The Arctic Ocean Climate – a balance between local radiation, advected heat and freshwater

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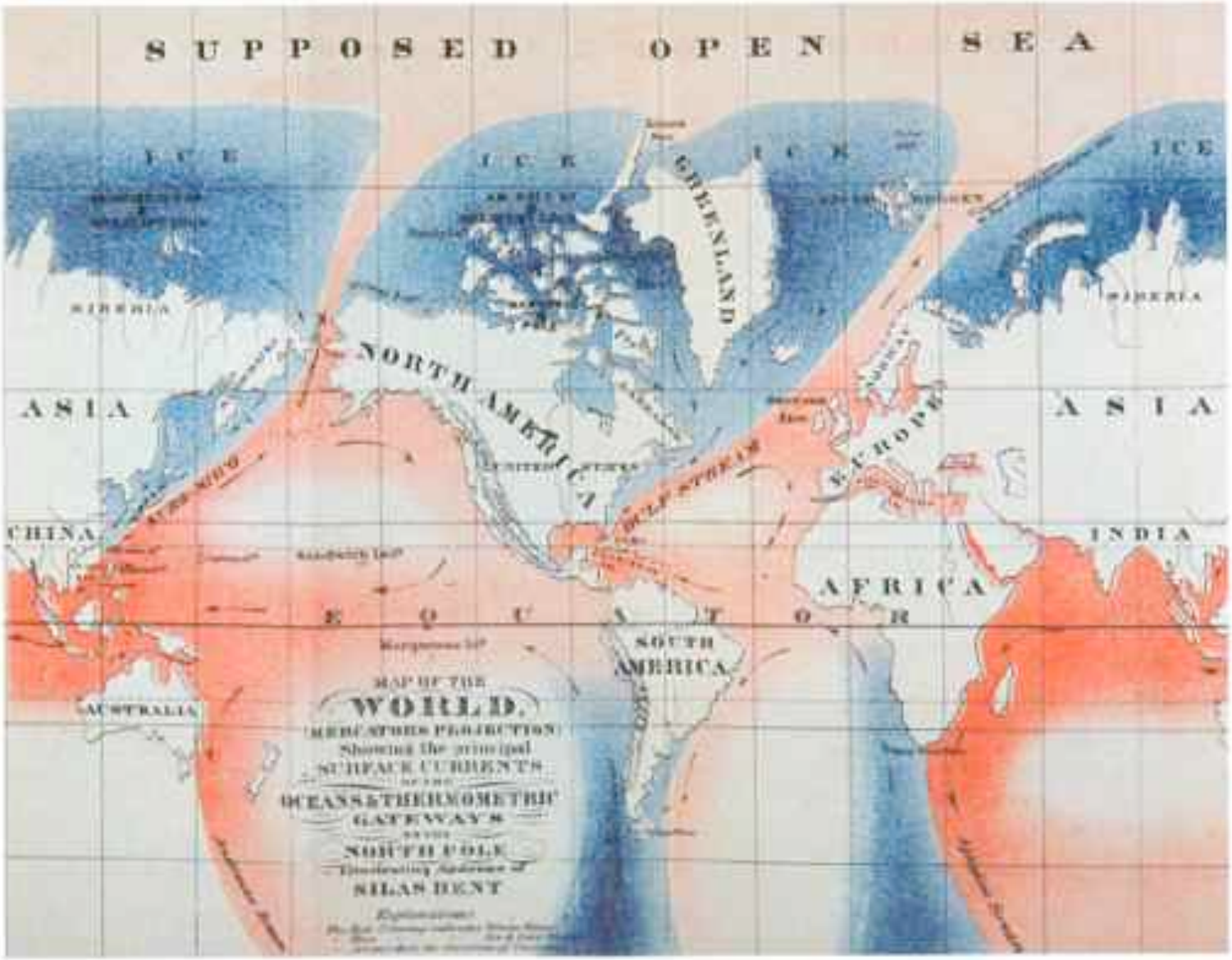
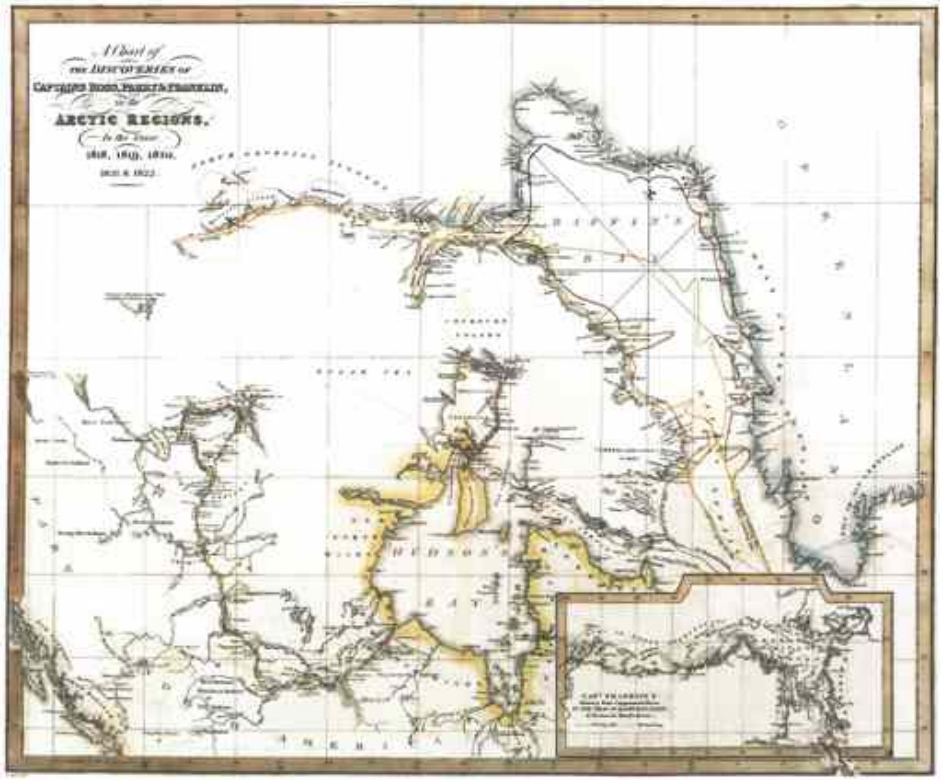
French Arctic Initiative, Collège de France, Paris, June 5th, 2013

Could there be an ice free ocean north of Eurasia and North America?



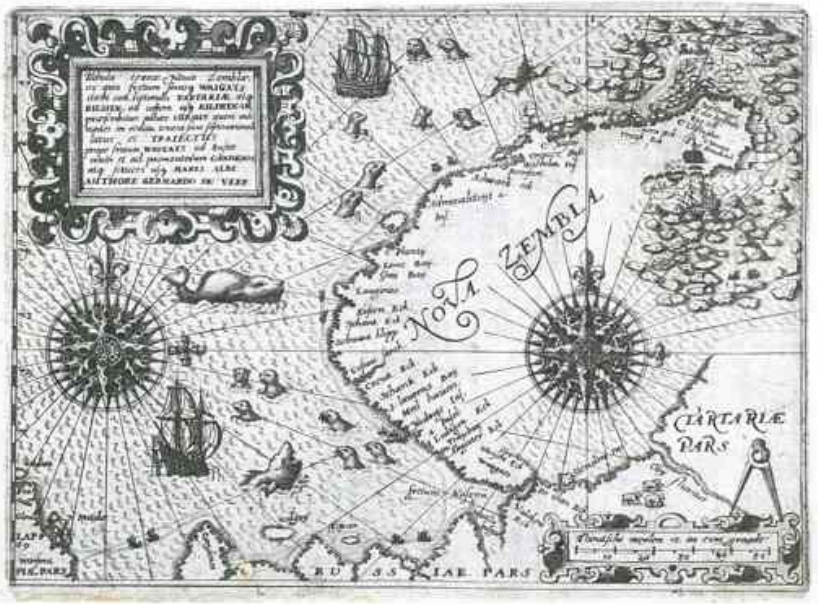
Bent 1872, (from Hayes, 2003)

This is perhaps a strange idea considering the many failed attempts find a **Northeast Passage and a Northwest Passage.**



Hayes, 2003

Parry's expedition 1819-1820 was perhaps the most successful of the many British expeditions in the 19th century to find the Northwest Passage.



Lainema & Nurminen, 2001

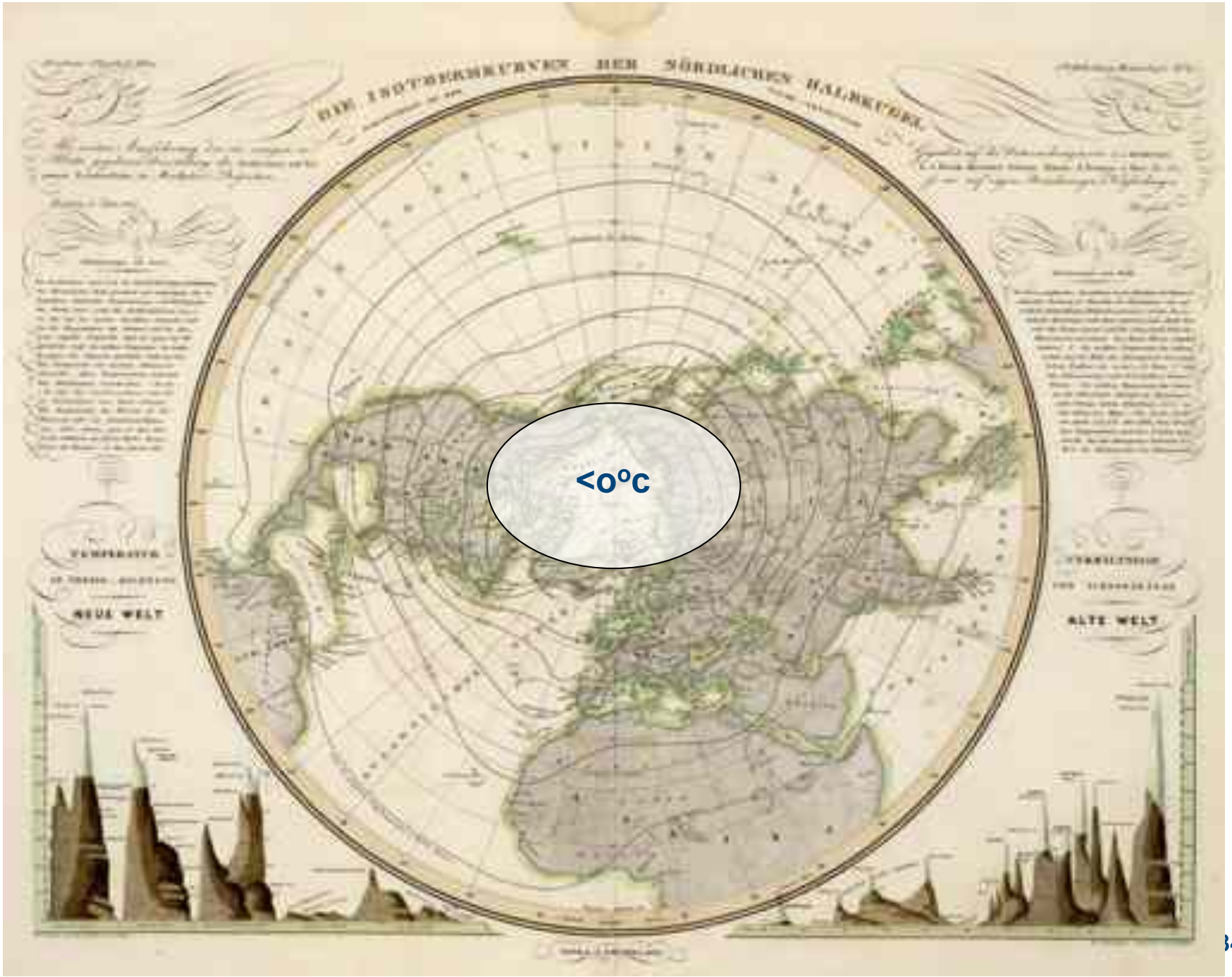
Delgado, 1999

Parry overwintering in Winter Harbour 1819-1820

The distribution of the surface air temperatures was well known

Berghaus Phys. Atlas, 1845

and showed that the annual mean temperature was below zero north of ~ 70°N



AWI, 1993

A vision of vessels penetrating into the open Arctic Ocean

Why an open Arctic Ocean?

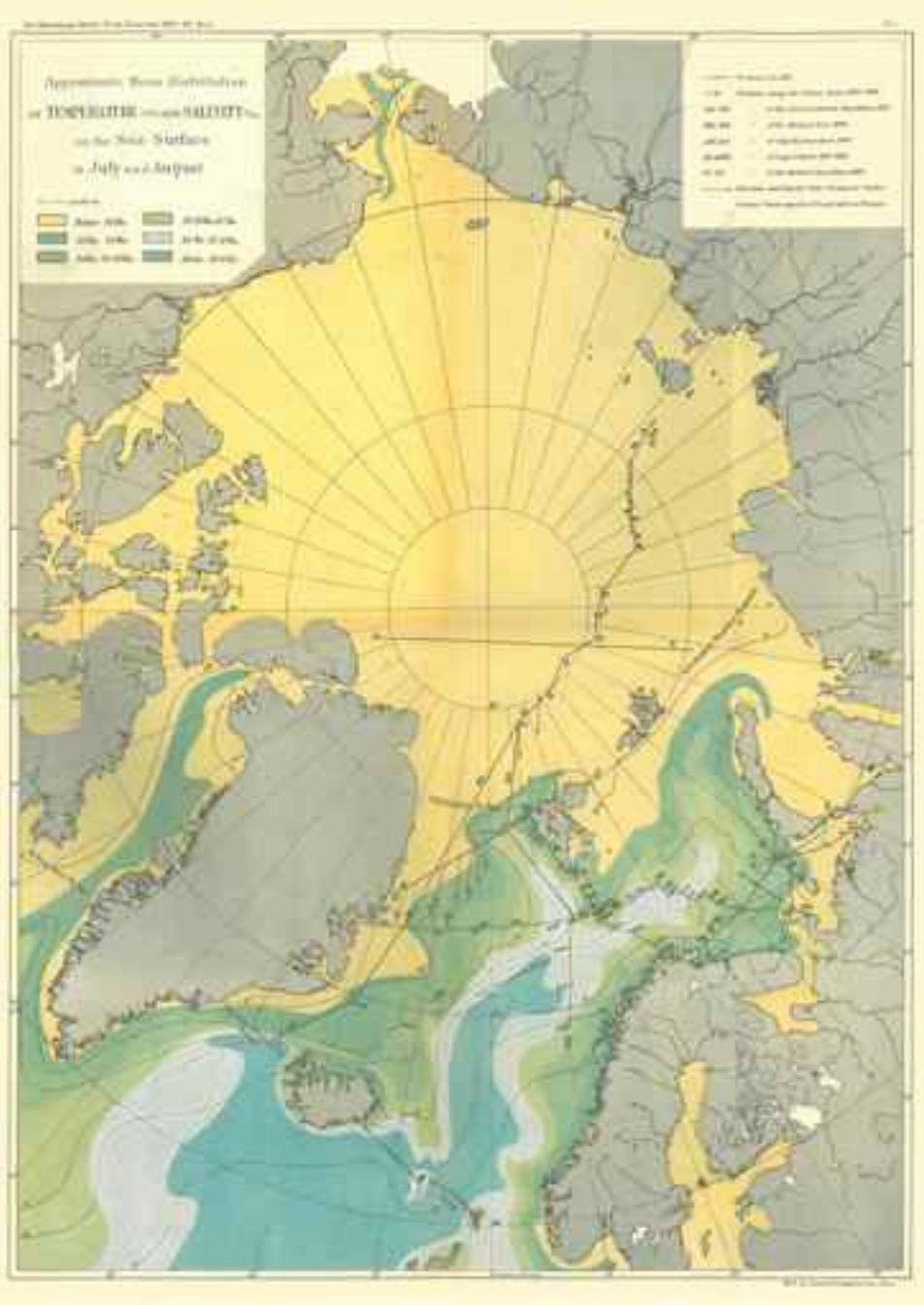
Observations: Open water seen in the north e.g. a permanent polynya north of the Laptev Sea coast.

Sea ice contains little salt. Perhaps sea water does not freeze?

Beyond the influence of river runoff the ocean would then be open.

The heat carried by the Gulf Stream prevents the Arctic Ocean from freezing.

The drift of Fram



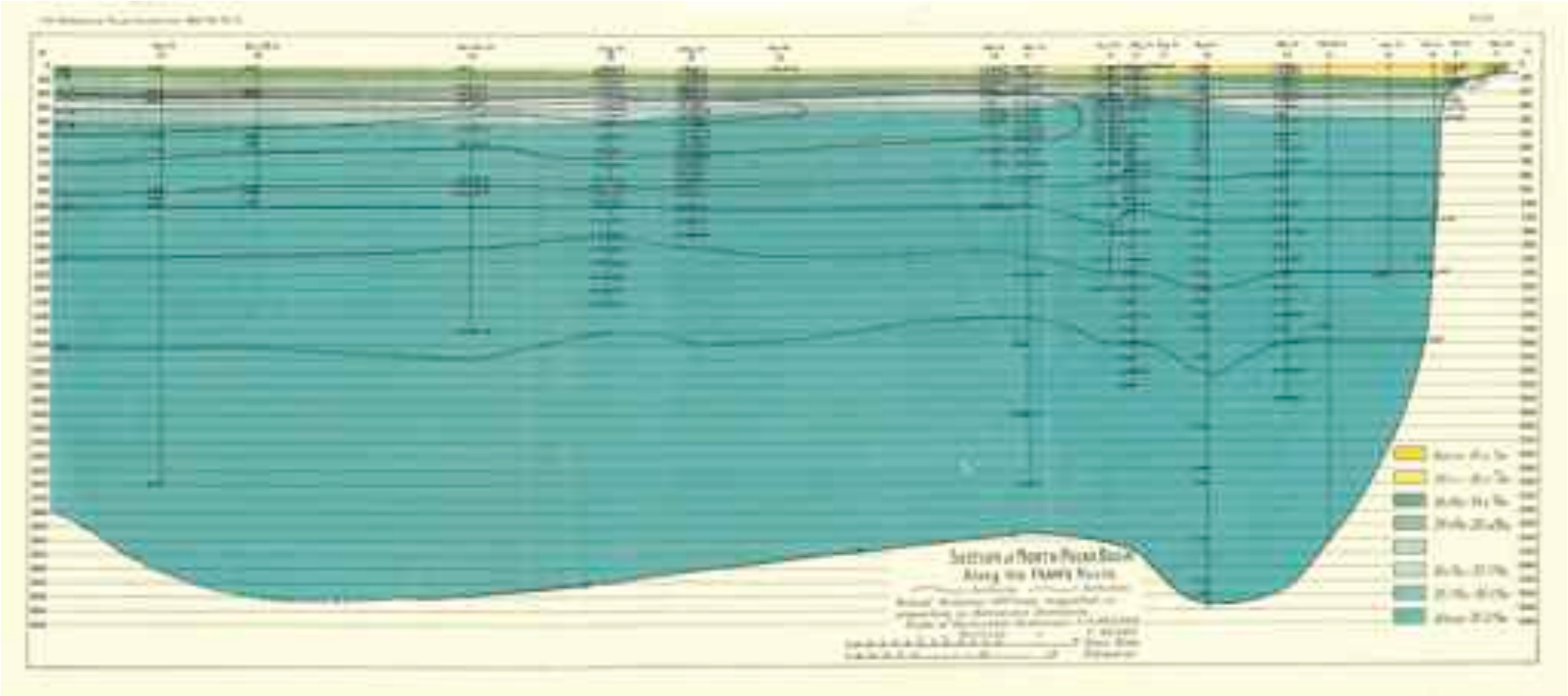
The discovery of parts of the wreckage of Juliette in southwest Greenland in 1884 gave Nansen the idea to drift with the ice across the Arctic Ocean.

