GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.3, PAGES 369-372, FEBRUARY 1, 1999

Interaction of the North Atlantic Current with the deep Charlie Gibbs Fracture Zone throughflow

Friedrich Schott, Lothar Stramma, and Jürgen Fischer

Institut für Meereskunde, Kiel, Germany

Abstract. The Charlie Gibbs Fracture Zone (CGFZ), a passage of 3600 m sill depth through the Mid-Atlantic Ridge near 52°N, is a known gateway for the passage of deep waters from the Northeast Atlantic into the western basin. During a shipboard survey of August 1997 deep current profiling yielded eastward deep flow through the passage while geostrophy calculated against an intermediate reference level resulted in westward relative deep transport. The reason was an unusual and deep-reaching northward excursion of the North Atlantic Current (NAC). Inspection of historical data showed that such interference of the NAC with the CGFZ regime occured occasionally in the past. Relocation of surface circulation patterns by decadal ocean-climate anomalies may thus be of significance also for the deep circulation.

Introduction

The supply of Deep Water from the eastern North Atlantic to the western basin past the Mid-Atlantic Ridge (MAR) through the Charlie Gibbs Fracture makes up an important branch of the southward return flow of the Atlantic meridional overturning circulation [*Dickson and Brown*, 1994; *Schmitz and McCartney*, 1993]. Produced by a mixture of overflow waters from the Iceland-Scotland Ridge and Northeast Atlantic Water, the Charlie Gibbs Fracture Zone (CGFZ) Water forms the middle layer of the Deep Western Boundary Current (DWBC) [*Smethie and Swift*, 1989] that exits the subpolar North Atlantic southward. The circulation of the subpolar North Atlantic is schematically summarized in Figure 1: The deepest branch of the DWBC is fed by overflow waters through the Denmark Straits. Small at the beginning, only about 2.5 Sv (Sv= $10^6 m^3 s^{-1}$) over the 500 m deep sill between Greenland and Iceland, the Denmark Strait Overflow Water (DSOW) rushes down the slopes and entrains surrounding warmer waters along the way, thereby multiplying its transport when arriving at the southern tip of Greenland [*Dickson et al.*, 1990]. The least dense layer of the DWBC, between about 1000 m and 2000 m, is fed by winter convection in the central [*Lazier*, 1973] and southern [*Pickart*, 1992] Labrador Sea. The intermediate layer, in the depth range of about 2000-3500 m, is made up by waters originating in the Northeast Atlantic, where waters overflowing the Iceland Scotland Ridge entrain warm, salty Northeast Atlantic waters. This deep current flows first southward along the eastern slope of the MAR, until the CGFZ allows westward connection of Deep Water flows past the MAR down to a sill depth of 3600 m. Its further path in the western basin is not quite clear yet. It is generally assumed that it follows the western flank of the MAR northward and then turns around the Irminger Sea to overlay the denser DSOW off Greenland (as indicated in Figure 1).

In fact there are two trenches in the CGFZ, the northern one at about 52°40'N and the southern one at 52°10'N. Earlier observations with moored current meter stations in the northern trench of the CGFZ yielded a mean westward transport of 2.5 Sv with, however, much larger variability than previously reported for the DSOW boundary current off Greenland [*Dickson et al.*, 1990], including intermittent periods of eastward flow [*Saunders*, 1994]. Moored current observations at the eastern entry of the southern trench yielded no net throughflow [*Dickson et al.*, 1980].

Paper number 1998GL900223.
0094-8276/98/1998GL900223$05.00

Deep Current Profiling Observations in August 1997

Here we report on a phase of deep eastward flow throughout the CGFZ regime, i.e. a reversal of the conveyor belt supply circulation, and relate it to a likely cause. The event was observed with current profiling measurements by Acoustic Doppler Current Profiler (ADCP), and with water mass property determinations by conductivity-temperature-depth-oxygen (CTD-O_2) recorder aboard R/V "Meteor" in August 1997. Shipboard ADCP profiling of the near-surface layers was carried out by a 75.6 kHz RDI system with a depth range of about 600 m. Deep current profiling was by self-contained ADCP attached to the CTD frame (LADCP), as described in *Fischer and Visbeck* [1993]. The vertically integrated shear profiles were subsequently referenced by positions from GPS combined with the Russian Global Navigation Satellite System (GLONASS) to obtain absolute currents.

