On the double-diffusive and cabbeling environment of the Arctic Front, West Spitsbergen

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Abstract

This paper describes the thermohaline characteristics of the Arctic Front to the west of Spitsbergen, in terms of the double-diffusive environment and the potential for densification through cabbeling. The front separates the warm, saline Atlantic water in the West Spitsbergen Current from the cooler, fresher water on the West Spitsbergen Shelf. We have investigated processes at the front that can contribute to, or enhance, mixing and water mass modification in relation to heat transport to the Arctic. Hydrographic data were collected along a cross-shelf section in September 2005. The double-diffusive properties along the section were determined by calculating Turner angles, and cabbeling was investigated with a simple linear mixing scheme. Double diffusion, in the form of diffusive layering, was found to be active within the Arctic Front, with considerable interleaving between water masses. Furthermore, mixing of water masses across the front was found to generate a potential increase in density of more than 0.03 kg m^{-3} through cabbeling, which would then promote sinking and convergence. Our analyses indicate that the two processes of double diffusion and cabbeling are active at the Arctic Front. We discuss their potential contribution to maintaining the density-compensated nature of the front, and conclude that they will promote isopycnal mixing and subsequent modification of the core water of the West Spitsbergen Current.

Atlantic water (AW) is a key constituent of Arctic oceanography. The northward flow of AW, combined with export of polar water and ice through Fram Strait, is the dominant heat source for the Arctic Ocean (Schauer et al. 2004). AW is transported into the Arctic through both the Barents Sea and Fram Strait, and it is the latter that is acknowledged to have the more significant influence on the temperature of the Arctic basins (Aagaard & Greisman 1975; Maslowski et al. 2004). Warm, salty AW is transported through Fram Strait in the West Spitsbergen Current (WSC), a rather complex, multipath, barotropic current (Manley 1995; Saloranta & Haugan 2001; Walczowski et al. 2005). The major contribution to the northward heat transport is within the more easterly Svalbard branch (Manley 1995; Schauer et al. 2004). This branch is confined, through topographic steering, to the upper part of the Svalbard continental slope (Fig. 1), and carries what has previously been termed the "warm core" of the WSC in the upper 200 m (Boyd & D'Asaro 1994).

To the west of the WSC, the AW is separated from the cold fresh polar waters of the Greenland Sea by a density front (Boyd & D'Asaro 1994). Along the shelf break there is a density front close to the surface that is associated with a layer of freshwater. Beneath this layer is a front, referred to as the Arctic Front, manifested in temperature (*T*) and salinity (*S*) fields (Saloranta & Svendsen 2001). The Arctic Front separates the WSC from the cooler, fresher Arctic-type waters on the shelf (Fig. 1), which are thought to originate from the East Spitsbergen Current (Saloranta & Svendsen 2001; Skogseth et al. 2005). The Arctic Front has no corresponding density front and in this respect it is said to be density compensated.

A consistent observation of the Svalbard branch of the WSC is the reported latitudinal cooling of the subsurface waters (Boyd & D'Asaro 1994; Saloranta & Haugan 2004). The rate of heat loss from the warm core is too great to be fully attributable to simple vertical heat flux through diapycnal processes. Rather, it is thought that

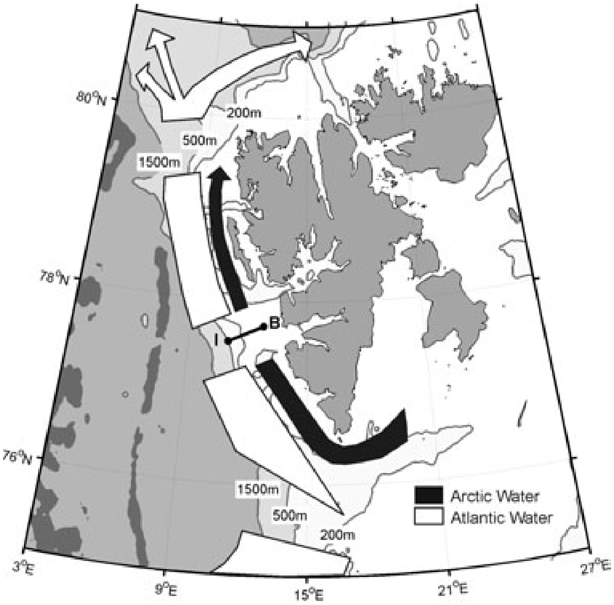

Fig. 1 Map of the Svalbard archipelago and regional bathymetry. The location of the hydrographic section across the shelf west of Spitsbergen is marked with a bold line, and the letters refer to the station identifiers at each end of the section. The current pathways of Atlantic water and Arctic-type waters are shown schematically.

