Arctic Mediterranean Exchanges: A consistent volume budget and trends in transports from two decades of observations

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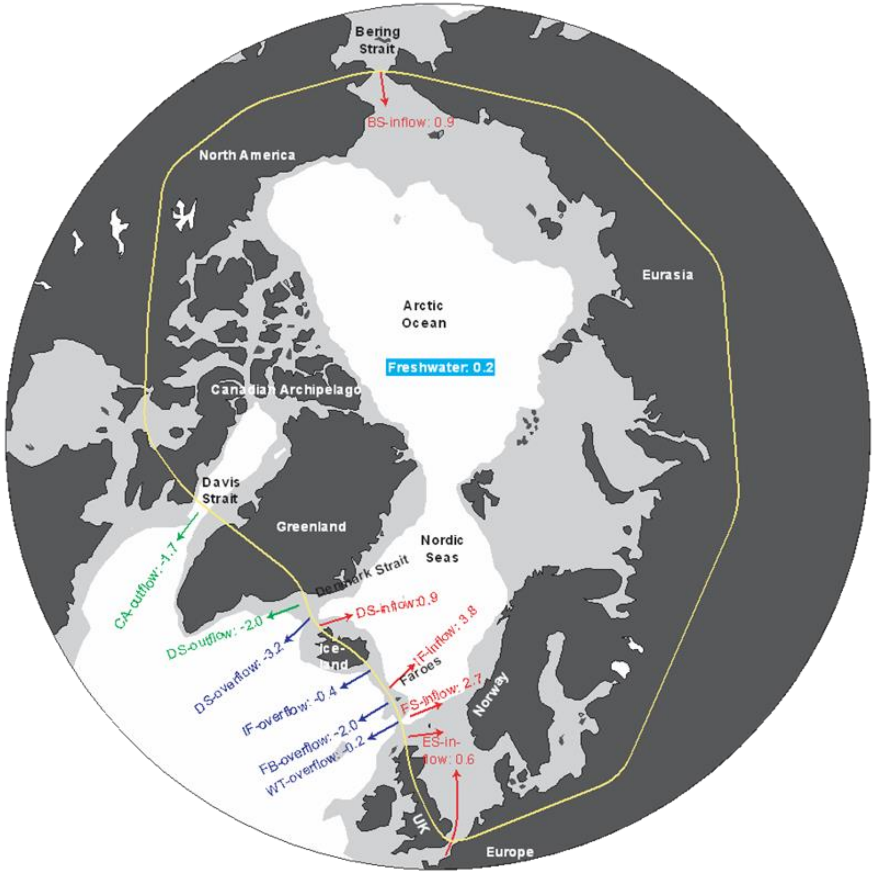

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History 1985 -2020

The ICES NANSEN Project 1985-1989
(North Atlantic-Norwegian Sea Exchanges)
https://ocean.ices.dk/Project/NANSEN/
See Hansen and Østerhus 2000

Nordic WOCE 1993-1998
(The World Ocean Circulation Experiment)

VEINS 1997 -2000
(Variability of exchanges in the northern seas)
https://cordis.europa.eu/project/rcn/35242_en.html

ASOF 2003-2006
Arctic-Subarctic Ocean Flux Array for European Climate
MOEN 2003-2006
Meridional overturning exchange with Nordic seas
ASOF-N: https://cordis.europa.eu/project/rcn/67950_en.html
ASOF-W: https://cordis.europa.eu/result/rcn/40986_en.html
MOEN: https://cordis.europa.eu/project/rcn/67527_en.html

NACLIM 2012-2017
North Atlantic Climate: Predictability of the climate in the North Atlantic/European sector related to North Atlantic/Arctic sea surface temperature and sea ice variability and change
https://cordis.europa.eu/project/rcn/105518_en.html

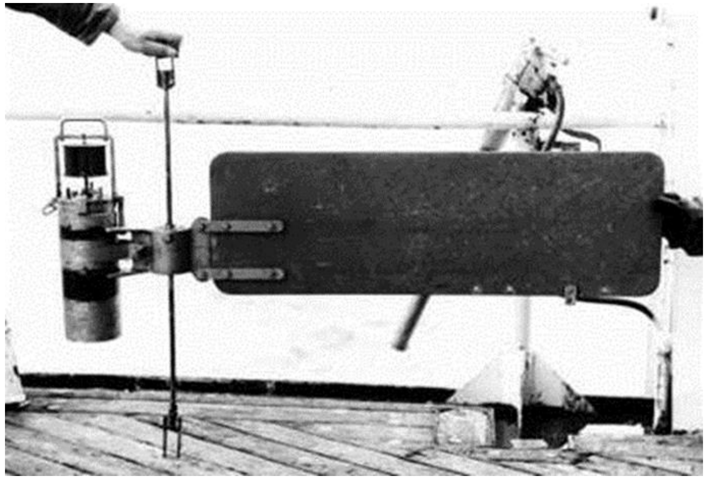
BLUE-ACTION 2016-2021
Arctic Impact on Weather and Climate
https://cordis.europa.eu/project/rcn/205997_en.html

The ICES NANSEN Project 1995-1989 (North Atlantic-Norwegian Sea Exchanges)

NANSEN was set up under ICES Council Resolution C.Res. 1985/4:9

Its specific objectives were to: study the hydrography and Atlantic–Norwegian circulation of the Iceland Basin, study the temporal and spatial variability of the inflows and outflows across the Greenland–Scotland Ridge. Research Vessel observations in support of NANSEN were collected from 1986 to 1989.

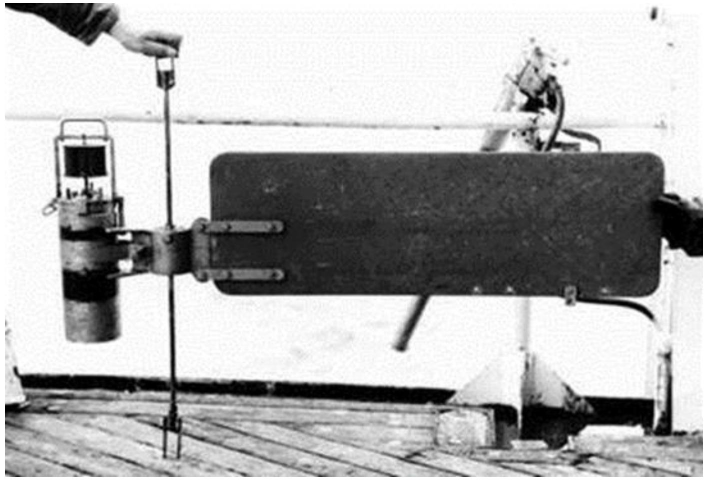
The scientific results have been published in ICES Cooperative Research Report No. 225: North Atlantic–Norwegian Sea Exchanges: The ICES NANSEN Project, 1998.
https://ocean.ices.dk/Project/NANSEN/