No open Polar Ocean was encountered by Nansen and Fram.

Nansen, 1902

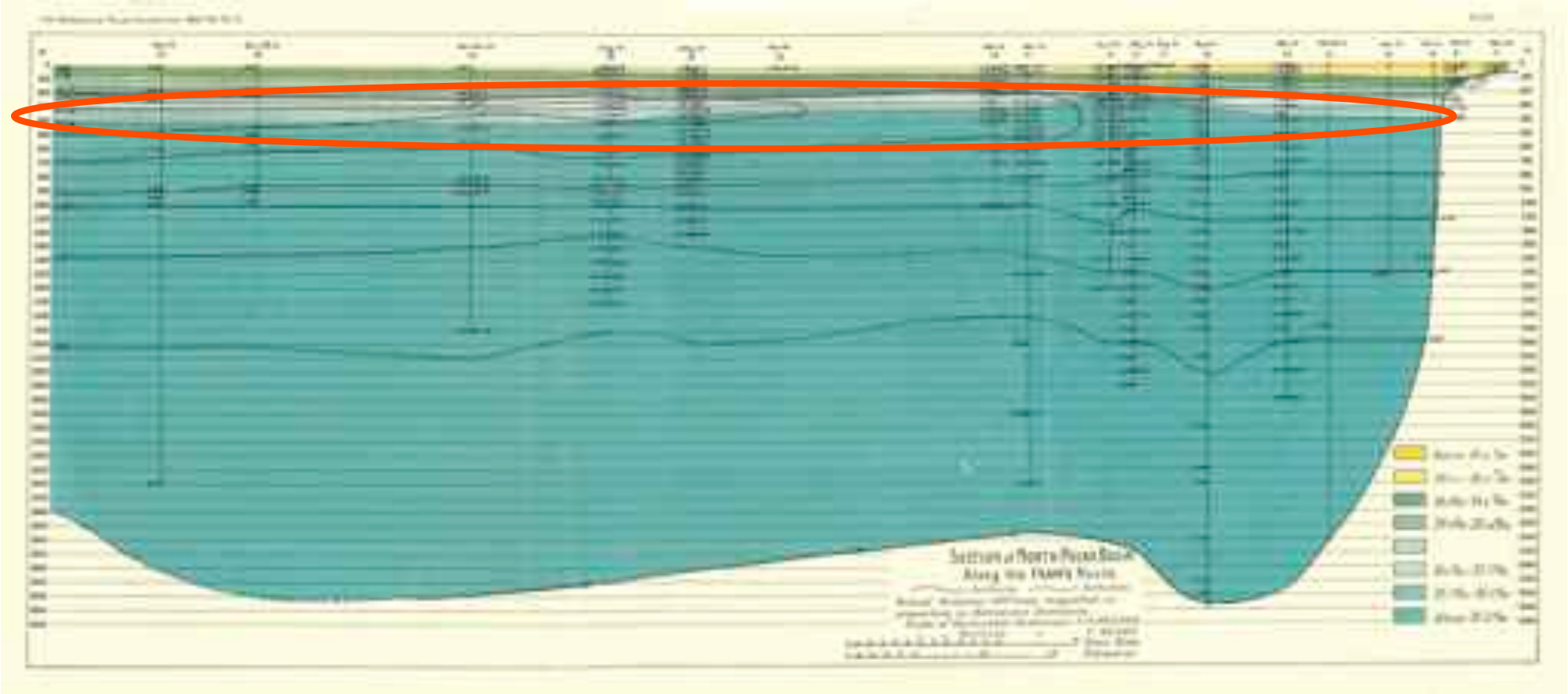
The Arctic Ocean is a deep ocean

A shallow ocean was expected because less water then has to be cooled to the freezing point to form ice.



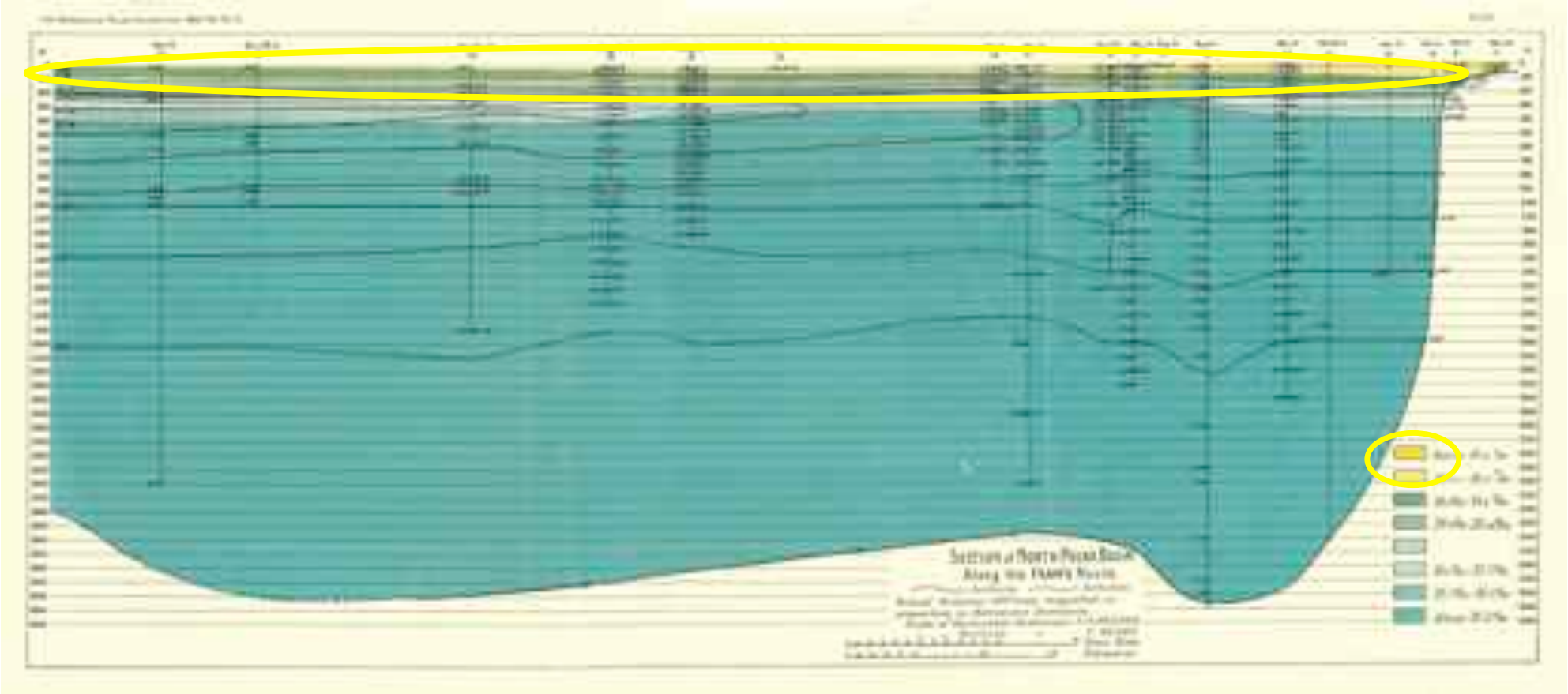
Nansen, 1902

The warm Atlantic water was found in the deep Arctic Ocean basin



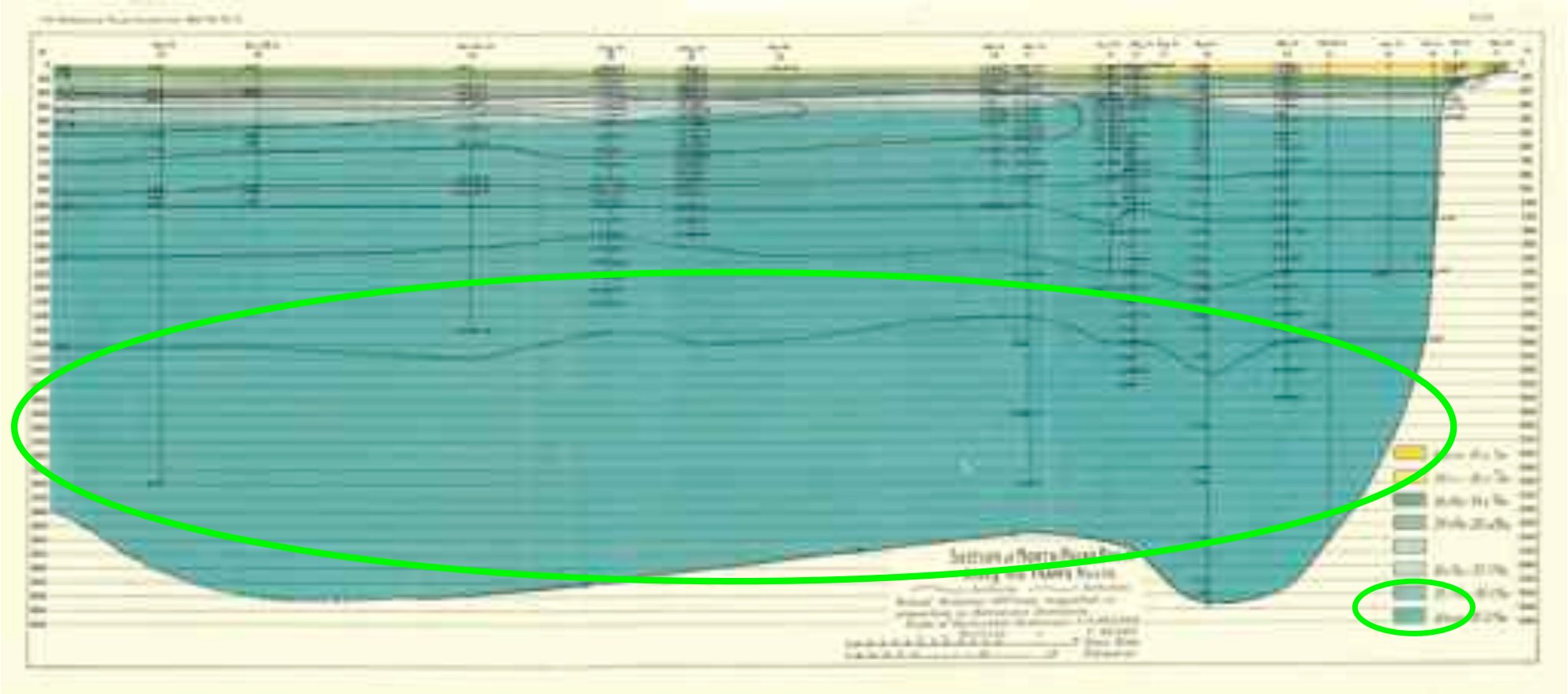
Nansen, 1902

but the Atlantic layer was isolated from the ice by low salinity surface water



Nansen, 1902

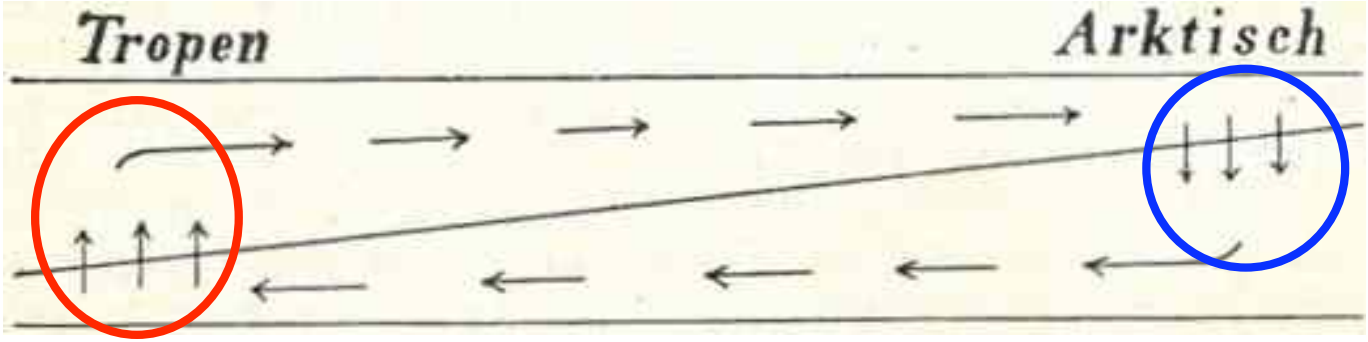
The bottom layer was found to be highly saline.



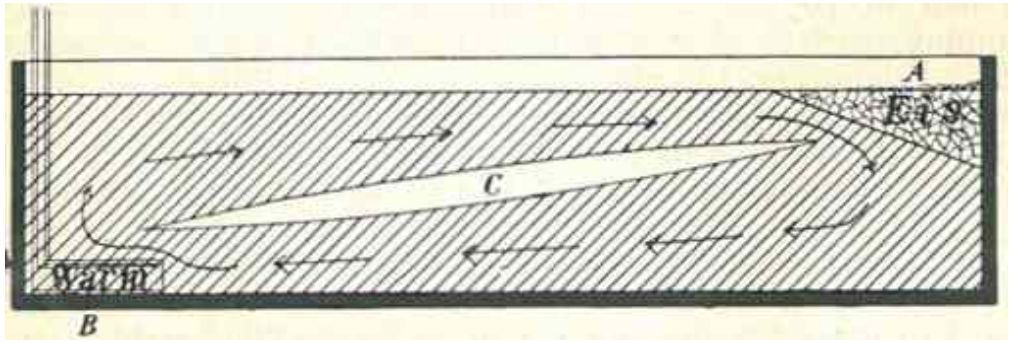
Nansen, 1902

The salinities were later found to be in error, but they got Nansen to speculate over possibility that ice formation and brine rejection on the shelves could generate the saline bottom water.

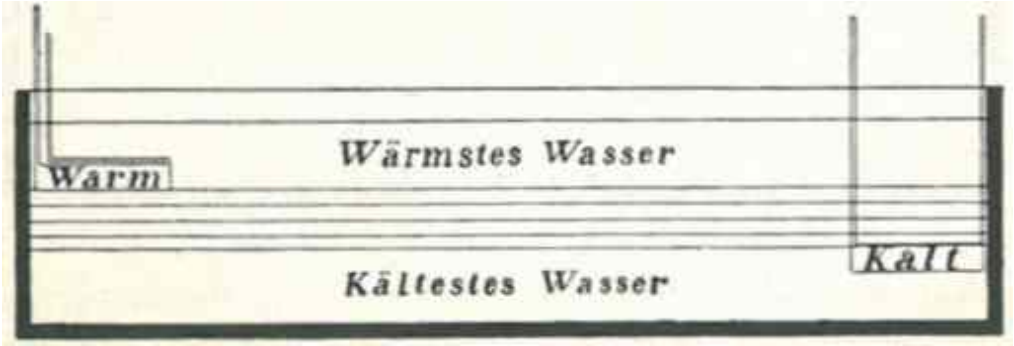
The ocean currents and the transport of heat from low to high latitudes were believed to be driven by the cooling taking place in the northern latitudes.



Such circulation was investigated experimentally by Sandström (1908).



A thermally driven circulation was found and the strength of the circulation depended on the relative vertical positions of the warm and cold sources.



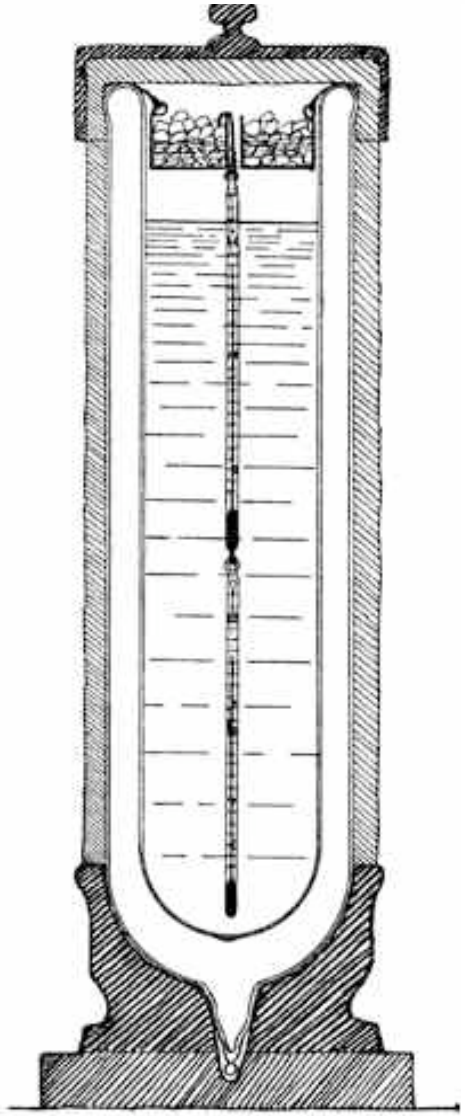
The warm source should be located below the cold source. In the opposite case no circulation was observed.

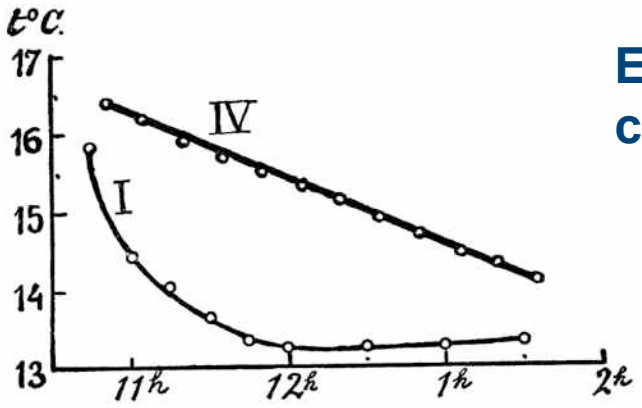
Sandström, 1908

Das Bodenwasser und die Abkühlung des Meeres.

Von

Fridtjof Nansen.





