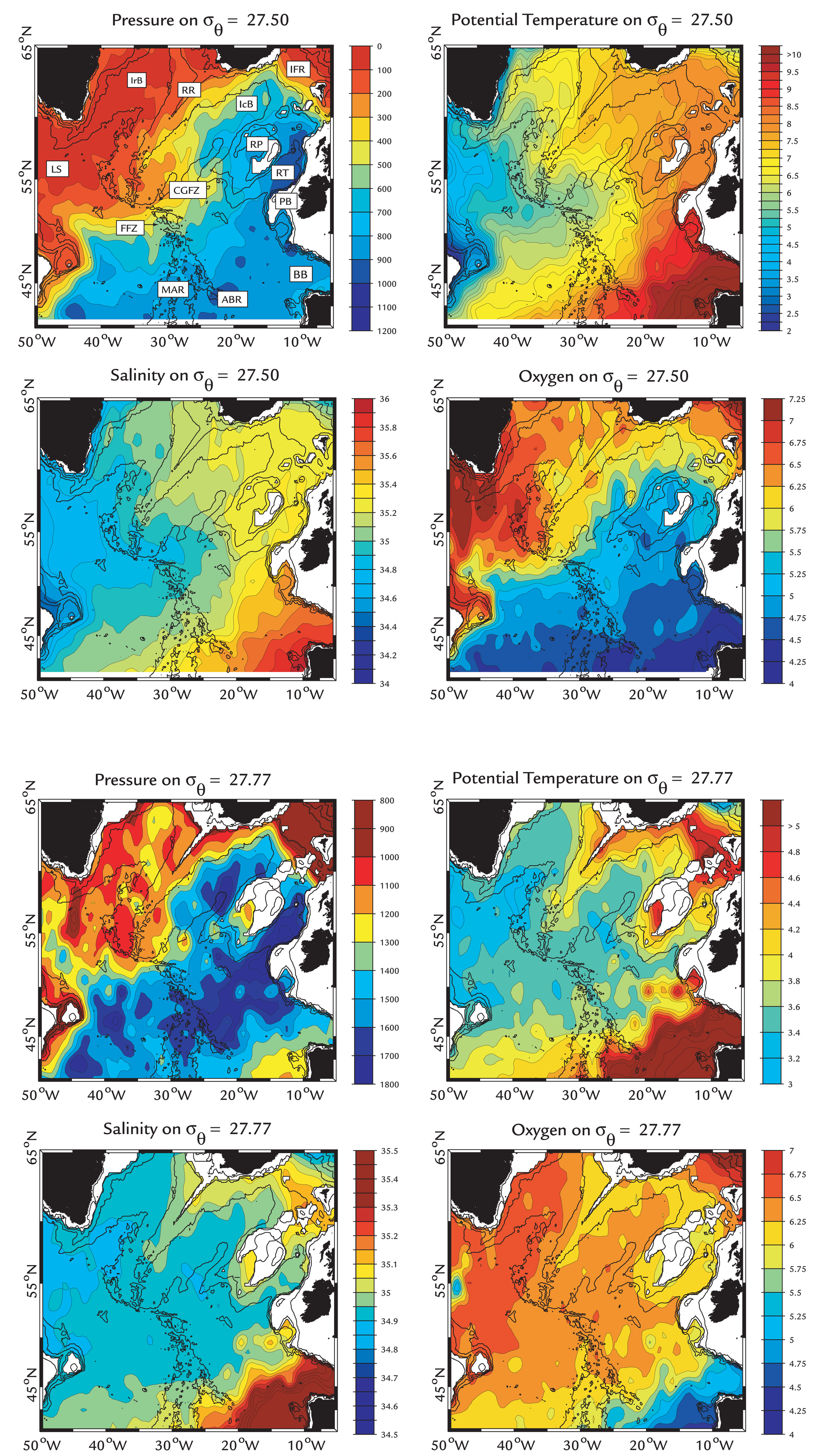
As part of a large international effort to directly observe the circulation throughout the subpolar North Atlantic Ocean during WOCE, several research groups from the U.S., the U.K., Germany and France collaborated in a major initiative to measure the absolute velocity at two levels in the northeastern North Atlantic using acoustically-tracked subsurface floats. The northeastern North Atlantic is important to the thermohaline circulation as this is where warm subtropical water is transported to high latitudes. A total of 223 float tracks, representing 328 float-years of data, were combined to generate maps of mean absolute velocity and eddy kinetic energy at the thermocline and Labrador Sea Water levels. We find that most of the mean flow transported northward by the North Atlantic Current at the thermocline level recirculated within the subpolar region, and relatively little entered Rockall Trough or the Nordic Seas. Saline Mediterranean Water reached high latitudes not by continuous, broad-scale, mean advection along the eastern boundary as previously described, but by a combination of narrow slope currents and mixing processes. At the Labrador Sea Water level, a strong, topographically-constrained current associated with the overflow of dense water from the Norwegian Sea flowed around the northwestern Iceland Basin along the continental slope and Reykjanes Ridge, and closed counterclockwise recirculations existed adjacent to this boundary current. At both levels, currents crossed the Mid-Atlantic Ridge, eastbound and westbound, preferentially over deep gaps in the ridge. The latter result demonstrates that seafloor topography can constrain even upper ocean circulation patterns, possibly limiting the ocean's response to climate change.