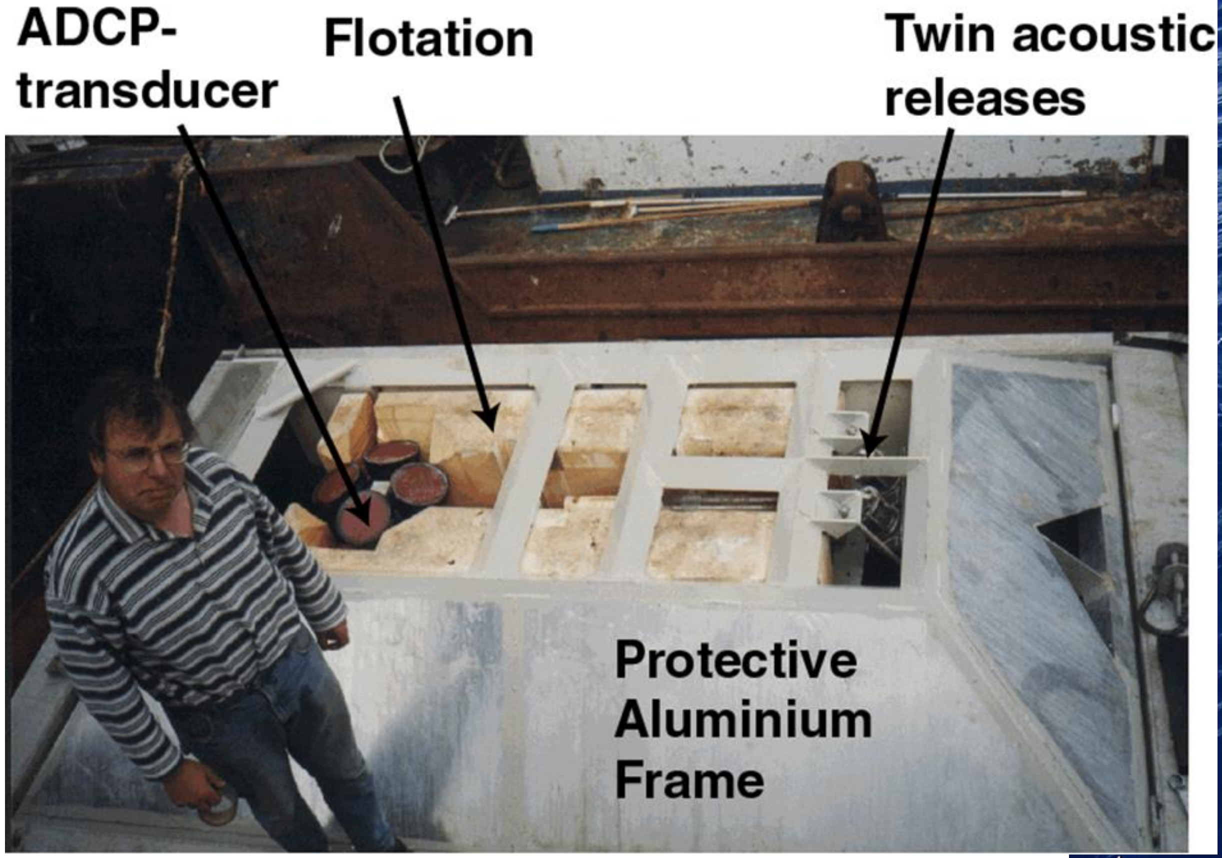
Nordic WOCE 1993-1998
(The World Ocean Circulation Experiment)

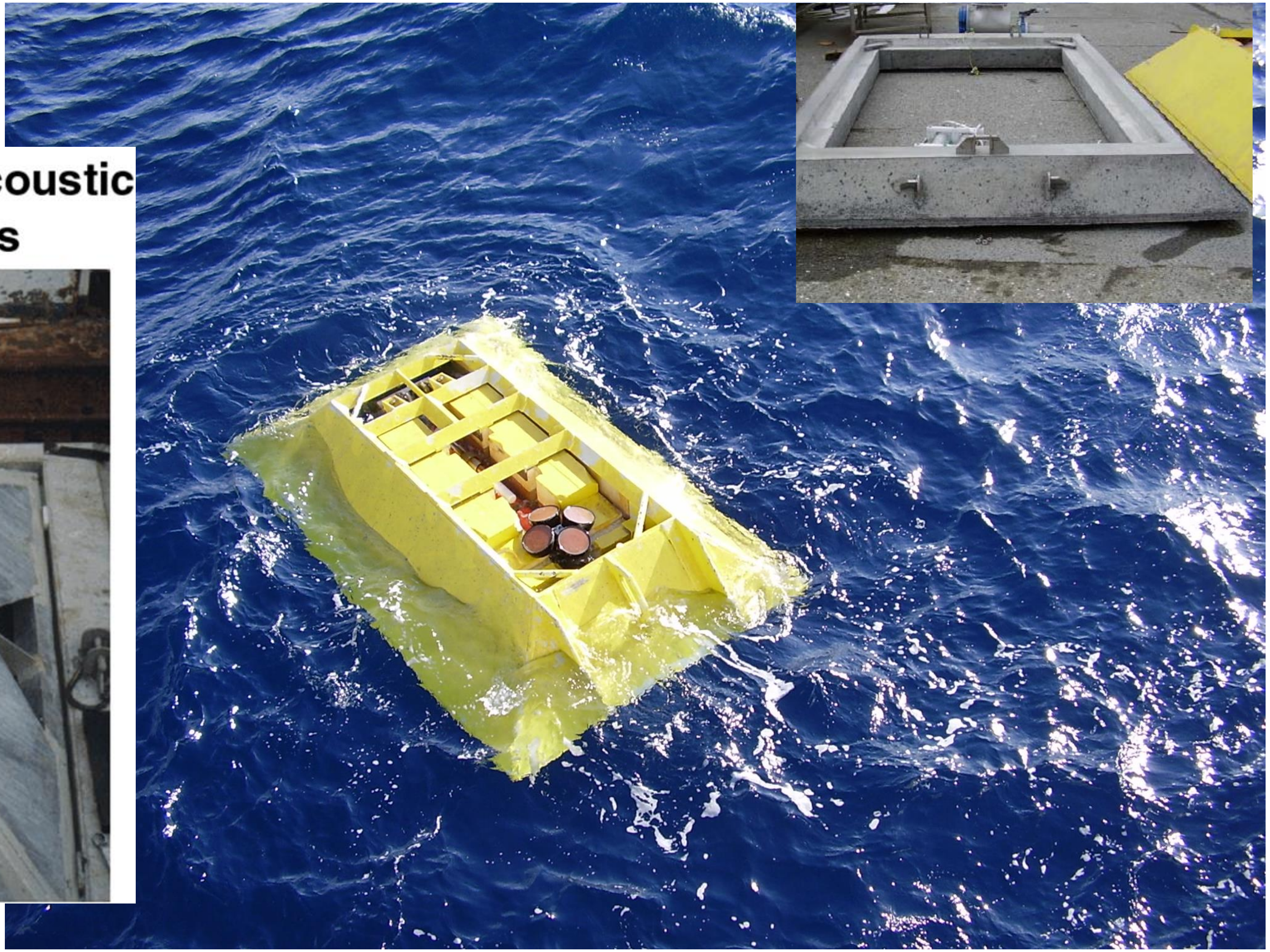
Nordic WOCE A Nordic component to the international WOCE programme with contributions from institutes in Iceland, the Faroe Islands, Norway, Denmark, Sweden, Finland, and Scotland.

Financed by the Environmental Research Programme of the Nordic Council of Ministers (NMR) 1993–1998, and by grants from the national Research Councils of the participating nations. Focused on the exchanges across the Greenland–Scotland Ridge with a field phase in 1994–1997.



