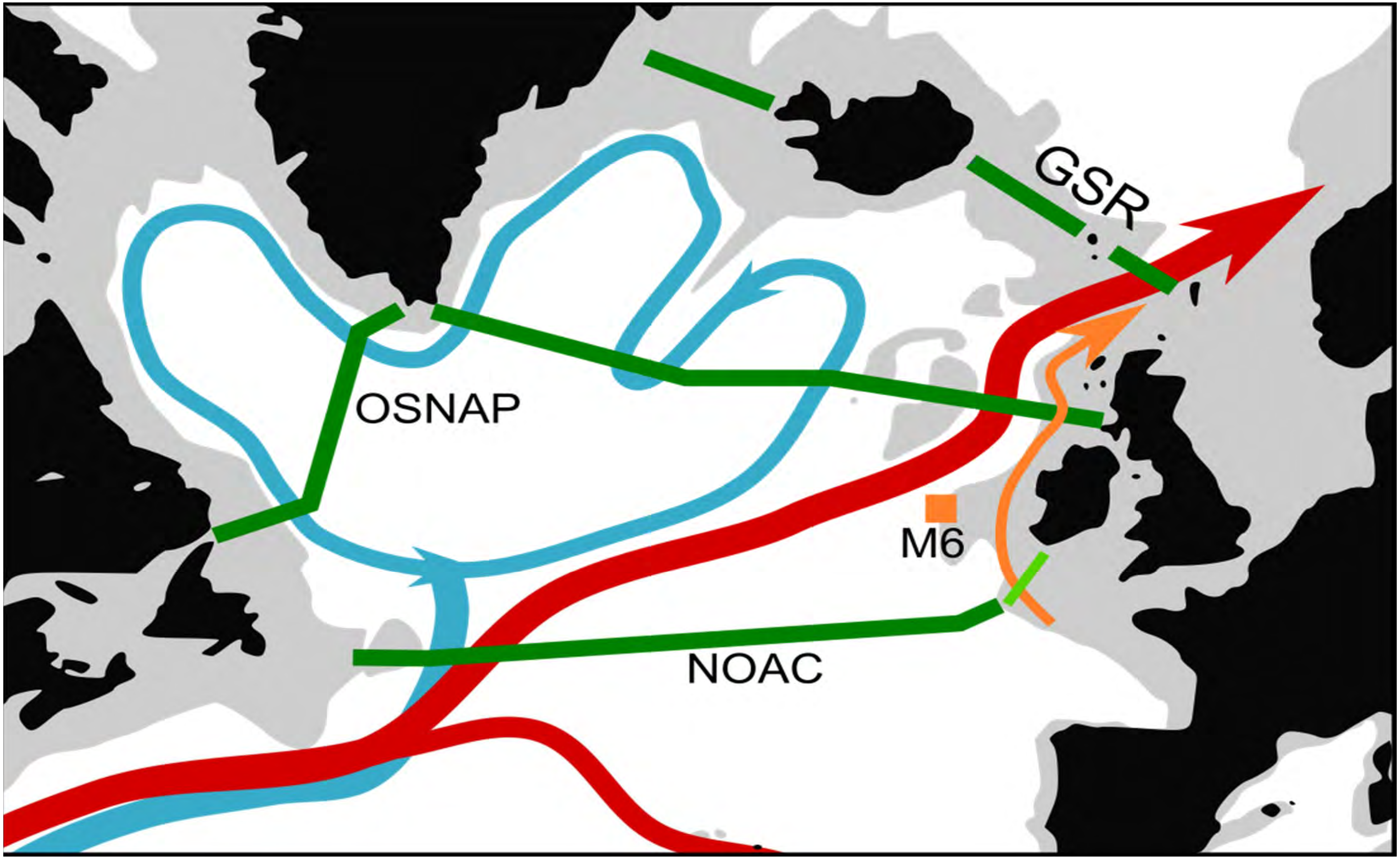
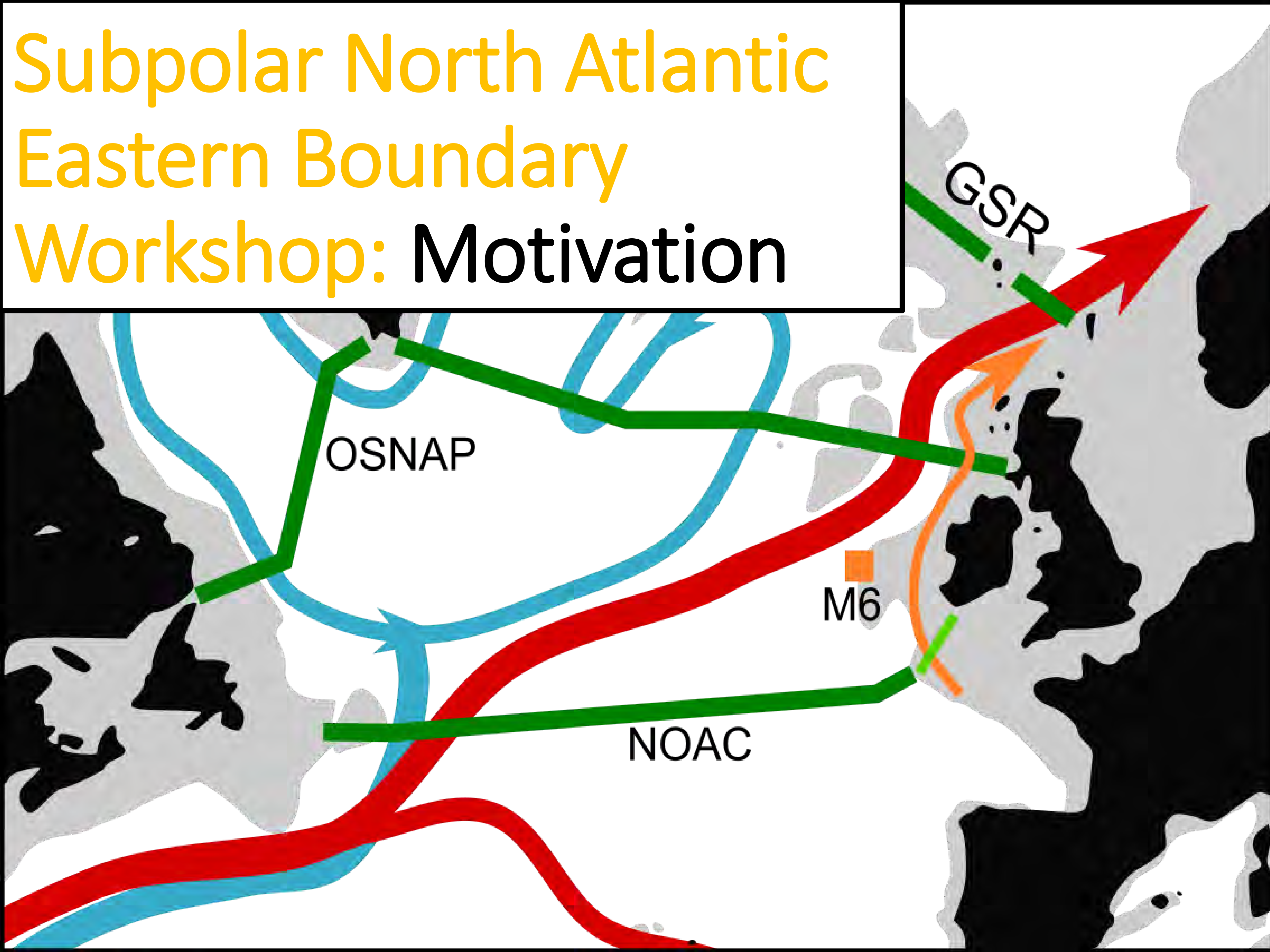
Blue-Action, A4 Project and ATLAS
Joint Workshop on Subpolar North Atlantic Eastern Boundary



Blue-Action and Atlas have received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreements **No 727852 (Blue-Action) and No 678760 (ATLAS). A4 (Aigéin, Aeráid, agus athrú Atlantaigh) is funded by the Marine Institute and the European Regional Development fund (grant: PBA/CC/18/01)**)

Subpolar North Atlantic Eastern Boundary Workshop: Motivation



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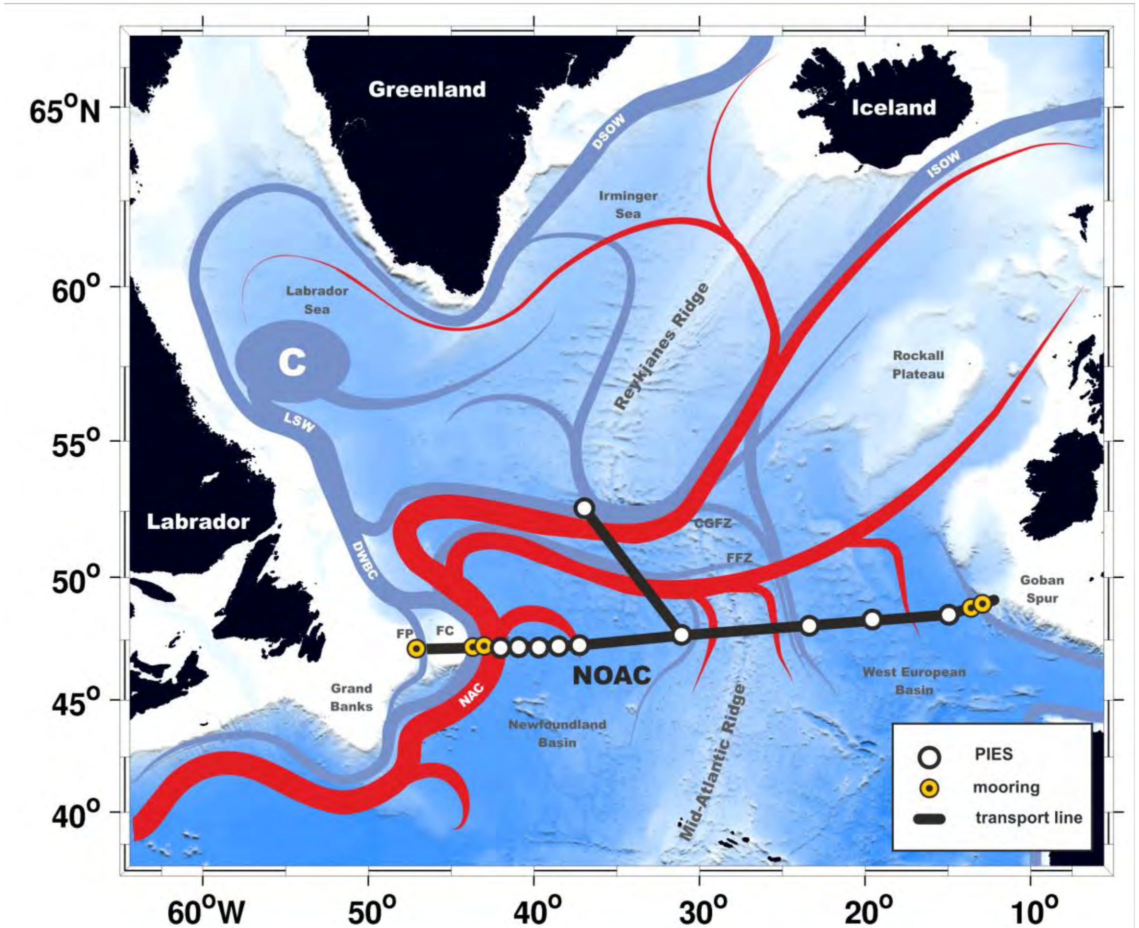
BUNDESAMT FÜR
SEESCHIFFFAHRT
UND
HYDROGRAPHIE

47^{o}N
NOAC and the Eastern Boundary Array

BSH Group: Kerstin Jochumsen, Birgit Klein, Holger Klein, Manuela Köllner, Martin Moritz
Uni Bremen Group: Monika Rhein, Dagmar Kieke, Christian Mertens, Hannah Nowitzki, Reiner Steinfeldt

Key Points



- Funding through federal cooperative project „RACE-NA-Synthesis“ until 2020 **-> array will be suspended**
- Eastern Boundary moorings will be continued at least until 2021.
- Transport estimates in Western Basin and at MAR 1993 -2018 available
- AMOC estimate at 47°N in progress
- Irish-German collaboration

The NOAC Observatory at 47°N

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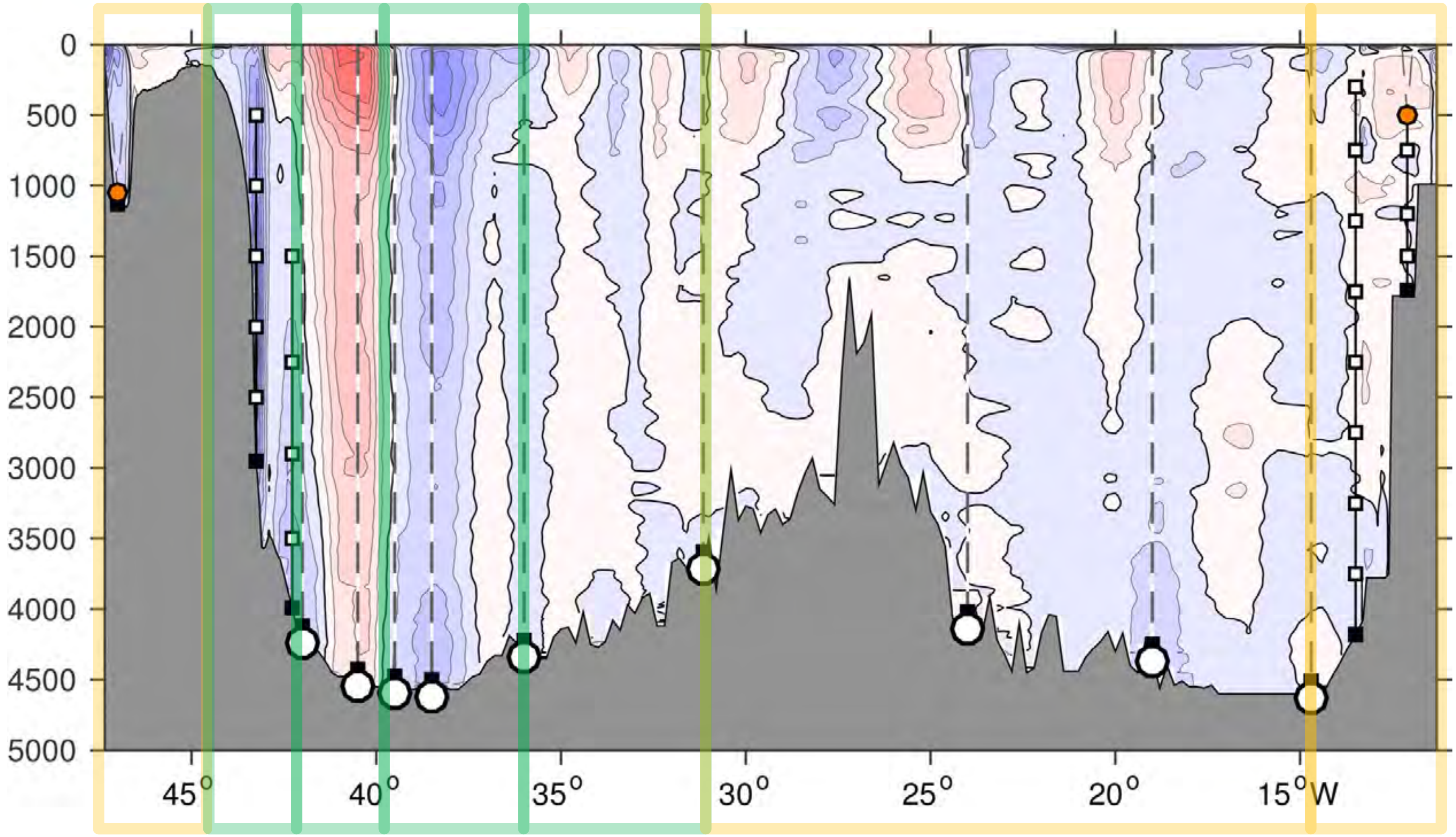

Transport estimates

Available

In progress

The Eastern Boundary (EB)

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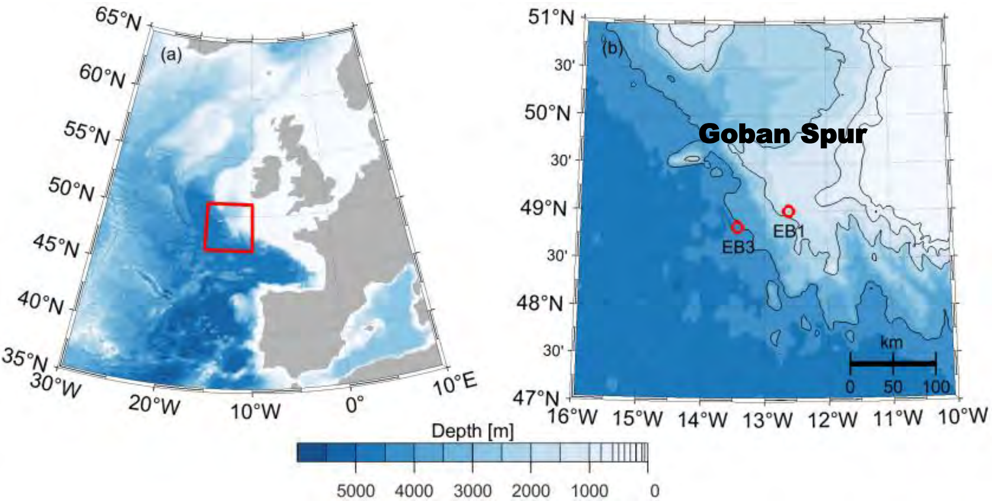

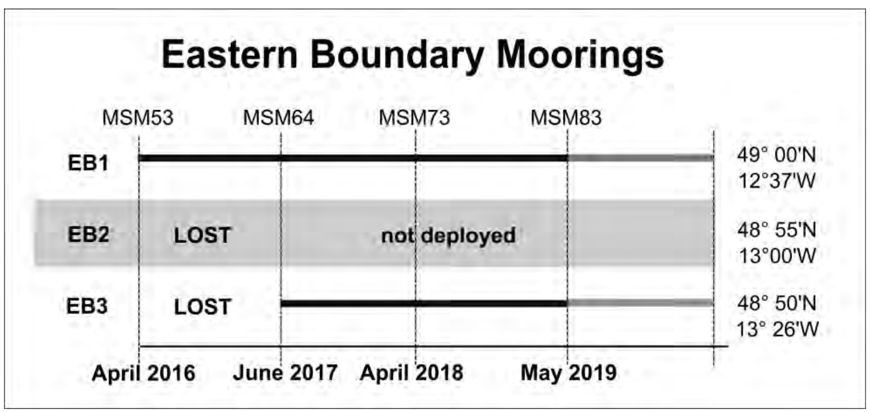

Main objectives

- Capture strength and variability of the EB current
- Monitor variability in transports and water mass properties associated with northward spreading of subtropical waters along the EB
- Analyse variations in fractions and mixing of source water masses feeding the North Sea

The Eastern Boundary

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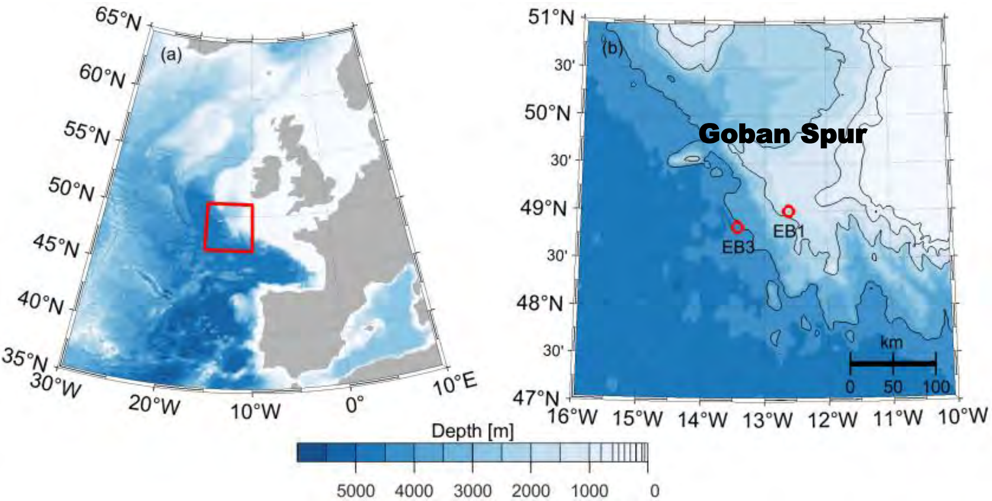

