The temperature and salinity fields in the eastern Eurasian Basin and their implication for the Arctic Ocean heat and freshwater balances

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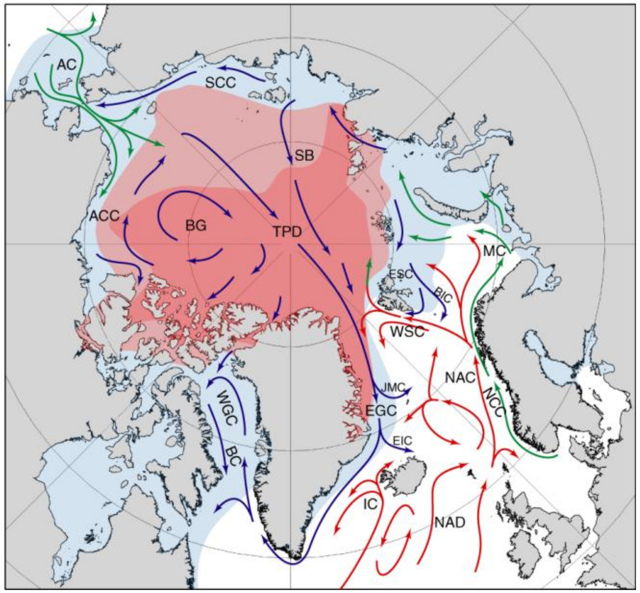
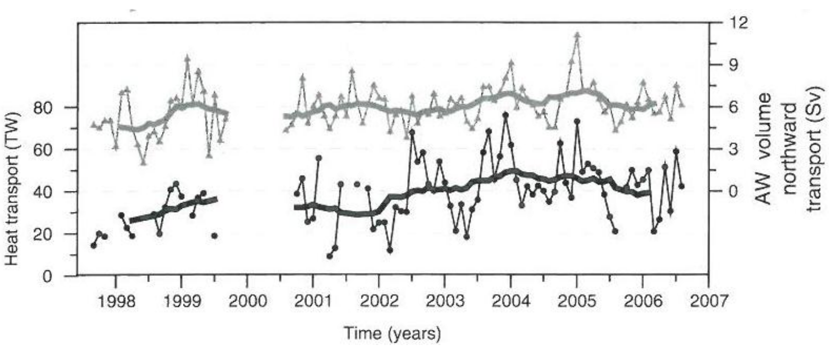
The surface circulation in the Arctic Mediterranean

**Two main inflow passage to the Arctic Ocean from the Nordic Seas & the North Atlantic:
Fram Straït and the Barents Sea**

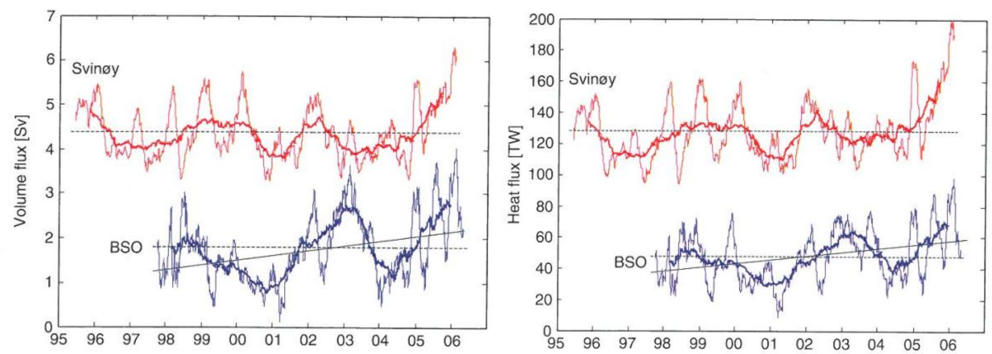
The transports of volume and heat through Fram Strait (FS) in the West Spitsbergen Current (below left) and through the Svinøy section and the Barents Sea opening (BSO) (below right) are comparable and show similar time variability



Rudels et al., 2012

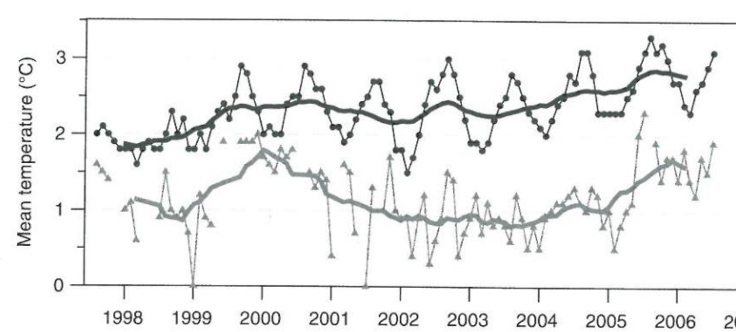


Schauer et al., 2008



Skagseth et al., 2008

The Atlantic water leaving the Arctic Ocean has lower temperature than the inflowing water



Schauer et al., 2008

Facts

Much of the variability of the Arctic Ocean water column, especially in the Atlantic layer, is due to advected waters from the south.

There are two inflows from the Nordic Seas, the Fram Strait branch (FSB) and the Barents Sea branch (BSB).

Questions

What are the characteristics of the two branches?

Do they contribute to the water column in different parts of the Arctic Ocean?

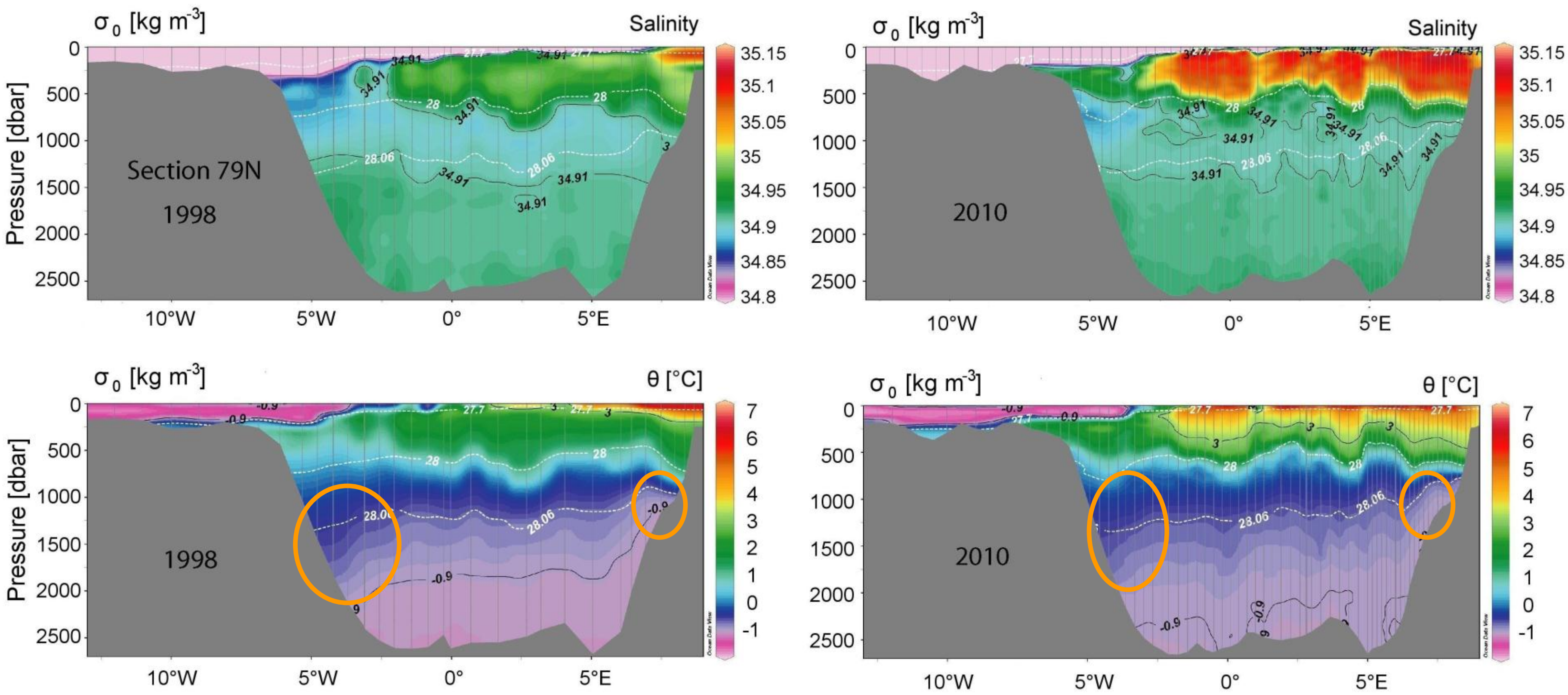
What does it imply that the Arctic Atlantic water leaving the Arctic Ocean (AAW) is colder than the entering Atlantic water (AW)? Heat loss or cooling?

Is it now possible to formulate a tentative volume and freshwater balance for the Arctic Ocean?

Can any sensible statements be made about the fate of the heat entering the Arctic Ocean through Fram Strait?

Salinity and potential temperature sections in Fram Strait

1998 **2010**

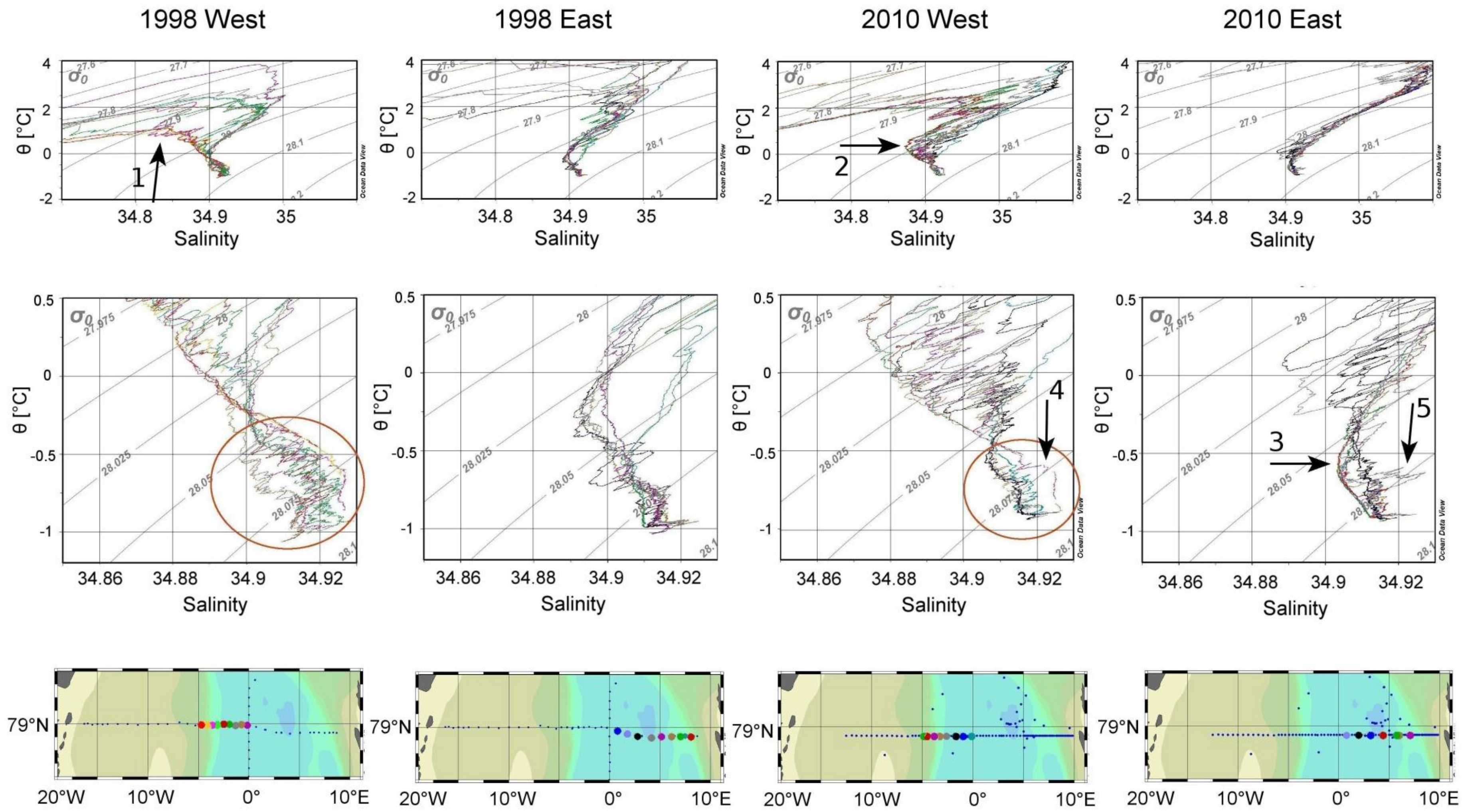


The Atlantic and intermediate water have become warmer and more saline the last 10 years.