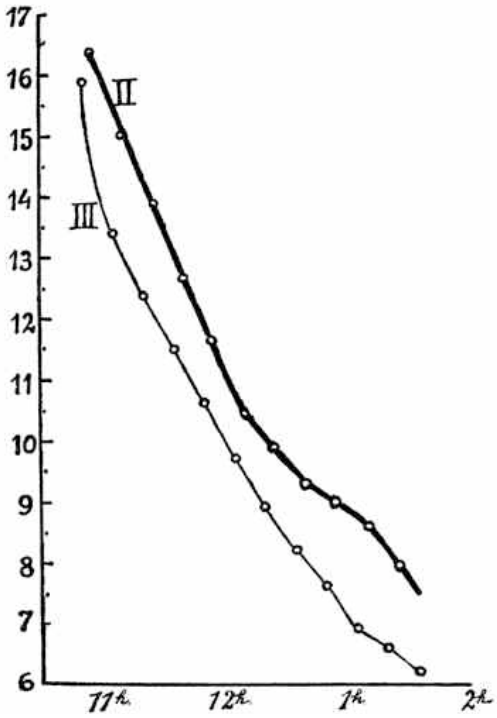
Experiments on the effects of cooling through melting of ice

Three cases

I: Ice melting directly on top of the water.

II & III: Ice melting on the water but in a metal bowl.

IV: Ice melting in a bowl above the water (Radiative cooling).



Nansen, 1912

The most important processes controlling and influencing the climate of the Arctic Ocean were then identified already 100 years ago:

Cooling at high latitudes makes water denser. It sinks and returns south, causing a compensating northward flow of warm water at the surface.

The input of freshwater stabilises the water column and inhibits upward mixing of warmer water from the deep ocean allowing ice to form.

Ice melts on and cools warm water but generates less dense surface water; the buoyancy input of melt water is larger than the buoyancy loss due to cooling.

The Arctic Ocean climate is a balance between transports and mixing!

Outline

Early observations in the Arctic Ocean.

The radiation and heat balances.

The circulation of Atlantic water in the Arctic Ocean and the heat transfer to ice and atmosphere.

Freshwater balance and freshwater transports.

The global thermohaline circulation, and its possible changes due to a warmer climate.

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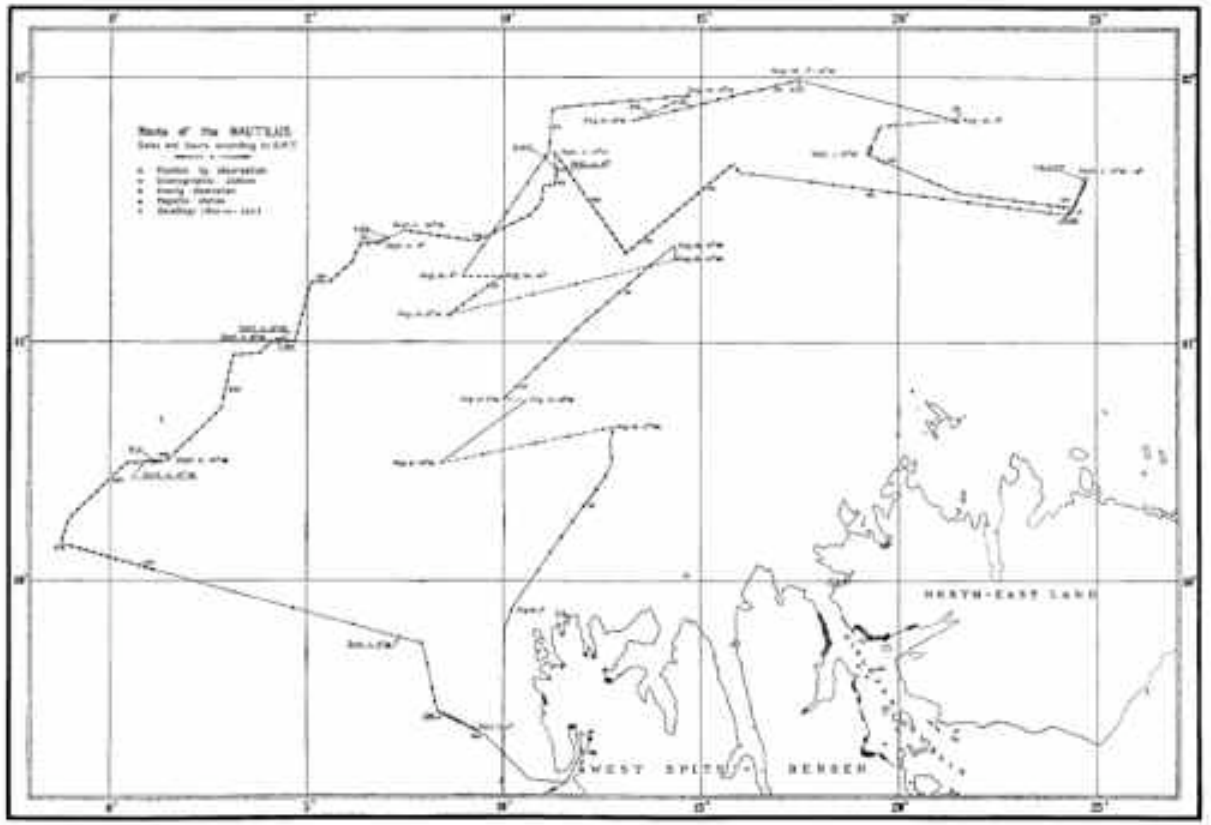
The field work in the Arctic Ocean has had its disappointments

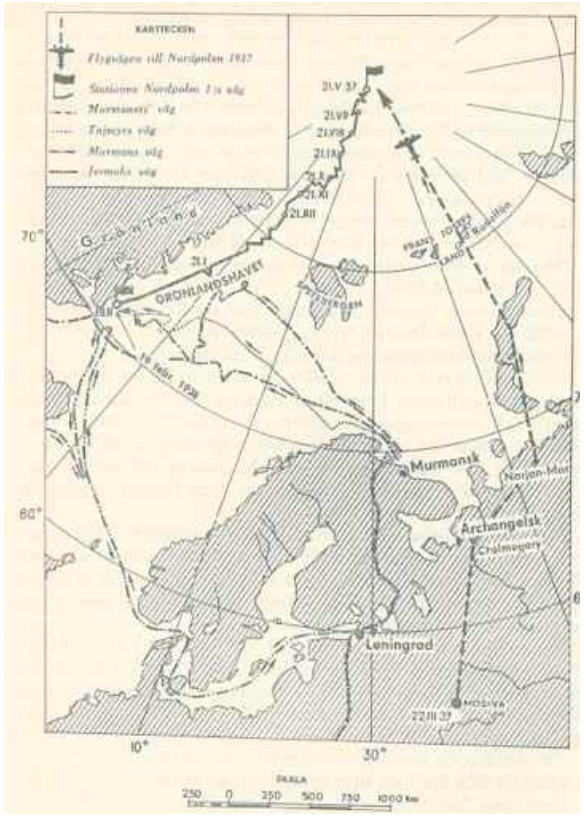
The Nautilus expedition 1931 – an attempt to explore the Arctic Ocean using a submarine.

H. Wilkins was expedition leader and H.U. Sverdrup oceanographer.

Wikipedia & Sverdrup, 1933

Nautilus route north of Svalbard





and successes.

The first Soviet ice station North Pole –1, led by I.D. Papanin,

May 1937 – February 1938.

The participant before the start of the expedition

Daily routines

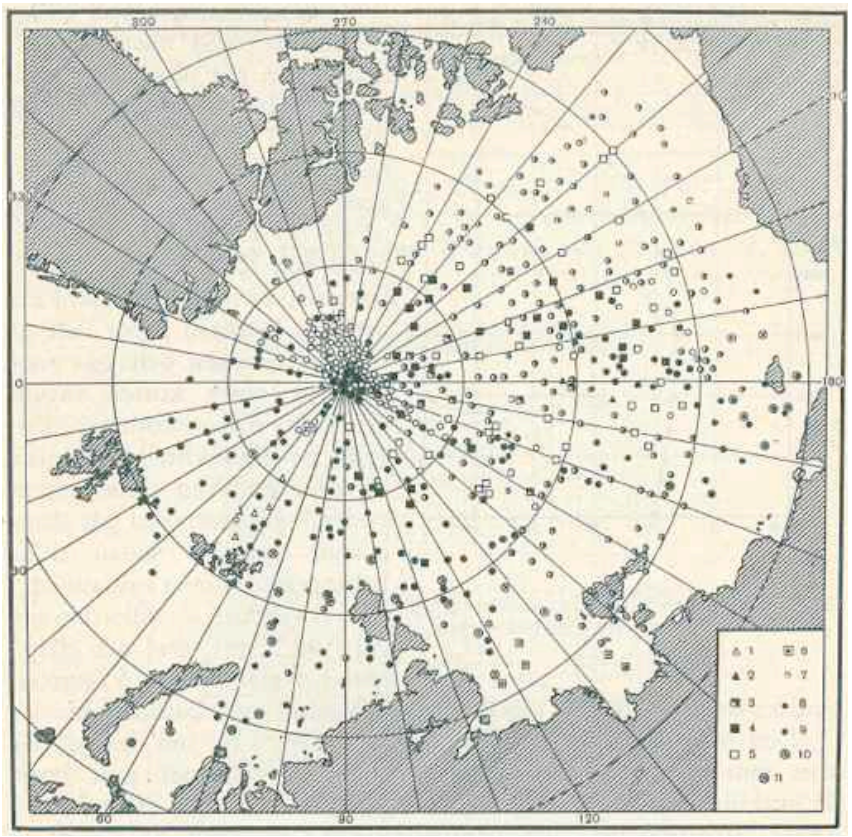
Ugryumov & Korovin, 2005

Nordpolen 1.

Vardagens arbete.

Laktionov, 1960

Soviet airborne hydrographic stations up the end of the 1950s.

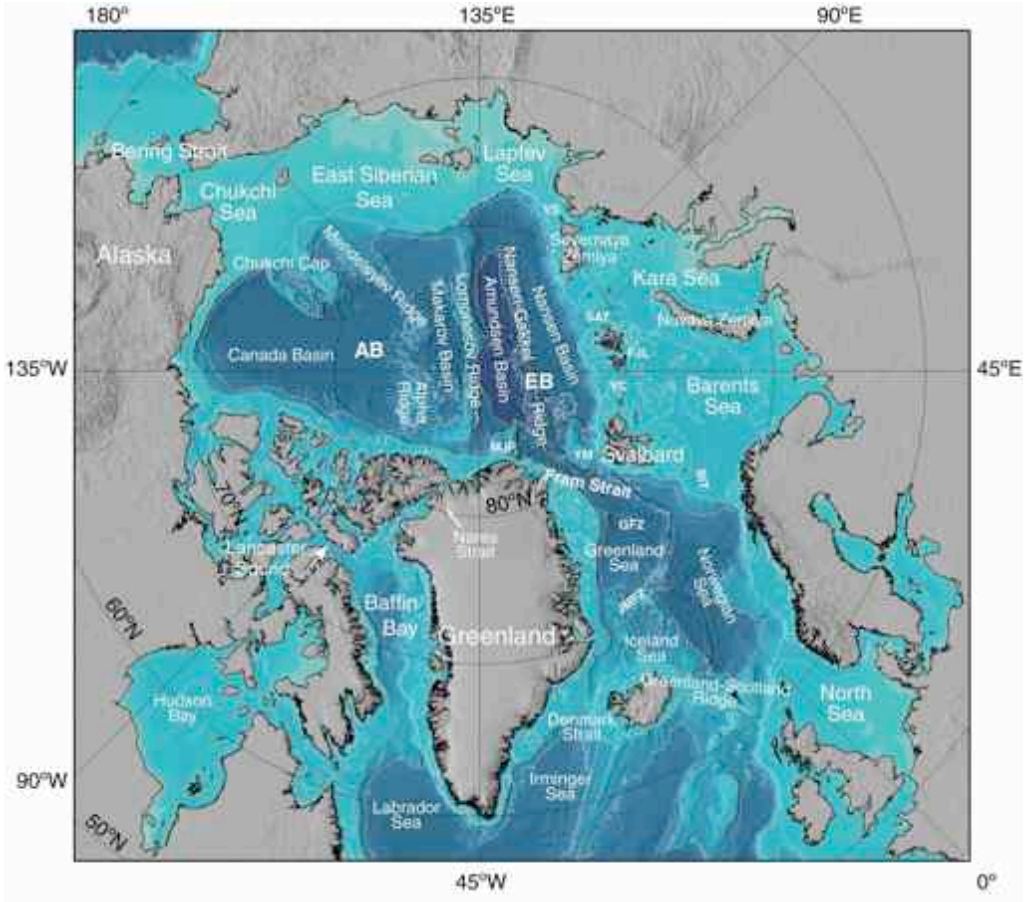


Laktionov, 1960

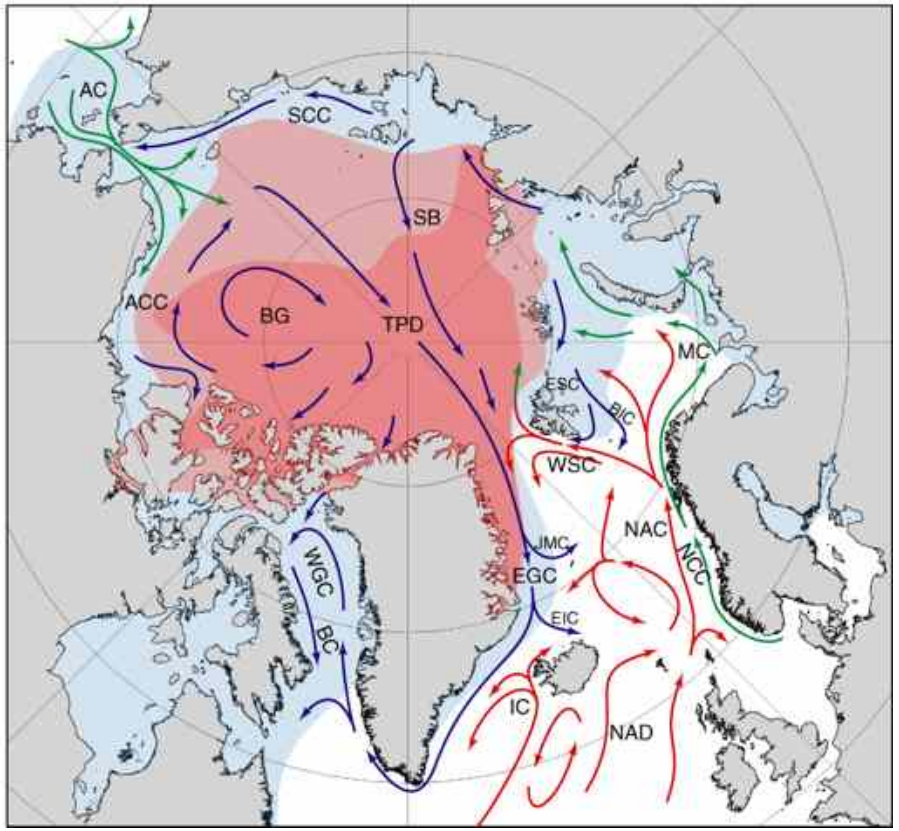
Sovjetiska flygplan på polen.

Manned ice camps up to 1975

CIA 1977



Ice camps and airborne expeditions added to the knowledge of the **bathymetry** of the Arctic Ocean



and provided information of the **extent, seasonal variations and drift of the sea ice** and of the **surface currents.**

Rudels et al., 2012

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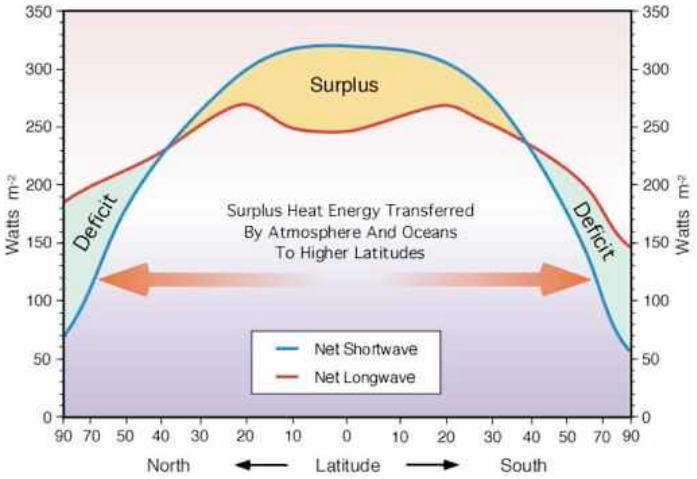
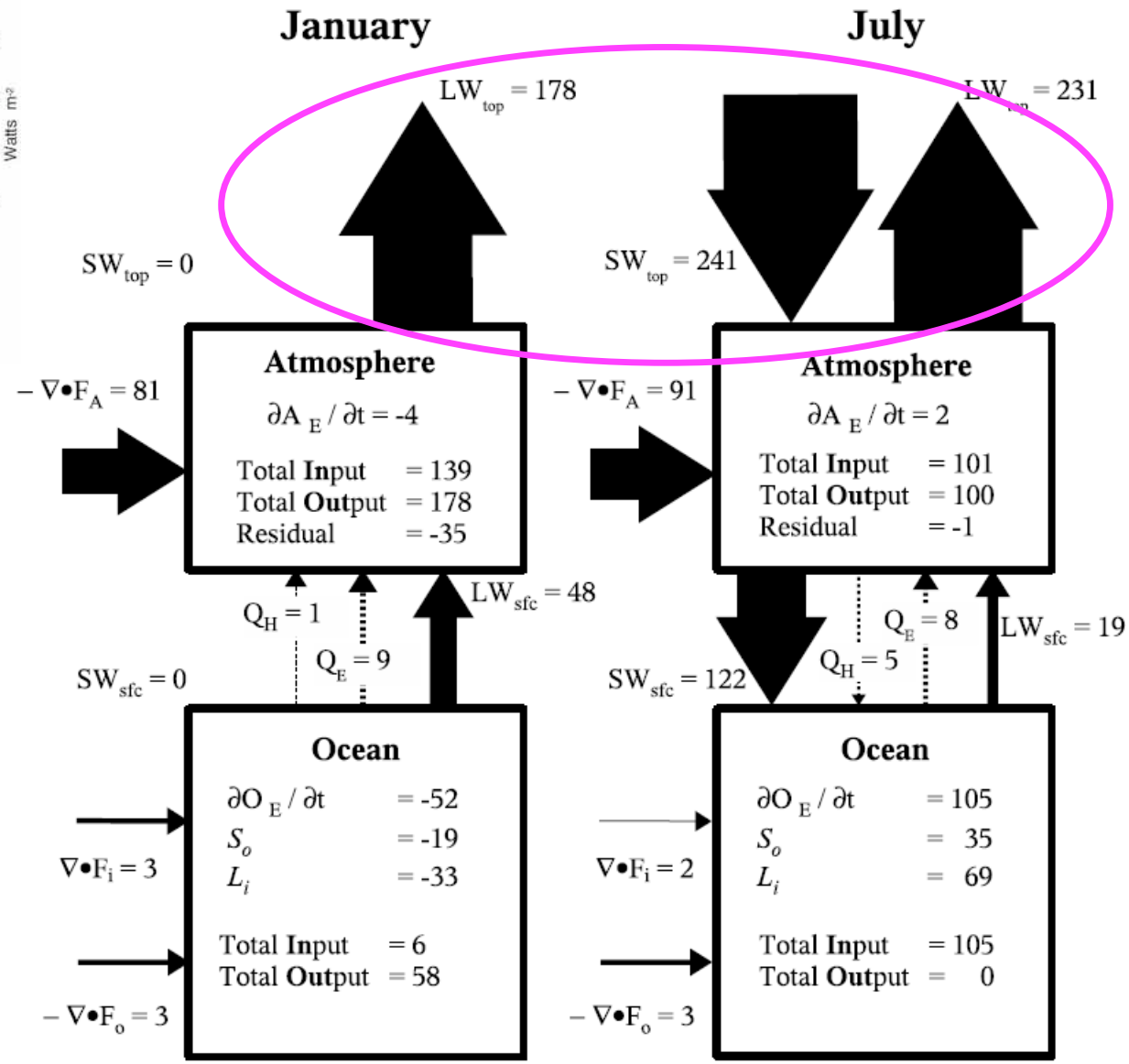
Heat balance north of 70 N