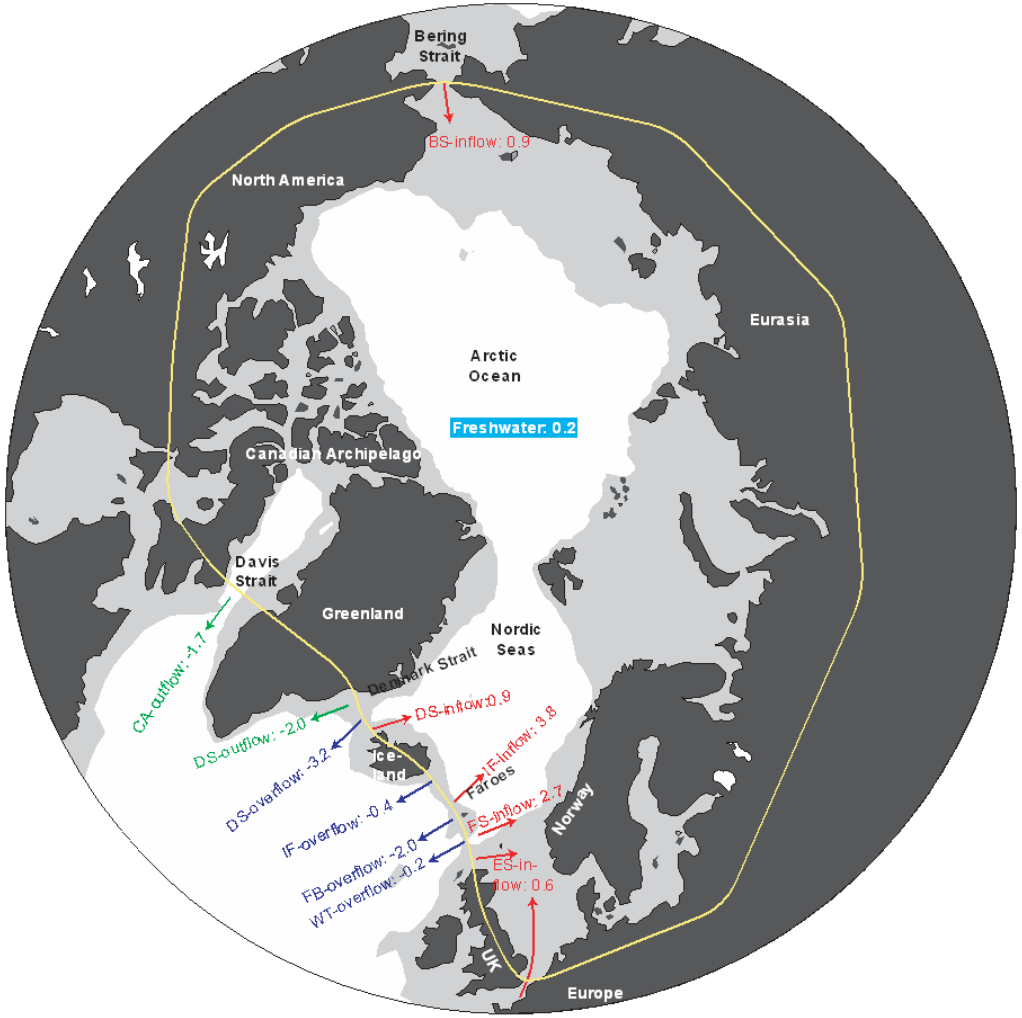
Nordic WOCE secret tools
Trawlproof ADCP frame





https://folk.uib.no/ngfso/Equipments/Moorings/Nordic%20WOCE%20Trawlproof%20frame.pdf

The exchange branches and their observing systems



- Denmark Strait Atlantic Inflow (DS-inflow)
- Iceland-Faroe Atlantic Inflow (IF-inflow)
- Faroe- Shetland Atlantic Inflow (FS-inflow)
- European Shelf Atlantic Inflow (ES-inflow)
- Bering Strait Pacific Inflow (BS-inflow)

- Denmark Strait Overflow (DS-overflow)
- Iceland-Faroe Ridge Overflow (IF-overflow)
- Faroe Bank Channel Overflow (FB-overflow)
- Wyville Thomson Ridge Overflow (WT-overflow)

- Canadian Archipelago/Davis Strait surface Outflow (CA-outflow)
- Denmark Strait surface Outflow (DS-outflow)

Bering Strait Pacific Inflow (BS-inflow)

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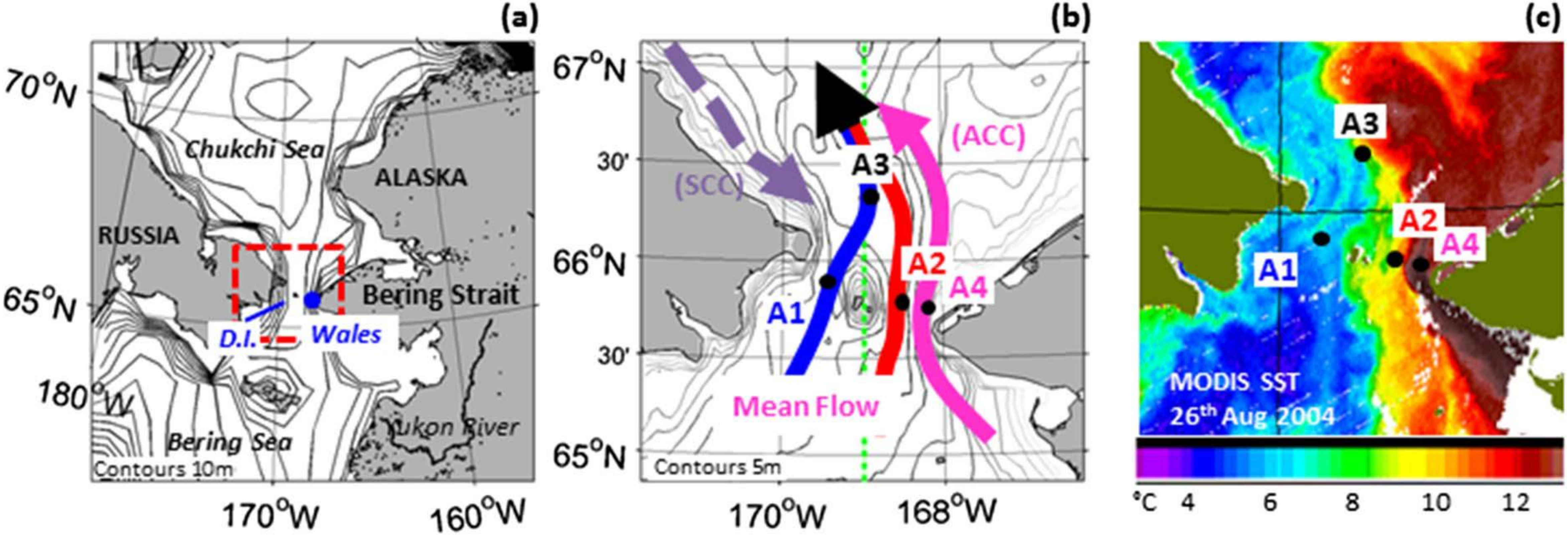

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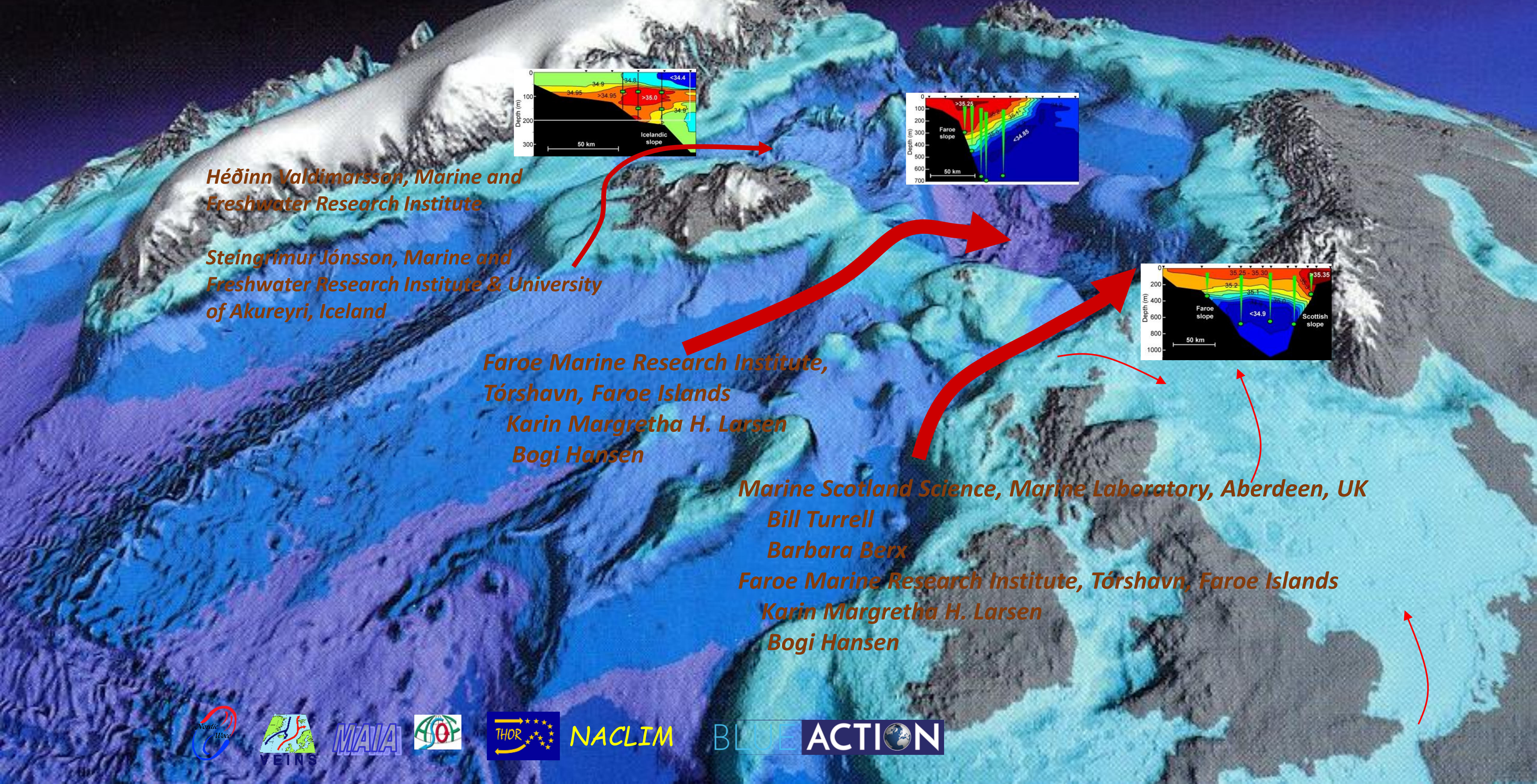
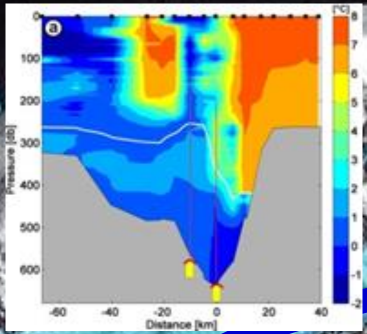
Atlantic Inflows