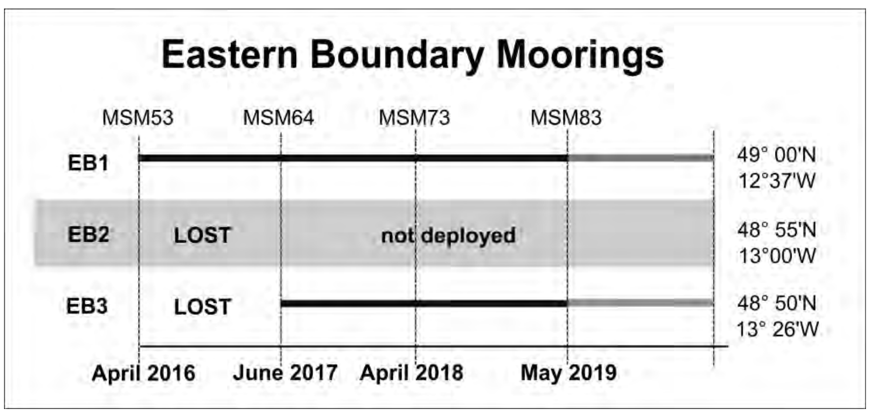

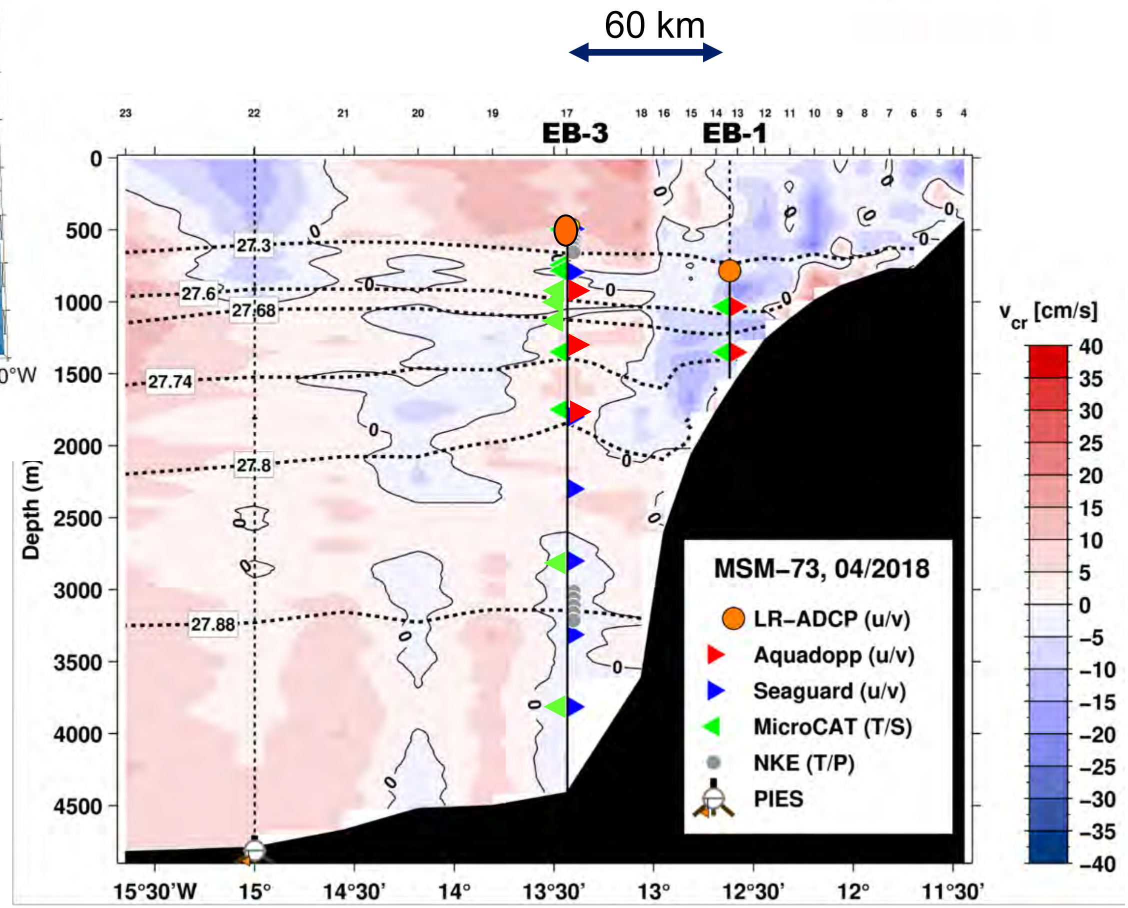

The Eastern Boundary

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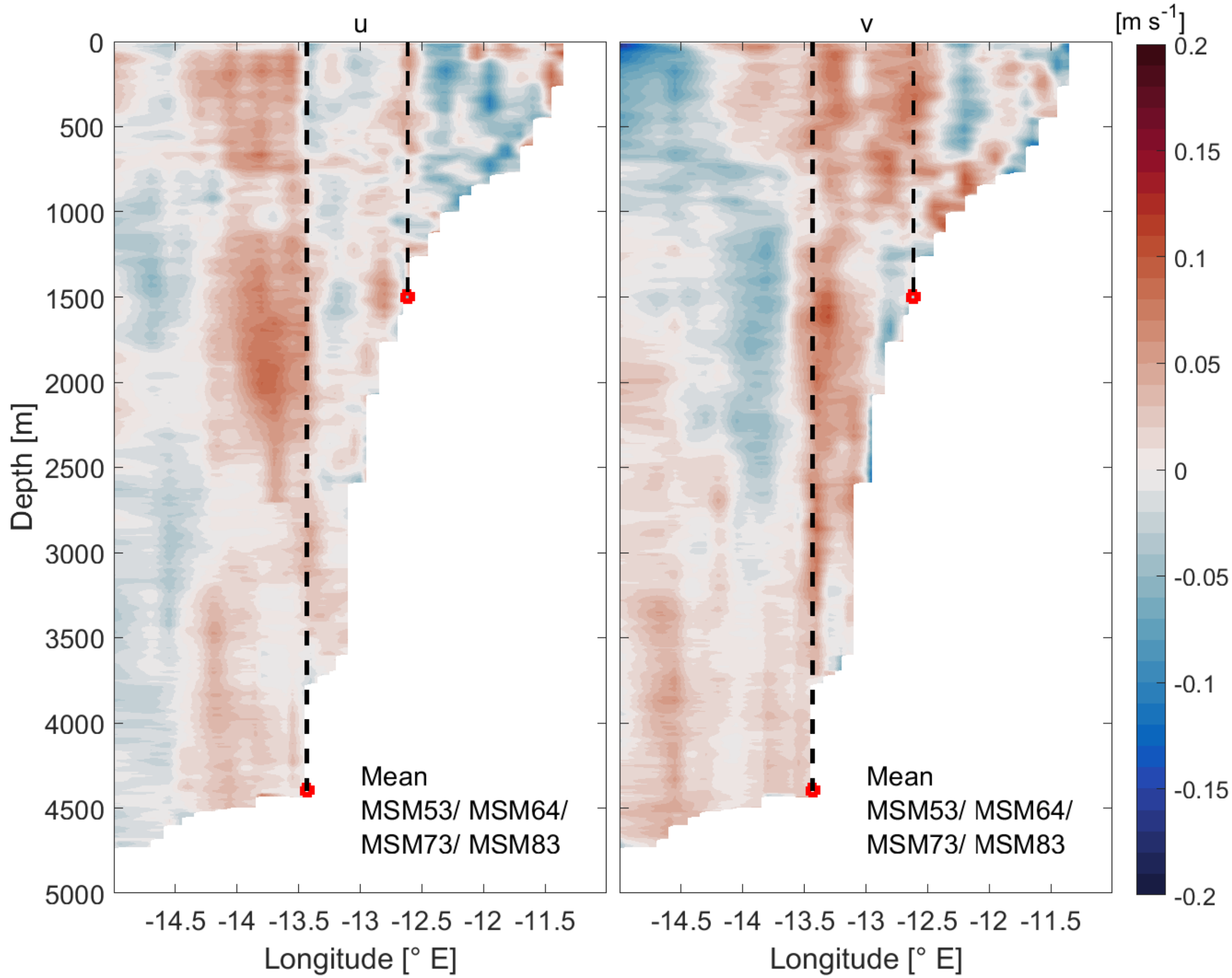
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE



The Eastern Boundary

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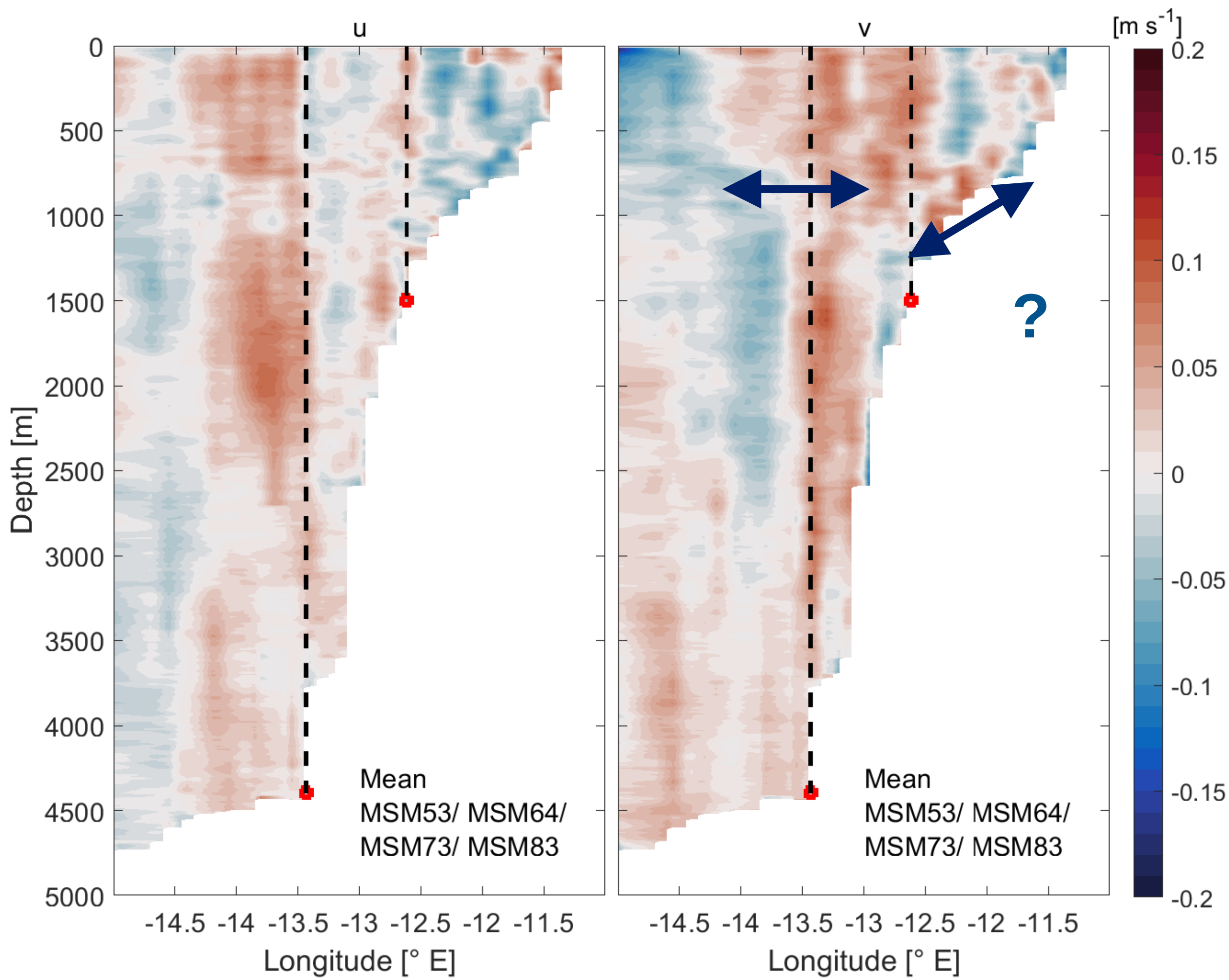
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE



Shallow mooring EB1

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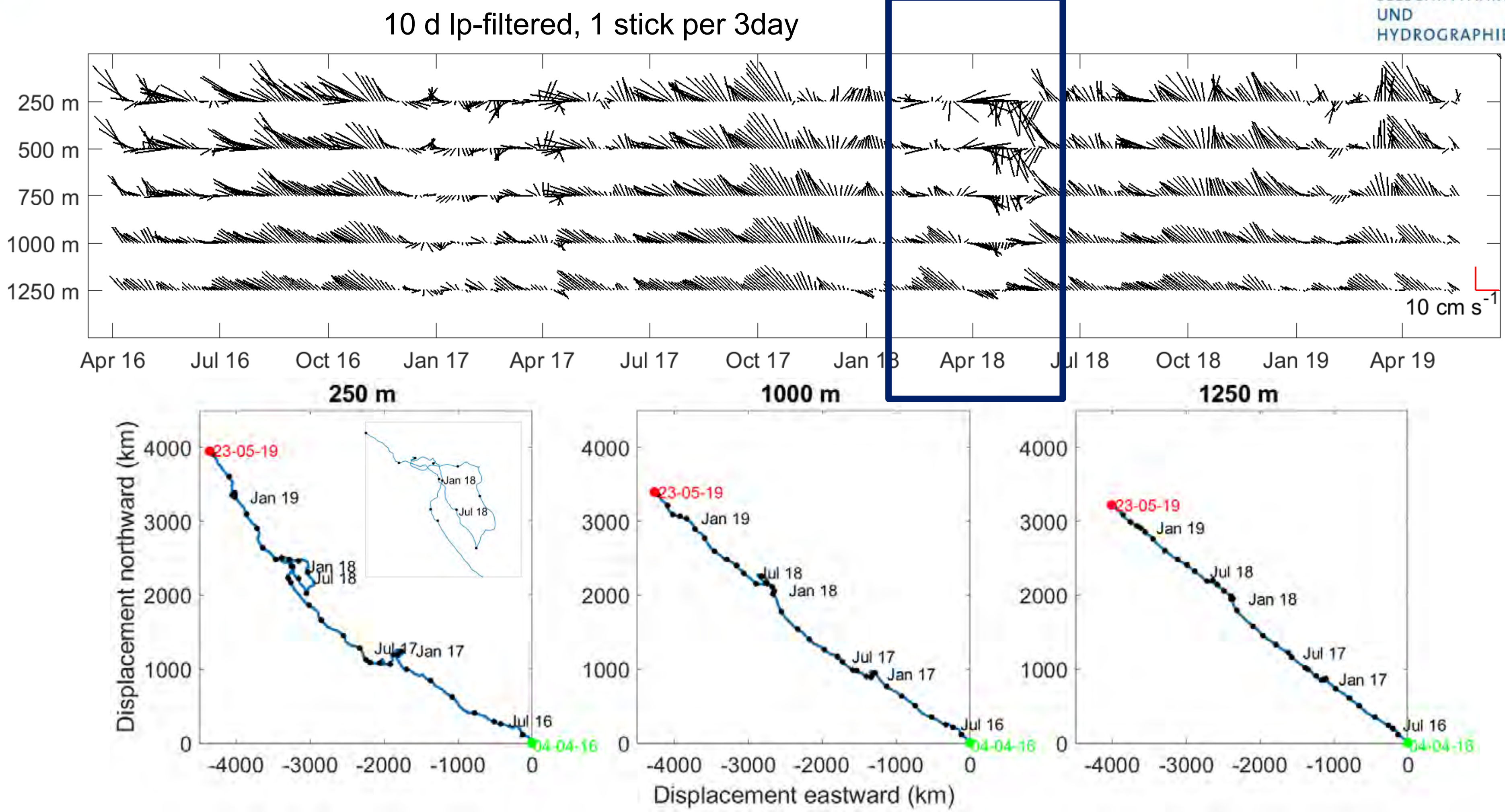
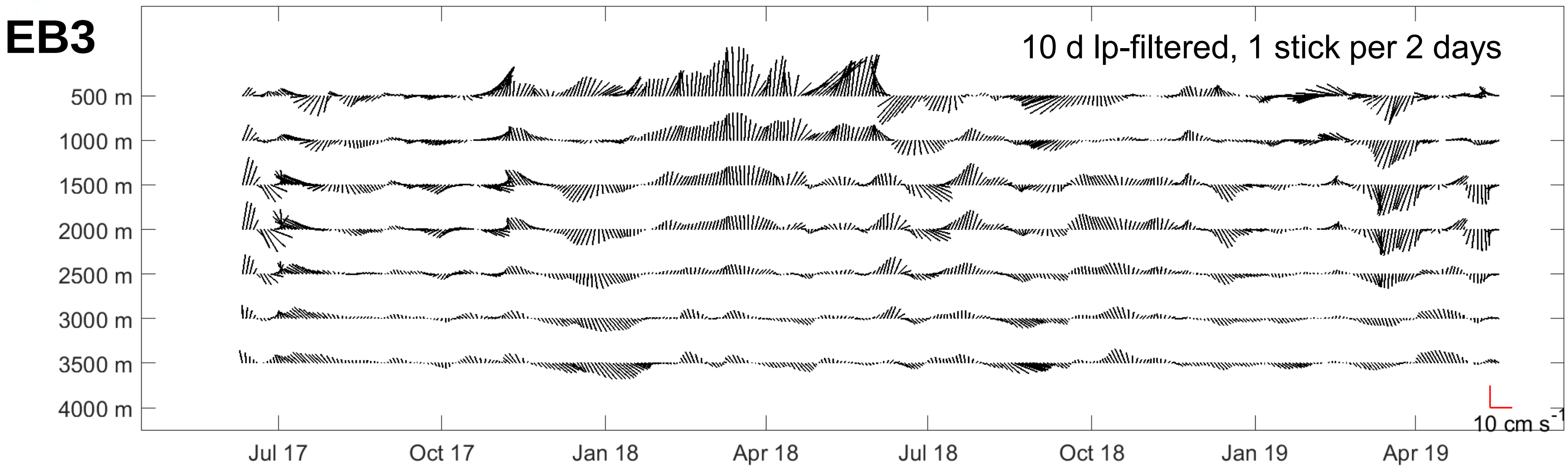
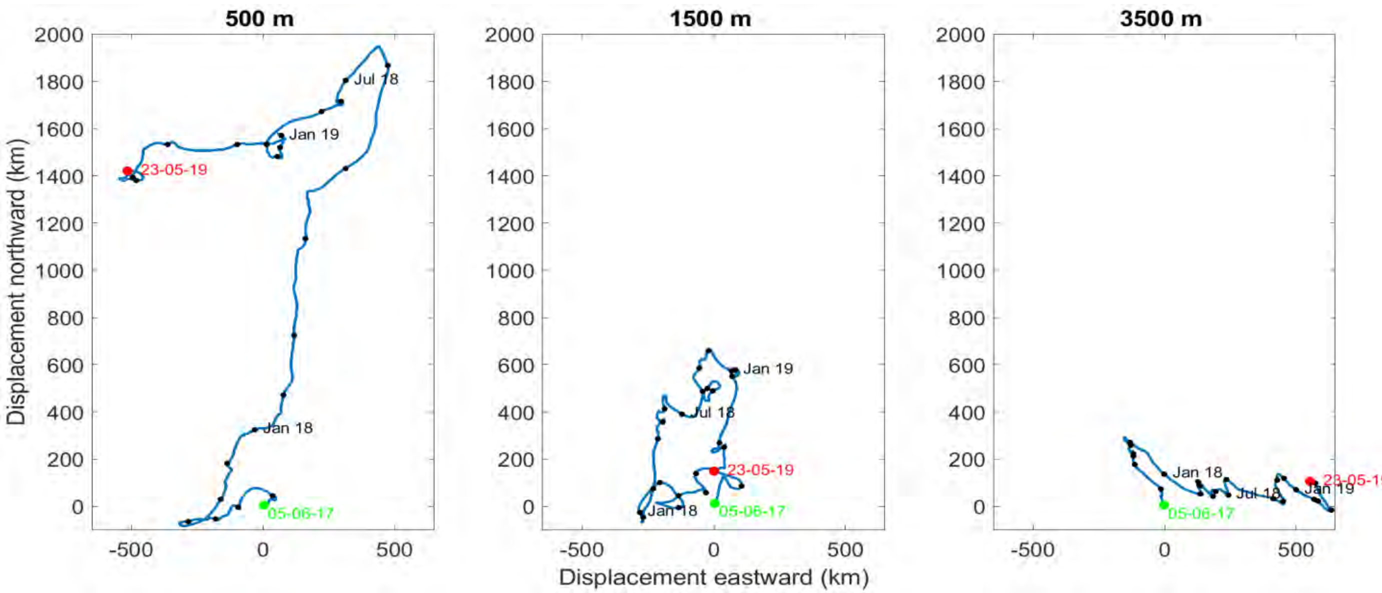
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE



Deep mooring EB3





Deep mooring EB3

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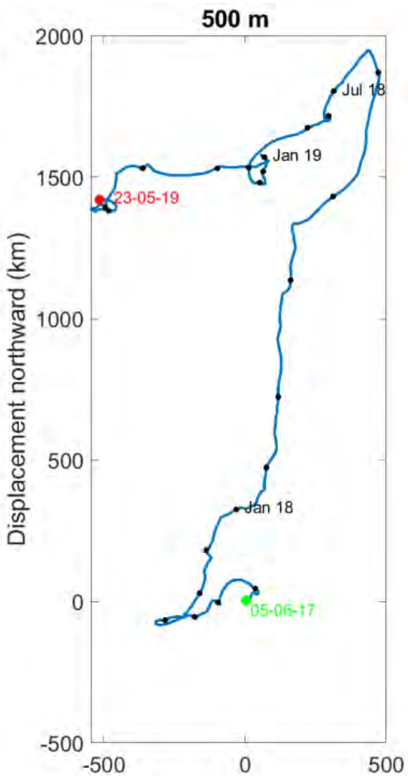
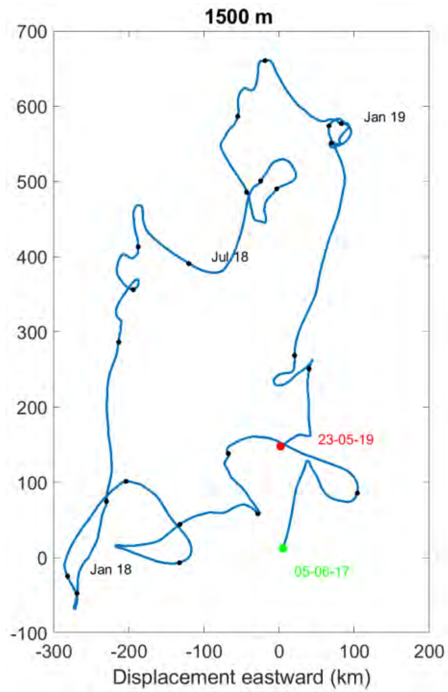
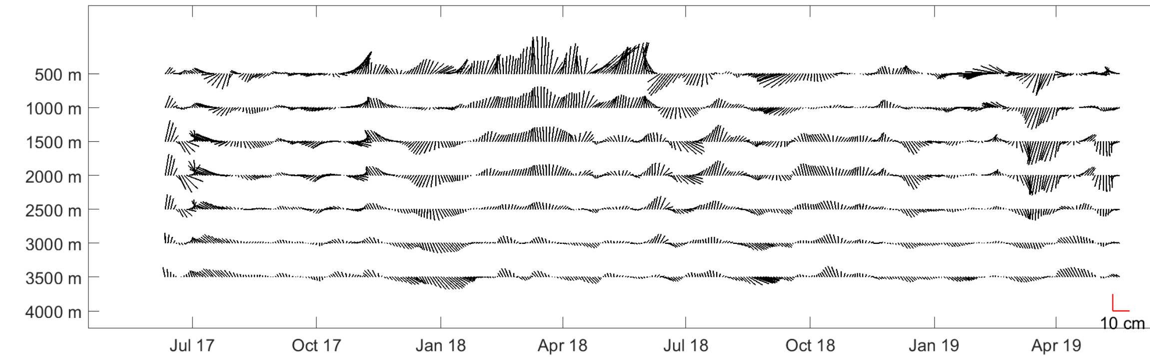
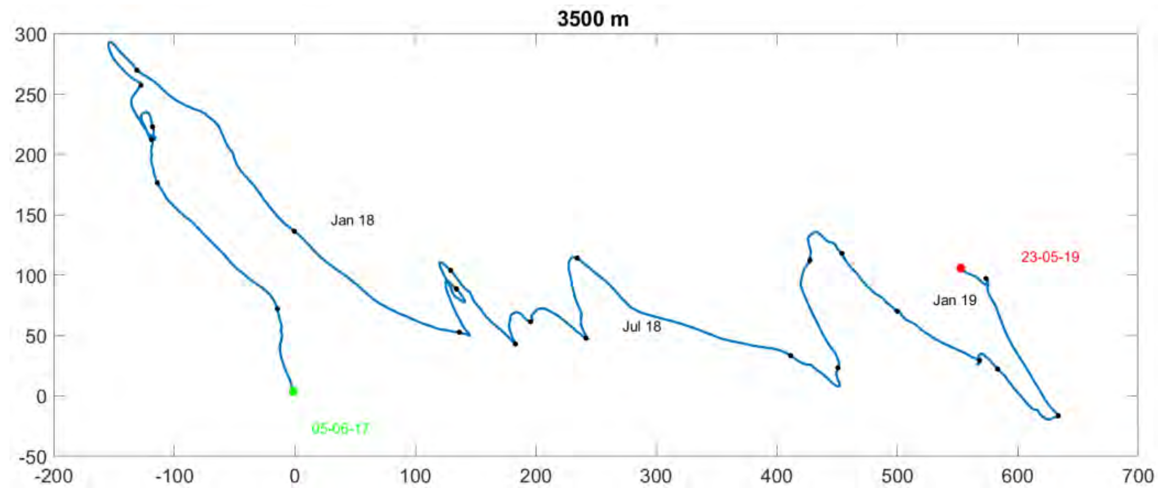
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

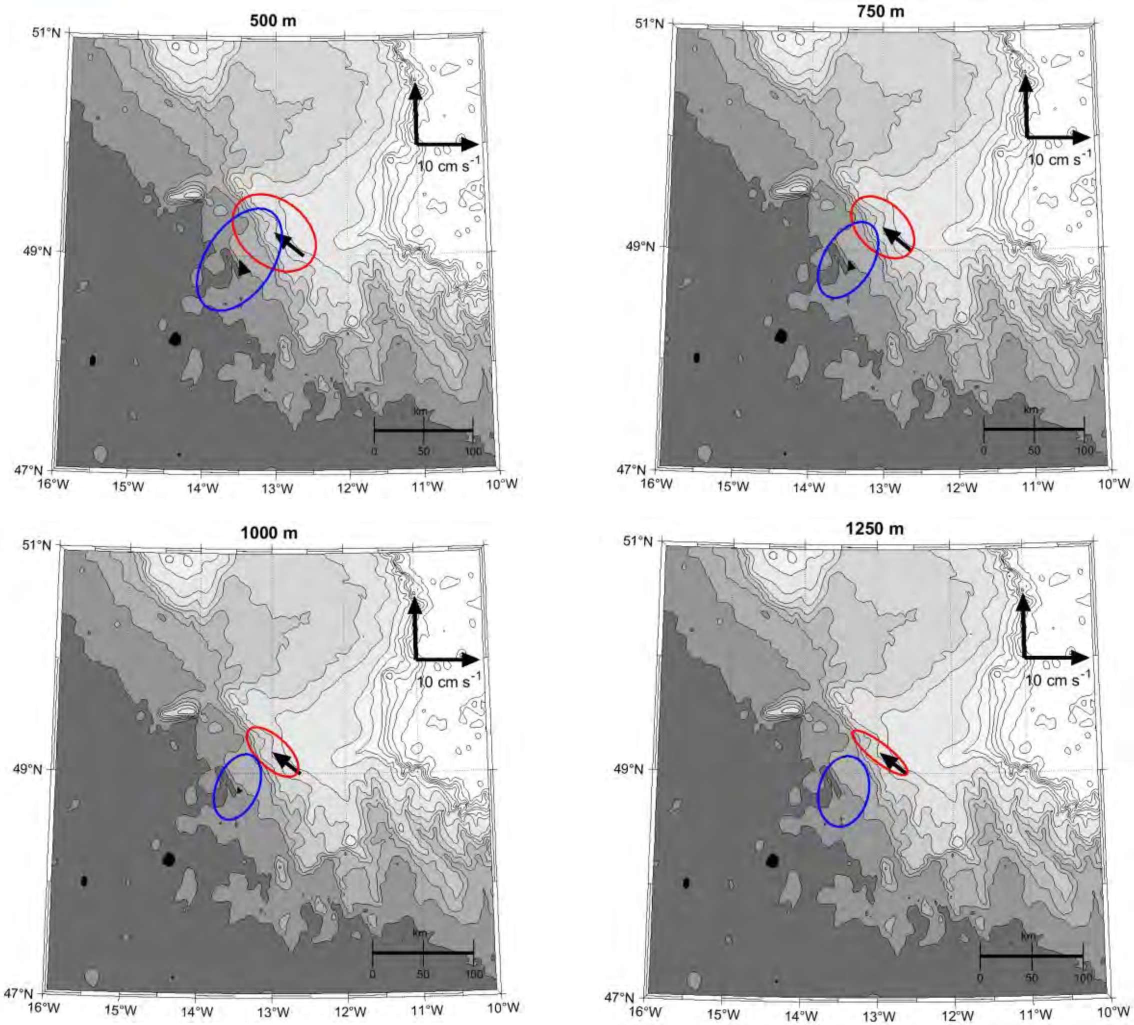


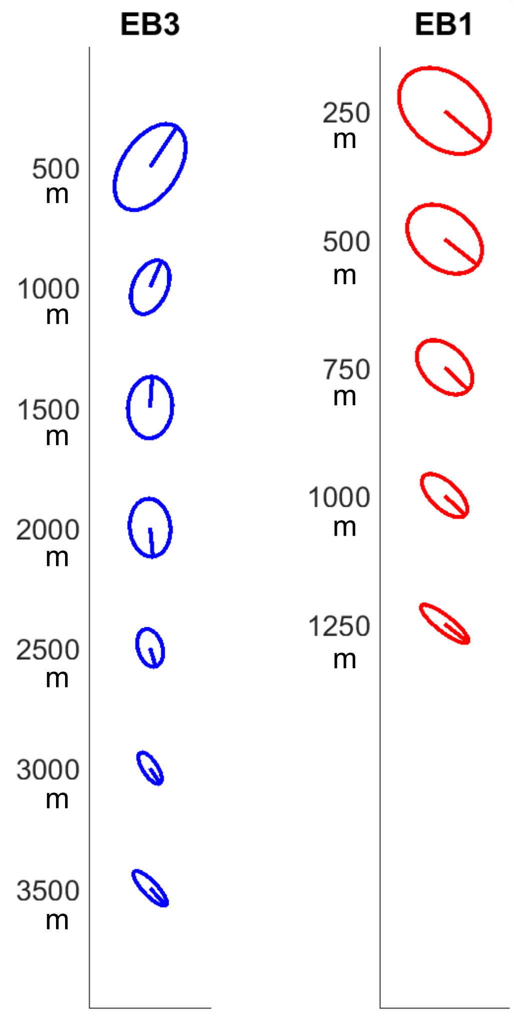






EB1 (2016-19) vs. EB3 (2017-19)





EB1 (2017-19) vs. EB3 (2017-19)

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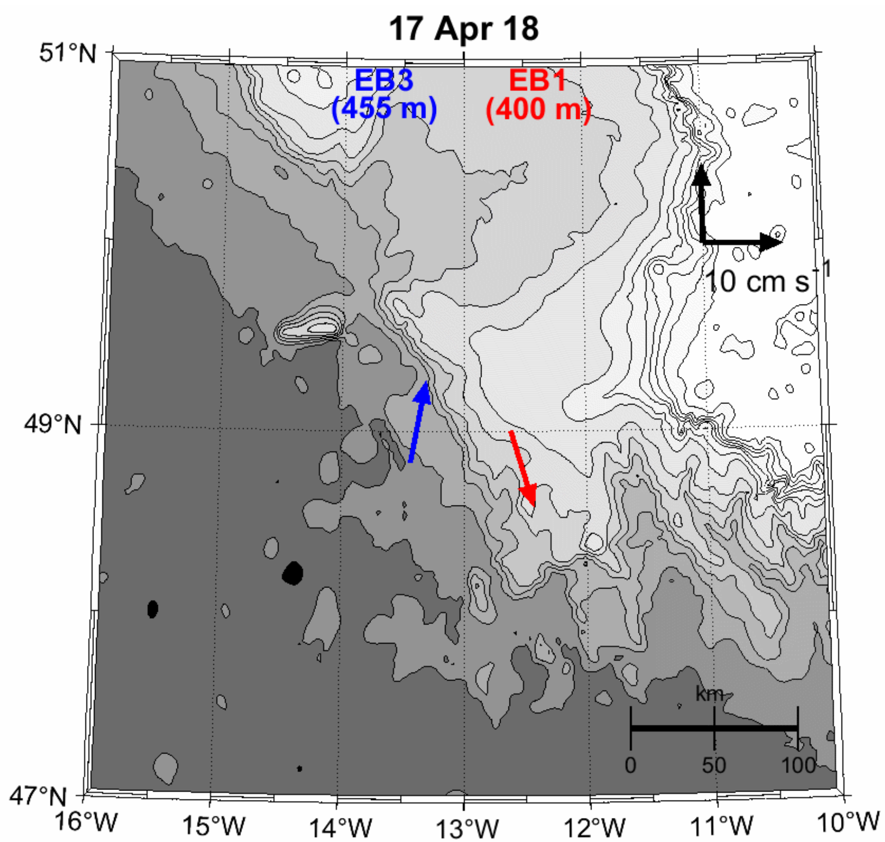
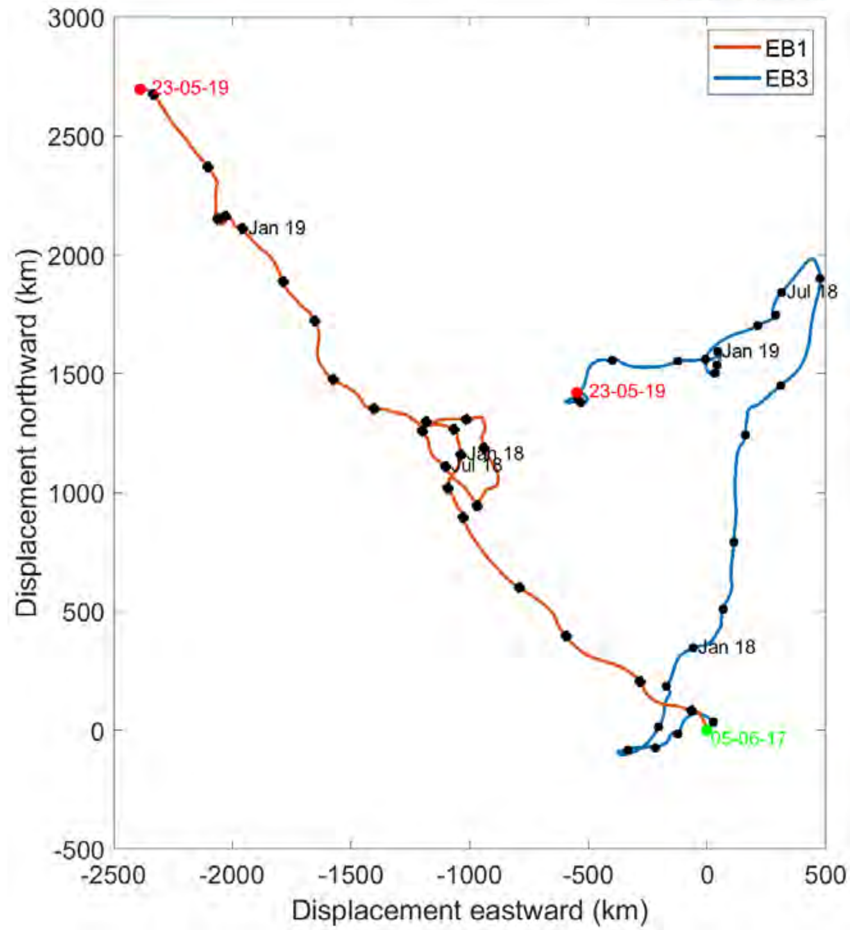
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE





Deep mooring EB3

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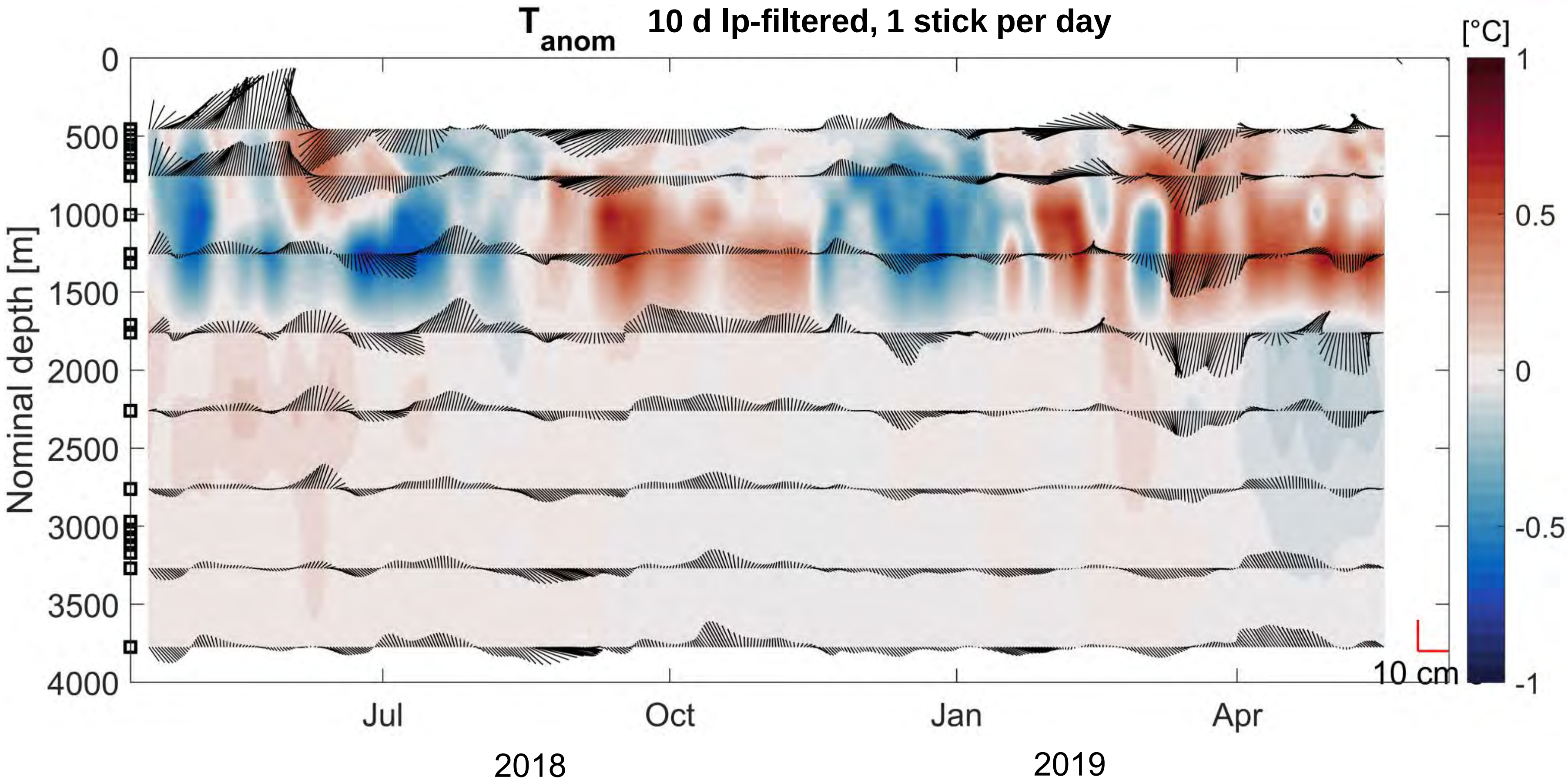
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE