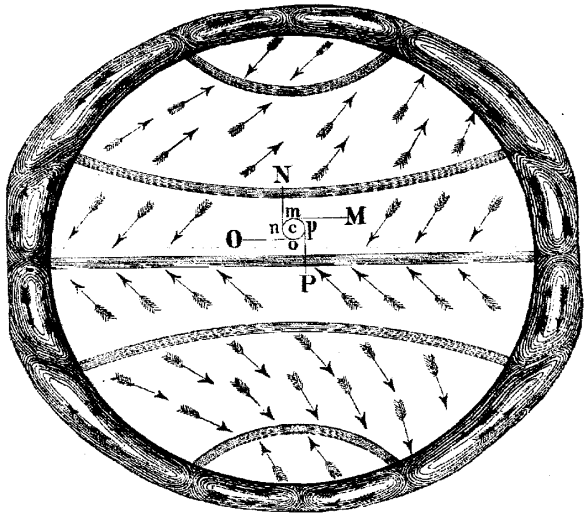


The heat loss at the top of the atmosphere has to be compensated by a meridional transport of heat from lower latitudes. Units Wm^{-2}



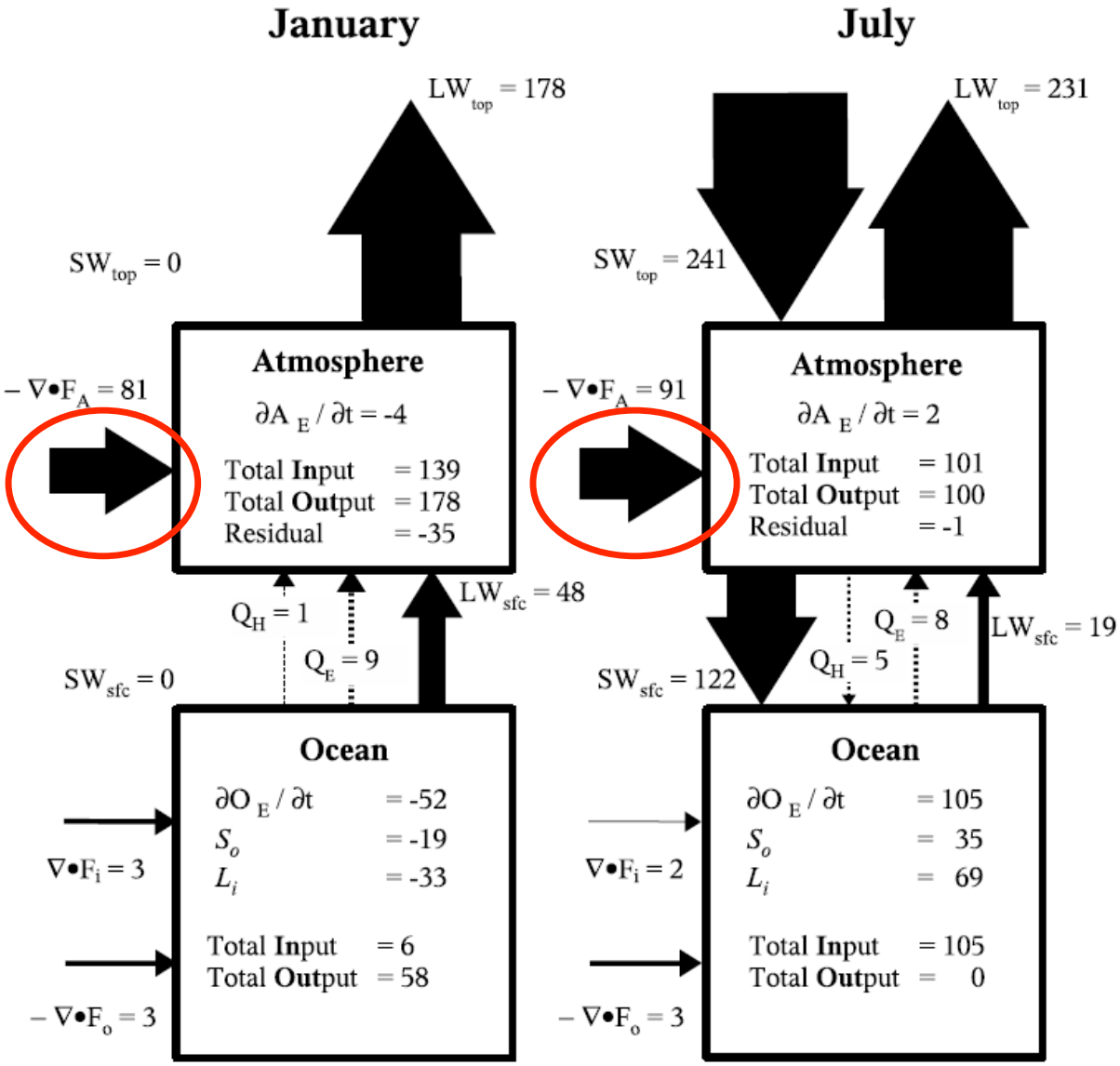
Serreze et al., 2007

Heat balance north of 70 N



Ferrel, 1856

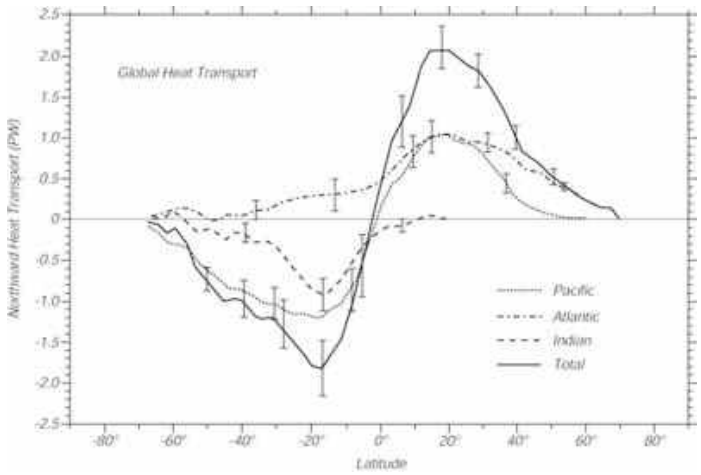
Most of this transport occurs in the atmosphere.

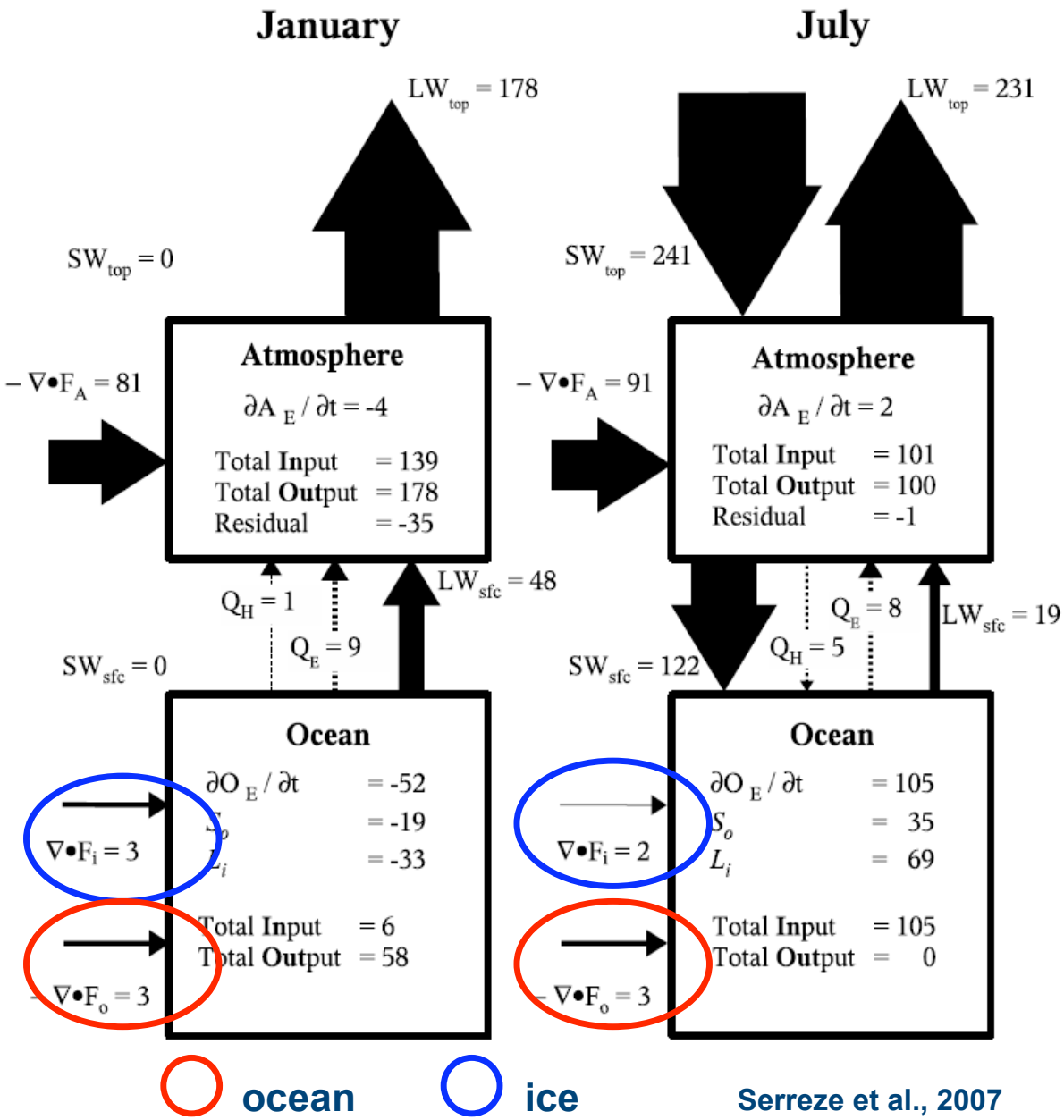


Serreze et al., 2007

Heat balance north of 70 N

But heat is also carried by the ocean
&
heat added in summer is stored by ice melt and released by freezing in winter.





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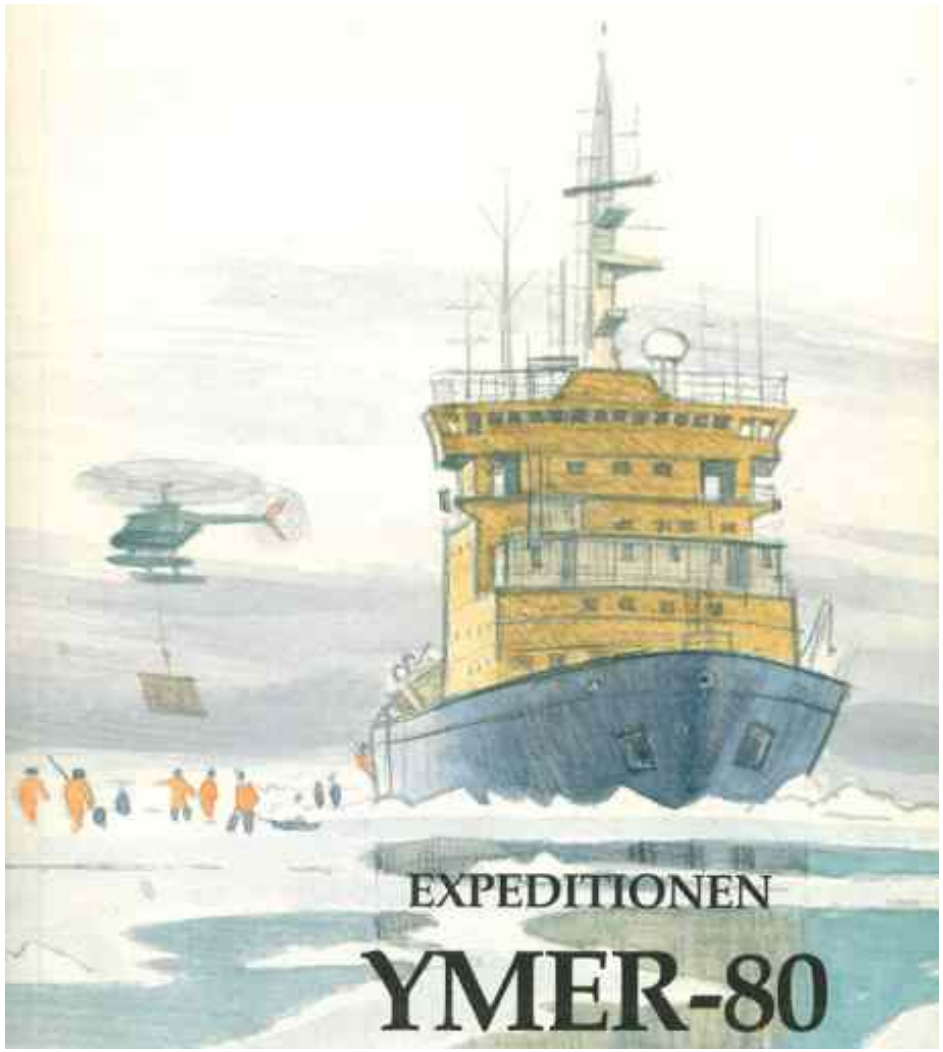
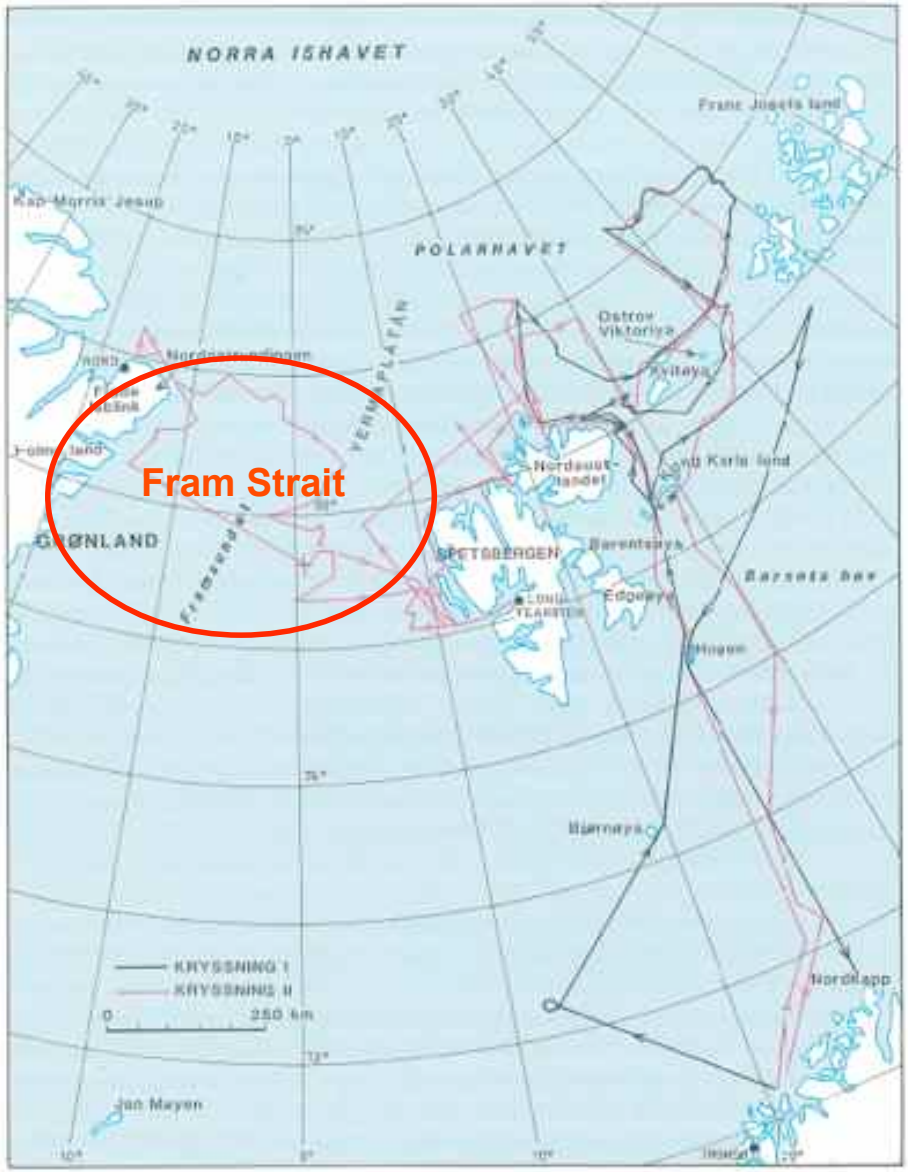


Ymer did not penetrate far into the Arctic Ocean but the expedition marked the beginning of a more intense icebreaker activity in the high Arctic.

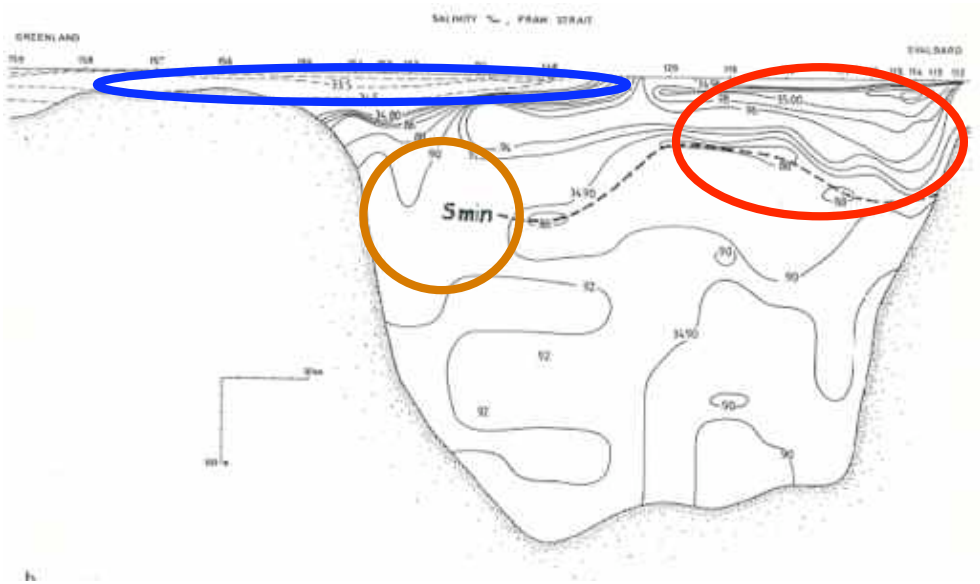
Ymer – 80 was one of the early scientific icebreaker expeditions



One research topics was: could a reduction of the freshwater input lead to a decrease of the Arctic Ocean ice cover, due to larger heat flux from the warm Atlantic water, and Ymer observed the transports through Fram Strait where the main inflow of warm Atlantic water takes place.