The larger spreading of the -0.5ºC and 0.5ºC isotherms in the East Greenland Current compared to the West Spitsbergen Current indicates the outflow of intermediate water from the Arctic Ocean

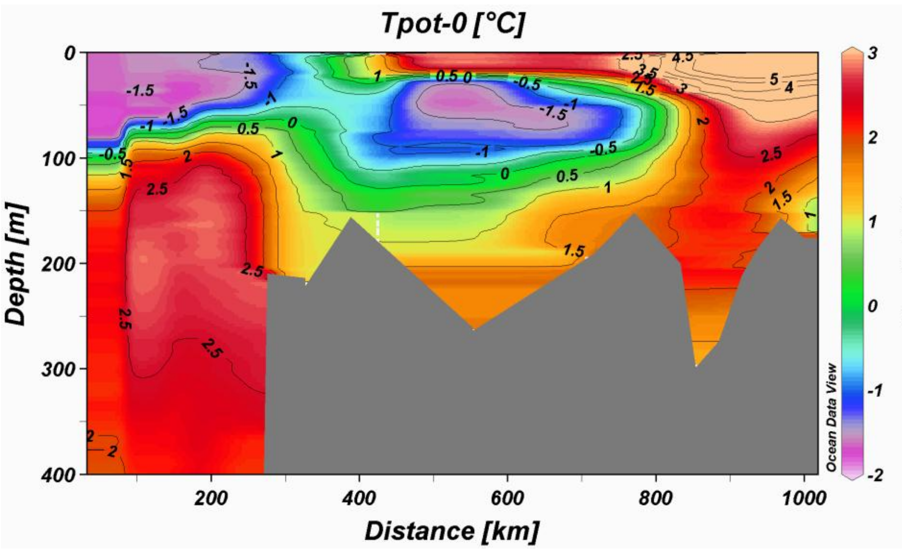
Rudels et al., 2012

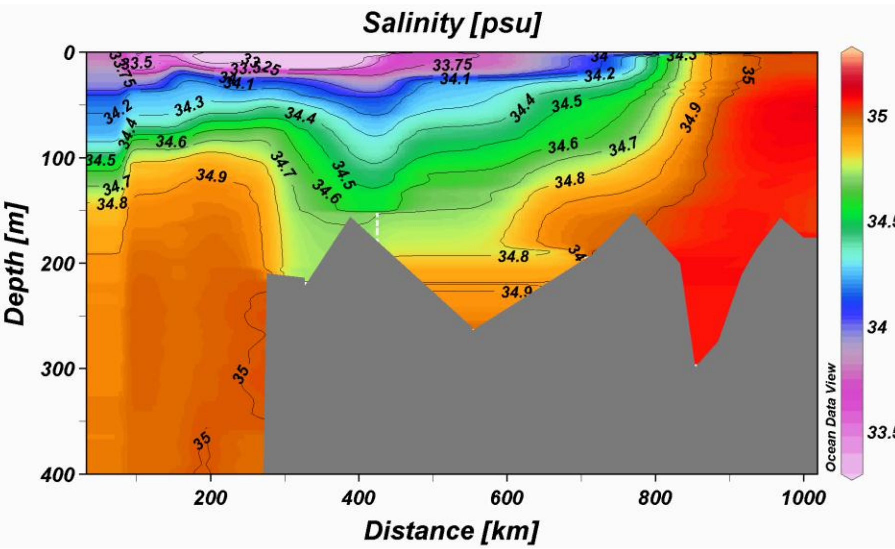
θS curves from the different parts of the Fram Strait section

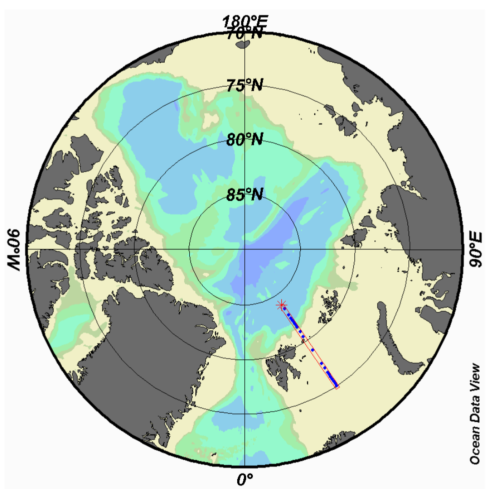


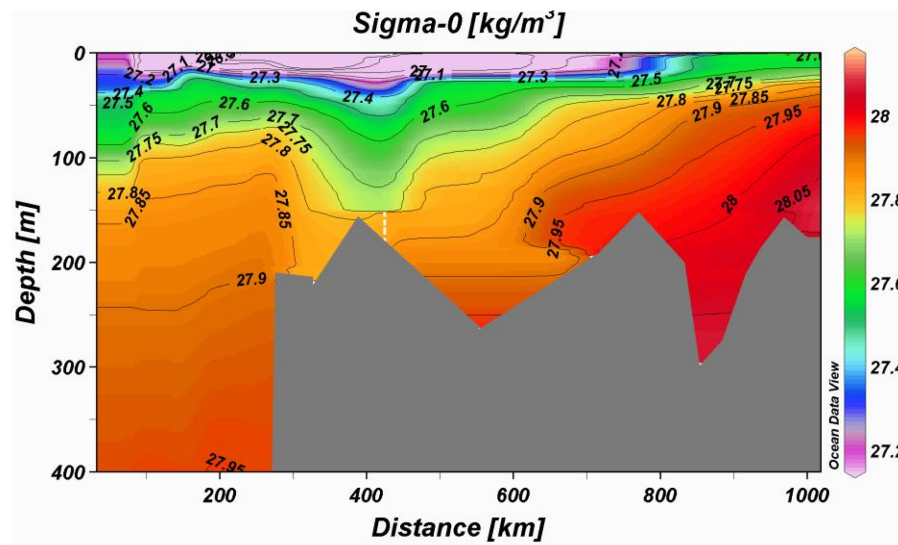
1: AAW from the Amerasian Basin, 2: AAW from the Amerasian Basin only seen as a salinity minimum, 3: Arctic Intermediate water from the Greenland Sea, 4: Amerasian Basin deep water, 5: possible eddy of Amerasian Basin Deep water. Circles indicate the decreased spreading of the θS characteristics of the deep waters with time

Section across the northern Barents Sea and the southern Nansen Basin 2007 showing FSB Atlantic core and the formation of the upper mixed layer in the FSB and BSB.
Only the part of the BSB passing north of the Central Bank is seen.





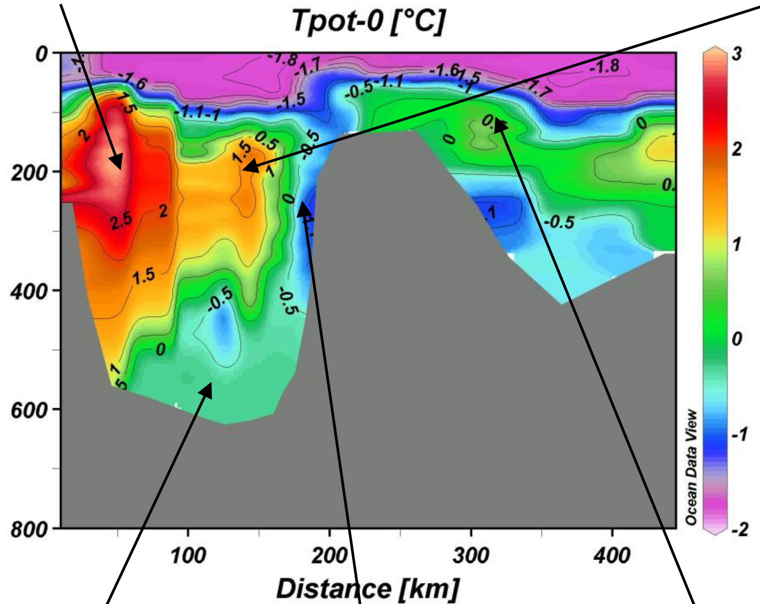


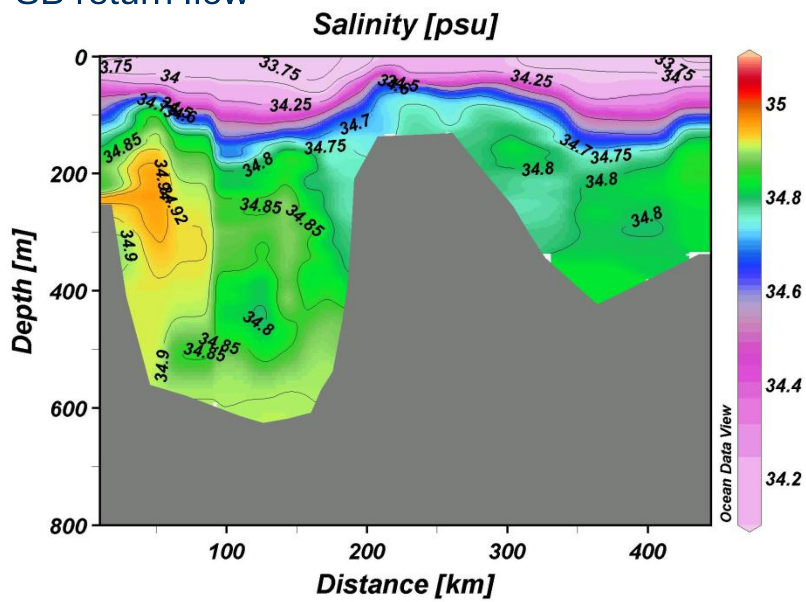


Conditions in the St. Anna and Voronin troughs 1996

FSB Atlantic water

FSB return flow

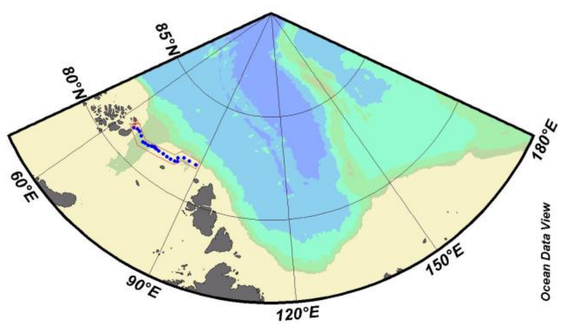


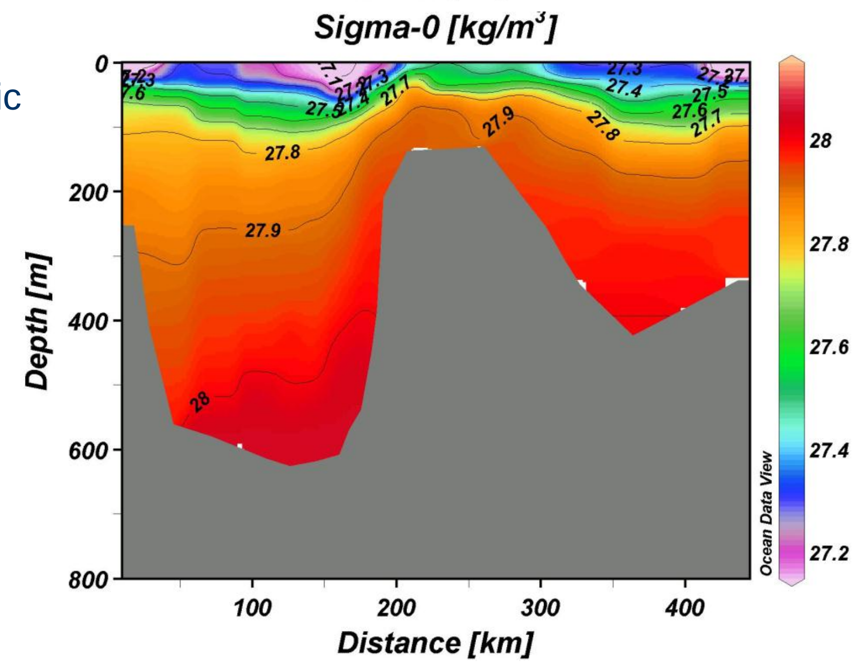


intermediate BSB contribution

BSB Atlantic water?

