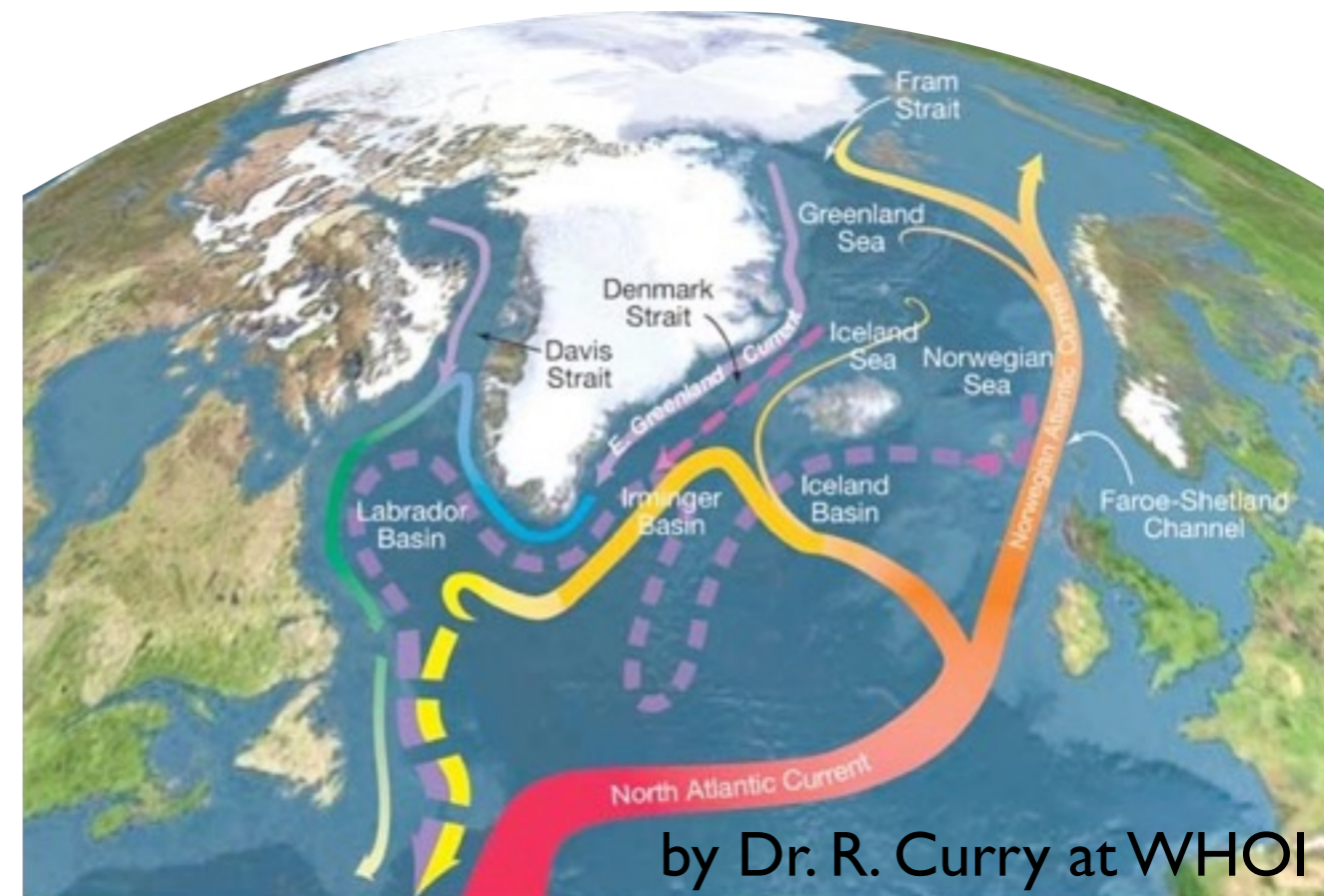


# The Arctic Ocean volume, heat and freshwater transports during 2004-2010

ARCGATE: Maximizing the potential of Arctic Ocean Gateway array

Takamasa Tsubouchi  
Wilken-Jon von Appen  
Ursula Schauer



# Arctic boundary observation

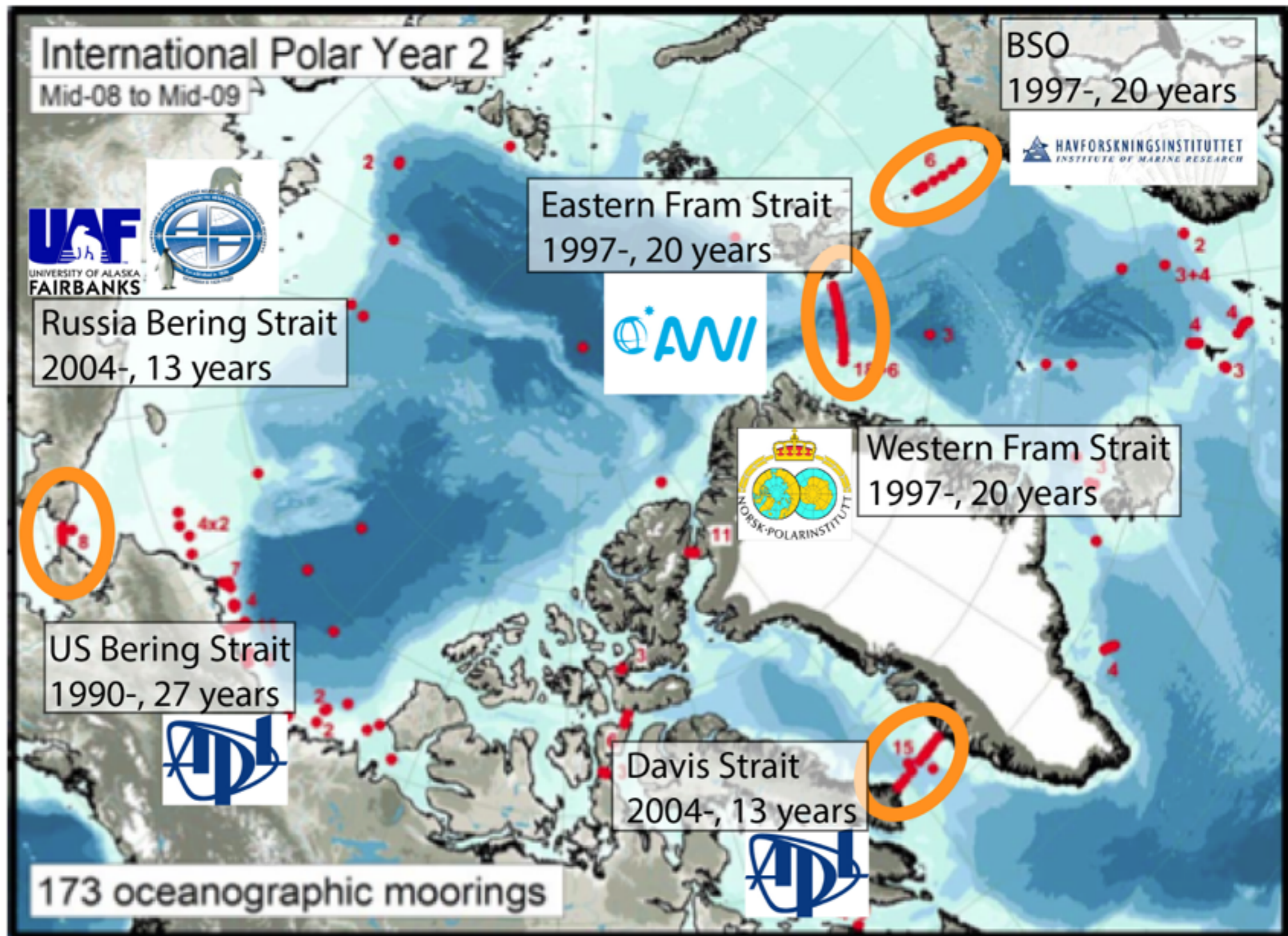
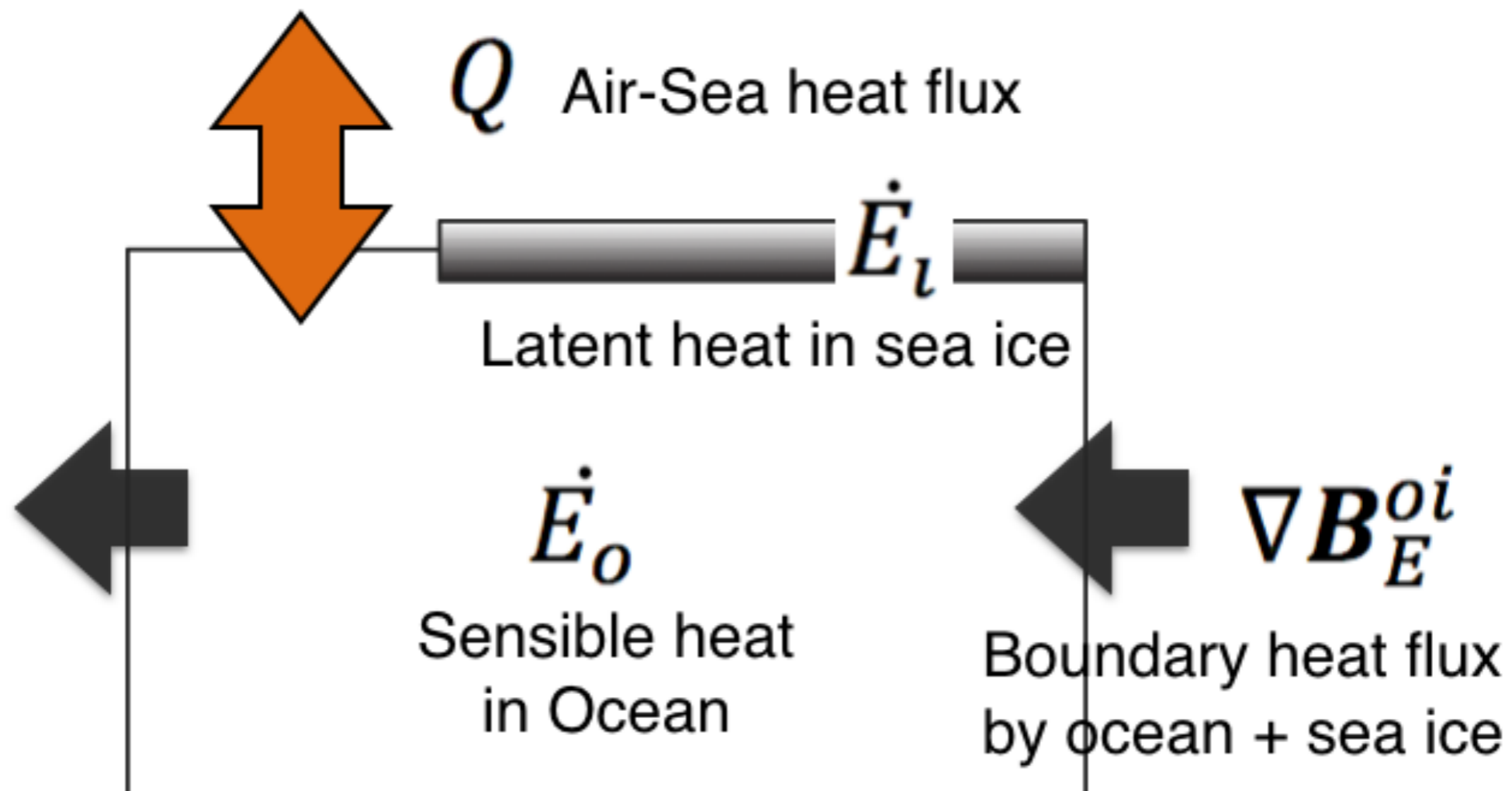


Fig. Mooring array during 2008-09, modified from Dickson et al. [2009]