lateral exchange with cooler neighbouring waters is the most likely mechanism. Westward diffusion of heat along isopycnals into the Greenland Sea through an energetic eddy field was proposed by Boyd & D'Asaro (1994). These ideas were developed by Nilsen et al. (2006), who investigated isopycnal mixing arising from the mesoscale eddy field associated with topographically trapped waves at the continental slope. They estimated lateral heat fluxes from the subsurface layers of the WSC to be O(1000) W m^{-2} from moored observations and modelling simulations of isopycnal mixing through eddy diffusion in both the on-shelf (eastward) and off-shelf (westward) directions (Nilsen et al. 2006). These estimates were found to be comparable to previous estimates based on the hydrographic climatology (Saloranta & Haugan 2004).

Some observed rates of northward cooling and freshening of the AW core are not consistent with pure isopycnal mixing (Boyd & D'Asaro 1994; Saloranta & Haugan 2004), and require a combination of additional mechanisms to achieve the necessary cooling/freshening ratio (Saloranta & Haugan 2004). Further water mass modification may be achieved through exchanges across the Arctic Front resulting in AW leaking onto the shelf (Saloranta & Svendsen 2001) or extensive flushing of the shelf by AW (Cottier et al. 2005). Identifying the key processes by which the warm Atlantic core of the WSC undergoes latitudinal cooling is essential for quantifying the delivery of heat to the Arctic.

It is clear that the dynamic interactions between water masses across the Arctic Front are important to the regional and Arctic oceanography; yet, beyond its broad hydrography, the details of the characteristics of the front are still rather sparsely observed and quantified. This paper begins to address these points by describing the varying thermohaline characteristics across the front, and by offering a qualitative assessment of the potential role of double diffusion and cabbeling in frontal dynamics and subsequent water mass modifications.

The phenomenon of double diffusion occurs when a water column that is gravitationally stable overall has an unstable temperature or salinity profile. This leads to either (i) salt fingering, with warm, salty water overlying cold, fresh water such that T and S both decrease with depth, or (ii) diffusive layering with cold, fresh water overlying warm, salty water with T and S increasing together with depth (Turner 1973). Double diffusion acts on the molecular scale, yet despite this it is capable of driving lateral interleaving across fronts by the release of potential energy through diffusive mixing of water masses with contrasting T–S characteristics (Stern 1967; May & Kelley 2001). The interleaving features, commonly referred to as intrusions (Herbert 1999), have important implications for horizontal mixing, as they can generate unusually large eddy diffusivities, with associated lateral salt and heat fluxes (Ruddick & Richards 2003). Significant water mass modification is possible through double diffusion (Talley & Yun 2001), and the interleaving process is also considered important in the maintenance of thermohaline fronts (Garrett & Horne 1978; Simeonov & Stern 2004).

The process of cabbeling is a consequence of the nonlinearity of the equation of state, and refers to the densification arising through isopycnal mixing of parcels of water with the same initial density, but differing temperature and salinity. The product of the mixing, with a greater density than the parent water masses, will therefore tend to sink, and this can lead to water mass transformation (Marsh 2000; Talley & Yun 2001; You 2003) and the maintenance of thermohaline fronts (Garrett & Horne 1978; Horne 1978; Lobb et al. 2003). This paper continues by presenting the hydrographic data collected across the Arctic Front, and describing the quantitative analyses for double diffusion and cabbeling. The results of these analyses are then presented and the paper concludes with a discussion of the double-diffusive environment and cabbeling in terms of the cross-front dynamics and the role in modification of AW.

Observations and methods

Hydrographic data were collected by the authors specifically for this study from RRS *James Clark Ross* during cruise JR127 in September 2005. A section of seven stations was occupied across the West Spitsbergen Shelf and over the shelf break with approximately 12 hours separating the first and the last stations. The 47-km-long section was oriented perpendicular to the isobaths, and water depths ranged from 100 m (Station B) to 470 m (Station I) (Fig. 1). At each station, vertical profiles of temperature and conductivity were measured to within 10 m of the seabed at 24 Hz using a Sea-Bird Electronics *911plus* conductivity–temperature–depth (CTD) system and a carousel water sampler. Data were calibrated against bottle samples and averaged to a 1-m bin size. Temperature was converted to potential temperature (θ) and density to potential density (σ_θ) using standard algorithms (Fofonoff & Millard 1983).

The hydrographic data were analysed with respect to two of the proposed frontal mixing mechanisms: double diffusion and cabbeling.

