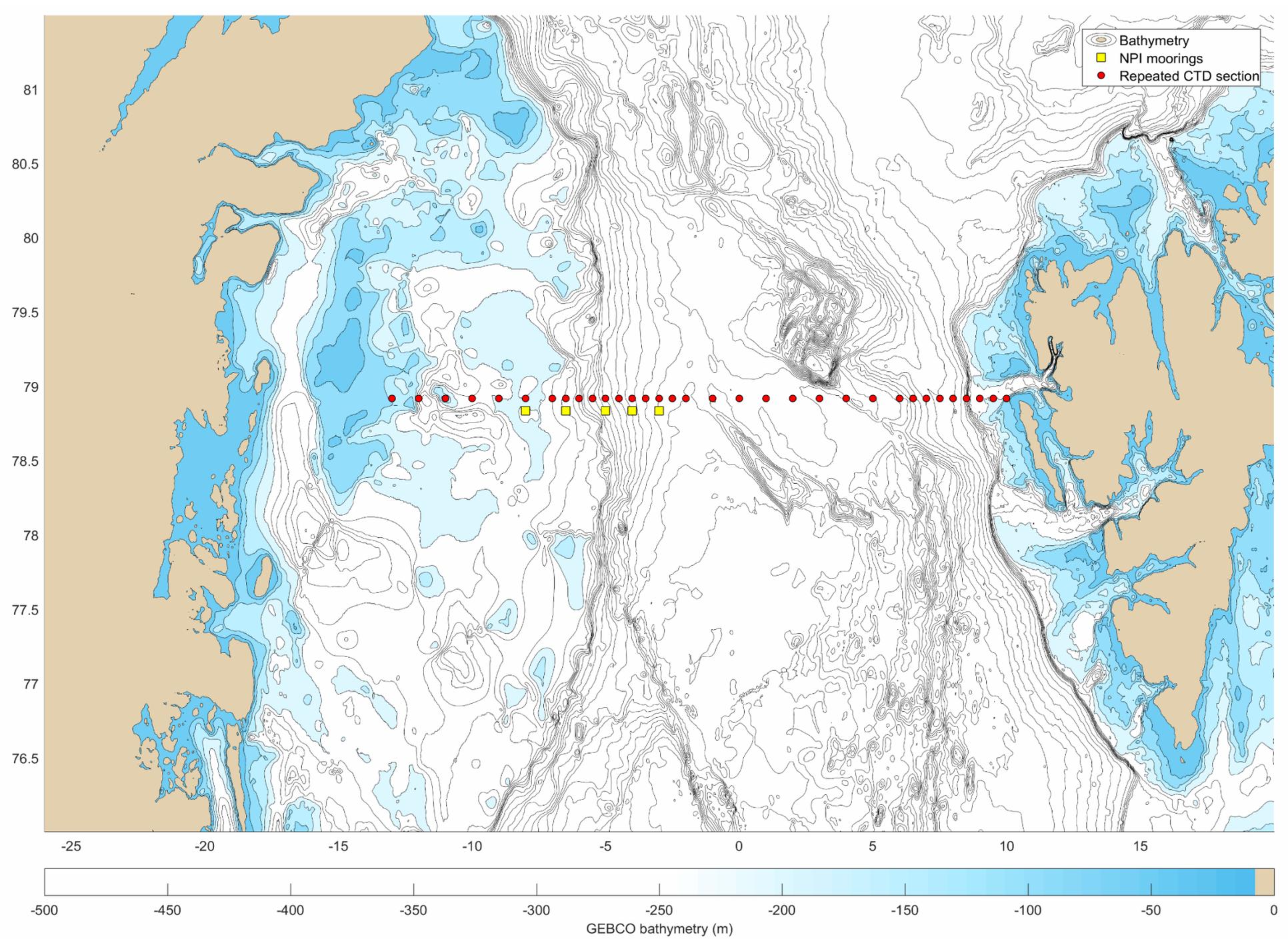


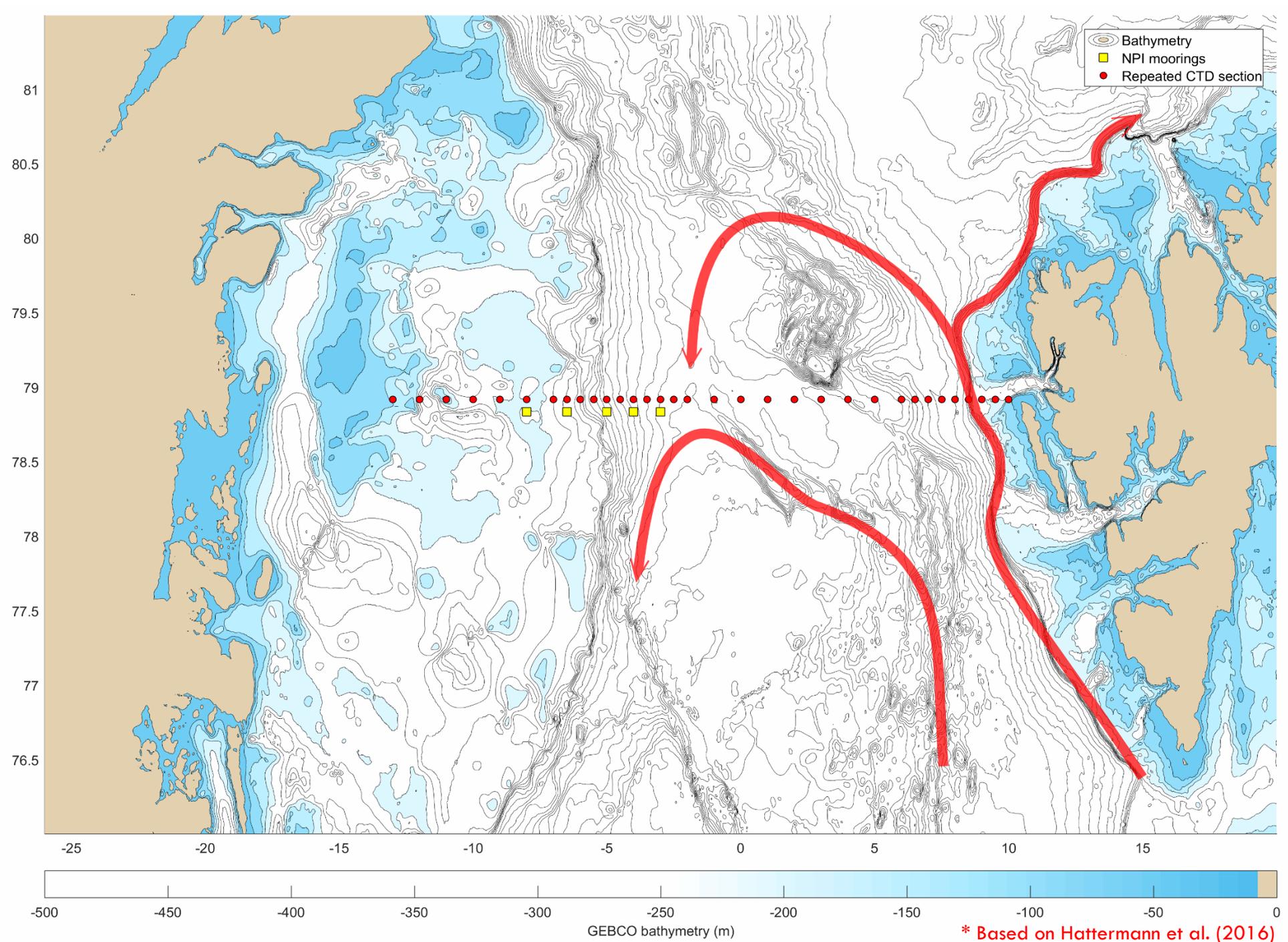


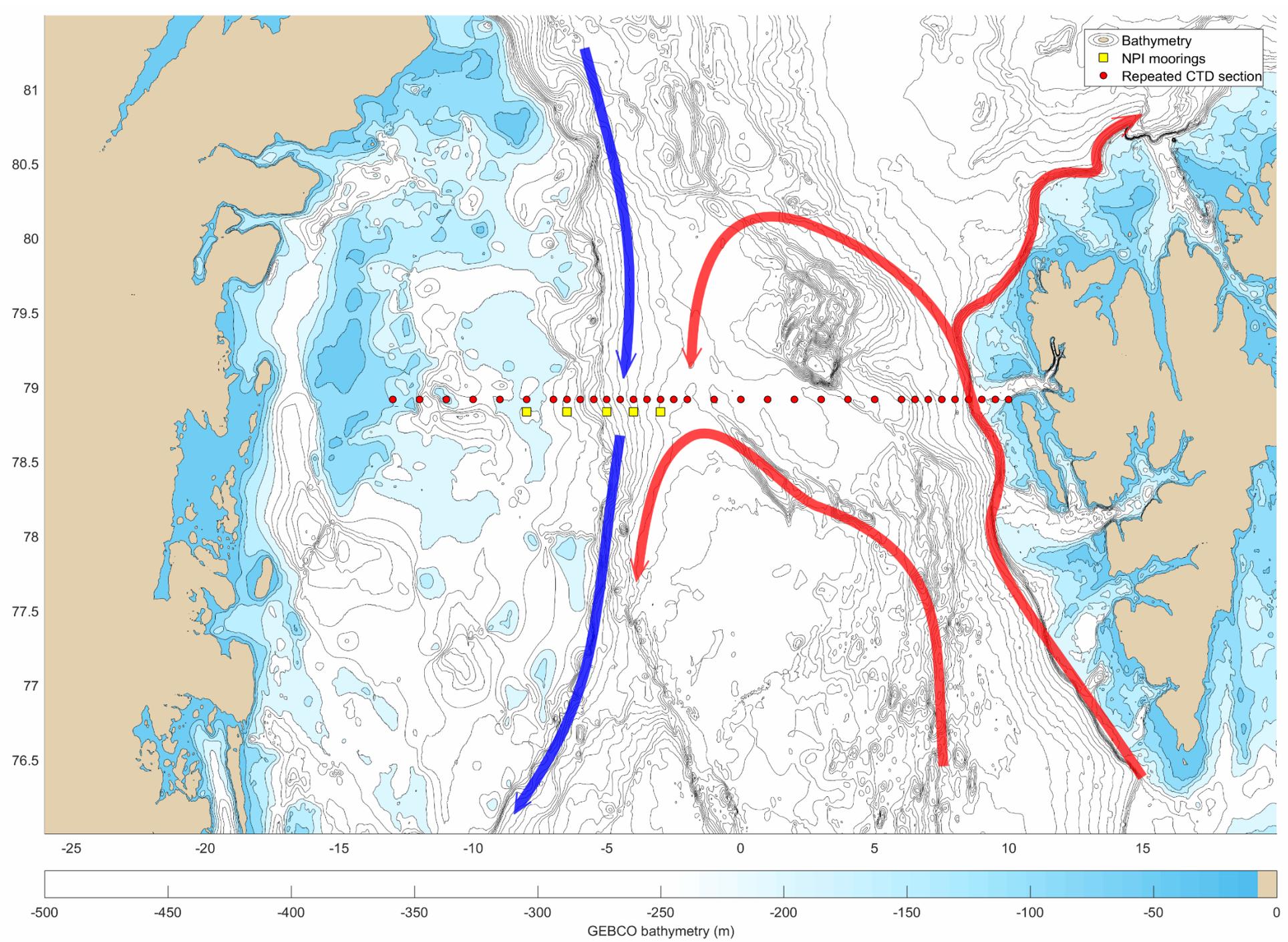
# Surface Freshening & Pacific Water in Fram Strait

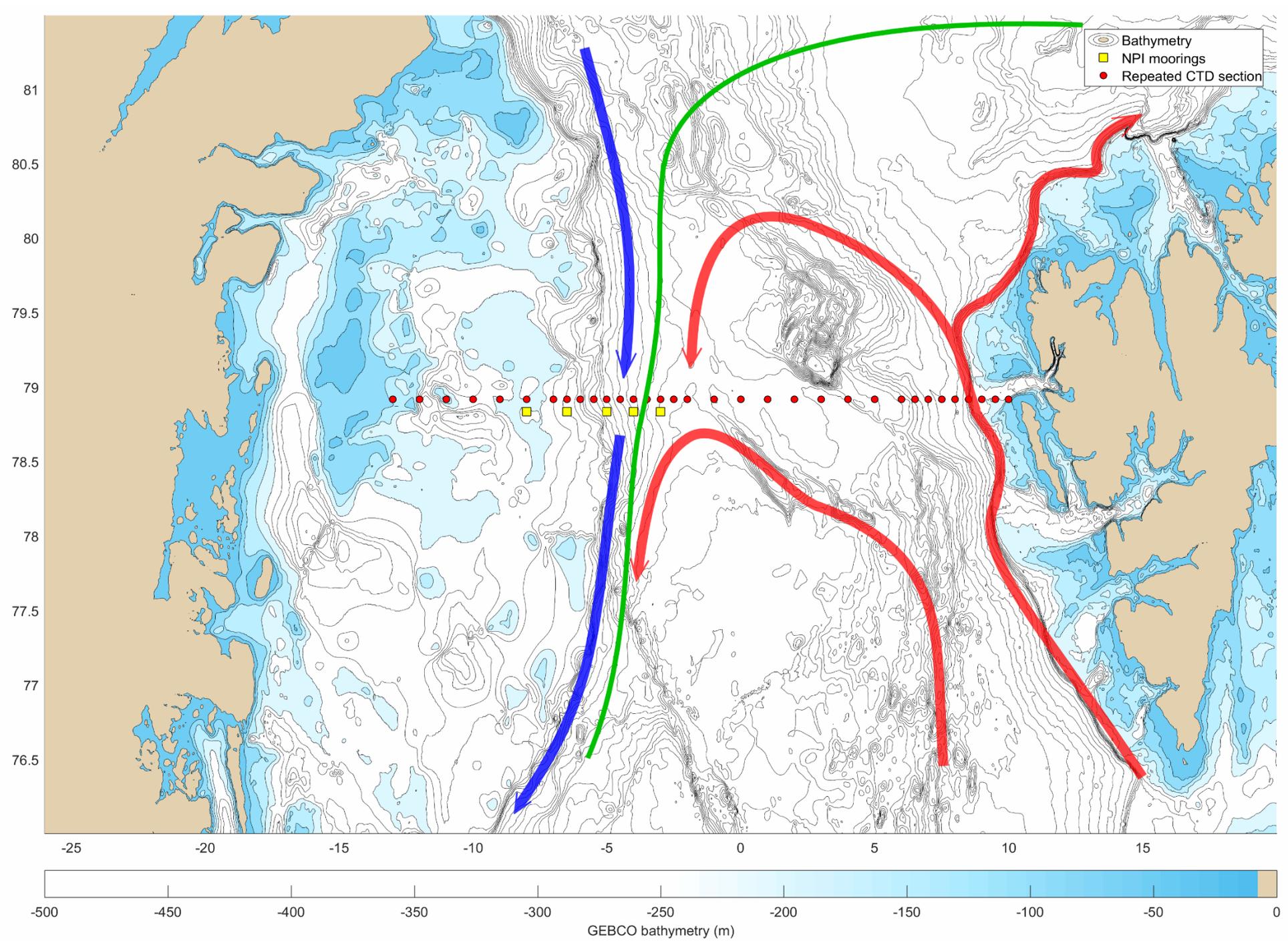
14th ASOF-ISSG Meeting and Workshop  
20<sup>th</sup> -22<sup>nd</sup> March 2017



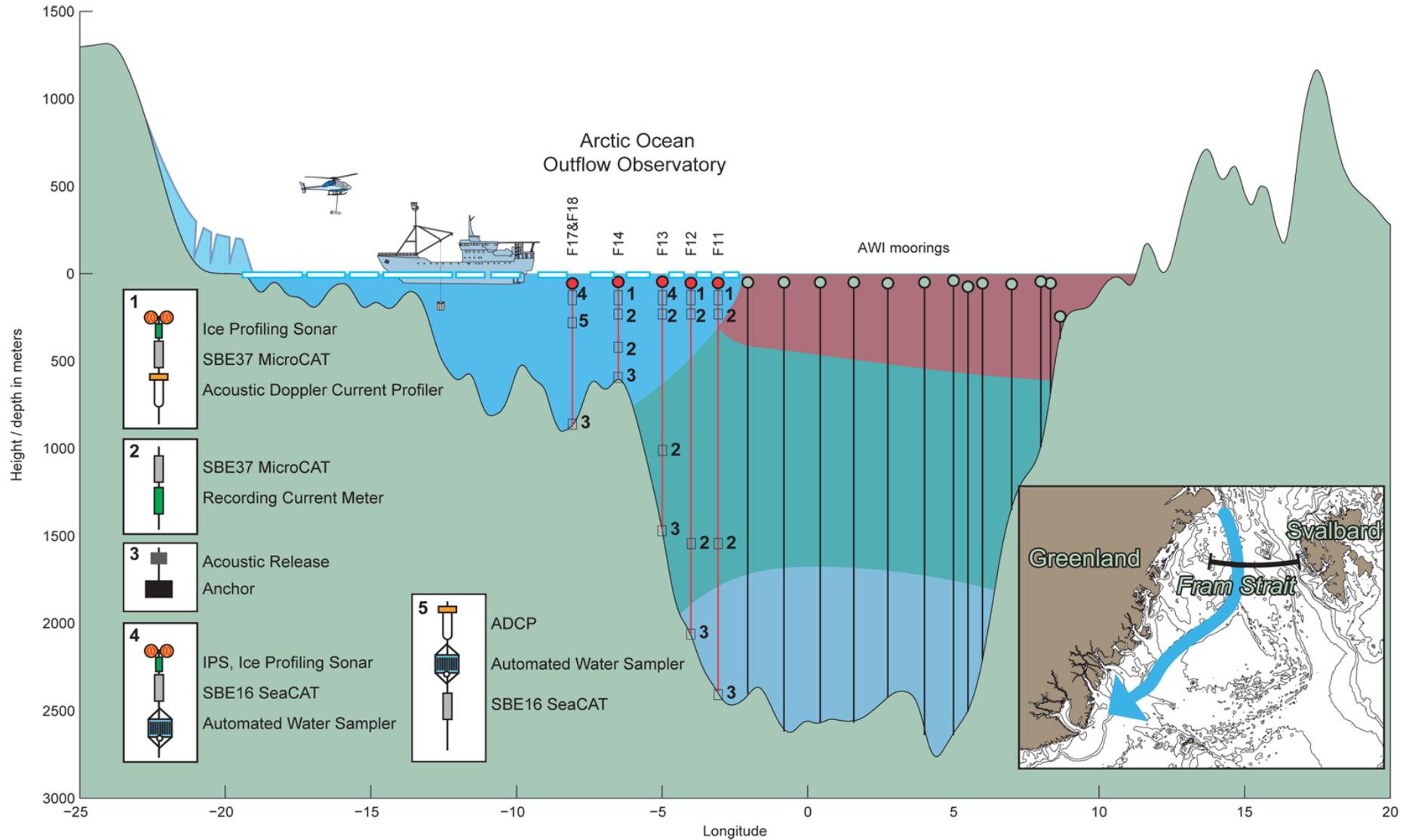






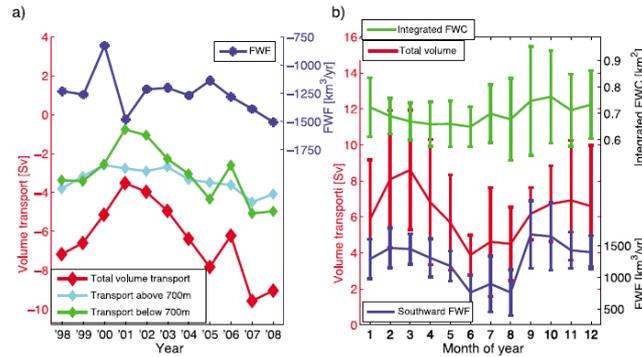


# The Fram Strait Observatory

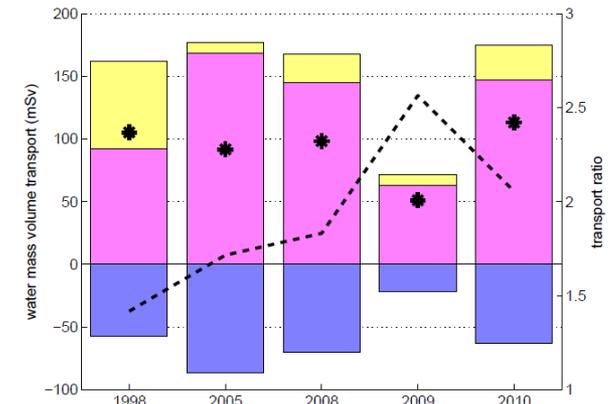


2017 is the 20<sup>th</sup> anniversary of the array & annually repeated CTD section

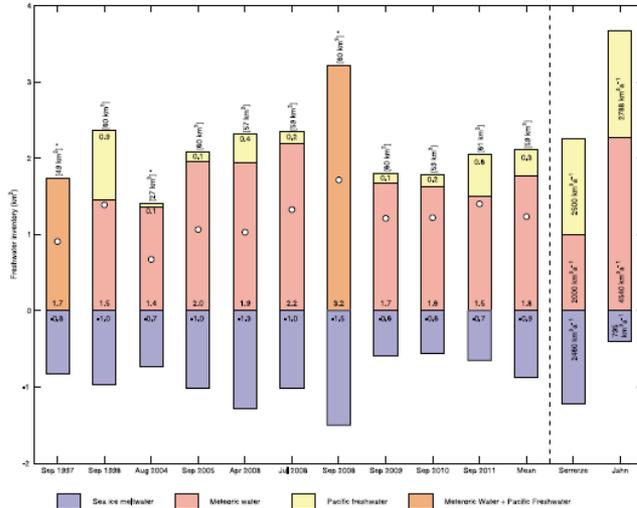
# Freshwater variability as large as longer trends?