Deep mooring EB3

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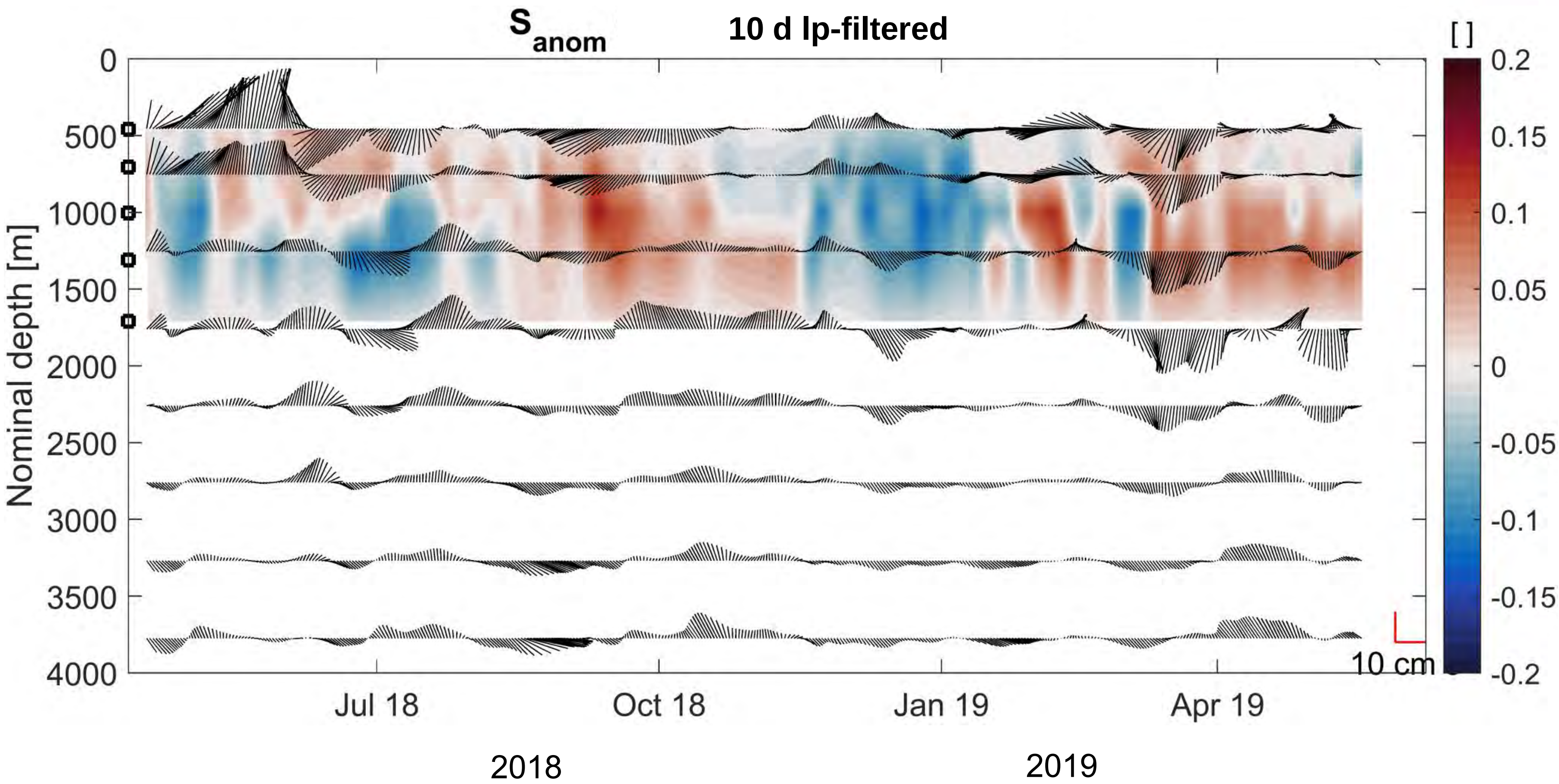
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE



Hydrographic variability

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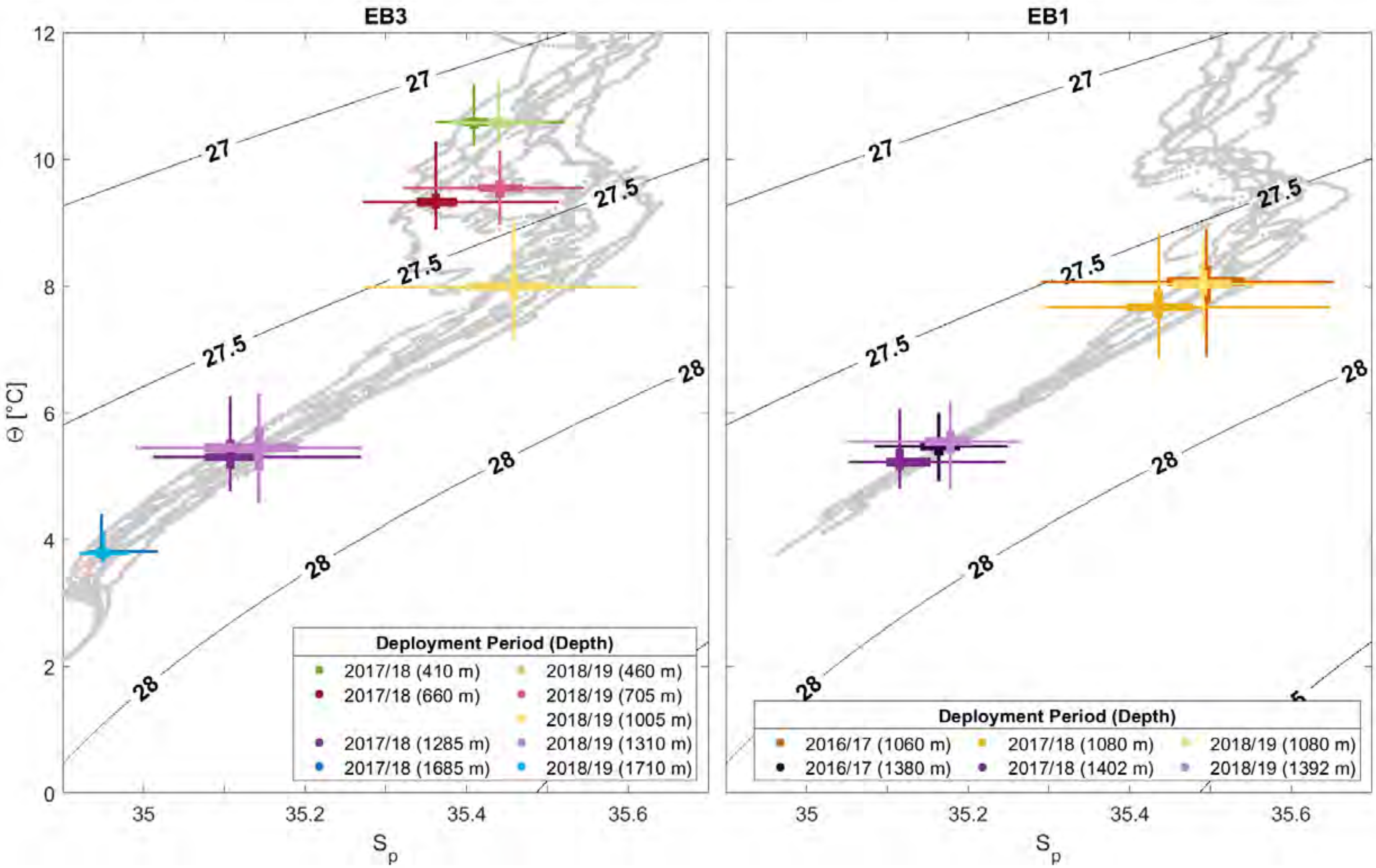

CTD Data at mooring positions (8 cruises between 2003 & 2019)

Min/ Max

Median 25/ 75 prct

Salinity variability in the MW layer

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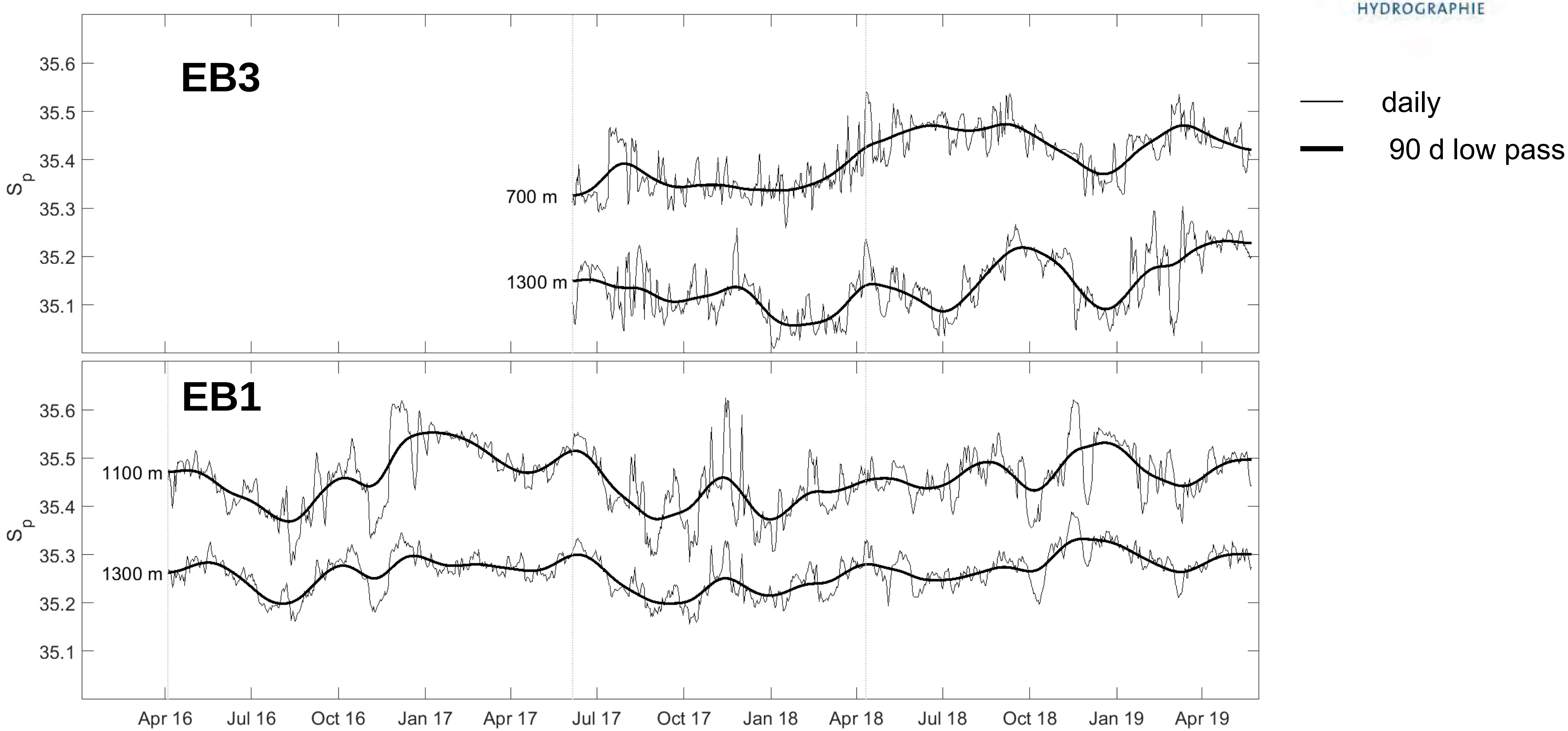

Work in progress

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BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

- Transport estimates
- Combine observations with ARGO, Altimetry, wind data and models
- understandig of the relevant processes (e.g. eddies, topographic waves)
- Maintain the EB array (add EB2?)
- Collaboration with EirOOS

EirOOS Moorings

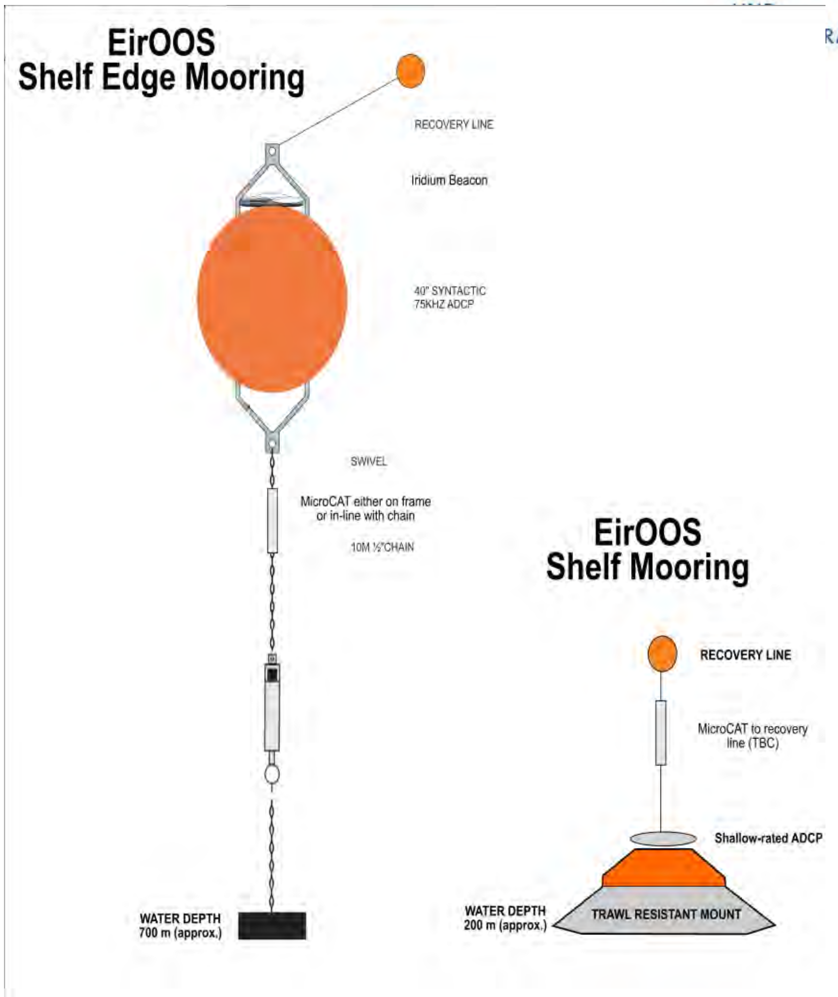
BUNDESAMT FÜR SEESCHIFFFAHRT ... RAPHIE

The EirOOS program (Irish Ocean Observing System) has funded 6 moorings to observe shelf and shelf-edge currents

2 x Shelf Edge
4 x On shelf

Technical Lead: Guy Westbrook, MI, MU, and NUIG involved

Equipment will be arriving in the next few months . The first deployments, dependent on available resources, are planned for Feb 2020, with turnarounds in summer 2020, and summer 2021 (in the first instance).



EirOOS Moorings

BUNDESAMT FÜR SEESCHIFFFAHRT UND

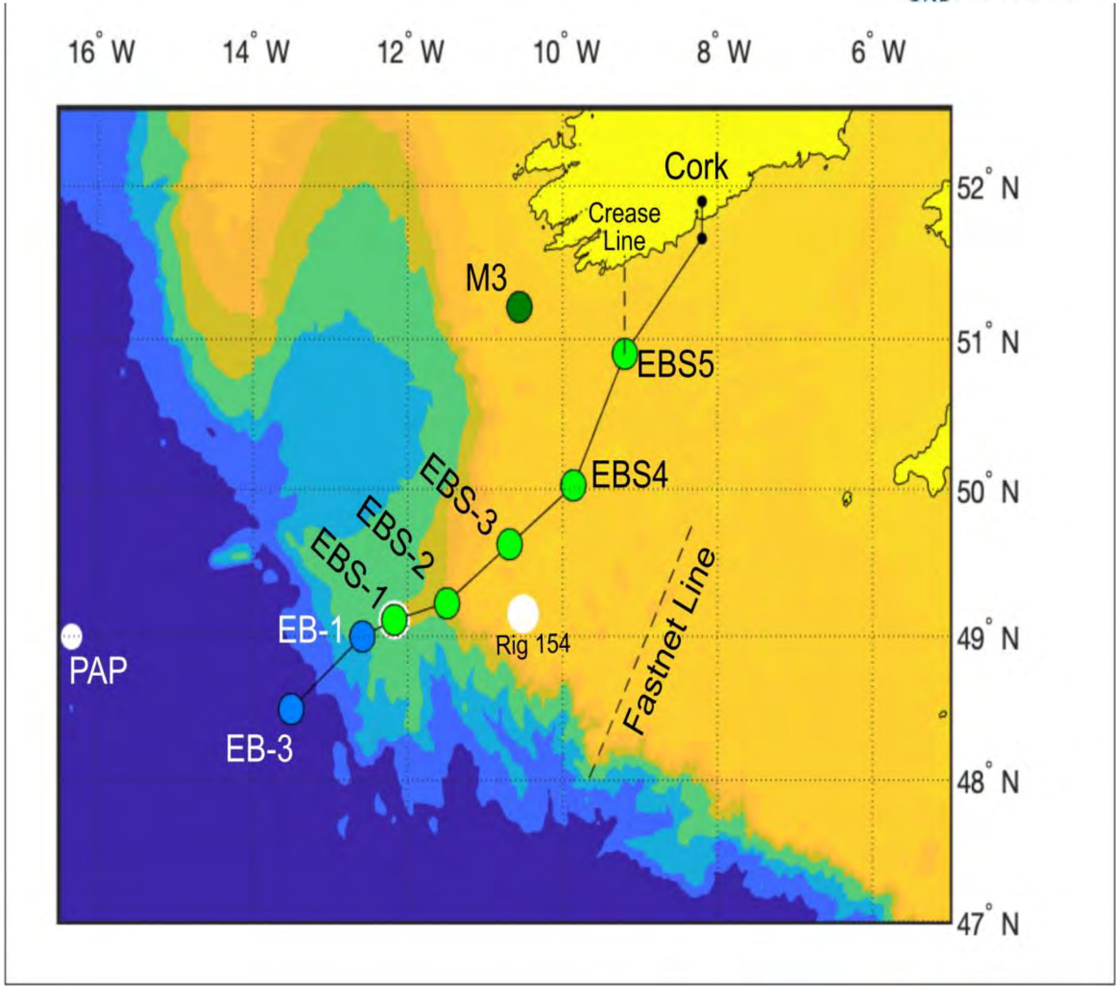
EB1 and EB3 are existing BSH moorings.

EBS-1, EBS-2 are shelf edge moorings in 1000 and 600 m of water respectively.

EBS-3, 4, 5 are on-shelf moorings (trawl-resistant mounts)—nominal positions on map.

M3 is an Irish Met Buoy

Other (UK) observations in the region are indicated in white.



Summary

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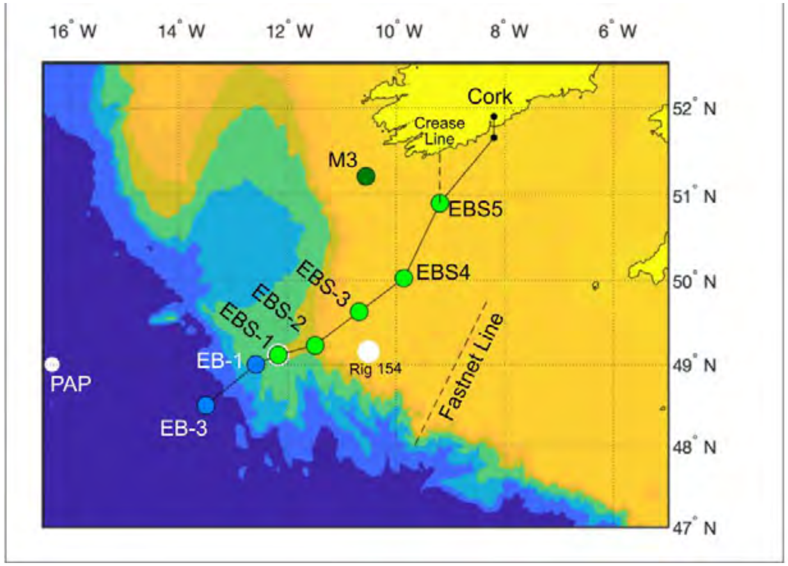
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

NOAC Array:

- Transport estimates in Western Basin and at MAR 1993 to 2018
- Transport time series for eastern basin in preparation
- AMOC estimate at 47°N in progress
- Ends in 2020
- Data available via PIs University Bremen: Monika Rhein, Dagmar Kieke

Eastern Boundary:

- two moorings: EB1 (Uni Bremen) & EB3 (BSH)
- EB1 operated by BSH from 2020
- planned until 2021 (recovery and redeployment)
- Planned joint cruise with Irish colleagues in 2021
- Extension of array inshore
- Data available via BSH: Birgit Klein, Kerstin Jochumsen, Martin Moritz



NOAC Publications

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Western Boundary Current	Rhein et al. (2011, DSR-II), 1/12° model, heat transports Mertens et al. (2014, JGR), WBC transports Schneider et al. (2015, JGR), Flemish Pass Rhein et al. (2019, JGR), WBC transports Kieke et al. (in prep), Flemish Pass
Western Basin	Rhein et al. (2011, DSR-II), 1/12° model, heat transports Mertens et al. (2014, JGR), NAC & NBR transports Rhein et al. (2019, JGR), flow between 44° W-31° W
Mid-Atlantic Ridge	Rhein et al. (2011, DSR-II), NAC transport at MAR Roessler et al. (2015, JGR), NAC transport at MAR Breckenfelder et al. (2017, JGR), 1/20° model, NAC and NAO at MAR
Eastern Basin	Nowitzki et al. (2019, in prep), NAC transport in eastern basin
Eastern Boundary Current	Moritz et al. (2019, in prep), eastern boundary moorings
Basin-wide	Rhein et al. (2011, DSR-II), 1/12° model, ocean heat transport Müller et al. (2017, JGR), 2 D eddies, abundance and temperature Müller et al. (2019, JGR), 3 D eddies, heat and freshwater

Thank you!

BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

Motivation

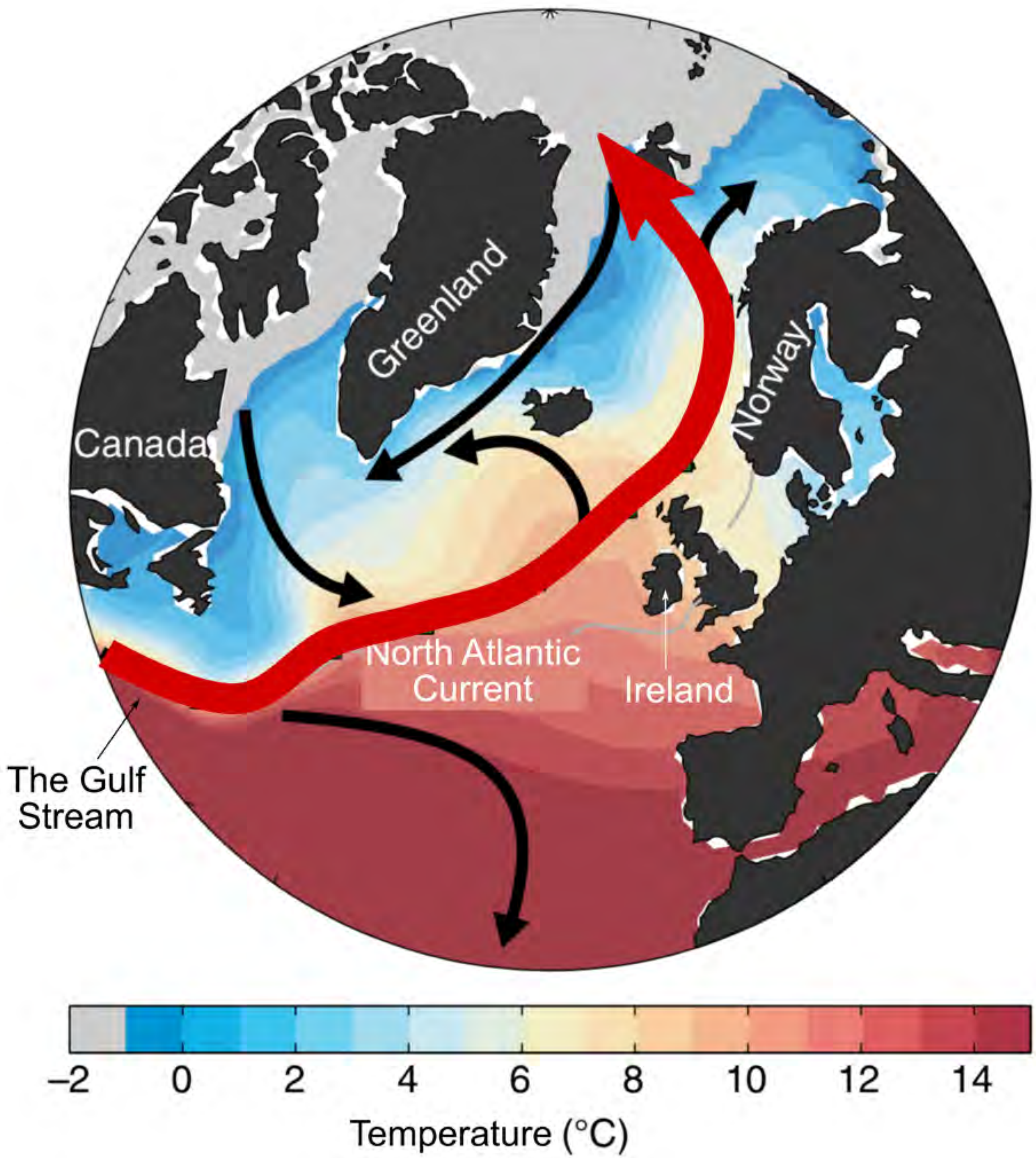
- Gather together groups involved in transport moorings arrays in the (eastern) subpolar North Atlantic (GSR, OSNAP, NOAC) connected to Blue-Action and Atlas
- Frame the societal questions of relevance for eastern subpolar NA ocean circulation
- Examine links with models and predictions

Outputs

- Proceedings to be published as Blue-Action deliverable
- Presentations to be made available
- Identification of two papers that we can work on as a group
- Identification of fieldwork co-operation

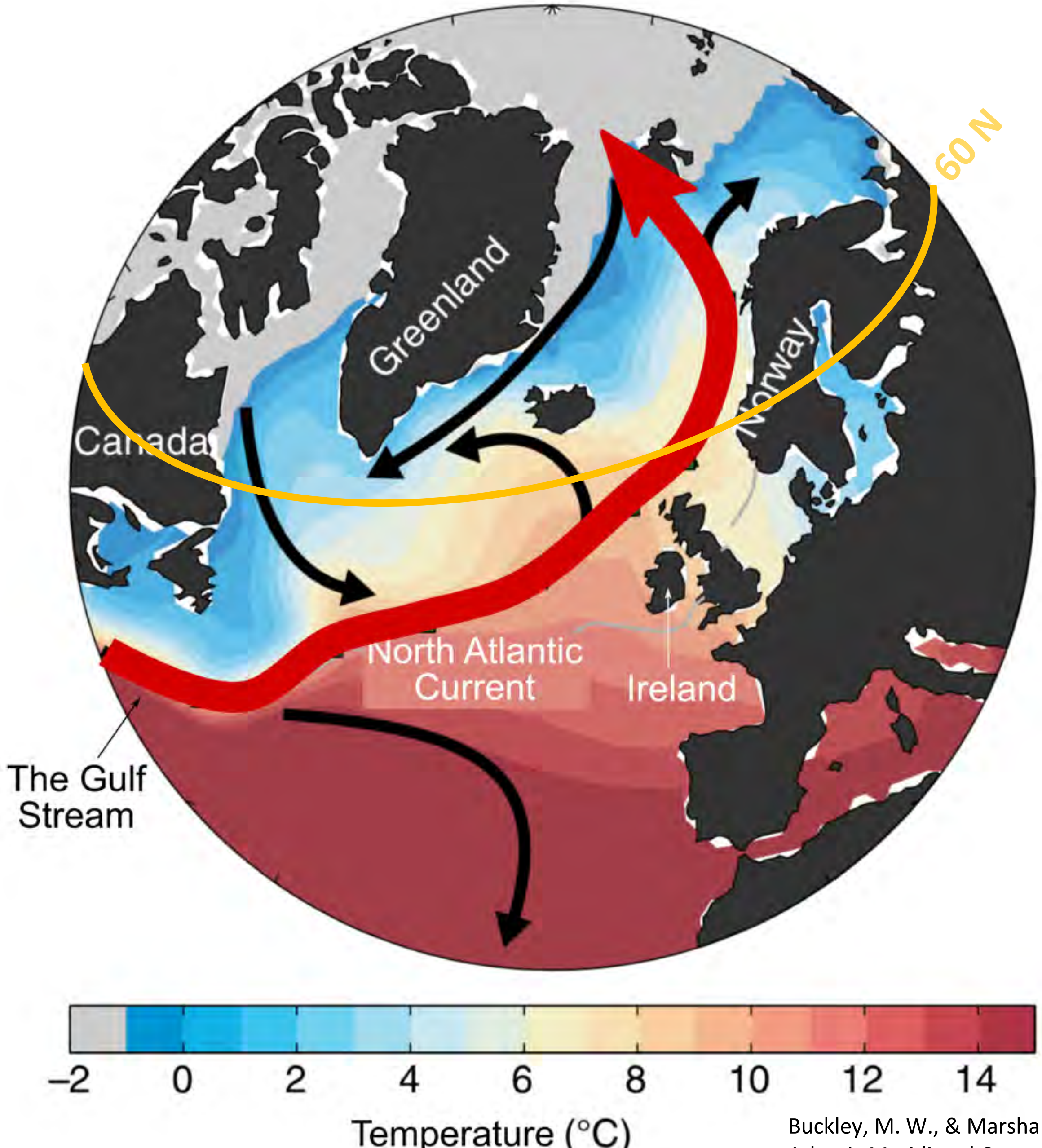
Structure

- Before lunch: Introduction to the 3 observatories
- After lunch: 3 sessions, 2-3 presentations, with breakout groups following each set of presentations
  - The big questions
  - Observations of circulation
  - Models and predictions



The warm ocean waters carried by the system of currents known as the Atlantic Meridional Overturning Circulation (AMOC), including the Gulf Stream and the North Atlantic Current, contribute to northwest Europe's mild climate.

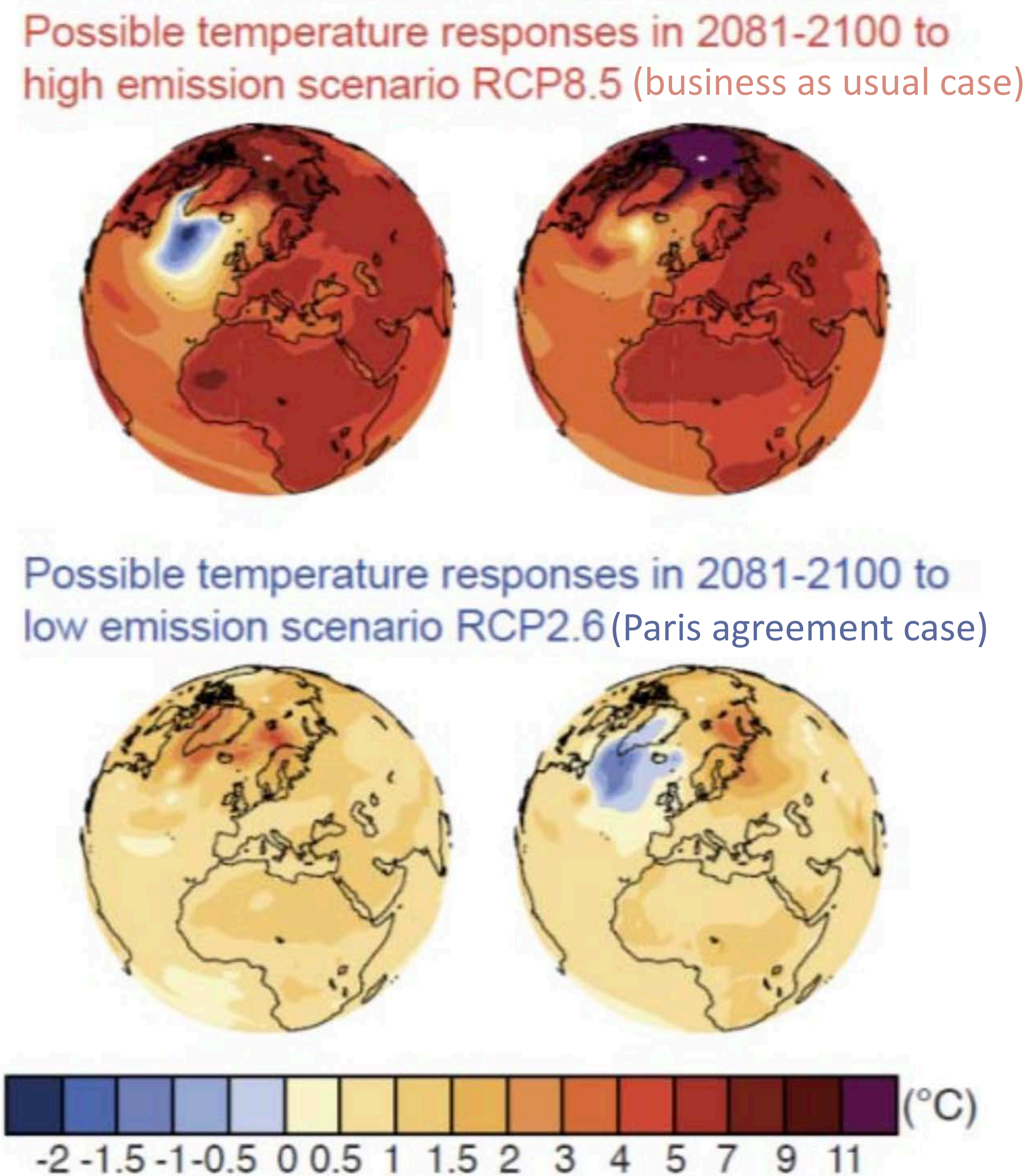
Årthun, M., Eldevik, T., Viste, E., Drange, H., Furevik, T., Johnson, H. L., & Keenlyside, N. S. (2017). Skillful prediction of northern climate provided by the ocean. *Nature communications*, *8*, 15875.



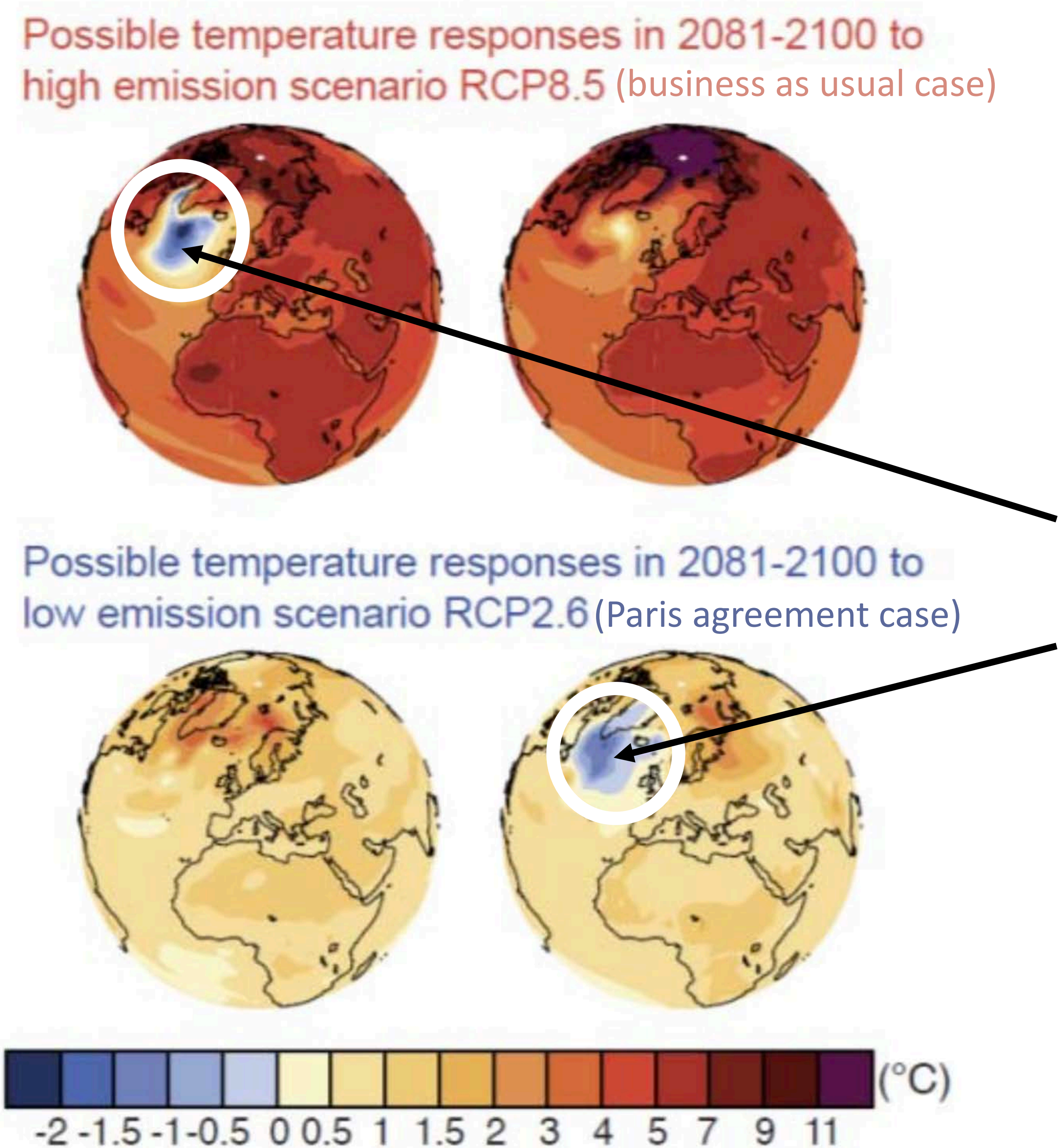
The warm ocean waters carried by the system of currents known as the Atlantic Meridional Overturning Circulation (AMOC), including the Gulf Stream and the North Atlantic Current, contribute to northwest Europe's mild climate.

Atlantic Ocean heat transport of around 1.3 PW is given up to the atmosphere north of 26.5°N resulting in the northern hemisphere atmosphere and ocean, especially north of 60°N, being up to 2-6°C warmer than equivalent latitudes in the southern hemisphere

Buckley, M. W., & Marshall, J. (2016). Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review. *Reviews of Geophysics*, *54*(1), 5-63.



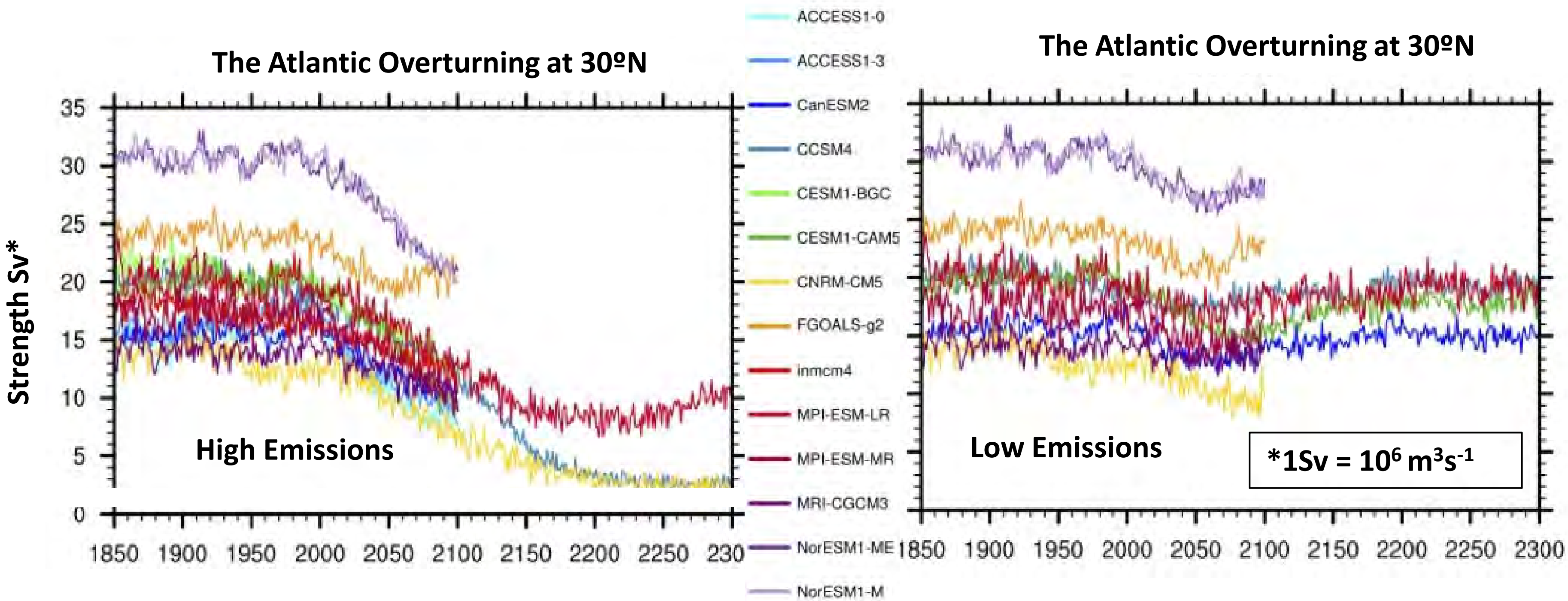
The world *on average* is warming up due to rising greenhouse gases



The world *on average* is warming up due to rising greenhouse gases

However, if the AMOC slows, extreme warming may not be the future for the North Atlantic

A future slowdown?