Double diffusion

The susceptibility of the water column to double-diffusive convection can be described by the vertical density ratio, a measure of the relative contributions of T and S to the stratification. An alternative measure of the degree of density compensation is given by the Turner angle (Tu), as proposed by Ruddick (1983), which provides a practical index for the nature and strength of double-diffusive activity through the water column. For each CTD profile, the susceptibility of the water column to double-diffusive convection was quantified by calculating the value of Tu down each CTD profile. Tu is defined as the four-quadrant arctangent of $(N^2_\theta - N^2_S)/(N^2_\theta + N^2_S)$, where $N^2_\theta = \pm g\alpha d_z\theta$ and $N^2_S = \pm g\beta d_z S$ (Ruddick 1983), and where α and β are the thermal expansion and haline contraction coefficients, respectively. As defined, the water column will be diffusively unstable between $-90° < Tu < -45°$, stable for $|Tu| < 45°$, unstable to salt fingering for $45° < Tu < 90°$ and gravitationally unstable for $|Tu| > 90°$. To compare conditions at each station, vertical profiles of Tu and the percentage of the water column susceptible to each of the four defined Tu regimes was calculated from the 1-m resolution CTD data over the depth interval 1–100 m.

Cabbeling

Mixing of water masses along isopycnal surfaces will lead to cabbeling, where the density of the product water is greater than either of the two parent water masses. To estimate the density increase resulting from such mixing we followed the same procedure described by Lobb et al. (2003). We selected two CTD stations with θ–S profiles representative of the two parent water masses on either side of the Arctic Front: Arctic-type waters on the shelf and AW in the WSC. It was assumed that the waters on either side of the front mixed along isopycnals and these parent water masses formed the mixing end members. For equal values of initial σ_θ the corresponding θ and S for each end member were mixed theoretically in differing proportions. The resulting increase in density was the difference between σ_θ of the product water and the initial σ_θ.

Results

The distribution of θ and S from all CTD data collected along the across-shelf section is plotted in Fig. 2. Three distinct domains can be identified in the distribution: (i) low salinity water with $S < 34.0$, which is confined to the surface layers, and in late summer results from freshwater inputs primarily from local glacial melt and precipitation; (ii) cold ($\theta < 4$°C) and rather fresh water ($S < 34.9$), which is Arctic-type shelf water originating from the East Spitsbergen Current; (iii) warmer ($\theta > 4$°C) and rather saline water ($S > 34.9$), which has the characteristics of AW. These domains are wholly consistent with previous descriptions of the regional hydrography (Saloranta & Svendsen 2001; Svendsen et al. 2002; Cottier et al. 2005).

Vertical property fields of θ, S and σ_θ are presented in Fig. 3. The dominant feature in the across-shelf section is

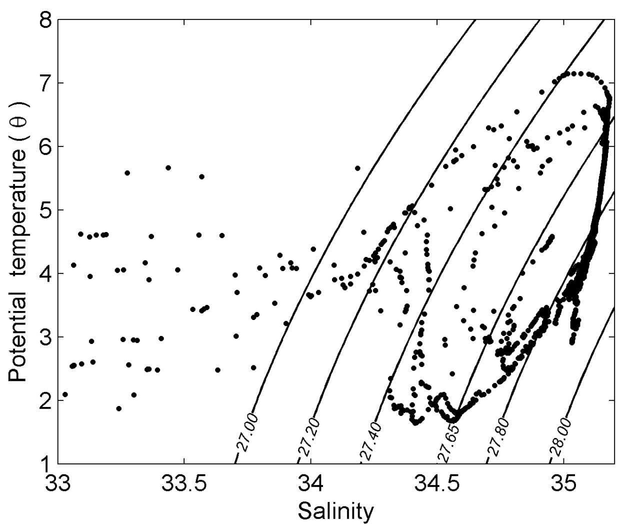

Fig. 2 The potential temperature (θ) plotted against salinity (S), with all the conductivity–temperature–depth (CTD) data points from the cross-shelf section, gives a broad illustration of the distribution of water mass characteristics of the region.