# The heat budget in the Arctic Ocean

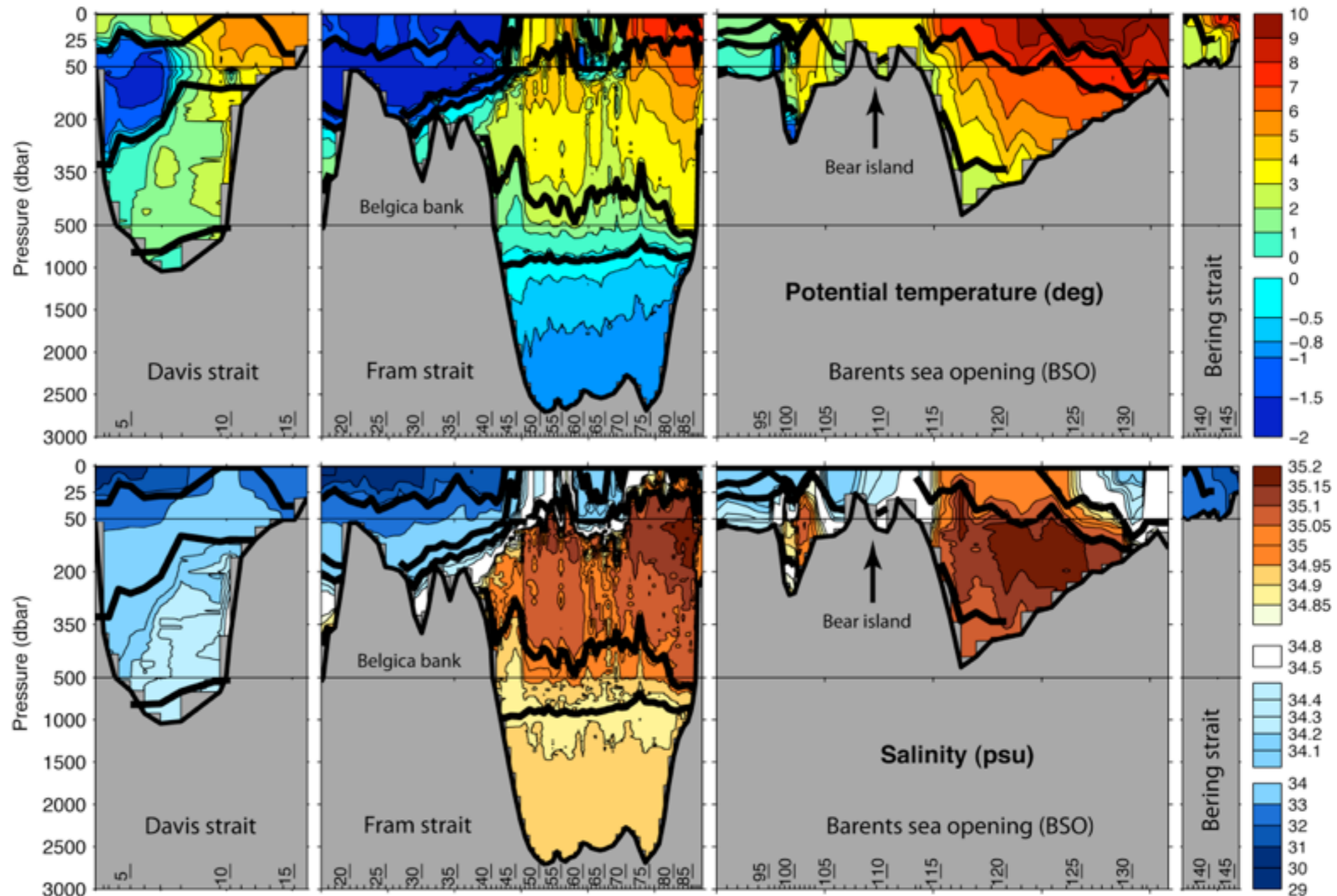
Little is known about oceanic heat temporal variability

$$\dot{E} = \dot{E}_o + \dot{E}_l = \nabla B_E^{oi} + Q$$



# The pan-Arctic approach: progress so far

- Quasi-synoptic estimate in summer 2005 [Tsubouchi et al., 2012].
- First seasonal cycle during 2005-06 [Tsubouchi et al. under review].



Tsubouchi et al.  
[2012, JGR]

# Objective of this study

Quantify “observation based” multi-year monthly volume, heat, FW transports during 2004-10.

Focus period: Oct. 2004 - May 2010  
(68 months)

# Data during 2004-2010

- ~1,000 moored instruments: microCAT (T, S: blue), RCM (T, (S),V: red), ADCP (V: green).
- 37 Repeat CTD sections in south of BSO.
- PIOMAS sea ice thickness & velocity data [Zhang and Rothrock, 2003]

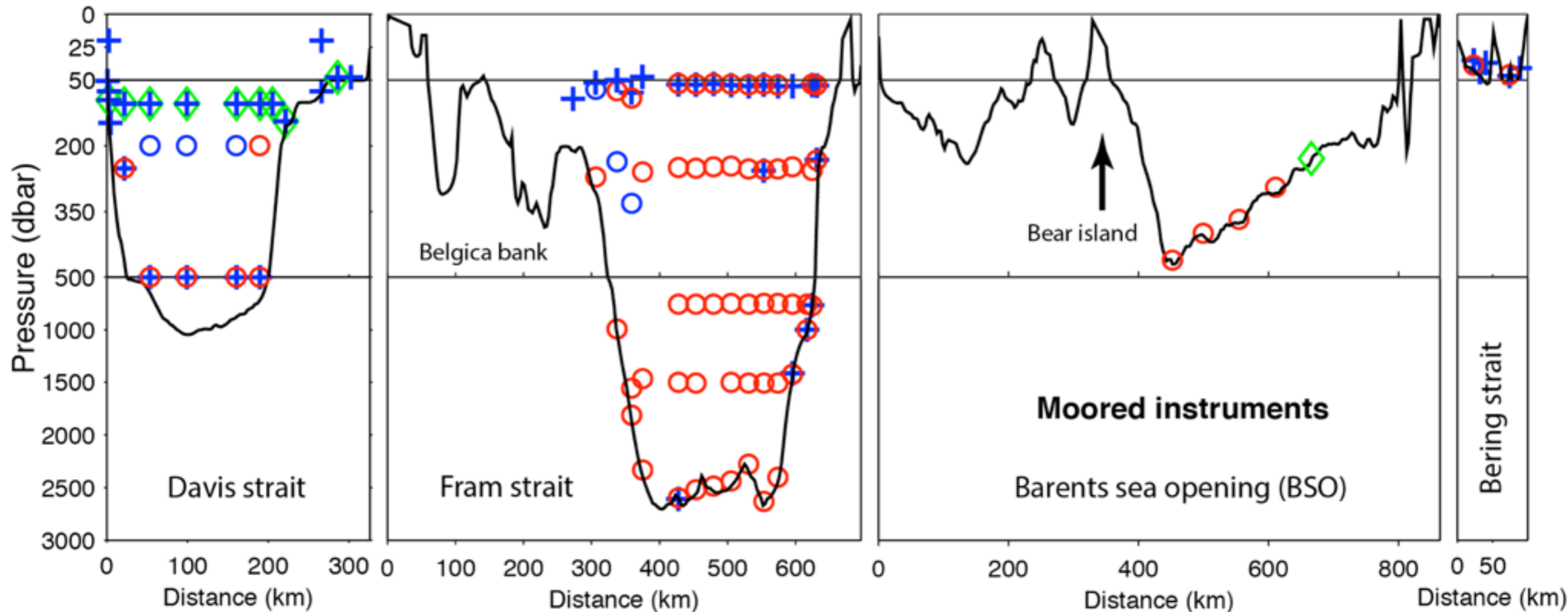
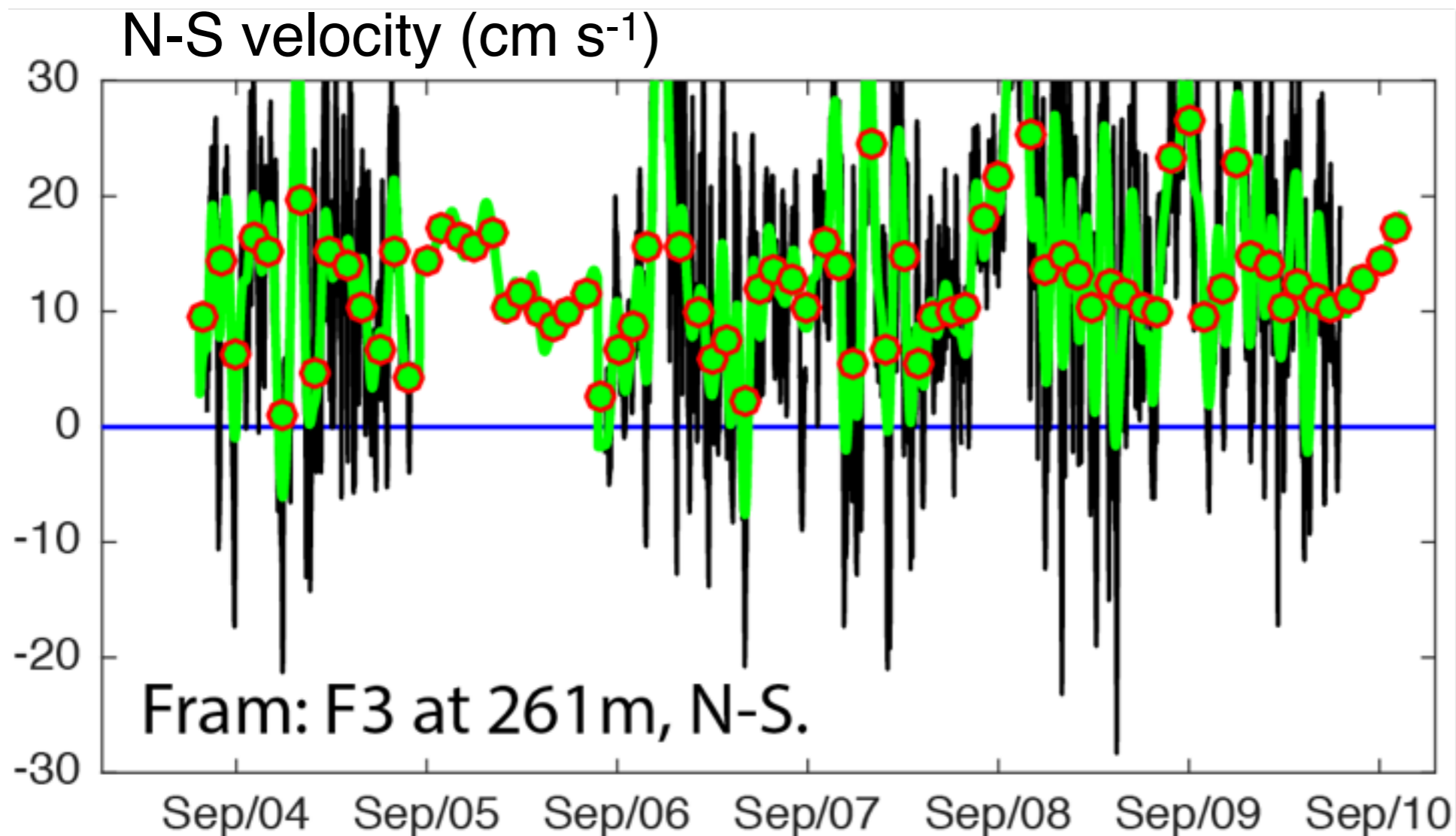


Fig. Mooring array in the Arctic four main gates

# Filtering and Gridding

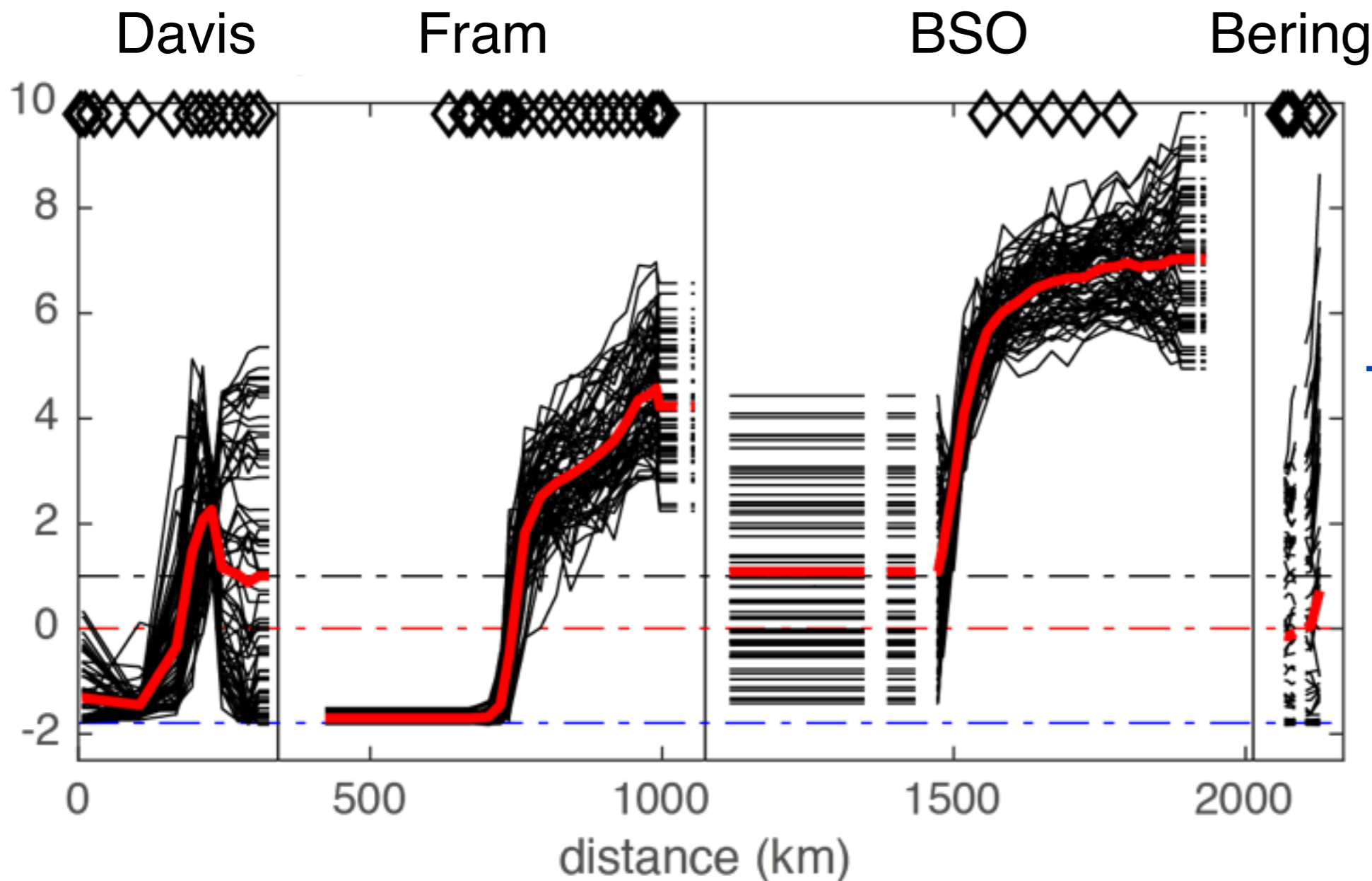
- De-tided and smoothed with Butterworth filter (27 days cutoff).
- Data gaps ( $> 30$ days) are filled by its mean annual cycle.
- Linear interpolation is applied vertically and horizontally.