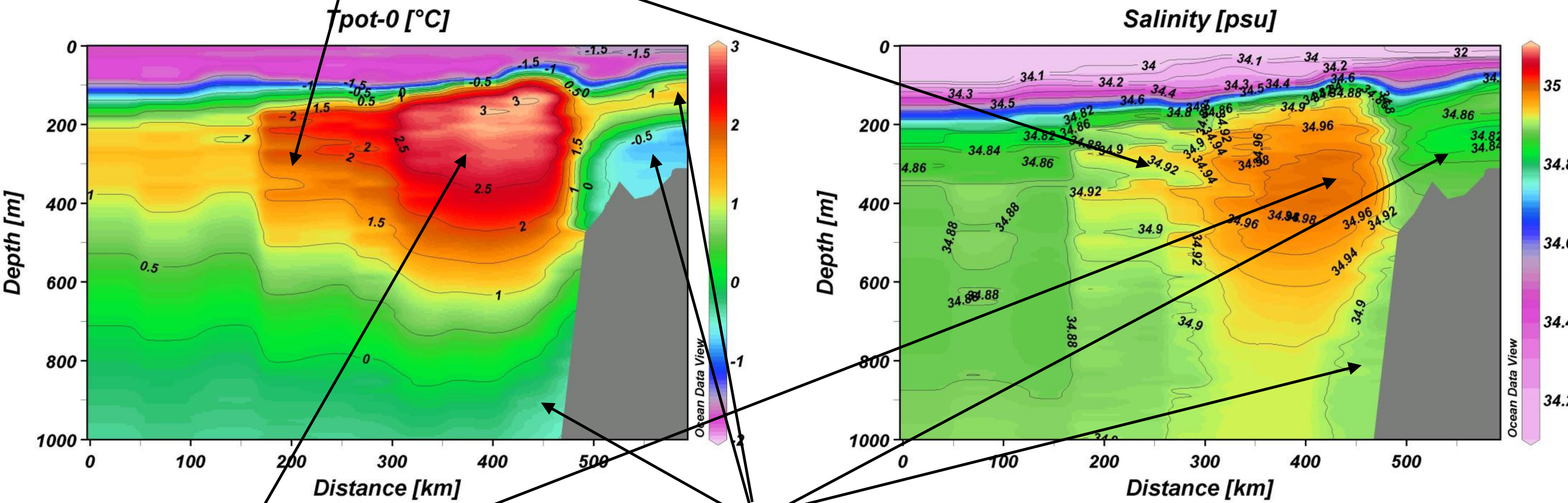
densest BSB contribution





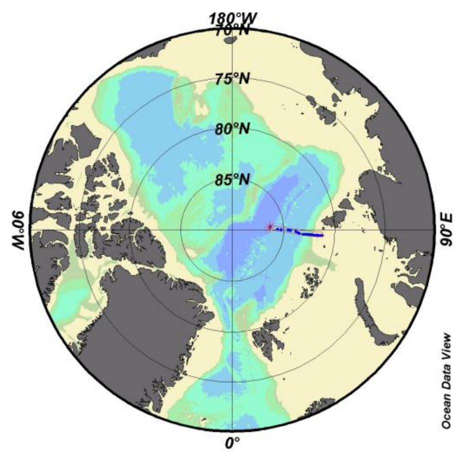
The Nansen Basin north of the eastern Kara Sea in 2007

interleaving structures



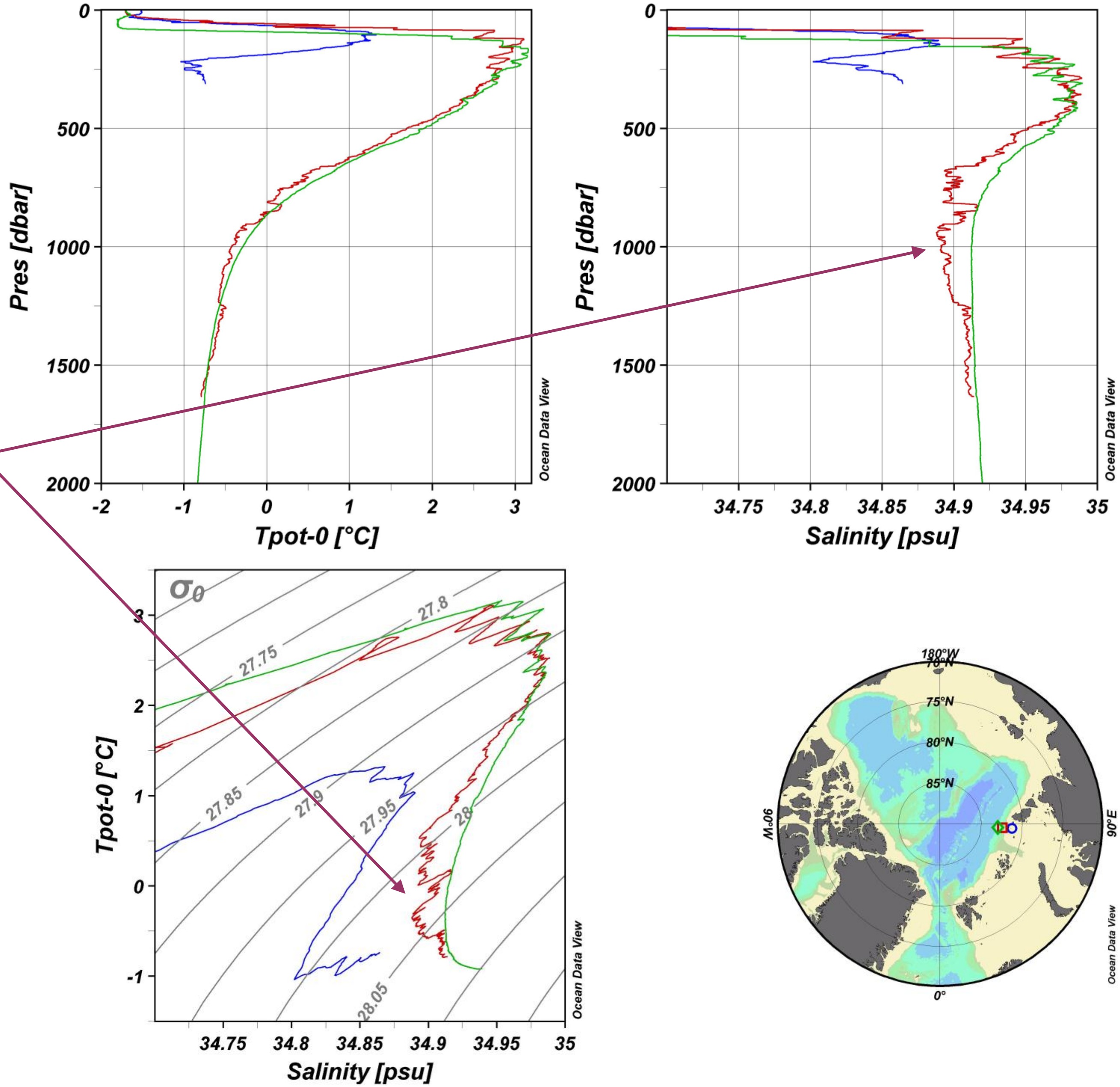
BSB located on the shelf and slope

FSB Atlantic core



The Barents Sea and the Fram Strait branches north of the Kara Sea

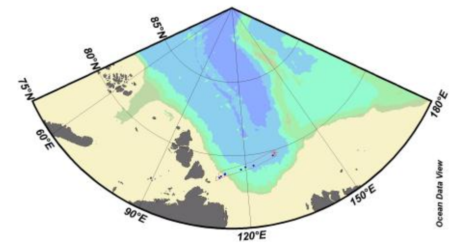
Barents Sea branch water that has entered the deep basin directly at the St. Anna Trough

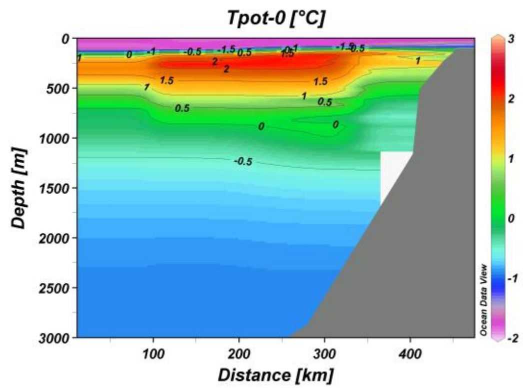


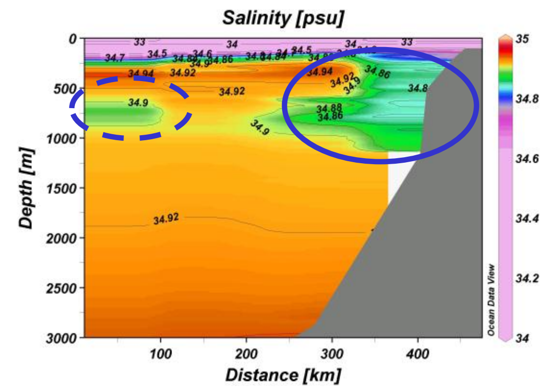
Potential temperature and salinity sections from the eastern Eurasian Basin I

Blue full lines indicate the BSB at the slope and broken lines possible BSB return flow