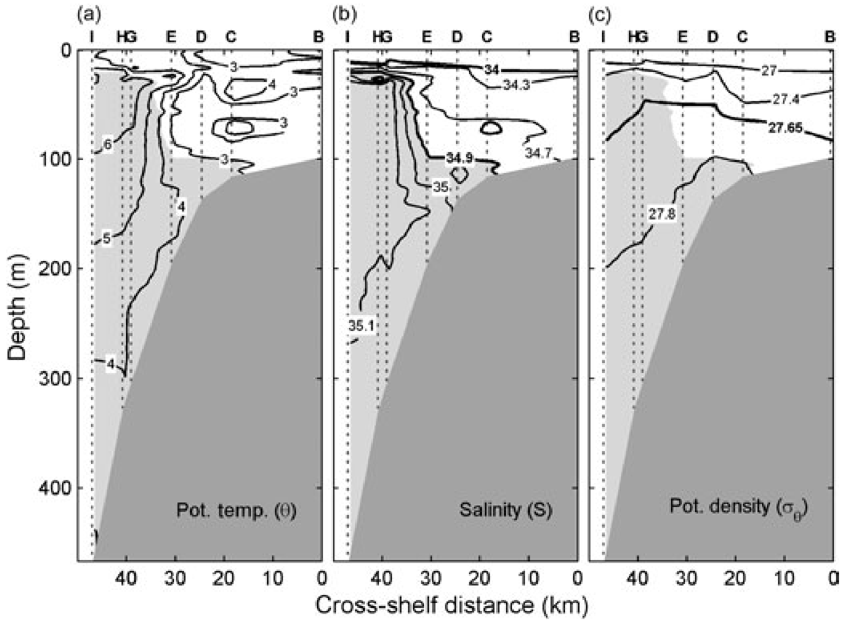

Fig. 3 Vertical sections crossing the shelf of (a) potential temperature, (b) salinity and (c) potential density. Letters and vertical dotted lines identify the stations and the light-grey shaded area in each section marks the extent of Atlantic water. Bold isohalines in (b) demarcate Atlantic water and fresh surface water. The bold 27.65 isopycnal in (c) is referred to in the text.

the steep front in both *T* and *S*, with near-vertical isotherms and isohalines, located over the shelf break between stations D and G. Here the water depth increases from 120 to 300 m over a distance of 20 km. The frontal region at the shelf break is not apparent in the density section, although the isopycnals (notably $\sigma_\theta = 27.8$) slope offshore.

In general, water on the shelf had salinities less than 34.9 and temperatures of less than 4°C. However, a lens of rather warmer and more saline water can be identified at 80 m at Station C. The wedge of surface water, shallower than 20 m, is demarcated by the 34.0 isohaline. There is also a subsurface temperature maximum of ~4°C, which is possibly a remnant of earlier summer warming. Off the shelf the water was warmer and more saline, and we define the boundary for AW as having a salinity of greater than 34.9 (Swift & Aagaard 1981). The salinity maximum ($S \approx 35.18$) in the AW at stations G, H and I was found at a depth of between 40 and 50 m. AW, indicated in the sections as the light shaded region, was also present on the shelf at Station C close to the bed.

Maximum lateral temperature and salinity gradients, of 3×10^{-1}°C km^{-1} and 5×10^{-2} km^{-1}, respectively, occurred between stations D and G at a depth of approximately 40 m. Between the same stations, lateral density gradients were generally weak, with a maximum magnitude of 7×10^{-3} kg m^{-3} km^{-1} and a mean value between 30 and 100 m in depth of 1×10^{-3} kg m^{-3} km^{-1}.

Results of the Turner angle analysis of the CTD data are shown in Fig. 4. A vertical section across the shelf is presented in Fig. 4a, with the double-diffusive regimes of diffusive layering and salt fingering shown as shaded regions. On the shelf double-diffusion is active over the majority of the depth, predominantly through diffusive layering. In contrast, off the shelf (stations G, H and I) double diffusion is most active below 50 m, predominantly through salt fingering. At station E, located in the front, diffusive layering is active in distinct layers between 50 and 100 m. There is also active diffusive layering below the surface waters.

These results are summarized in Fig. 4b, which shows that in the depth interval of 1–100 m, the proportion of the water column susceptible to double-diffusive convection of either the diffusive layering or salt-fingering type amounted to 45–70%. The remaining proportion of the water column was predominantly stable. The proportion of each double-diffusive mode (diffusive layering or salt fingering) varied across the front: diffusive layering dominated the shelf area (stations B, C and D), whereas salt fingering was dominant off the shelf (stations G, H and I). The greatest percentage of double diffusivity occurred within the Arctic Front at Station E, where diffusive layering was dominant.

A density increase as a result of cabbeling was found to occur along isopycnals between $\sigma_\theta = 27.4$ and 27.8 (Fig. 5). The maximum density increase exceeded 0.03 kg m^{-3} for mixing of waters with $\sigma_\theta = 27.65$, where the largest differences in θ ($\Delta\theta \sim 5$°C) and S ($\Delta S \sim 0.6$) occurred.