1. RAFOS and MARVOR Float Trajectories in the Subpolar North Atlantic



Trajectories of all 223 acoustically-tracked, eddy-resolving subsurface drifting floats launched in the northern North Atlantic in 1993-1995 and 1996-2001, representing 328 float-years of data. The floats were deployed at two levels: an upper-ocean thermocline density surface (σ_θ = 27.5; red tracks; see also Figure 2), and an isobaric layer at 1500-1750 m depth, the core layer of Labrador Sea Water (LSW, blue tracks). The float data were collected as part of the U.S. Atlantic Climate Change Experiment (ACCE – a component of the World Ocean Circulation Experiment), the European EUROFLOAT Project, the German *Sonderforschungsbereich* (SFB) Subpolar Program, the French *Actions de Recherche sur la Circulation dans l'Atlantique Nord-Est* (ARCANE) during 1996-2001, and the U.S. North Atlantic Current Study (NACS) in 1993-1995. The floats were submerged from 1.5-5 years and tracked using an array of 18 moored sound sources that was maintained by the cooperating groups. Labeled landmarks include Greenland (G), Iceland (I), Ireland (Ir) and the Iberian Peninsula (IP).

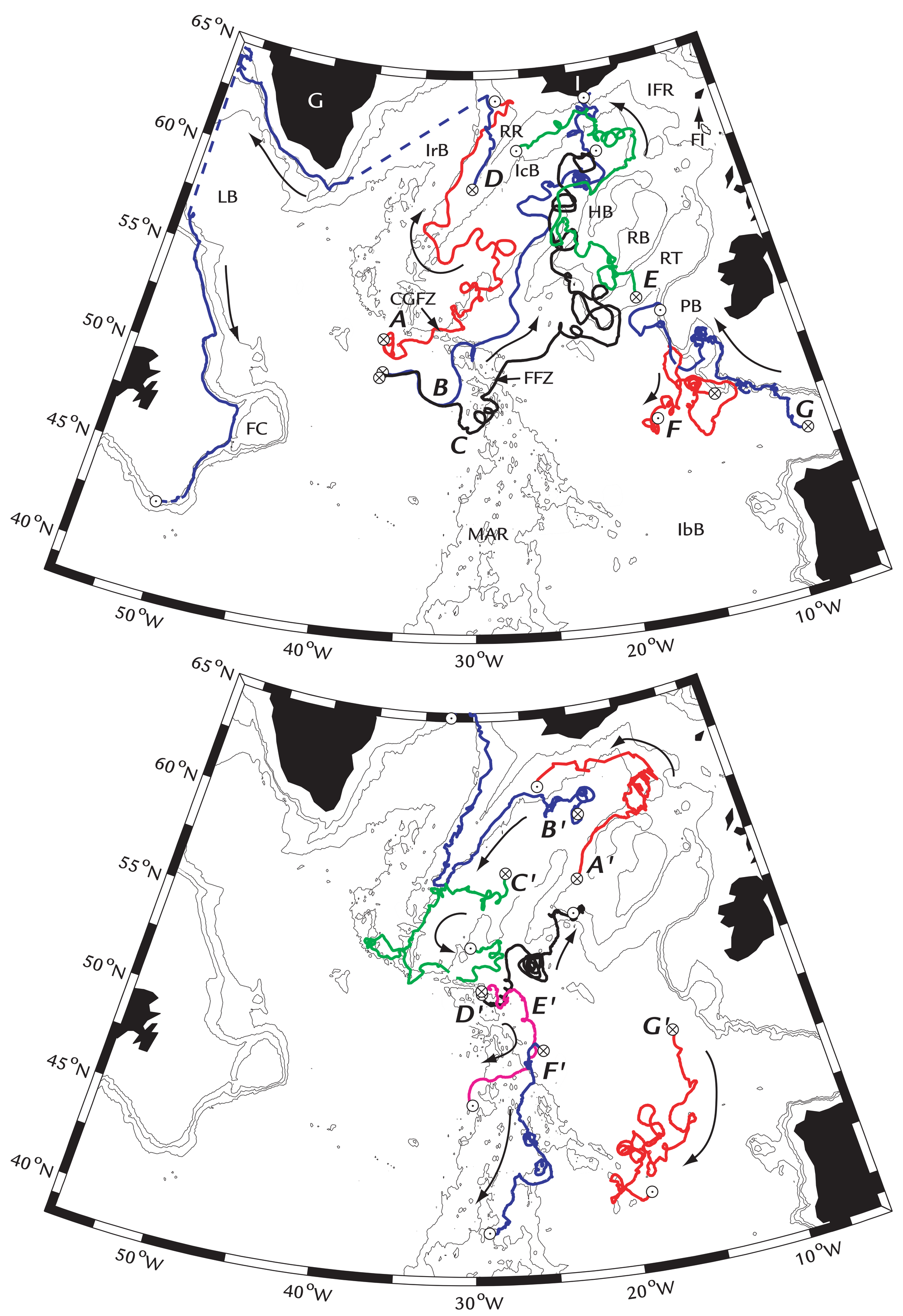
2. Hydrographic Distributions at Two Float Levels



These maps of mean pressure, potential temperature, salinity and dissolved oxygen (O_2) on two density surfaces corresponding to the two levels of the float data (from HydroBase) set the hydrographic context for the float observations. Upper panels: σ_θ = 27.50, which varies in depth from near the sea surface in the northwestern corner of the domain to ~1000 m near the eastern boundary. Lower panels: σ_θ = 27.77, which ranges in depth from 1100 m in the northwest to 1800 m in the southeast.

At the upper level, the warm subtropical thermocline waters spread northward mainly in the northeastern North Atlantic. Two sources for this warm water have been proposed: the Mediterranean Water (MW) in the southeast (θ > 10°C) that enters the North Atlantic through the Strait of Gibraltar, and the water transported by the Gulf Stream and NAC from the western basin (5.5°C< θ < 6.5°C). At the lower level, the large-scale temperature contrast from southeast to northwest illustrates the competing influence of Deep Mediterranean Water (θ > 7°C) and LSW (θ < 3.4°C). LSW spreads into the eastern North Atlantic across the Mid-Atlantic Ridge at ~50°N. The influence of warmer saltier Iceland Scotland Overflow Water, which enters the northern Iceland Basin through the Faroe Bank Channel, is apparent along the continental slope south of Iceland and on both flanks of the Reykjanes Ridge (θ > 3.8°C). Geographic abbreviations are: Labrador Sea (LS), Irminger Basin (IrB), Reykjanes Ridge (RR), Iceland Basin (IcB), Iceland-Faroes Ridge (IFR), Rockall Plateau (RP), Rockall Trough (RT), Porcupine Bank (PB), Bay of Biscay (BB), Azores-Biscay Rise (ABR), Mid-Atlantic Ridge (MAR), Faraday Fracture Zone (FFZ), Charlie-Gibbs Fracture Zone (CGFZ).