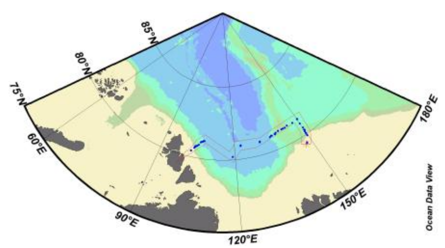
Polarstern 1993

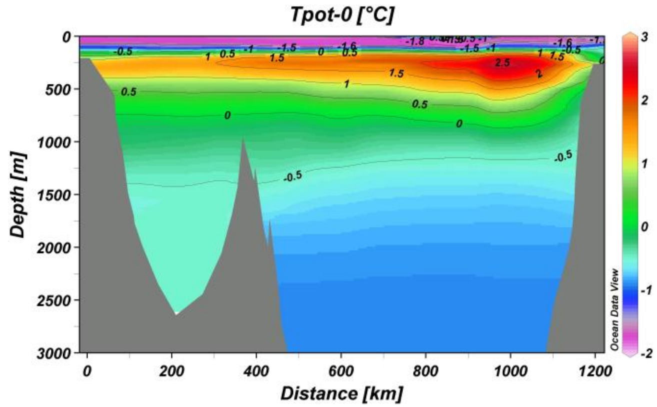


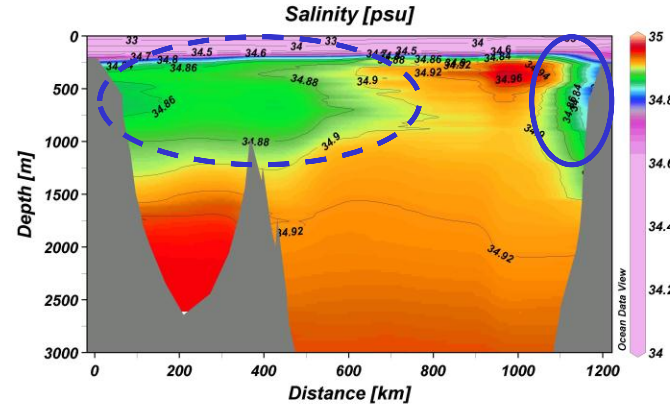




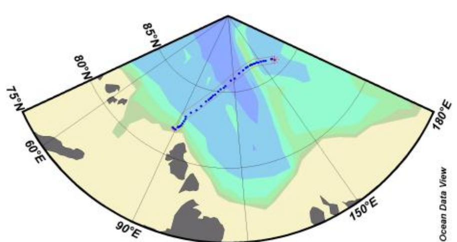
Polarstern 1995

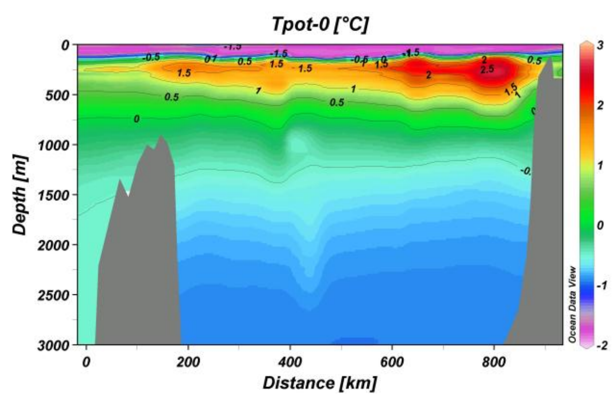


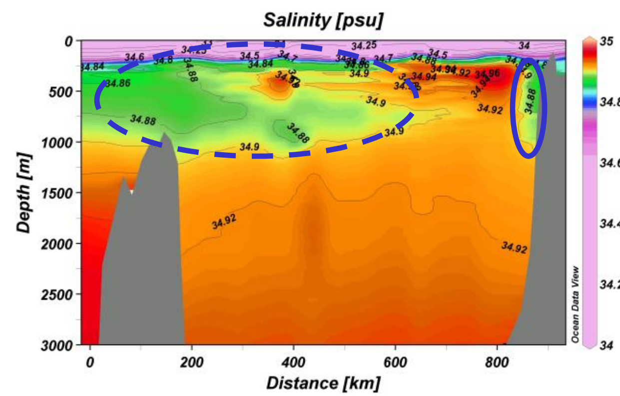




Polarstern 1996

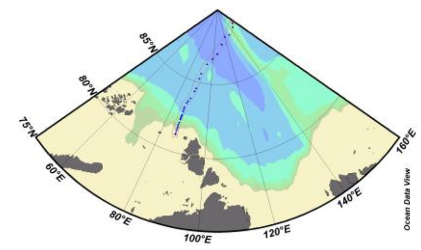


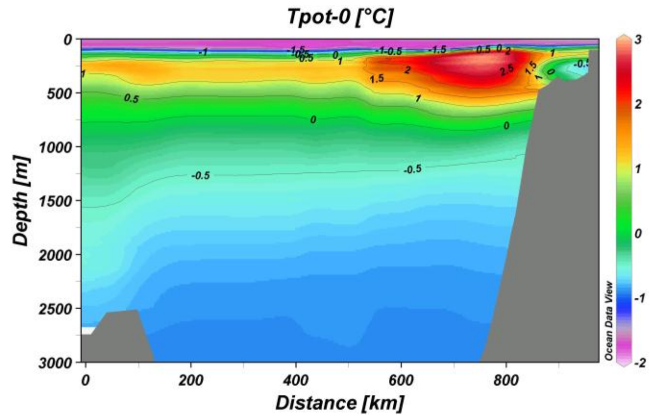


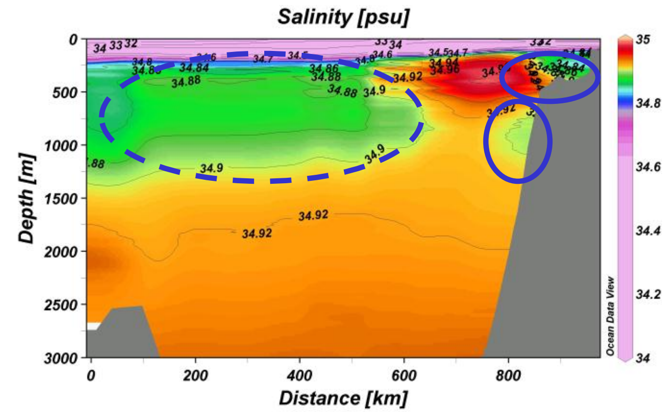


Potential temperature and salinity sections from the eastern Eurasian Basin II

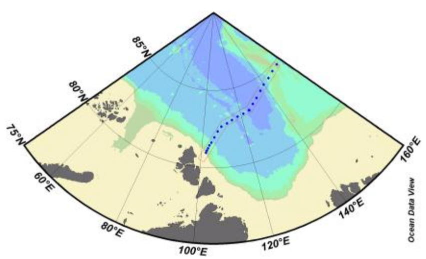
Polarstern 2007

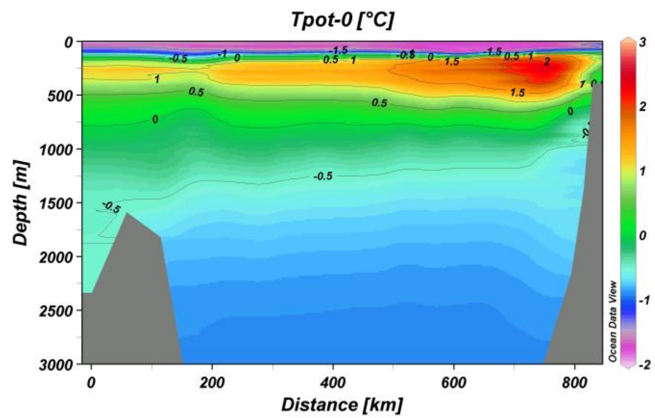


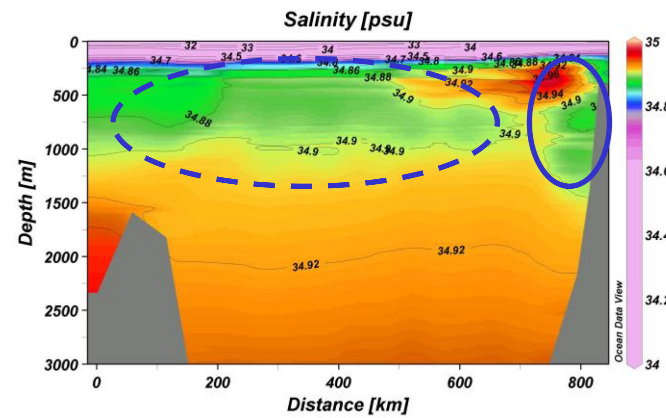




Polarstern 2011







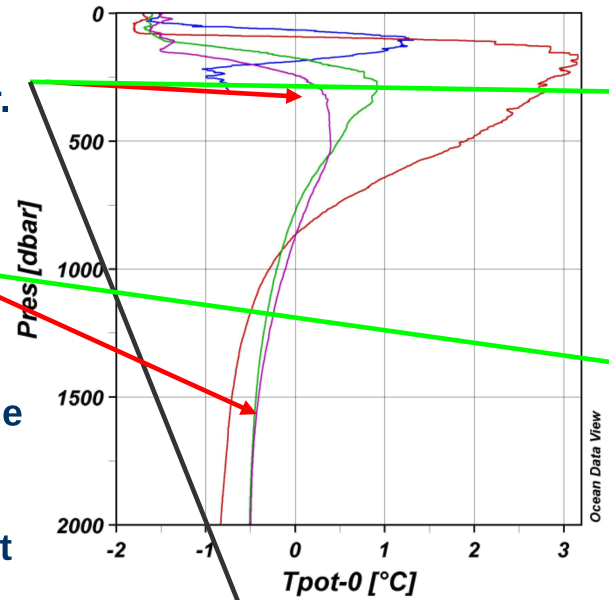
The temperature and salinity maxima of the Fram Strait branch are confined to the Nansen Basin, and the less saline Barents Sea branch forms an envelope around the warm, saline FSB core

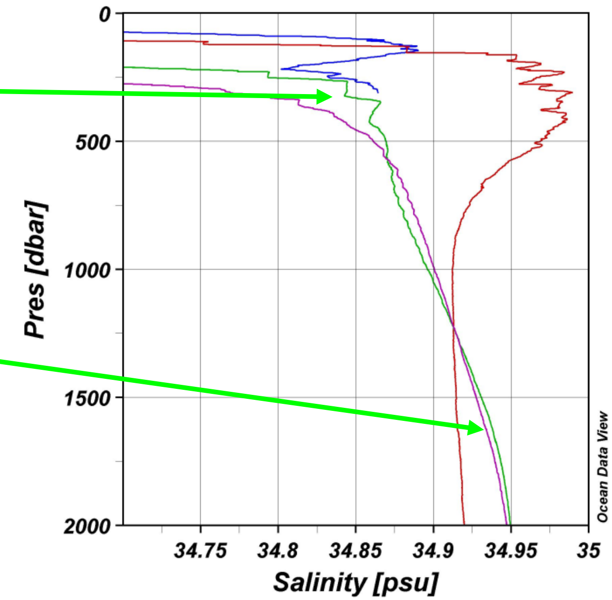
The water columns in the Makarov and Canada basins compared to the two inflow branches

The temperature maximum is colder, less saline and denser.

The intermediate and deep waters have become more saline and warmer due to shelf-slope convection

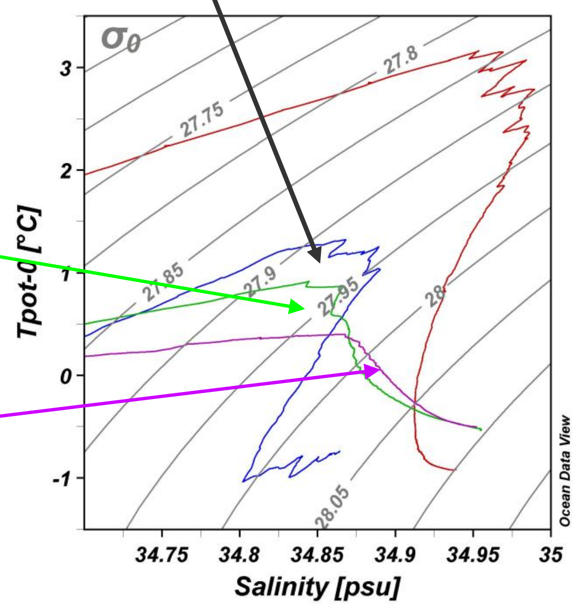
Slope convection brings saline water down from the shelves, which entrains heat from the Atlantic layer and transports it downwards

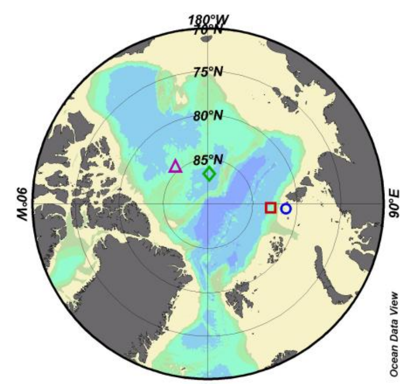




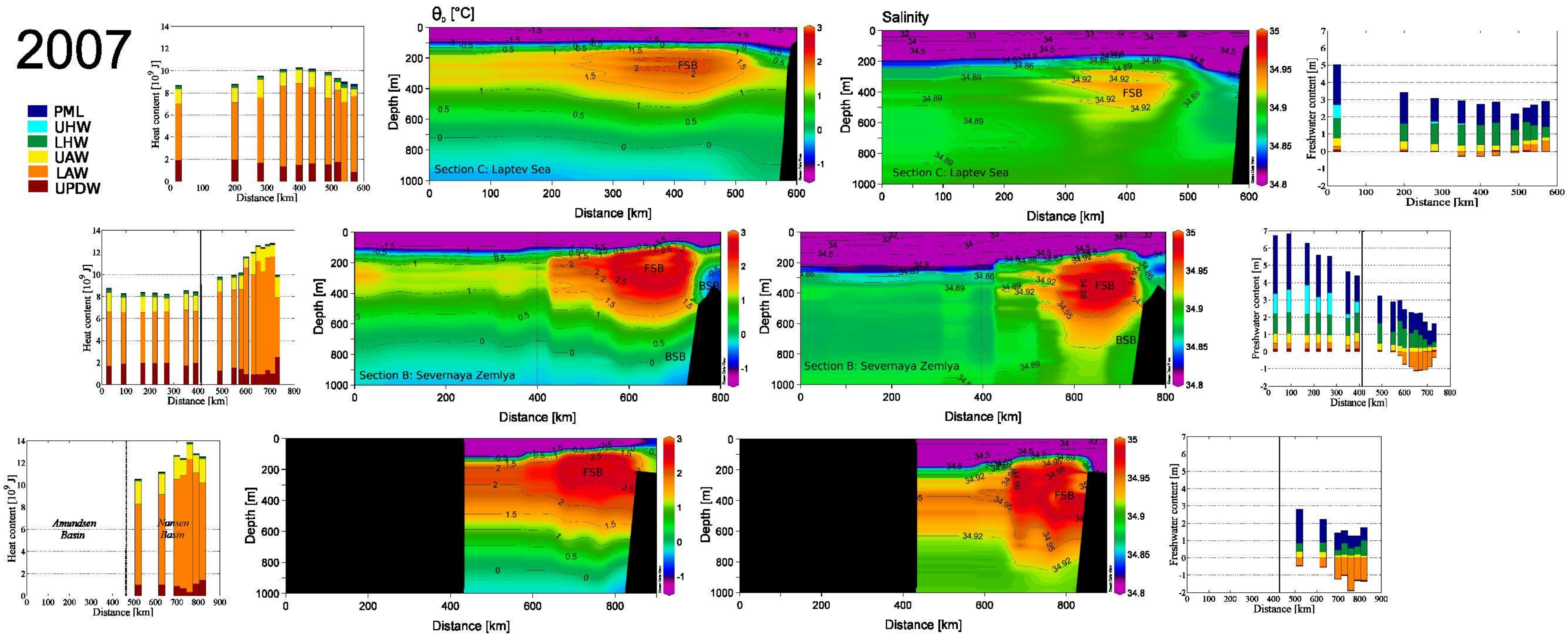
colder, denser & more saline

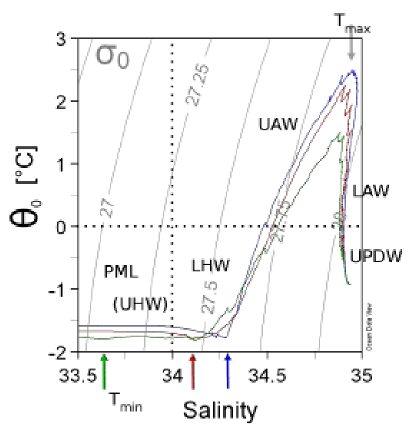
change in slope and becoming warmer & more saline