**Figure 2.** (a) Annual mean volume transports in the EGC: total transport, transport above 700 dbar, transport below 700 dbar, and the FWF. (b) Mean seasonal cycles of total volume transport, FWF, and the integrated FWC with  $\pm 1$  standard deviation.



**Fig. 4.** Meridional volume transports of LFW and components in the Fram Strait between  $10.6^{\circ}\text{W}$  and  $4^{\circ}\text{E}$  for the years shown. The bars show the portion of every component: FPW (top, yellow), MW (magenta, middle) and FSIM (blue, bottom). The asterisks represent the LFW transport and the line the ratio of MW to FIFB transports.



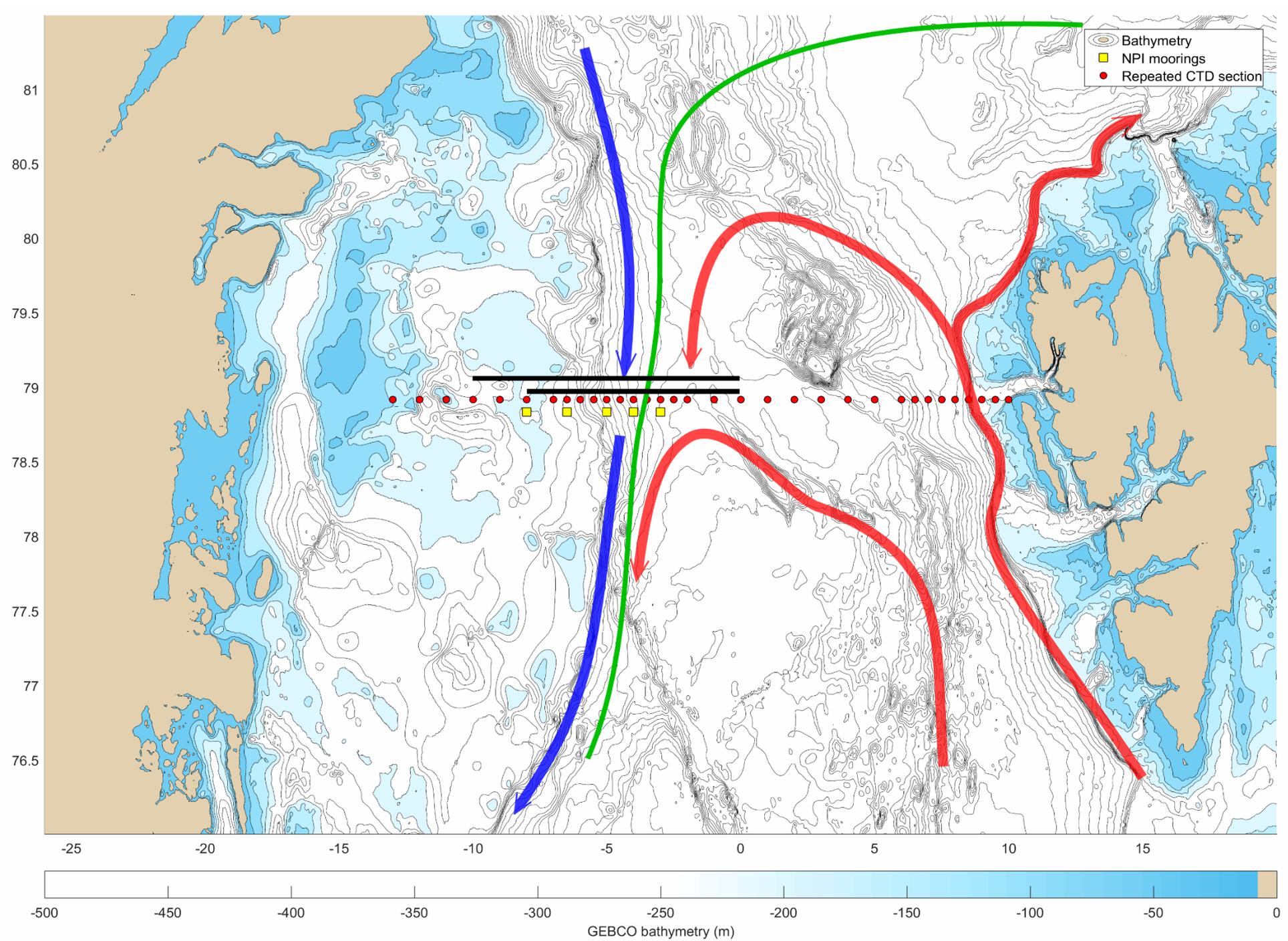
**Figure 13.** Inventories of net sea ice meltwater, meteoric water and Pacific freshwater at Fram Strait above 300 dbar between  $10^{\circ}\text{W}$  and the Greenwich meridian. Where the Pacific freshwater and meteoric water could not be separated due to a lack of nutrient measurements the combined inventory is plotted in orange. The total water area of each section is shown in brackets above each bar. Numbers within each bar segment indicate the inventory of that freshwater component in  $\text{km}^3$ . Bars marked with an asterisk were excluded when calculating the mean bar. The position of the white dots indicates the net freshwater inventory in  $\text{km}^3$ . Bars on the right show the volume transport of each freshwater fraction through Fram Strait listed in the studies of Serreze et al. [2006] and Jahn et al. [2010].

Three studies have looked at **changes** in the freshwater content/transport in the EGC.

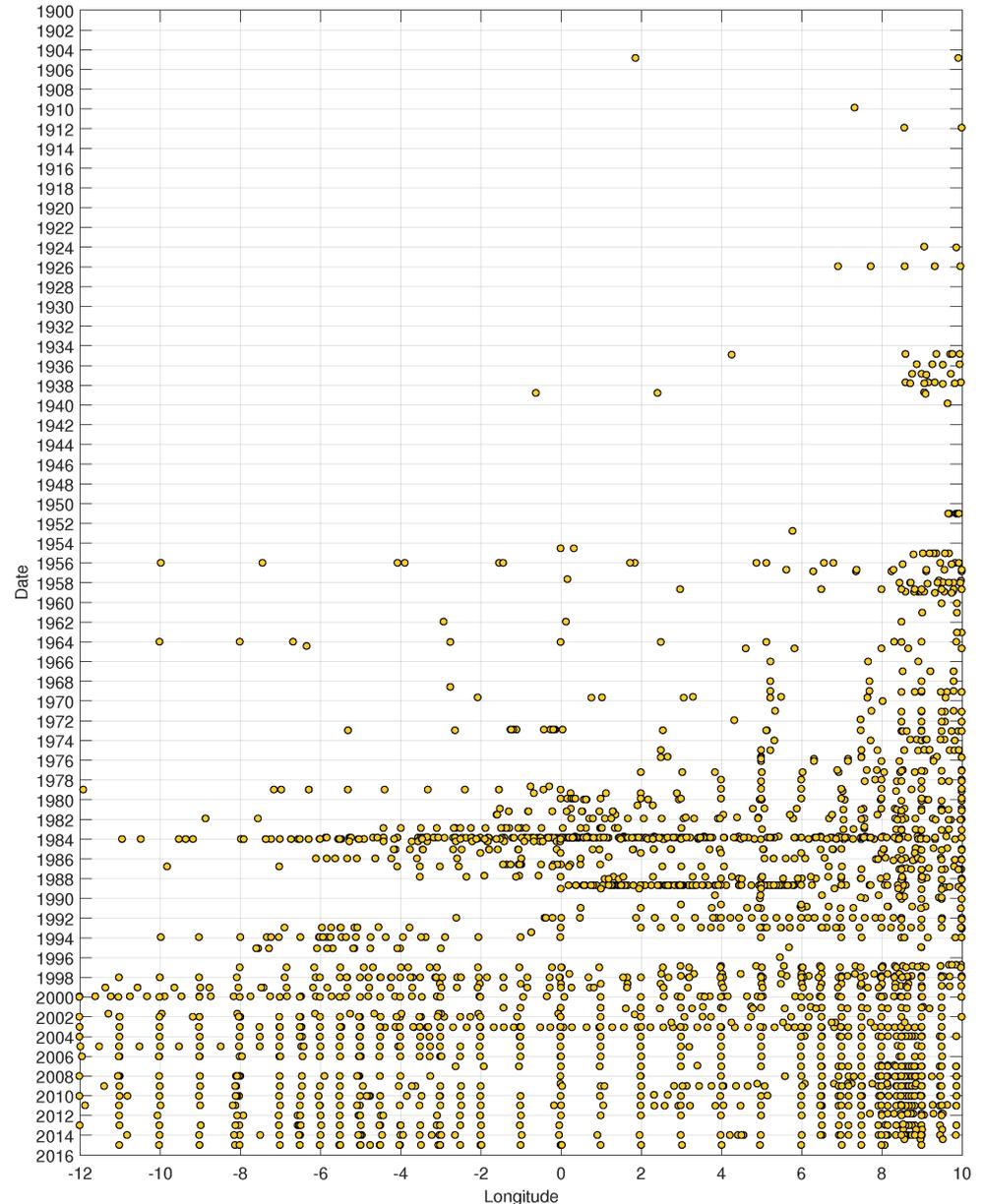
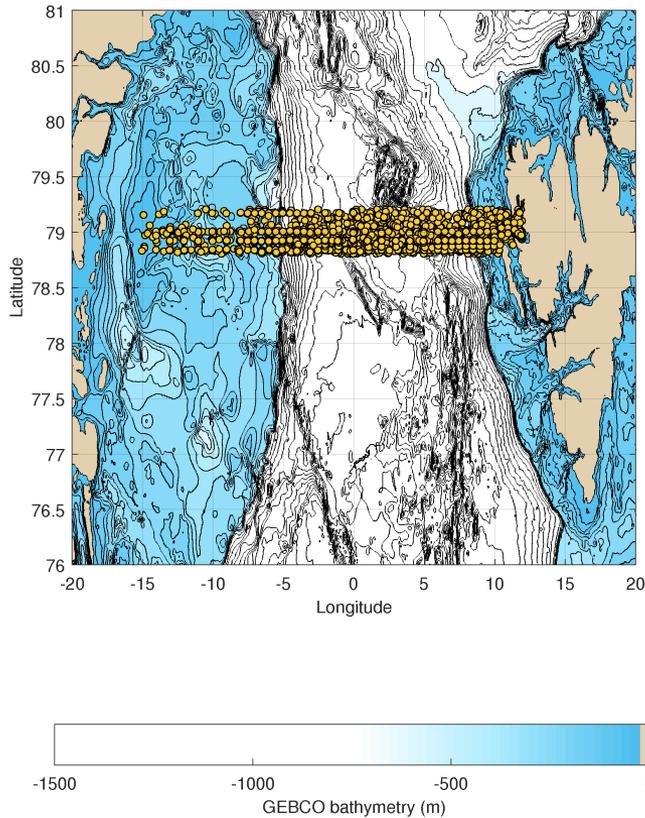
All three observe large inter-annual variability

All three studies have had quite broad zonal coverage ( $0-8^{\circ}\text{W}$  or  $0-10^{\circ}\text{W}$ ).

All three looked at different depth ranges, or used tracer to separate water masses.

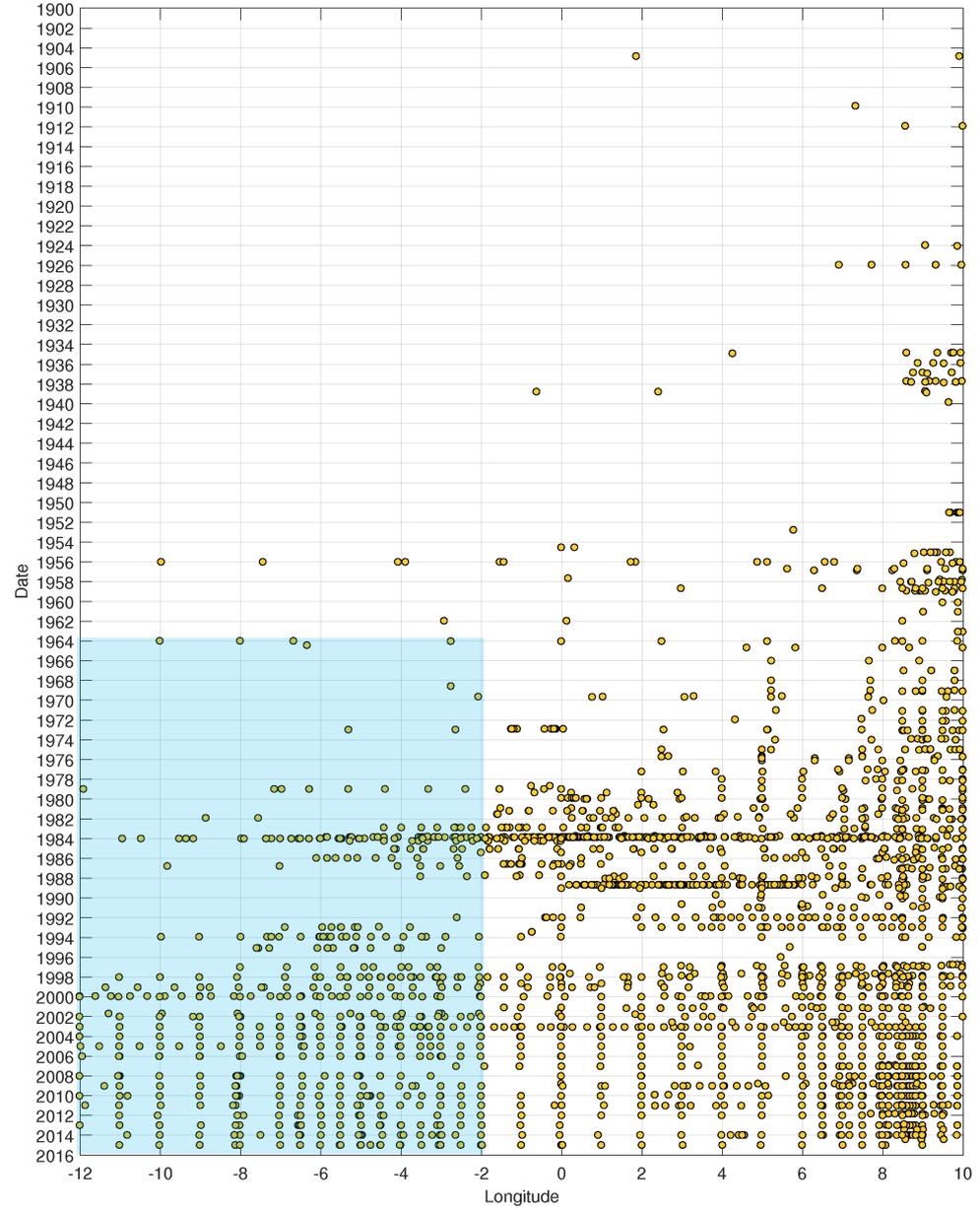
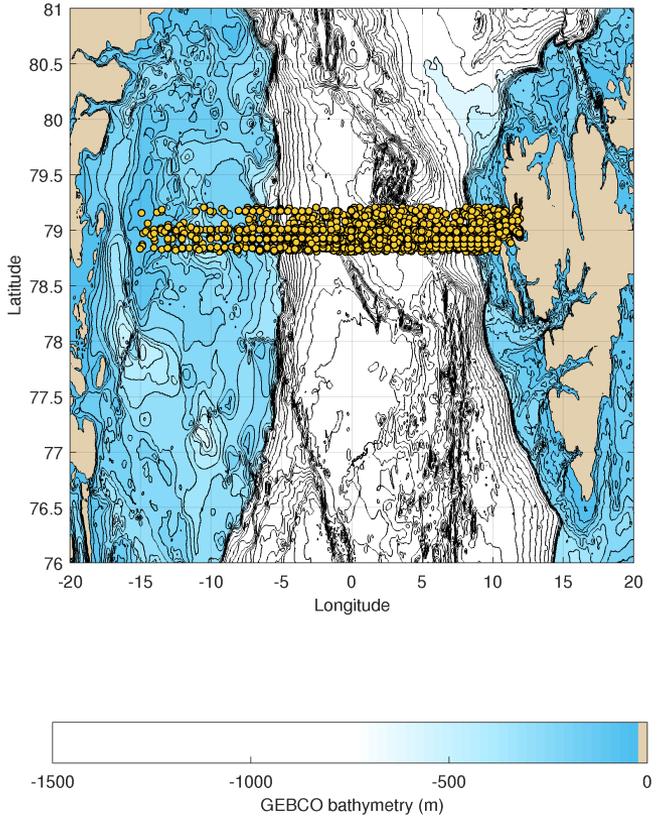


