# The Arctic Front: structure and dynamics

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> Water masses Front Dynamics

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#### Abstract

During summer expeditions of r/v 'Oceania' to the Arctic Seas, the Arctic Front has been crossed and investigated each time since 1987. The 1993 cruise initiated more detailed investigations of this phenomenon. In the area delimited by longitudes  $2^{\circ}41'W$  and  $3^{\circ}05'E$  and latitudes  $70^{\circ}54'N$  and  $72^{\circ}32'N$ , five CTD transects were done with the CTD cast every 5 or 2 nm on each transect.

The location and direction of the front have been defined. The geostrophic component of the general circulation shows good agreement with the earlier data: a strong current (up to 40 cm s<sup>-1</sup>) on the Atlantic side of the front, about zero velocity in the middle and a weak current (5–10 cm s<sup>-1</sup>) on the Arctic side of the front. The steepest horizontal gradients were  $ca \ 0.5^{\circ}$ C km<sup>-1</sup> (temperature) and  $ca \ 0.04$  psu km<sup>-1</sup> (salinity). The data reveal the complicated structure of the front with its intrusions, meanders and gyres.

## 1. Introduction

There is some confusion as far as the definition of the Polar Front and/or Arctic Front is concerned. One name or the other is used by different authors to describe the contact zone between Polar-Arctic and Arctic-Atlantic waters. To avoid this we will follow Swift's (1986) definition: the Polar-Arctic water contact zone is called the Polar Front, and Arctic-Atlantic water contact zone – the Arctic Front.

The Greenland, Iceland and Norwegian Seas, sometimes called the GIN Sea (Hopkins, 1991), form a major, semi-enclosed basin which, by providing a strong two-way horizontal exchange between the Polar Sea (Arctic Ocean) and the North Atlantic Ocean, and at the same time by being the primary site for deep- and bottom-water formation, plays a very important role, unique among the world's oceans.

The water masses of the GIN Sea arise from two parent water bodies: the Polar Water (PW) from the Polar Sea, which is cold and of low salinity, and the North Atlantic Water (NAtW), which is warm and of high salinity (Hopkins, 1991). The main body of Atlantic waters comes through the Faroe-Shetland Channel and moves farther to the north and north-east, mainly with the Norwegian Atlantic Current (NAtC). At about lat. 64–65°N, part of the NAtC turns north and moves along the eastern edge of the Norwegian Basin up to Mohn's Ridge. Here it joins up with the Jan Mayen Current (JMC) and turns east and north-east, the combined currents forming the south-eastern and eastern limbs of the Greenland Gyre (GG).



Fig. 1. The area of investigation at the Arctic Front





The main body of the Polar Waters comes through the Fram Strait and moves southwards with the East Greenland Current (EGC). To the north of Jan Mayen Island some of the Polar Waters turn to the east as the Jan Mayen Current, which forms the southern part of the GG. Over Mohn's Ridge the polar water of the JMC meets the Atlantic waters of a so far unnamed current to form the Arctic Front, which was the subject of our investigation (Fig. 1).

#### 2. Data and methods

Every summer since 1987, except summer 1990, the Institute of Oceanology PAS has carried out an investigation of the Norwegian-Barents Sea Confluence Zone and the Greenland Sea along the 0° meridian. Each time



Fig. 3. The station grid at the Arctic Front

a well-marked front was found over Mohn's Ridge between 70 and  $72^{\circ}$ N (Fig. 2). Since summer 1993 the front has been investigated in greater detail. During 6 days (17–22 July 1993), in the area delimited by  $2^{\circ}41'$ W,  $3^{\circ}05'$ E,  $70^{\circ}54'$ N and  $72^{\circ}32'$ N, five CTD transects across the front were done (Fig. 3). CTD stations were located every 10, 5 and 2 nm, with records made down to 1000 and 2000 m using a Sea Bird 9/11 instrument. Readings were stored in a 486 PC and averaged every 1 and 5 dbars. The one thousand dbars no-motion level was chosen for the geostrophic calculations.

#### 3. Results

The surface waters on both sides of the front are stratified with respect to temperature and density in the upper, approximately 100 m-deep layer (Fig. 4). The seasonal thermocline was located predominantly in the layer between 10 and 80 m and was much stronger on the Arctic side (a  $4-6^{\circ}$ C drop in temperature) than in the Atlantic domain (a decrease of  $2.5-3^{\circ}$ C).