Three potential temperature and salinity sections taken from the Barents Sea slope (bottom), the Kara Sea slope (centre) and the Laptev Sea slope (top) in 2007

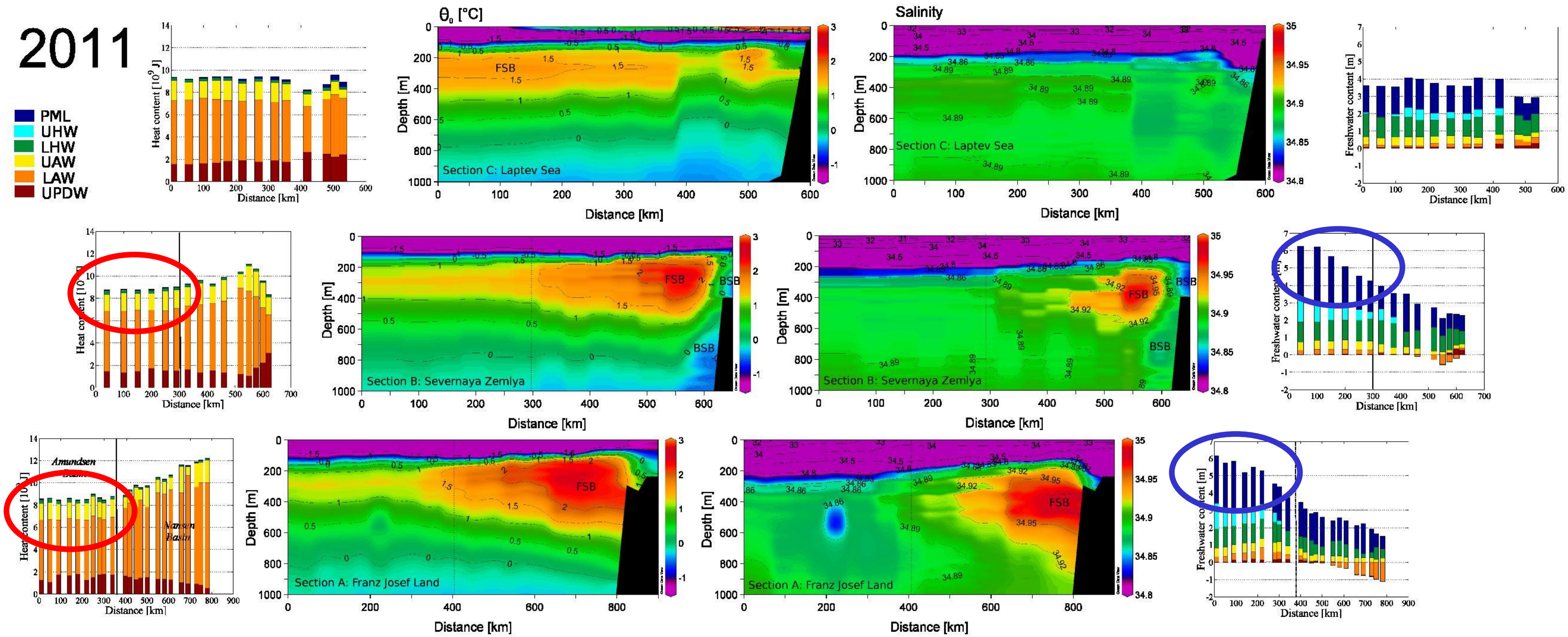




The columns to the left show the heat content, relative to –1.9ºC, and the columns to the right the freshwater content, relative to 34.9, in the different water masses on different stations. The vertical line indicates the position of the Gakkel Ridge

The negative freshwater content in the AW has to be subtracted to get the total amount of freshwater in the upper 1000m of the water column

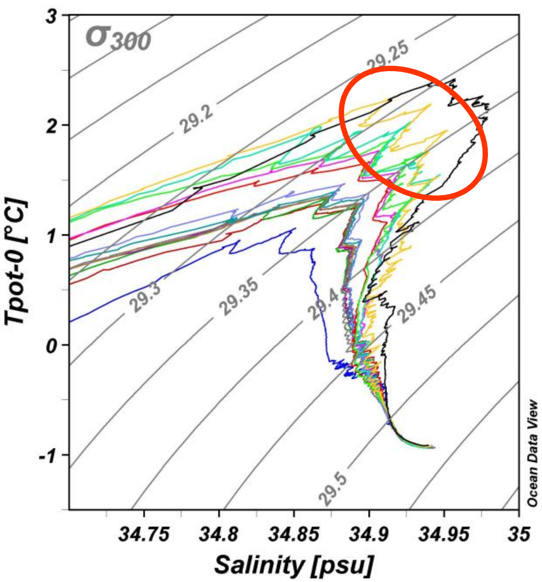
Three potential temperature and salinity sections taken from the slope off Franz Josef Land (bottom), the slope off Severnaya Zemlya (centre) and the Laptev Sea slope (top) in 2011.



The heat and freshwater contents are reduced and the volume of the denser upper Polar Deep water increases close to the Severnaya Zemlya slope, indicating an inflow of Barents Sea branch water. The freshwater input is larger on the two eastern sections than in 2007.

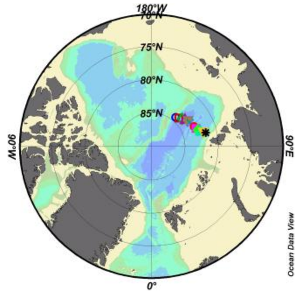
The temperature of the AW and the total heat content appear constant across the Amundsen Basin, while the freshwater content in the upper layers increases towards the Lomonosov Ridge.

Summary of changes in water mass characteristics in the eastern Eurasian Basin

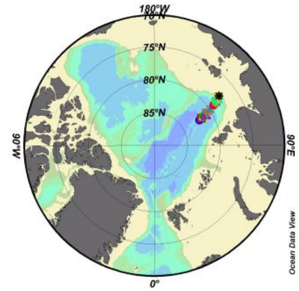


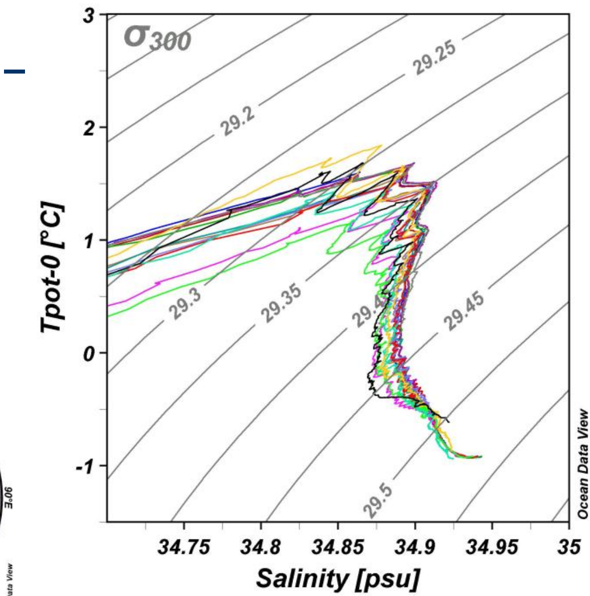
Lomonosov Ridge – Nansen Basin

These warm structures are only found in the Nansen Basin and are not seen crossing the Gakkel Ridge