The characteristics of interleaving are inversions of temperature and/or salinity, most easily seen in θ–S data (Walsh & Carmack 2003). In Fig. 5 interleaving was identified at Station E, lying between the two end member profiles (D and G). Five intrusions were identified

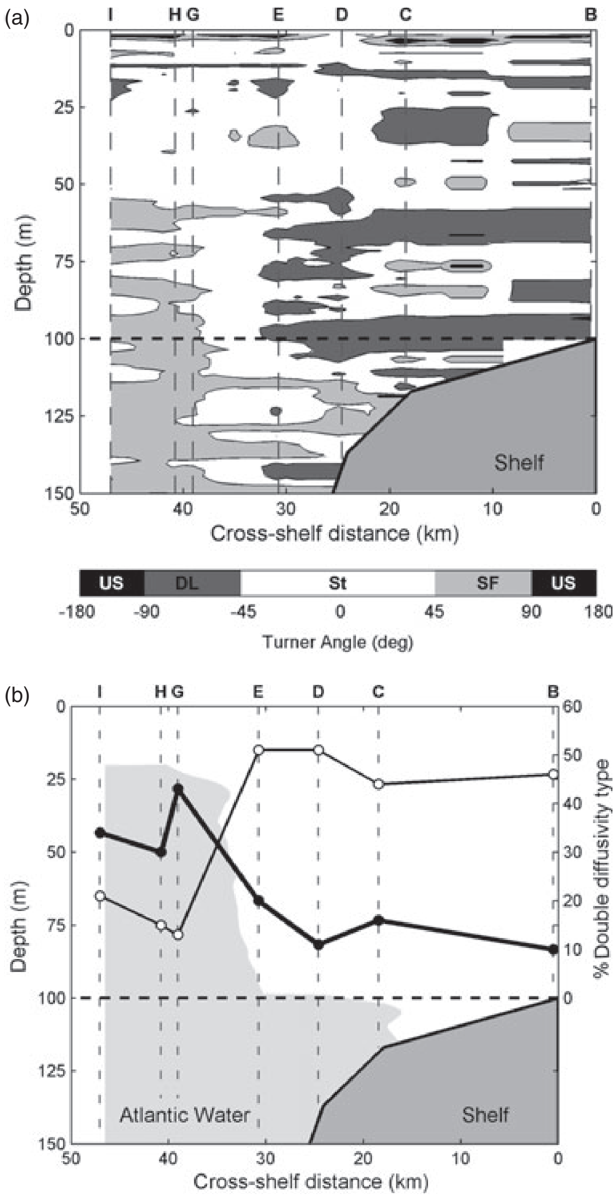

Fig. 4 (a) Vertical section across the shelf showing the distribution of Turner angles derived from the conductivity–temperature–depth (CTD) data. The block shading illustrate the unstable (US), diffusive layering (DL), salt fingering (SF) and stable (St) regimes. (b) Vertical section showing the proportion of double-diffusive convection type (●, salt fingering; ○, diffusive layering) occurring at each station across the shelf. Depth is indicated on the left-hand *y*-axis and the percentage of double-diffusivity type is marked on the right-hand *y*-axis. The extent of Atlantic water is indicated by the light-grey shaded area and the horizontal dashed line is the 100-m depth limit for the calculation of the proportions.

between 40 and 80 m in depth that have a typical vertical length scale of 5 m, and the distance of 14.4 km between stations D and G constrains the magnitude of their horizontal length scale.

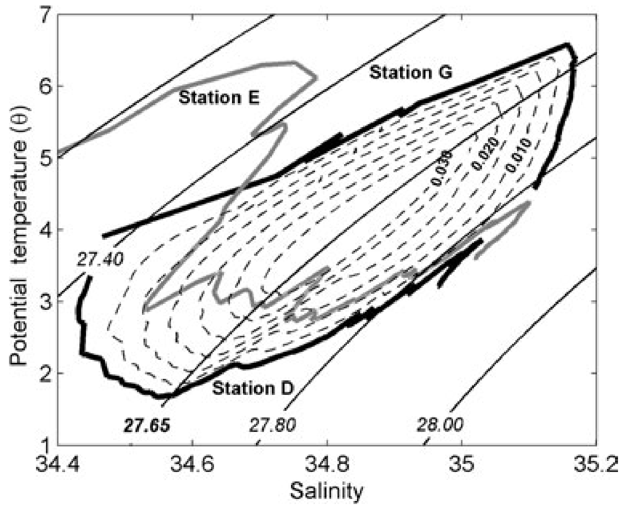

Fig. 5 The potential temperature (θ) plotted against salinity (S) illustrates the increase in density through linear mixing of water mass end members and cabbeling. The shelf water end member is Station D and the Atlantic water end member is Station G; indicated by bold black lines. Station E, within the Arctic Front, is indicated by the bold grey line. The increase in potential density through linear mixing of varying proportions of the end members is indicated by the dashed black contours of equal density change. Contours are drawn at 0.005 kg m^{-3} intervals.