# CTD Profiles from Fram Strait



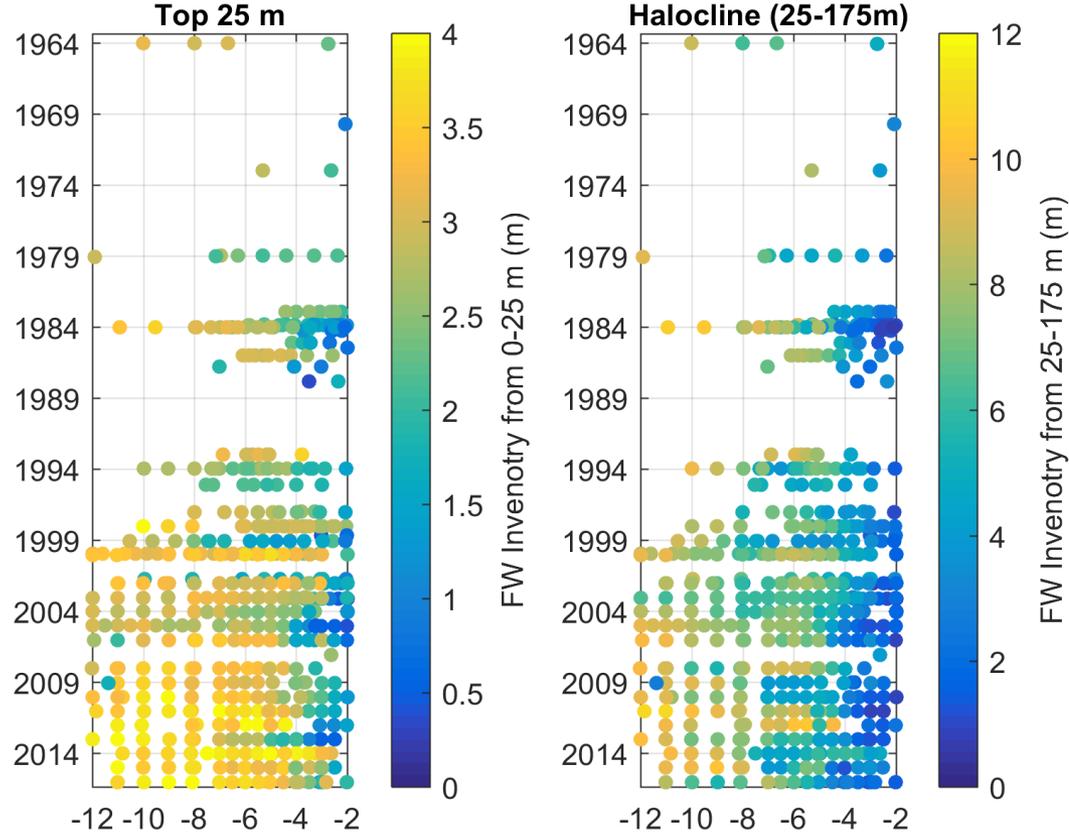
- First section across western Fram Strait was in 1956. Occasional sections 1956-1992. Annual sampling after 1997
- Longer record in Eastern Fram Strait
- Existing studies have looked at the 1997-2011 period

# CTD Profiles from Fram Strait



- We're going to focus on the period 1964-present when we have fairly frequently repeated sections
- We're going to look at the region from 2-12° W, which avoids some variability associated with the frontal zone

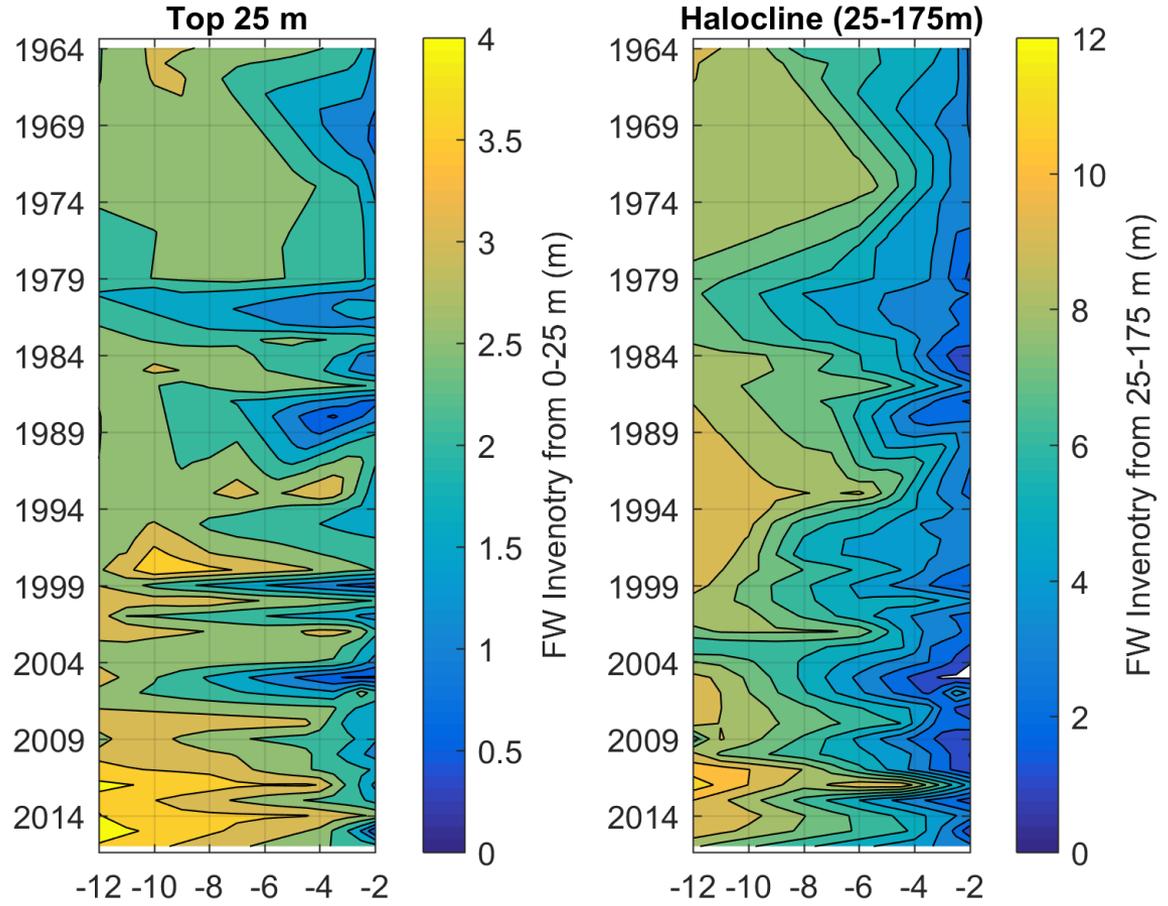
# Freshwater Inventories in Fram Strait



$S_{\text{ref}} = 35.2$

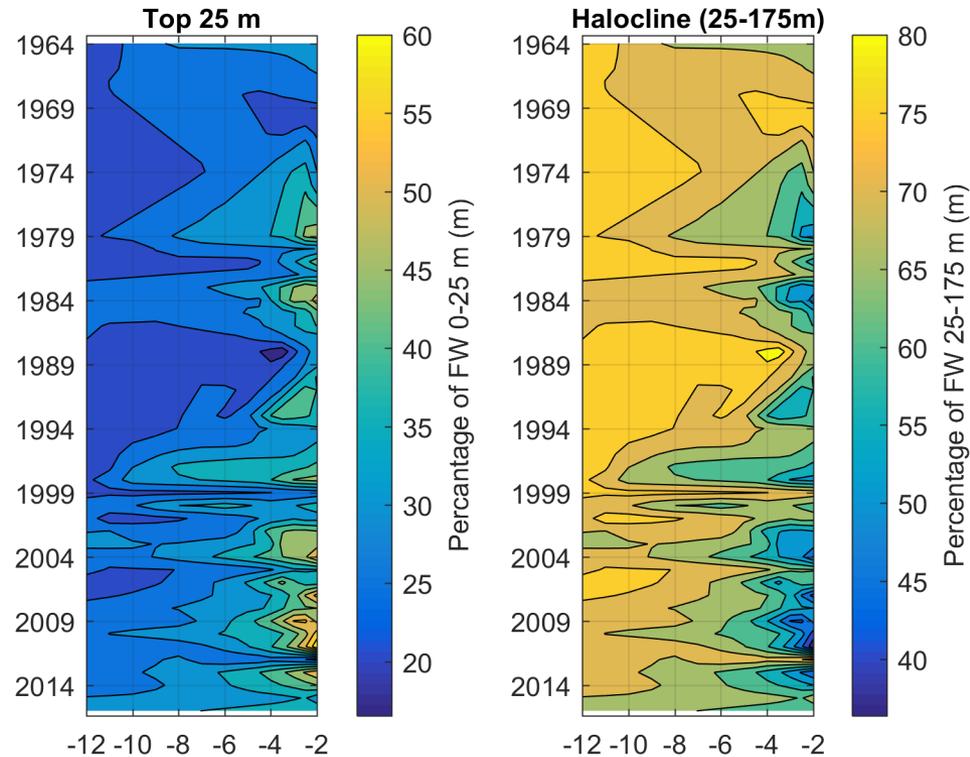
- Split into two layers. A surface layer and a halocline layer.
- Immediately obvious that FW inventories in the surface layer are higher in recent years
- Freshwater Inventories are also larger in the Halocline layer in recent years.
- But in the Halocline the change is smaller percentage of the total and there is more variability

# Freshwater Inventories in Fram Strait



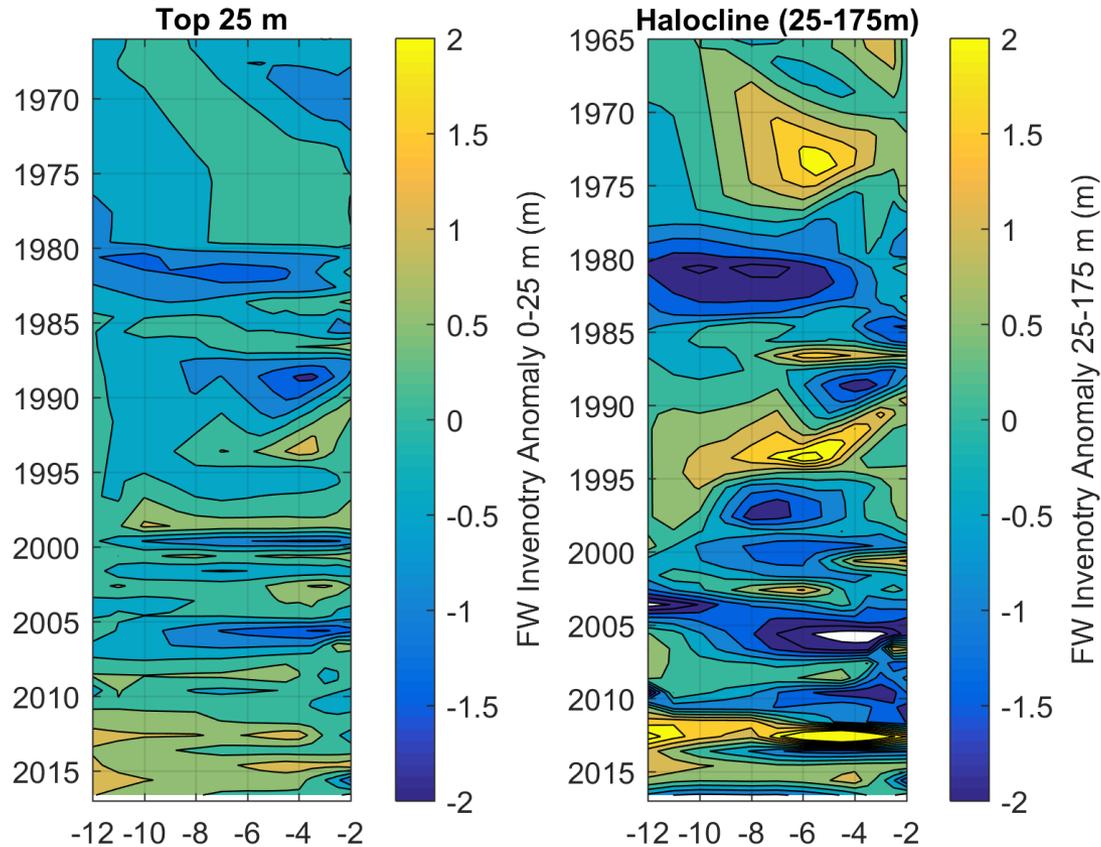
- Simple contouring of inventories makes the pattern clearer.
- Note that we've recently broken records in both the surface layer and the halocline
- The increasing trend is stronger in the top 25 m.
- While changes are larger in the halocline (different scale, much thicker layer) but more variable

# ~35% of freshwater is now in the top 25 m



- 1964 division was about 25% surface, 75% halocline
- 2016 division was about 35% surface 65% halocline
- Extreme values in the frontal zone are where PSW overlies pure Atlantic water.
- N.B. : This is only the summer situation

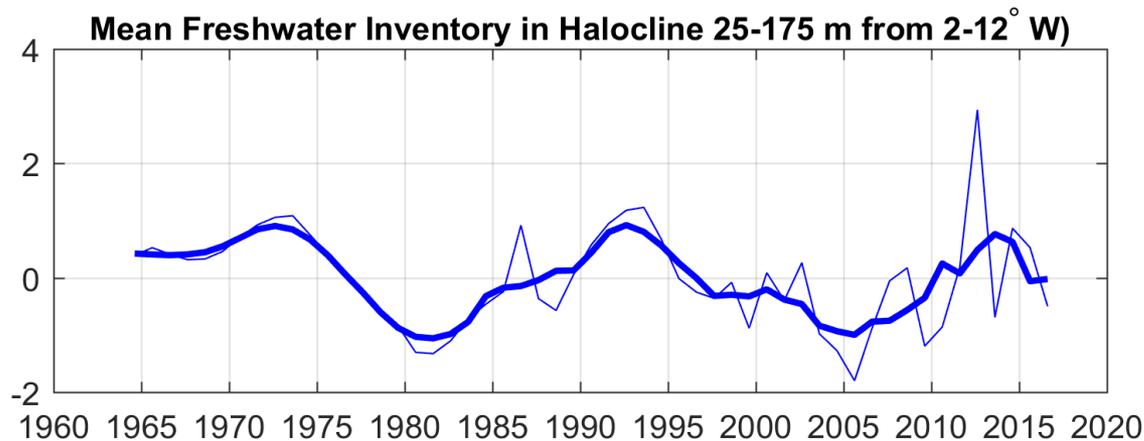
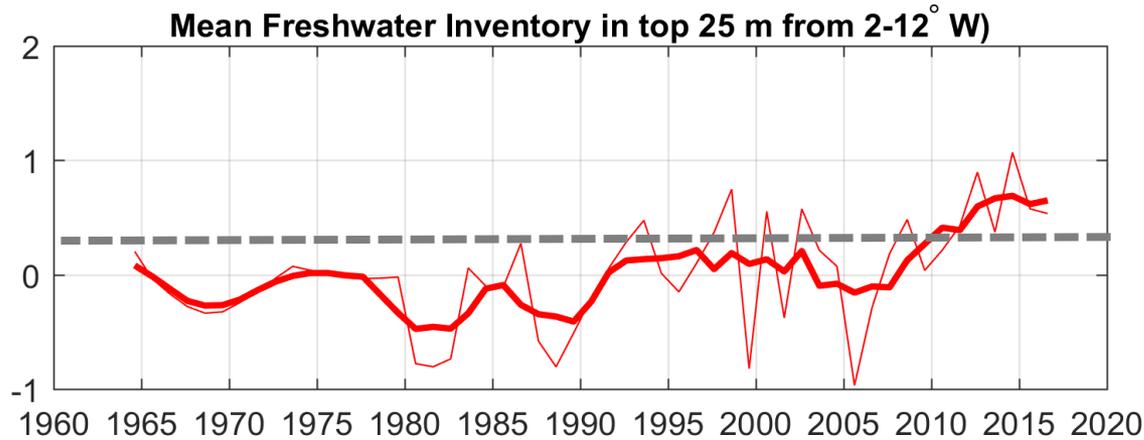
# FW Variability: Surface vs. Halocline



- These are anomaly plots (1965-2016 mean subtracted from values at each longitude)
- The contours and colour scales are the same for the surface and halocline

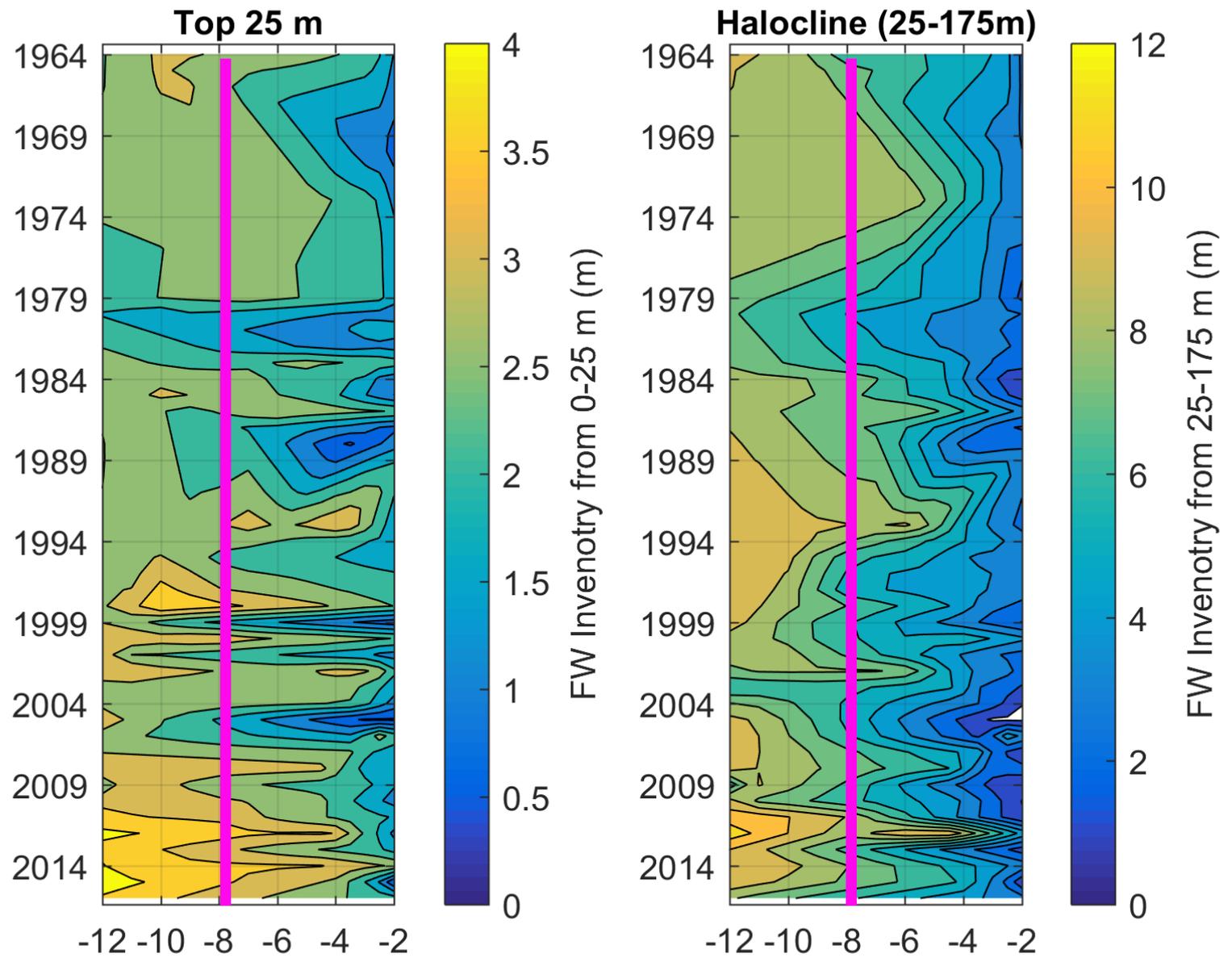
- The magnitude of variations is larger in the halocline, largely because it is a much thicker layer (150 m vs 25 m)
- Top 25 m shows a trend (esp in the west). Interannual variability dominates the halocline