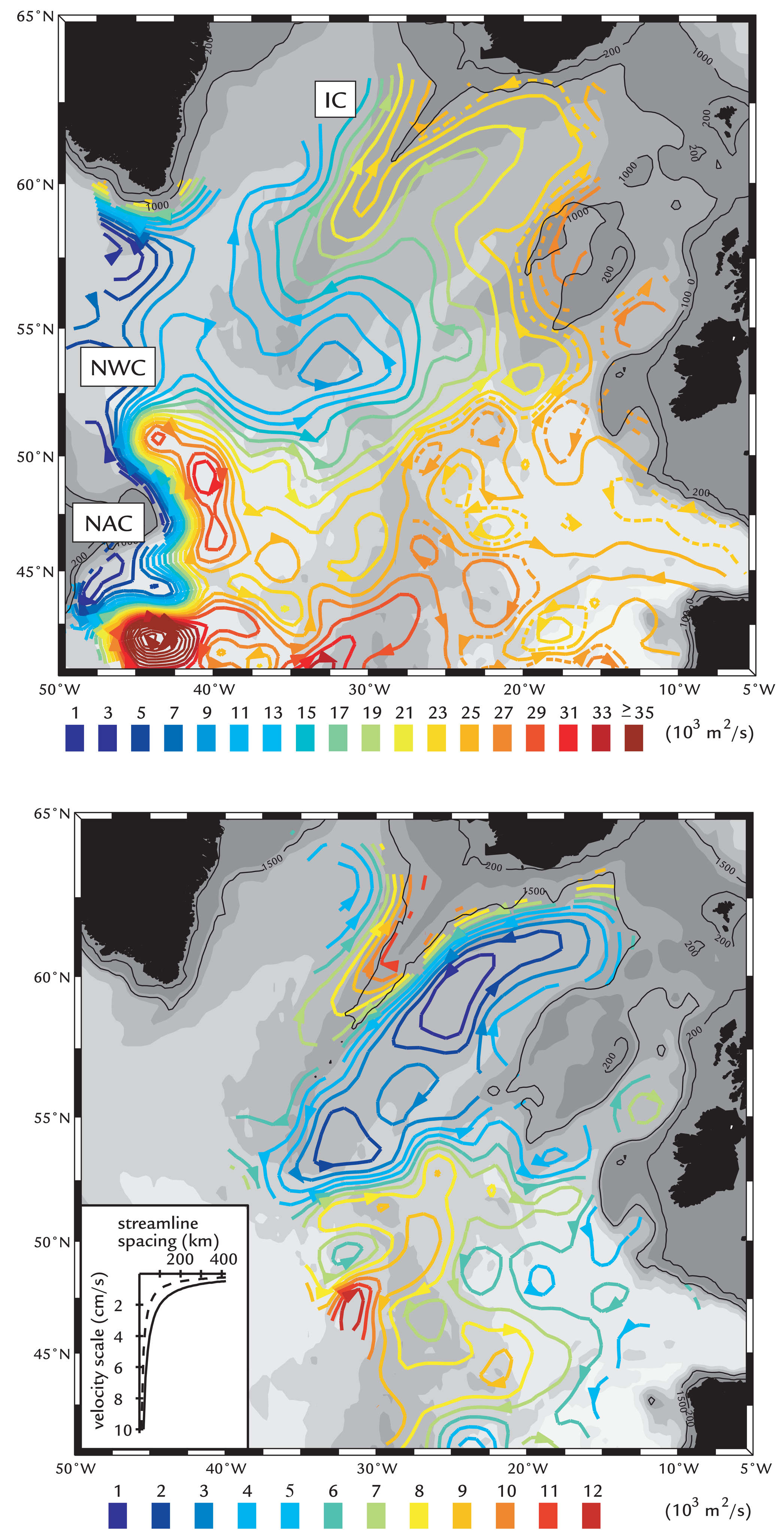
3. Some Individual Float Tracks from Thermocline and LSW Levels.



