Subpolar Mode Water formation traced by neodymium isotopic composition

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[1] The formation of Subpolar Mode Water (SPMW) is documented by combining neodymium isotopic composition (Nd IC) as a conservative tracer with salinity, temperature and O_2 concentration. Nd IC reveals a more pronounced eastward extension of the Labrador Current, particularly its Subarctic Intermediate Water component, than the other parameters. Nd IC also suggests that waters flowing through the Denmark Strait do not significantly contribute to the SPMW formation. A two end-member mixing, involving Subarctic Intermediate Water (and maybe ultimately Labrador Current Water) and North Atlantic Central Water, is proposed to explain SPMW formation. These results provide important insight into the processes controlling the Nd IC in the North Atlantic Subpolar Gyre, which could provide a means for reconstructing the northward extension of the Gulf Stream in the past. *INDEX TERMS:* 4825 Oceanography: Biological and Chemical: Geochemistry; 4283 Oceanography: General: Water masses; 4267 Oceanography: General: Paleoceanography; 1040 Geochemistry: Isotopic composition/chemistry; 4875 Oceanography: Biological and Chemical: Trace elements. **Citation:** Lacan, F., and C. Jeandel (2004), Subpolar Mode Water formation traced by neodymium isotopic composition, *Geophys. Res. Lett.*, *31*, L14306, doi:10.1029/2004GL019747.

1. Introduction

[2] Subpolar Mode Water (SPMW) refers to waters resulting from the mixing and subsequent convection of subtropical and polar water masses in the northern North Atlantic [*McCartney and Talley*, 1982]. They occupy approximately the first 1000 m of the North Atlantic Subpolar Gyre (Figure 1). These waters strongly interact with the atmosphere and play an important role in the formation of the North Atlantic Deep Water (NADW) [*McCartney*, 1992]. Their formation is therefore a significant factor regulating the global thermohaline circulation and the climate.

[3] Studying SPMW formation has proven difficult, however, notably because of the number and complexity of the processes involved. Due to large air-sea heat fluxes and substantial continental fresh water runoff, temperature and salinity are not conservative in many parts of that area. In addition geographically variable subduction and convection further obscure the hydrographic patterns, in particular the distribution of O_2 concentration.

[4] In this study, we use neodymium isotopic compositions (Nd IC) as a conservative tracer in order to describe SPMW formation. The Nd IC is expressed as:

$$\varepsilon_{Nd} = \left(\frac{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{Sample}}{\left(\frac{^{143}Nd}{^{144}Nd}\right)_{CHUR}} - 1 \right) \times 10^4 \qquad (1)$$

where CHUR stands for Chondritic Uniform Reservoir and represents a present day average earth value; $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ [*Jacobsen and Wasserburg*, 1980]. The Nd IC of the continents is heterogeneous, varying from −45 in old granitic cratons to +12 in recent mid oceanic ridge basalts [*Goldstein and Hemming*, 2003]. In the ocean, Nd is a trace element, predominantly found in the dissolved form (90 to 95% [*Jeandel et al.*, 1995]). Its residence time is around 500 to 1000 years [*Tachikawa et al.*, 2003]. Through lithogenic inputs, different water masses acquire different Nd IC. Therefore ε_{Nd} can be used as a tracer of events in a water mass history (e.g., along-slope flows and ensuing lithogenic inputs). On the other hand, away from those inputs, ε_{Nd} behaves conservatively in the ocean and since variations are observed between different water masses, it is used as a water mass tracer [*Piepgras and Wasserburg*, 1987; *Jeandel*, 1993; *Jeandel et al.*, 1998; *Lacan and Jeandel*, 2001, 2004].

2. Sampling and Methods

[5] Samples were collected during the Signature/GINS cruise, on board R/V *Marion Dufresne* (IPEV), in July–August 1999. Ten stations were occupied in the Labrador, Irminger and Iceland Basins and 3 stations in the Denmark Strait (Figure 1). Unfiltered samples were analyzed for Nd IC and concentration following the procedure described by *Jeandel* [1993] and *Jeandel et al.* [1998], slightly modified in the case of Nd IC measurement. For the latter, samples are preconcentrated onboard on C_{18} cartridges. They are then returned to the laboratory for further separation on a cationic resin and final purification on HDEHP-coated Teflon® powder. The column for the cationic resin was redesigned (3 mm int. Ø, 15 cm high; reservoir: 22 mm int. Ø, 5 cm high) and its volume reduced to 1 cm^3 to lower the blanks and to shorten the processing time. Nd IC was measured on a Finnigan MAT 261 Thermo Ionization Mass Spectrometer, in static mode, as Nd^+. The national Rennes Nd standard (recommended value $^{143}Nd/^{144}Nd = 0.511963 \pm 13$ (2σ)) (C. Chauvel, personal communication 2002), calibrated against the La Jolla standard, recommended value $^{143}Nd/^{144}Nd = 0.511850 \pm 20$ (2σ) (G. W. Lugmair, personal