# Mean FW anomaly changes as line graphs

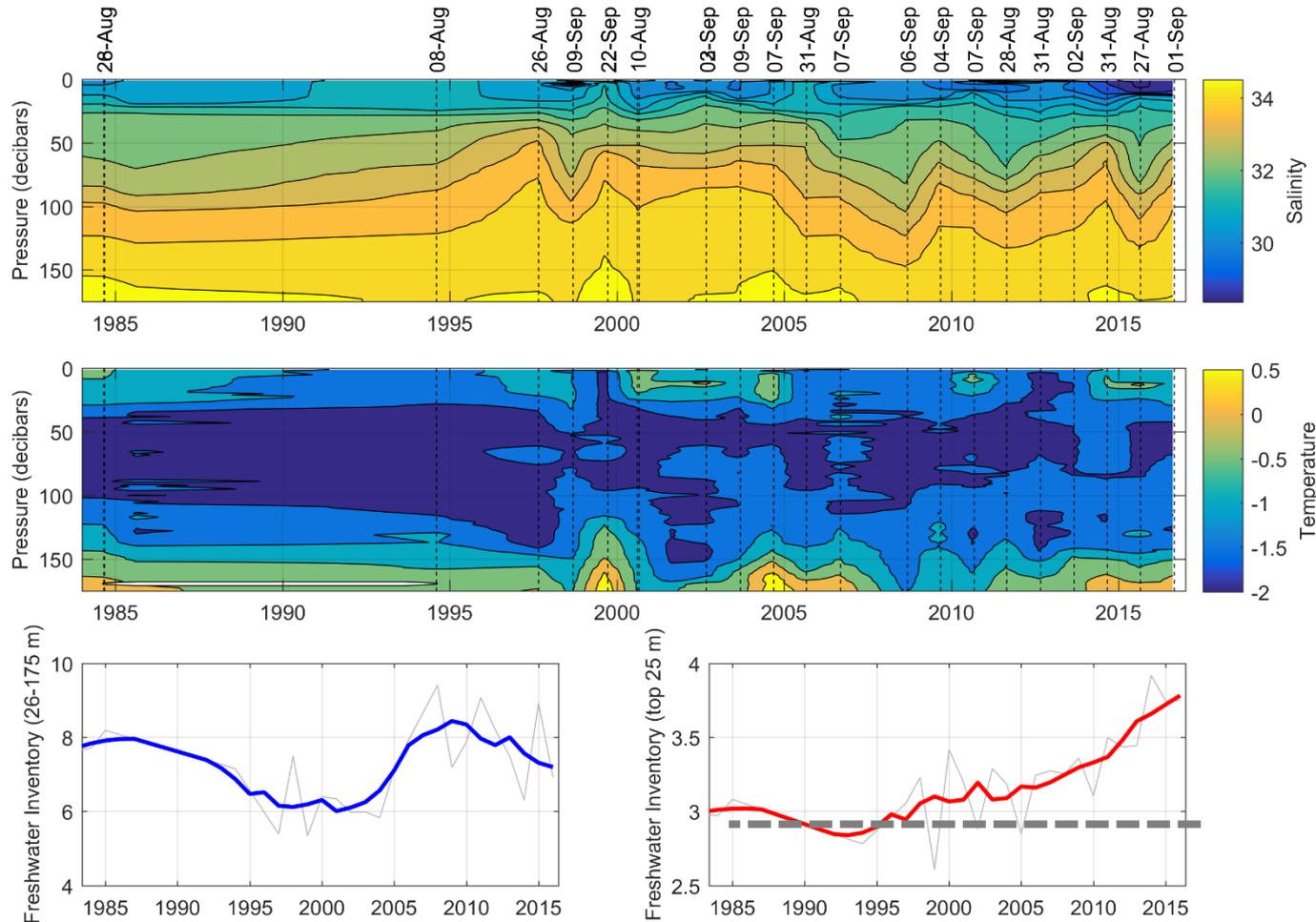


- Mean FW inventories anomalies from 2-12° W
- Annual means (fine) 3-year running mean (bold).
- Surface inventory has increased 0.7 m since 1990, rapidly in recent years (post 2010)
- The halocline shows variability but no trend

# Let's take a slice at 8°W...

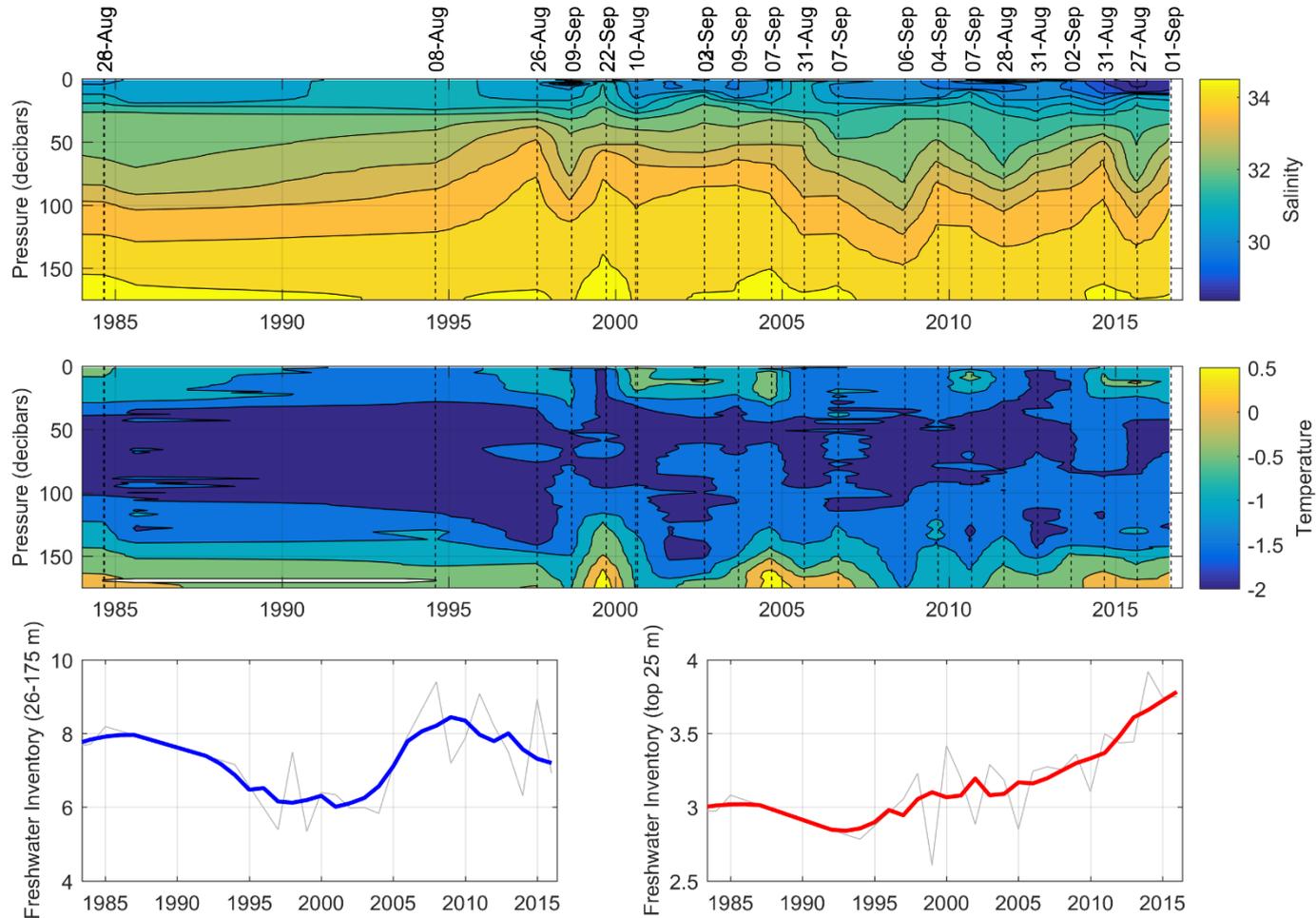


# Slice at 8° W



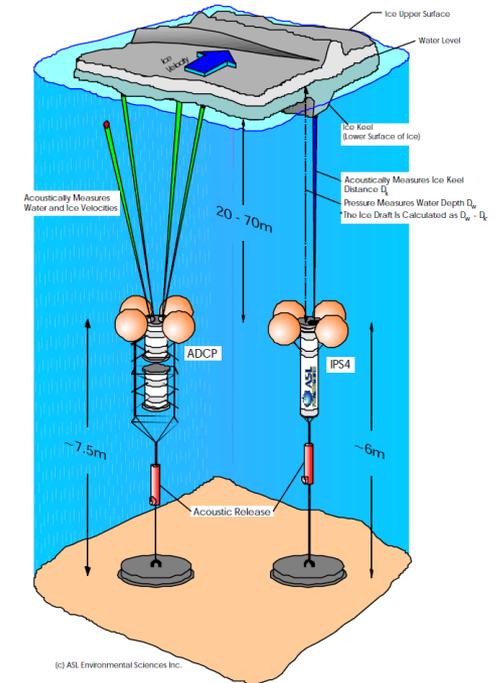
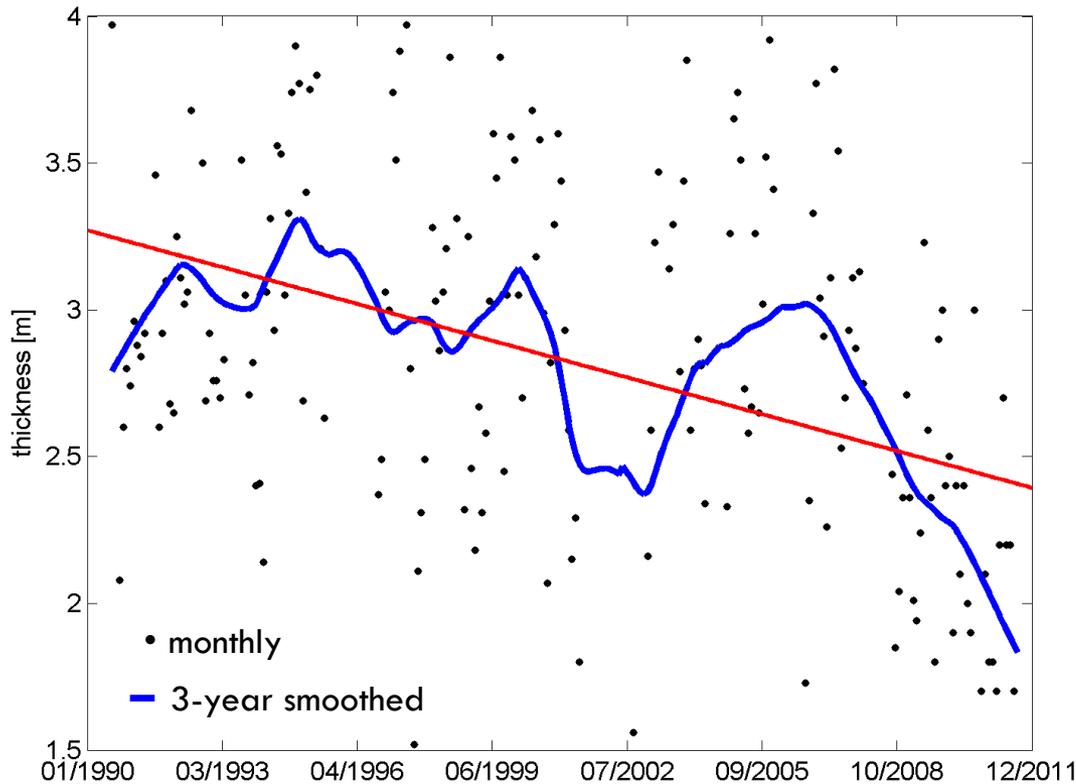
- This is how the 25 m layer was chosen
- Note how there are co-incident warm Atlantic signals both above and below the cold halocline at some times

# Slice at 8° W



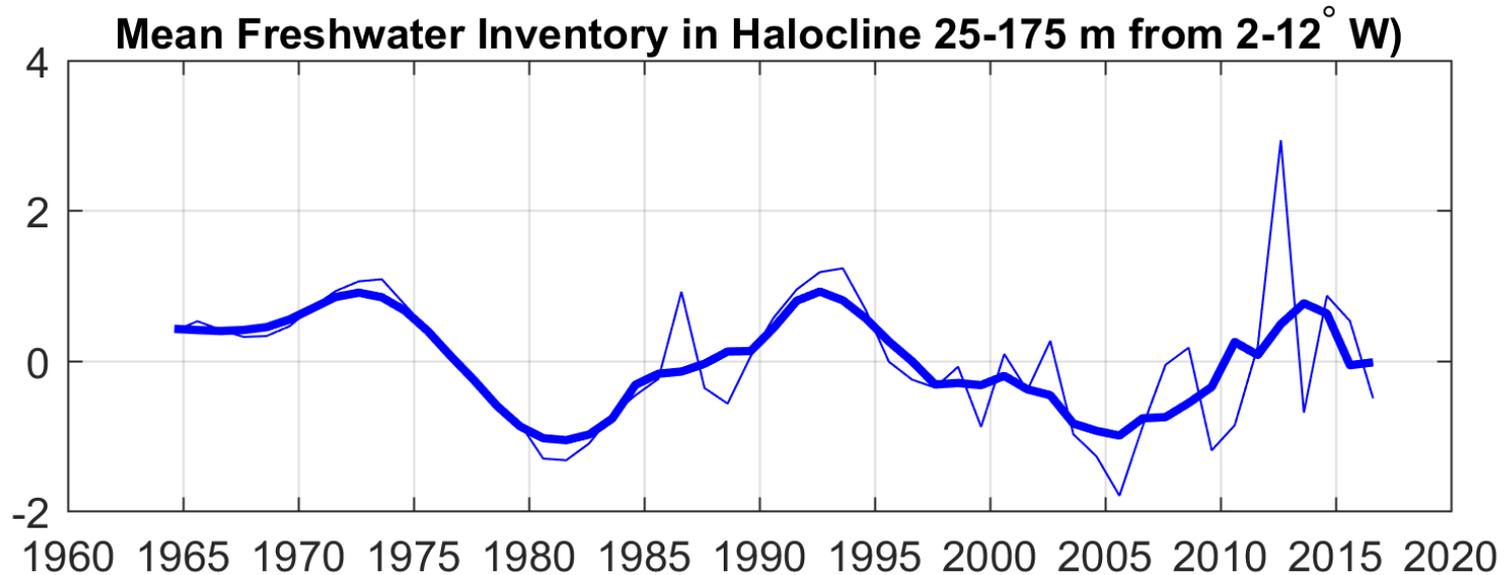
- Fresh events at the surface coincide with subsurface temperature maxima, just above the halocline
- So? Is the new fresh water released by warm Atlantic water melting sea ice? ... possibly.

# IPS-measured decrease in sea ice thickness



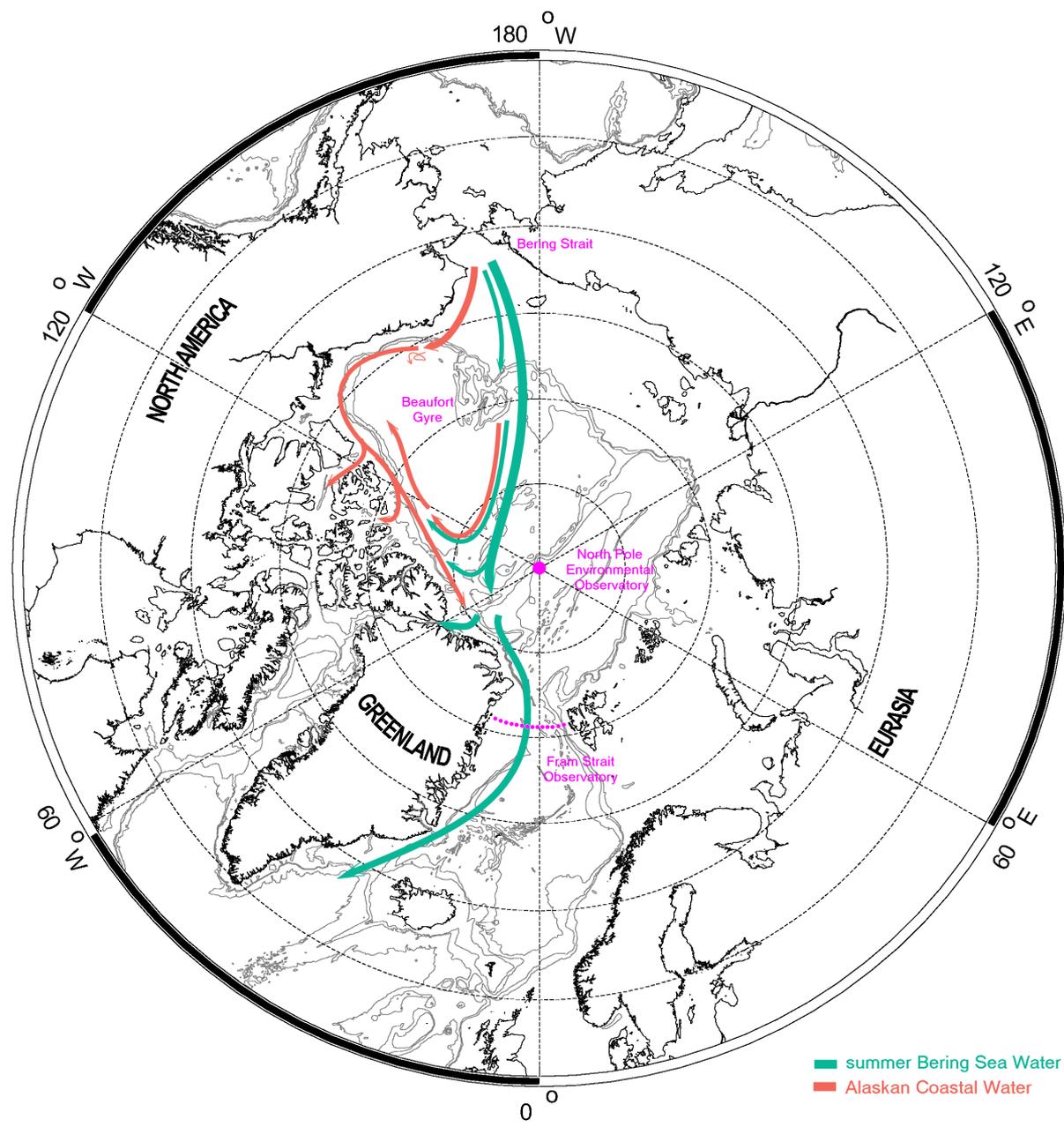
- Reduction of about 80 cm between 1990 and 2011
- $-40 \pm 8$  cm/decade or  $-14\%$ /decade
- Sharper decline in more recent years.
- The pattern and magnitude are similar to the surface freshening