Northward flowing warm, saline Atlantic water in the West Spitsbergen Current
southward flowing cold, low salinity Polar water in the East Greenland Current
Southward flowing cooled Atlantic water in the East Greenland Current .

Ymer temperature section in Fram Strait

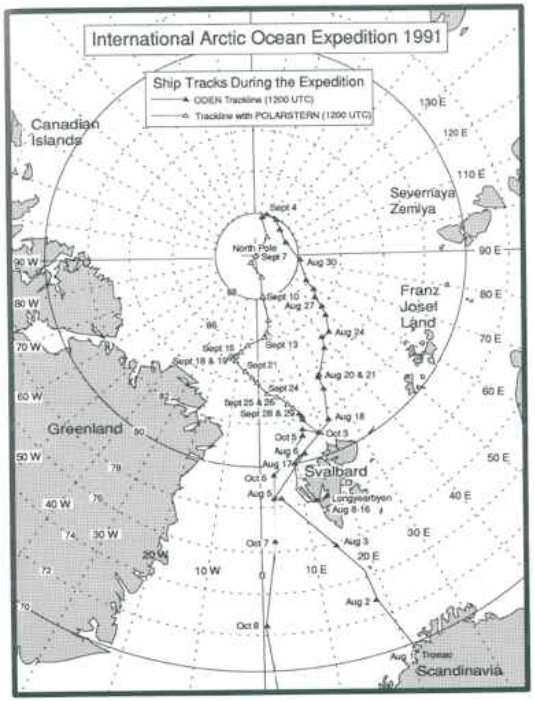


Ymer salinity section in Fram Strait

Rudels, 1987

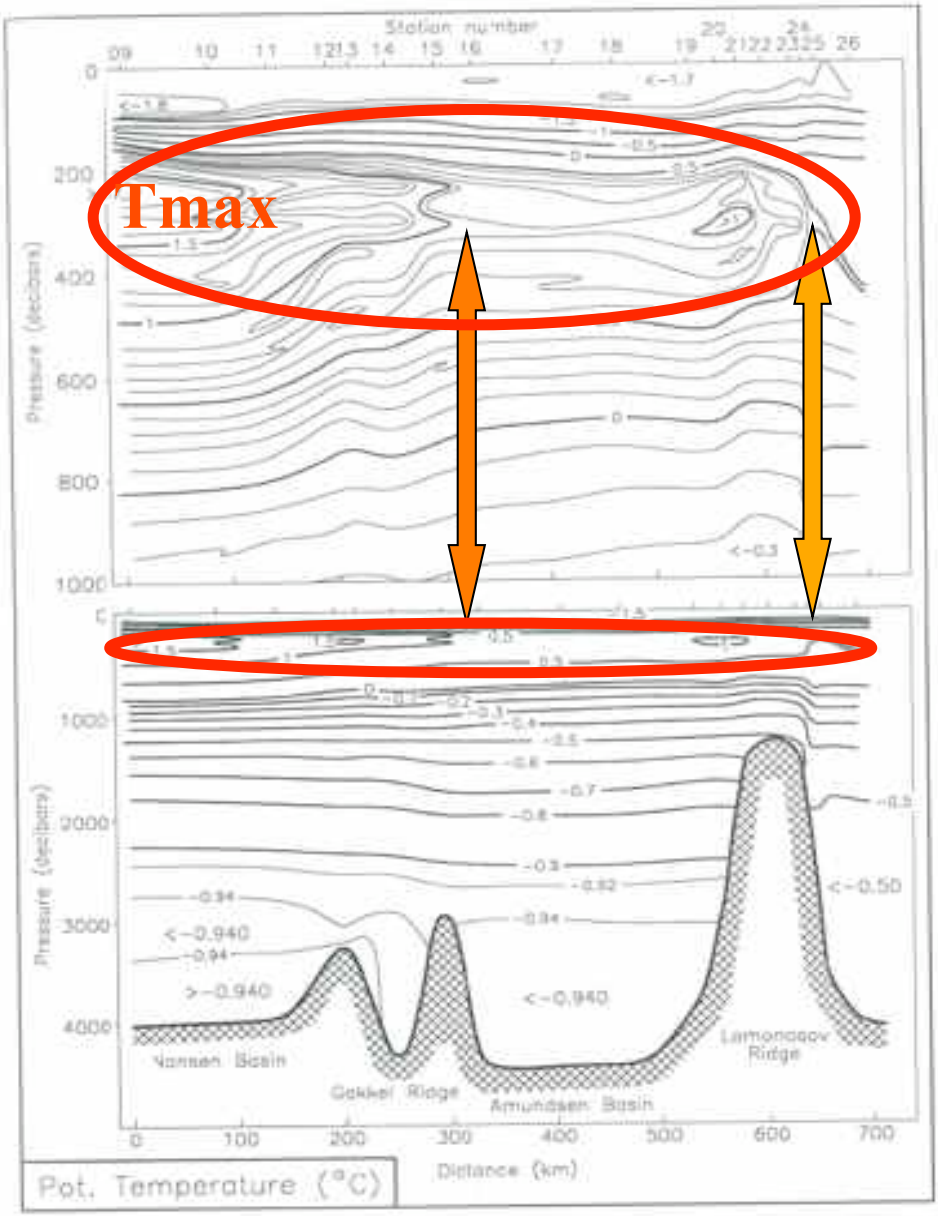
The circulation of Atlantic water in the Arctic ocean

Oden in the Arctic Ocean 1991



The eastern section from Svalbard to the Makarov Basin across the Lomonosov Ridge.

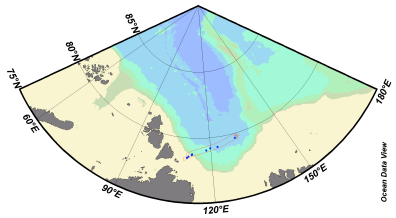
Two temperature fronts

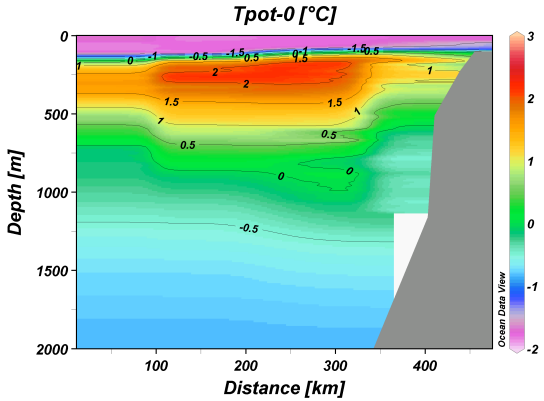


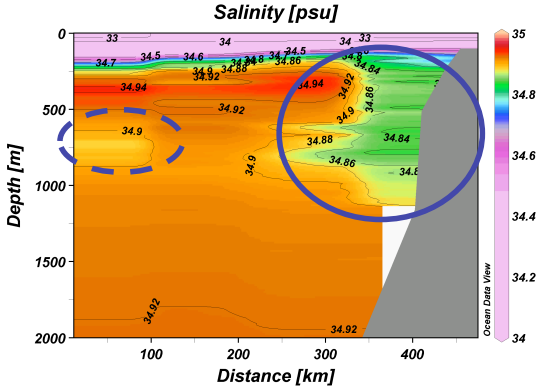
temperature section

Potential temperature and salinity sections from the eastern Eurasian Basin indicating a colder,less saline inflow from the Barents Sea.

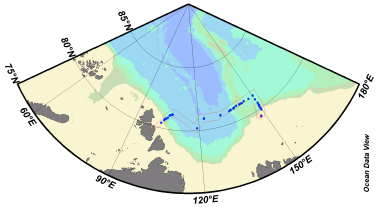
Polarstern 1993

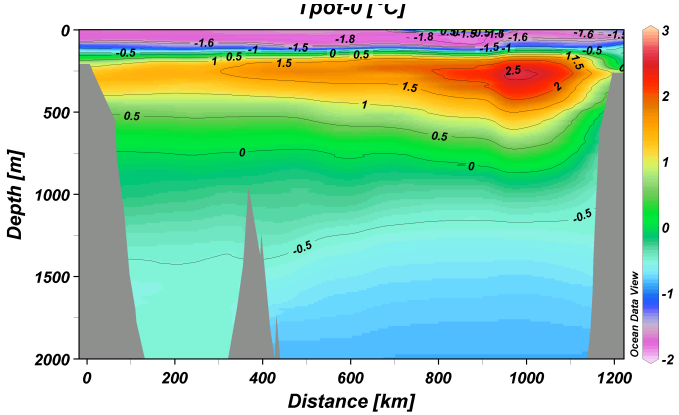


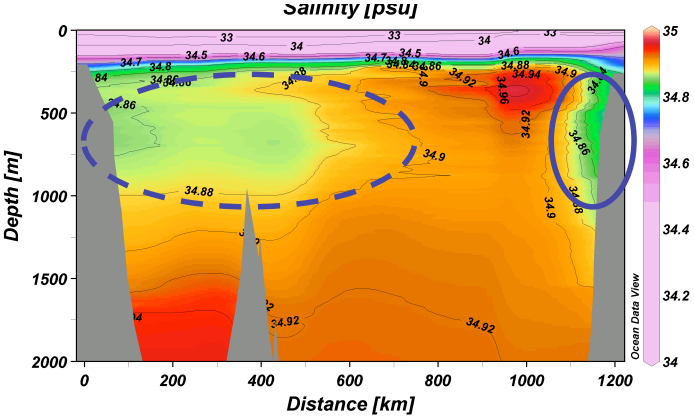




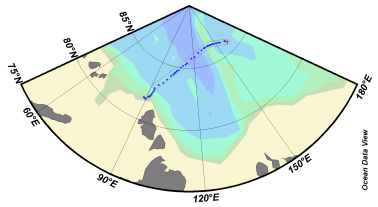
Polarstern 1995

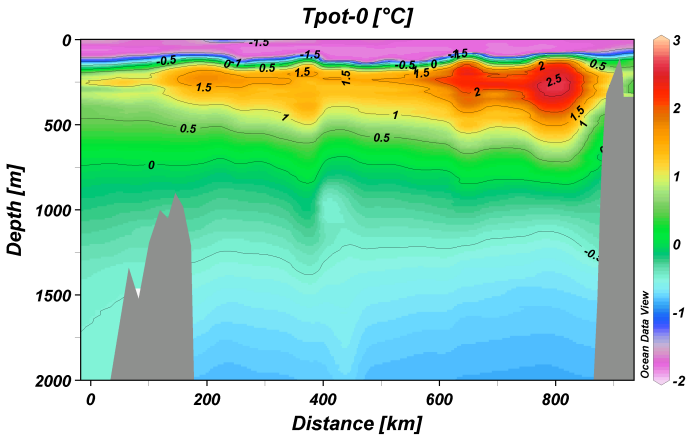


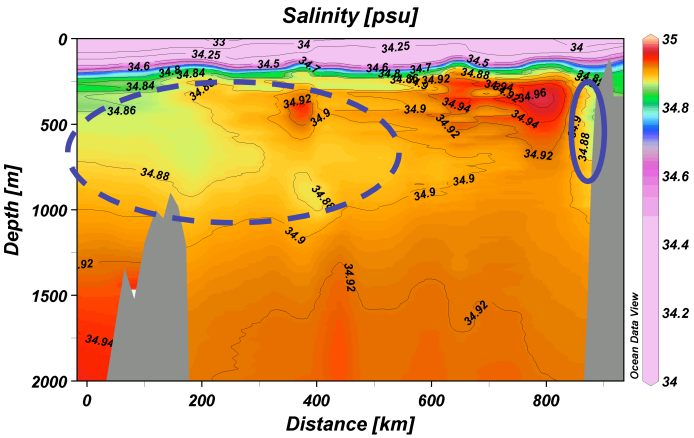




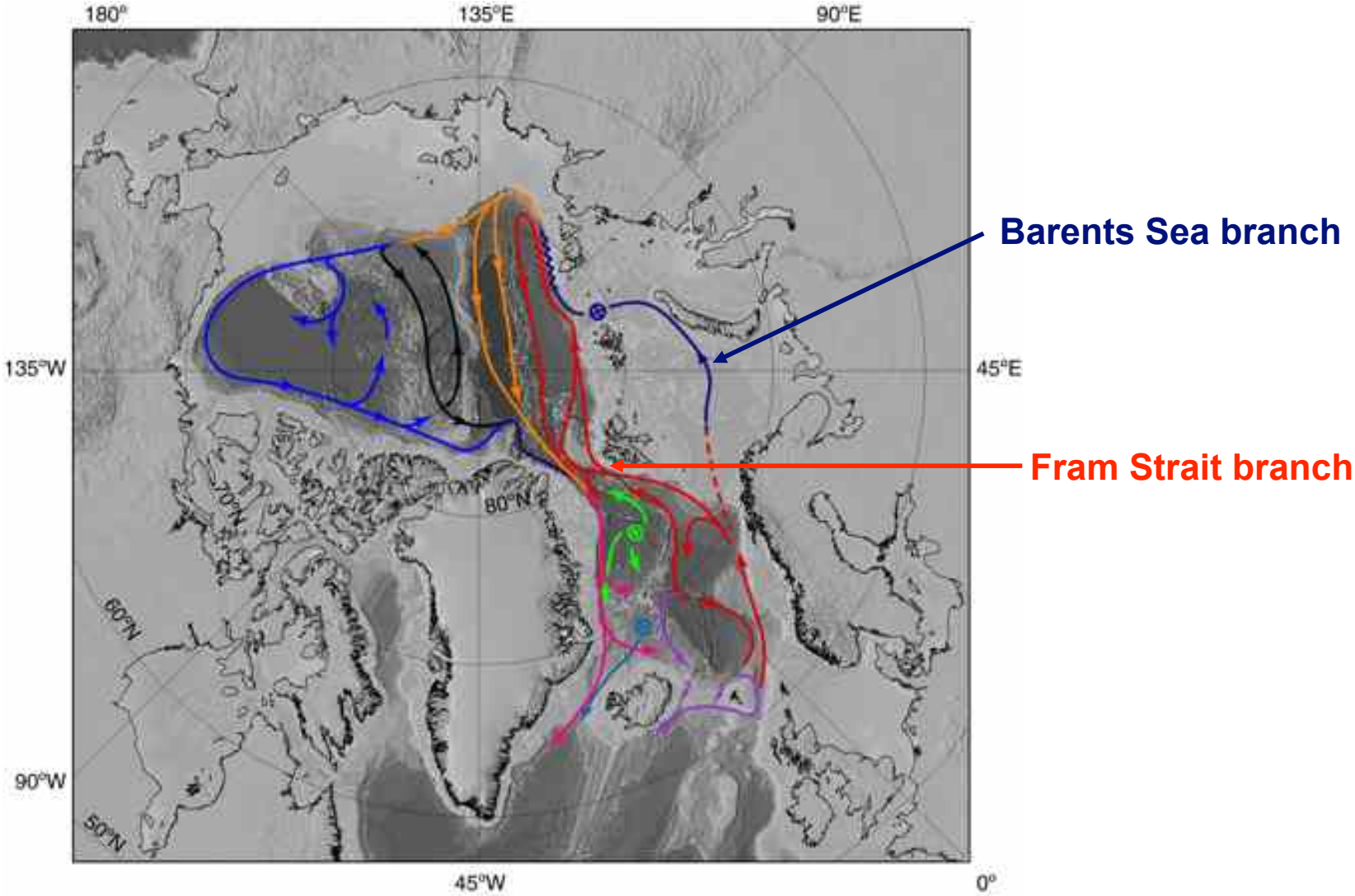
Polarstern 1996







The Fram Strait inflow branch mainly stays in the Nansen Basin and exits through Fram Strait colder than it entered.
The colder and less saline Barents Sea branch supplies most of the Atlantic and intermediate water in the other parts of the Arctic Ocean.

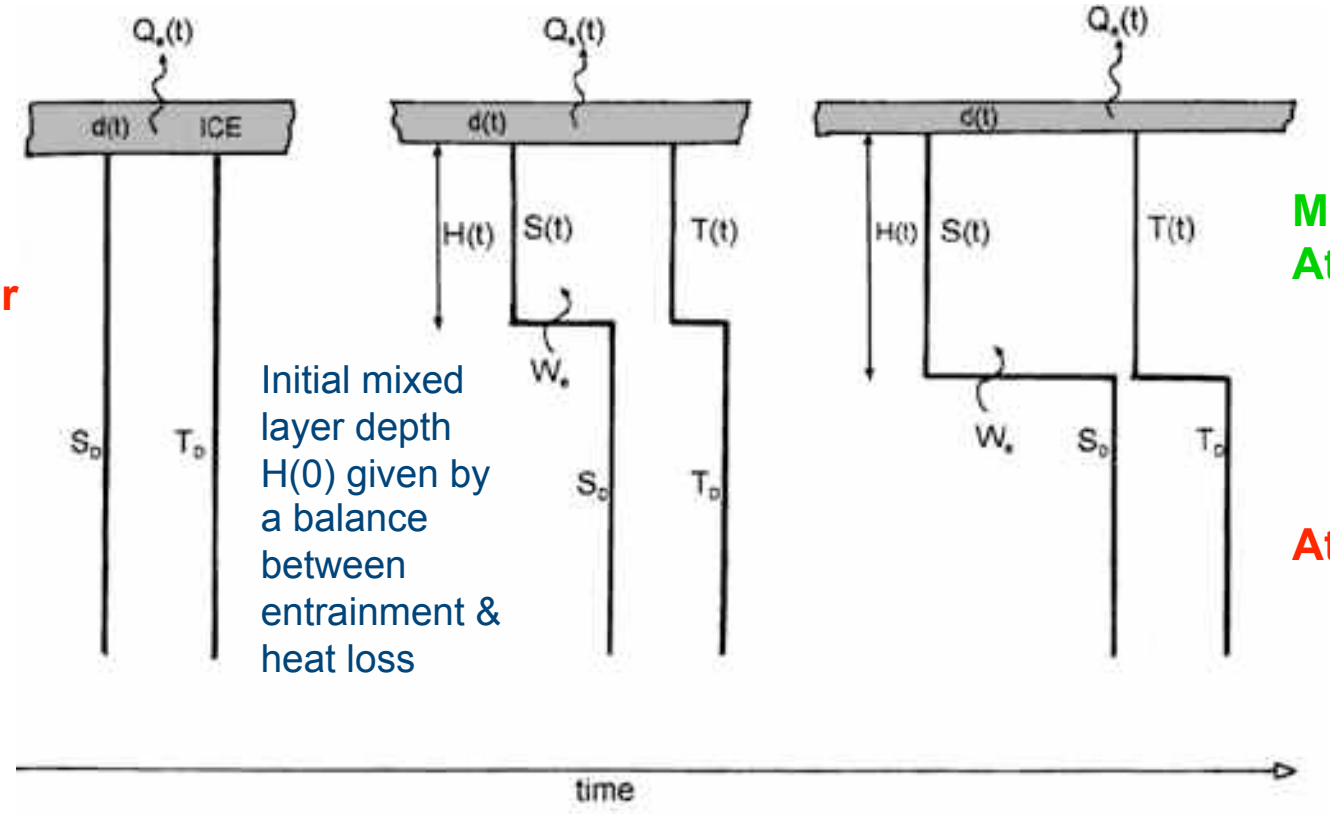


Rudels et al., 2012

Evolution of the ice cover and the upper layer temperature, when ice is melting on warmer water and heat loss to the atmosphere takes place

ICE

Atlantic water



Melt water + Atlantic water

Atlantic water

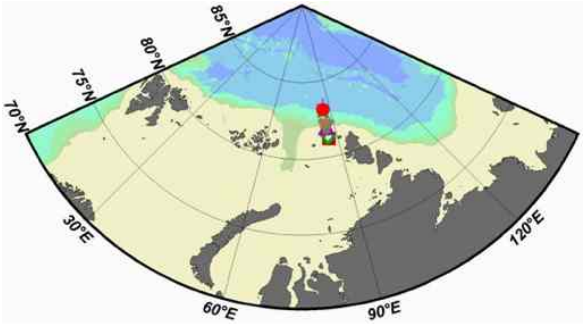
A low salinity surface layer is created, which deepens by wind mixing.