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communication, 2001) gave $^{143}Nd/^{144}Nd = 0.511968 \pm 17$ (2σ, 29 runs), which corresponds to a La Jolla value of 0.511855. No corrections were applied to measured isotopic ratios. The reproducibility of the Nd IC measurement was 0.4 ε_{Nd} unit, blank values were 700 pg (3.5% of the most depleted sample and 2% on average). Nd concentrations were measured by isotopic dilution with a Perkin-Elmer Elan 6000 Inductively Coupled Plasma Mass Spectrometer. Reproducibility of Nd concentration measurements was better than 5% and blanks values lower than 3%.

3. Hydrology

[6] The North Atlantic Subpolar Gyre consists of the following components (Figure 1):

[7] - The North Atlantic Current (NAC), which extends the Gulf Stream and carries waters of subtropical origin, first eastwards, along ~50°N, then northward at ~22°W, and produces the Subpolar front;

[8] - The Irminger Current (IC), which extends the NAC, south of Iceland;

[9] - The East Greenland Current (EGC), which carries both arctic waters coming from the Nordic Seas through the Denmark Strait and subtropical waters brought by the IC;

[10] - The West Greenland Current (WGC), which extends the EGC along the western Greenland coasts;

[11] - The Labrador Current (LC), which combines waters from the WGC and from Baffin Bay.

[12] - Off Newfoundland, part of the LC branches out to the east and joins the NAC. The resulting loop is called the North Atlantic Subpolar Gyre (NASG), and extends down to the depth of the Mid-Atlantic Ridge [*Schmitz*, 1996; *Read*, 2001].

[13] The upper waters of the subpolar gyre are characterized by thick layers of low stability (SPMW), which presumably originate as deep mixed layers in winter. In general the thickness of these layers range from 400 m in the eastern part of the gyre to 1000 m in the Labrador Basin [*McCartney and Talley*, 1982].

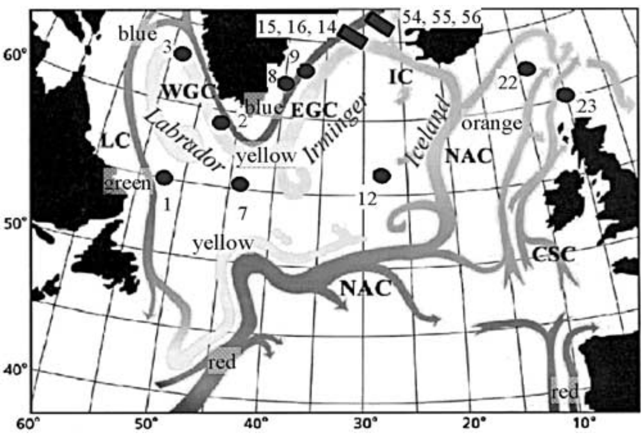

Figure 1. Main circulation features of the upper layer of the northern North Atlantic (current acronyms defined in the text). Red lines denote water ≈15°C, yellow ≈4°C and blue ≈0°C, with shadings of oranges and greens indicating intermediate temperatures. Red dots indicate the locations of the signature/GINS cruise stations presented in this study. Station numbers are labeled. Figure adapted from *Schmitz* [1996]. See color version of this figure in the HTML.

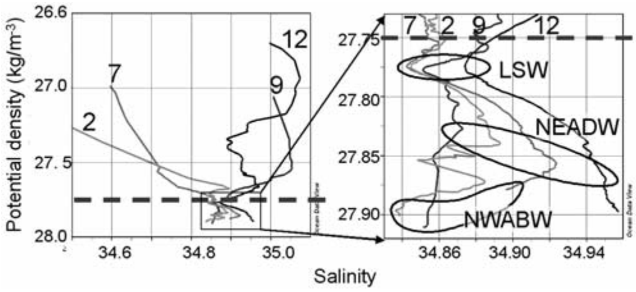

Figure 2. Salinity profiles from 4 representative stations (labeled). Left panel: full depth profiles. Right panel: zoom on the deep part. Three water masses are clearly identifiable on the right panel by their salinity extrema: Labrador Sea Water (LSW), North East Atlantic Deep Water (NEADW) and North West Atlantic Bottom Water (NWABW). The red dotted line denotes the lower limit of the SPMW defined here as the upper limit of the LSW ($\sigma_\theta = 27.75$ kg.m^{-3}). See color version of this figure in the HTML.

