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The Norwegian Atlantic Current in the Lofoten basin inferred from hydrological and tracer data (^{129}I) and its interaction with the Norwegian Coastal Current

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[1] From three hydrological sections taken across the Lofoten Basin in May 2000, we estimated geostrophic transports of 7.2 Sv (Sverdrup = 10^6 m^3 s^{-1}) for the Norwegian Atlantic Current (NAC) and its division between northern (4.8 Sv) and eastern (2.4 Sv) branches. From ^{129}I/^{127}I concentration ratio measurements and transport estimations, we calculated ^{129}I mass flux across the three sections. It appears that in the Lofoten Basin (a) ^{129}I tracer-laden Norwegian Coastal Current (NCC) is transporting northward 55 kg/y of ^{129}I assuming a volume flux of 0.7 Sv, (b) the estimated mass fluxes of ^{129}I by the NAC and the NCC are comparable, (c) the total mass flux of ^{129}I by the NAC and NCC, accounts only for about 1/3 of the ^{129}I annual discharge (350 kg/y) from two reprocessing plants based in France and UK. If these measurements are representative of annual mean, it suggests an important transfer of ^{129}I outside the NAC/NCC system. *INDEX TERMS:* 4860 Oceanography: Biological and Chemical: Radioactivity and radioisotopes; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4512 Oceanography: Physical: Currents; 4532 Oceanography: Physical: General circulation; 4536 Oceanography: Physical: Hydrography. **Citation:** Gascard, J.-C., G. Raisbeck, S. Sequeira, F. Yiou, and K. A. Mork (2004), The Norwegian Atlantic Current in the Lofoten basin inferred from hydrological and tracer data (^{129}I) and its interaction with the Norwegian Coastal Current, *Geophys. Res. Lett.*, *31*, L01308, doi:10.1029/2003GL018303.

1. Introduction

[2] The Norwegian Atlantic Current (NAC) is a very important source of salt and heat for the Arctic Ocean and there is a great interest in understanding its dynamics. In particular two aspects are highly relevant: (1) the NAC splitting in 2 branches in the Lofoten Basin (Figure 1), i.e., the eastern branch entering the Barents Sea and the northern branch progressing towards Fram Strait and (2) interactions between the NAC and the Norwegian Coastal Current (NCC) transporting fresh waters, originating from the Baltic Sea, towards the Barents Sea [*Björk et al.*, 2001]. South of Norway, the NCC collects tracer materials from the North Sea [*Livingston et al.*, 1982] and in particular radioactive tracers originating from nuclear fuel reprocessing plants located in France (La Hague) and UK (Sellafield). These plants have discharged a total of more than three tons of the long-lived radioactive isotope ^{129}I (half-life = 15.7 million years) into the English Channel and the Irish Sea [*Raisbeck and Yiou*, 1999]. Transit time estimates of these discharges from La Hague and Sellafield to the Lofoten basin, are about 2 and 4 years respectively [*Yiou et al.*, 2002]. Using these transit times, the discharge records of the two reprocessing plants, and assuming that all released ^{129}I is transported by the NCC and the NAC, we estimated that the total mass flux of ^{129}I through the Lofoten basin in 2000, should have been ~350 kg/y, with 80% coming from La Hague.

[3] We are presenting in this paper, important results concerning volume transports associated with the NCC/NAC system and NAC splitting in two branches in the Lofoten Basin as well as calculations of ^{129}I transported by the NCC and transferred into the NAC, indicating a total mass flux of ^{129}I equivalent to only 1/3 of the total annual discharges.

2. Description of the Norwegian Sea Main Currents

2.1. The Norwegian Coastal Current

[4] The NCC has not yet been studied thoroughly through dedicated current observations. *Björk et al.* [2001] have estimated a total transport of 0.7 Sv associated with the NCC from vertical potential energy distribution which fits fairly well with earlier estimations. The NCC characteristics indicate it is a very fresh current with most of its water originating from the Baltic Sea [*Björk et al.*, 2001]. Most of the transfer of radionuclides from the North Sea into the NCC, is occurring in the Skaggerak region [*Livingston et al.*, 1982].