The salinity in this layer also decreased from about 35.0 psu at the surface to 34.8 psu at 80 m in the Arctic waters and from about 35.1 psu to 35.0 psu on the Atlantic side. Unlike the Arctic domain, the vertical salinity differentiation in the upper 100 m layer of Atlantic waters is very weak or does not exist at all (Fig. 4).

Density gradients in the seasonal pychocline are slightly higher in Arctic waters: in the 0-80 m surface layer, the potential density rises from ca 27.4 to 27.8–27.9, in Atlantic waters from ca 27.4 to 27.7. Below the seasonal pycnocline, vertical changes in temperature, salinity and density are very small down to depths of 1000–2000 m in Arctic waters, but on the other side of the front, in Atlantic waters, both temperature and salinity remain the same for some meters of depth, and then decrease by  $3-4^{\circ}C$  and ca 0.2 psu through a layer of about 200 m. The density increase caused by the drop in temperature prevails over the density decrease generated by the fall in salinity; it is this rise in density that is observed in this discontinuity layer, which is the downward extension of the Arctic Front. Its depth increases from ca 100–200 m to 700–900 m when moving away from the front to the south (Figs. 5, 6, 7). In the  $ca \ 100-200 \text{ m}$  to 400-600 mlayer it is directed more steeply downwards, and at greater depths it becomes more horizontally orientated. The direction and slope of the front, and the horizontal gradients across it, varied considerably in space and, most probably, in time as well, but this cannot be proved since we did not do a time series. The horizontal gradients across the front were: temperature -0.1-0.2 °C km<sup>-1</sup>, salinity -ca 0.01 psu km<sup>-1</sup> and potential density  $ca \ 0.005 \ \mathrm{km^{-1}} \ \delta \ \theta$  (Fig. 8).





Fig. 4. Potential temperature (a), salinity (b), potential density (c) and TS relations (d) across the Arctic Front











Fig. 7. Potential density distribution along transect V









Fig. 8. Some physical characteristics and its gradients at the 200 m level across the Arctic Front along transect V; temperature (a), salinity (b), density (c), geostrophic velocity (d)



Fig. 9. Potential temperature  $[^{\circ}\mathrm{C}]$  (a) and salinity [psu] (b) distributions at 20 m



Fig. 10. Potential temperature  $[^{\circ}\mathrm{C}]$  (a) and salinity [psu] (b) distributions at 300 m



Fig. 11. The depth of the 27.8 potential density (a) surface and the thickness of the layer between the 27.8 and 27.9 isopycnal surfaces (b)





Despite some differences in temperature and salinity, the front is not seen at the sea-surface; in the horizontal plane, it appears below 50–80 m (Fig. 9 and 10) and is recorded down to 700–800 m (Fig. 6). The depth of some isopycnal surfaces and the thickness of the layer between two isopycnal surfaces (Fig. 11) show the position of the front even more clearly.

The Arctic Front shown here by the horizontal distribution of temperature, salinity and density has a complicated shape (meanders), and is accompanied by cyclonic and anticyclonic gyres on both sides, the most pronounced of which is the large anticyclonic gyre in the Atlantic domain at about  $3^{\circ}E$  and  $71^{\circ}30'N$ .

Detailed measurements at transect V (Figs. 5, 6) show that the shape of the front is complicated in the vertical plane as well. Particular attention should be paid to the bodies of fresher and colder waters of different sizes 'diving' under the front on its Arctic side. The salinity of most of them



Fig. 13. Geostrophic currents  $[\text{cm s}^{-1}]$  at 50 m (reference level 1000 m)



Fig. 14. Geostrophic currents  $[\text{cm s}^{-1}]$  at 200 m (reference level 1000 m)

is less than 34.86, from 0.2 to 0.6 psu lower than that of the surrounding waters. In temperature distribution they are marked by closed isotherms or by the bending of isotherms (Fig. 5). Intrusions of Arctic waters into the Atlantic domain and vice versa are also evident.