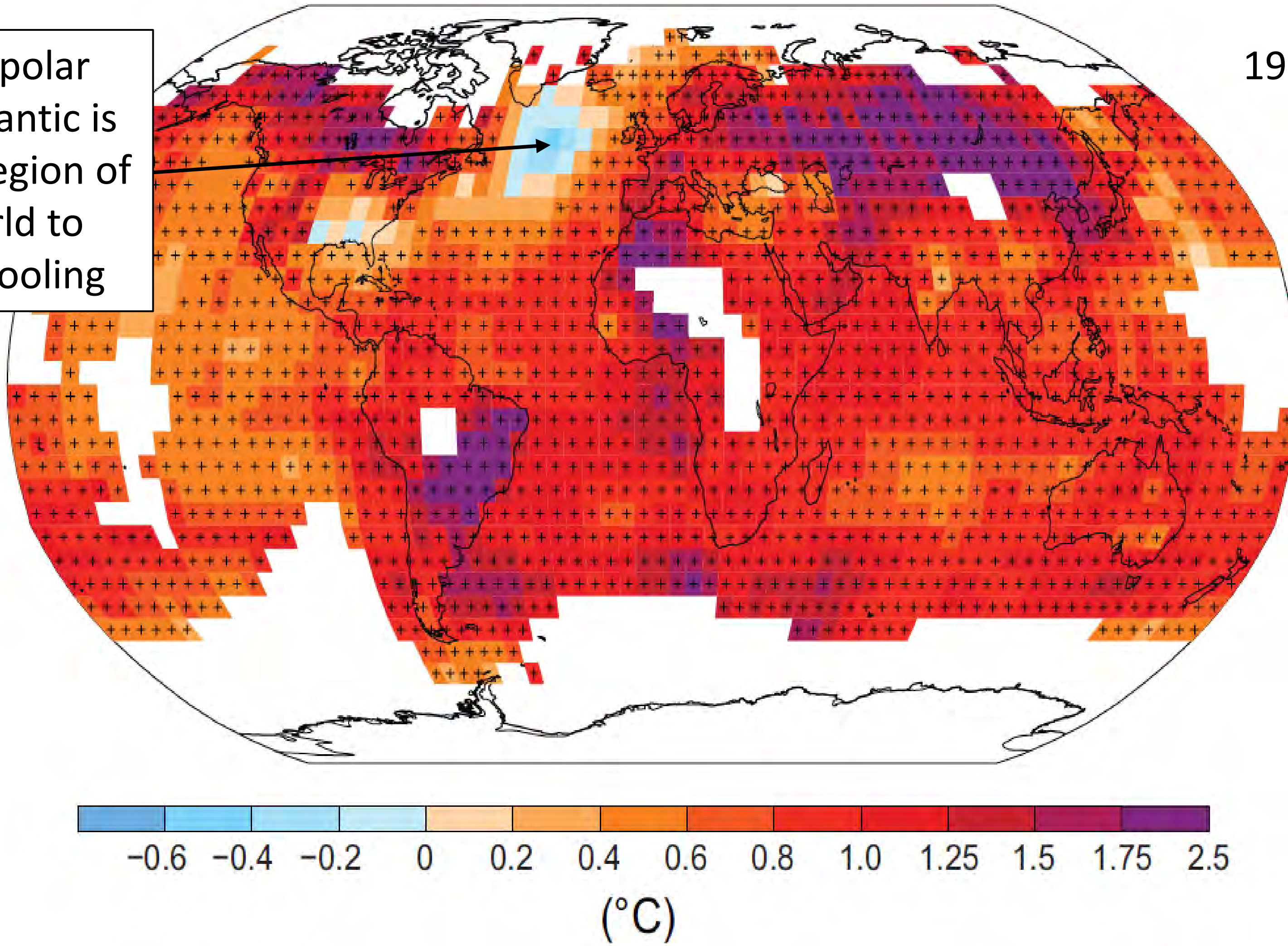


It is **'very likely'** that the AMOC will weaken over the 21st century [IPCC]

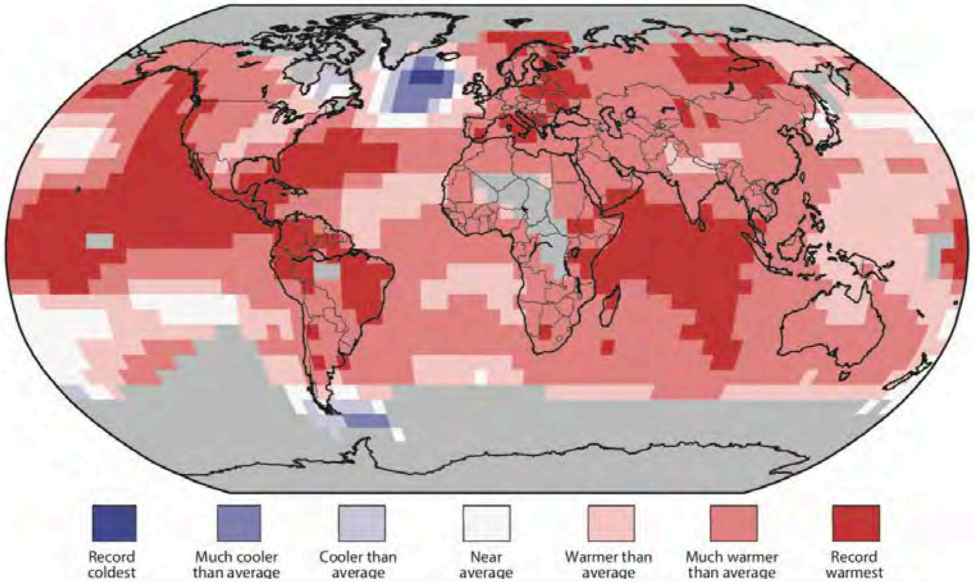
The Atlantic Warming Hole

The subpolar North Atlantic is the only region of the world to show a cooling

1901-2012



Unusual Atlantic in recent years



Coldest temperatures ever recorded south of Iceland in 2015 when globally a new record for warmest year on record is set.

Coldest and freshest values in Iceland basin (ICES Report)

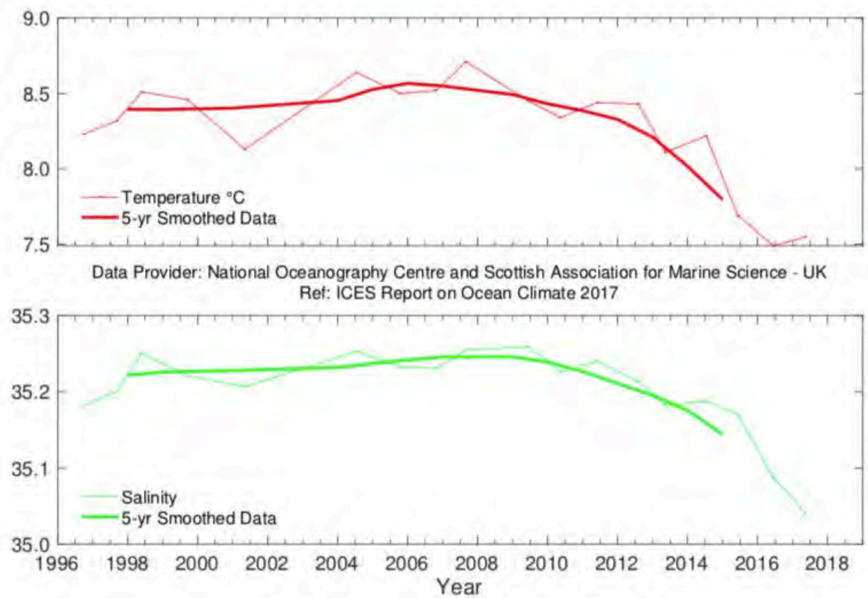
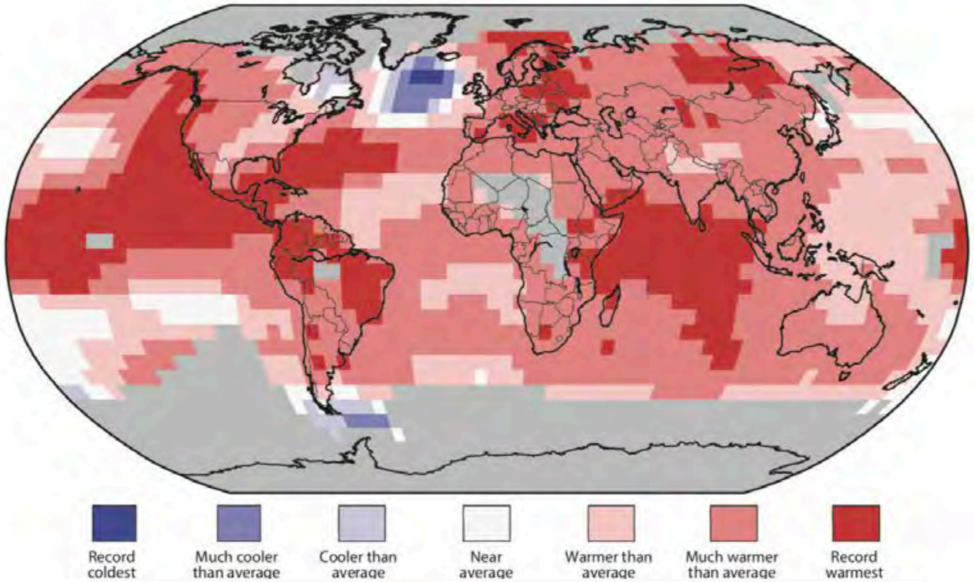


FIGURE 62.
Iceland Basin: Temperature (upper panel) and salinity (lower panel) for the upper ocean (potential density 27.20–27.50 kg m^{-3}, representing the top 500 m and excluding the seasonally warmed surface layer).

Unusual Atlantic in recent years



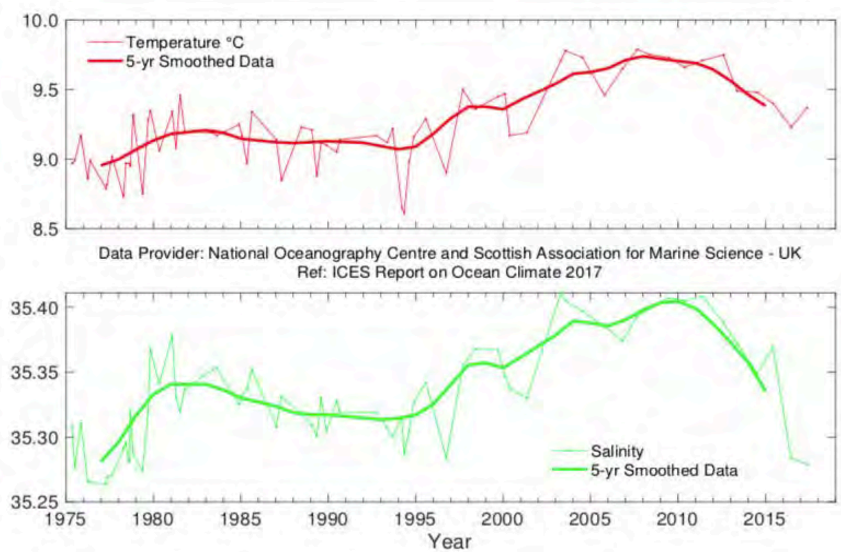


FIGURE 60. Rockall Trough: Temperature (upper panel) and salinity (lower panel) for the upper ocean (potential density 27.2–27.50 kg m⁻³, representing the top 800 m, but excluding the seasonally warmed surface layer).

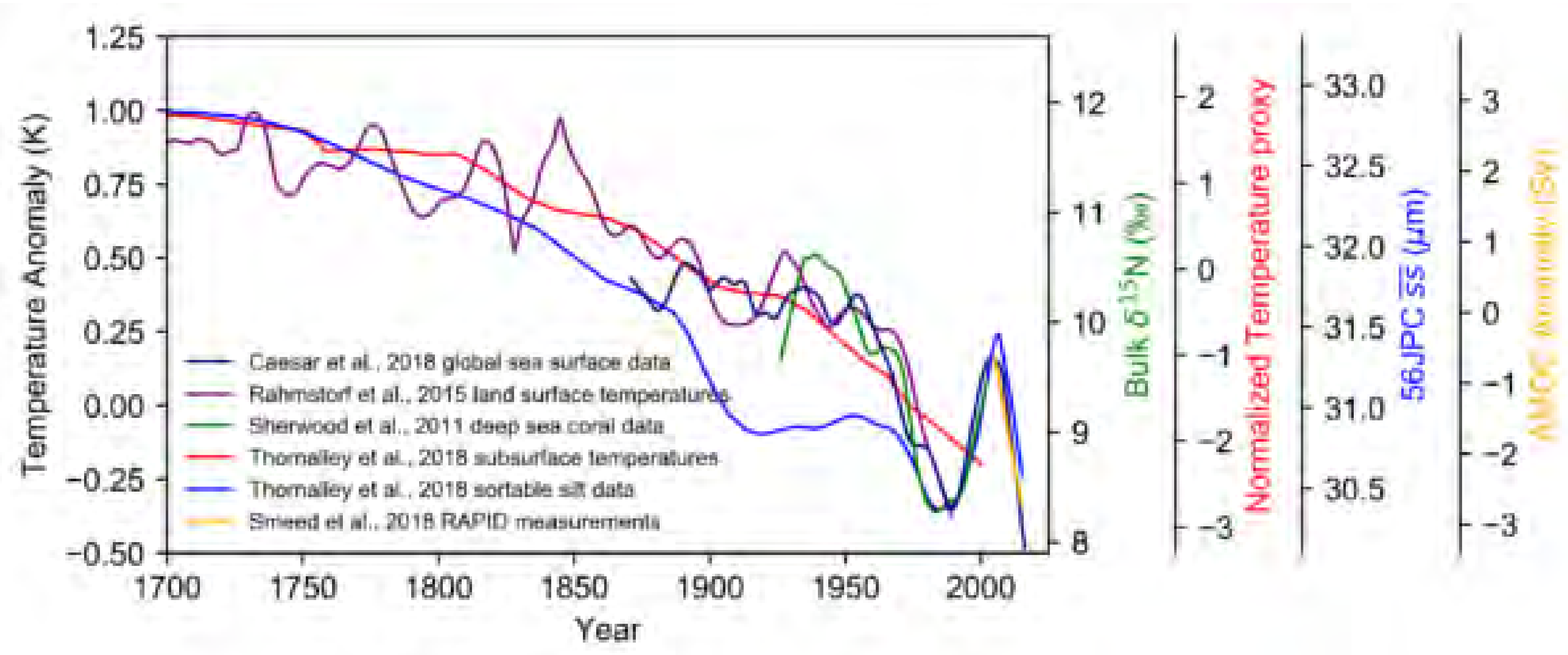
Coldest temperatures ever recorded south of Iceland in 2015 when globally a new record for warmest year on record is set (NOAA figure).

Coldest and freshest values in Iceland basin (ICES Report)

Trend towards very fresh values throughout the eastern subpolary gyre (e.g. Rockall trough, ICES Report)

Penny's talk later to cover in more detail…

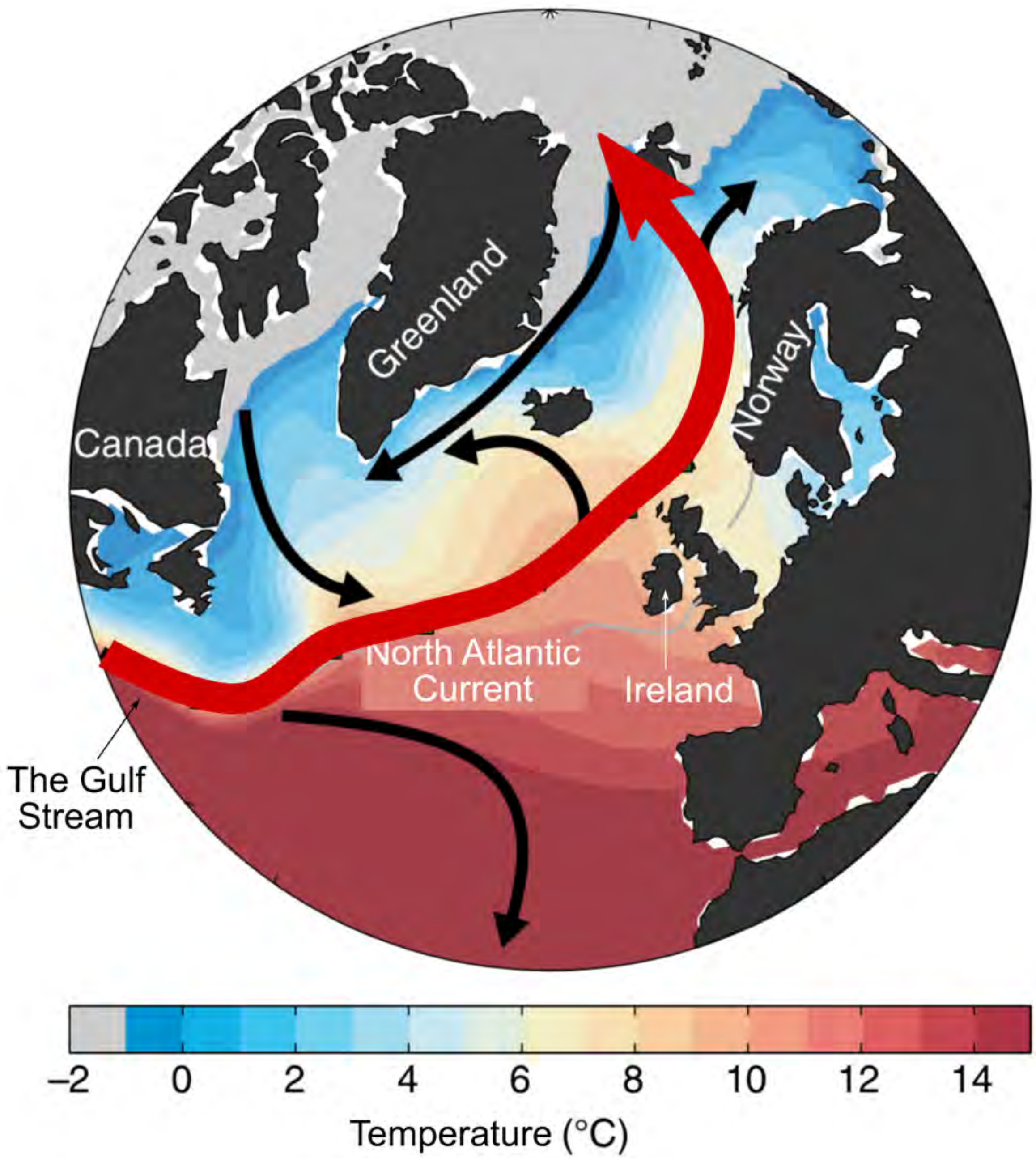
Is the warming hole indicative of a longterm decline in the Overturning?