2.2. The Norwegian Atlantic Current

[5] Recent estimates of the Atlantic water inflow to the Norwegian Sea, have been reported by *Hansen and Østerhus* [2000] and *Orvik et al.* [2001]. Average inflows across the Svinøy section vary from 6.8 to 8 Sv. In the context of the MAIA project for Monitoring the Norwegian Atlantic Inflow towards the Arctic, a time series with 30-day resolution based on coastal and deep basin water levels, has been constructed for the period 1975–1999 [*Vefsnmo and McClimans*, 2003]. The average flow is 7.2 Sv with an interannual variability up to 0.9 Sv and a seasonal variability more than 2 Sv. The Atlantic inflow through the Norwegian Sea comprises an off-slope baroclinic transport and a barotropic shelf slope jet. MAIA estimated the barotropic transport in the fast track slope

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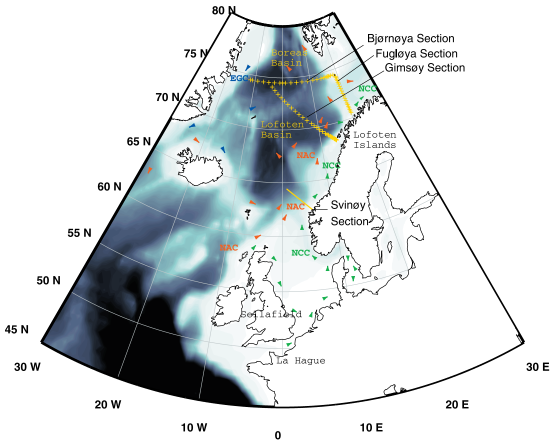

Figure 1. General map showing the main currents in the Nordic Seas and the 3 sections taken during the Lofoten 2000 experiment.

jet as a linear function of the sea surface rise across the jet by the following equation $Q_{BT} = (g/f)\ H\ (\Delta\zeta)$ where $\Delta\zeta$ is the surface rise across the jet and H is the average depth of the jet current, g is gravity and f the Coriolis parameter. The baroclinic transport is estimated on the basis of hydrographic data alone by the following equation $Q_{BC} = (g/f)\ H_1^2/2\ (\rho_2/\rho_2 - \rho_1)$ where H_1 is the average thickness of the current in the upper layer and ρ_1 and ρ_2 are respectively the density of the upper and lower layers. *Orvik et al.* [2001] also described the NAC as made of 2 branches: the topographically controlled and mostly barotropic inner branch with an annual mean inflow of 4.2 Sv and the baroclinic outer branch with a total mean inflow of 3.4 Sv resulting in an annual mean Atlantic total inflow of 7.6 Sv. This can also be compared to the 3.7 Sv + 3.3 Sv estimates by *Hansen and Østerhus* [2000] based on direct current measurements around the Faeroe Islands and corresponding to the inner and outer branches of the NAC respectively.

2.3. The Barents Sea Branch and the Fram Strait Branch: The NAC Great Divide

[6] A split of the NAC occurs in the Lofoten basin midway between the Lofoten Islands and Bear Island. One branch of the current is progressing northward west of Bear Island (Bjørnøya), becoming the West Spitsbergen Current before entering Fram Strait. The other branch of the current enters the Barents Sea between Norway and Bjørnøya and is heading towards the East.

2.3.1. The Barents Sea Branch

[7] The inflow of Atlantic water into the Barents Sea was estimated to be about 1.6 Sv by *O'Dwyer et al.* [2001] and 2 Sv by *Ingvaldsen et al.* [2002]. There is a considerable variability including flow reversal for a significant amount of the time. It appears that geostrophic calculations (baroclinic component) across the section between Bjørnøya and Norway, cannot provide reliable transport estimates due to the dominant barotropic structure of the Atlantic water flowing into the Barents Sea.