Discussion

In this paper we have described the density-compensated Arctic Front located at the Svalbard continental slope, and presented the first assessment of its double-diffusive nature and potential water mass modification through isopycnal processes. The hydrography of the front, as observed in September 2005, is found to be consistent with previous descriptions (Boyd & D'Asaro 1994; Saloranta & Svendsen 2001; Cottier et al. 2005). However, the existence of this *T–S* front is not always clear (Haugan 1999), and at some locations along the West Spitsbergen Shelf it is absent under certain shelf-exchange conditions (Cottier et al. 2005).

The hydrographic structure on the shelf undoubtedly has a seasonal nature, particularly the depth of the surface layer, which is formed primarily through glacial melt and precipitation (Svendsen et al. 2002), and the occurrence of a subsurface temperature maximum is likely to be related to summer warming. However, in general the shelf hydrography remains stratified, even during winter (Boyd & D'Asaro 1994; Cottier et al. 2005). It is important to correctly interpret the lens of rather saline water on the shelf at a depth of 80 m at Station C. Unlike many other Arctic shelves, the West Spitsbergen Shelf is dominated by advected sea ice rather than locally formed sea ice (Boyd & D'Asaro 1994), and consequently such saline water is unlikely to be the result of brine released during the previous winter. Furthermore, the lens has a temperature of >3°C, which is thus consistent with cross-front leakage and the layering of AW with shelf waters as described by Saloranta & Svendsen (2001).

Although Saloranta & Svendsen (2001) associated leakage of AW with the presence of submarine valleys, or channels, cutting across the shelf, our observations show that it also occurs in a location without such topographic features. Either this leakage can occur along the length of the shelf or these pockets of AW are readily advected. Complete summertime flushing of the shelf area by AW, as reported by Cottier et al. (2005), has not occurred at this location. This raises questions of the generality of the flushing phenomenon in both time and space; is it associated solely with across-shelf channels or does it occur on an interannual basis only?

One widely reported aspect of the shelf hydrography is the presence of a surface density front associated with a wedge of fresh water (Boyd & D'Asaro 1994; Saloranta & Svendsen 2001). Our results do not reveal this front, as the surface layer depth is rather uniform and the westward extent of surface water is beyond our section. The distinct surface layer, demarcated by the 34.0 isohaline in Fig. 3b, and a rather strong pycnocline at about 20 m in depth, will tend to minimize heat loss through diapycnal processes. Consequently, it is valid for us to focus our discussions on what has been termed the subsurface layer with respect to cooling of the warm core of the WSC (Boyd & D'Asaro 1994; Saloranta & Haugan 2004; Nilsen et al. 2006).

Within the front (Station E) there is evidence in the subsurface layer of interleaving between the Arctic waters on the shelf and the AW (Fig. 5). This observation is reinforced by the active diffusive layering at Station E in the depth range 50–100 m (Fig. 4a). There are a number of important consequences of the interleaving process. First, it sets up a lateral mixing of heat and salt (Ruddick & Richards 2003), and the magnitude of associated lateral eddy diffusivities are reported to range from a few to several thousand $m^2\ s^{-1}$ (Ruddick & Gargett 2003). Second, it brings contrasting water masses together over a broad interface, which will enhance water mass transformation (Talley & Yun 2001). Third, it permits diapycnal mixing through double diffusion at the interface of the interleaving layers (Schmitt et al. 2005). The interleaving situation is illustrated schematically in Fig. 6. From the limited dataset it is not realistic to make quantitative estimates for each contributory process, but they are clearly active and likely to be relevant to the modification of the inshore branch of the WSC. Whereas this is the first description of such interleaving features in the front to the west of Spitsbergen, CTD data presented by Haugan (1999: fig. 4) provide additional examples of interleaving in waters of 600 m in depth. Interleaving will promote water mass modification in the warm core through double diffusion.

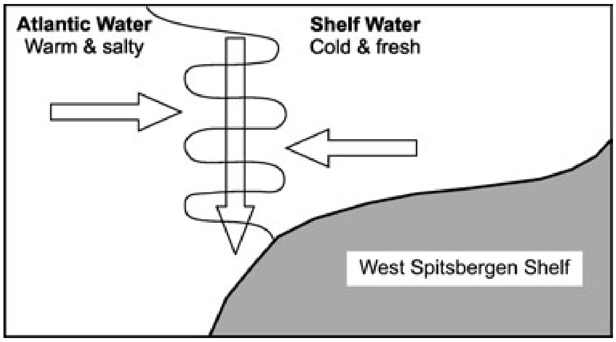

Fig. 6 Diagram of the double diffusive interleaving that occurs at the Arctic Front between Atlantic water and the Arctic-type shelf waters. The interleaving permits effective isopycnal mixing between contrasting water masses, leading to increased density of the product water, sinking and convergence.