Caesar et al., (2018) *Nature* linked the lack of warming in the North Atlantic gyre to a decline in Atlantic overturning, which they say started around 1960

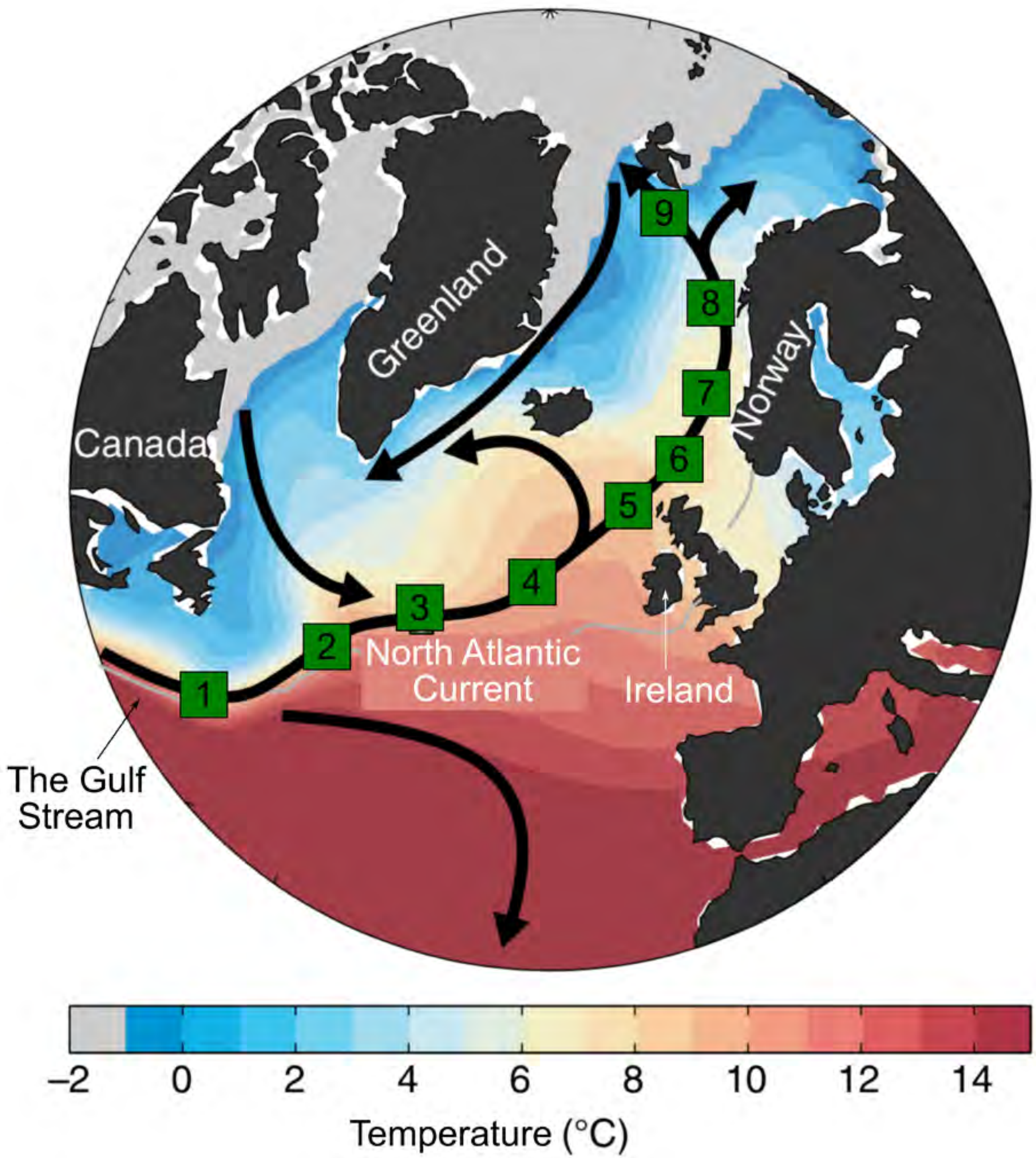
Maynooth University
National University of Ireland Maynooth

ICARUS
Irish Climate Analysis and Research Units



The warm ocean waters carried by the system of currents, including the Gulf Stream and the North Atlantic Current, contribute to Ireland and northwest Europe's mild climate

Årthun, M., Eldevik, T., Viste, E., Drange, H., Furevik, T., Johnson, H. L., & Keenlyside, N. S. (2017). Skillful prediction of northern climate provided by the ocean. *Nature communications*, *8*, 15875.

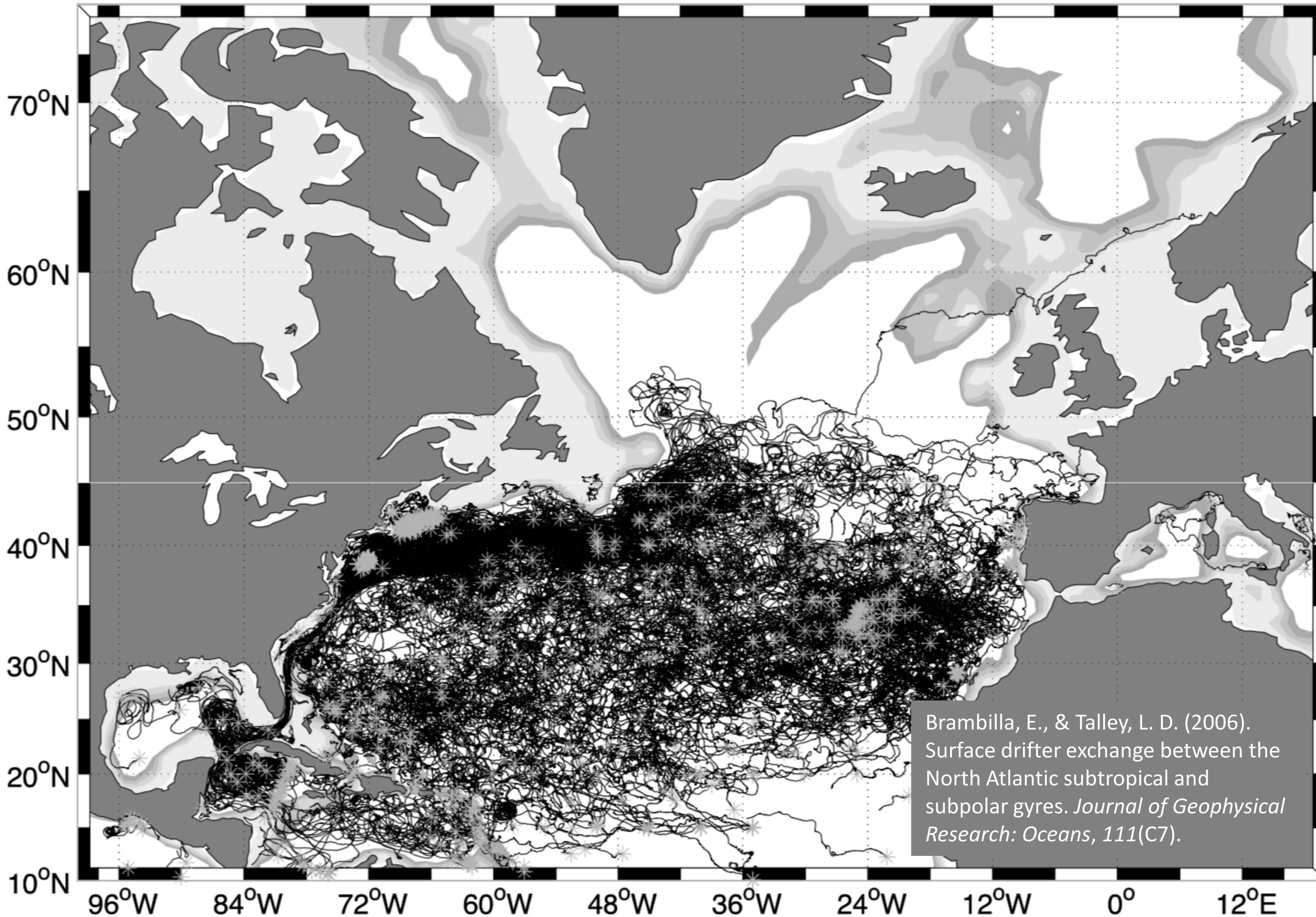


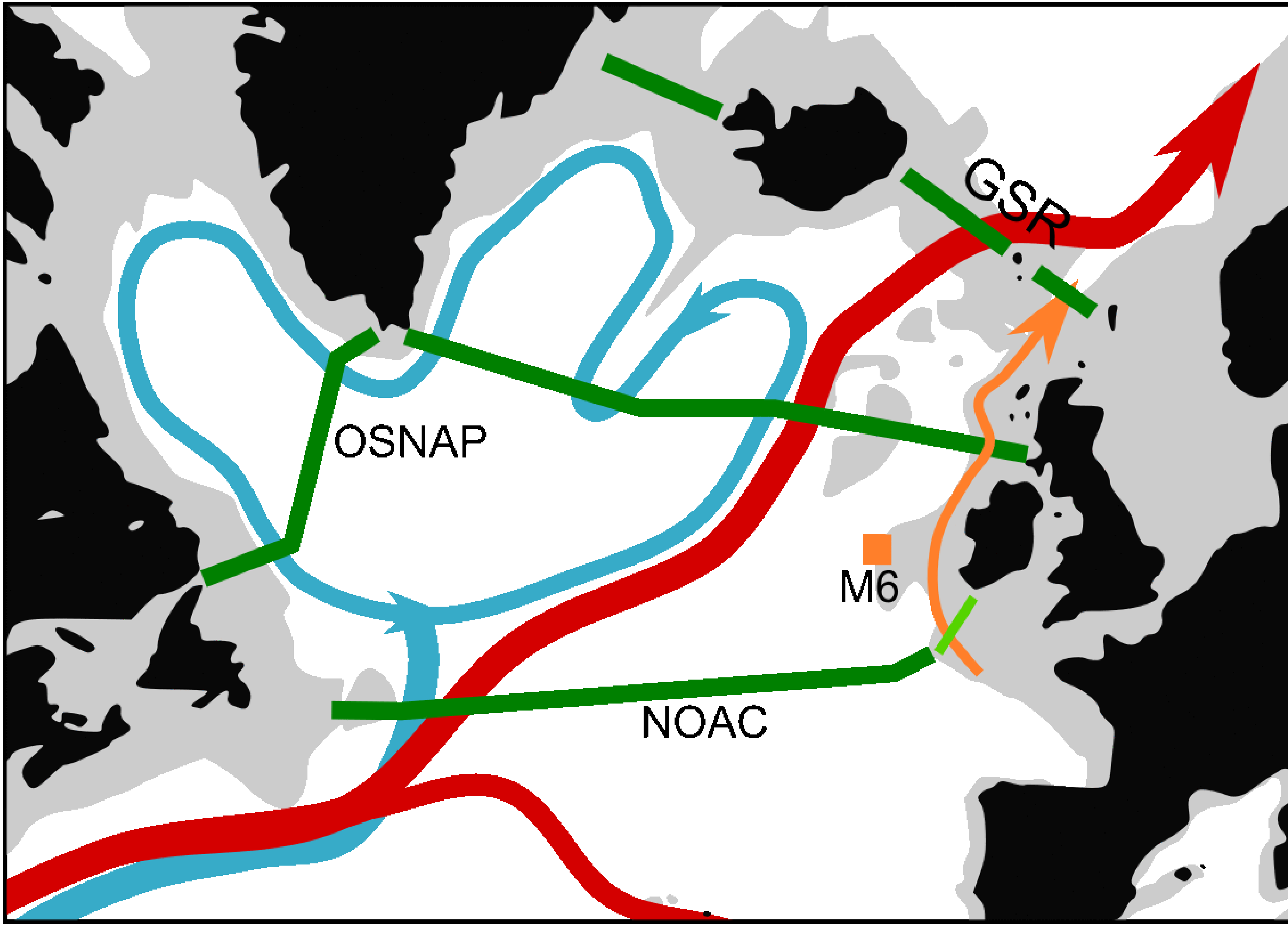
The warm ocean waters carried by the system of currents, including the Gulf Stream and the North Atlantic Current, contribute to Ireland and northwest Europe's mild climate

And this ocean highway leads to predictability as warm anomalies track from Canada to north of Norway

André's talk later to cover in more detail…

Årthun, M., Eldevik, T., Viste, E., Drange, H., Furevik, T., Johnson, H. L., & Keenlyside, N. S. (2017). Skillful prediction of northern climate provided by the ocean. *Nature communications*, *8*, 15875.


70°N
60°N
50°N
40°N
30°N
20°N
10°N
96°W
84°W
72°W
60°W
48°W
36°W
24°W
12°W
0°
12°E
Brambilla, E., & Talley, L. D. (2006). Surface drifter exchange between the North Atlantic subtropical and subpolar gyres. *Journal of Geophysical Research: Oceans*, *111*(C7).

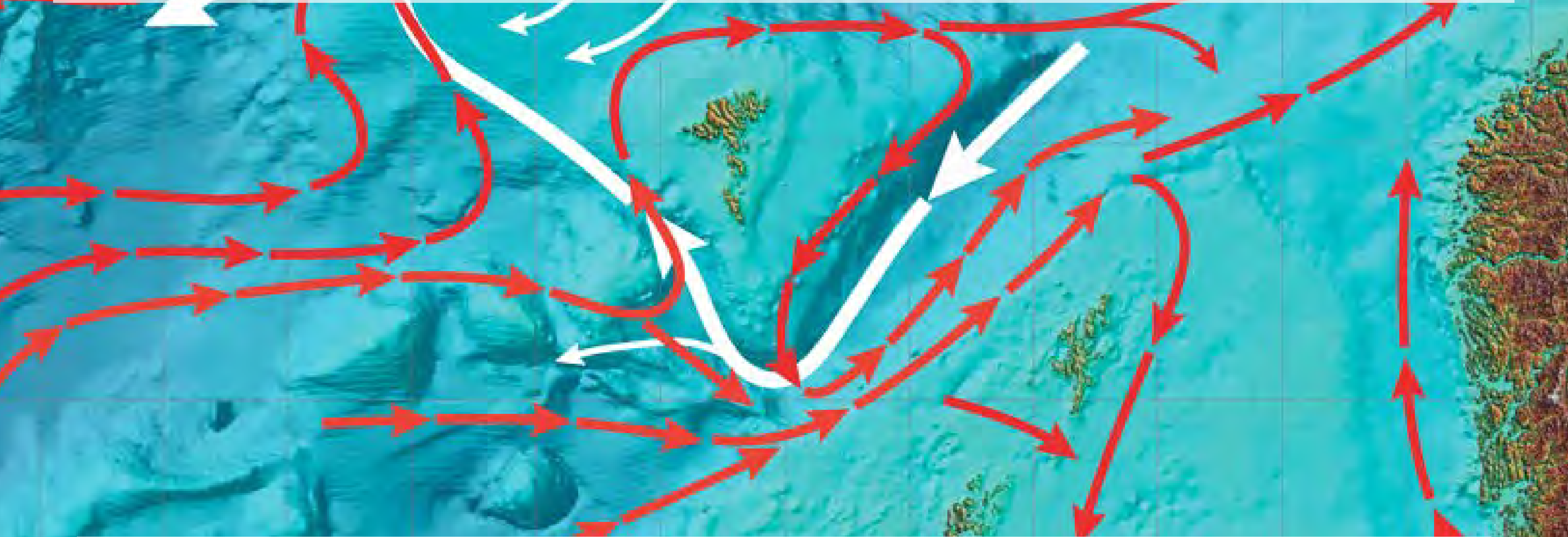

GSR
OSNAP
M6
NOAC

Is the Eastern Subpolar NA:

- the canary in the coalmine for a collapsing overturning?
- the key to unlocking decadal climate predictions for societal good?

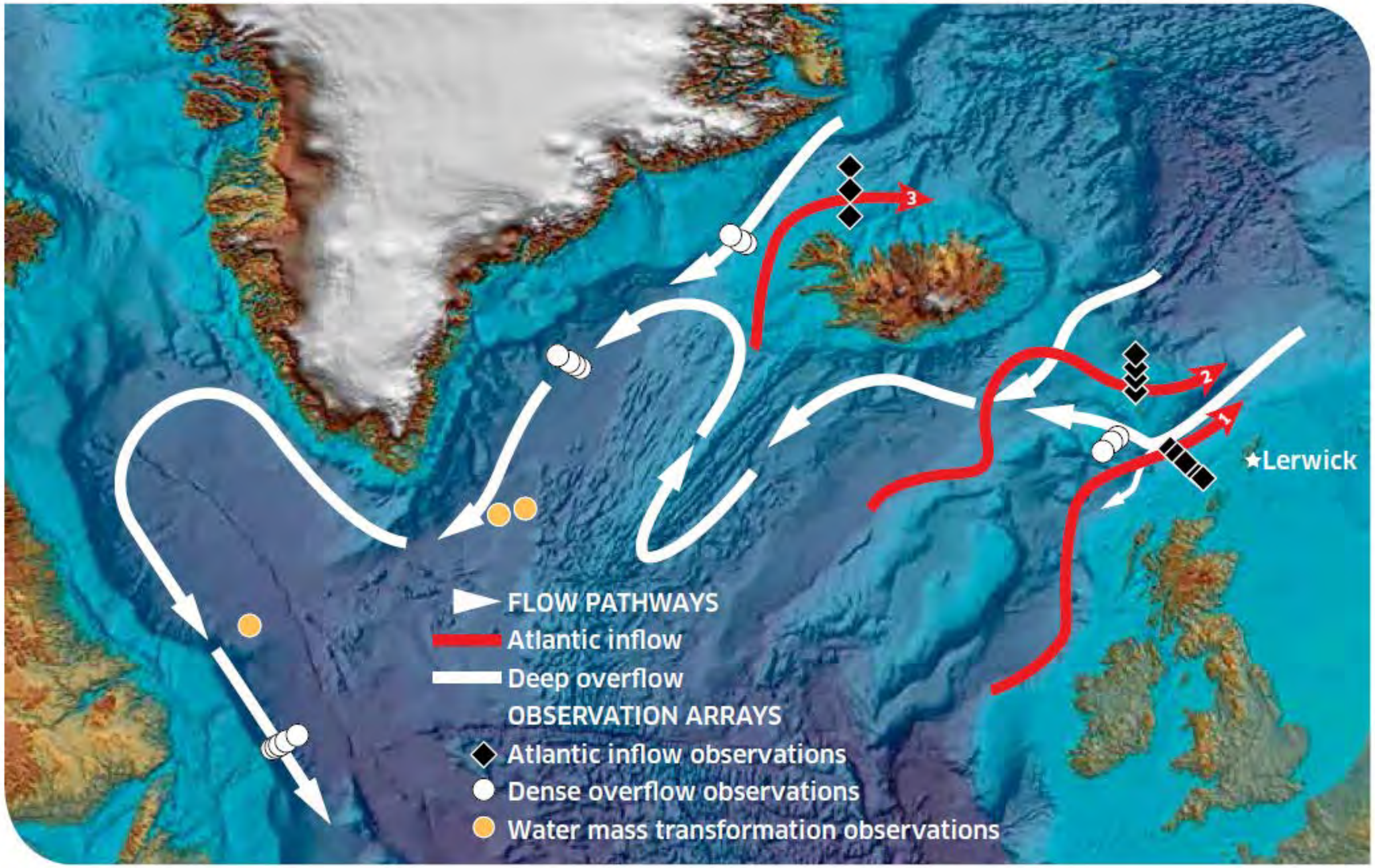
Blue-Action and Atlas have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 727852 (Blue-Action) and No 678760 (ATLAS). A4 (Aigéin, Aeráid, agus athrú Atlantaigh) is funded by the Marine Institute and the European Regional Development fund (grant: PBA/CC/18/01)