Daily de-tided (black)  
Daily smoothed (green)  
Monthly mean (red)

# Monthly Temperature fields

- Captures major water mass distributions & variabilities
  - AW in WSC and BSO, Polar water, large variability in Bering Strait.

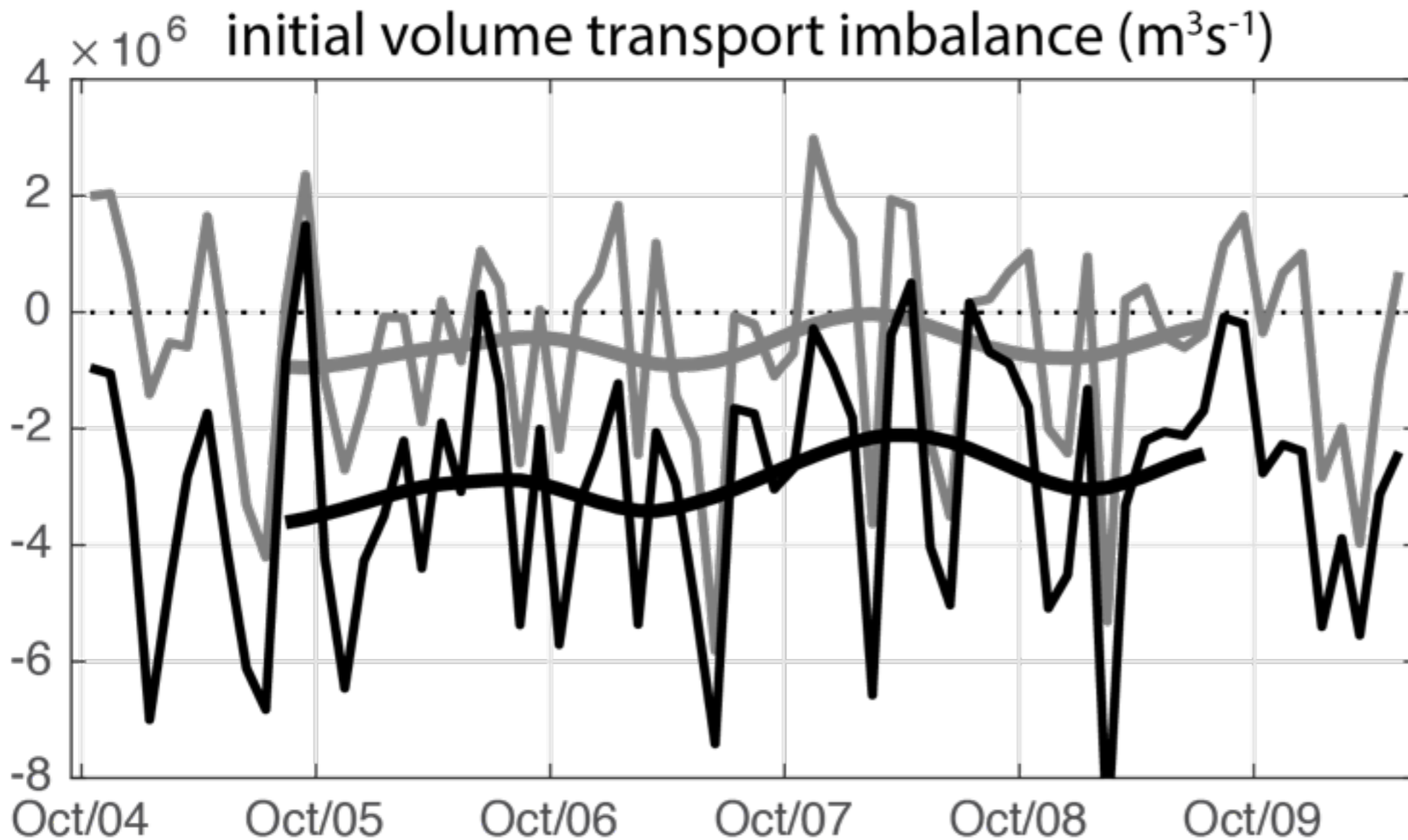


Temperature at 50m.  
Monthly in black,  
average in red.



# Monthly initial volume transport imbalance

- Initial imbalances is  $-3.0 \pm 2.2$  Sv.
- Of which, below 1,500m accounts for  $-2.4 \pm 0.9$  Sv.

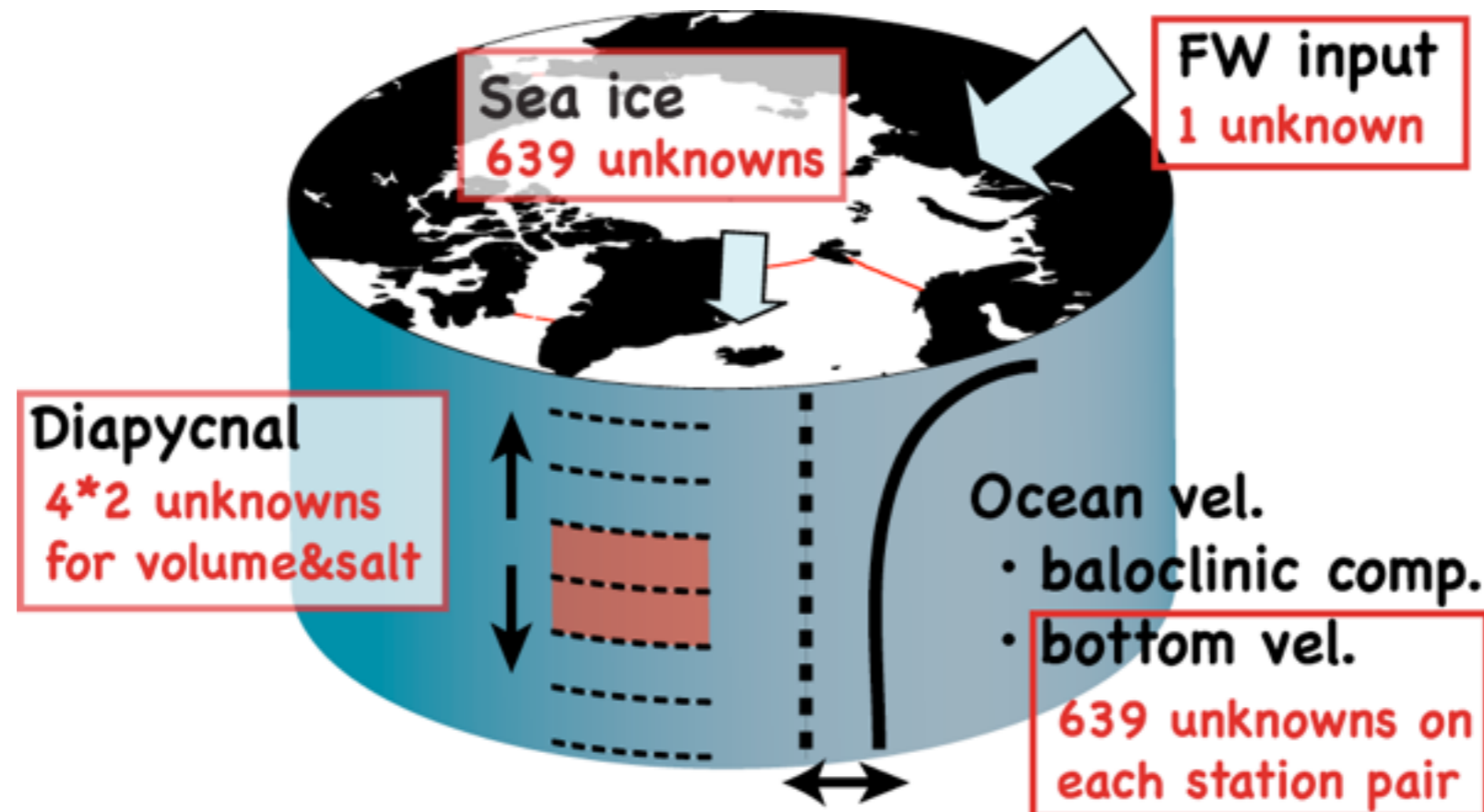


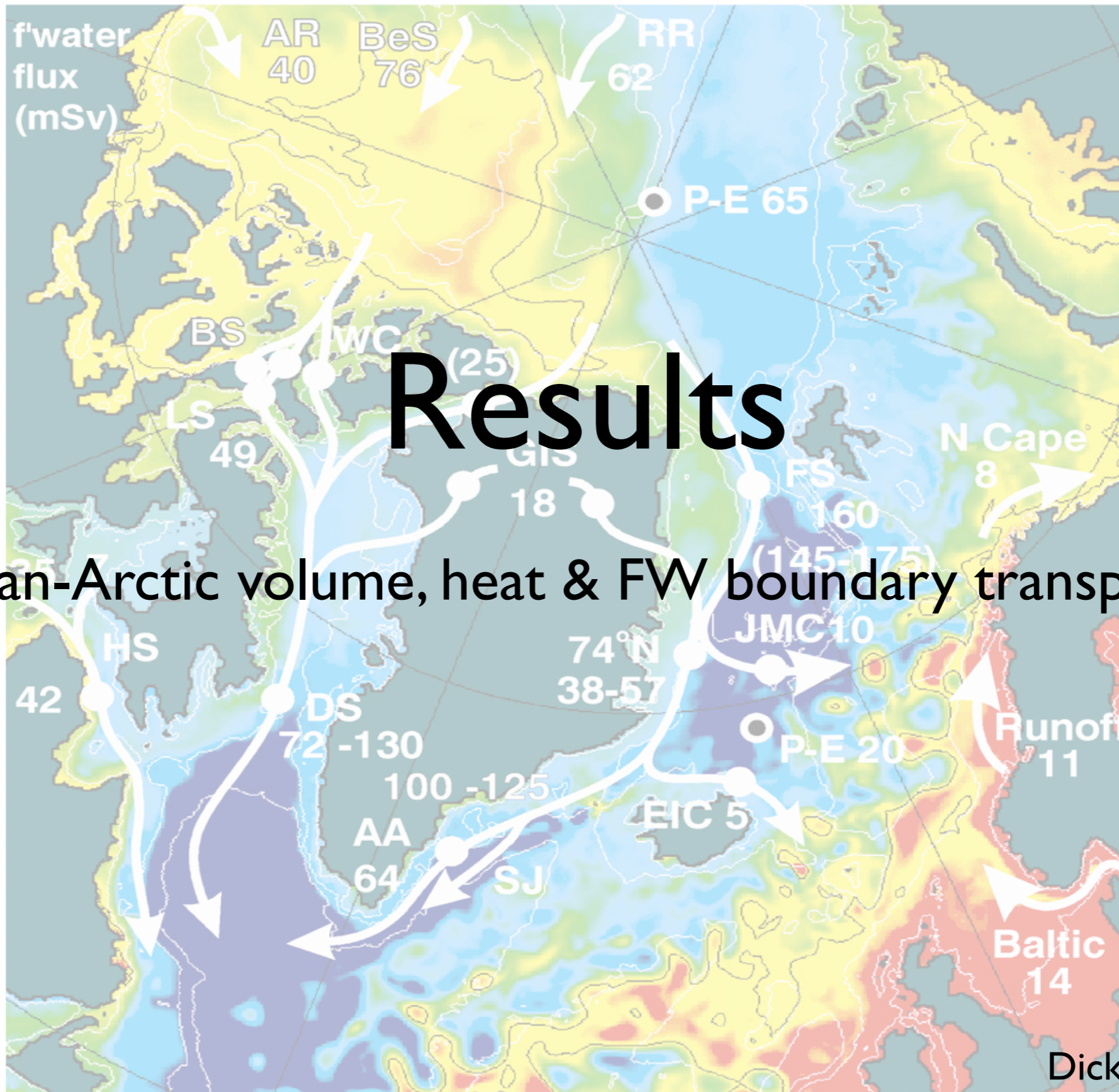
Full depth (black),  
above 1,500m (grey).

# Inverse model: unknowns & constraints

Obtain volume and salt conserved monthly velocity field for consecutive 68 months.

- 1287 unknowns are derived from 12 constraints.
- Bottom vel (639), Sea ice (639), FW input (1), Diapycnal (8)
- Volume & Salt: 5 layers and whole layer





# Mean velocity field during 2004-2010

- Captures major current system.
- Polar water outflow, AW inflow, PW inflow.