[14] The SPMW includes waters of widely variable properties within the Subpolar Gyre. They have temperature varying from ~8–10°C in its eastern part, to ~5–7°C in the Irminger Basin and ~3.5–4°C in the Labrador Basin. Those variations indicate the presence of different types of SPMW and their progressive cooling along their cyclonic circulation. In the southern section of the loop, we find SPMW with a strong subtropical dominance, influenced notably by North Atlantic Central Water (NACW). In the western section of the loop, we find SPMW with a strong subpolar signature, imparted notably by the Subarctic Intermediate Water (SAIW) [*Arhan*, 1990; *Pollard et al.*, 1999; *Talley*, 1999; *Read*, 2001].

4. Results and Discussion

[15] In order to characterize the Nd signature of the SPMW, we had to define the hydrological boundaries. Salinity profiles for 4 selected stations representative of our whole dataset are shown in Figure 2. Whereas, the profiles display large differences in their upper part, their deep parts are very similar. A very distinct salinity minimum, associated with the Labrador Sea Water (LSW), is found throughout the gyre at $\sigma_\theta \approx 27.77$ kg.m^{-3} (≈1650 m depth). Since this water mass is precisely identifiable (it also displays marked potential temperature and dissolved oxygen concentration extrema, not shown here), its upper boundary was chosen as the SPMW lower boundary ($\sigma_\theta \approx 27.75$ kg.m^{-3}) throughout the gyre (Figure 2), and we assume that the entire water column above this isopycnal is occupied by SPMW. This assumption is a simplification of the reality, as some other water masses occur in this depth range at certain stations, although SPMW is always predominant.

[16] Mean SPMW characteristics, calculated at each station are reported in Table 1 and plotted in Figure 3 (full data available in auxiliary material[1]). Each mean value is

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL019747.

Table 1. Mean Properties Calculated at Each Station Between the Surface and the Isopycnal σ_θ = 27.75 kg.m^{-3}

Station Number	Location	Depth of the 27.75 kg.m^{-3} Isopycne (m)	Mean Potential Density (kg.m^{-3})	Mean Salinity	Mean Potential Temperature (°C)	Mean ε_{Nd}	Uncertainty	Number of ε_{Nd} Data	Mean Nd Concentration (10^{-12}g.g^{-1})	Uncertainty
1	55.03°N, −52.14°E	-	27.49	34.66	4.14	−15.1	0.5	2	2.5	*0.2*
2	58.92°N, −47.12°E	1000	27.65	34.80	3.79	−13.9	0.2	5	2.7	0.1
7	55.55°N, −43.97°E	900	27.66	34.80	3.67	−15.0	0.4	3	2.9	0.1
9	62.70°N, −37.59°E	1000	27.64	34.95	4.87	−14.0	0.4	4	2.7	0.0
12	56.37°N, −27.82°E	1220	27.52	34.94	5.64	−14.8	0.2	7	2.8	0.1
14	65.02°N, −30.23°E	1090	27.59	35.03	5.80	−13.6	0.3	3	2.5	0.2
15	65.32°N, −30.88°E	890	27.56	35.05	6.20	−13.5	0.3	3	2.5	0.1
16	65.17°N, −30.52°E	980	27.58	35.03	5.82	−14.2	*0.3*	1	2.6	0.3
22	62.75°N, −9.01°E	-	27.43	35.24	8.17	−13.0	0.6	4	2.3	0.3
23	60.50°N, −5.00°E	450	27.42	35.26	8.26	−12.9	0.1	3	2.4	0.2
54	66.16°N, −27.50°E	200	27.10	33.73	−0.75	−11.0	0.3	3	8.4	4.2
55	66.08°N, −27.25°E	260	27.40	34.75	5.48	−11.9	0.9	3	4.2	1.1
56	66.01°N, −26.98°E	350	27.25	34.29	3.49	−10.9	0.8	5	3.7	0.8

Stations 1 to 23 = SPMW. Station 54, 55 and 56 = Denmark Strait. Uncertainties (for ε_{Nd} and Nd concentration) are in most cases the average deviation from the mean. When a single datum is available, the uncertainty is the external precision of the measurement, reported in italic.

calculated from 1 to 7 data (depending on the station), with a mean value of 3.5. This vertical resolution certainly does not catch all hydrological variabilities. However, the relatively small data dispersion at each station (average deviation from the mean of 0.3 ε_{Nd} units, on average for stations 1 to 23) suggests that the presented results would hold with a higher resolution.