# So what might cause variability in the EGC Halocline?



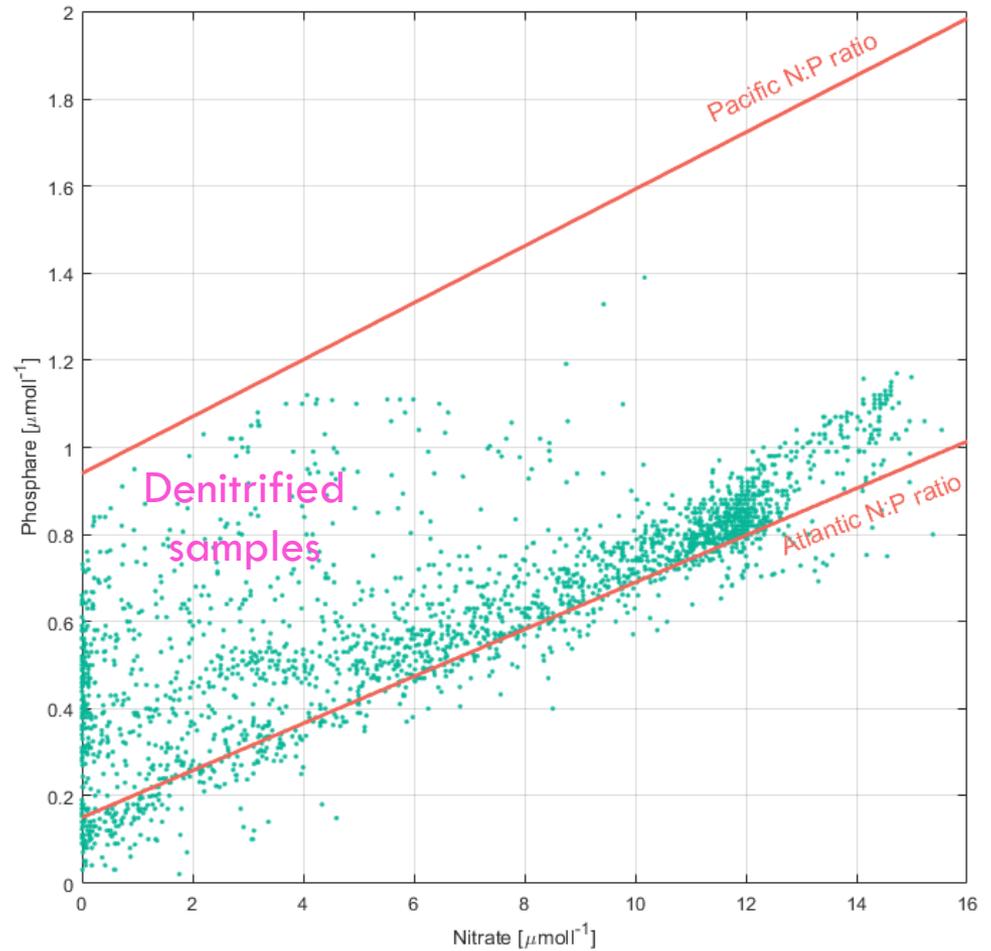
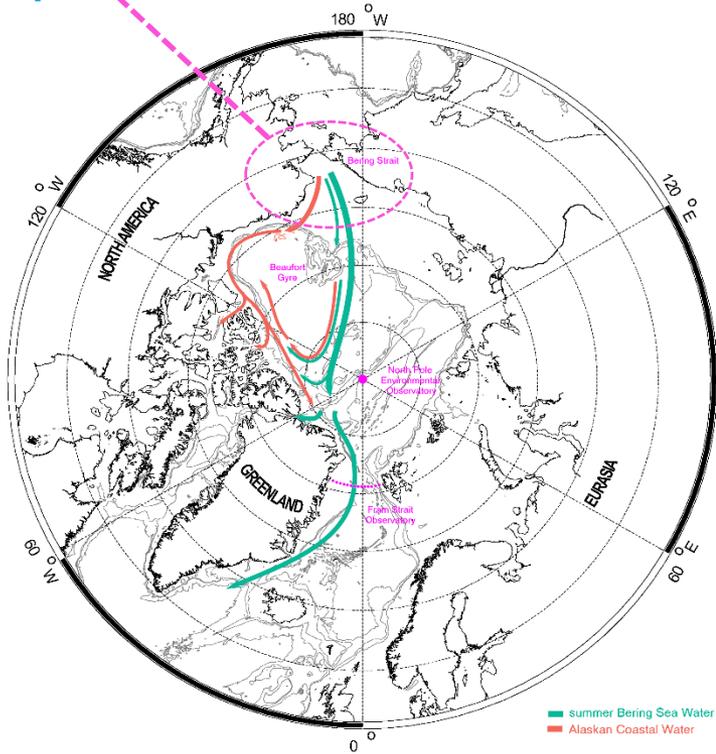
- 1) The fraction of *Pacific Water* in the outflow from the Arctic Ocean
- 2) The strength of the West Spitsbergen Current

# Pacific Water in the Arctic Ocean



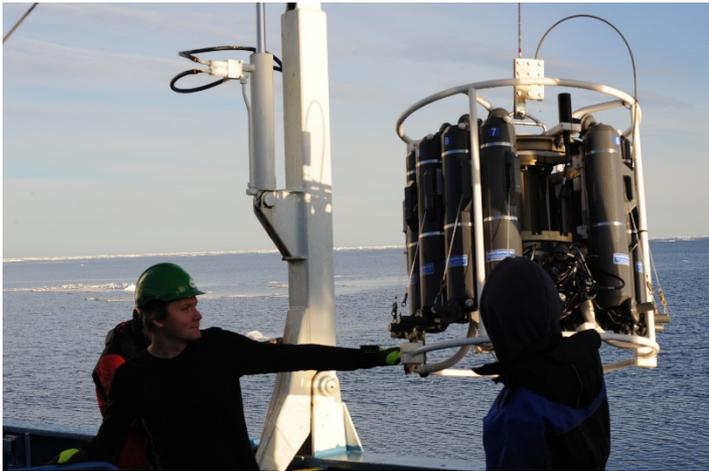
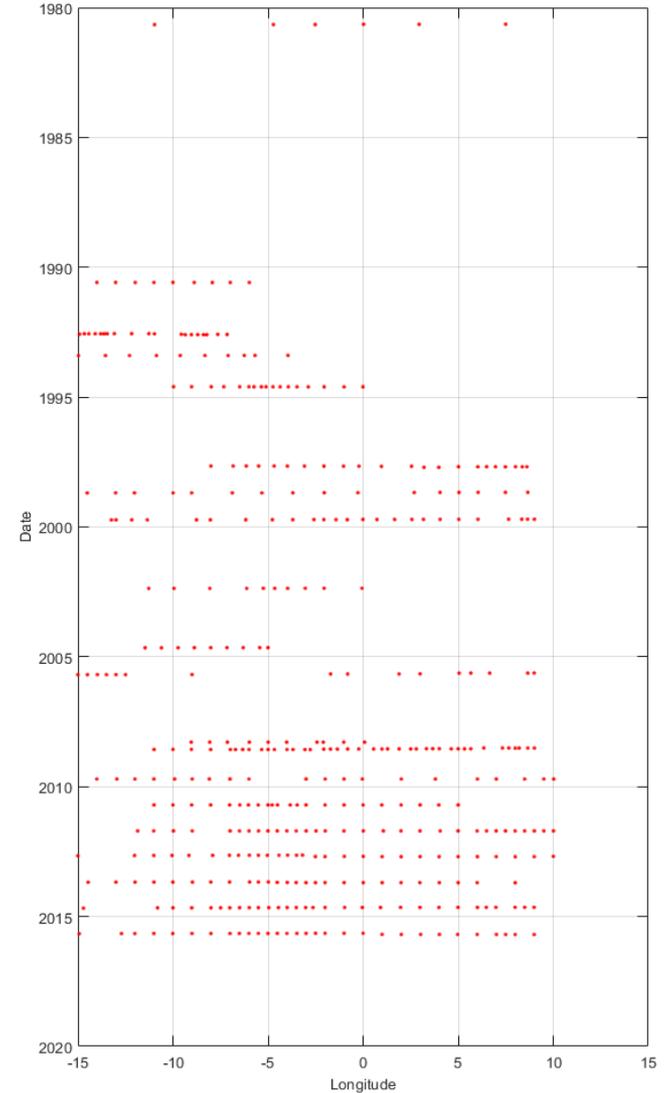
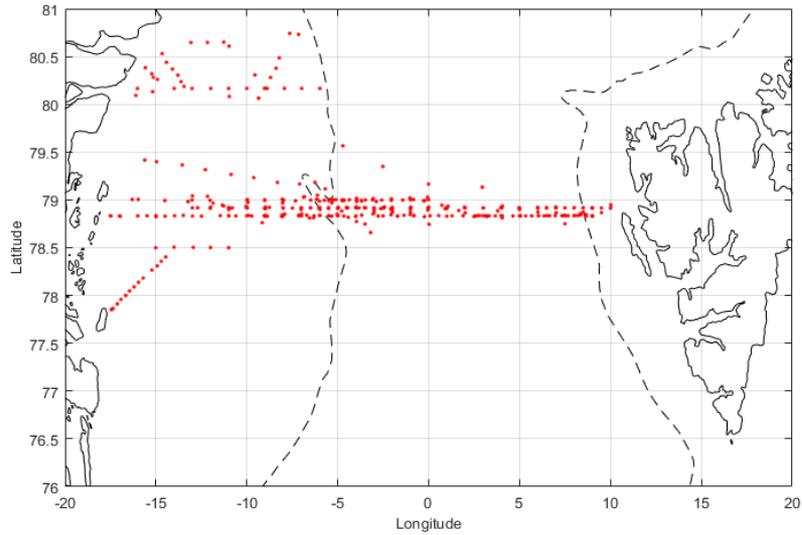
# Tracing Pacific Water

Denitrification  
Zone

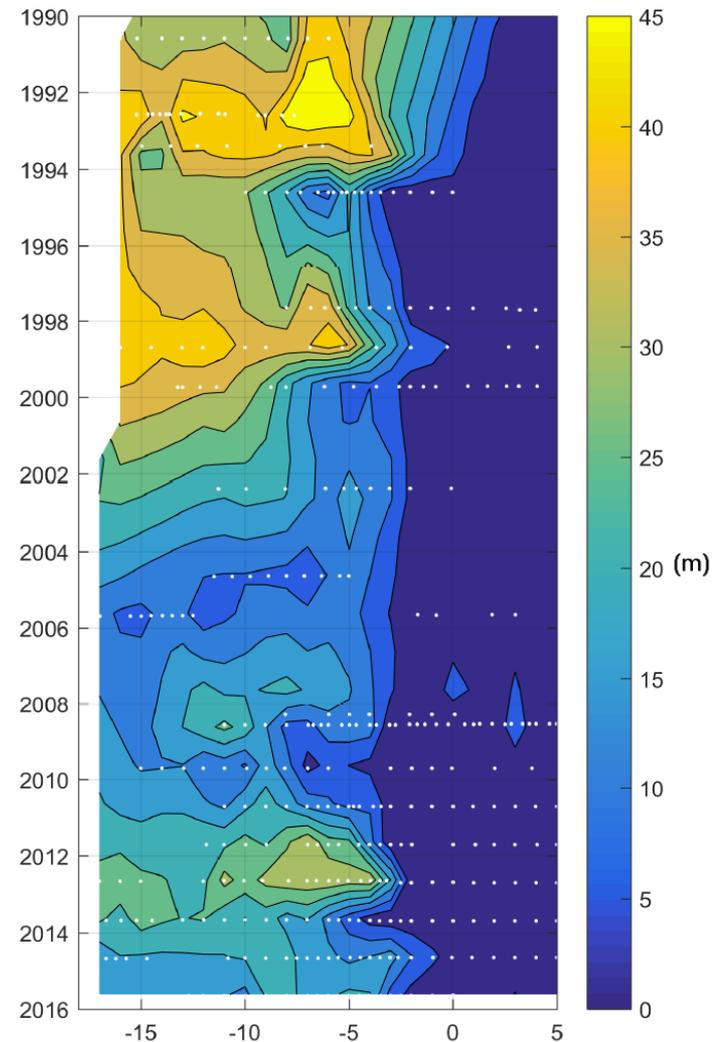
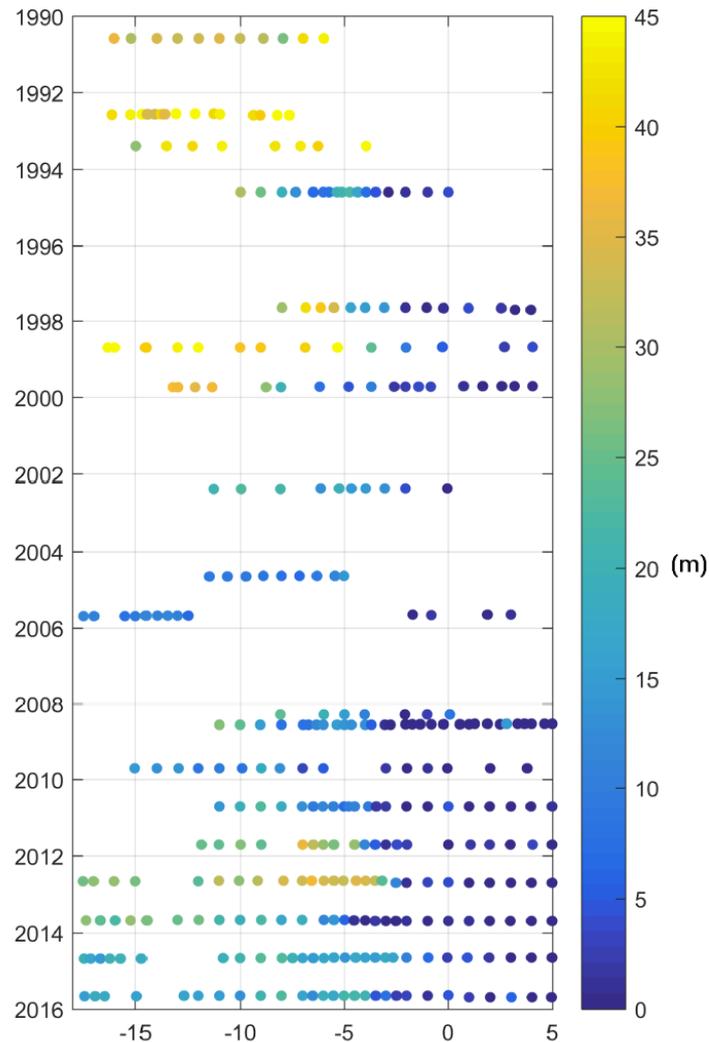


Well established technique used by Jones et al. (1998) and many more in the last two decades

# Nutrient Measurements in Fram Strait



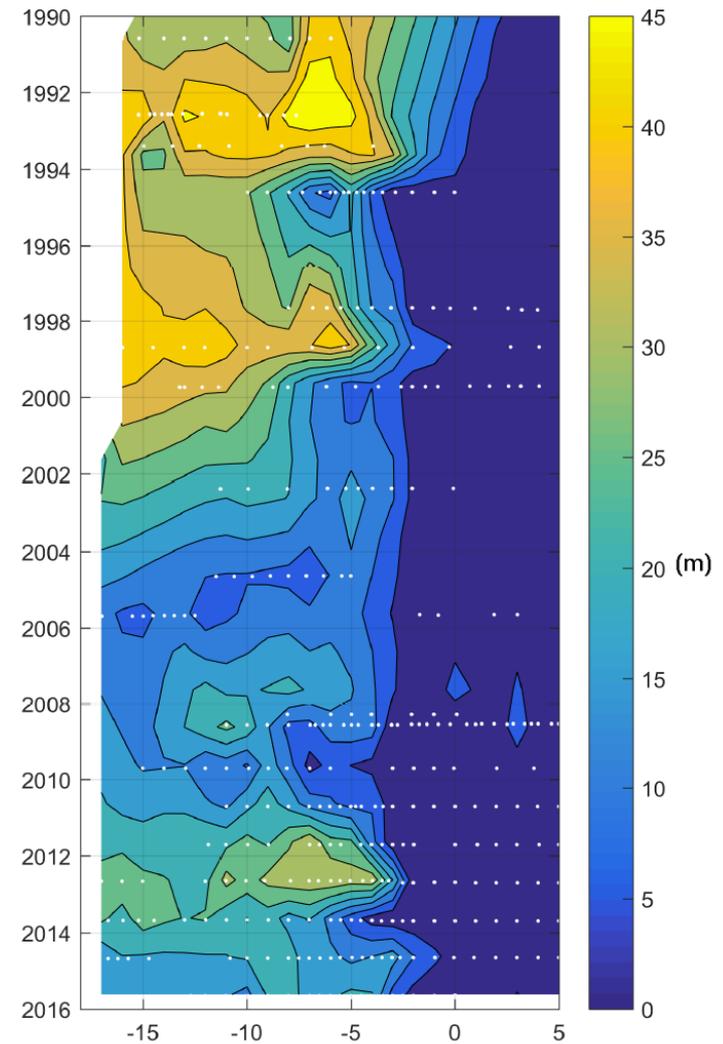
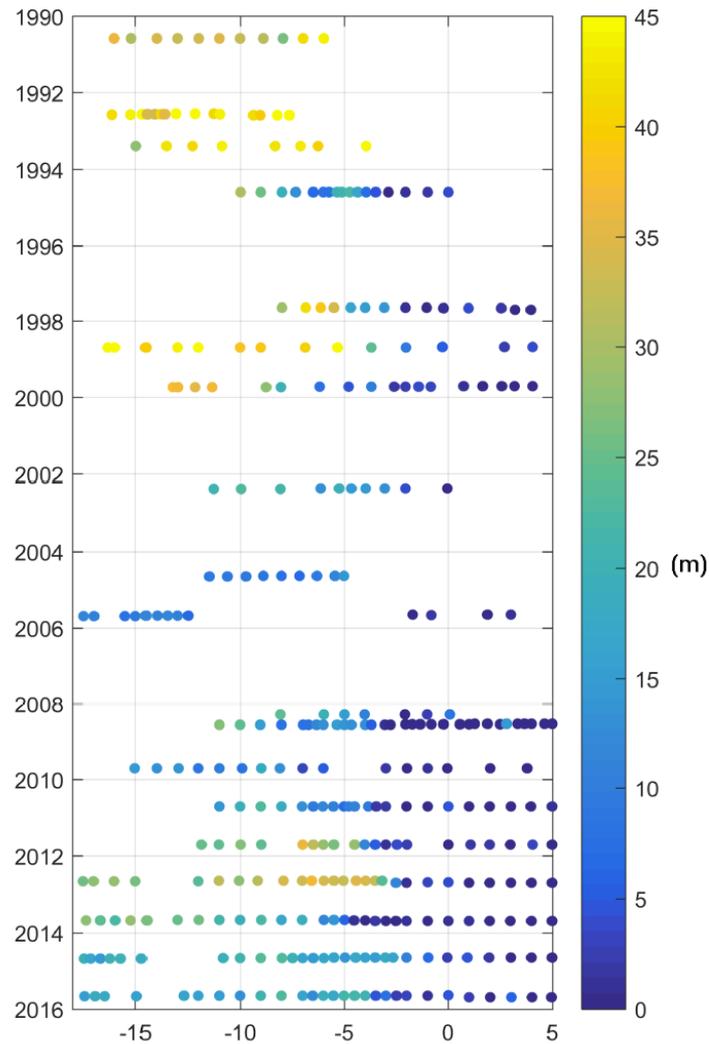
# Pacific Water inventories (25-75m)



Much higher values in 1990's.  
A 45 m inventory = almost 90 % Pacific water.