Figures 2 and 3 show the results from a closely spaced section of CTD and lowered ADCP current profiling of the CGFZ (section location shown as I in Figure 1). The CGFZ Water is characterized by a salinity maximum (Figure 2). In the Irminger Basin the CGFZ Water is bounded by the isopycnals 27.8 and 27.88, while the layer bounded by σ_Θ = 27.74 to 27.8 marked by a salinity minimum (Figure 2), is the Labrador Sea Water layer. Below 27.88 the water is influenced by DSOW. While conventional geostrophic currents from the CTD hydrography, referenced against the pressure surface 1000 dbar yielded a westward geostrophic transport of 7.0 Sv below 1500 m (Figure 3a), the directly measured LADCP current profiles showed large eastward barotropic flow (Figure 3b) yielding a total eastward transport through the CGFZ below 1500 m of 6.5 Sv. When also referenced with respect to 1000 dbar, the relative LADCP section (Fig-

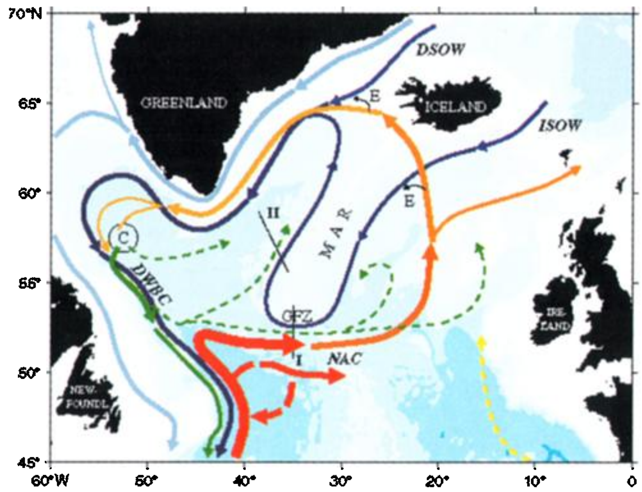

Figure 1. Schematics of mean North Atlantic Warm and Cold Water circulation: northward warm water flow (red) is by the North Atlantic Current (NAC) with partial recirculation east of the Grand Banks. Deep southward return flow (blue) of cold waters in the Deep Western Boundary Current (DWBC) is supplied by Denmark Straits Overflow Water (DSOW) as the deepest layer and by Labrador Sea Water (LSW) as its shallowest layer (green). LSW is formed by winter convection (C) in the central and southern Labrador Sea and partially recirculates through the Northeast Atlantic before exiting southward. The middle layer of the deep cold water export is made up by Iceland- Scotland Overflow Water (ISOW) that first flows southward along the mid- Atlantic Ridge (MAR), then passes through the Charlie Gibbs Fracture Zone (CGFZ) into the deep western basin where it enters the southward DWBC. Entrainment of surrounding waters into overflow currents is indicated by E.

ure 3c) agreed well with geostrophy (Figure 3a) and also yielded a relative deep transport toward the west of similar size, 6.8 Sv. Hence, geostrophic calculations relative to 1000 dbar or any other reference depth would lead to completely unrealistic results.