[17] In Figure 3, the EGC and the eastward influence of the LC appear quite clearly on the ε_{Nd} map, whereas they are less apparent with salinity, temperature and oxygen concentration. Among the differences between the ε_{Nd} and the other distributions, ε_{Nd} suggests a greater eastward influence of the Labrador Current. At station 12, ε_{Nd} is −14.8. The only other water masses in the NASG having $\varepsilon_{Nd} \leq 14.8$ are found in the Labrador Sea. Furthermore, the only lithogenic sources with such signatures in this region are Greenland and the Labrador coast [*Lacan*, 2002] (available at http://francois.lacan.free.fr/job.htm). Therefore, the Nd IC at station 12 evidences that SPMW at this location originates in the Labrador Current. This is consistent with the formation of the Subarctic Intermediate Water (SAIW) in the Labrador Current and its subsequent advection and subduction eastward [*Arhan*, 1990]. The present observation shows the eastward extension of SAIW as far as east as 26.8°W. This result is also consistent with Read's conclusion that SAIW ceases to exist as a water mass east of 26°W (at the front of the NAC, along ≈53°N) [*Read*, 2001].

[18] Another important feature in Figure 3 is a sharp gradient in the Denmark Strait, shown by all parameters (ε_{Nd}, S, θ and [O2]). This front strongly suggests that water from the Nordic Seas do not play a significant role in SPMW formation. This could partly result from their entrainment to deeper level with underlying water downstream of the sill. Therefore, waters from the Labrador Current seem to be the only cold and fresh end-member taking part to the SPMW formation. One can then assume that SPMW result from a two end-member mixing: SAIW (formed in the Labrador Current) and subtropical water brought within the North Atlantic Current (NACW). In order to test this hypothesis, we plotted SPMW properties and those of these two end-members on ε_{Nd} - S and θ- S diagrams (Figure 4).

[19] On both diagrams, the data fit two end-member mixing curves, which confirms the hypothesis of a two end-member mixing and the conservative behavior of the averaged parameters (θ, S, ε_{Nd}) used here. The ε_{Nd} − S diagram clearly discriminates Denmark Strait waters and confirms that they do not take a significant part in SPMW formation. In contrast, in the θ − S diagram, Denmark Strait waters properties align rather well with SPMW, which could lead to the erroneous opposite conclusion.

[20] From these results, we quantified the composition of different types of SPMW, using the end-members characteristics defined in Figure 4. Based on ε_{Nd} data, SPMW entering the Nordic Seas above the Iceland-Scotland ridge (stations 22 & 23) is composed of ≈44% NACW (and therefore ≈56% SAIW). At station 9, In the East Greenland Current, NACW relative contribution decreases to ≈22% (similar proportions are found using salinity: 38% and 19% of NACW, respectively). NACW contributions appear small

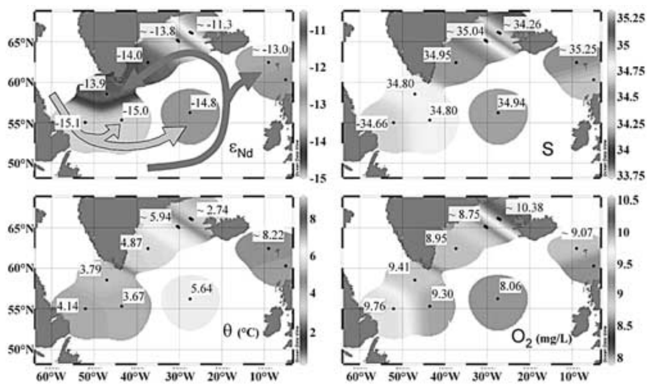

Figure 3. Mean characteristics (ε_{Nd}, salinity, potential temperature and dissolved oxygen concentration) averaged at each station between the surface and σ_θ = 27.75 kg.m^{-3}. Data were interpolated using the *VG Gridding* algorithm (Ocean Data View, http://www.awi-bremerhaven.de/GEO/ODV). Arrows (on the ε_{Nd} map) schematize water mass transports: 1) cold, fresh and with a low ε_{Nd}, from the Labrador Current (light blue) and 2) warm, saline and with a high ε_{Nd}, from the subtropical gyre (red). See color version of this figure in the HTML.