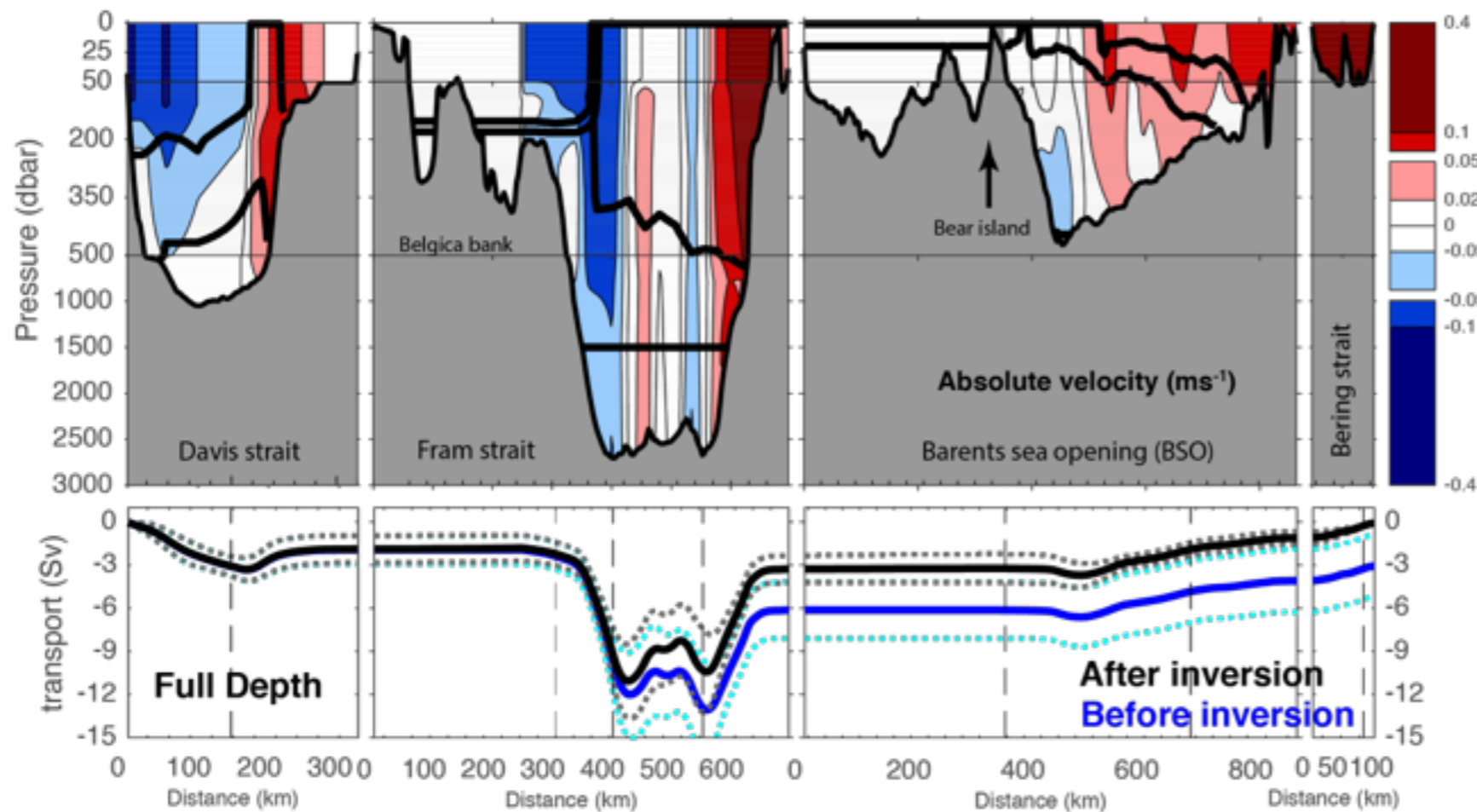


Table: volume transport comparison

(Sv)	This study	reference
Davis	$-1.9 \pm 1.0$	$-1.6 \pm 0.5$ (*1)
Fram	$-1.4 \pm 1.2$	$-2.0 \pm 2.7$ (*2)
BSO	$2.2 \pm 1.0$	$2.0$ (*3)
Bering	$1.0 \pm 0.5$	$0.8$ (*4)
Net	$-0.10 \pm 0.06$	$-0.8$

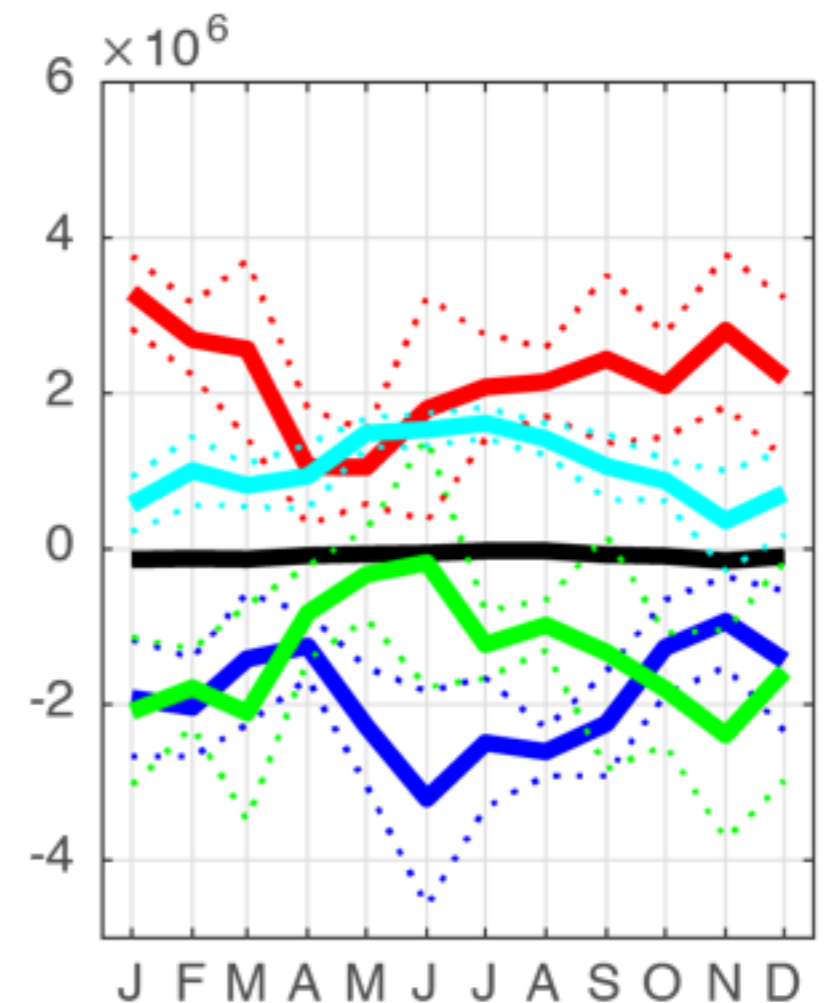
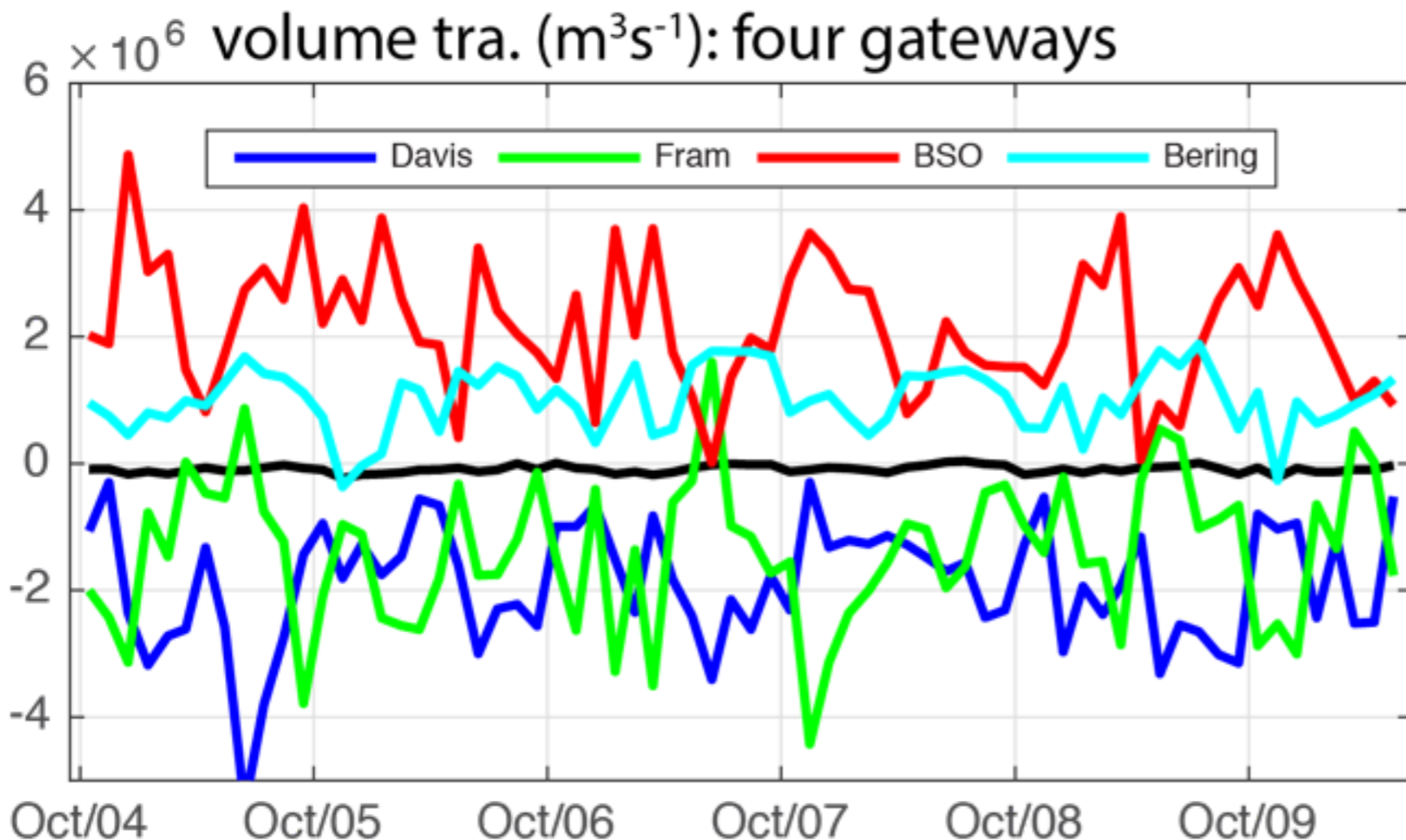
Fig. (top) mean volume & salt closed velocity field. (Bottom) cumulative full depth volume transport.

\*1 Curry et al., 2014, \*2 Schauer et al., 2008, \*3 Smerdsrud et al., 2010, \*4 Woodgate et al., 2005

# Volume transports: each gateway

- Net transport is almost zero in each month.
- Seasonality.
  - Strong BSO inflow in winter.
  - Strong Bering inflow in summer.