Overflows



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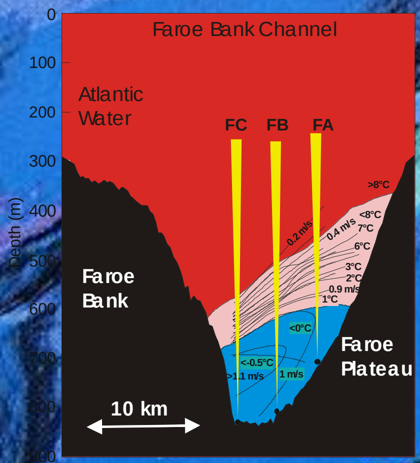

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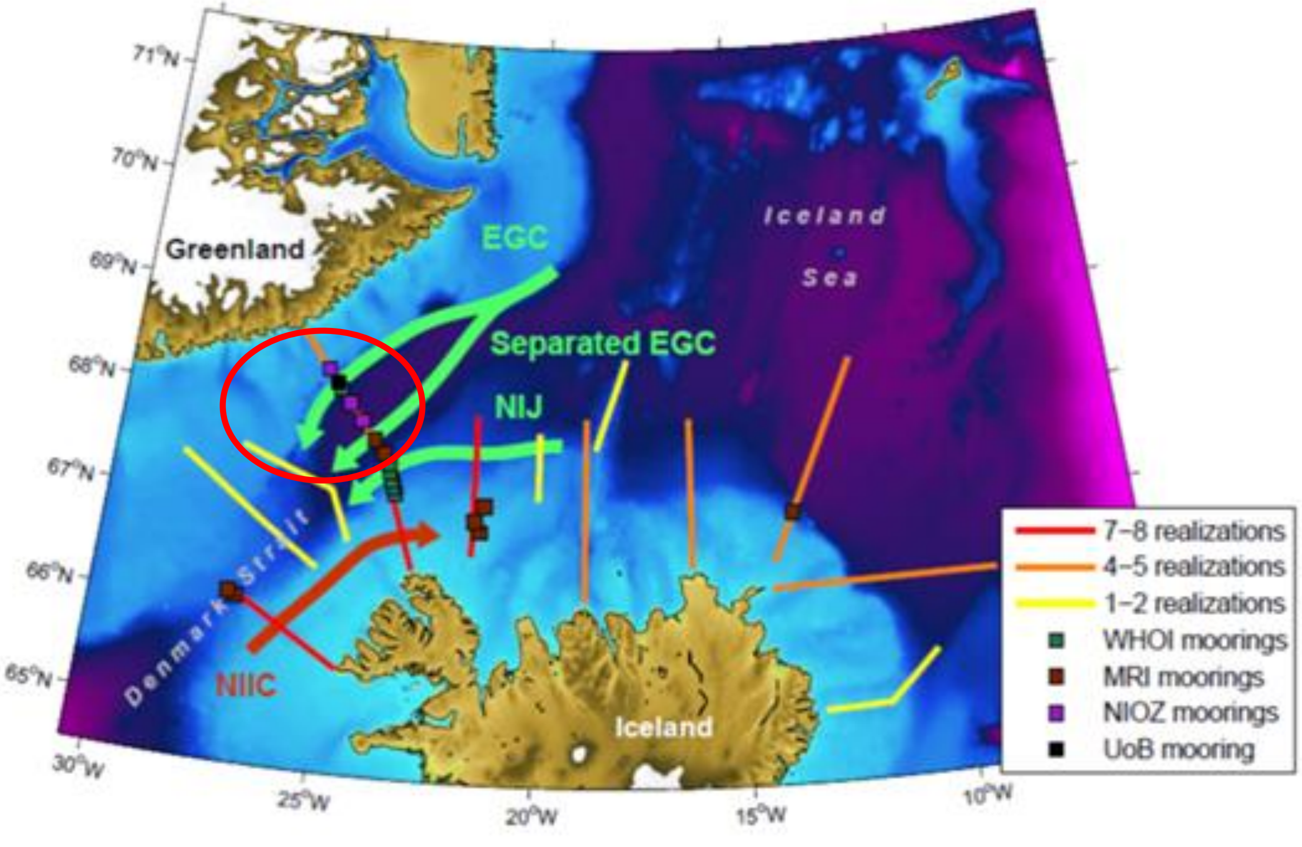
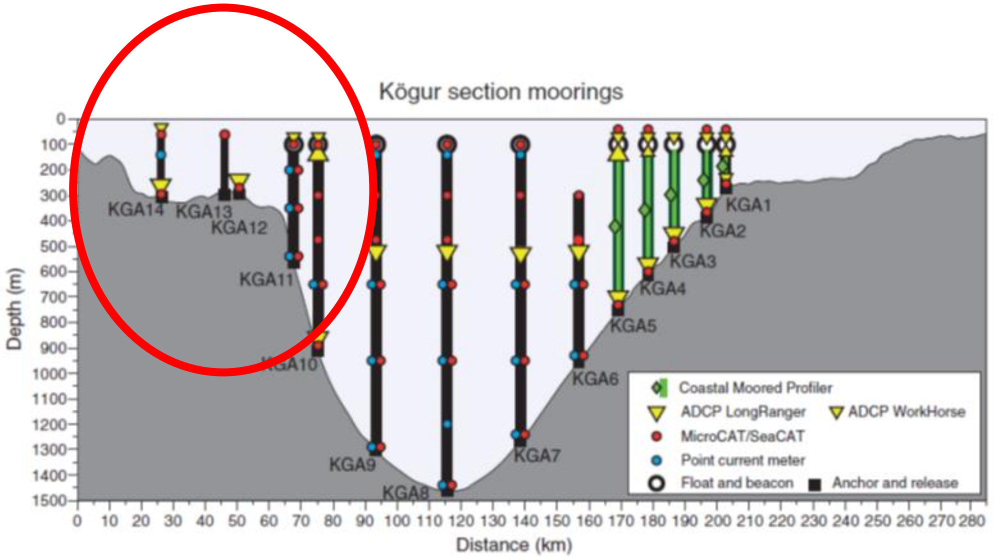
Stuart Cunningham

NACLIM

BLUE ACTION

Denmark Strait surface Outflow (DS-outflow)