Representative float trajectories on the 27.5 σ_θ surface (top panel) and at the 1500-1750 m level (bottom panel) Markers 'x' and '.' indicate launch and surface positions, respectively. Floats A, B and C in the upper panel, all launched in the North Atlantic Current, indicate the eastward, then northeastward flow along the front with average float speed of 10-15 cm s^{-1}. Floats A and B were both funneled across the Mid-Atlantic Ridge at the Charlie-Gibbs Fracture Zone, but at depths more than 1000 m above the ridge crest (see also Figure 5). In the Iceland Basin, their paths diverged: float A looped back westward and then turned northward along the western flank of the Reykjanes Ridge while float B continued northeastward through the Iceland Basin, exhibiting significant eddy motions with speed occasionally exceeding 30 cm s^{-1}. Float C was guided via another deep channel across the ridge, the Faraday Fracture Zone (FFZ), then also turned northeastward into the Iceland Basin where it, too, showed relatively strong eddy activity. Float D, which was constrained by strong bathymetric slopes around the Irminger and Labrador Basins, traces out the continuation of the cyclonic subpolar gyre in the west, with speeds up to 40 cm s^{-1} (west of Greenland). Contrary to expectation, floats deployed near the eastern boundary north of 50°N typically did not enter Rockall Trough, but drifted into the Iceland Basin along the southern and western edge of the Rockall Plateau with speeds generally < 15 cm s^{-1} (float E). Floats launched south of that parallel typically revealed persistent eddy activity and drifted out into the ocean interior (float F). However, continuous northward flow over and along the steep continental slope was intermittently observed, with speeds generally < 10 cm s^{-1} (float G). Geographic labels are as in Figure 2, with the addition of Hatton Bank (HB) and Faroe Islands (FI).

At the lower level (lower panel), a strong and persistent flow is seen to begin on the western flanks of Hatton Bank in the northern Iceland Basin and continue southwest of the Faroe Islands towards the eastern flank of the RR (float A'). This strong flow pattern is accelerated by the Iceland-Scotland overflow of Nordic waters through the Faroe Bank Channel. Track B' typifies the organized flow of these waters as they cross over the RR into the Irminger Basin. Track C' traces out the cyclonic circulation at the southern end of the Iceland Basin. It crosses briefly into the Irminger Basin before turning east through the CGFZ into the southern Iceland Basin. Floats D', and E' show the spread of the LSW into the Iceland Basin and south along the eastern slope of the MAR, respectively. Float F' extends this southward movement much farther south while float G' indicates the slow drift south in the Iberian Basin.