The change in the form of double diffusion between the shelf and the shelf slope is related to the temperature and salinity stability of the water column. On the shelf, at Station D for example, the water is predominantly stable with respect to salinity but is unstable with respect to temperature, with warmer water lying beneath cooler waters (Fig. 5). This situation gives rise to the diffusive layering form of double diffusion (Fig. 4a). The active diffusive layering across the front is likely to support the formation of the regular interleaving structures identified at Station E in Fig. 5. In contrast, at Station G, there is a gradual decrease in salinity below 50 m, with the temperature profile having a stable form. This leads to salt fingering.

Cabbeling is a product of isopycnal mixing, and at the front this is likely to be further enhanced by the process of interleaving that was identified in Fig. 5, and was discussed earlier. Our analysis of the data has shown a potential increase in density through cabbeling of greater than 0.03 kg m^{-3} when mixing water across the front. This maximum is located along $\sigma_\theta = 27.65$, which has a very small lateral gradient (Fig. 3c) requiring minimal work to achieve isopycnal mixing.

Clearly this theoretical approach draws on a number of assumptions. First, that such isopycnal mixing actually occurs. Significantly, at Station E there is water with the required θ–S properties that are not found in the parent water masses and can only result from such isopycnal mixing. Second, the estimate of densification is reliant on identifying appropriate parent water masses as the end members. Fig. 2 shows that the θ–S signature for the two parent water masses is distinct and well defined on either side of the front. Finally, our estimates are based on one section only. However, in late summer, we would expect to see the smallest contrast in θ–S properties between the parent water masses. Therefore, we consider our estimate of the magnitude of densification to be valid along much of the Arctic Front west of Spitsbergen.

The dynamical effect of densification is increased vertical velocity leading to convergence of waters at the front (Garrett & Horne 1978; Ruddick & Gargett 2003), and this is illustrated in Fig. 6. Therefore, the hydrographic contrast between the AW and the Arctic waters, the generation of interleaving layers and the process of cabbeling through isopycnal mixing, may act to maintain the T–S front. It is unlikely that the cabbeling process will generate a new, distinct water mass, as has been reported elsewhere (Talley & Yun 2001). Additionally, the absolute vertical heat and salt fluxes associated with the double-diffusion processes are most likely to be secondary to those produced by externally forced mixing. However, we conclude that the double-diffusive processes support interleaving of water masses leading to convergence at the front, and thereby permit the required isopycnal mixing for cooling of the warm core (Saloranta & Haugan 2004; Nilsen et al. 2006). Although these mesoscale effects may make the greater contribution to lateral heat flux, in this paper we offer a mechanism that supports such isopycnal processes.

Despite the acknowledged importance of the Arctic Front west of Spitsbergen in modifying the communication of the WSC with cooler shelf waters, there are rather few descriptions of it. Here we have illustrated the density-compensated nature of the front and identified the regimes of double-diffusive activity. We have also shown from the CTD data that thermohaline interleaving is a characteristic of the front. Finally, we presented evidence for active cabbeling, which will lead to convergence. These processes will tend to promote water mass modification and provide a mechanism for the maintenance of the T–S contrast at the front. Future work should focus on the spatial and temporal extent of the interleaving characteristics and quantify these processes in supporting isopycnal mixing across the front.

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References

Aagaard K. & Greisman P. 1975. Toward new mass and heat budgets for the Arctic Ocean. *Journal of Geophysical Research 80*, 3821–3827.

Boyd T.J. & D'Asaro E.A. 1994. Cooling of the West Spitsbergen Current: wintertime observations west of Svalbard. *Journal of Geophysical Research 99*, 22597–22618.

Cottier F.R., Tverberg V., Inall M.E., Svendsen H., Nilsen F. & Griffiths C. 2005. Water mass modification in an Arctic fjord through cross-shelf exchange: the seasonal hydrography of Kongsfjorden, Svalbard. *Journal of Geophysical Research 110*, e12005, doi:10.1029/2004JC002757.

Fofonoff P. & Millard R.C. 1983. Algorithms for computation of fundamental properties of seawater. *UNESCO Technical Papers in Marine Science 44*, 53.

Garrett C. & Horne E. 1978. Frontal circulation due to cabbeling and double diffusion. *Journal of Geophysical Research 83*, 4651–4656.

Haugan P.M. 1999. Structure and heat content of the West Spitsbergen Current. *Polar Research 18*, 183–188.

Herbert D. 1999. Intrusions: what drives them? *Journal of Physical Oceanography 29*, 1382–1391.

Horne E. 1978. Interleaving in the subsurface front in the Slope Water off Nova Scotia. *Journal of Geophysical Research 83*, 3659–3671.