2.3.2. The Fram Strait Branch

[8] Reliable estimates of flow transport across Fram Strait are difficult mainly due to the time and space variability of the currents in the Strait. Total transport values are significantly higher than the total transport measured further south in the NAC indicating significant recirculation in Fram Strait. *Piechura et al.* [2001] carried out several transects across the Lofoten and Boreas Basins in June–July 2000. In particular, two sections taken north-west of the Lofoten Islands and west of Bjørnøya, indicated a geostrophic transport (referenced to 1000m depth) of 7.59 Sv and 4.27 Sv respectively, compared to 5.58 Sv and 2.1 Sv measured across these two sections by using acoustic Doppler current profilers (ADCP) but limited to the first 150m below the surface.

3. Description of the Lofoten 2000 Experiment

[9] Three hydrological transects have been made in the Lofoten Basin in May 2000 (Figure 1) during a cruise led by *Francisco Rey* (IMR Bergen) on board the Norwegian research vessel *R/VJohan Hjort*: the Gimsøy section from the Lofoten Islands to the Greenland Sea, the Bjørnøya section from the Greenland Sea to Bjørnøya and the Fugløya section from Bjørnøya to Norway across the Barents Sea Opening. In the context of MAIA, about 300 water samples have been collected along these transects for ^{129}I analysis. Extraction of carrier free iodine from 100 ml samples of seawater and measurements of $^{129}I/^{127}I$ were carried out at the Accelerator Mass Spectrometry (AMS) facility based in France (Gif sur Yvette) [*Yiou et al.*, 2004]. The ^{129}I data are presented as $^{129}I/^{127}I$ ratios since this is the parameter of the seawater that we actually measure. The advantage of this procedure is that it is independent (1) of the chemical form (iodate or iodide) of the iodine in the seawater, (2) of eventual loss of iodine between sampling and chemical treatment, and (3) of the chemical yield of the extraction step. Measurement uncertainties concerning $^{129}I/^{127}I$ are estimated as 7%.

3.1. Hydrology and Transport Estimates Across Gimsøy, Bjørnøya and Fugløya Sections

3.1.1. The Gimsøy Section

[10] In Figure 2 we see clearly the Atlantic Water mass extending from the surface down to about 500 m depth (2°C isotherm and 35 psu isohaline) and from the shelf break up to 73°N where a front separates the warm and salty Atlantic Water mass from the colder and fresher Greenland Sea Arctic Intermediate Water. On the shelf near the Lofoten Islands appears the NCC characterised by a very fresh water mass originating mainly from the Baltic Sea and, locally, from Norwegian fjords. The NAC baroclinic transport estimated across the Gimsøy section is 4.9 Sv (referred to a level of no motion at 700m depth) including the NAC inner (2.5 Sv) and outer (2.4 Sv) branches. This baroclinic transport does not take into account the barotropic jet-like component of the NAC inner branch located above the continental slope which, according to MAIA estimates, should amount to about 2.3 Sv so as to reach a total transport of about 7.2 Sv. So our estimated total transport for the NAC inner branch in May 2000 is 4.8 Sv which can be compared to 4.2 Sv estimated by *Orvik et al.* [2001].

3.1.2. The Bjørnøya Section

[11] At 74.30°N along the so-called Bjørnøya section, (Figure 2) shows again the extension of the Atlantic layer which is narrower than along the Gimsøy section. The