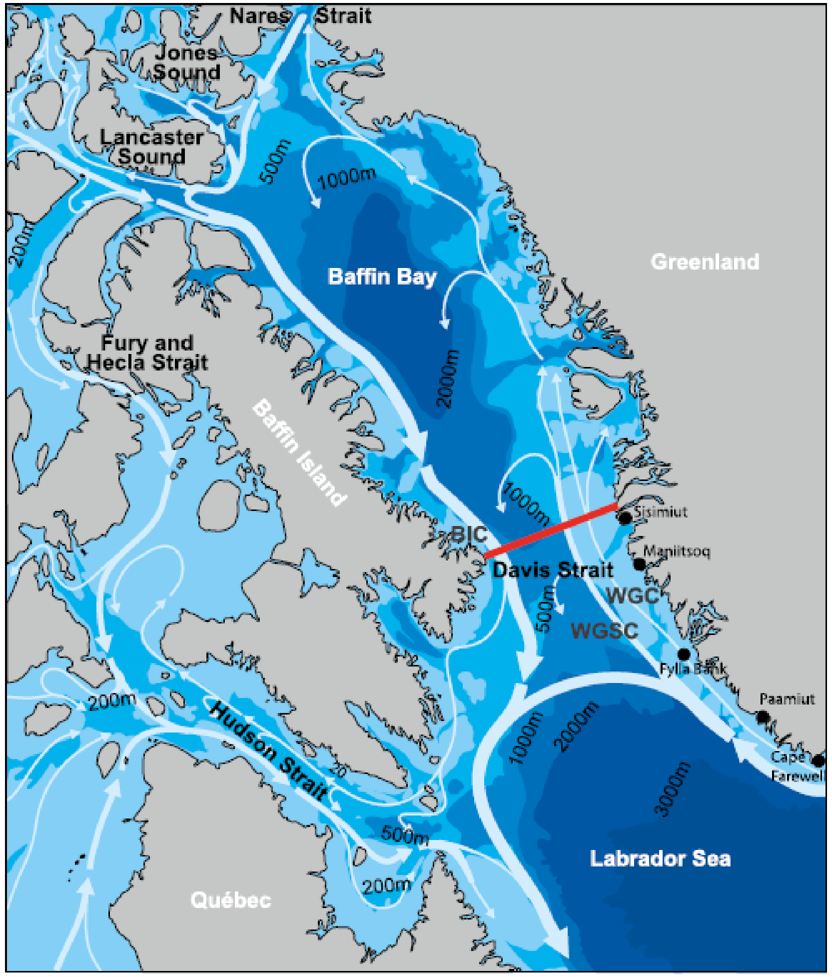


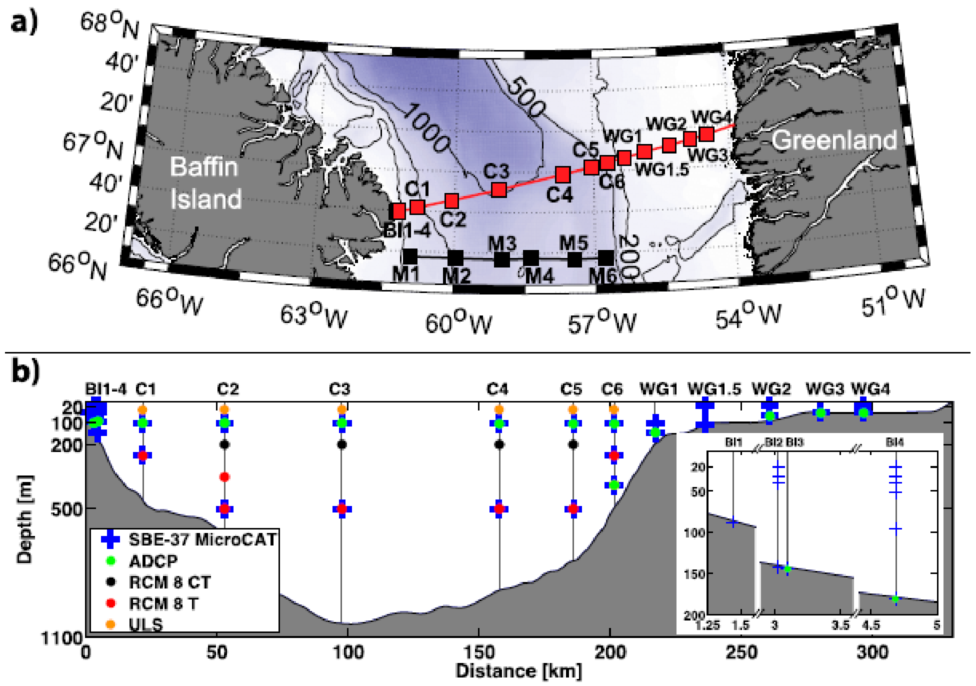


2011/12 /13/14

Laura de Steur,
Royal Netherlands Institute for Sea Research NIOZ, Texel, The Netherlands

Canadian Archipelago/Davis Strait surface Outflow (CA-outflow)





2004-ongoing

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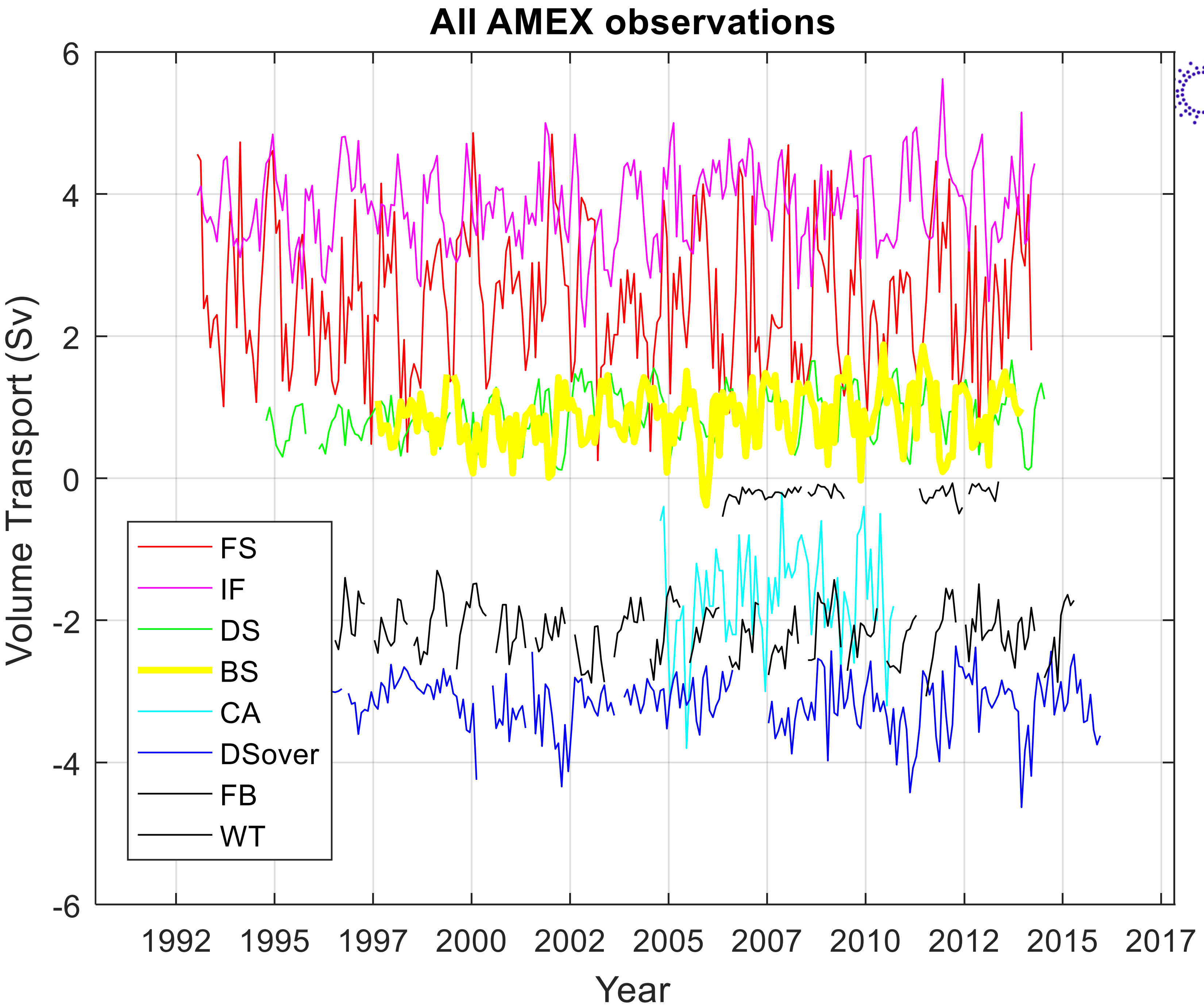
Craig M. Lee
Beth Curry