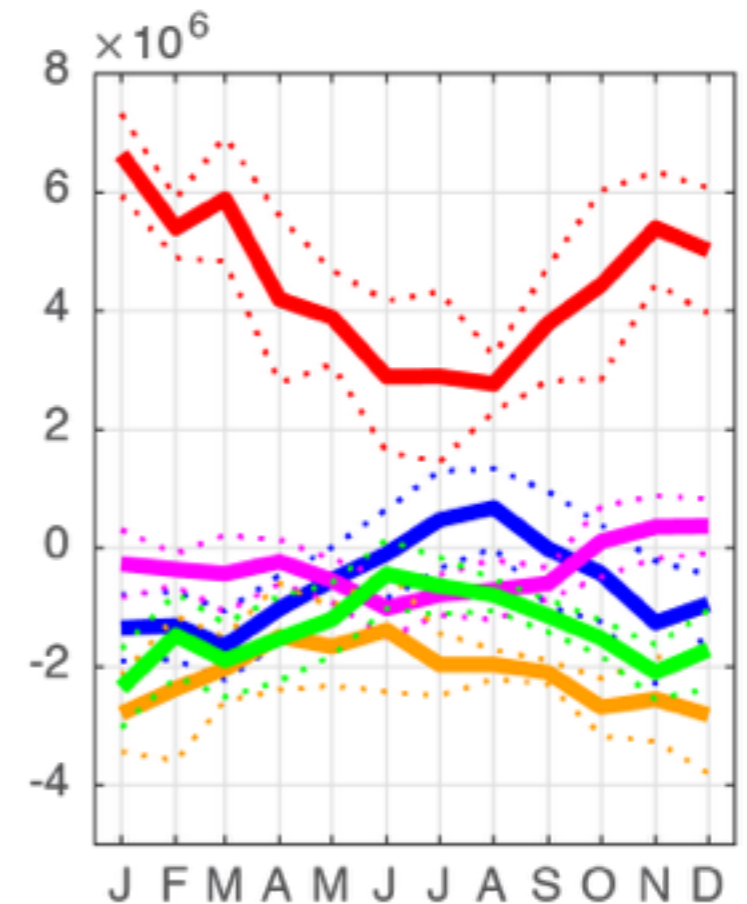
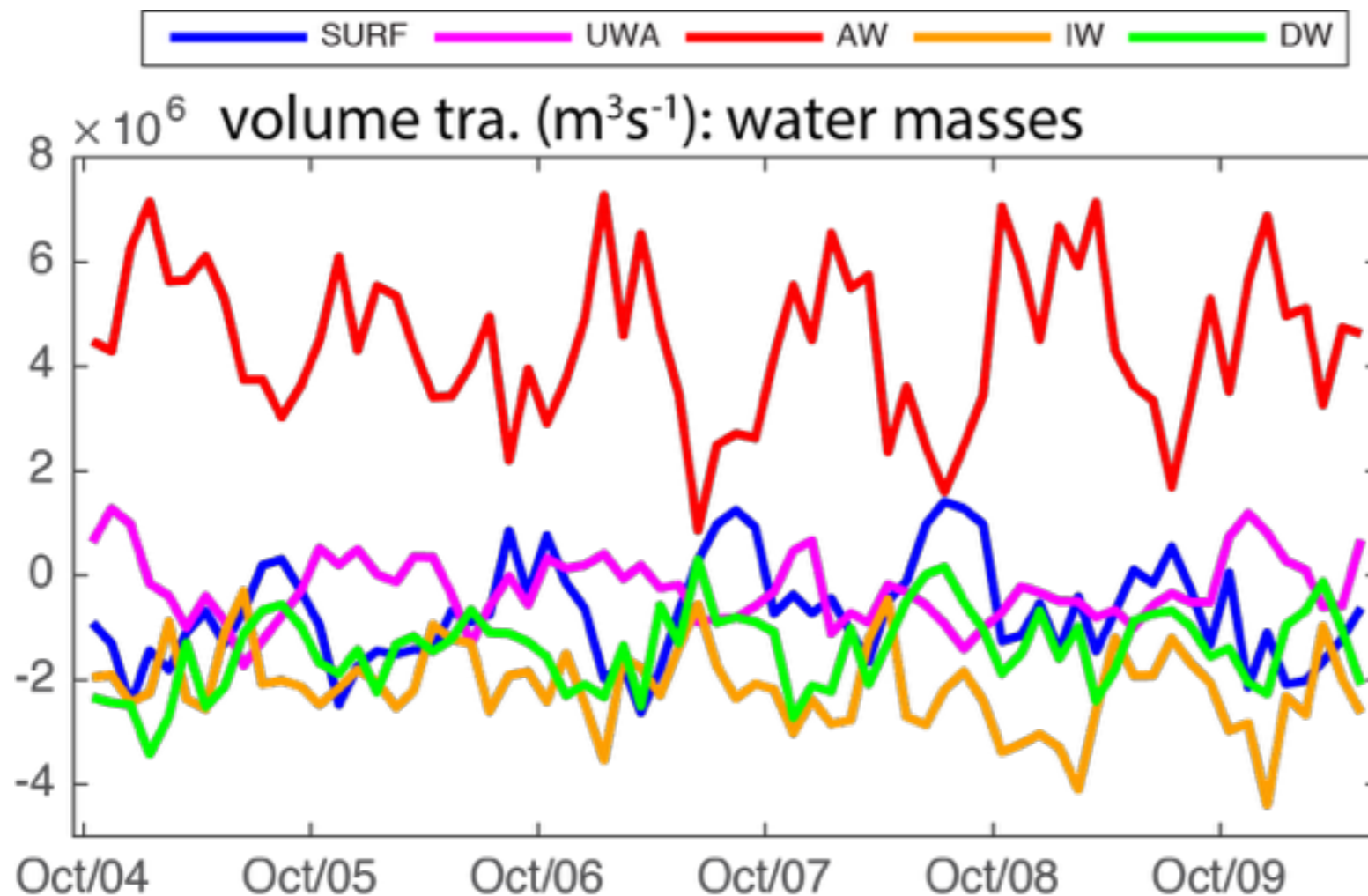
(Sv)	long term	JFM	JAS
Davis	$-1.9 \pm 1.0$	-1.8	-2.4
Fram	$-1.4 \pm 1.2$	-2.0	-1.2
BSO	$2.2 \pm 1.0$	+2.9	+2.2
Bering	$1.0 \pm 0.5$	+0.8	+1.4



# Volume transports: water mass

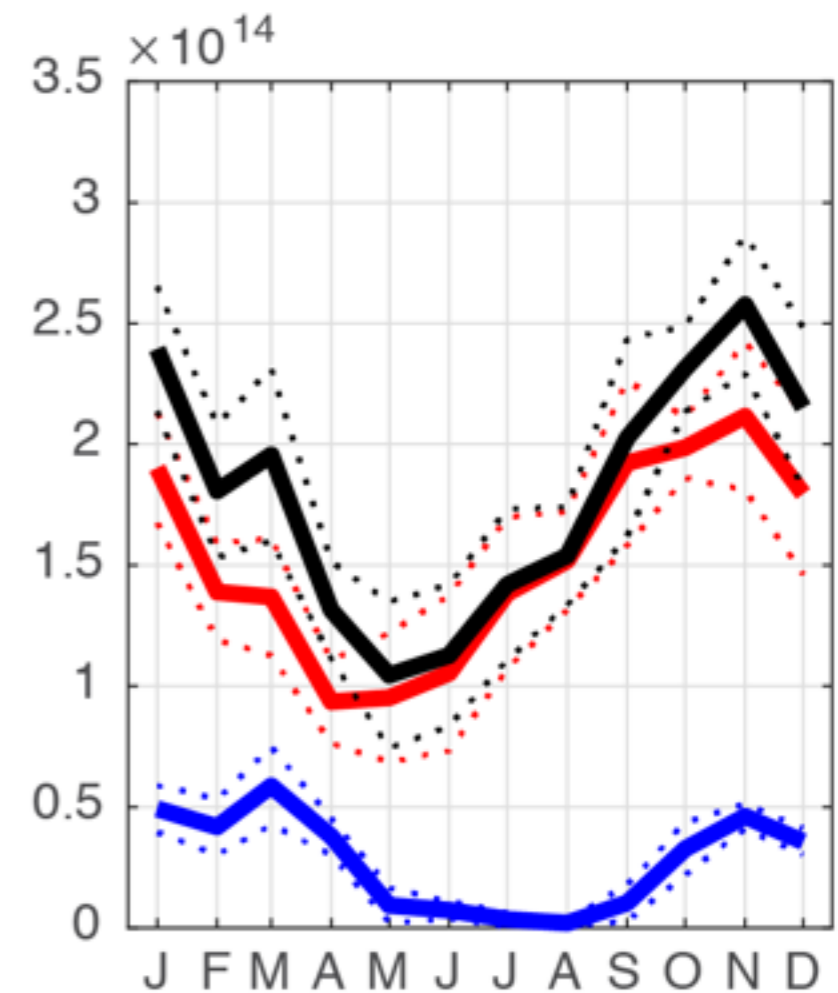
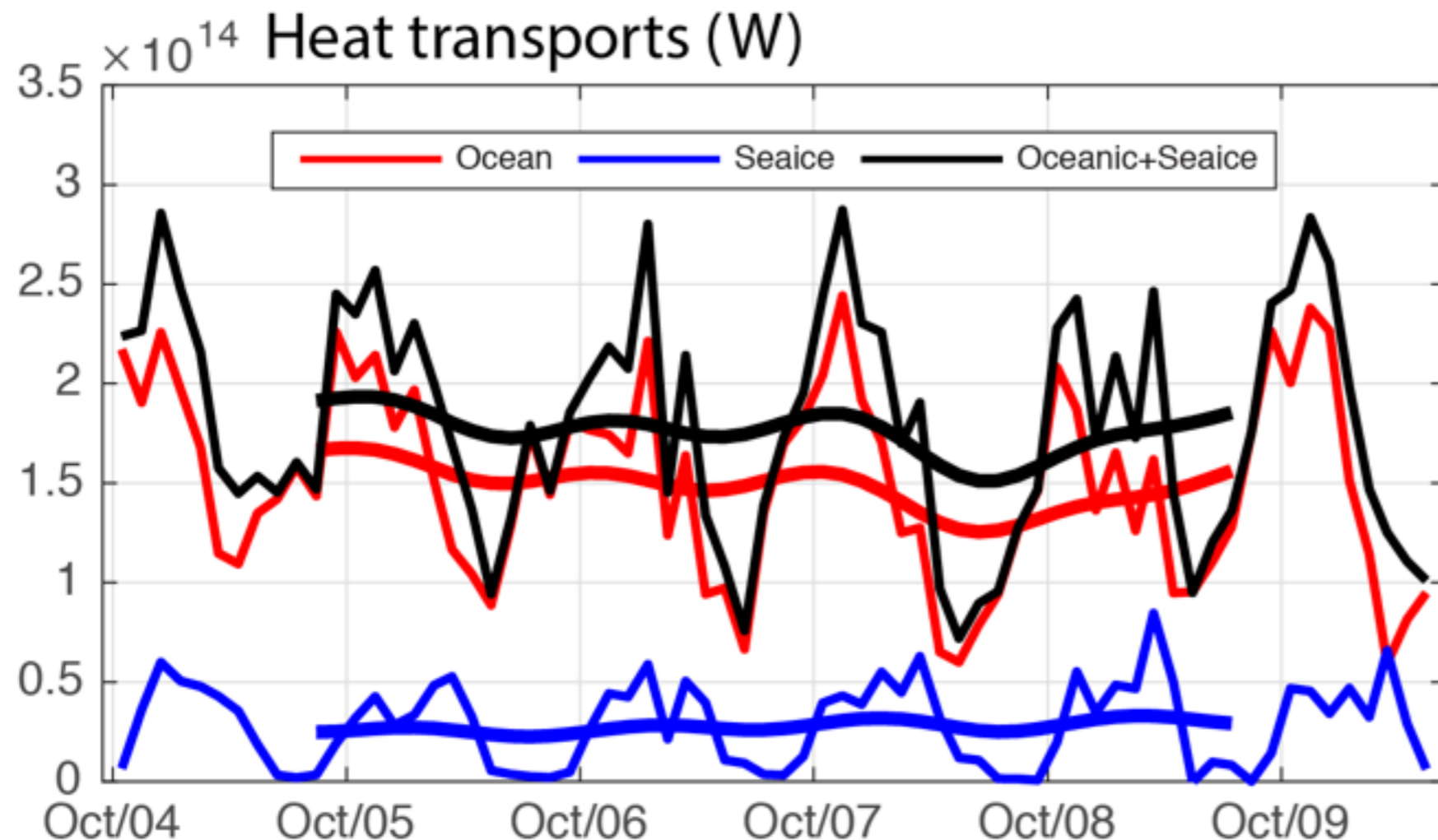
- Double cell overturning structure.
- AW inflow: strong in winter, weak in summer.
- DW outflow ( $-1.4 \pm 0.8$  Sv) may be too strong.