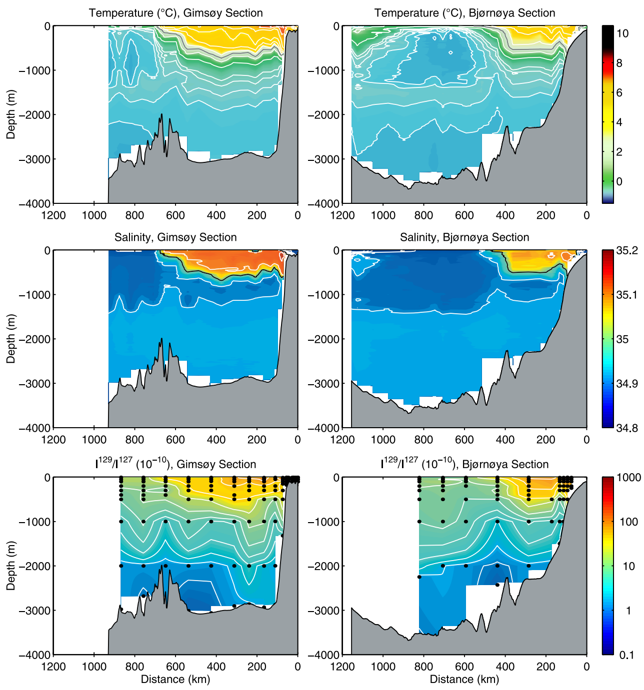

Figure 2. Two sections (Gimsøy and Bjørnøya) taken south and north of the Lofoten Basin in May 2000 and representing potential temperature, salinity and ^{129}I/^{127}I concentration ratios.

geostrophic flow through this section, calculated the same way, indicates a baroclinic transport of about 2.5 Sv and about half of the NAC Atlantic water (inner branch) entering into the Barents Sea between 72°N and 73°N.

3.1.3. The Fugløya Section

[12] Along 20°E, the Fugløya section (Figure 3) reveals a quite homogeneous Atlantic Water mass distribution, in particular in the deepest part of the section (i.e., the northern part). This water mass is still well separated from the fresh water layer extending over the continental shelf north of Norway (i.e., the southern part of the section). The fresh water mass represents the NCC which turned eastward. Based on direct currentmeter measurements [*Ingvaldsen et al.*, 2002], the current structure is believed to be mostly barotropic and highly variable across the Barents Sea opening. Due to that fact, geostrophic transports cannot be estimated from hydrographic data along the Fugløya section and in the shelf areas of the Gimsøy and Bjørnøya sections.

3.2. ^{129}I/^{127}I Ratios Along the Three Sections

[13] Iodine concentration ratios (^{129}I/^{127}I) have been measured along the 3 sections as indicated in Figures 2 and 3. These ratios, expressed in Iodine Units (IU 10^{-10}), range from 1 IU in deep and bottom waters, up to nearly 1000 IU in the NCC near the Lofoten Islands. Typical values of the NAC vary from 10 to 100 IU. The Atlantic water masses of the Barents Sea branch show remarkable high and uniform concentration ratios ($\sim$100 IU) from surface to bottom (Figure 3). These ratios are much higher than those observed upstream in the NAC along the Gimsøy section (42 IU on average), indicating an important transfer of ^{129}I from the NCC to the NAC in the Lofoten Basin. This is most likely due to high eddy kinetic energy characterising the circulation in the Lofoten Basin enhancing NCC/NAC interactions.

4. ^{129}I Equivalent Annual Transport Estimates Across the 3 Sections

[14] ^{129}I transport is expressed in equivalent kg per year assuming a constant value of 60.10^{-3} grams of ^{127}I per m^3 of water. ^{127}I concentration is known to be proportional to salinity [*Truesdale et al.*, 2000]. However, for the samples studied, the range of salinities (34.1–35.2) is only about 3%, which is small compared to other uncertainties, and has thus been neglected. We have calculated ^{129}I transport across the off-shelf part of the Gimsøy and Bjørnøya sections based on (1) the baroclinic geostrophic transports across these 2 sections estimated from hydrographic data and (2) the observed ^{129}I/^{127}I ratios (not the mean value) along these 2 sections (Figures 2 and 3). We have assumed that the total volume transport of Atlantic water across the Barents Sea opening is equal to the total baroclinic flow across the Gimsøy section minus the total baroclinic flow across the Bjørnøya section (Figure 4). In addition, we have taken into account the mean value of the ^{129}I/^{127}I ratios measured along the Fugløya section to calculate the total flux of ^{129}I across this section, assuming a uniform flow across this section. This is justified since the ^{129}I/^{127}I ratios are very homogeneous all along this section and from top to bottom, in contrast with Gimsøy and Bjørnøya sections. Figure 4 indicates that, without taking into account ^{129}I transported by the NCC, the difference (30 kg/y) between