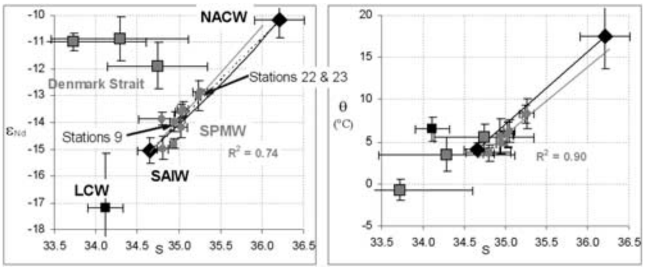

Figure 4. Mean SPMW properties at each station (grey circles) reported on an ε_{Nd} versus salinity diagram (left panel) and a potential temperature versus salinity diagram (right panel). The properties of the two end-members defined in the text are shown by black diamonds. SAIW properties were defined as the SPMW properties at station 1 (located in the Labrador Current). NACW properties are mean values based on 5 measurements carried out in the subtropical gyre (4 data from its western part, 36°N–62°W [*Piepgras and Wasserburg*, 1987] and one from its eastern part 28°N–30.5°W [*Spivack and Wasserburg*, 1988]). Labrador Current Water (LCW) properties are based on 3 data points from the upper 50 m of the Labrador Current (black square). Error bars are calculated differently for different parameters. a) for parameters with a large number of data (salinity and temperature, except for the NACW and LCW) error bars are standard deviations; b) for parameters with a small number of data (salinity and temperature for the NACW and LCW, and ε_{Nd} in all cases except station 16) error bars are the average deviation from the mean; c) for parameters with only one datum (ε_{Nd} at station 16) error bars are the external precision of the measurement. Theoretical mixing curves are shown by black lines. In the case of the ε_{Nd} – S diagram, this curve is a hyperbole. However because the two end-member concentrations are not very different (2.5 ± 0.2 and 2.1 ± 0.1 10^{-12}g.g^{-1}, for SAIW and NACW respectively), this hyperbole is hardly distinguishable from a strait line (represented by a dotted line). Linear regressions for the SPMW properties are shown by grey lines. The coefficients of determination (R^2) are reported.

(and SAIW contributions appear large) in comparison with absolute contributions expected from hydrological studies ([e.g., *Hansen and Østerhus*, 2000; *Read*, 2001] suggest that SPMW inflow to the Nordic Seas is mainly composed of NACW). This discrepancy probably reflects the fact that, since SAIW itself likely contains significant amounts of NACW (brought to the Labrador Current within the NASG), the *absolute* contributions of the NACW are probably larger than the *relative* contributions reported here.

[21] Little is known about SAIW formation. Since it originates in the Labrador Current and is characterized by a salinity minimum, its formation likely involves Labrador Current Water (LCW) in addition to NACW. As shown in Figure 4, the LCW properties align with the SAIW-SPMW-NACW line on the ε_{Nd} – S diagram. If LCW Nd concentration was similar to those of the other water masses, this alignment would suggest that the LCW is the ultimate cold and fresh end-member of the mixing. However, LCW Nd concentration (3.8 ± 0.9 10^{-12}g.g^{-1}, estimated from 3 samples taken within the upper 50 m in the Labrador Current) is larger than those of SPMW. Therefore, if LCW is the cold and fresh end member of the two end-members mixing suggested above, its Nd concentration would need to decrease significantly before mixing. Such a process is likely, considering recent results documenting significant Nd subtraction at ocean boundaries (F. Lacan and C. Jeandel, Neodymium isotopes as a new tool for quantifying exchange fluxes at the continent-ocean interface, submitted to *Earth and Planetary Science Letters*, 2004), which could occur without modifying the Nd IC of the water mass. Likewise, the fact that LCW properties do not align with the others on the θ – S diagram does not exclude the possibility of a LCW end-member, since temperature is not conservative at the surface in the Labrador Current. In order to better establish whether the LCW is the ultimate end-member, we would need more precise Nd and hydrological data from this water mass.

5. Conclusion

[22] ε_{Nd} is conservative in the studied area. It identifies the influence of SAIW as far east as 26.8°W. It indicates that waters flowing through the Denmark Strait do not significantly contribute to the SPMW formation. These results are based on data integrated over the all SPMW depth range. Although simplified, this description allows a good reconstruction of ε_{Nd} and salinity of this layer of the North Atlantic Subpolar Gyre. A two end-member mixing, involving SAIW (and maybe ultimately LCW), and NACW can describe SPMW formation. ε_{Nd} reflects the relative contributions of the two end-members along the NASG. Paleo-records of the ε_{Nd} signature obtained from planktonic foraminifera [*Vance and Burton*, 1999] could record past variations in the relative contribution of these two end members and provide information on changes in the northward extension of the Gulf Stream.

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