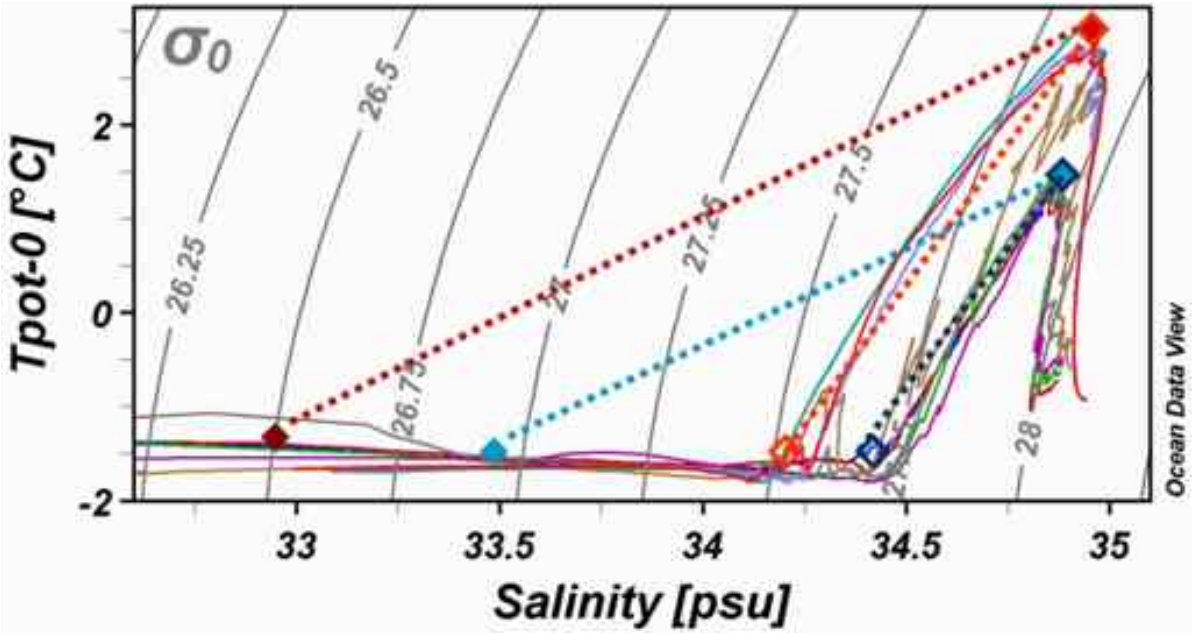
Heat loss creates negative buoyancy, while melting adds positive buoyancy.

Since the ice melt is caused by oceanic heat, the stability between the surface layer and the warm water below depends upon the fraction ϕ of heat Q' going to ice melt.

The reservoir of sensible heat in the mixed layer will eventually be removed.
If ϕ_o is the fraction giving minimum ice melt the salinity of the upper layer becomes:

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





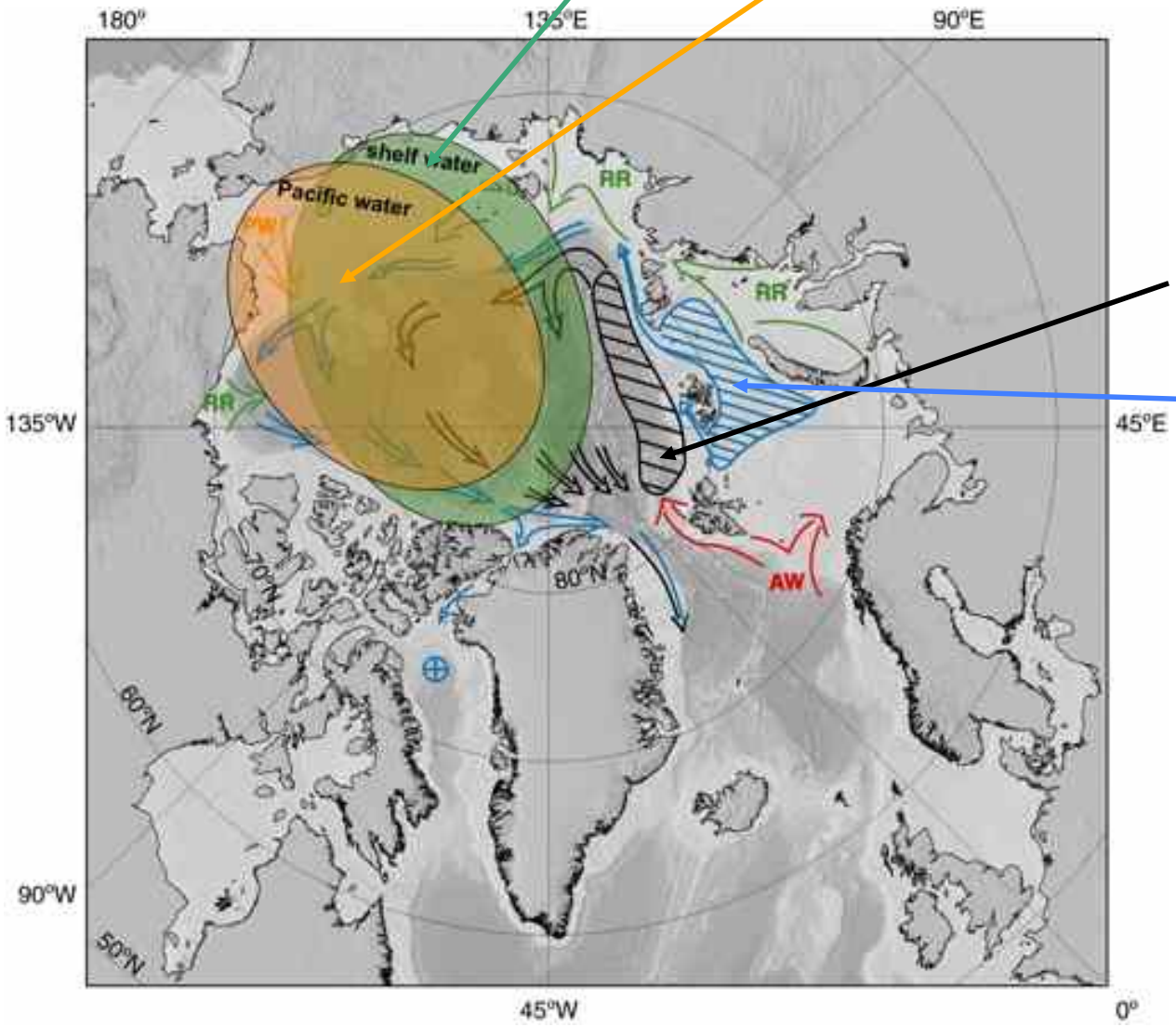
Open diamonds indicate the salinity at the freezing point for the Fram Strait branch and the Barents Sea branch , when only the fraction $\phi_o \approx 2\alpha L(c\beta S_A)^{-1}$ goes to ice melt.

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

North of the Laptev Sea and farther east this layer becomes covered by low salinity water from the shelves carrying river runoff and Pacific water and isolated from the surface processes.



The Atlantic inflow melts sea ice in the Nansen Basin north of Fram Strait and in the northern Barents and Kara seas forming a less dense and less saline upper layer.

The winter convection reaches to the Atlantic layer in the Nansen Basin.

Rudels et al., 2012

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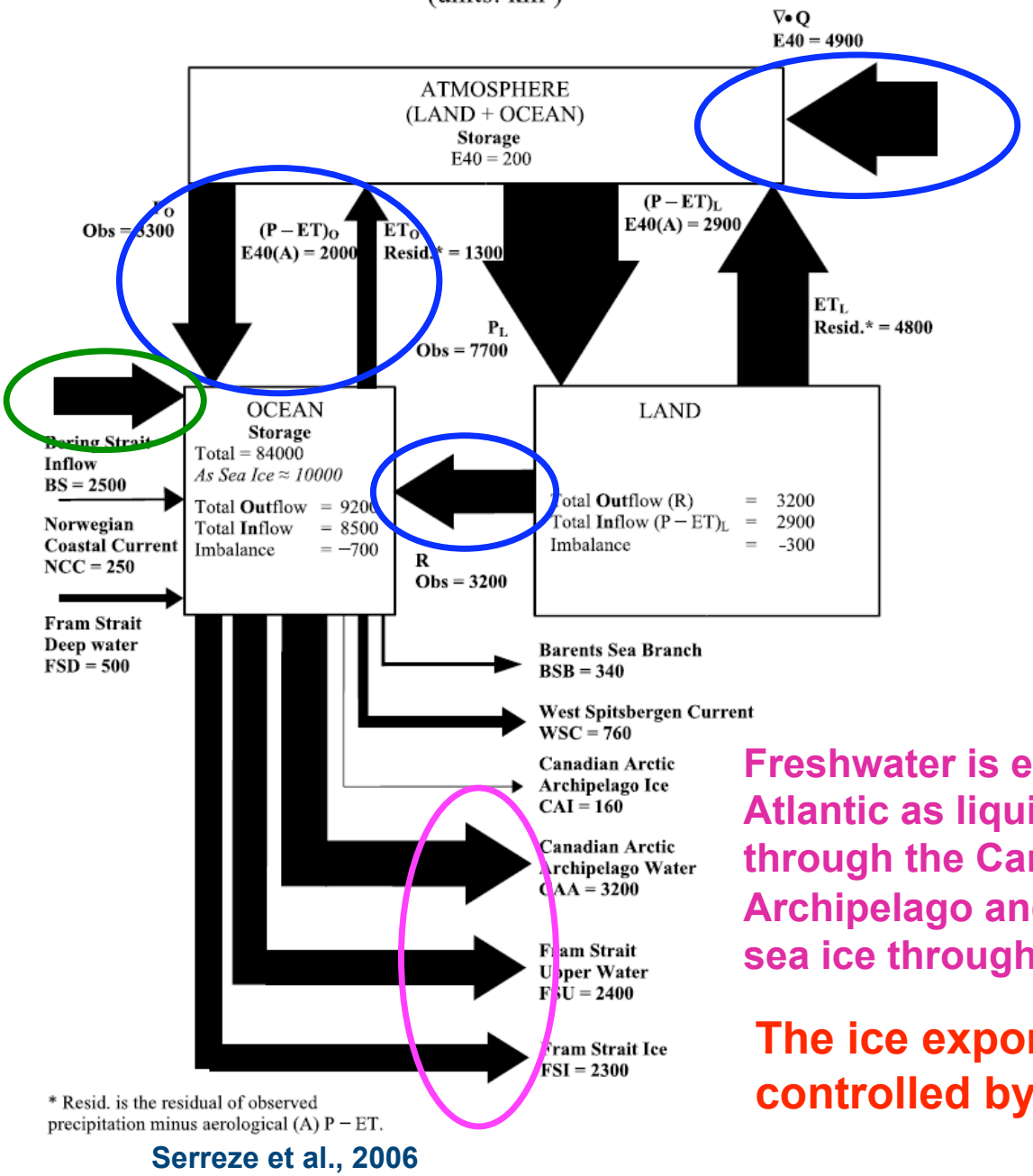
Arctic Basin Freshwater Budget



Serreze et al., 2006

Freshwater is transported by the atmosphere – river runoff & net precipitation

Freshwater is supplied by the ocean through Bering Strait

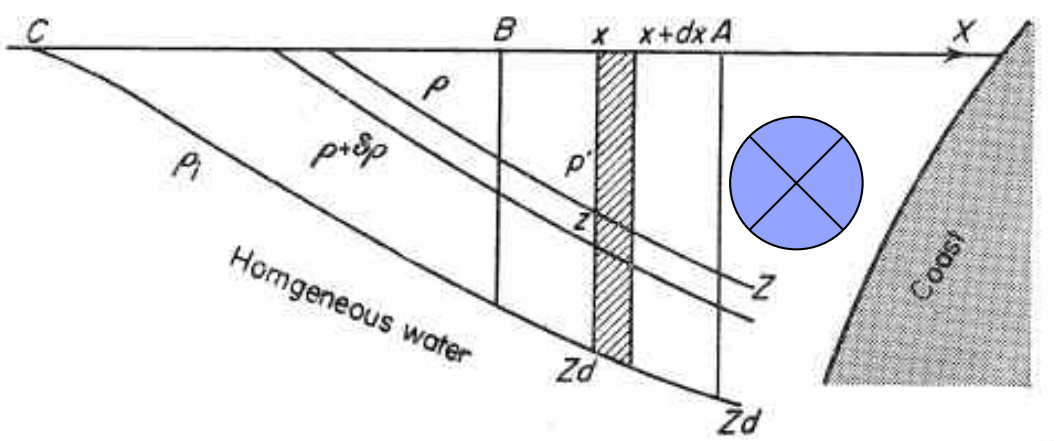
Freshwater is exported to the North Atlantic as liquid freshwater through the Canadian Arctic Archipelago and Fram Strait and as sea ice through Fram Strait

The ice export is mainly controlled by the wind fields!

The liquid freshwater export

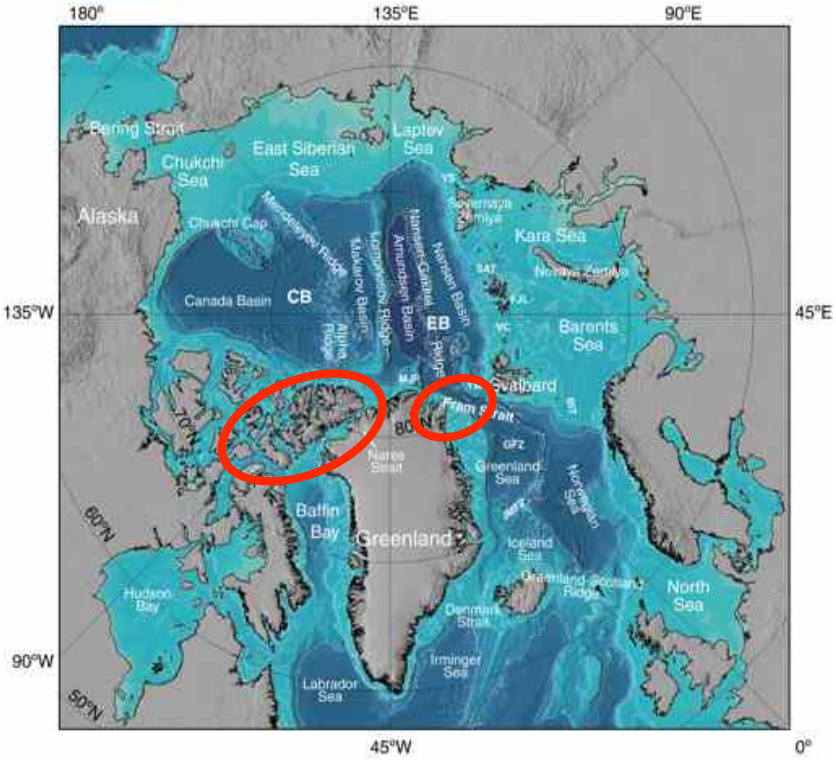
In cold waters the density is mainly controlled by the salinity.

For a geostrophically balanced flow ir the upper layer, the **transport of freshwater only depends upon the number of openings, the thickness of the freshwater storage and the salinity of the lower layer.**



Defant, 1961

The width of the current is independent of the total transport.



Only three openings are wide enough to have a geostrophic flow; Fram Strait and two channels in the Canadian Arctic Archipelago.

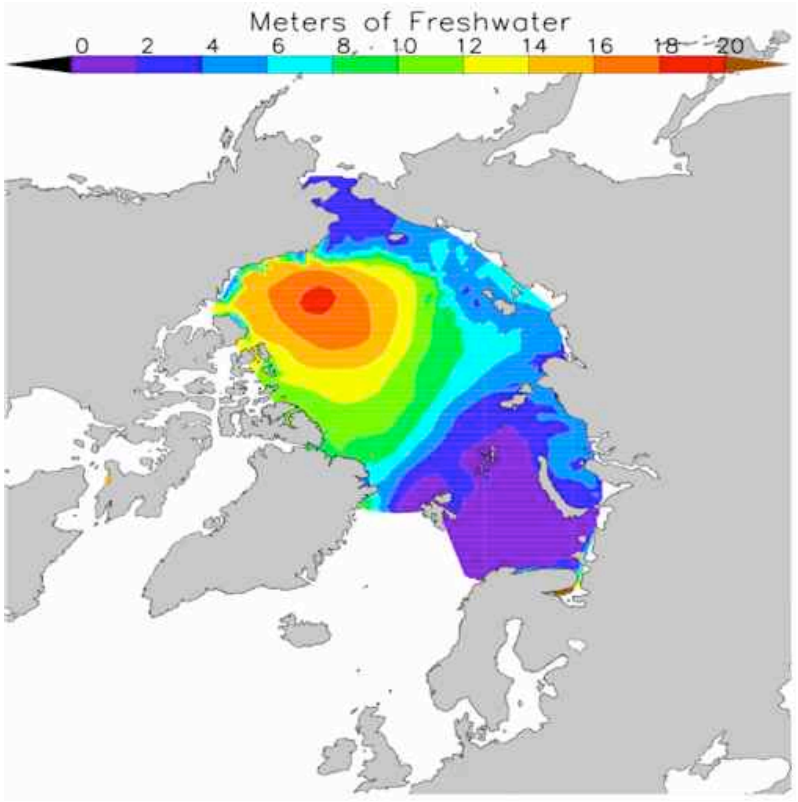
The liquid freshwater export, F, can then be used to determine the mean freshwater storage, m, in the Arctic Ocean

With three openings the present average freshwater storage is: m ~ 8.25 m

If there were only seasonal sea ice and no ice export, the net freshwater input would increase by 0.08-0.09 Sv

The freshwater content then rises to: 10.1 m

The freshwater storage in the Arctic Ocean increases as $(F)^{1/2}$ while the residence time of freshwater decreases as $(F)^{-1/2}$.