(Sv)	mean	JFM	JAS
SURF+UAW	-1.0	-1.8	-0.3
AW	+4.5	+6.0	+3.2
IW+DW	-3.5	-4.3	-2.9



# The Heat transports

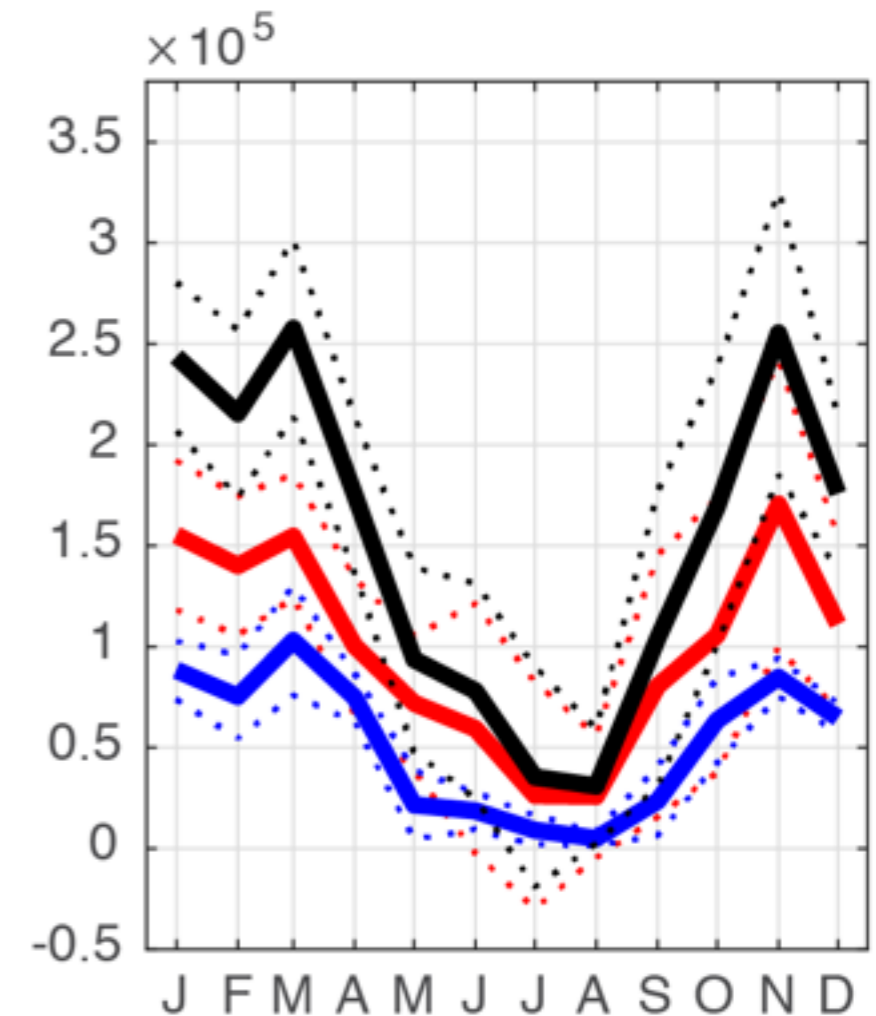
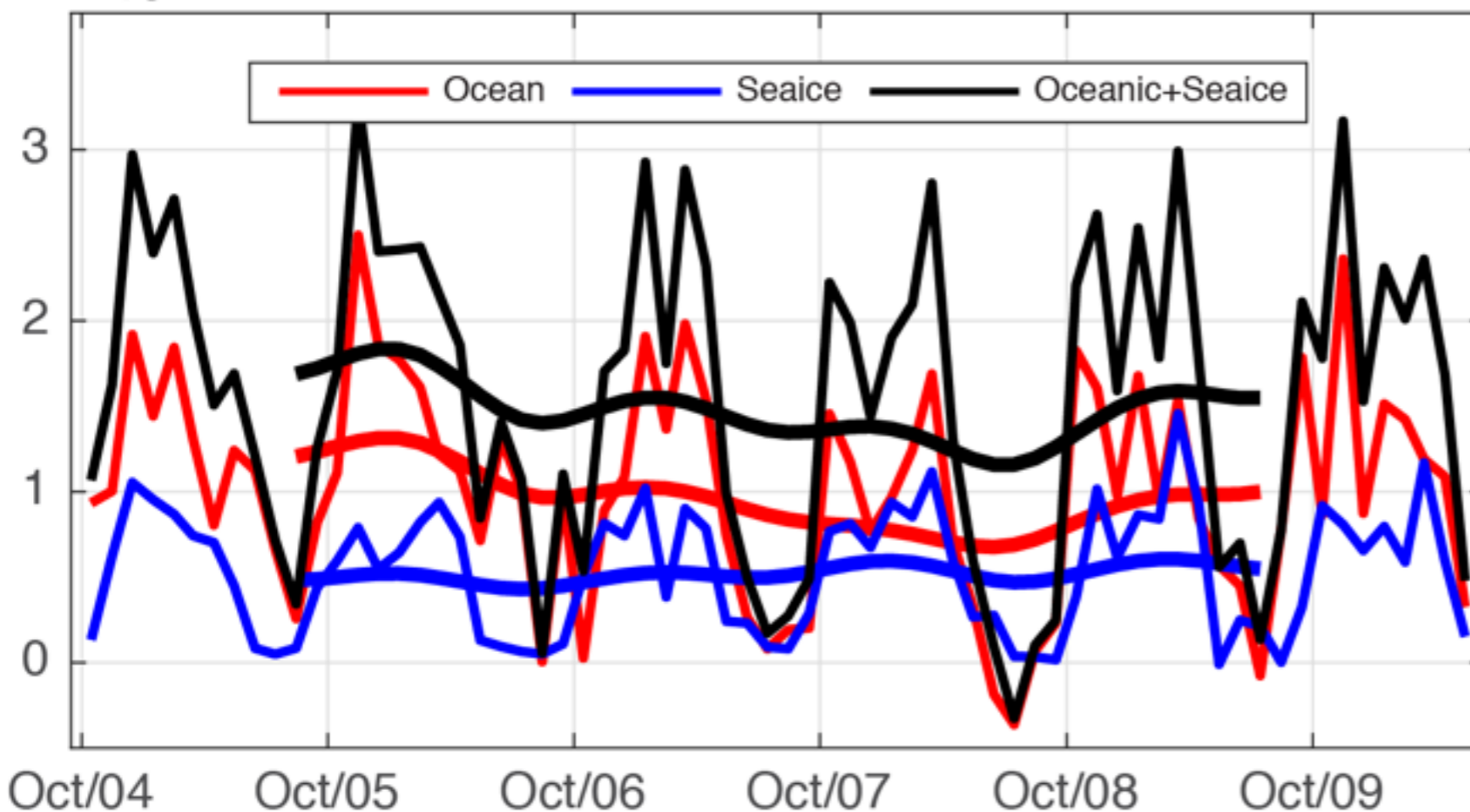
- The heat transport is  $180 \pm 57$  TW (68 monthly ave & std).
  - Seasonality:  $\sim 250$  TW in Nov,  $\sim 100$  TW in May.
  - Inter-annual variability:  $196 \pm 56$  TW in 2004-05,  $165 \pm 71$  TW in 2007-08.
- \*12 monthly ave & std from Oct to following Sep.



# The FW transports

- The FW transport is  $156 \pm 91$  mSv (68 monthly ave & std).
  - Seasonality:  $\sim 250$  mSv in Nov-Mar,  $\sim 50$  mSv in Jun-Aug.
  - Inter-annual variability:  $163 \pm 79$  mSv in 2004-05,  $121 \pm 103$  mSv in 2007-08.
- \*12 monthly ave & std from Oct to following Sep.

$\times 10^5$  FW transports ( $\text{m}^3\text{s}^{-1}$ )





# Putting into a big picture

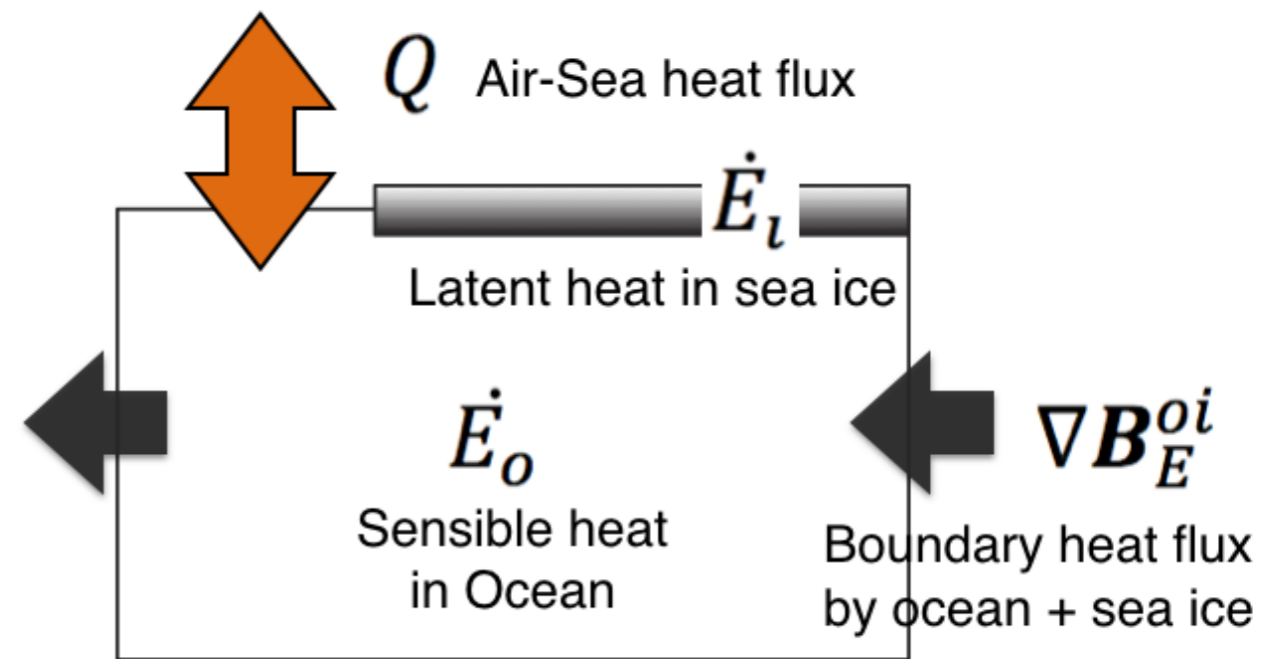
- Heat budget
  - $180 \pm 57 \text{ TW} \sim 15.9 \pm 5.0 \text{ Wm}^{-2}$
  - MERRA has the best agreement.

$$\dot{E} = \dot{E}_o + \dot{E}_l = \nabla B_E^{oi} + Q$$

Long-term air-sea heat fluxes  
north of  $70^\circ\text{N}$  ( $\text{Wm}^{-2}$ )

NRA	ERA40	JRA25	MERRA
5	11	14	19

Porter et al. [2010], Cullather & Bosilovich [2012]

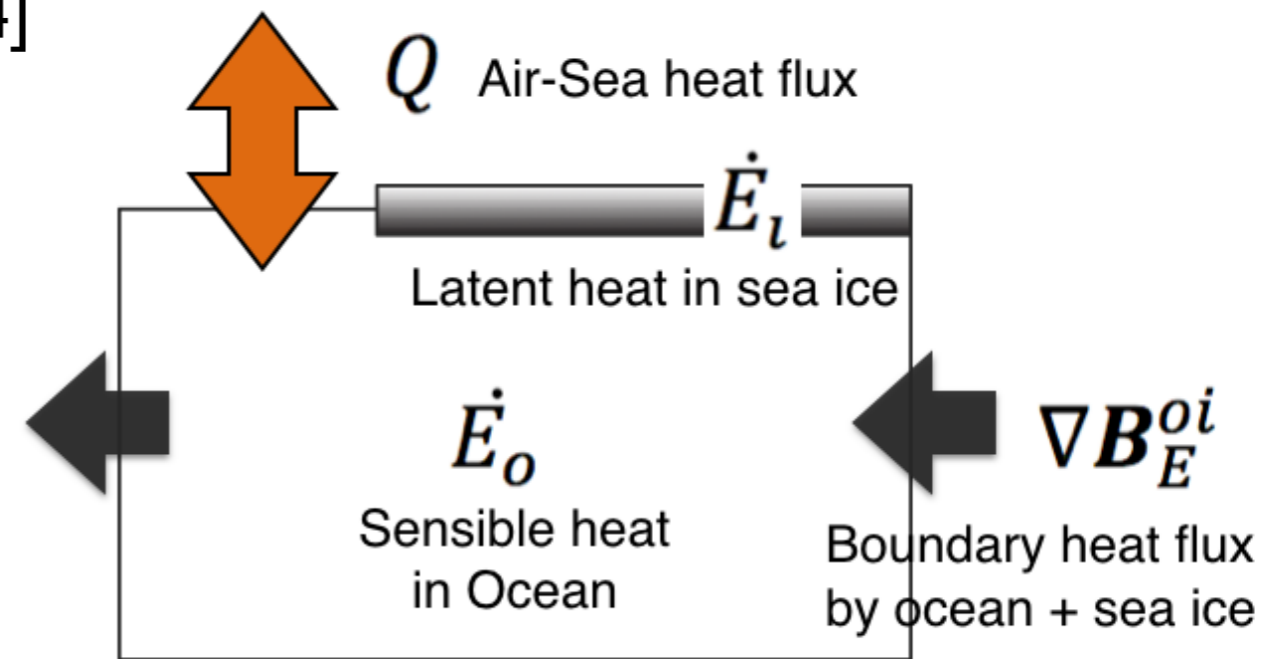


Note that  $10 \text{ W/m}^2$  is equivalent to  
1m sea ice melt in a year.

# Putting into a big picture

- FW budget
  - Boundary:  $156 \pm 91$  mSv
  - Surface:  $\sim 214$  mSv. Haine et al. [2015]
  - FW content:  $\sim 25$  mSv. Rabe et al. [2014]
  - Imbalance of  $\sim 33$  mSv - significant?

$$\dot{E} = \dot{E}_o + \dot{E}_l = \nabla B_E^{oi} + Q$$



# What changes by changing $T_{ref}$ ?

- Total heat transport DOES NOT change.
- Temperature transport in each piece of section DOES change.
- e.g. WSC:  $33 \pm 14$  TW-eq ( $1.01 \pm 0.18^\circ\text{C}$ ),  $113 \pm 34$  TW-eq ( $-1.8^\circ\text{C}$ ).

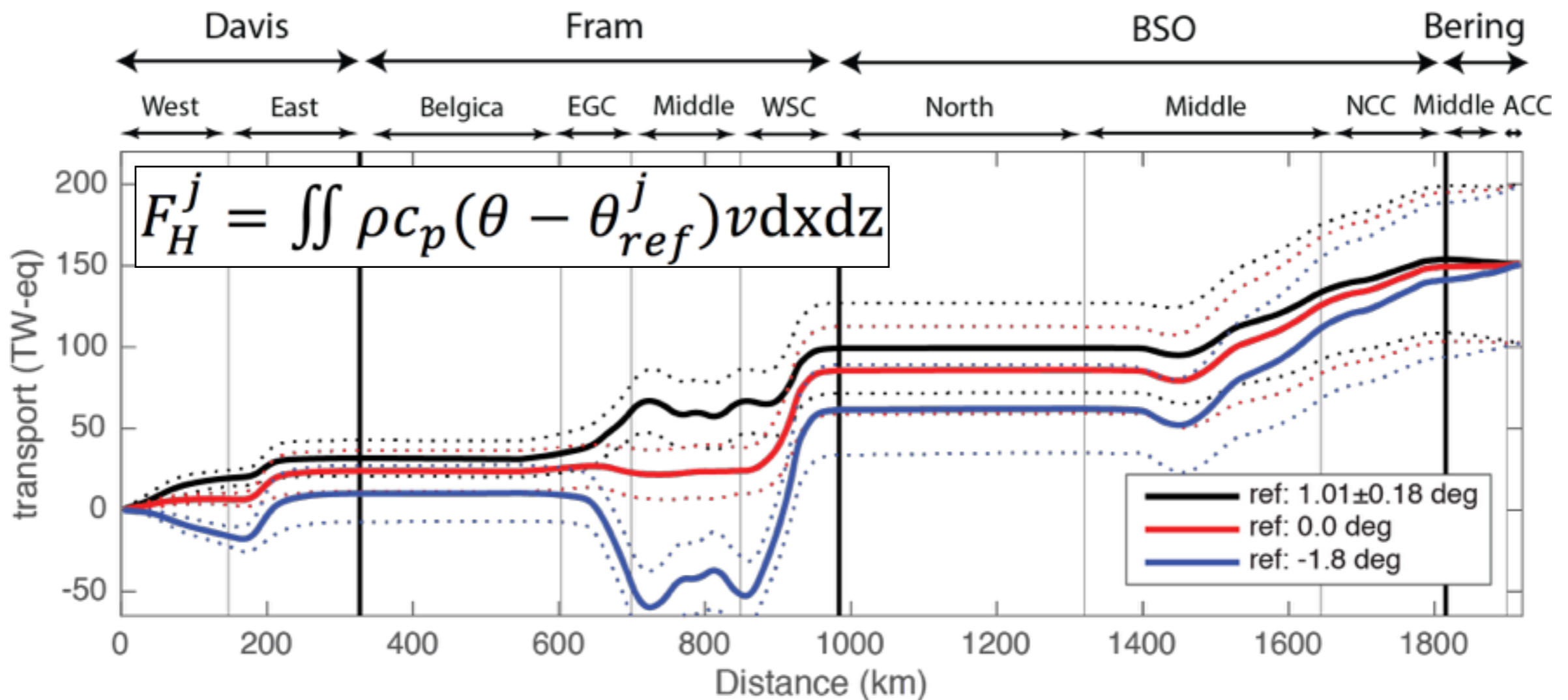


Fig. Accumulative full depth heat transport along sections.