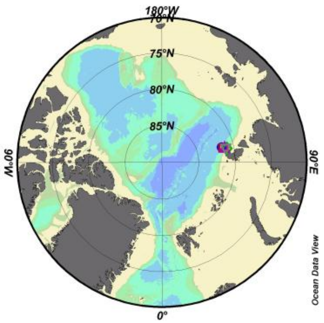


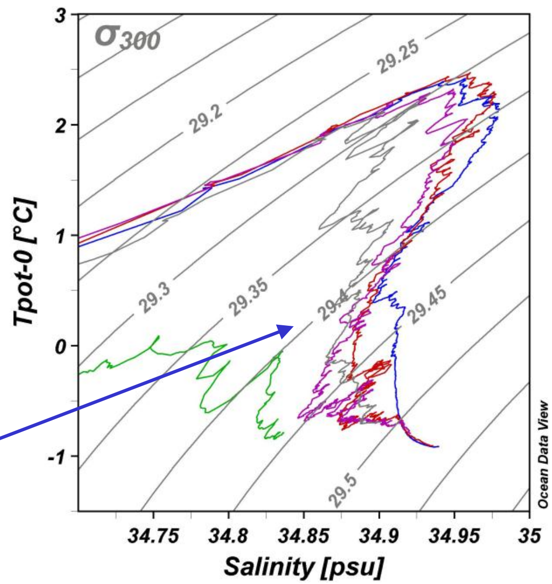
Gakkel Ridge – Laptev Sea



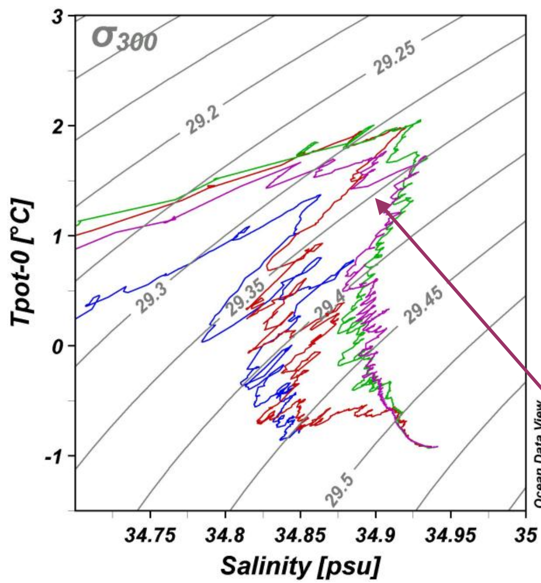


Severnaya Zemlya

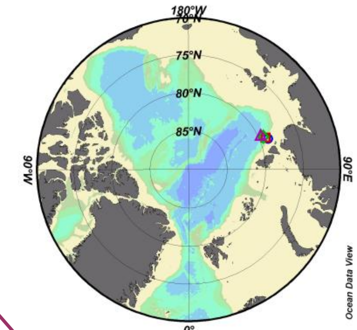




BSB input from the shelf

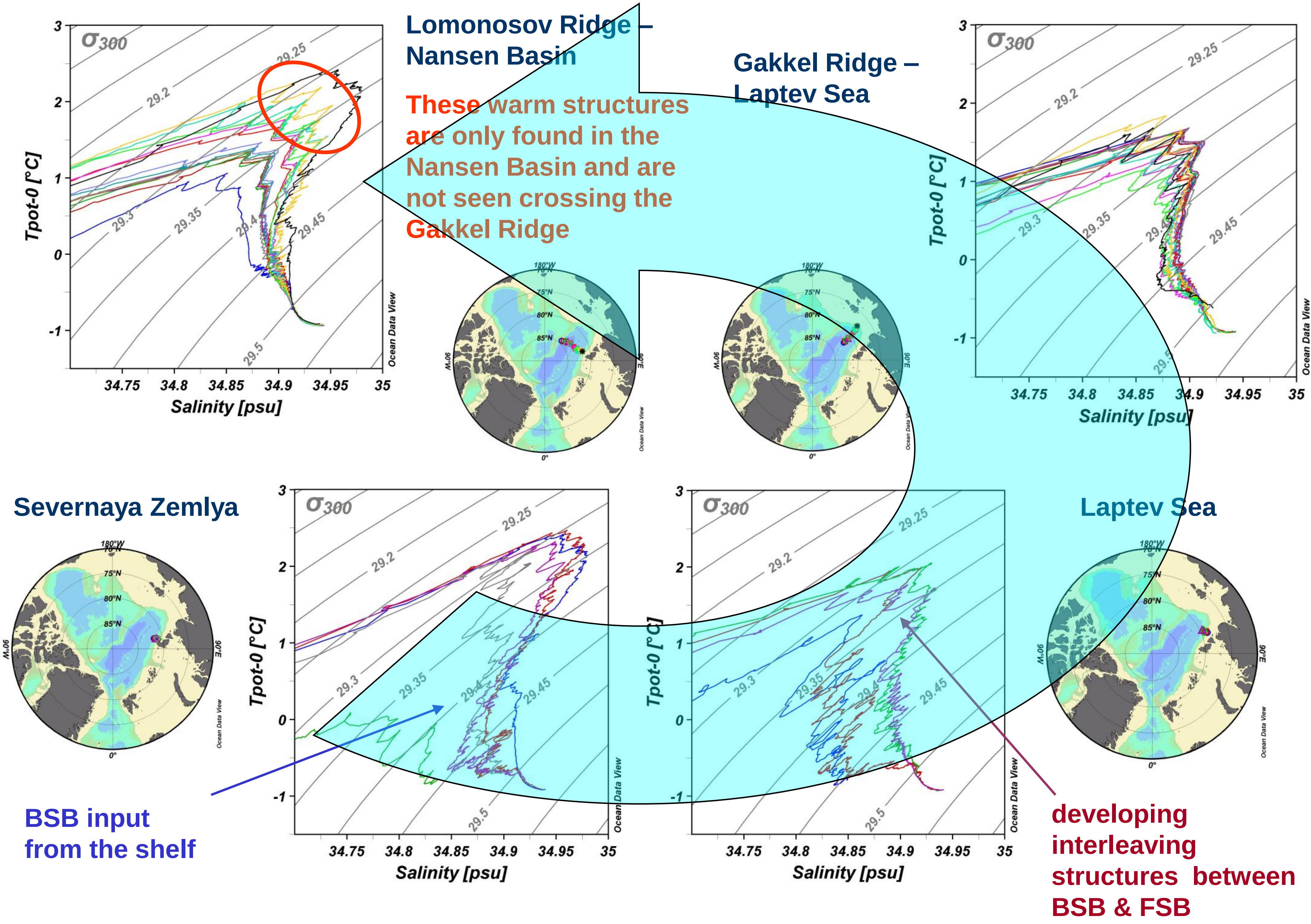


Laptev Sea

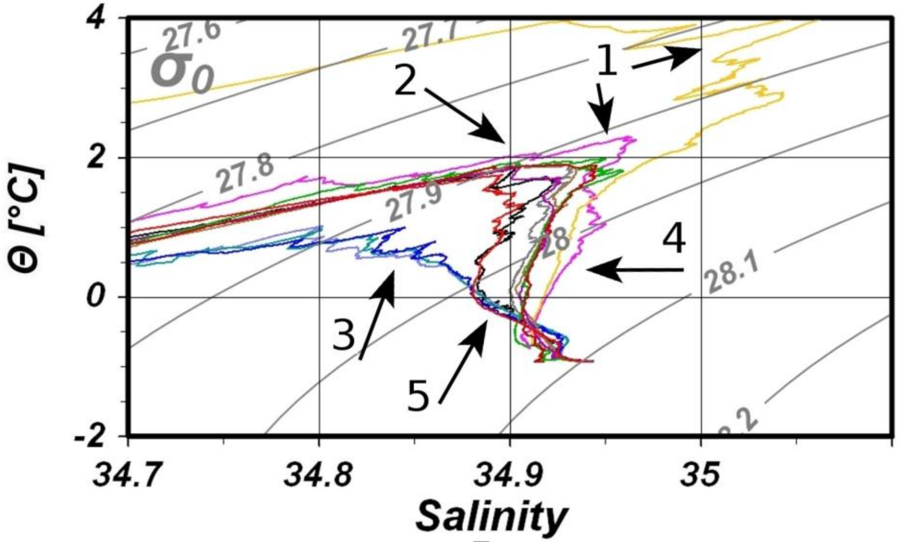


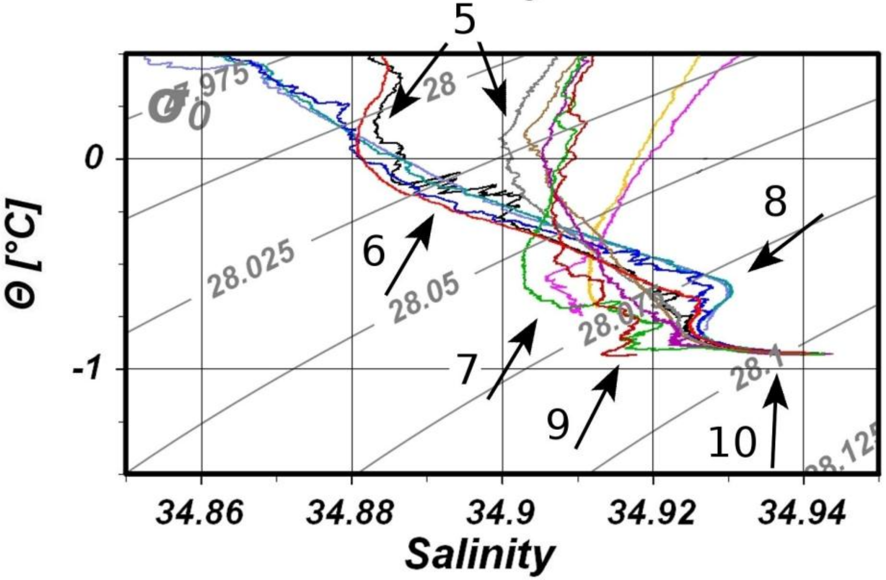
developing interleaving structures between BSB & FSB

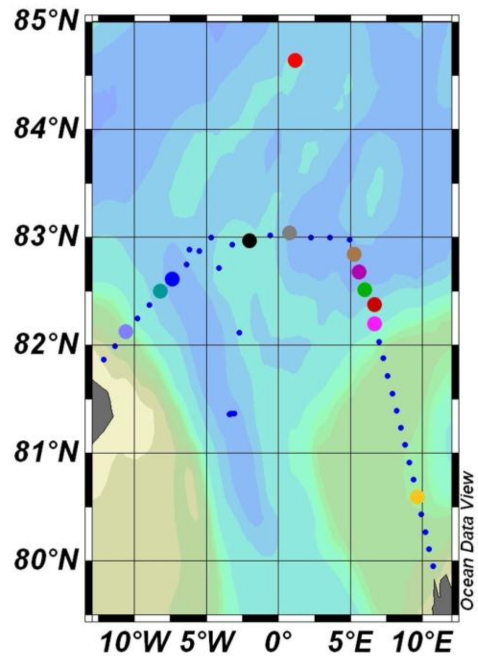
The inferred circulation



Different water masses north of Fram Strait in 2004







1: Atlantic water
2:Arctic Atlantic water, Eurasian Basin
3: Arctic Atlantic Water, Amerasian Basin
4: Dense Atlantic Water
5: Upper Polar Deep Water, Eurasian Basin
6: Upper Polar Deep Water, Amerasian Basin
7: Arctic Intermediate Water (Nordic Seas)
8: Amerasian Basin Deep Water
9: Nordic Seas Deep Water
10: Eurasian Basin Deep Water

Rudels et al., 2012

Volumes and freshwater transports through the different passages

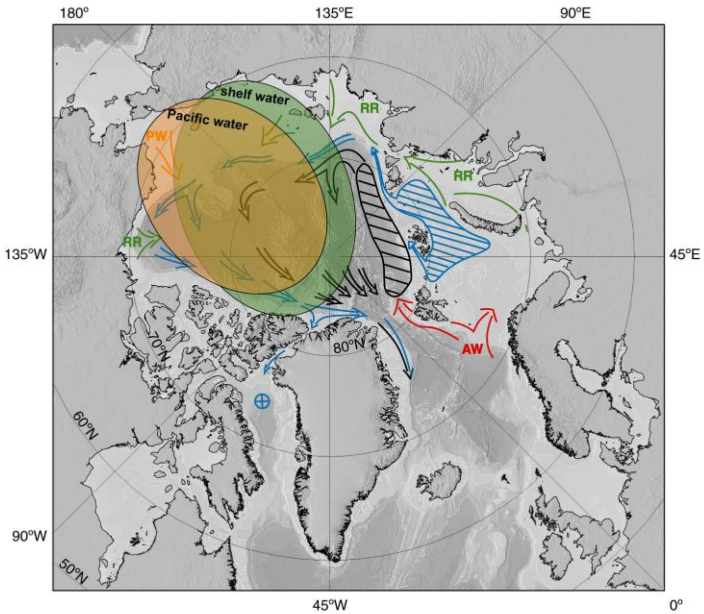
Passage	volume Sv	salinity	freshwater Sv
Bering Strait	0.8	31.5	0.0786
Barents Sea AW	1.5	35.06	–0.0060
Barents Sea NCC	1.8	34.3	0.0320

Salinity relative to the mean total inflow salinity in Fram Strait – 34.92

River Runoff	0.1	0	0.1
P-E	0.065 (0.029)	0	0.065 (0.029)
Ice export	0.09	0	–0.09

Canadian Arctic Archipelago (CAA) ??

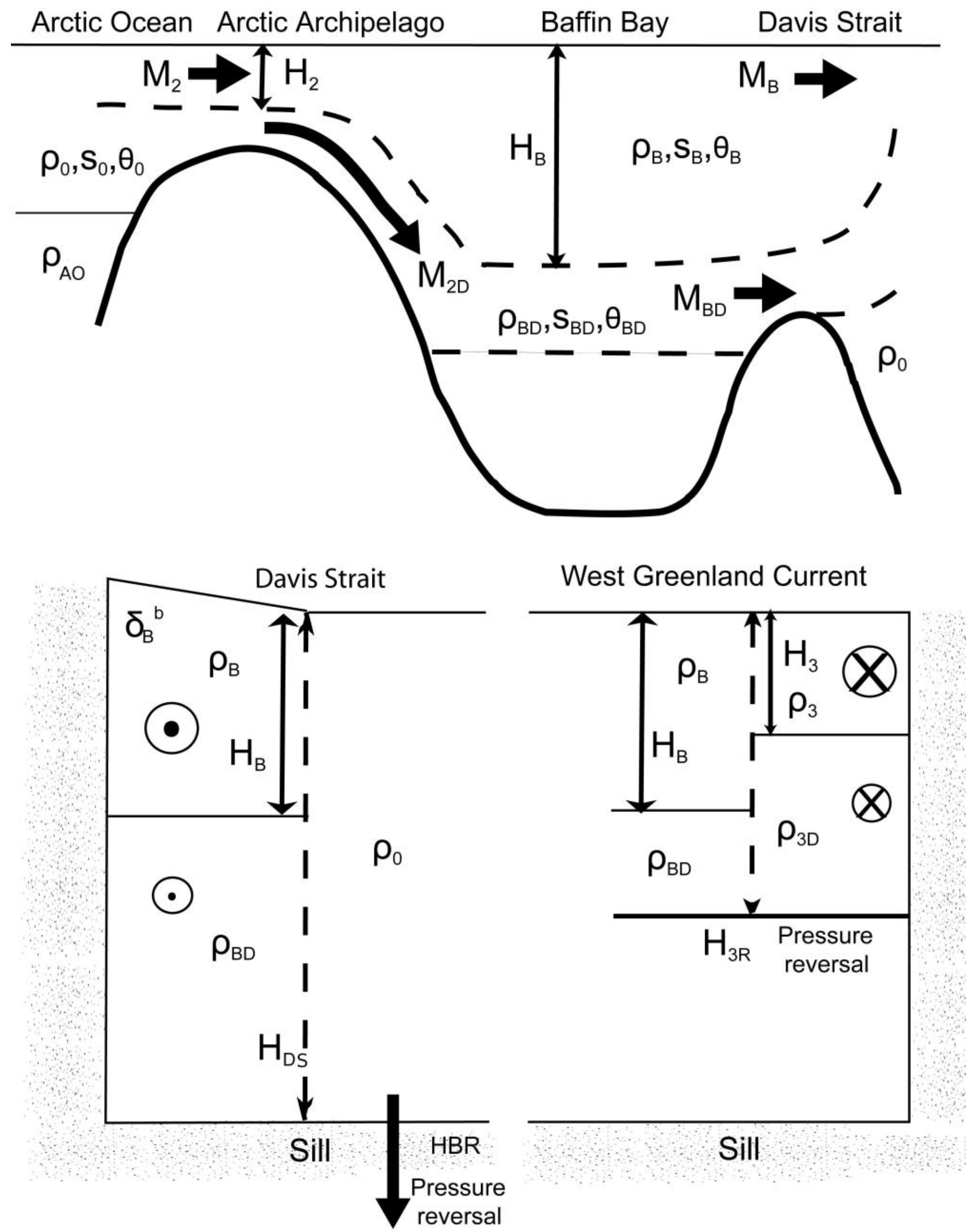
Sources: Dickson et al., 2007; **Skagseth et al., 2011**; Aagaard & Carmack 1989