Serreze et al., 2007

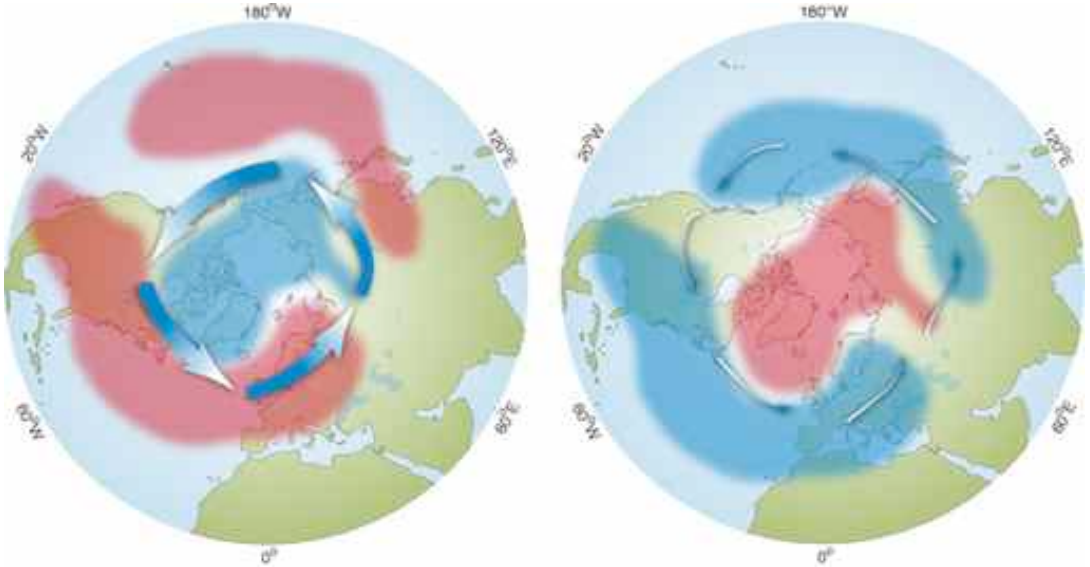
These results are independent of mixing mechanisms and entrainment.

The mixed layer thickness is not uniform throughout the deep Arctic Ocean!

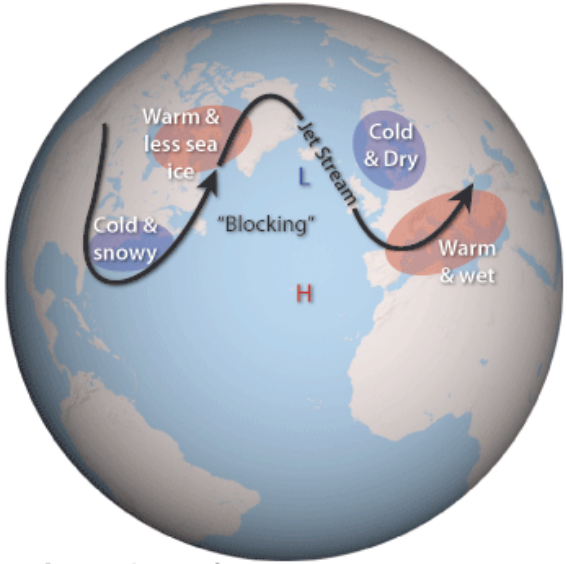
Atmospheric circulation patterns such as the Arctic Oscillation and

AO positive

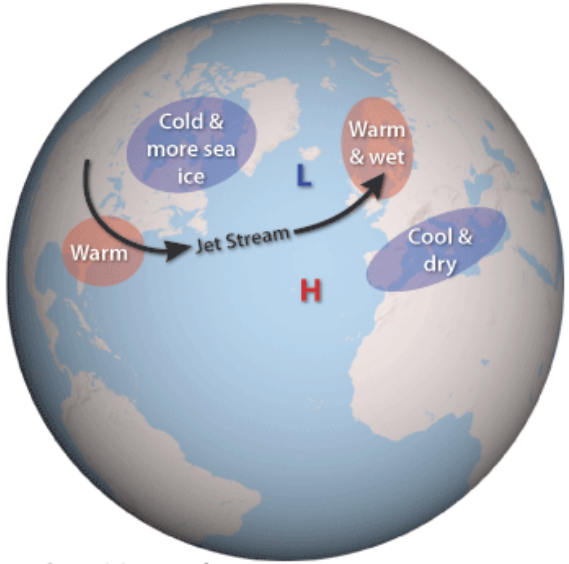
AO negative



Goodman



NAO Negative Mode



NAO Positive Mode

the North Atlantic Oscillation will affect the distribution and the exports of freshwater in the Arctic Ocean

Outline

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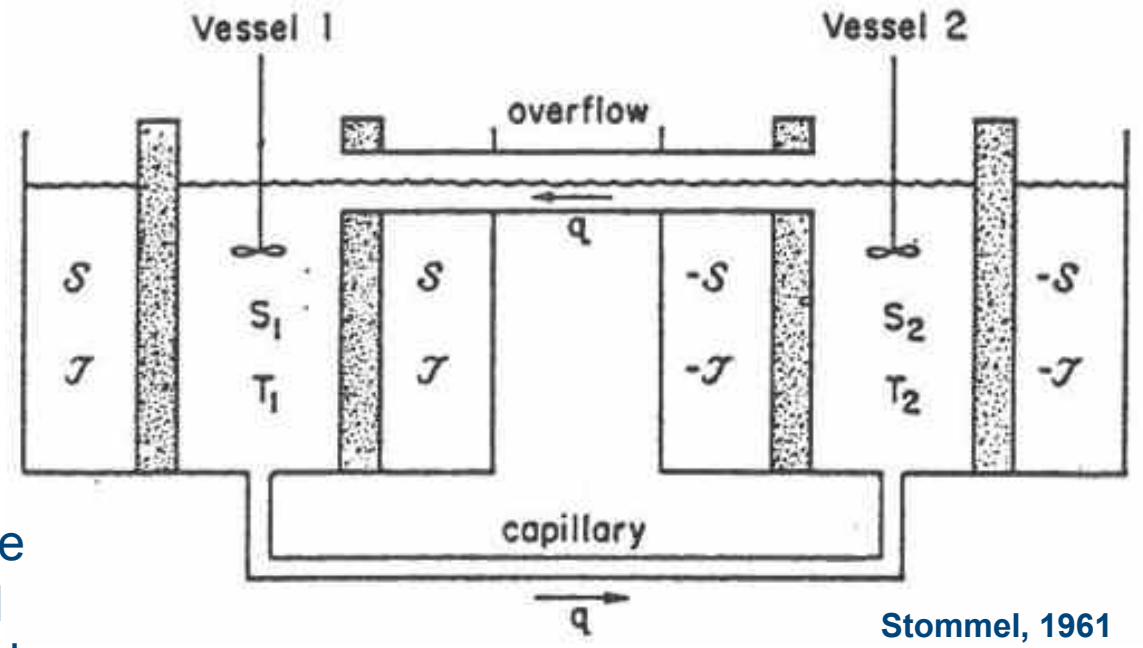
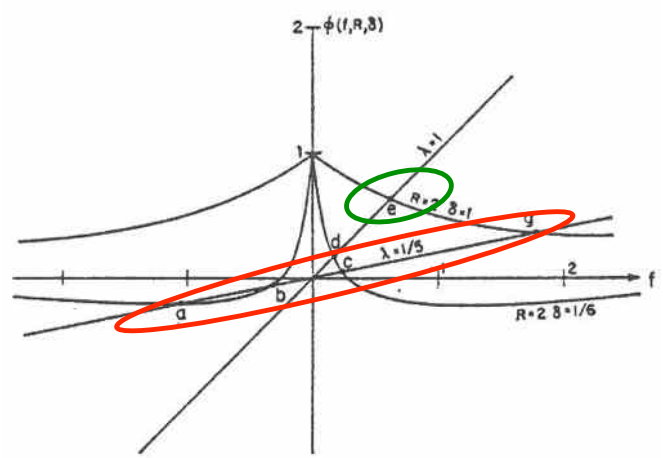
Stommel two-box model

driven by heating and cooling and evaporation and precipitation.

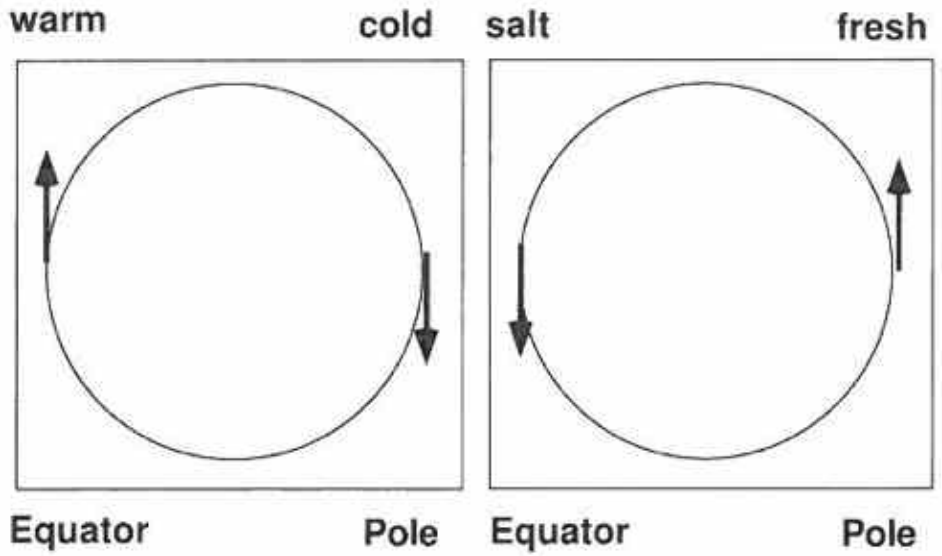


Stommel, 1961

The different time constants for the restoring forces of **heat (fast)** and **salt (slow)** create instabilities and different circulation pattern.



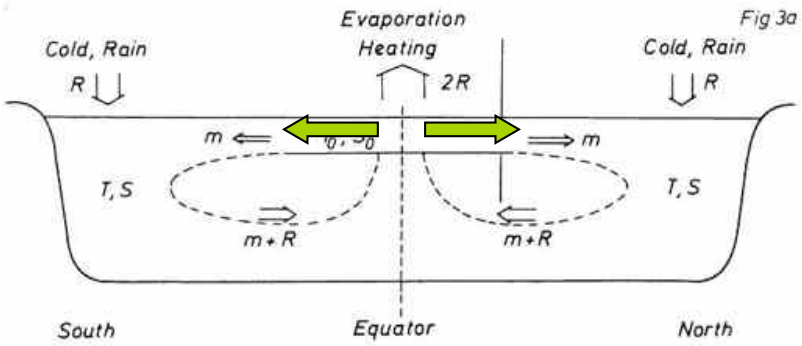
Thermally driven **Freshwater driven**



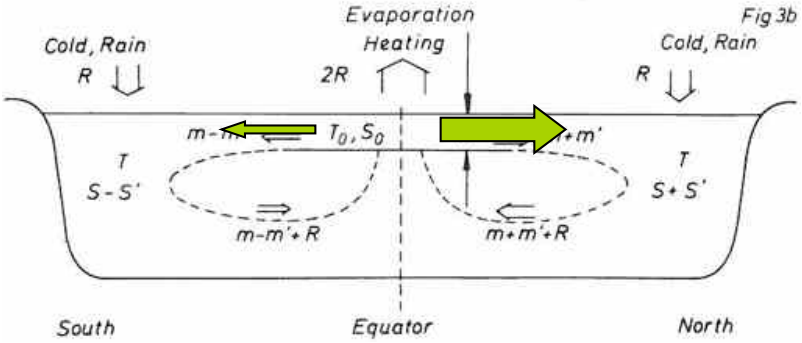
○ One cold solution ○ Three (1-2 warm) solutions

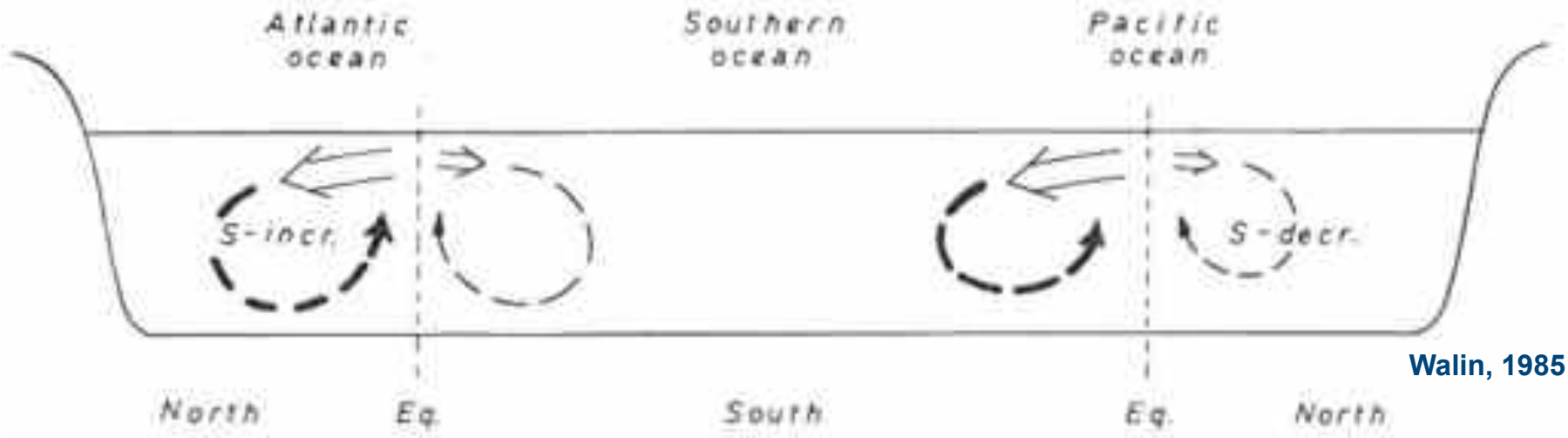
Djikstra, 2005

The slow removal of salinity perturbations can allow disturbances to grow, and



a symmetric circulation around the equator might be transformed into a world wide overturning circulation.

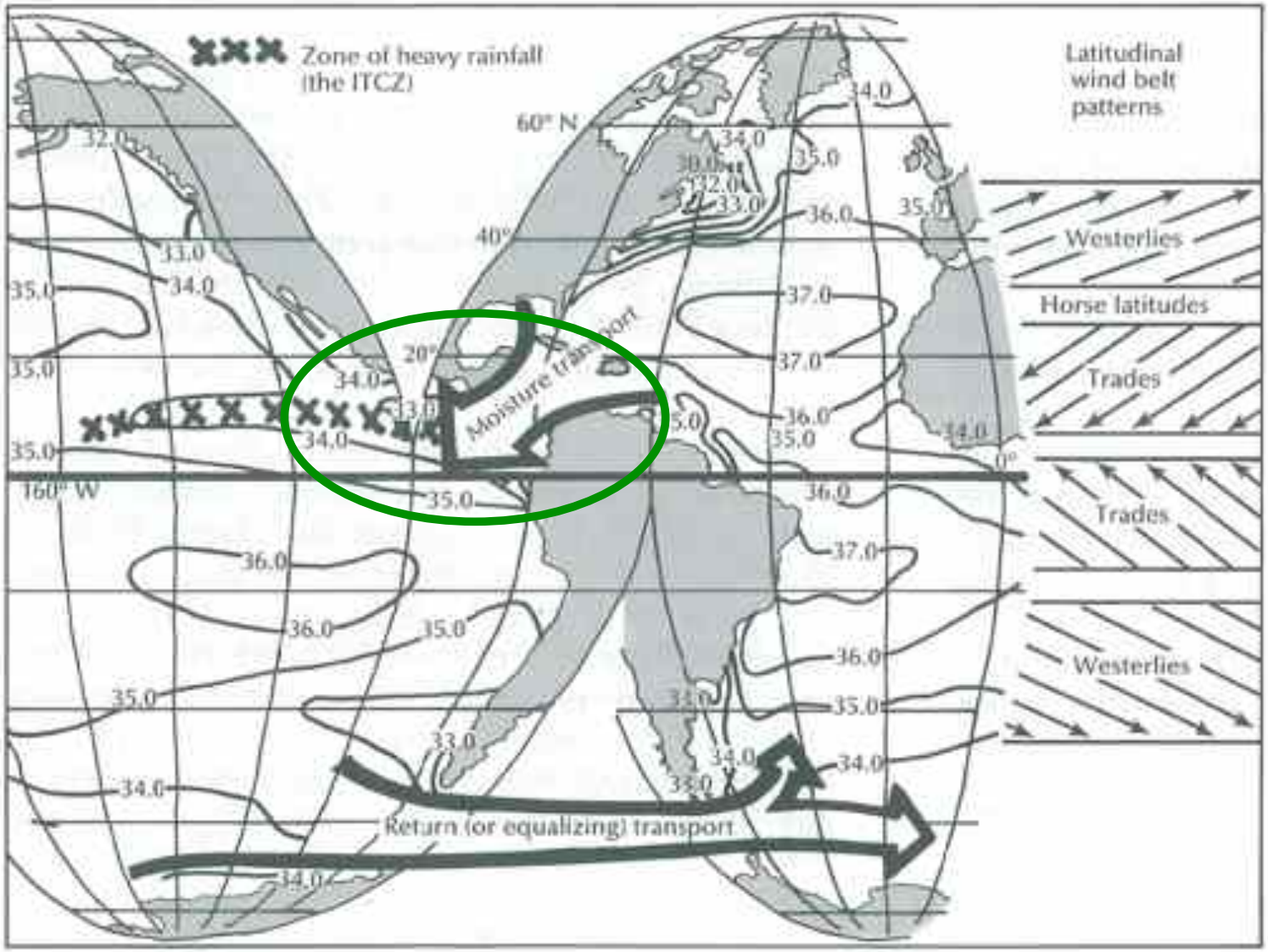




Walin, 1985

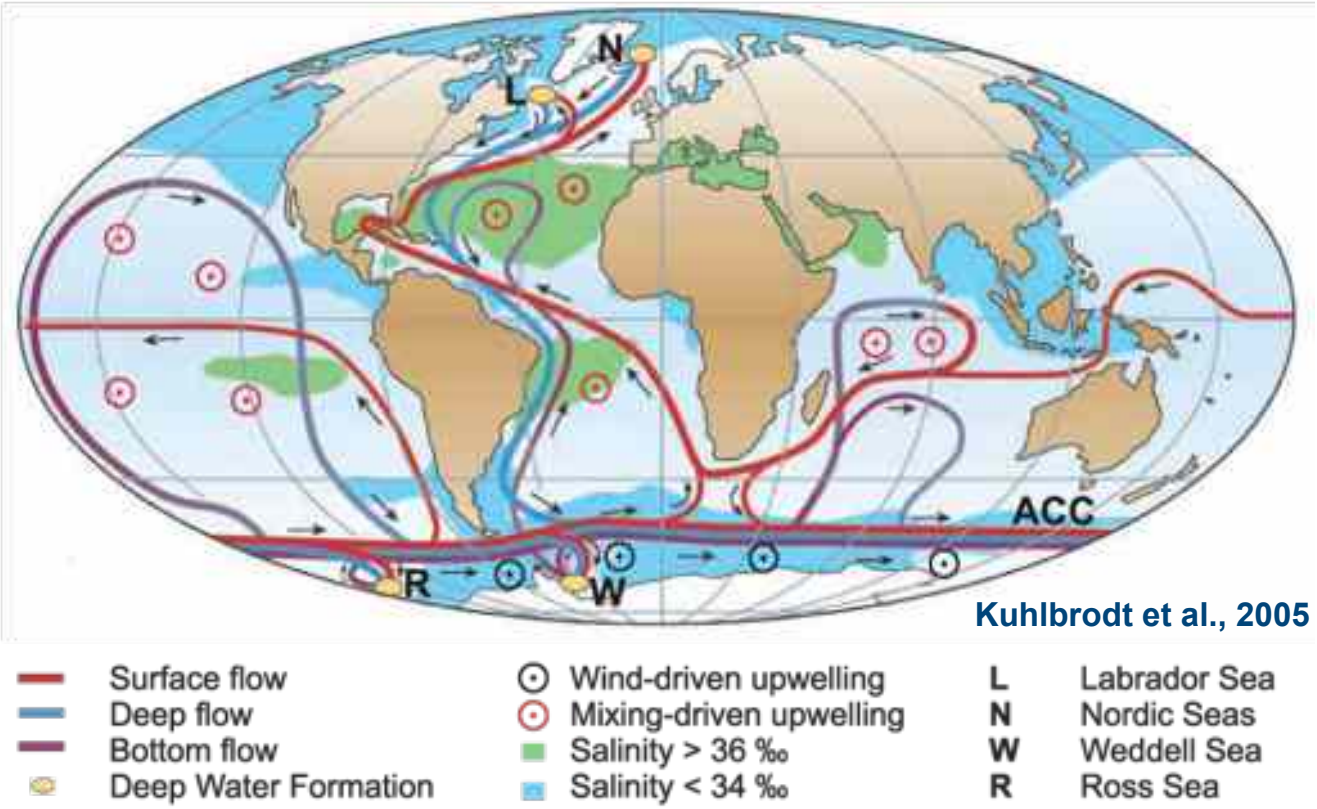
Deep mixing, bringing the water back to the surface layer must also be present.