Huge variations: In 2006 there was almost no Pacific Water in Fram Strait

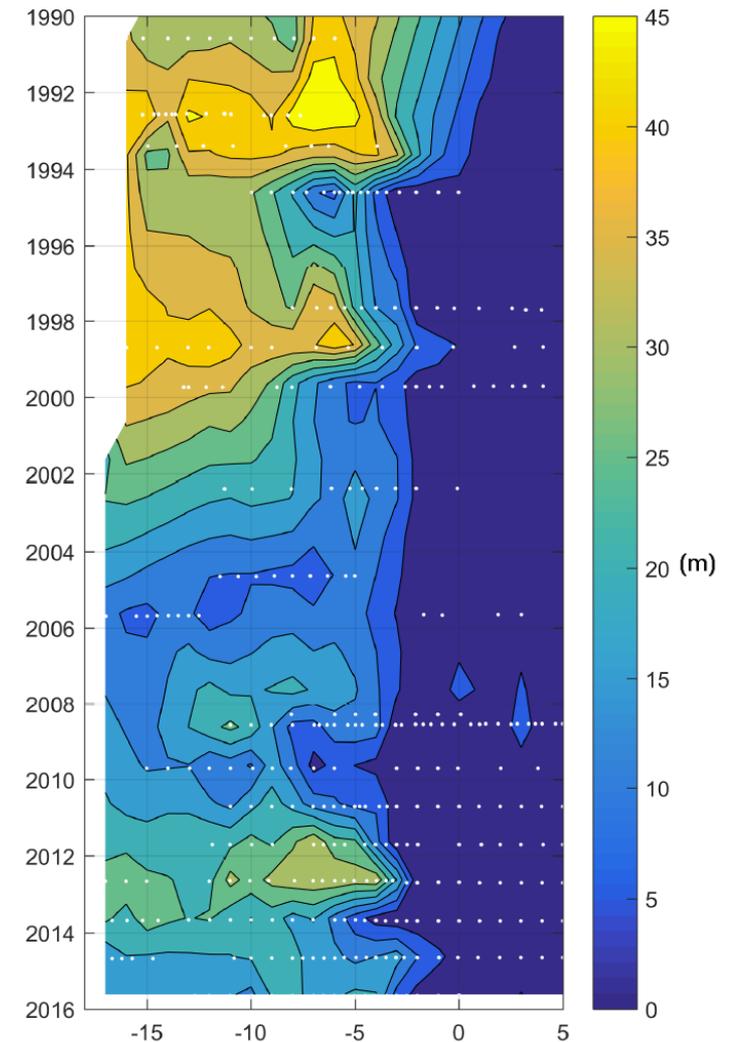
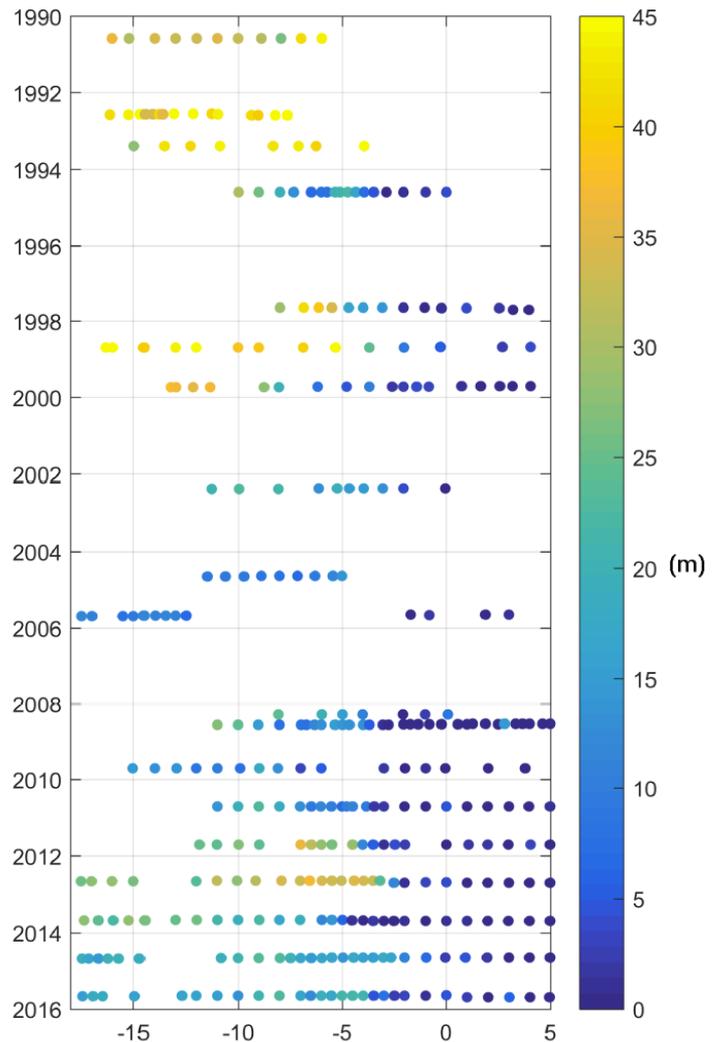
# Pacific Water inventories (25-75m)



There were significant pulses of Pacific Water in 1992, 1998, 2009 and 2012

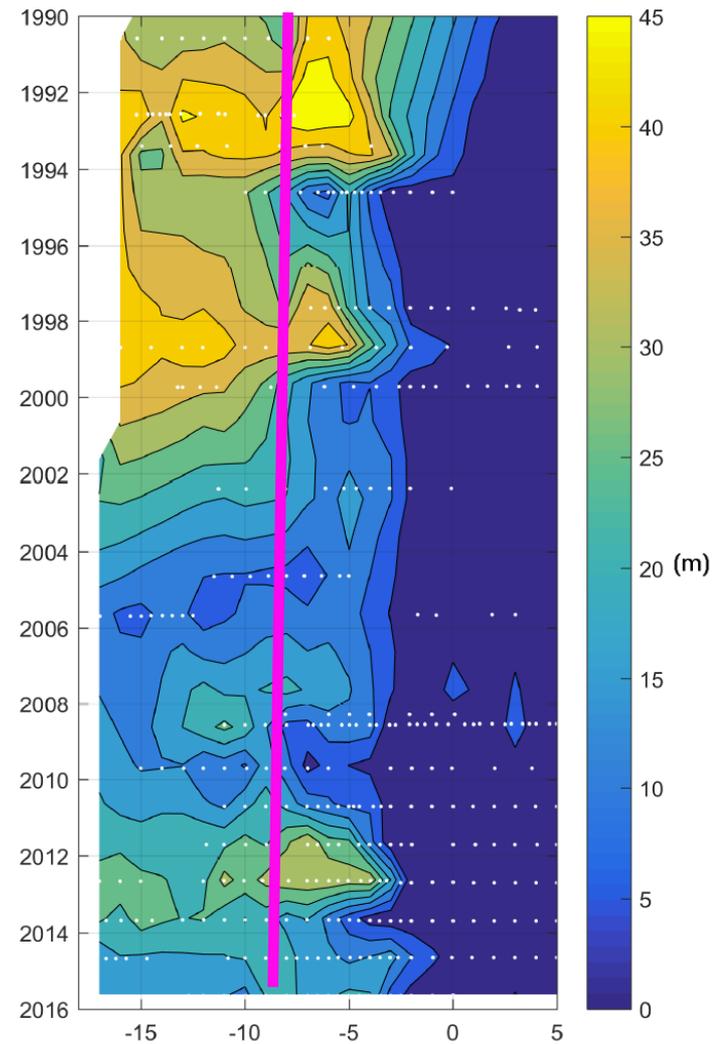
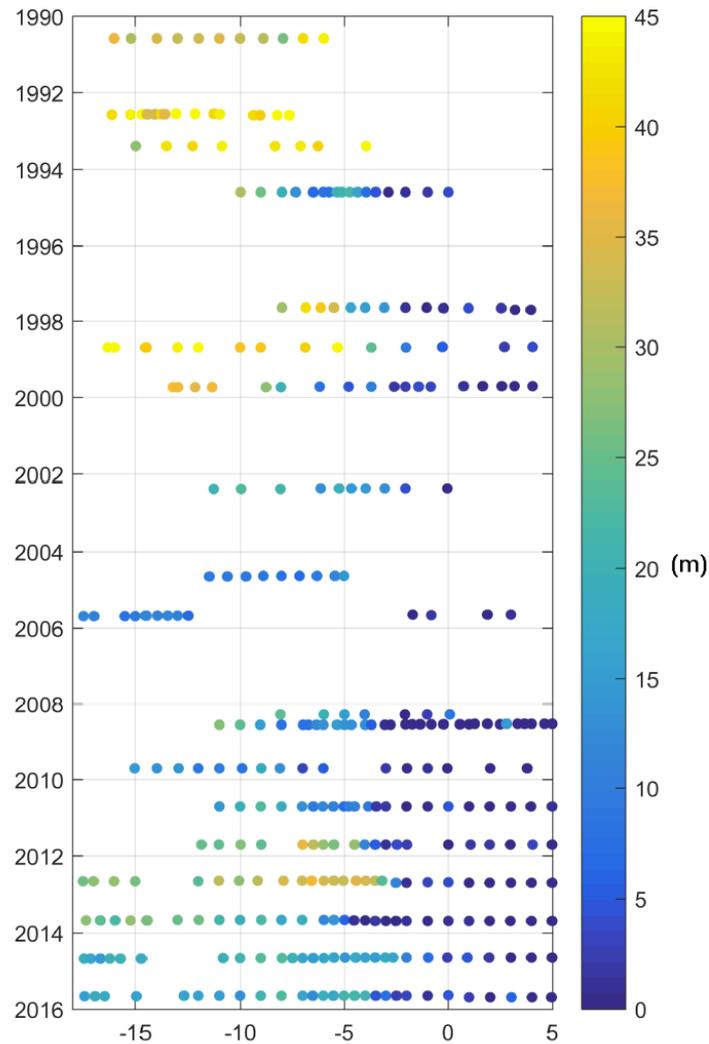
Maxima were much higher in the 1990's than in 2009 and 2012

# Pacific Water inventories (25-75m)



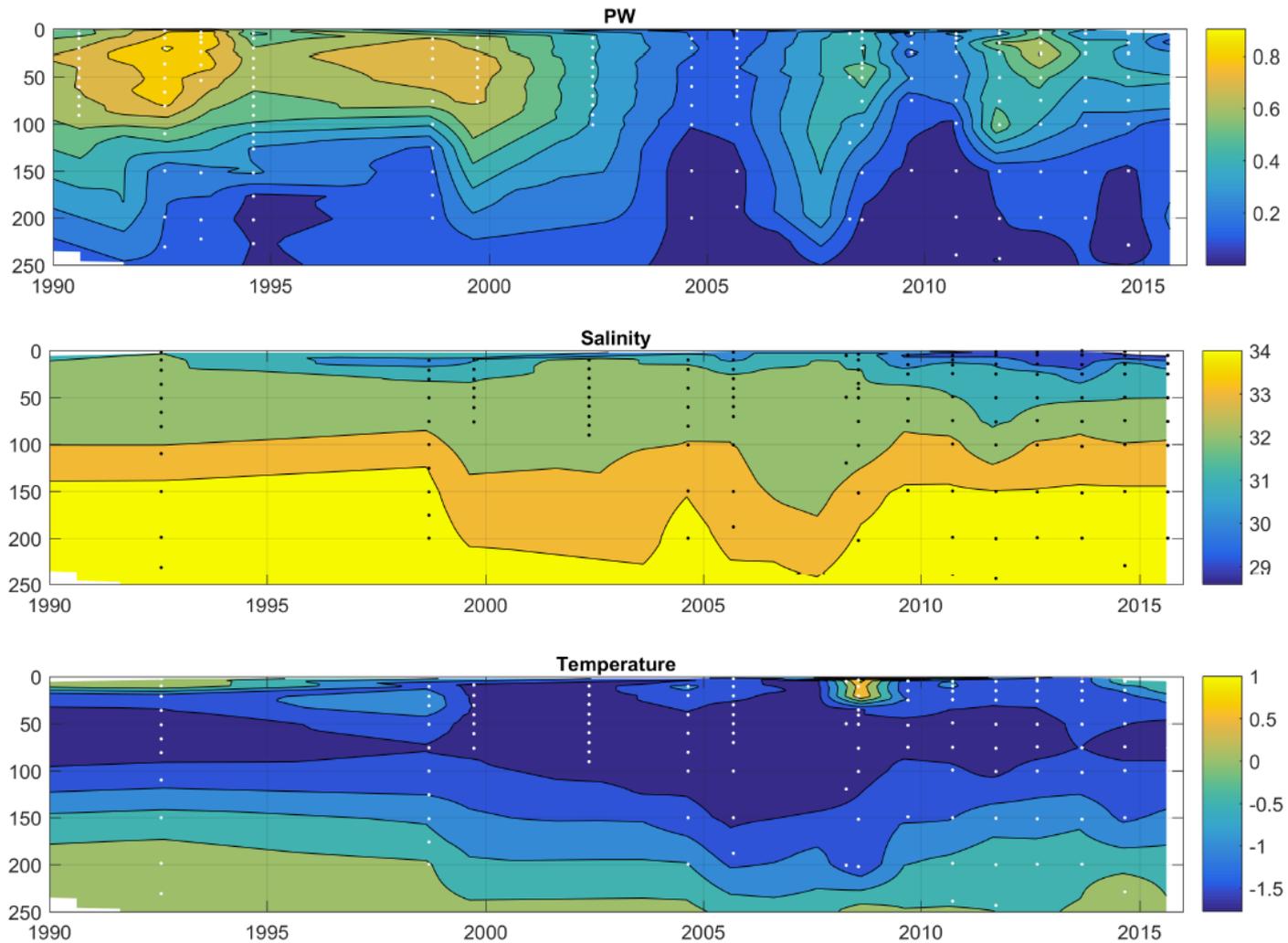
Peak inventories typically occur in the core of the EGC and are lower over the shelf

# Pacific Water inventories (25-75m)



Let's look at a section along 8°W...

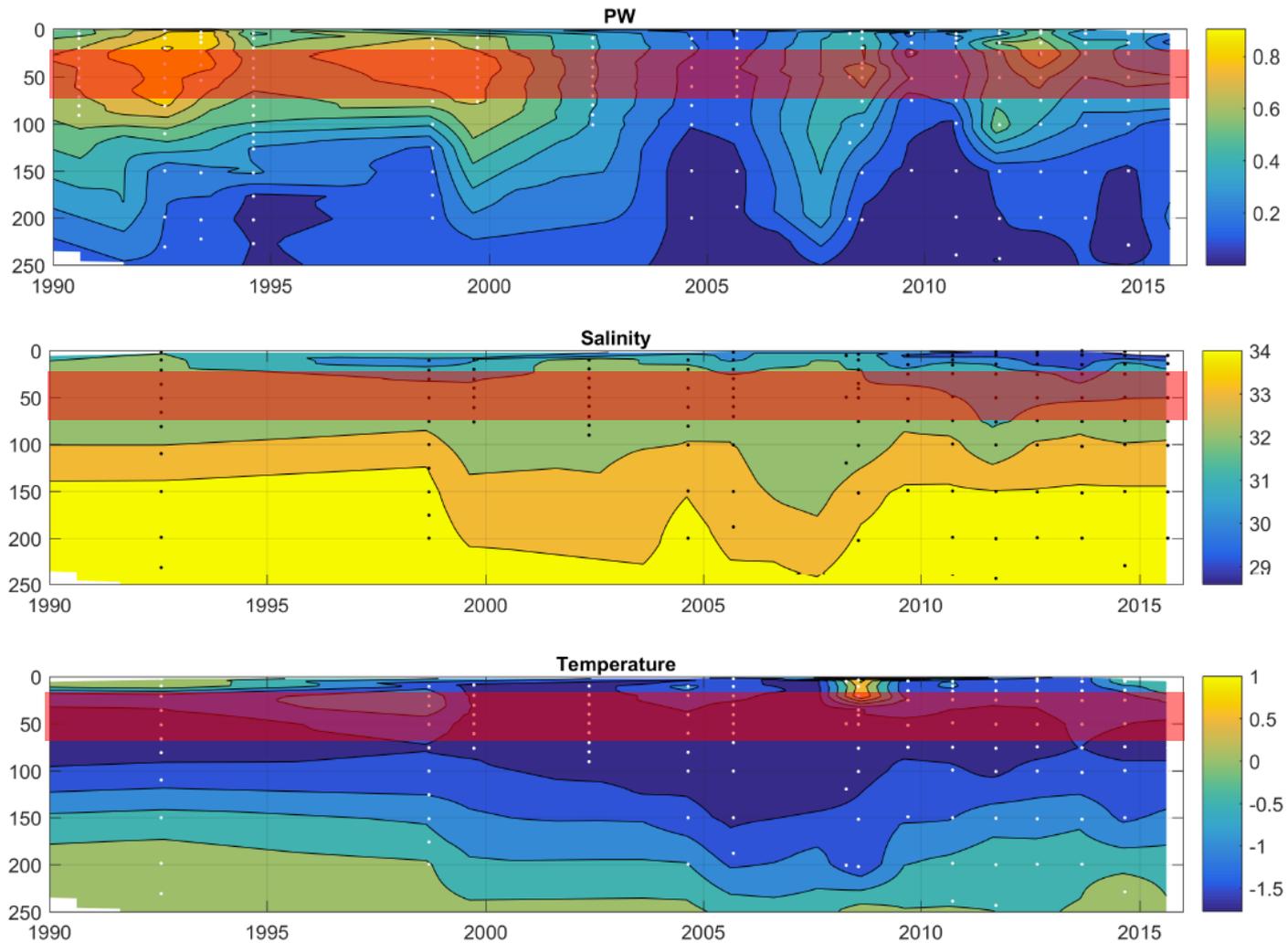
# Pacific Water Fractions at 8°W



Pacific Water maxima are slightly subsurface, perhaps partly due to dilution by sea ice meltwater?