When looking for probable causes of such drastic changes in the Deep Water circulation of the CGFZ regime, one has to be aware of the fact that the North Atlantic Current (NAC) is meandering eastward just south of the CGFZ (Figure 1), and that occasional northward excursions of its path towards the position of the CGFZ have been observed. The NAC passes northward around the Grand Banks through a number of recirculation cells, then turns eastward while rounding the "Northwest Corner" at about 51°N, 44°W [*Rossby*, 1994]. It then follows a meandering path eastward. Its climatological mean position at 35°W, the longitude of the CGFZ, is about 50°N. Just east of the MAR, the NAC seems to take a turn northward at times, paralleling the MAR, rather than continuing eastward [*Krauss*, 1986]. The evidence we will present suggests that we encountered such an event of a northward excursion, where the NAC was passing over the CGFZ with the already described drastic consequences for the Deep Water supply of the western subpolar North Atlantic from the eastern source region.

Figure 4 shows shipboard ADCP current vectors for the near-surface flow, taken along several sections occupied by the "Meteor" during July to August 1997, and a schematic interpretation of the current systems involved. Off Greenland, the East- and West Greenland Current, respectively, are recognizable on both sides of Cape Farewell, and on the southern side the Labrador Current. The strong currents near 50°N, 43°W indicate the NW corner, leading over into two eastward- meandering NAC bands. Away from the boundary, strong mesoscale eddies dominate the currents. A larger- scale zonal current feature is located along the 35°W section north of 52°N. Its large vertical extent can be seen from the LADCP cross section of Figure 3b. This is the northward extension of the northern band of the NAC also present in a surface signature in the thermosalinograph records. The water masses show that the southern part of that current core is occupied by high-salinity warm and relatively oxygen- poor Gulf Stream Water (marked red in Figure 4, see also Figure 2, top), separated by a front (between stations 68 and 69, near 52°30'N) from a low- salinity, colder and oxygen- richer regime to the north which represents surface water from the Labrador-Irminger Sea that is carried along with the northern flank of the North Atlantic Current.

What is curious is the northward displacement of the deep eastward core from the surface NAC maximum in Figure 3b which is clearly associated with the upper-layer salinity maximum (Figure 2). A possible interpretation is a meridional slant of the NAC core in Figure 3b or a superposition of a mesoscale eddy causing a westward countercurrent north of the surface NAC core as visible in Figure 4.

Inspection of Some Historical Data for NAC Excursions

Earlier water mass investigations [*Arhan*, 1990] had shown that the waters to the north of the northern NAC current band near the CGFZ are made up by Subarctic Intermediate Water, while to the south of the southern band, located south of 50°N, the water is pure North Atlantic Central Water (NACW), (both also referred to as varieties of Subpolar Mode Water). The water in between these two current bands is a mixture of Subarctic Intermediate Wa-

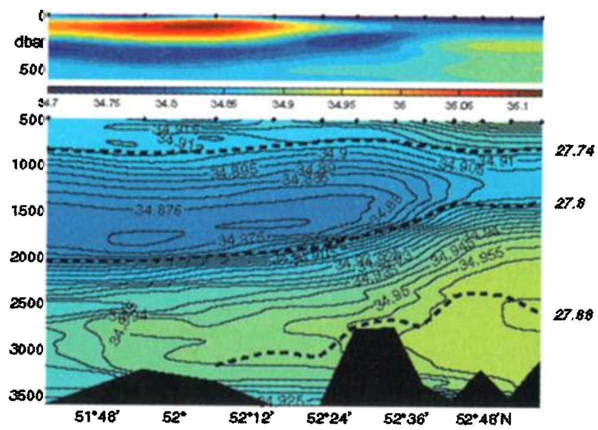

Figure 2. Salinity distribution of the Charlie Gibbs Fracture Zone in which CGFZ throughflow is characterized by a maximum located between the isopycnals 27.80 and 27.88 observed during "Meteor" cruise in August 1997 (section I in Figure 1).