4. Mean Streamfunction Fields at Thermocline and LSW Levels

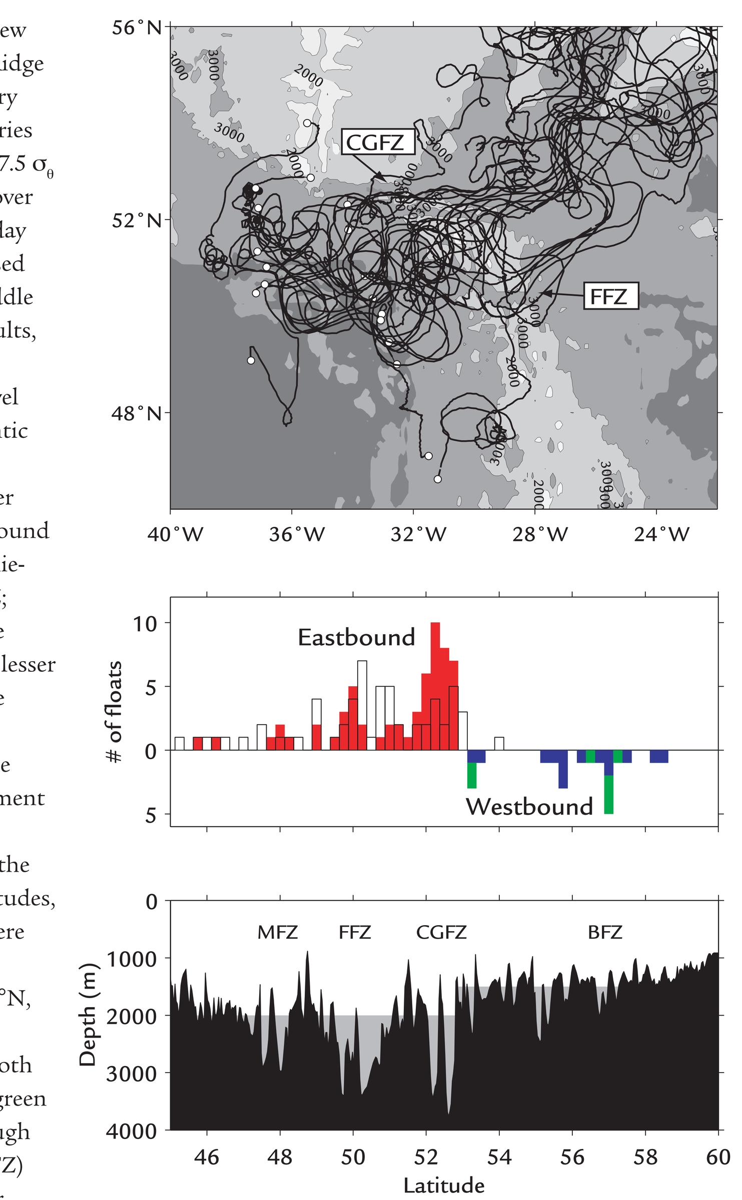


Mean streamfunction for the subpolar North Atlantic from subsurface float data at two levels. a) upper level, thermocline, density σ_θ = 27.5; b) lower level, Labrador Sea Water, depth 1500-1750 m. See abstract for summary of results. Mapping of gridded float velocity into streamfunction fields was done using standard objective analysis techniques, with a decorrelation scale of 100 km. Arrowheads show the direction of flow along the contours. The nomogram in the lower panel gives speed in cm s^{-1} as a function of line separation (solid line for upper panel, dashed for lower panel), and the contours give volume transport per unit depth. Note that two higher-resolution contours, 24,000 and 26,000 m^2 s^{-1}, have been added to the upper panel near the eastern boundary. Labeled features are: North Atlantic Current (NAC), Northwest Corner (NWC), Irminger Current (IC).

Acknowledgements: This research was supported by the U.S. National Science Foundation, the Deutsche Forschungsgemeinschaft in Germany, Institut Français de Recherche pour l'Exploitation de la Mer, Service Hydrographique et Océanographique de la Marine, Centre National de la Recherche Scientifique in France, and the European Commission EUROFLOAT Project. We are very grateful for the help and support of all the technicians and research assistants who expertly contributed to this project. H. Hunt Furey was instrumental in the preparation of the figures.

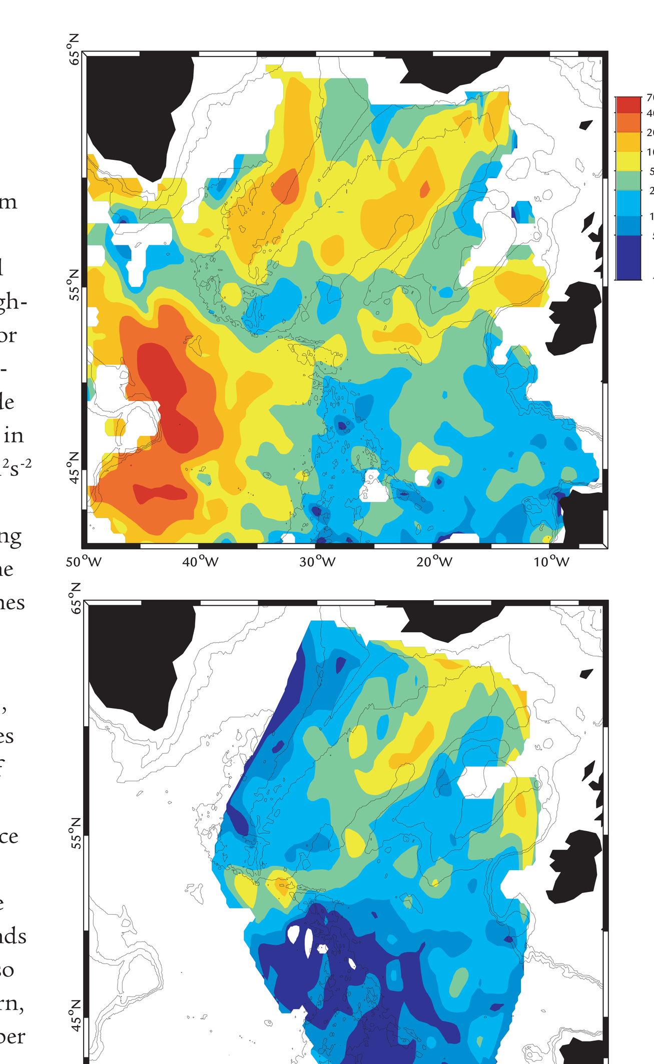
For more information, see: Bower, A.S., B. Le Cann, T. Rossby, W. Zenk, J. Gould, K. Speer, P. L. Richardson, M. D. Prater and H.-M. Zhang, 2002. Directly-measured, mid-depth circulation of the northeastern North Atlantic Ocean. *Nature,* 419, 603-607.