Most of the inventory is from 25-75 m but low fractions extend down to 200 m

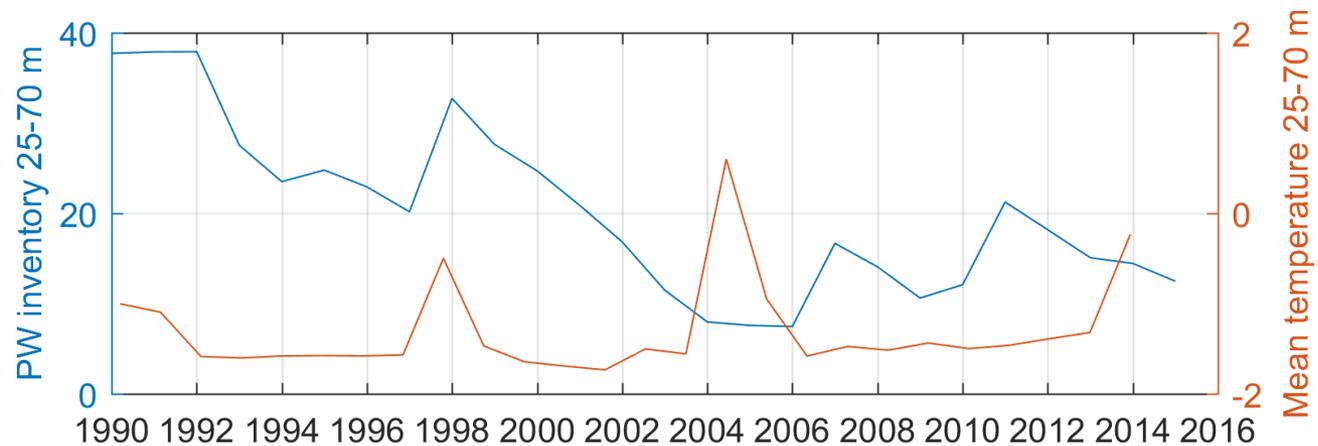
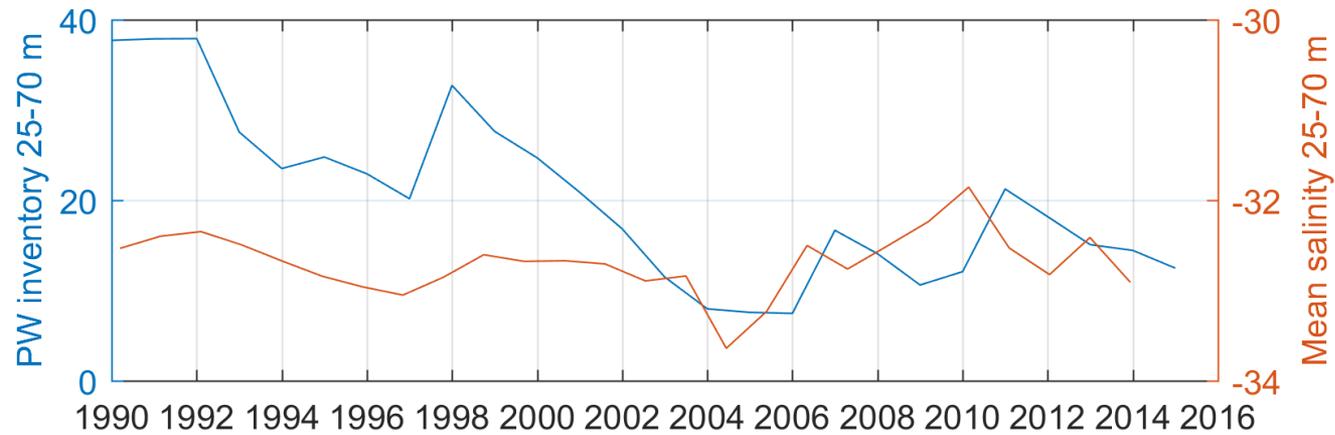
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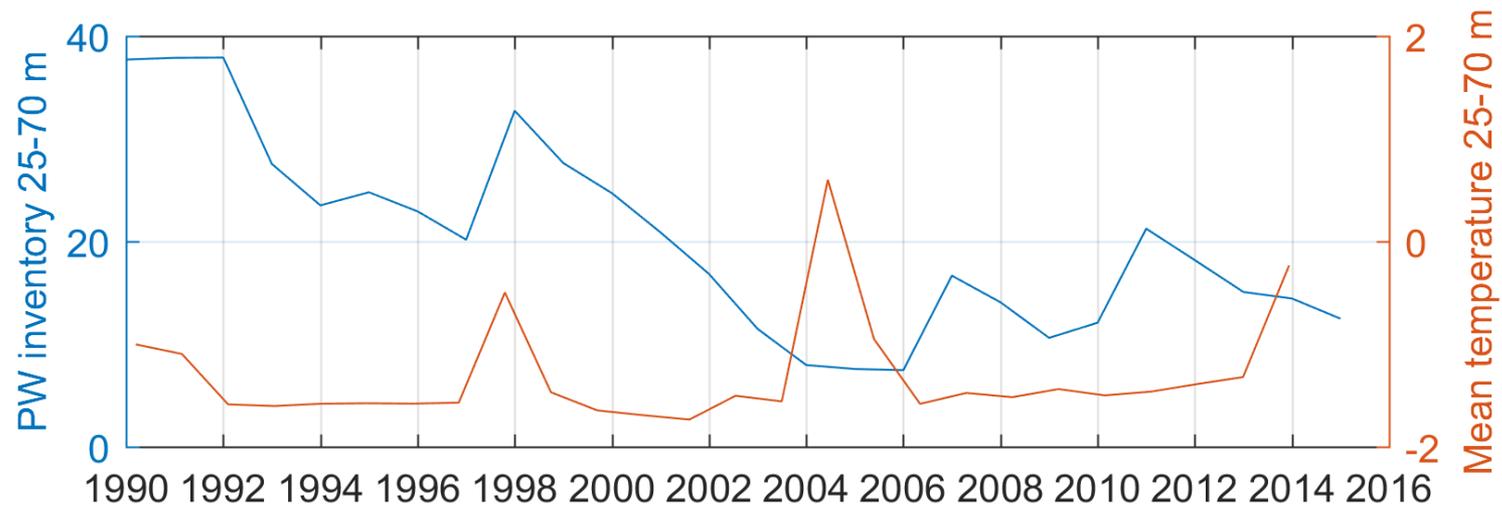
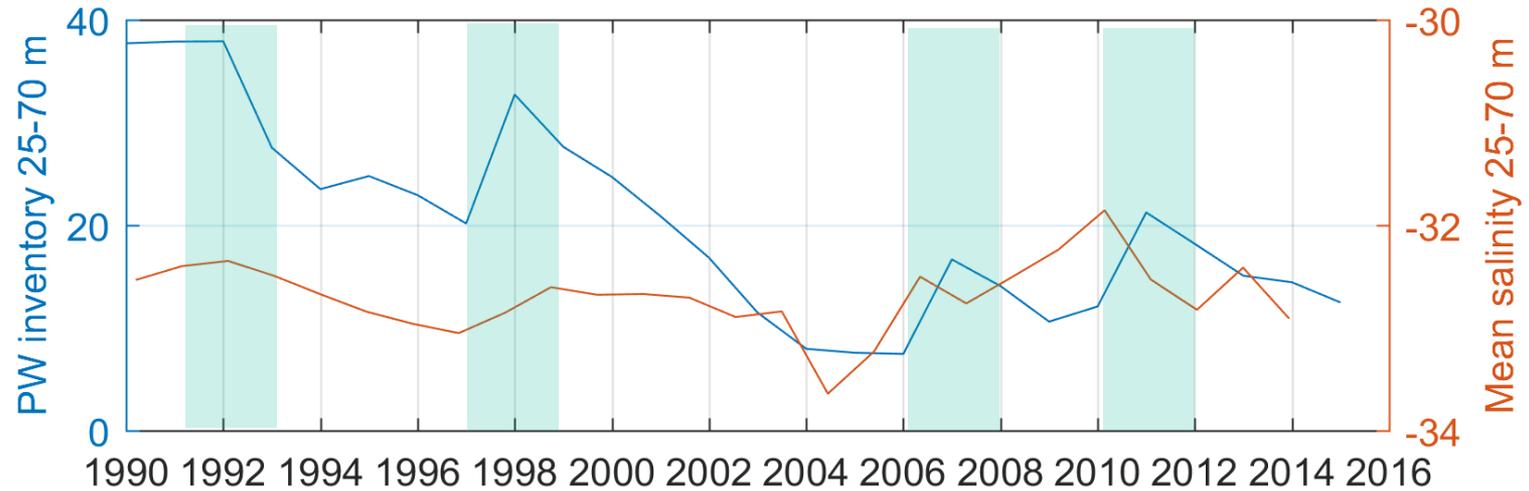
# 25-75m Pacific Water inventories at 8°W



Comparing Pacific Water inventories with mean temperature and salinity for the same layer. Note inverted Salinity scale.

There is some correlation, but the relationship is far from pure.

# Pacific Water Variability at 8°W



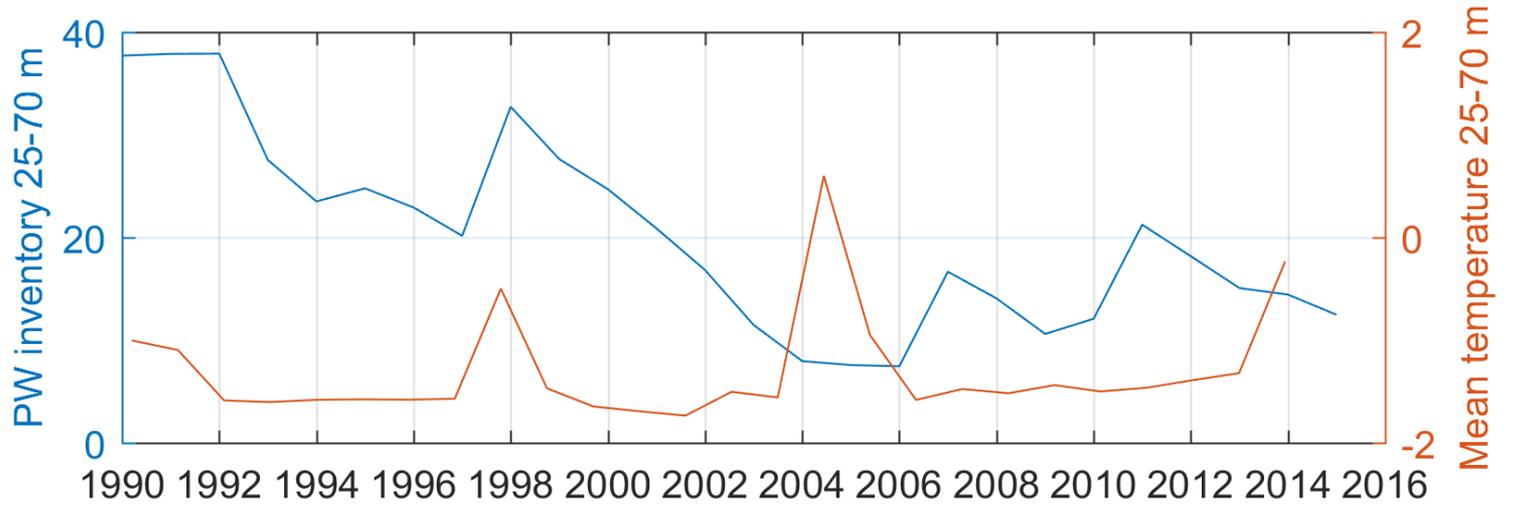
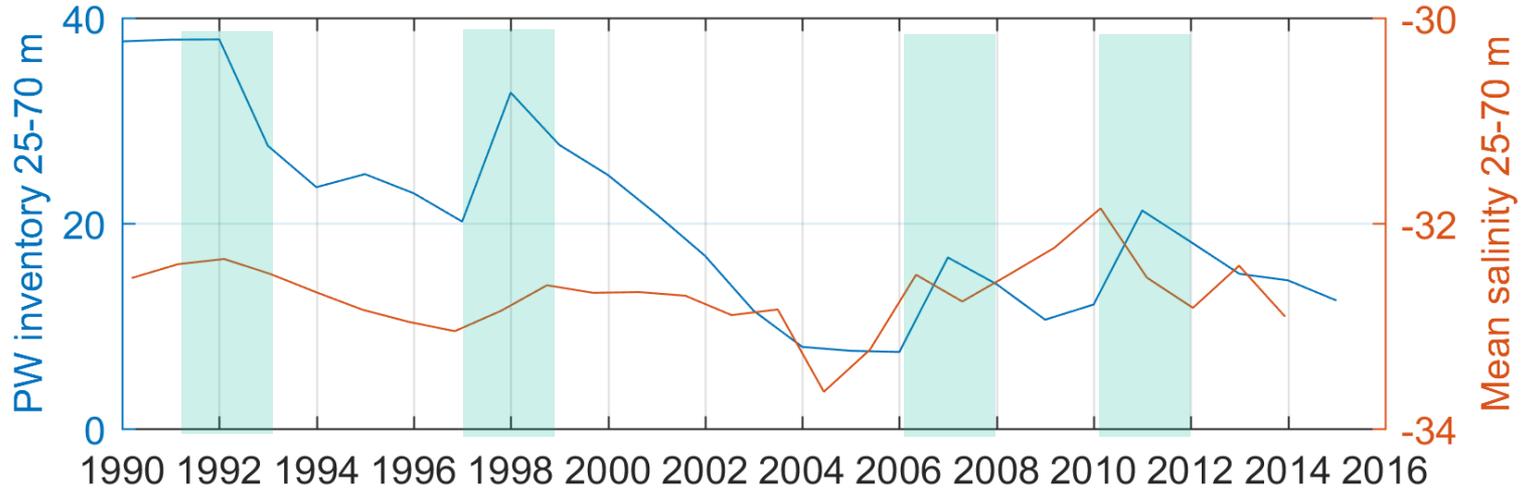
General pattern: Pacific Water maxima are weakly associated with salinity minima. There is an even weaker relationship with temperature minima

# Pacific Water Variability at 8°W



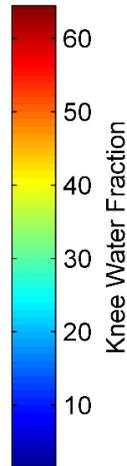
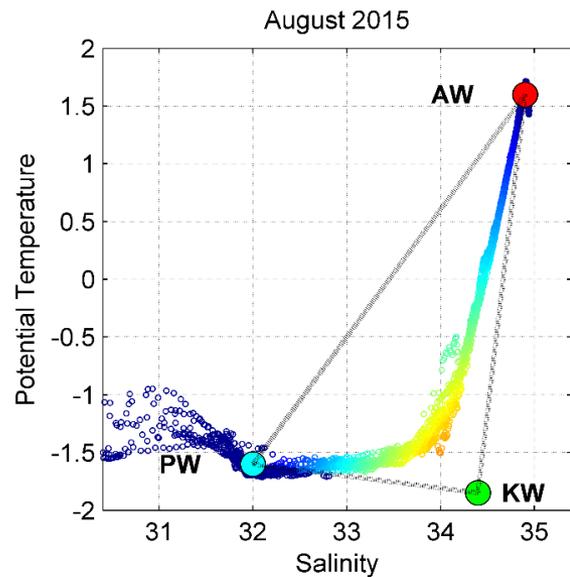
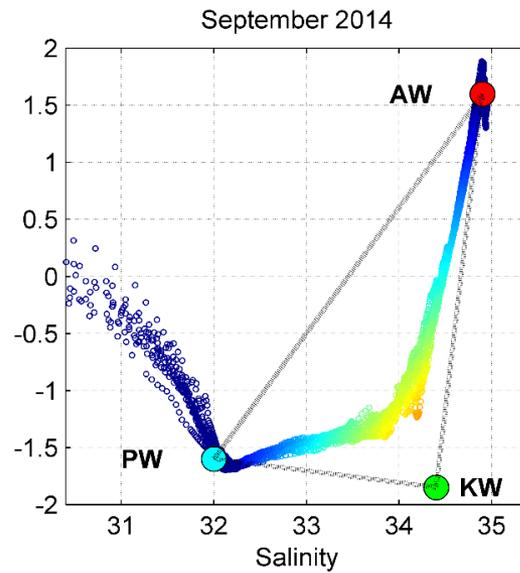
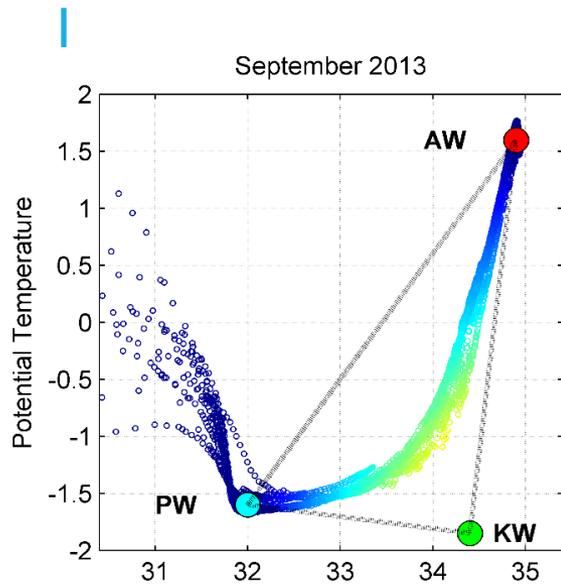
Clear anomaly around 2005 coinciding with the West Spitsbergen Current temperature maximum event (more on this later...)

# Pacific Water Variability at 8°W



So what normally replaces Pacific Water if it's not return or recirculating Atlantic Water?

# “Knee Water”



There are 3 principal surface water masses in Fram Strait besides Pacific Water

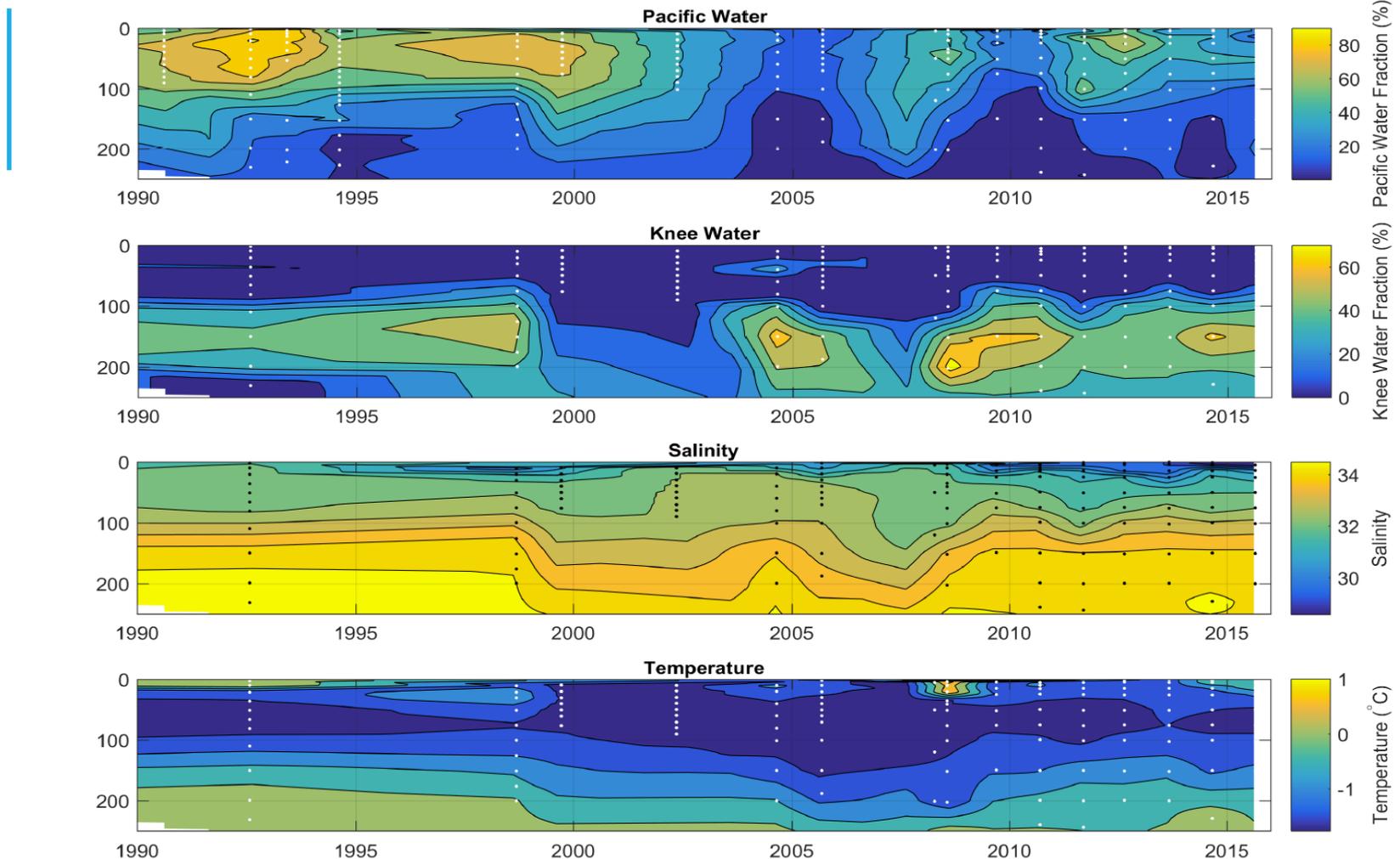
**AW:** Either Arctic Atlantic water or Re-circulating Atlantic water.