Calculated against the 1000 db reference level (the assumed no-motion level), the geostrophic circulation shows quite strong currents directed generally north-eastwards (Fig. 12) with a velocity of up to 40 cm s<sup>-1</sup> at the sea surface. The waters move in the same direction on both sides of the front (Figs. 13, 14) but do so faster on the Atlantic side than on the Arctic side. Total geostrophic transport across transect V is over 6 Sv: 6.8 Sv to the north-east and 0.4 Sv in the opposite direction. It is a suprisingly high value, never mentioned before in any publication. The 1000 db no-motion level was determined by the depth of CTD casts at transect V. At the other transects, the CTD was lowered down to nearly 2000 m, so we were able to try another reference level – 1600 db (Figs. 15, 16). The velocity was ca 2 cm s<sup>-1</sup> faster and the transport ca 30% greater.











Fig. 17. Cumulative TS relation at the Arctic Front (Hopkins' classification)

Finally, it would be interesting to find out what types of water masses we are dealing with here. Among the numerous classifications, those presented by Hopkins (1991) seem to be the most suitable. For comparison, Swift's classification (Swift, 1986) is presented as well. So we have the following water masses (Fig. 17):

- Norwegian Atlantic Water (Nw AtW) T > 2°C and S > 35.0 psu (Swift calls this Atlantic Water, AW T > 3°C and S > 34.9 psu).
- Greenland Arctic Surface Water (GArSW) T > 2°C; S < 34.9 psu (Swift: Arctic Surface Water (ASW) T > 2°C; S < 34.9 psu)</li>

- Atlantic Intermediate Water (AtIW) T > 0°C; S = 34.9–35.0 psu (Swift: Lower Arctic Intermediate Water (LAIW) T < 0–3°C; S > 34.9 psu)
- Greenland Arctic Intermediate Water (GArIW) T <  $2^{\circ}$ C; S < 34.9 psu (Swift: upper Arctic Intermediate Water (SuAIW) T and S the same)
- Norwegian Deep Water (NwDW)  $T = 0-(-2)^{\circ}C; S = 34.9-34.94 psu$ (Swift: Norwegian Sea Deep Water (NSDW) T and S the same).

Thus two surface waters (NwAtW and GArSW), two intermediate waters (AtIW and GArIW) and one deep water (NwDW) were recorded. In the upper 1000 m of the region NwAtW and GArIW are dominant. The former occupies the whole layer to the right and above the front, the latter the area to the left and below the front. Arctic surface water was recorded in a thin layer to the left of the front, whereas Norwegian deep or bottom water was found at a depth close to 2000 m a few times only.

#### 4. Discussion and conclusions

Detailed investigations of the area between 71° to 72°N and 3°W to 3°E over Mohn's Ridge show a well-developed frontal zone separating Arctic and Atlantic waters – the Arctic Front. This front was observed in the layer from a depth just below the seasonal thermocline (50–80 m) down to 800–900 m. In the upper part it was nearly vertical in structure, becoming more and more horizontal with depth, so that at about 500–900 m Atlantic (surface) waters were overlying Arctic intermediate waters. The frontal zone was observed to have a complicated structure: gyres, meanders, and intrusions of different sizes from meters to tenths of kilometers can be seen in both horizontal and vertical planes. Intrusions of warm saline Atlantic waters into the relatively homogenous waters of the Arctic domain could be one of the causes of the so-called 'chimneys' that develop later during winter cooling.

The very interesting phenomenon of less saline, colder waters 'diving' under the front was observed. Different-sized bodies of waters of salinity 34.86 psu or even 34.82 psu were found just below or to the left of the front in surrounding waters of at least 34.88 psu. Moreover, fine examples of isopycnal mixing in the frontal zone were recorded and demonstrated on TS diagrams (Fig. 18). The waters on both sides of the front move in the same direction with a calculated mean geostrophic velocity of *ca* 5–10 cm s<sup>-1</sup> in the Arctic domain and 10–20 cm s<sup>-1</sup> in the Atlantic domain; the highest velocity of Atlantic waters was over 40 cm s<sup>-1</sup>. The geostrophic





Fig. 18. Temperature (a), salinity (b), potential density (c) and TS relations (d) at station 116 on the Arctic Front

transport of both currents together was suprisingly high -6-8 Sv. Such strong currents and such a large volume of transported waters here have never been mentioned before and were unexpected. Our data for 1987–1993 also show that this is a permanent feature, at least in summer; the shift of the front from year to year are minimal.

### References

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