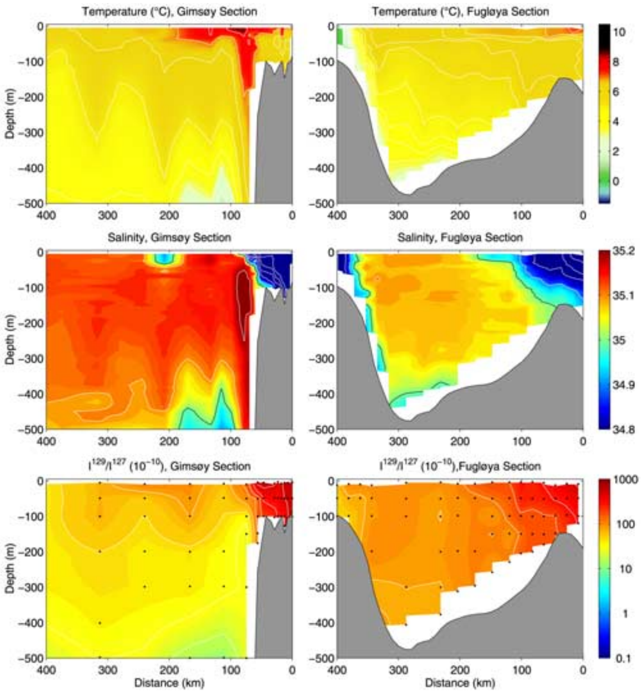

Figure 3. Fugløya section taken in May 2000 and representing potential temperature, salinity and ^{129}I/^{127}I concentration ratios. At the same scale but restricted to the shelf, the Gimsøy section (Figure 2) is shown again for comparison.

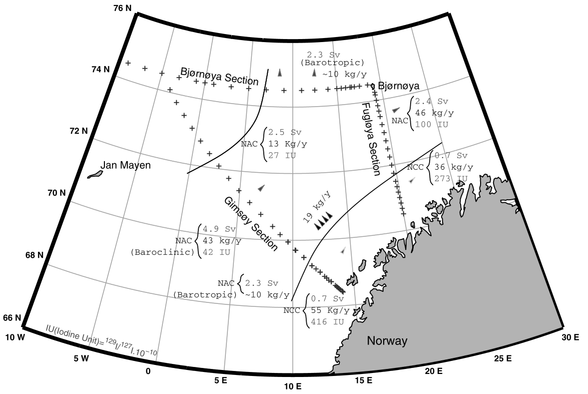

Figure 4. Calculations of (1) NAC geostrophic (baroclinic) offshore transports across Gimsøy and Bjørnøya sections, (2) NAC total transports across Fugløya section deduced from the difference between transports estimated in (1) across Gimsøy and Bjørnøya sections, (3) ^{129}I transports (equivalent annual mass flux) by the NAC across each of the 3 sections (4) NCC total transport (0.7 Sv) and associated ^{129}I equivalent annual mass flux across the Gimsøy and Fugløya sections (shelf) + transfer to the NAC (19 kg/y).