Lobb J., Weaver A.J., Carmack E.C. & Ingram R.G. 2003. Structure and mixing across an Arctic/Atlantic front in northern Baffin Bay. *Geophysical Research Letters 30*, No.16, 1833, doi:10.1029/2003GL017755.

Manley T.O. 1995. Branching of the Atlantic Water within the Greenland–Spitsbergen Passage: an estimate of recirculation. *Journal of Geophysical Research 100*, 20627–20634.

Marsh R. 2000. Cabbeling due to isopycnal mixing in isopycnic coordinate models. *Journal of Physical Oceanography 30*, 1757–1775.

Maslowski W., Marble D., Walczowski W., Schauer U., Clement J.L. & Semtner A.J. 2004. On climatological mass, heat and salt transports through the Barents Sea and Fram Strait from a pan-Arctic coupled ice–ocean model simulation. *Journal of Geophysical Research 109*, CO3032, doi:10.1029/2001JC001039.

May B.D. & Kelley D.E. 2001. Growth and steady state stages of thermohaline intrusions in the Arctic Ocean. *Journal of Geophysical Research 106*, 16783–16794.

Nilsen F., Gjevik B. & Schauer U. 2006. Cooling of the West Spitsbergen Current: isopycnal diffusion by topographic vorticity waves. *Journal of Geophysical Research 111*, CO8012, doi:10.1029/2005JC002991.

Ruddick B. 1983. A practical indicator of the stability of the water column to double-diffusive activity. *Deep-Sea Research 30*, 1105–1107.

Ruddick B. & Gargett A.E. 2003. Oceanic double-infusion: introduction. *Progress in Oceanography 56*, 381–393.

Ruddick B. & Richards K. 2003. Oceanic thermohaline intrusions: observations. *Progress in Oceanography 56*, 499–527.

Saloranta T.M. & Haugan P.M. 2001. Interannual variability in the hydrography of Atlantic water northwest of Svalbard. *Journal of Geophysical Research 106*, 13931–13943.

Saloranta T.M. & Haugan P.M. 2004. Northward cooling and freshening of the warm core of the West Spitsbergen Current. *Polar Research 23*, 79–88.

Saloranta T.M. & Svendsen H. 2001. Across the Arctic Front west of Spitsbergen: high-resolution CTD sections from 1998–2000. *Polar Research 20*, 177–184.

Schauer U., Fahrbach E., Østerhus S. & Rohardt G. 2004. Arctic warming through the Fram Strait: oceanic heat transport from 3 years of measurements. *Journal of Geophysical Research 109*, C06026.

Schmitt R.W., Ledwell J.R., Montgomery E.T., Polzin K.L. & Toole J.M. 2005. Enhanced diapycnal mixing by salt fingers in the thermocline of the tropical Atlantic. *Science 308*, 685–688.

Simeonov J. & Stern M. 2004. Double-diffusive intrusions on a finite-width thermohaline front. *Journal of Physical Oceanography 34*, 1723–1740.

Skogseth R., Haugan P.M. & Jakobsson M. 2005. Watermass transformations in Storfjorden. *Continental Shelf Research 25*, 667–695.

Stern M. 1967. Lateral mixing of water masses. *Deep-Sea Research 14*, 747–753.

Svendsen H., Beszczynska-Møller A., Hagen J.O., Lefauconnier B., Tverberg V., Gerland S., Ørbæk J.B., Bischof K., Papucci C., Zajaczkowski M., Azzolini R., Bruland O., Wiencke C., Winther J.-G. & Dallmann W. 2002. The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. *Polar Research 21*, 133–166.

Swift J.H. & Aagaard K. 1981. Seasonal transitions and water mass formation in the Iceland and Greenland Sea. *Deep-Sea Research 28*, 1107–1129.

Talley L.D. & Yun J.-Y. 2001. The role of cabbeling and double diffusion in setting the density of the North Pacific Intermediate Water salinity minimum. *Journal of Physical Oceanography 31*, 1538–1549.

Turner J.S. 1973. *Buoyancy effects in fluids*. Cambridge: Cambridge University Press.

Walczowski W., Piechura J., Osinski R. & Wieczorek P. 2005. The West Spitsbergen Current volume and heat transport from synoptic observations in summer. *Deep-Sea Research I 52*, 1374–1391.

Walsh D. & Carmack E.C. 2003. The nested structure of Arctic thermohaline intrusions. *Ocean Modelling 5*, 267–289.

You Y. 2003. Implications of cabbeling on the formation and transformation mechanism of North Pacific Intermediate Water. *Journal of Geophysical Research 108*, No. C5, 3134, doi:10.1029/2001JC001285.