# What changes by changing $S_{ref}$ ?

- Total FW transport DOES NOT change (almost).
- FW transport in each piece of section DOES change.
- e.g. EGC:  $-4 \pm 11$  mSv-eq ( $34.70 \pm 0.02$ ),  $95 \pm 21$  mSv-eq ( $35.2$ ).

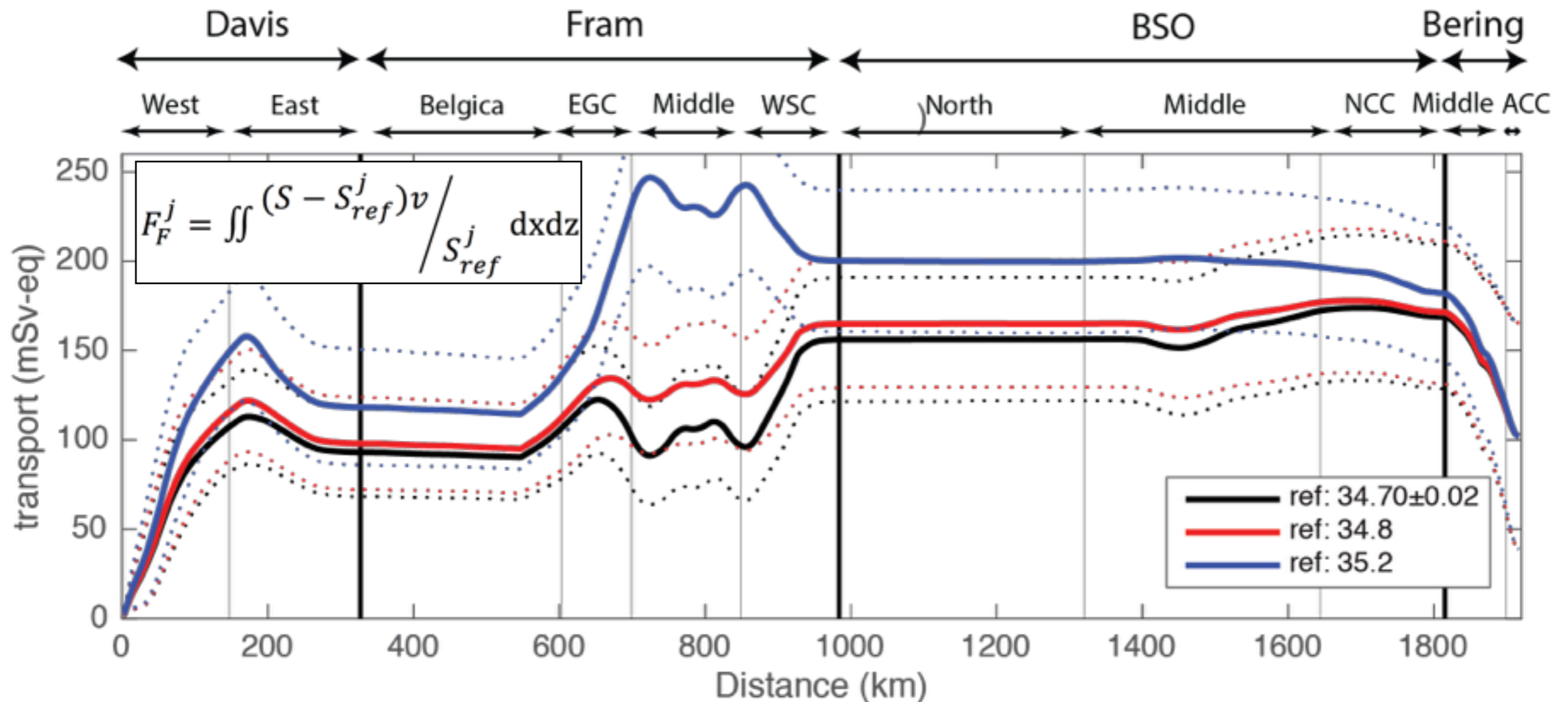


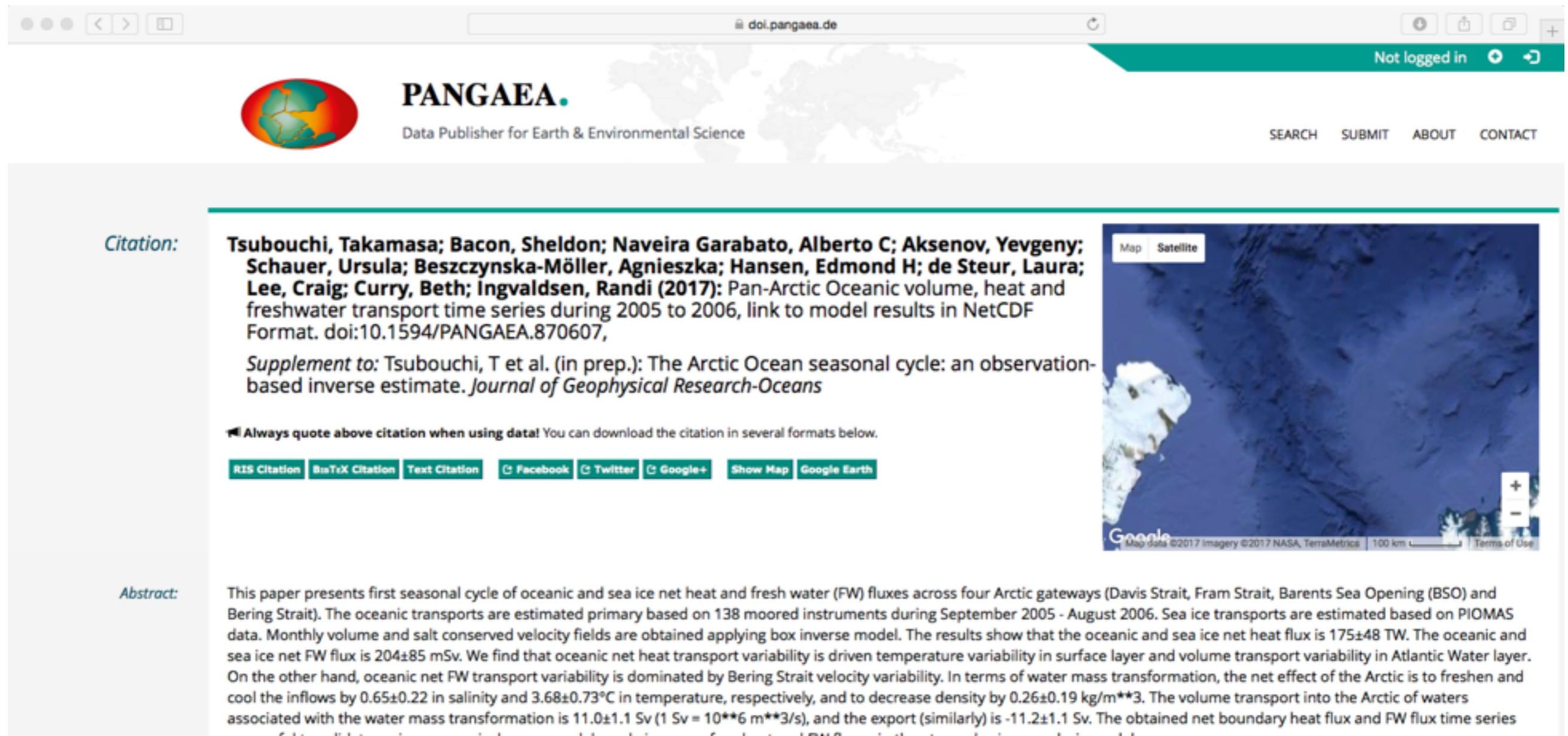
Fig. Accumulative full depth FW transport along sections.

# Take home message

- Mass & salt conserved velocity field is crucial to calculate heat & FW transport.
- Choice of reference value is arbitrary.
  - For heat, any value is possible.
  - For FW, sensible values (34.7-35.2) only introduce error of ~1%.
- Recognise the impact of choice of reference values.
  - Total heat & FW DOES NOT change (For FW, almost).
  - Partial sectional values DOES change.

# Data on PANGAEA

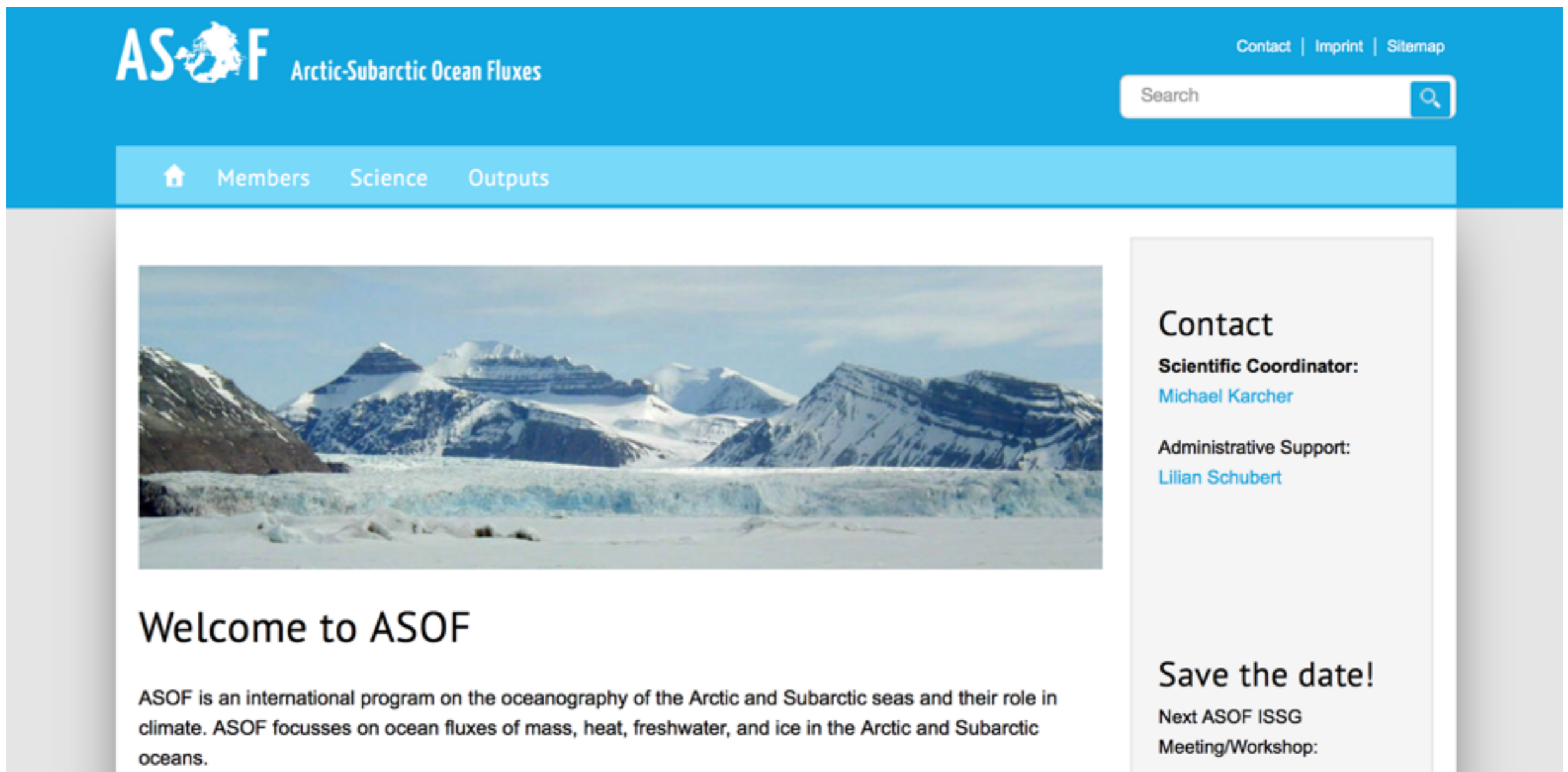
- One year data is available.
- Search Tsubouchi, then you will find it.
- 68 month data will be available in this summer.