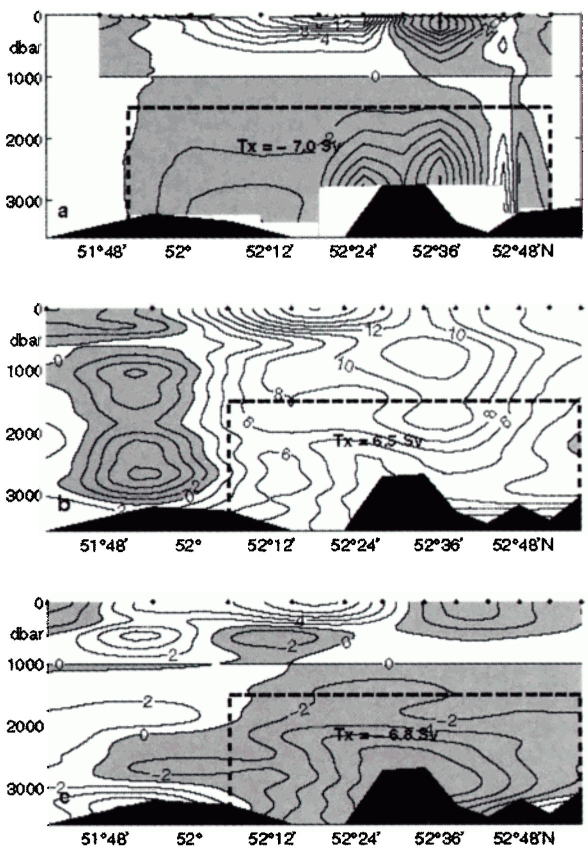

Figure 3. Deep currents of the Charlie Gibbs Fracture Zone (section I in Figure 1) a) geostrophic current relative to 1000 dbar, yielding deep westward current shear and a transport of 7.0 Sv westward below 1500 m b) directly measured LADCP currents, yielding 6.5 Sv eastward below 1500 m c) current section as in c), but referenced to 1000 dbar, yielding 6.8 Sv westward below 1500 m. (Dashed lines define transport boxes; currents are in cms^{-1}, contour interval is 2.0 cms^{-1}.)

ter and NACW. Our own investigation showed the highest salinity and lowest oxygen values in the southern band of the NAC near 50°N. The lowest salinities are observed in the Labrador Current, the central Labrador Sea and the central Irminger Basin (green in Figure 4). The waters in the East- and West Greenland Currents (dark blue in Figure 4) are slightly more saline than those in the Labrador Sea. North of the CGFZ the water shows salinities similar to the water in the NAC but higher in oxygen (yellow in Figure 4) hence this water is a mixture of water from the NAC and water from the eastern subpolar gyre, also called Modified North Atlantic Water [*Heywood et al.*, 1994]. Most of the water mass distribution and current field observed in August 1997 is as expected, but the important observation is the location of the northern band of the NAC right above the CGFZ.

Not much is known about the north-south variability of the NAC location in the CGFZ environment. The variability of the Subarctic Front associated with the northern core of the NAC was observed along a supply vessel route running from the entrance of the Mediterranean to ocean weather ship (OWS) C, located at the western exit of the CGFZ at 52.75°N, 35.5°W. Between 1976 and 1985, the Subarctic Front was observed in most cases at least 50 km south of OWS C but in some observations, mainly in the years 1981 to 1985, the front was located right at OWS C [*Belkin and Levitus*, 1996]. However, on other cruises during these years, the front had again moved southeastward. These observations thus indicate variability in the range of one to a few months but also some longterm changes. Another view at the stratification variability is made possible by time series of hydrocasts obtained at OWS C. Annual- mean temperatures at a depth of 125 m at station C showed temperature changes at decadel time scales [*Levitus et al.*, 1994]. In recent years, satellite altimetry has become available to study near-surface circulation variability. These studies showed that in some years (1988, 1992 and 1993) the signal near the CGFZ was weak while in 1987 a distinct core of the NAC was observed above the CGFZ [*Heywood et al.*, 1994]. In summary, the ancillary data suggest that the NAC may frequently approach the CGFZ and cause situations as described here.