the ^{129}I crossing the Gimsøy section (43 kg/y) and the Bjørnøya section (13 kg/y), is much less than the ^{129}I crossing the Fugløya section (46 kg/y). The 16 kg/y difference can only be attributed to a transfer of ^{129}I from the ^{129}I tracer-laden NCC to the NAC north of the Lofoten Islands (i.e., between the Gimsøy and Fugløya sections) where the NAC splits in 2 branches. Since we have also measured ^{129}I/^{127}I ratios in the NCC both along the Gimsøy and Fugløya sections, we can also calculate the total amount (19 kg/y) of ^{129}I that has been released between these 2 sections by the NCC and transferred to the NAC considering NCC transport is 0.7 Sv [*Björk et al.*, 2001]. Assuming NCC is uniform across the shelf, we took average values for ^{129}I/^{127}I ratios along Gimsøy (416 IU) and Fugløya (273 IU) shelf sections. The result (19 kg/y) is remarkably close to the 16 kg/y of ^{129}I necessary to balance the NAC transport in the Lofoten Basin, based on our calculations. This close fit supports indirectly some important assumptions we made concerning the NAC great divide in the Lofoten Basin and the related barotropic versus baroclinic components of the current system.

5. Discussion and Conclusion

[15] In the southern part of the Norwegian Sea, the NCC is the main carrier of ^{129}I. About half of this radionuclide is transferred into the NAC west of Norway by the time the NAC reaches the Lofoten Basin and splits in 2 branches. An additional significant transfer of ^{129}I from the NCC into the NAC occurs north of the Lofoten Islands. This transfer in turn supports transport estimations of 0.7 Sv by the NCC north of Norway as estimated by *Björk et al.* [2001]. The total transports associated with the 2 branches of the NAC, the Fram Strait branch and the Barents Sea branch, are equal to 4.8 Sv and 2.4 Sv respectively. West of the Lofoten and Bjørnøya Islands, the barotropic component of the NAC inner branch (slope current) should be about 2.3 Sv. Considering ^{129}I/^{127}I mean concentration ratio of about 20 IU averaged over the entire water column near the shelf break, this would correspond to a barotropic transport of less than 10 kg/y of ^{129}I in addition to 43 kg/y of ^{129}I due to the NAC baroclinic transport. So the annual mass flux of ^{129}I related to the NAC is quite comparable to the part advected by the NCC (55 kg/y) but the total annual mass flux of ^{129}I related to both the NAC and the NCC west of the Lofoten islands, is only equivalent to about 1/3 of the total annual discharges (i.e., 350 kg/y). Are there plausible explanations for this apparent discrepancy? First, the measured ^{129}I/^{127}I ratio may not be representative of the whole year, in particular for the NCC. Indeed, further south along the Norwegian coast, significant spatial and temporal variability in this ratio has been observed [*Yiou et al.*, 2002]. But even a doubling of the ^{129}I/^{127}I ratio in the NCC, would still leave half of the ^{129}I total annual discharges unaccounted for. A second factor might concern the geostrophic calculation and the representativeness of the May 2000 situation for estimating an NAC annual mean transport. MAIA pointed out a seasonal variability for the baroclinic transport across the NAC ranging from 4 Sv during spring, up to 6 Sv during fall. Accordingly, the May 2000 situation should correspond to a low value for the baroclinic transport related to the NAC. However, in May 2000, we estimated the baroclinic transport across the Gimsøy section to be 4.9 Sv to which another 2.3 Sv for the barotropic part of the slope current, needs to be added to fit the annual NAC mean transport proposed by MAIA (7.2 Sv). This would tend to indicate our estimated NAC volume transport is well representative of yearly average. A third factor might be an important transfer of ^{129}I outside the NAC/NCC system before entering the Lofoten basin.

[16] The above estimations and inferences about the NAC, NCC and the NAC great divide in the Lofoten basin, would not have been possible without taking advantage of ^{129}I, a remarkable tracer for understanding the complex ocean circulation in this important part of the world ocean. Needless to say, knowledge of the rates at which radionuclides are dispersed throughout the whole Norwegian coastal circulation system, is also highly relevant to the establishment of safety levels for discharges of these nuclides over time.

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