**PW:** Polar surface water

**KW:** Knee water (following Budeus et al.). Cannot be formed locally by mixing of AW and PW as it's too cold

The source of KW is not very well known, but most likely from cooling and interaction with freshwater in the Arctic Ocean.

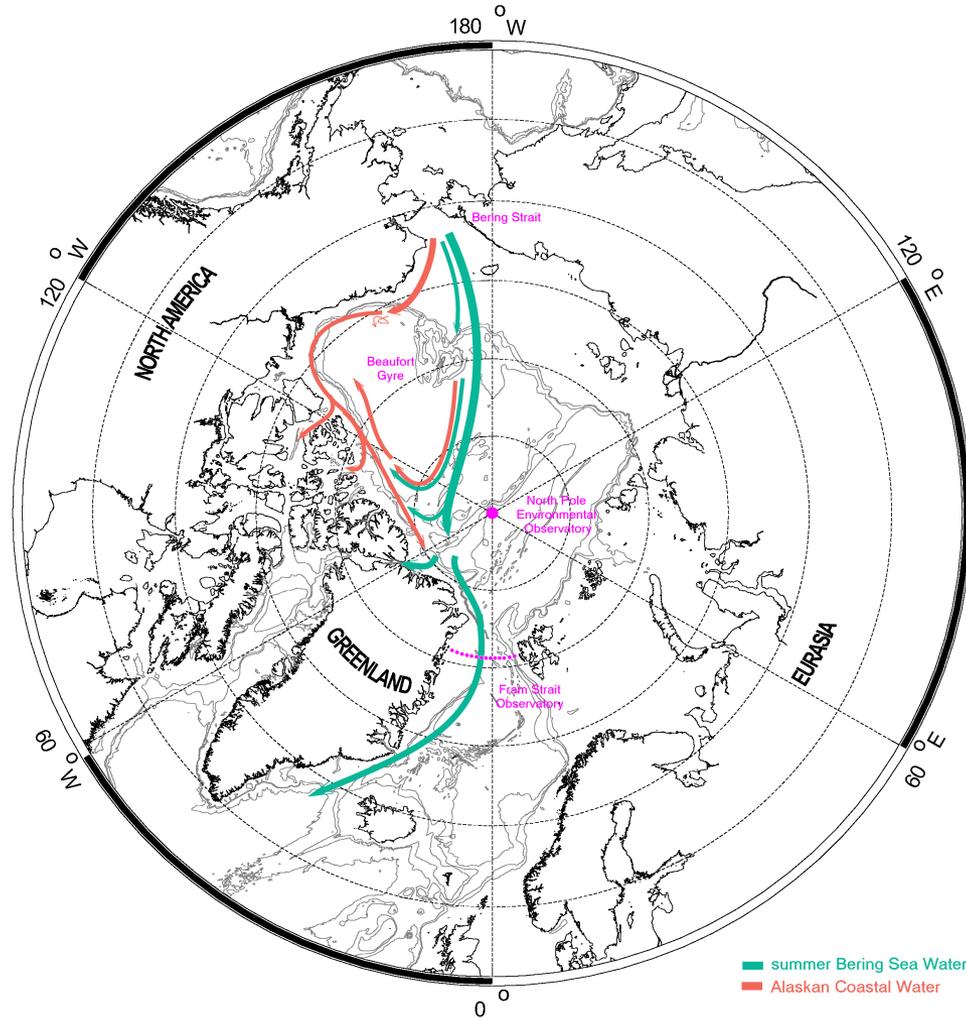
# Pacific and Knee Water Switching



Pacific Water and Knee Water maxima alternate in the EGC in Fram Strait. (Figure is at 8°W)

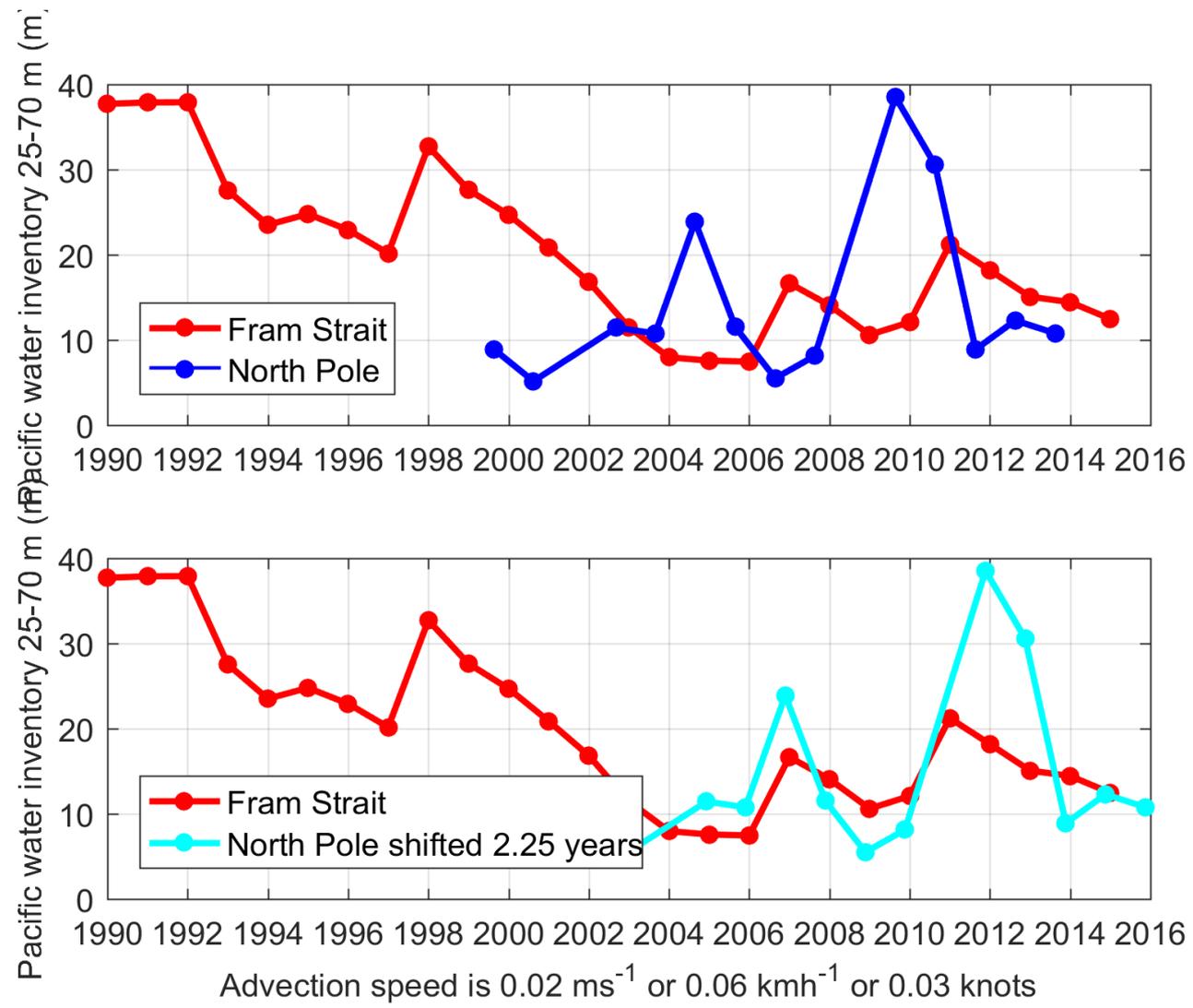
PW and KW are Arctic water masses, suggesting variability is driven by upstream processes, not local AW recirculation

# North Pole Comparison



- The North Pole Environmental Observatory (NPEO) is about 1 200 km upstream of the Fram Strait observatory.
- Nutrient samples were collected at the NPEO from 2005 to 2015, providing 10 years of overlap with the Fram Strait observatory.

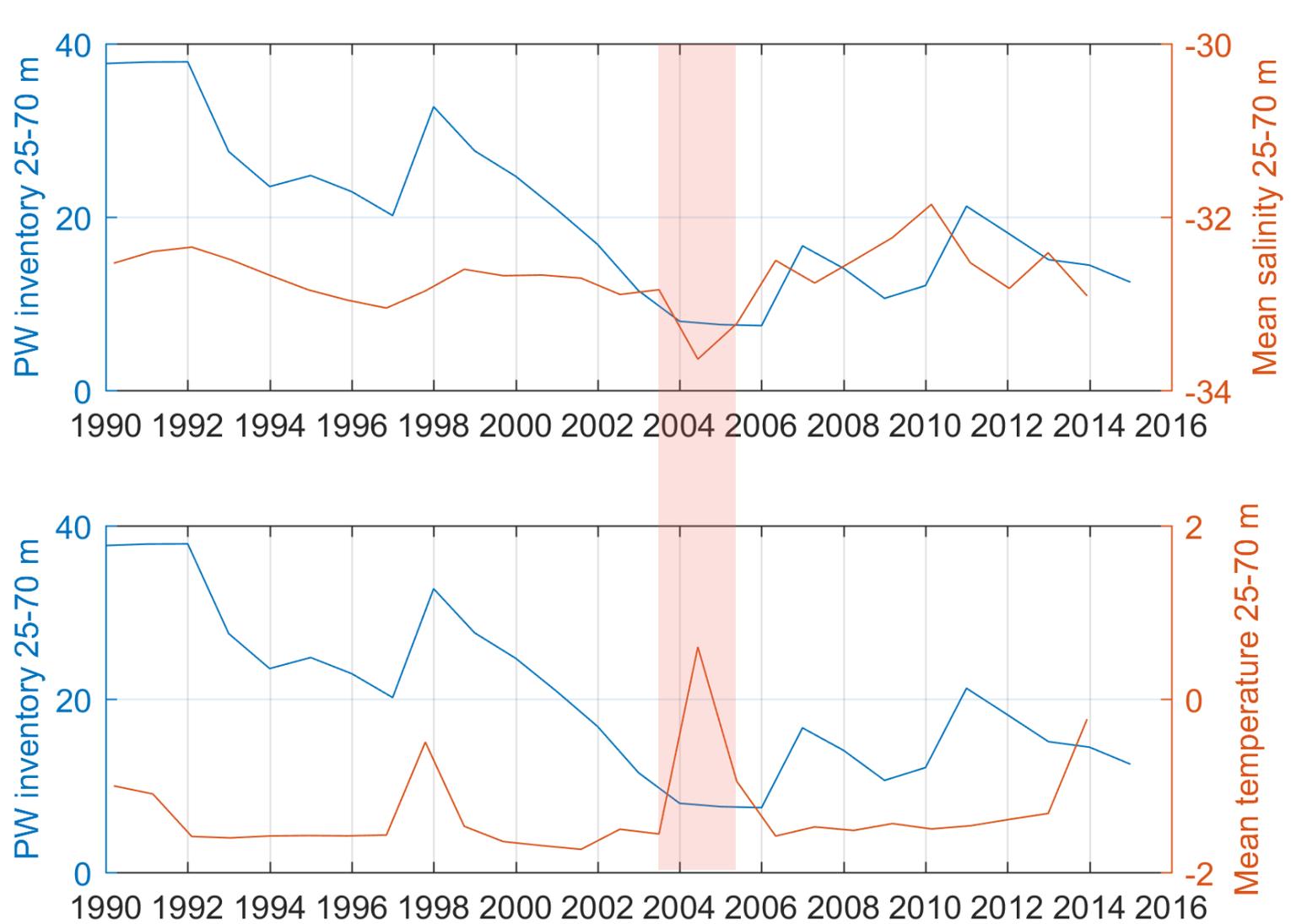
# North Pole Comparison



Adjusting for advection, peaks in the Pacific Water inventory line up nicely.

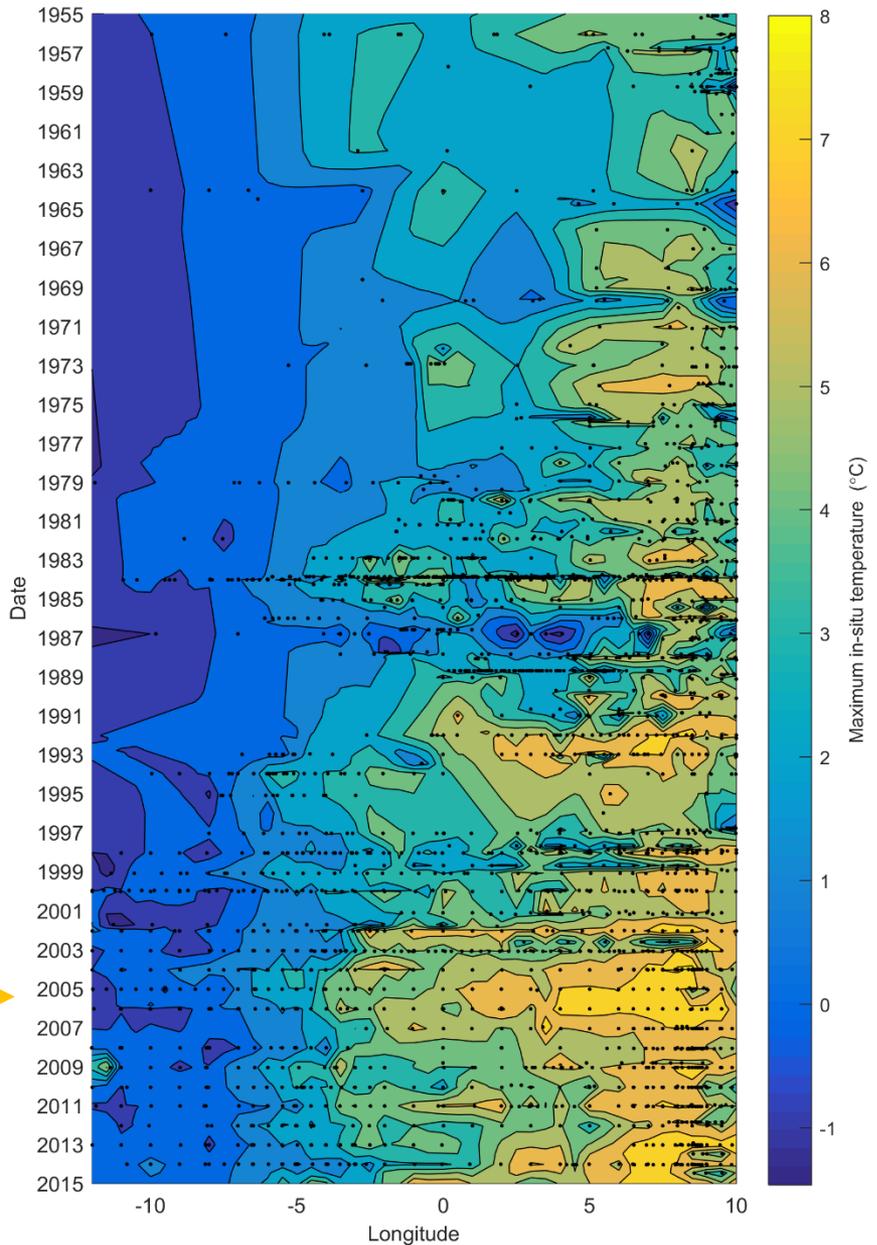
Not yet sure why peaks AND troughs are more extreme at the North Pole.

# Atlantic Water Events



One major anomaly: The 2005 strong recirculation of Atlantic water in Fram Strait (T+ , S+)

# Temperature Maxima in Fram Strait



2005-2006 Atlantic water event



# Summary: Surface Freshening

In *summer* 30-35% of freshwater is found in the top 25 m. A region only sampled once a year during CTD sections.

The *summer* freshwater inventory in the top 25 m from 2-12°W increased by about 0.7 m between 1995 and 2016

2012 & 2014 both saw record breaking mean *summer* freshwater inventories in the top 25 m from 2-12°W

Mean *year-round* sea ice thickness in Western Fram Strait decreased by 0.8 m between 1990 and 2011. A similar order of magnitude



# Summary: Pacific Water

Pacific water makes up between 10 % and 90 % of the halocline in the EGC

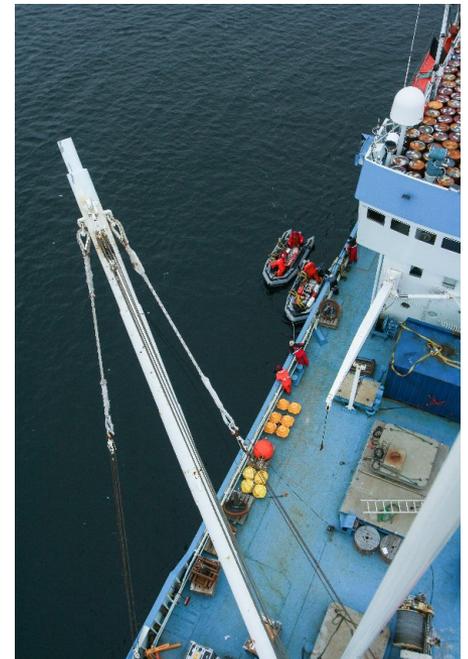
Variations in the fraction of relatively fresh Pacific water are partly responsible for short variations in the freshwater content of the halocline in the EGC lasting 2-3 years

Pacific water peaks were higher during and shortly after the very positive NAO-phase from 1988-95 than they are today, but the frequency of the variability is similar.

Pacific Water in the EGC halocline normally alternates with Knee Water – probably from the Arctic Ocean halocline

Pacific Water inventories in the EGC correlate well with Pacific Water inventories at the North Pole suggesting variability is controlled by upstream processes, not AW recirculation in Fram Strait.

However, in exceptional years Pacific Water is displaced by water of Atlantic origin which recirculates in Fram Strait.



# A slide for any skeptics ...