Results

Bering Strait
North America
Eurasia
Arctic Ocean
Canadian Archipelago
Davis Strait
Greenland
Nordic Seas
Denmark Strait
Europe



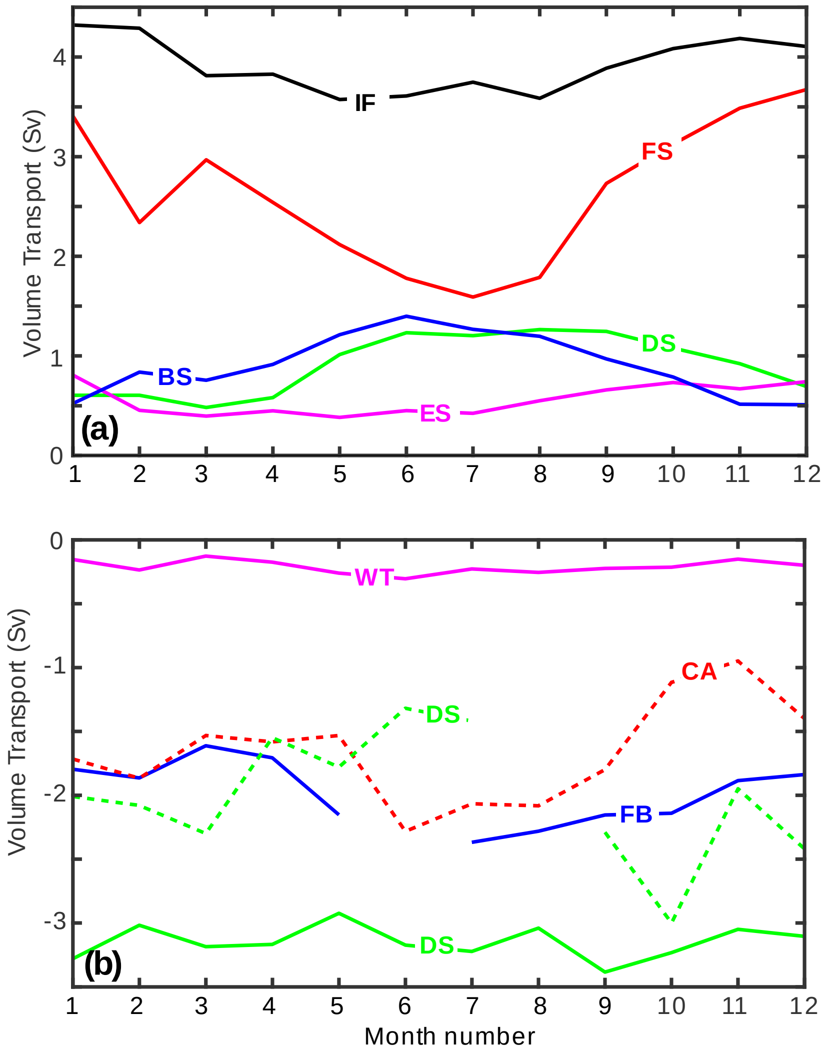
All AMEX observations
Volume Transport (Sv)
6
4
2
0
-2
-4
-6
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
2017
Year
FS
IF
DS
BS
CA
DSover
FB
WT

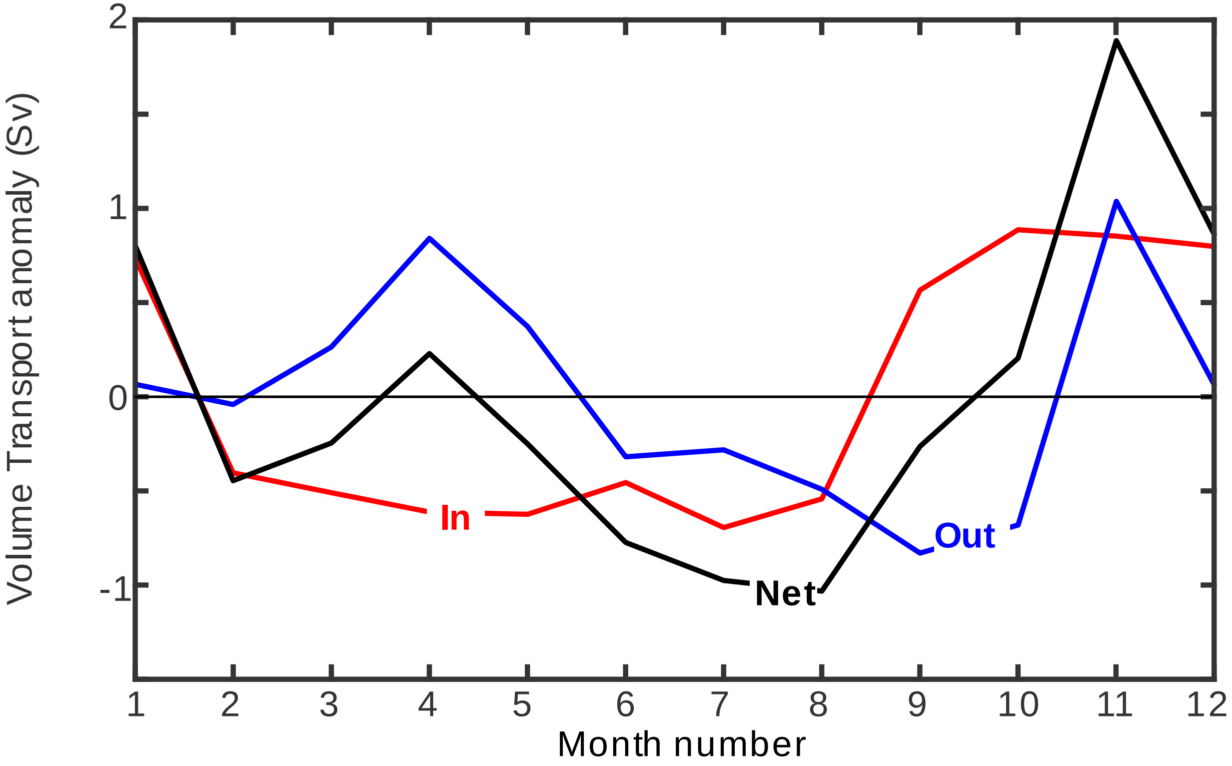
Average volume transports

Branch Full name	Branch Abbrev.	Period yyyy/mm-yyyy/mm	Months	Gaps	Avg. Sv	Std. Sv
Inflows:						
Denmark Strait Atlantic	DS-inflow	1994/10-2015/12	250	5	0.9±0.1	0.3
Iceland-Faroe Atlantic	IF-inflow	1993/01-2015/12	276	0	3.8±0.5	0.6
Faroe-Shetland Atlantic	FS-inflow	1993/01-2015/12	276	0	2.7±0.5	1.1
European Shelf Atlantic	ES-inflow	1993/01-2015/12	276	0	0.6±0.2	0.3
Bering Strait Pacific	BS-inflow	1997/08-2013/12	197	0	0.9±0.1	0.4
Overflows:						
Denmark Strait	DS-overflow	1996/05-2015/12	218	18	-3.2±0.5	0.4
Iceland Faroe Ridge	IF-overflow	n.a.			-0.4±0.3	
Faroe Bank Channel	FB-overflow	1995/12-2015/12	206	35	-2.0±0.3	0.3
Wyville Thomson Ridge	WT-overflow	2006/05-2013/05	61	24	-0.2±0.1	0.1
Surface outflows:						
Canadian Archipelago	CA-outflow	2004/10-2010/09	72	0	-1.7±0.2	0.7
Denmark Strait	DS-outflow	2011/09-2012/07	11	0	-2.0±0.5	0.5
Runoff and precipitation:						
Freshwater input	Freshwater	n.a.			0.2	