Some evidence on deep current variability is also available. A nine-months long time series of deep currents, obtained during 1975-76 in the northern trough of the CGFZ resulted in westward flow but with periods of stagnation or even weak reversal to eastward flow [*Shor et al.*, 1980] . The low- frequency current fluctuations of this mooring record resulted in eddy kinetic energies with peaks in the band 17 to 48 days at depths below 2500 m while at 1000 m the

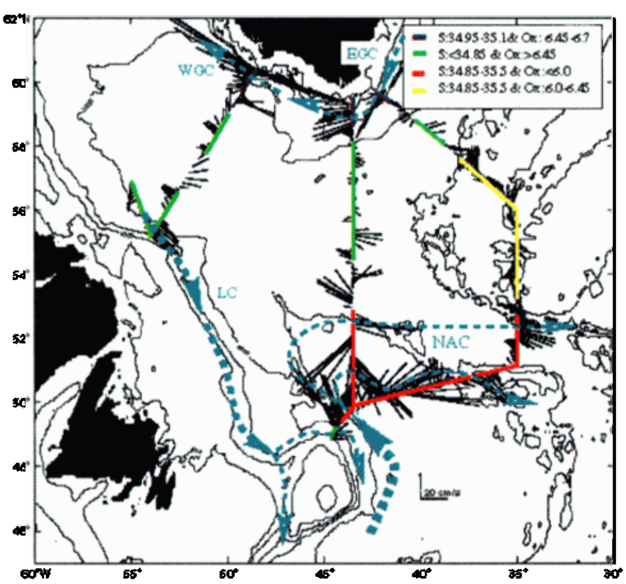

Figure 4. Near-surface currents, measured by shipboard ADCP (between 60 and 140 m depth) and water mass identification from salinity/oxygen classes at 150 m depth (defined classes are shown in the inset), and schematic flow field interpretation (in cyan); the eastward current core near the Charlie Gibbs Fracture Zone is due to a northward excursion of the North Atlantic Current (NAC), which causes the eastward reversal of the CGFZ Water flow. Also indicated are the Labrador Current (LC), the East Greenland Current (EGC) and the West Greenland Current (WGC).

energy at periods longer than 48 days was slightly elevated [*Schmitz and Hogg*, 1978]. The observations in 1988-89 of [*Saunders*, 1994] were more complete, with moored stations in both transform valleys for a duration of 15 months. Several deep- current reversals were found, some lasting for two months, but mostly not correlated between both valleys of the CGFZ. How much of this deep variability is related to near- surface effects as reported by us here needs further study.

Hydrographic observations (e.g. [*McCartney*, 1992]) indicate that the CGFZ Water spreads northward at the western flank of the MAR. Our conclusion that the NAC branch in August 1997 was so deep-reaching as to flush the Northeast Atlantic Deep Water backwards toward the east, and thus shut down completely the supply of CGFZ Water for the Deep Western Boundary Current, is supported by the weak velocities in the LADCP profiles fluctating to both directions with amplitudes of only 2 cms^{-1} in August 1997 at the western flank of the MAR (section II; Figure 1) where deep northward flow is expected. One may now further conclude on a rather crucial role of the NAC for the pathways of the deep water supply out of the eastern North Atlantic. If the NAC takes a more northerly route for an extended period of time, the CGFZ supply could be flushed backwards similarly long, requiring the export to seek other exits, and changing the compositon of the northern deep circulation system.

Acknowledgments. This is a contribution of Sonderforschungsbereich (SFB) 460, Kiel University. We thank K. Lohmann and F. Morsdorf for help with the figures and C. Mertens for data analysis support.

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J. Fischer, F. Schott, and L. Stramma, Institut für Meereskunde an der Universität Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany. (e-mail: jfischer@ifm.uni-kiel.de; fschott@ifm.uni-kiel.de; lstramma@ifm.uni-kiel.de)

(Received September 22, 1998; revised November 3, 1998; accepted November 10, 1998.)