5. Funneling of Floats over Gaps in the Mid-Atlantic Ridge



Top panel shows close-up view of the southern Reykjanes Ridge and fracture zone bathymetry along with example trajectories of individual floats on the 27.5 σ_θ surface that were funneled over the Charlie-Gibbs and Faraday Fracture Zones as they crossed the Mid-Atlantic Ridge. Middle panel summarizes these results, showing the distribution of latitudes where all upper-level floats crossed the Mid-Atlantic Ridge. Floats in the North Atlantic Current at the upper level crossed the ridge eastbound preferentially over the Charlie-Gibbs Fracture Zone (CGFZ; 31/61), the Faraday Fracture Zone (FFZ; 11/61), and to a lesser extent, the Maxwell Fracture Zone (MFZ; 4/61) (red bars; float depths 200-800 m). The distribution of float deployment latitudes, unfilled bars, is significantly different from the distribution of crossing latitudes, suggesting that the floats were funneled over the various fracture zones. North of 53°N, floats crossed the Reykjanes Ridge from east to west at both levels (blue for upper-level, green for lower level) mainly through the Bight Fracture Zone (BFZ) and two unnamed gaps near 53.5°N and 55°N. North of 53°N, the gaps are not aligned east-west and the distribution of float crossing latitudes is therefore somewhat wider around these gaps. Bottom panel shows depth along the ridge crest.

6. Eddy Kinetic Energy from Float Observations



Eddy kinetic energy (EKE; cm^2s^{-2}) from the float data for the 27.5 σ_θ surface (top panel) and the 1500-1750 m level (bottom panel). These are the first high-resolution maps of subsurface EKE for the subpolar North Atlantic. EKE varies by almost two orders of magnitude within the domain, from >400 cm^2s^{-2} in the western boundary NAC to ≤10 cm^2s^{-2} over the Mid-Atlantic Ridge south of the CGFZ. EKE decreases sharply along the path of the NAC where it leaves the western boundary (52°N) and branches into several weaker currents. Distinct local EKE maxima occur in the center of the Iceland Basin (~200 cm^2s^{-2}), over the western slope of the Reykjanes Ridge (>200 cm^2s^{-2}), and southwest of Rockall Plateau (>100 cm^2s^{-2}). These maxima also appear in maps of surface EKE, with slightly higher magnitude (200-400 cm^2 s^{-2}), but this subsurface map reveals that this variability extends through the water column. This is also apparent in the lower level EKE pattern, which generally tracks that of the upper layer with magnitude about ½-1/10 that of the upper level. The maximum in the Iceland Basin at the lower level has a magnitude of about 100 cm^2 s^{-2}. On the other hand, the upper level EKE maximum on the western slope of the Reykjanes Ridge is not mirrored at the deeper level, perhaps due to the stronger baroclinicity of the Irminger Current. Further study is needed to explain the structured distribution of EKE in this region.