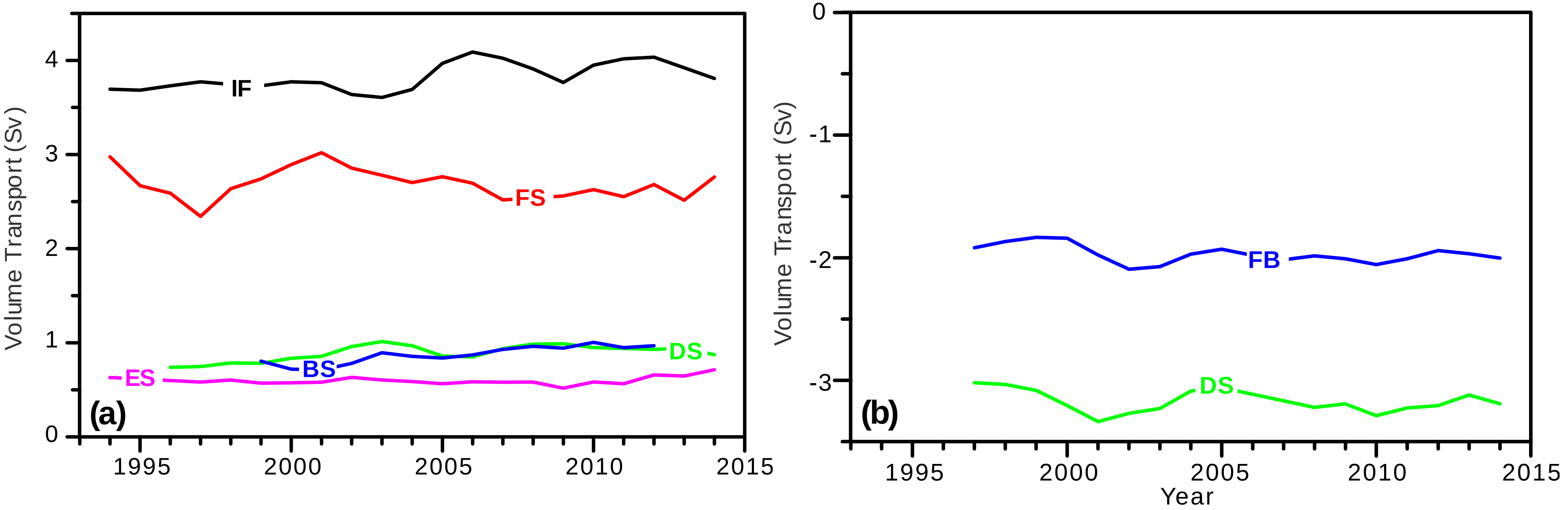
Combining all the inflow transports with the freshwater input, we get the total "***AM-import***", which has an average value of **9.1 Sv.** Likewise, we can combine all the overflow transports with the surface outflow transports to an "***AM-export***" with an average value of **-9.5 Sv**. Hence, the export exceeds the import so that the average "***Net import***" (AM-import + AM-export) is -0.4 Sv. Combining the various uncertainty terms, this number has an uncertainty exceeding 1 Sv.

Seasonal variation



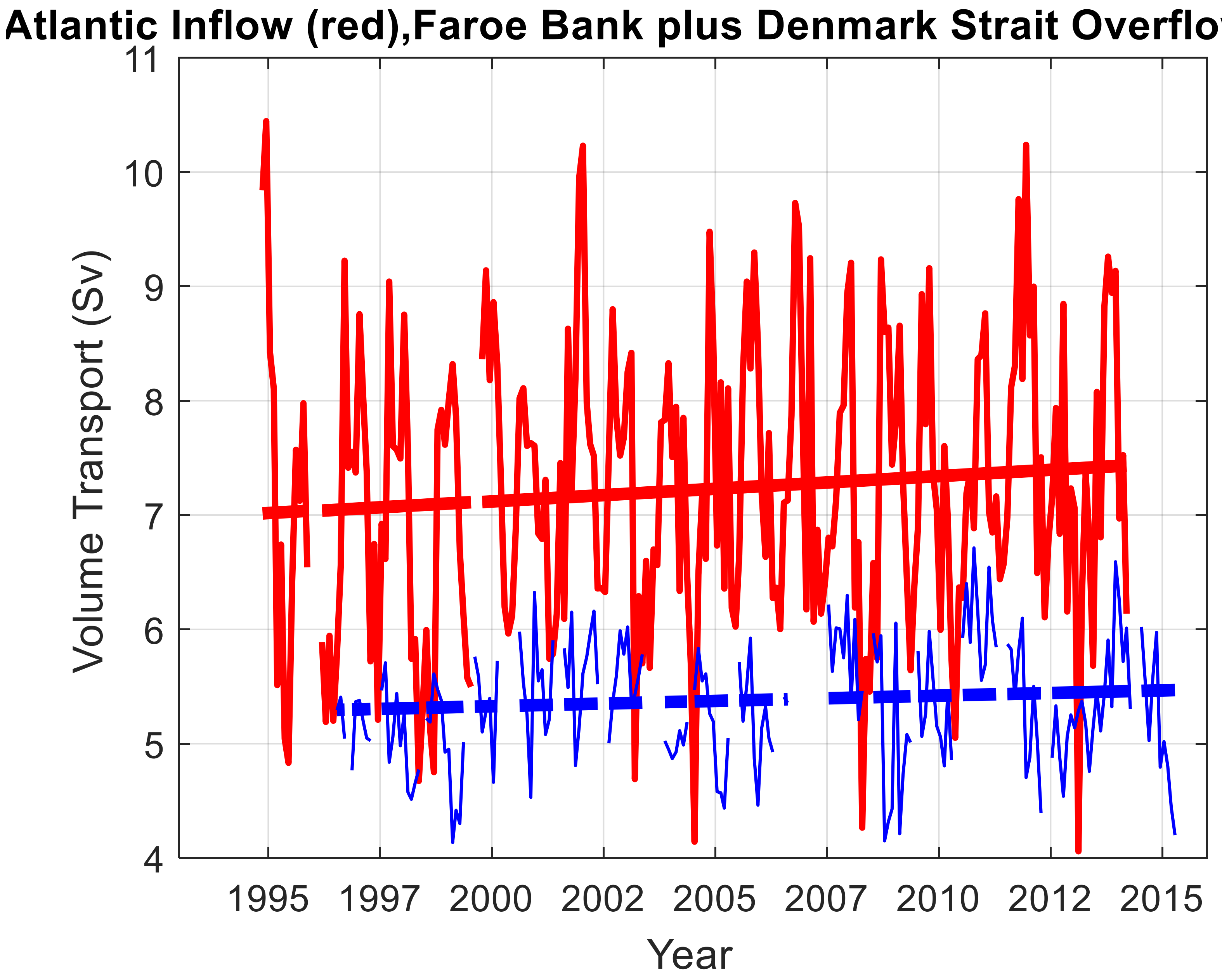


Long-term variations



Low-passed (3-year running mean) volume transport of the five inflow branches (a) and the two main overflow branches (b). The value for each year is the average of the values for all observed months of the year, the preceding year, and the following year. To minimize bias from missing months, the values have been de-seasoned before averaging

Atlantic Inflow (red), FB+DS Overflow (blue)