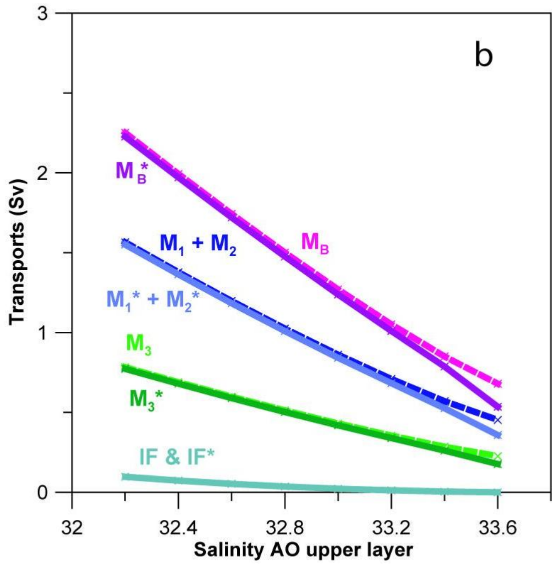
The outflow of Polar water through the Canadian Arctic Archipelago is driven by the higher sea level in the Arctic Ocean,

This is partly due to the freshwater input to the Arctic Ocean and partly caused by the higher sea level in the Pacific Ocean.

Rudels et al., 2012

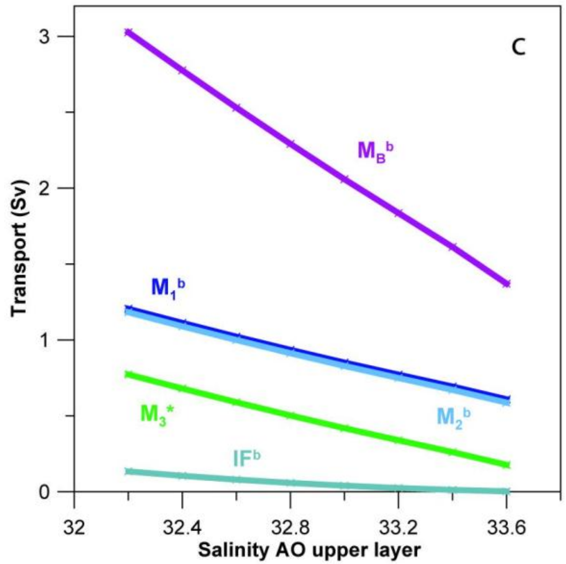


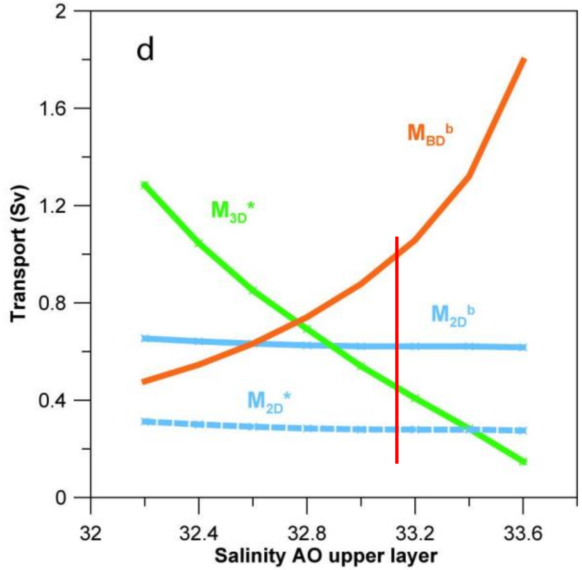
Rudels, 2011



The barotropic pressure gradient increases the outflow in the upper layer and drives a deeper inflow through Nares Strait and also forces the deep water to leave Baffin Bay.

The salinity of the Polar water that gives a balance of the deep in and outflows to Baffin Bay is taken as the salinity of the CAA upper outflow





M_1 = Lancaster Sound upper
M_2 = Nares Strait upper
M_3 = West Greenland Current upper
M_B = Davis Strait upper
M_1^b = Lancaster Sound upper + barotrop
M_2^b = Nares Strait upper + barotrop
M_B^b = Davis Strait upper + barotrop
M_{2D} = Nares Strait deep + barotrop
M_{3D} = West Greenland Current deep
M_{BD}^b = Davis Strait deep + barotrop

Rudels, 2011

Transports estimates through the Canadian Arctic Archipelago

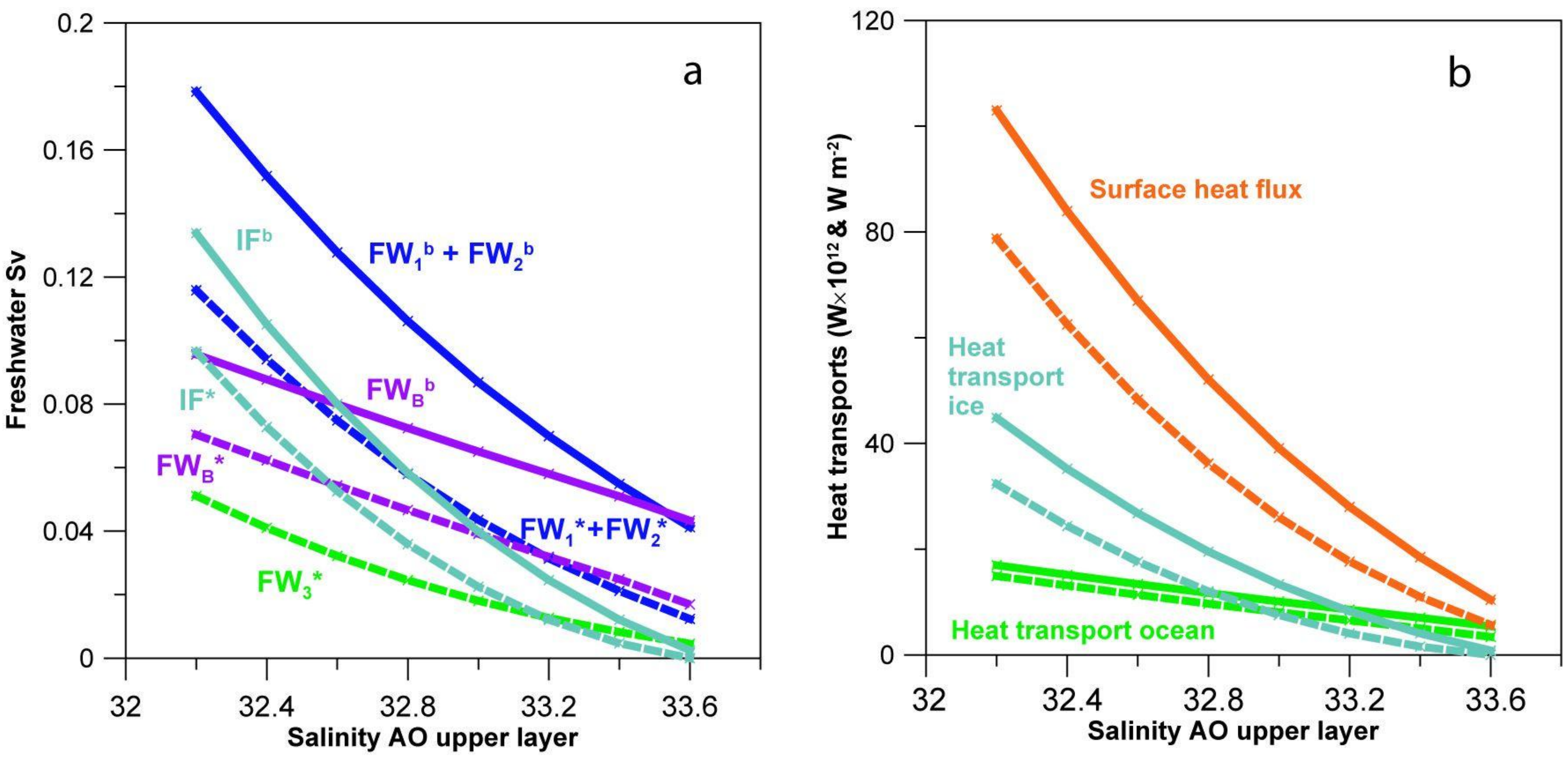
Table 3. The Obtained Transports and Characteristics of the Exchanges Through the Canadian Arctic Archipelago and Baffin Bay[a]

	Transports for Upper Layer Salinity of 33	Transports for Upper Layer Salinity of 33.2	Some Other Transport Estimates	Source
Transport upper layer Lancaster Sound	0.85 Sv	0.77 Sv	0.7 Sv	1
Transport upper layer Nares Strait	0.83 Sv	0.75 Sv	0.72 Sv	2
Transport lower layer Nares Strait	0.62 Sv	0.62 Sv		
FW transport upper layer Lancaster Sound	0.044 Sv	0.035 Sv	0.048 Sv	1
FW transport upper layer Nares Strait	0.043 Sv	0.034 Sv	0.028 Sv	2
Transport upper layer WGC	0.42 Sv	0.34 Sv	0.4 Sv, 0.8 Sv	3, 4
Transport lower layer WGC	0,54 Sv	0.41 Sv		
FW transport upper layer WGC	0.018 Sv	0.013 Sv		
Transport upper layer Davis Strait	2.06 Sv, 1.52 Sv net	1.84 Sv, 1.54 Sv net	2.30 Sv, 2.6 Sv	3, 4
Transport lower layer Davis Strait	0.88 Sv, 0.34 Sv net	1.06 Sv, 0.65 Sv net		
FW transport upper layer Davis Strait	0.065 Sv	0.058 Sv	0.116 Sv, 0.092 Sv	3, 4
Ice export Davis Strait	0.041 Sv	0.025 Sv	0.011 Sv, 0.013 Sv, 0.021 Sv	3, 4, 5
Heat transport CAA and WGC	10.10×10^{12} W	8.56×10^{12} W	20×10^{12} W, 18×10^{12} W	3, 4
Latent heat export ice	13.37×10^{12} W	8.24×10^{12} W		
Corresponding surface heat loss	39.1 Wm^{-2}	28.0 Wm^{-2}		

[a]The freshwater transports are computed relative to 34.8. To compare the derived transports in Davis Strait with those observed the total net transports shall be used. Sources: 1, *Prinsenberg et al.* [2009]; 2, *Münchow and Melling* [2008]; 3, *Curry et al.* [2011]; 4, *Cuny et al.* [2005]; and 4, *Tang et al.* [2004]

Rudels, 2011

The volume and freshwater dependence upon the salinity of the upper layer in the Arctic Ocean can also be related to the freshwater content m, the depth of the upper layer H_1 and the number of outlets through the Archipelago



$$g' \approx g\beta(S_2 - S_1) \qquad m = \frac{(S_2 - S_1)H_1}{S_2} \qquad M = n \times \frac{g\beta S_2 m H_1}{2f} \qquad F_W = n \times \frac{g\beta S_2 m^2}{2f}$$