The screenshot shows the PANGAEA website interface. At the top, there is a navigation bar with the PANGAEA logo (a globe) and the text "PANGAEA. Data Publisher for Earth & Environmental Science". To the right of the logo, there are links for "SEARCH", "SUBMIT", "ABOUT", and "CONTACT". The main content area displays a citation for a 2017 paper by Tsubouchi, Takamasa; Bacon, Sheldon; Naveira Garabato, Alberto C; Aksenov, Yevgeny; Schauer, Ursula; Beszczynska-Möller, Agnieszka; Hansen, Edmond H; de Steur, Laura; Lee, Craig; Curry, Beth; Ingvaldsen, Randi. The citation text is: "Tsubouchi, Takamasa; Bacon, Sheldon; Naveira Garabato, Alberto C; Aksenov, Yevgeny; Schauer, Ursula; Beszczynska-Möller, Agnieszka; Hansen, Edmond H; de Steur, Laura; Lee, Craig; Curry, Beth; Ingvaldsen, Randi (2017): Pan-Arctic Oceanic volume, heat and freshwater transport time series during 2005 to 2006, link to model results in NetCDF Format. doi:10.1594/PANGAEA.870607, Supplement to: Tsubouchi, T et al. (in prep.): The Arctic Ocean seasonal cycle: an observation-based inverse estimate. *Journal of Geophysical Research-Oceans*". Below the citation, there is a note: "Always quote above citation when using data! You can download the citation in several formats below." and a row of buttons for "RIS Citation", "BisTrX Citation", "Text Citation", "Facebook", "Twitter", "Google+", "Show Map", and "Google Earth". To the right of the citation, there is a satellite map of the Arctic region. Below the citation, there is an "Abstract:" section with the following text: "This paper presents first seasonal cycle of oceanic and sea ice net heat and fresh water (FW) fluxes across four Arctic gateways (Davis Strait, Fram Strait, Barents Sea Opening (BSO) and Bering Strait). The oceanic transports are estimated primary based on 138 moored instruments during September 2005 - August 2006. Sea ice transports are estimated based on PIOMAS data. Monthly volume and salt conserved velocity fields are obtained applying box inverse model. The results show that the oceanic and sea ice net heat flux is  $175 \pm 48$  TW. The oceanic and sea ice net FW flux is  $204 \pm 85$  mSv. We find that oceanic net heat transport variability is driven temperature variability in surface layer and volume transport variability in Atlantic Water layer. On the other hand, oceanic net FW transport variability is dominated by Bering Strait velocity variability. In terms of water mass transformation, the net effect of the Arctic is to freshen and cool the inflows by  $0.65 \pm 0.22$  in salinity and  $3.68 \pm 0.73^\circ\text{C}$  in temperature, respectively, and to decrease density by  $0.26 \pm 0.19 \text{ kg/m}^3$ . The volume transport into the Arctic of waters associated with the water mass transformation is  $11.0 \pm 1.1$  Sv (1 Sv =  $10^6 \text{ m}^3/\text{s}$ ), and the export (similarly) is  $-11.2 \pm 1.1$  Sv. The obtained net boundary heat flux and FW flux time series

# ASOF's role to promote this study

- Endorsement
- Gateway to the PANGAEA web link
- Present the time series as scientific deliverable




The screenshot shows the ASOF website homepage. The header is blue with the ASOF logo (Arctic-Subarctic Ocean Fluxes) on the left and navigation links (Contact, Imprint, Sitemap) and a search bar on the right. Below the header is a light blue navigation bar with icons for Home, Members, Science, and Outputs. The main content area features a large photograph of a snowy mountain range. Below the photo is the heading "Welcome to ASOF" and a paragraph describing the program. On the right side, there is a "Contact" section listing the Scientific Coordinator (Michael Karcher) and Administrative Support (Lilian Schubert), and a "Save the date!" section for the next ASOF ISSG Meeting/Workshop.

**ASOF** Arctic-Subarctic Ocean Fluxes

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Home Members Science Outputs



## Welcome to ASOF

ASOF is an international program on the oceanography of the Arctic and Subarctic seas and their role in climate. ASOF focusses on ocean fluxes of mass, heat, freshwater, and ice in the Arctic and Subarctic oceans.

### Contact

**Scientific Coordinator:**  
[Michael Karcher](#)

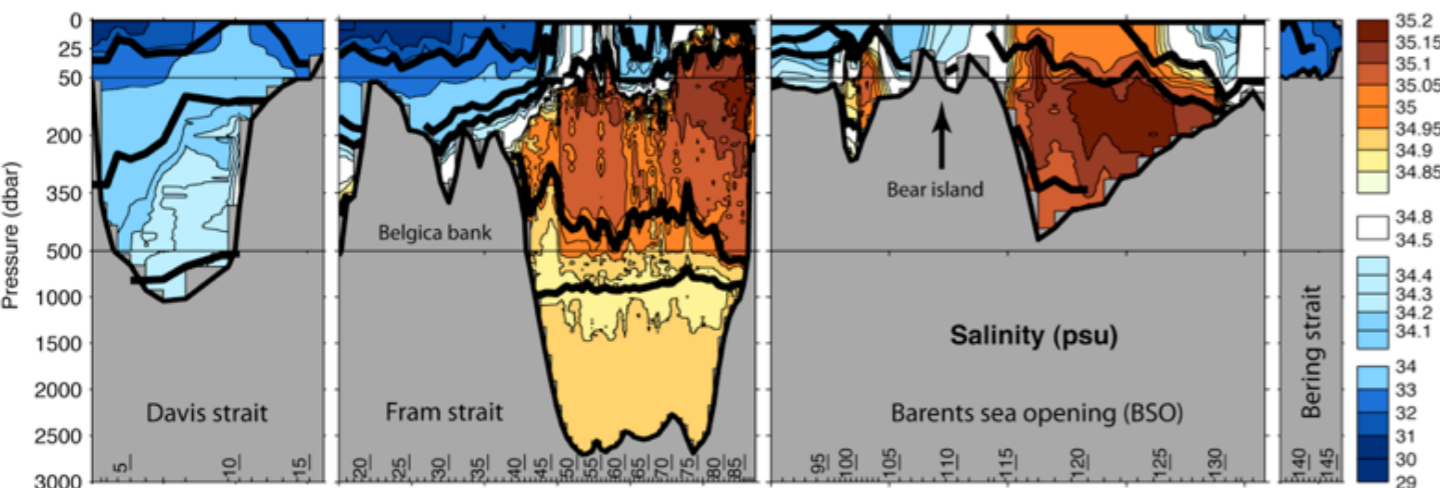
**Administrative Support:**  
[Lilian Schubert](#)

### Save the date!

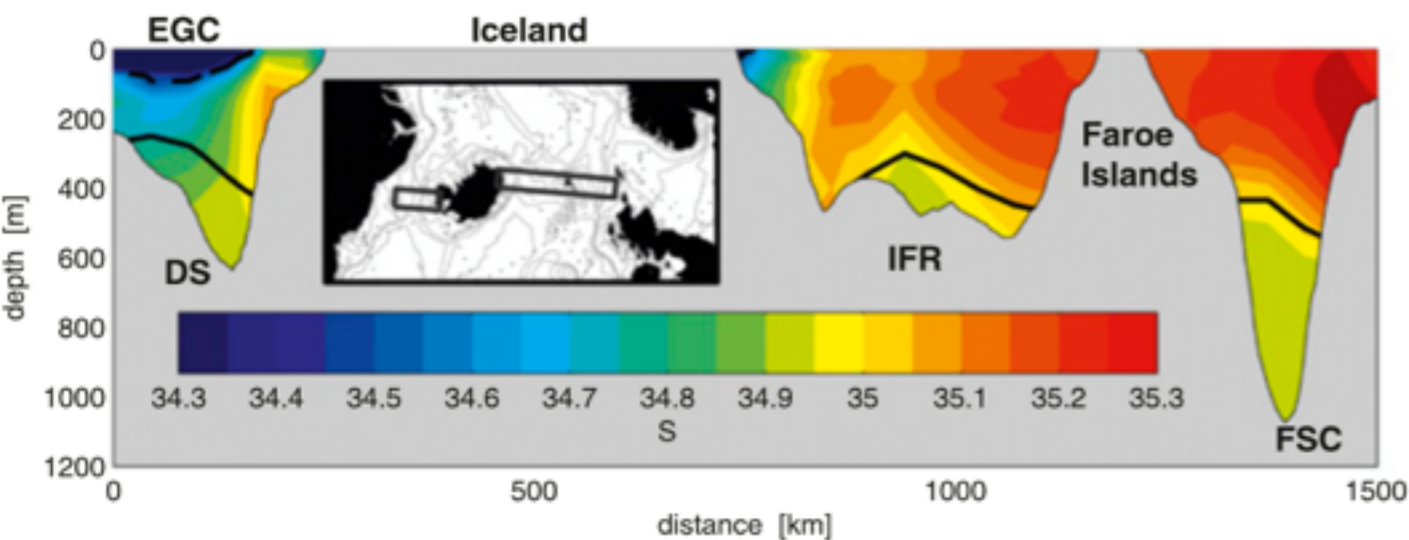
Next ASOF ISSG  
Meeting/Workshop:

# What is next break though?

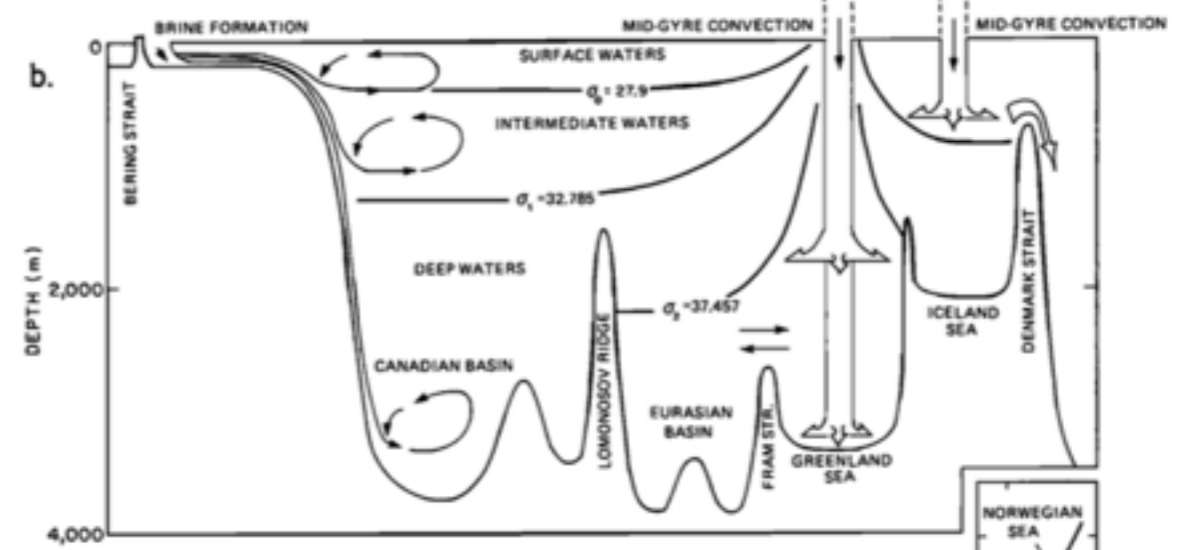
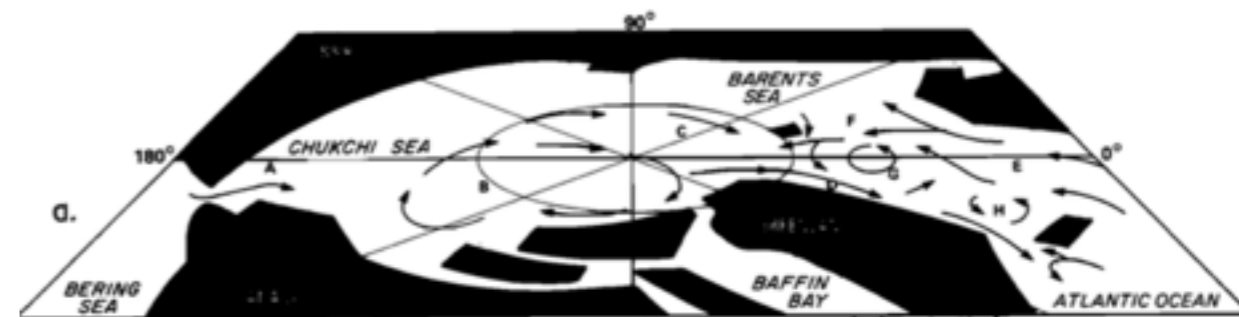
- Include Greenland-Scotland Ridge section in the box inverse model.
- Two boxes - Arctic Ocean & Nordic Seas.
- Initial focus period would be 2004-2010 (same as this study).



Tsubouchi et al. [2012, JGR]



Eldevik & Nilsen. [2013, JC]



AaGaard et al. [1985, JGR]



# Summary

- Oceanic volume, heat & FW transports under mass and salt constraints during Oct 2004 - May 2010.
- Volume tra. has Seasonality in each gateway and water masses.
- Double cell over-turning structure and its seasonality.
- Heat transport is  $180 \pm 57 \text{ TW} \sim 15.9 \pm 5.0 \text{ Wm}^{-2}$
- FW transport is  $156 \pm 91 \text{ mSv}$ .
- The seasonal & interannual variability in the Heat & FW transports
- I am looking for a job. - ideally related work.

# Acknowledgement

- The Arctic main gateways have been measured by six research institutes in the world: UW for Davis Strait and for the US side of Bering Strait; NPI and AWI for Fram Strait; IMR for BSO; UAF and AARI for the Russian side of Bering Strait.
- The pan-Arctic approach is developed under two UK NERC projects, ASBO and TEA-COSI.
- This work is supported by EU Marie Curie project, ARCGATE.