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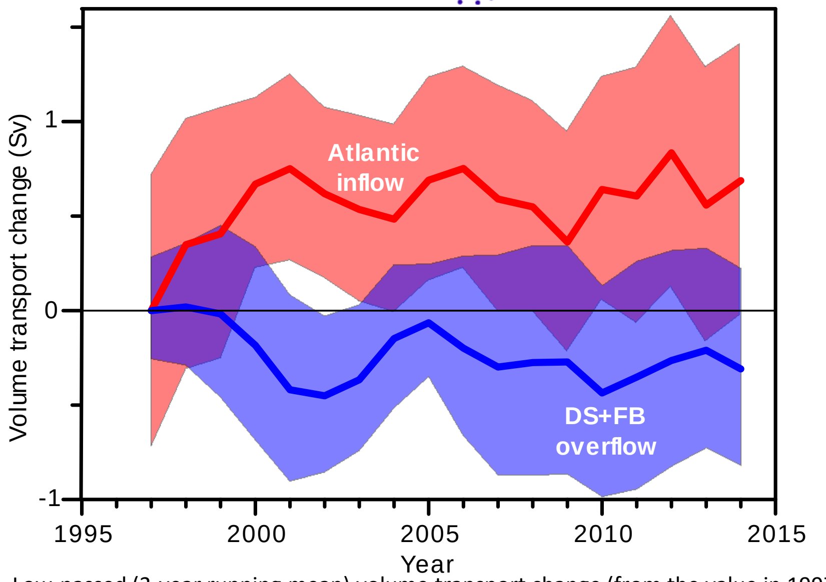
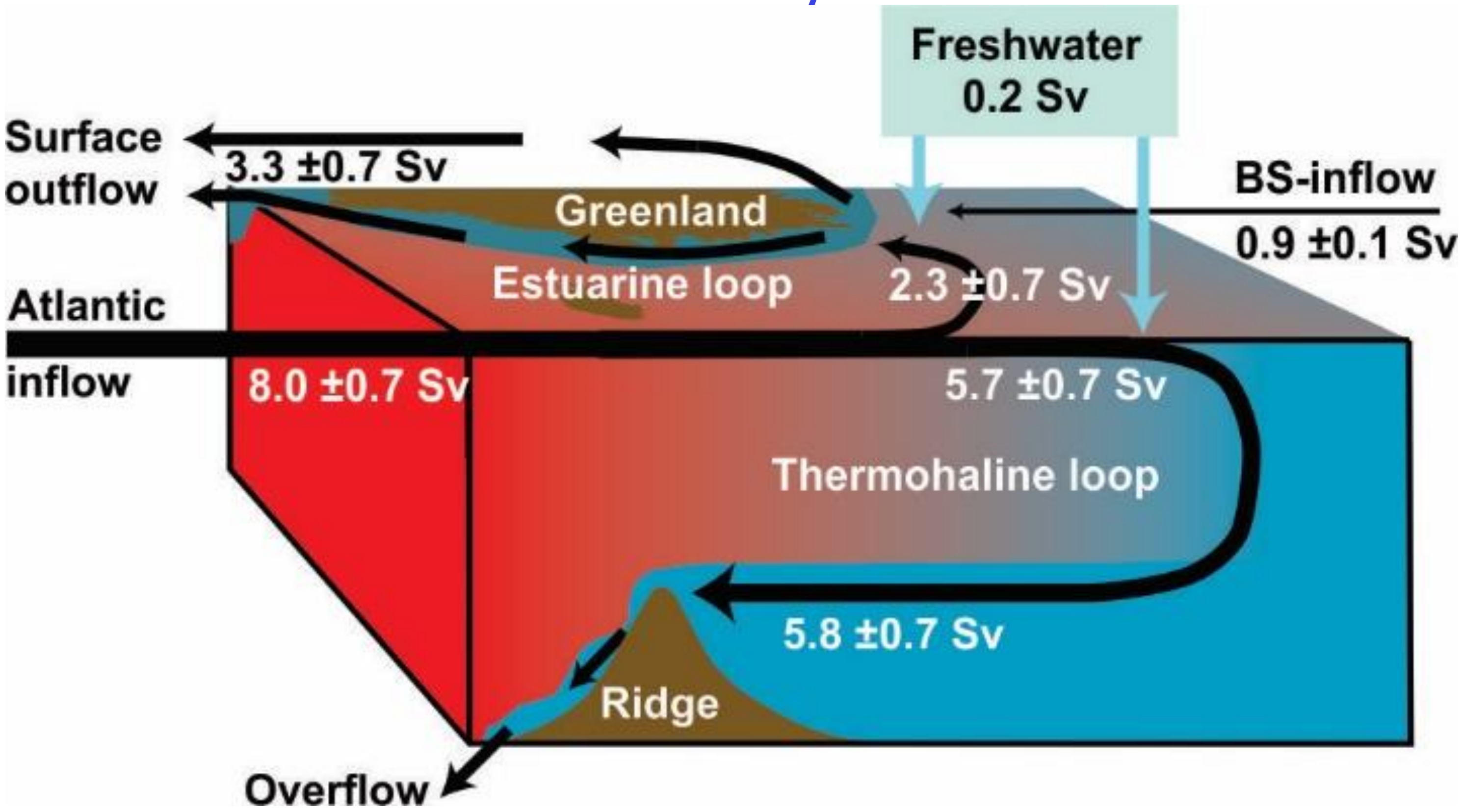


Low-passed (3-year running mean) volume transport change (from the value in 1997) of the sum of the four Atlantic inflow branches (thick red line) and the sum of the two main overflow branches (thick blue line). The value for each year is the average of the de-seasoned values for all observed months of the year, the preceding year, and the following year. The coloured areas represent the 95% confidence interval

Branch	Period	Years	Trend (Sv yr-1)	Rel. tr. (yr-1)
DS-inflow	1997-2015	18	0.004±0.011	0.4 %
IF-inflow	1993-2015	23	0.012±0.013	0.3 %
FS-inflow	1993-2015	23	-0.006±0.024	-0.2 %
ES-inflow	1993-2015	23	0.003±0.005	0.5 %
BS-inflow	1998-2013	16	**0.016±0.014**	**1.8 %**
All inflows	1998-2013	15	0.040±0.046	0.4 %
DS-overflow	1997-2015	14	-0.007±0.015	-0.2 %

The AM as a double estuary



Overall budget for the AM-exchanges where the circulation within the AM is simplified into two loops: a thermohaline loop converting Atlantic inflow and freshwater into overflow, and an estuarine loop converting all three types of AM-import into surface outflow.

The AM may be seen as a double estuary (e.g. Rudels, 2010) with both an estuarine and a thermohaline circulation.

To a first approximation, overflow water may therefore be considered a mixture of Atlantic water and freshwater in a mixing ratio of 99:1, based on the typical salinities of Atlantic water (~35.3) and overflow water (~34.9).

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Conclusions

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- On average, the AM-import is found to total 9.1±0.7 Sv with a fairly consistent seasonal variation that has an amplitude close to 1 Sv and maximum import around October
- Our data give a good balance between average import and export with only 0.4 Sv more water being exported than imported on the average, which is well below the combined quoted uncertainties
- AM-exchanges as a whole are not likely to have weakened during the two decades from the mid-1990s to the mid-2010s
- Certainly, the combined transport of the two main overflow branches did not weaken and they account for almost 90 % of the total overflow
- Around 70 % of the Atlantic inflow is converted into overflow and the observed stability of the total Atlantic inflow further indicates that the thermohaline loop of the AM remained stable during our observational period
- The overflow is a key component of the AMOC, any weakening of the AMOC during this period cannot have been caused by weakened overflow or weakened overturning in the AM

Recommendations

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- We recommend that more effort is put into quantifying the exchange branches that up to now have not been adequately observed
  - the East Greenland Current (something is still rotten in the Strait of Denmark)
  - the overflow across the Iceland-Faroe Ridge
  - the inflow over the Scottish shelf.
- We therefore strongly recommend that all possible efforts are made to maintain the established monitoring systems. These systems are demanding in manpower and continued funding and short-term scientific discoveries are not always guaranteed, but they are the safest way to stay alert against possible future changes since it is not yet clear where and how a disruption of the AM-exchange systems will first be manifested or which indices may serve as early warning indicators.

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