Volumes and freshwater transports through the different passages

Passage	volume Sv	salinity	freshwater Sv
Bering Strait	0.8	31.5	0.0786
Barents Sea AW	1.5	35.06	–0.0060
Barents Sea NCC	1.8	34.3	0.0320
Salinity relative to the mean total inflow salinity in Fram Strait – 34.92			
River Runoff	0.1	0	0.1
P-E	0.065 (0.029)	0	0.065 (0.029)
Ice export	0.09	0	–0.09
CAA upper layer	–1.6	33.1	–0.083
CAA lower layer	–0.62	34.45	–0.008
Fram Strait Net outflow	–1.96		–0.088 (–0.052)

Sources: Dickson et al., 2007; Skagseth et al., 2011; Aagaard & Carmack 1989; Rudels, 2011,

Anatomy of the net outflow through Fram Strait I

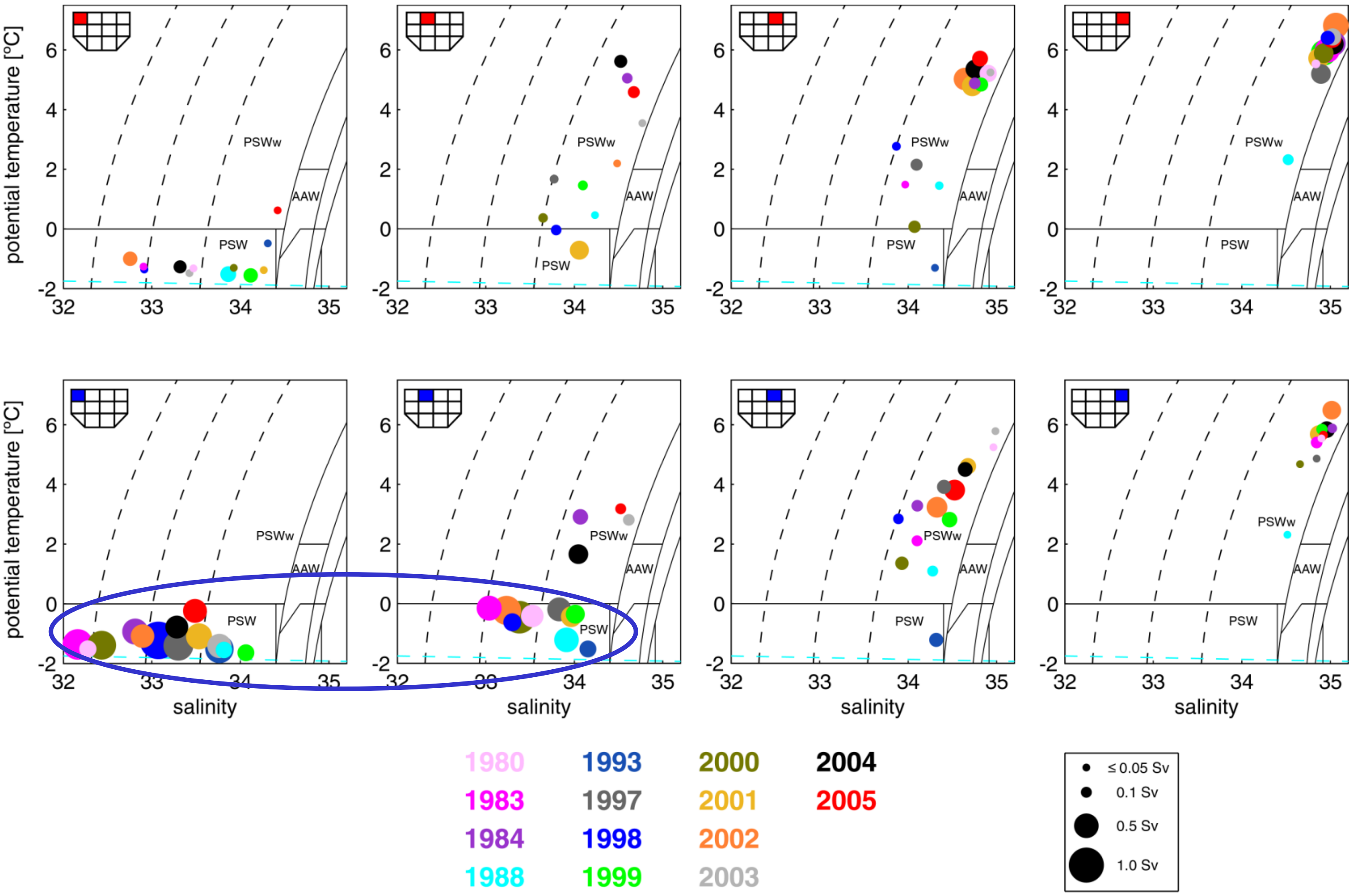
Assume that 1.5 Sv of the combined Barents Sea inflow are transformed into, or remain, dense water that can only leave the Arctic Ocean through Fram Strait and has a mean salinity of 34.8.

This implies a freshwater transport in the deeper layers of 0.005 Sv

The remaining volume, 0.46 Sv, would then leave as a shallow upper layer water transporting 0.083 Sv (0.047 Sv) of freshwater. This requires a salinity of 28.57 (31.34).

The numbers within brackets refer to the **Aagaard & Carmack (1989)** E-P estimate.

The mean salinity of the low salinity Polar water leaving the Arctic Ocean through Fram Strait has a salinity around 33.



Rudels et al., 2008

Anatomy of the net outflow through Fram Strait II

Assume that 1.5 Sv of the combined Barents Sea inflow are transformed into, or remain, dense water that can only leave the Arctic Ocean through Fram Strait and has a mean salinity of 34.8.

This implies a freshwater transport in the deeper layers of 0.005 Sv

The remaining volume, 0.46 Sv, would then leave in the shallow upper layer, transporting 0.083 Sv (0.047 Sv) of freshwater. This implies a salinity of 28.57 (31.34).

The mean salinity of the outflowing upper layer is higher than this, around 33.

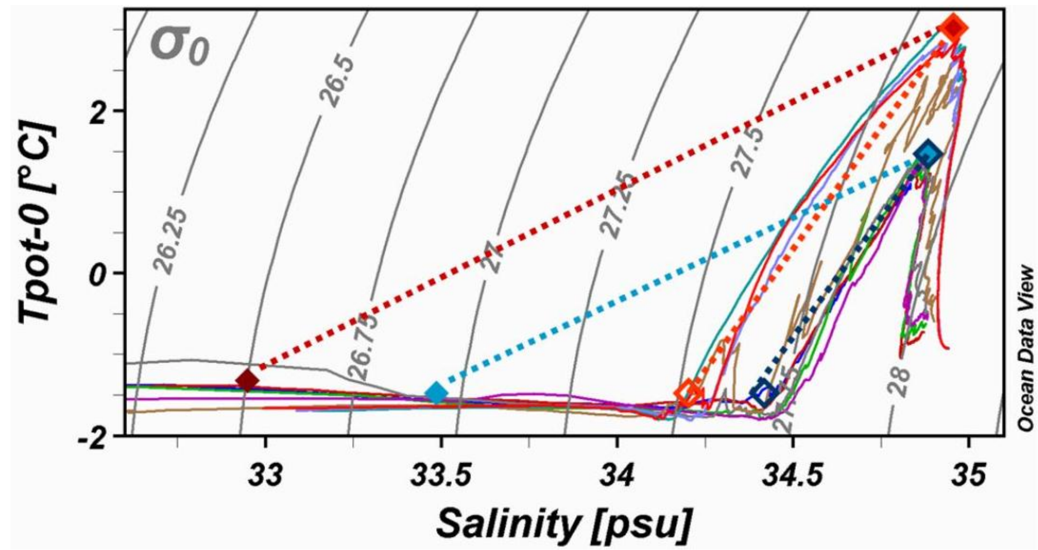
To attain a salinity of 33, 1. 05 Sv (0.39 Sv) of the Fram Strait inflow water, with salinity 34.92, must be mixed into the upper layer. This implies that 1.50 Sv (0.85 Sv) of upper layer water must leave through Fram Strait to achieve freshwater balance.

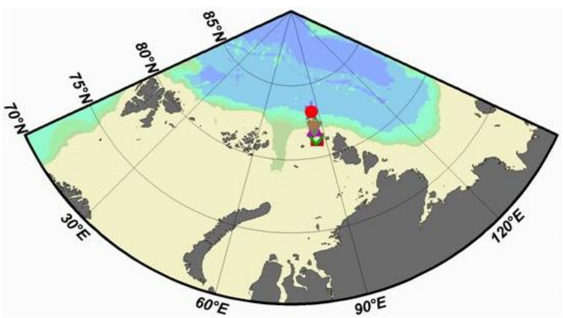
Since the major part of the low salinity shelf water enters the Arctic Ocean from the Laptev Sea, it is difficult to see how the then isolated Fram Strait inflow branch can interact with the low salinity shelf outflow.

One possible mechanism is ice melt on top of the AW as in enters through Fram Strait.

If the inflowing AW is cooled from 2.6°C to –1.9°C, 19 TW (7 TW) are released.
The melt water layer prevents heat from reaching the ice, and not all heat is used for ice melt.
Observations and theoretical considerations suggest that about 1/3 of the heat loss goes to melting ice.

Salinity and temperature in the Atlantic layers (diamonds) of the Fram Strait branch (red) and the Barents Sea branch (blue) north of the Kara Sea.





Open diamonds indicate the salinity at the freezing point, when only a fraction $\phi_o \approx 2\alpha L(c\beta S_A)^{-1}$ goes to ice melt.

$$S_1 = \frac{S_A}{\left(1+\frac{\phi_o c\Delta T_A}{L}\right)} \approx \frac{S_A}{\left(1+\frac{2\alpha\Delta T_A}{\beta S_A}\right)}$$

For comparison the salinity when all heat goes to ice melt is shown as solid diamonds

$$S_1 = \frac{S_A}{\left(1+c\Delta T_A L^{-1}\right)}$$

Rudels, 2010

The low salinity layer found above the Fram Strait inflow branch is created by sea ice melting on top of the AW. If the water is cooled by 4.5 degrees, from 2.6^{o}C to –1.9^{o}C 19 TW (7 TW) are released.

Because a low salinity melt water layer prevents heat from reaching the ice, not all heat is used for ice melt. Observations and theoretical considerations indicate that about one third of the heat loss goes to ice melt.

This implies that 0.019 Sv (0.007 Sv) of freshwater is added to the inflowing water, reducing the salinity of the 1.05 Sv (0.39 Sv) from 34.92 to 34.31 (34.31).

The freshwater carried by the low salinity Polar water has to be reduced by the corresponding amount, leading to a low salinity Polar outflow of 0.46 Sv with salinity 30.02 (31.87) carrying 0.064 Sv (0.040 Sv) of freshwater through Fram Strait.

The formation of 1 Sv of lower halocline water and a total outflow of 1.5 Sv of low salinity Polar water appear high, and it is possible that the net precipitation given by Serreze et al. (2006) and Dickson et al. (2007) is too high and that the older estimate from Aagaard & Carmack (1989) is closer to reality.

Summary & Conclusions

The two Atlantic inflow branches entering the Arctic Ocean are examined.

It is found that the heat and salt carried by the Fram Strait branch is mainly confined to and returns towards Fram Strait within the Nansen Basin.

The Atlantic water influence beyond the Gakkel Ridge mostly derives from the Barents Sea inflow branch.

The observed reduction of temperature and salinity in the subsurface Atlantic layer in the Nansen Basin is largely due to mixing with colder, less saline Barents Sea branch water.

Recent estimates, especially of the strength of Norwegian Coastal Current and of the outflow through the Canadian Arctic Archipelago, is used to formulate volume and freshwater balances for the Arctic Ocean, which imply a net outflow of ~2 Sv and a freshwater export of ~0.088 Sv (~0.052 Sv) through Fram Strait.

Most of the heat lost by the Fram Strait inflow, 19 TW (7 TW), goes to the atmosphere, 2/3, and to ice melt, 1/3, north of Svalbard where the lower halocline water is formed.

The rest of the heat (and salt) is used to increase, through mixing and through compensation, the temperature and salinity of the colder, less saline Polar waters that supply the net outflow through Fram Strait.

Thank you for your attention