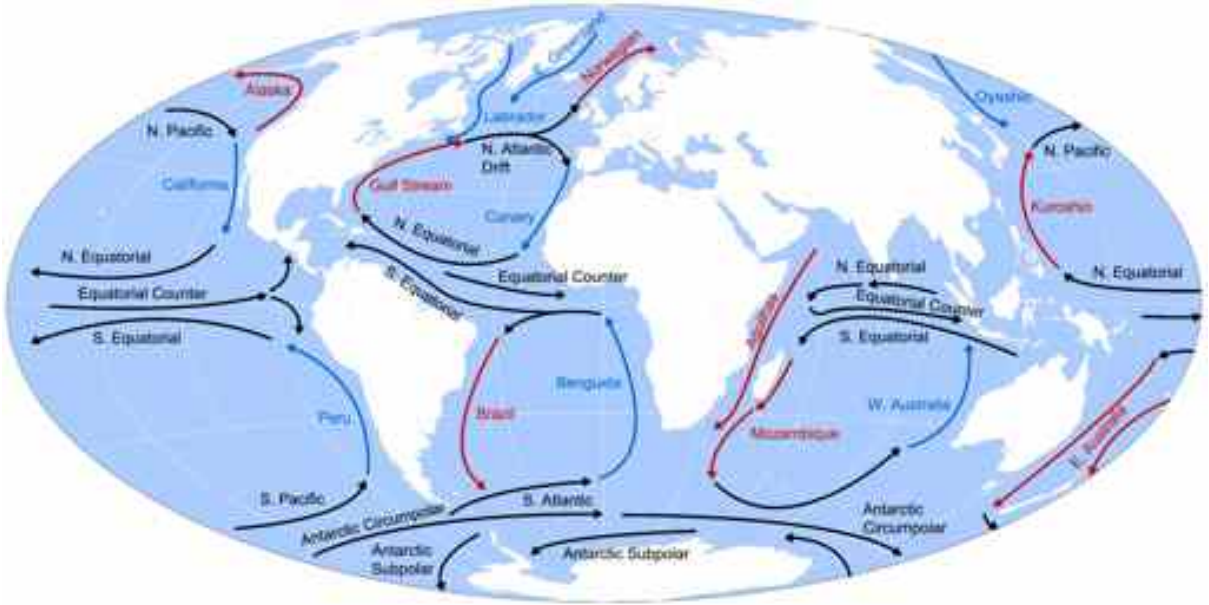
The transport of water vapour across the Isthmus of Panama **makes the North Pacific surface water less dense relative to the North Atlantic.**
Its sea level is higher, allowing for a return flow of low salinity water through Bering Strait.



Neshyba, 1986

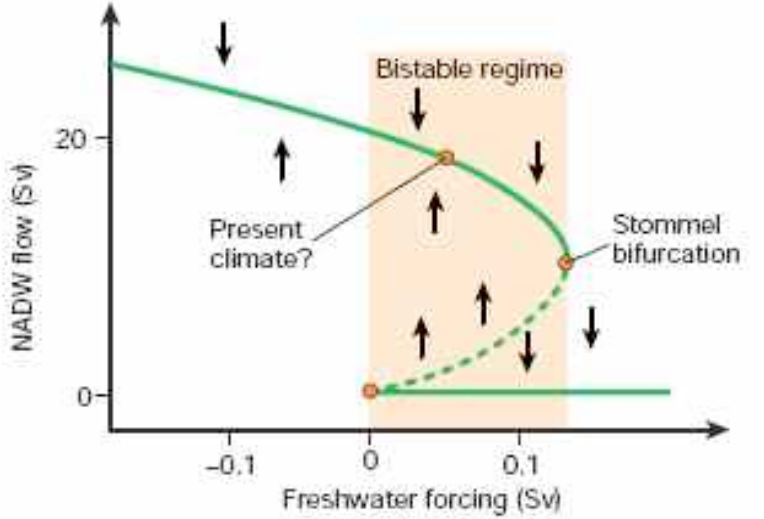
The higher salinity in the North Atlantic forces the global overturning circulation and brings heat to the northern North Atlantic.





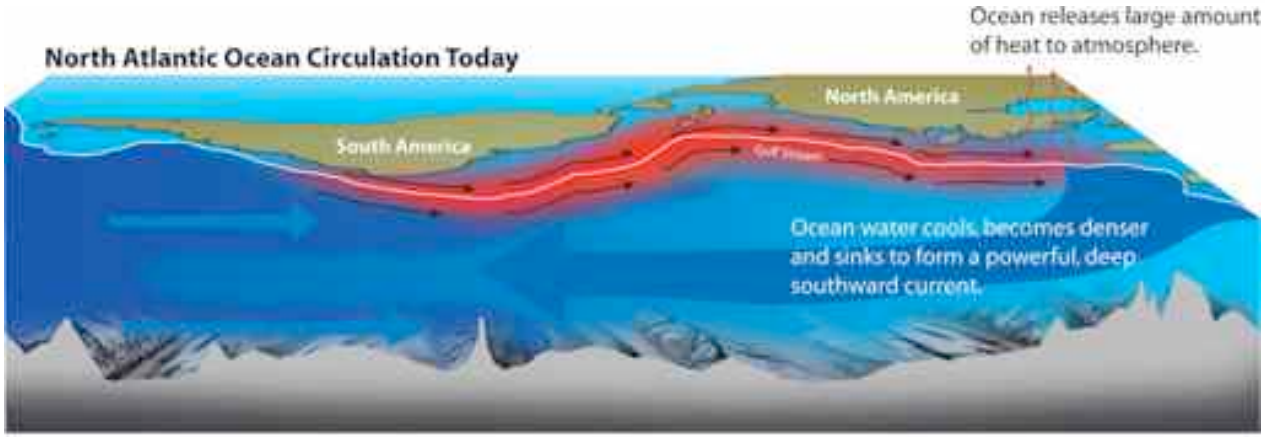
The wind driven circulation accounts for much of the meridional oceanic heat transport and perhaps close to 40 % even in the North Atlantic.

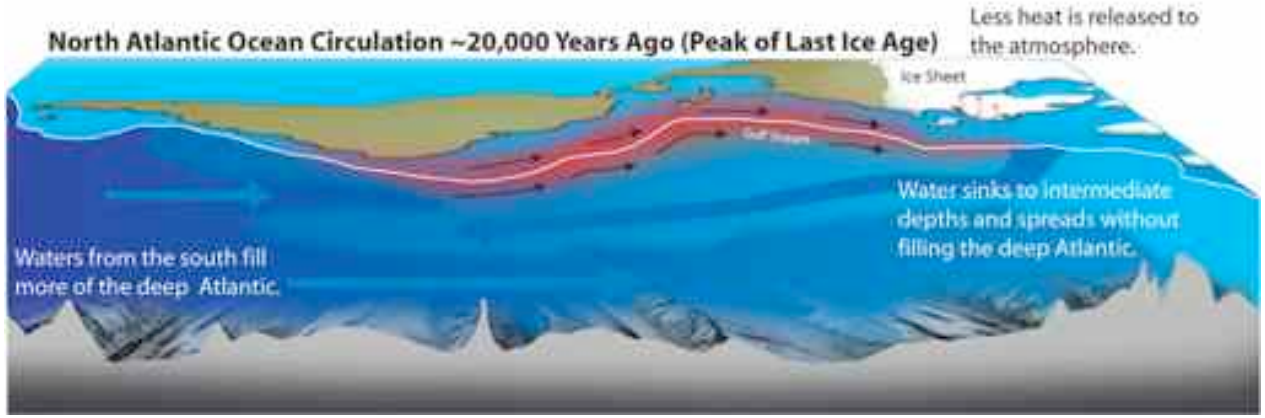
The Stommel type of models and the effects of freshwater input are more often discussed in the context of a breakdown of the thermohaline circulation due to increased freshwater input.



Rahmstorf, 2006

How valid are such simple models?





Weakening and breakdowns have occurred in the past and the question is:

Can they happen again?

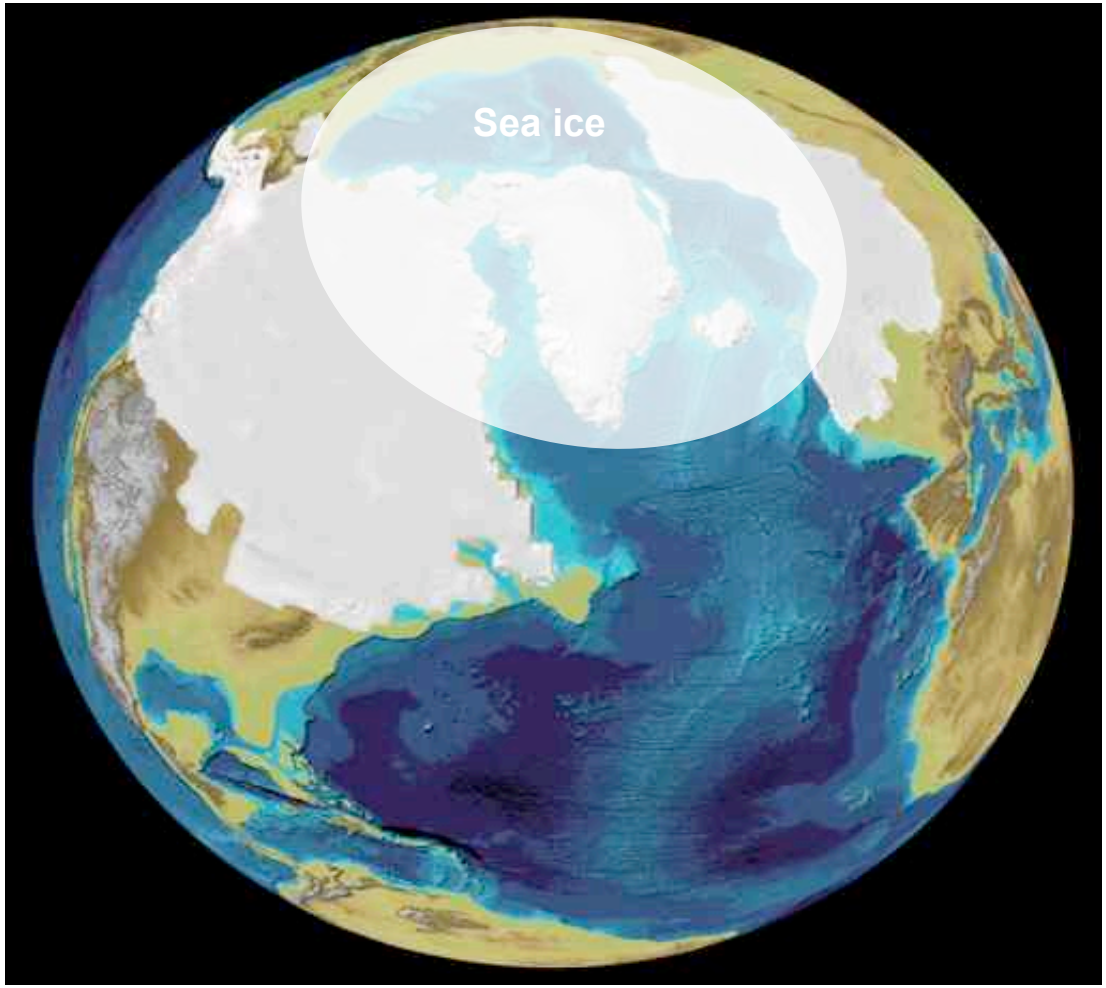


Figure by Martin Jakobsson

During the last glacial maximum there was more ice on land, a higher albedo and the temperatures at high latitudes were lower, implying less outgoing long wave radiation.

The energy balance could be maintained by export of ice to lower latitudes, where it would melt.

Ice discharge from the glaciers could, and did, flood the North Atlantic.

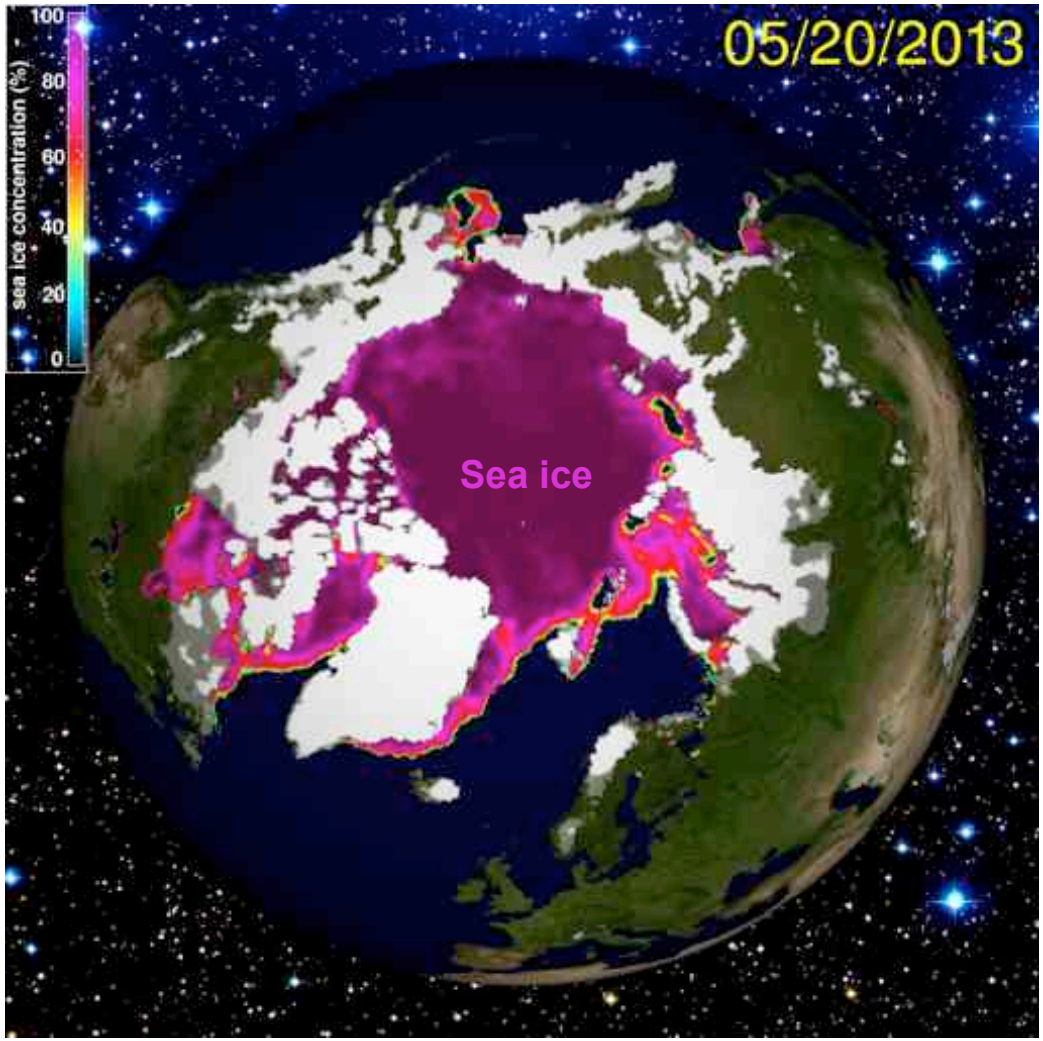
The Arctic Ocean would, by the high albedo and the ice export, strongly influence the global climate.

Today the atmosphere provides most of the meridional heat transport, partly through the condensation of water vapour.

Eventually no ice export may be needed for the heat balance, signaling the advent of a seasonal ice cover.

The transport of oceanic sensible heat might become smaller due to weaker thermal forcing rather than through an increased freshwater input.

The effects of a melting of the Greenland ice sheet are, however, largely unknown.



The cryosphere today

The climate in the Arctic today appears controlled by processes occurring at lower latitudes, especially the meridional transport of water vapour that affects both the heat balance and the radiation balance.

The ocean – open questions:

How much, and by what processes, does the Atlantic water lose heat in the Nansen Basin beyond the melt area north of Fram Strait?

How much does this reduce the sea ice production in the Nansen Basin?

Why does the fraction of oceanic heat loss to ice giving minimum ice melt appear to realistically predict the salinity in the melt water layer?

How well can the mean freshwater export and freshwater storage be estimated by the assumption of geostrophic flow through the passages?

What drives the Atlantic water inflow, the large-scale wind fields (e.g wind stress curl), or the mixing and water transformations in the Arctic Ocean?

Does an increased inflow of warm Atlantic water lead to a larger heat flux to ice and atmosphere, or is the heat flux determined by the strength of the mixing processes?

What were the impacts of the closing and opening of Bering Strait on the evolution of the glacial periods?

Thank You for Your Attention

Acknowledgement: I want to thank Martin Jakobsson for providing information and figures of the Arctic Ocean during the last glacial maximum.

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