Transport in the Faroe-Shetland Channel and beyond



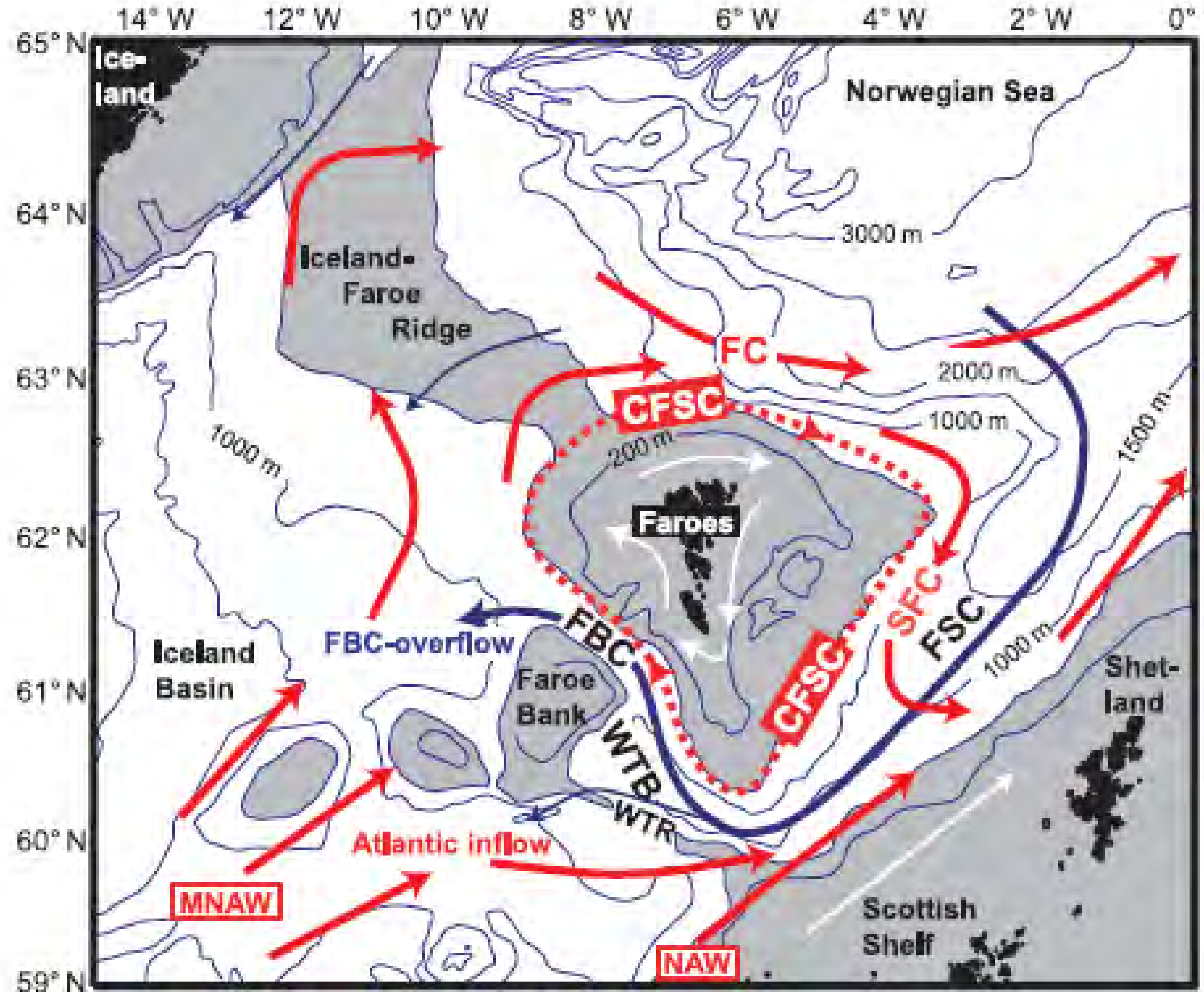
Bee Berx, Karin Margretha Larsen, Berit Rabe, Leon Chafik, Hjalmar Hatun

Observations in the Faroe-Shetland Channel (FSC)



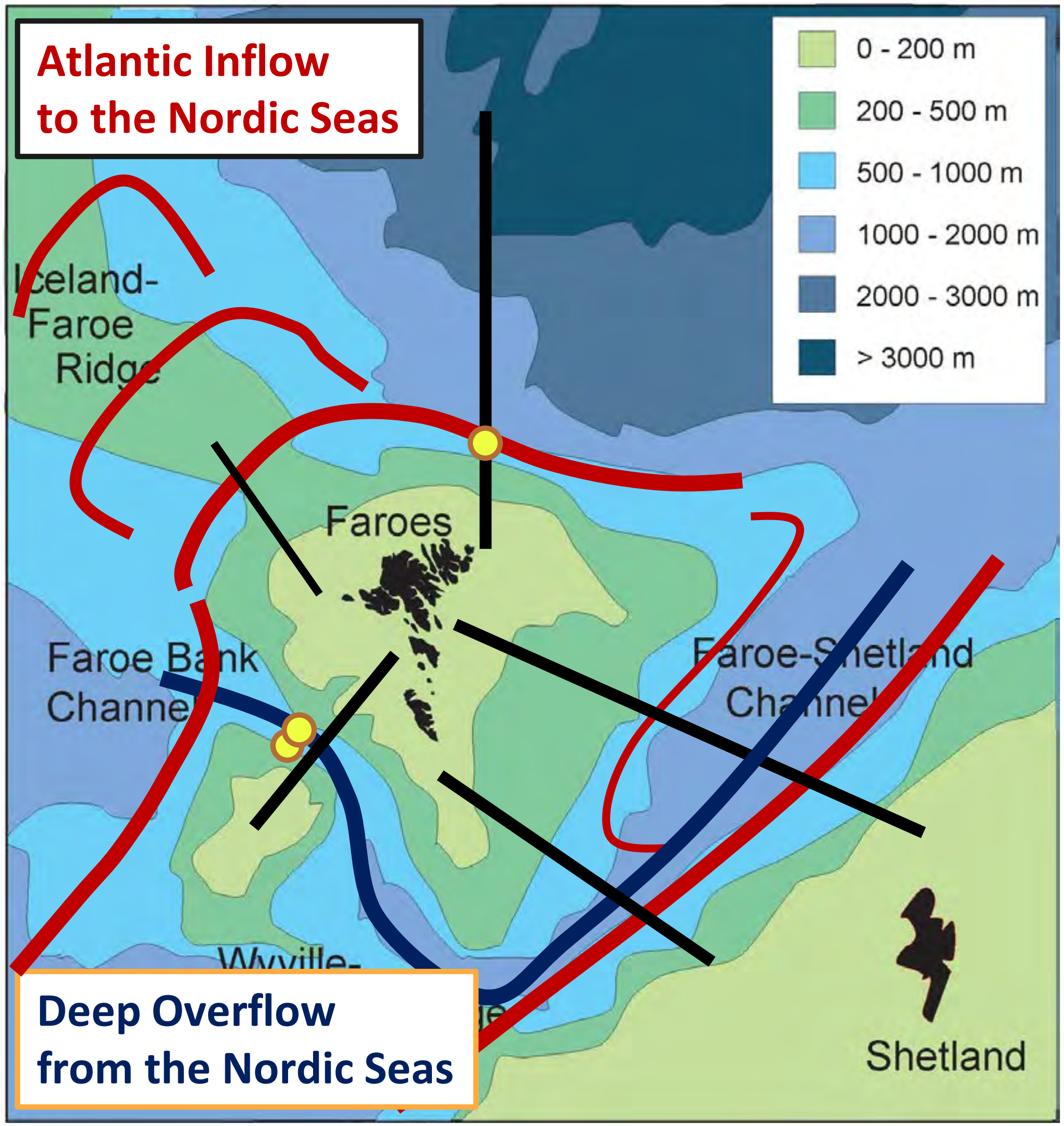
Nordic WOCE	VEINS Variability of Exchanges in the Northern Seas 1997-2000	MAIA Monitoring the Atlantic Inflow toward the Arctic 2000-2002	MOEN Meridional Overturning Exchange with Nordic Seas 2002-2005	THOR ThermoHaline Over-turning – at Risk? 2008-2012	NACLIM North Atlantic Climate 2012-2017	BLUE ACTION Arctic Impact on Weather and Climate 2016-2021

The Faroe-Shetland Channel



Hansen et al., 2017, Ocean Science

HAVSTOVAN
FAROE MARINE RESEARCH INSTITUTE



Projects:

- Blue-Action
- AtlantOS
- Jerico3
- Danish national projects

Main research fields:

- Greenland-Scotland Ridge exchanges
- Subpolar Gyre (Physical-biologial couplings)
  - Basin-Shelf interactions
- Norwegian Sea Gyre circulation
  - Faroe Current, recirculation in FSC, links to FBC overflow

Observations:

- Standard sections
- Faroe Current (inflow) (> 20yrs)
- Faroe Bank Channel overflow (> 20yrs)
- Faroe Shetland Channel (MSS) (> 20yrs)
- Other observations:
  - Iceland-Faroe Ridge (UniHAM, DMI)
  - Faroe Shelf (Partner in H2020 Jerico3)

Planned GSR monitoring by HAV

The Faroe Current:

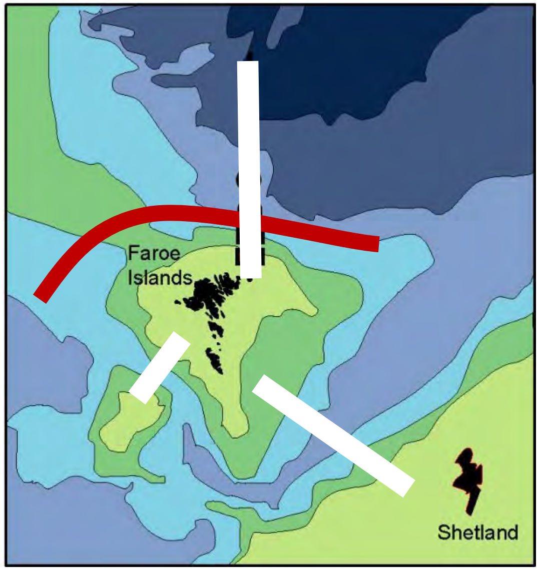
Standard CTD sections

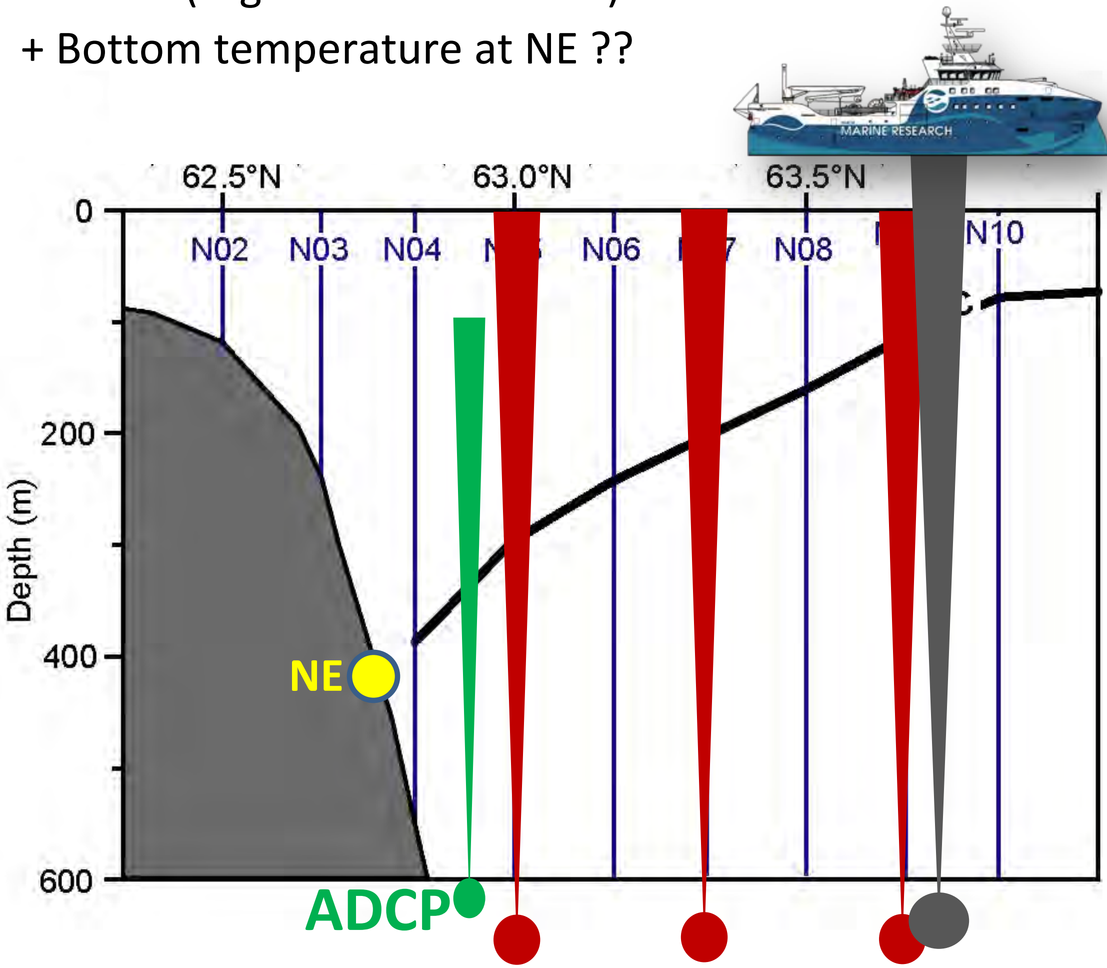
+ Satellite altimetry

+ 1 ADCP

+ 3 PIES (together with UHAM)

+ Bottom temperature at NE ??





Data upload from vessel

The Faroe Bank Channel:

Two ADCP's

Standard CTD sections

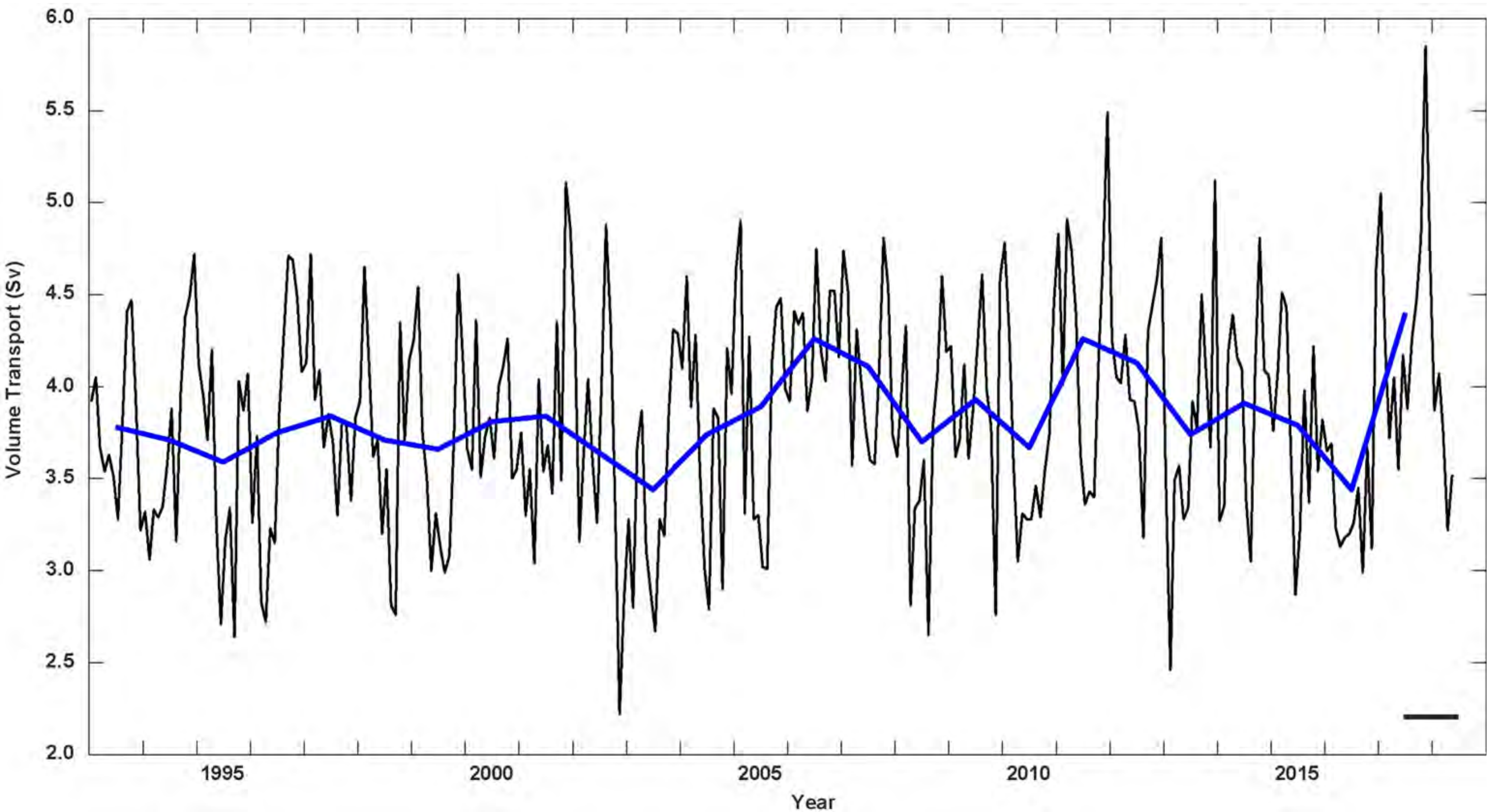
The Faroe Shetland Channel (together with MSS):

Standard CTD sections

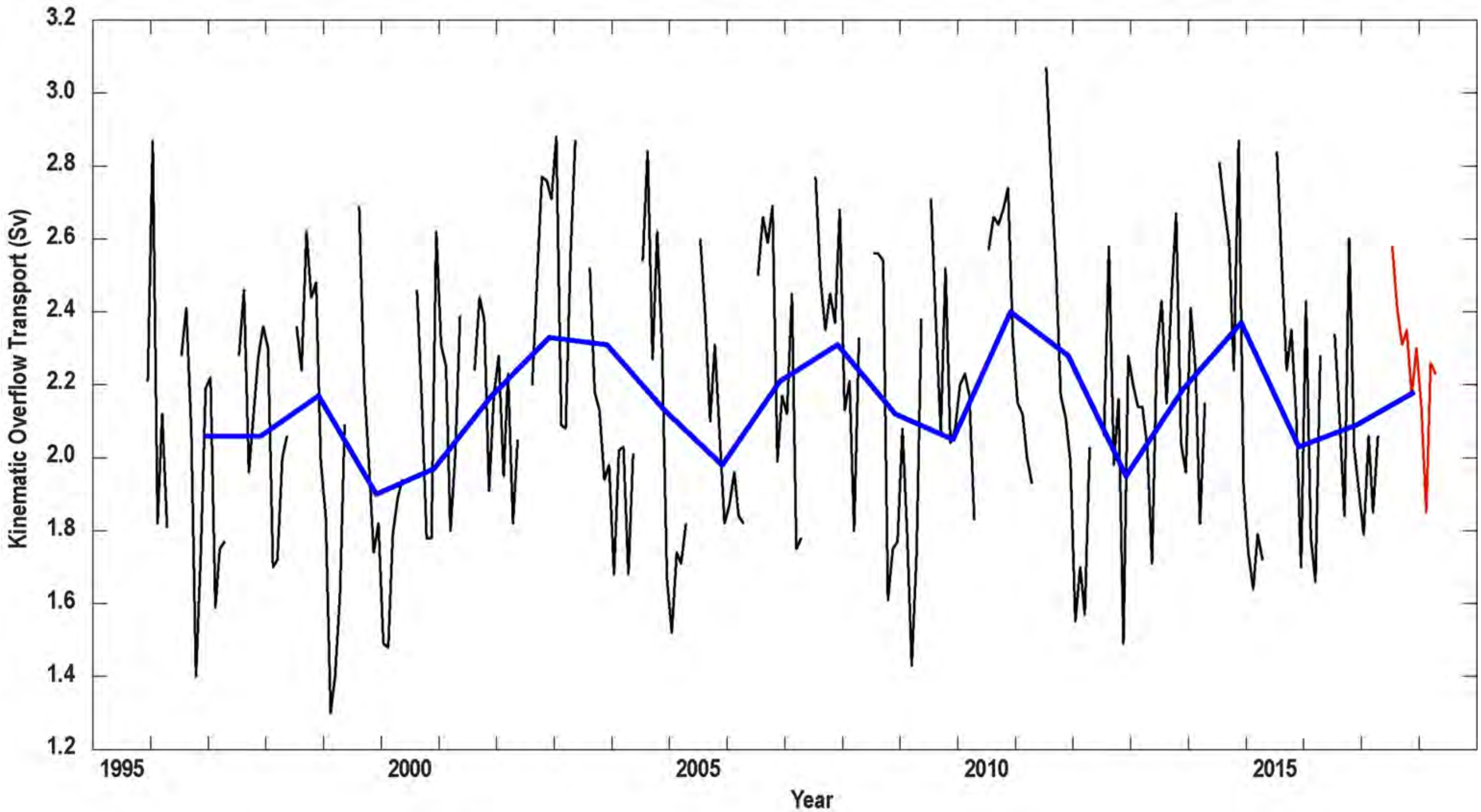
Other initiatives?

Faroe Current transport

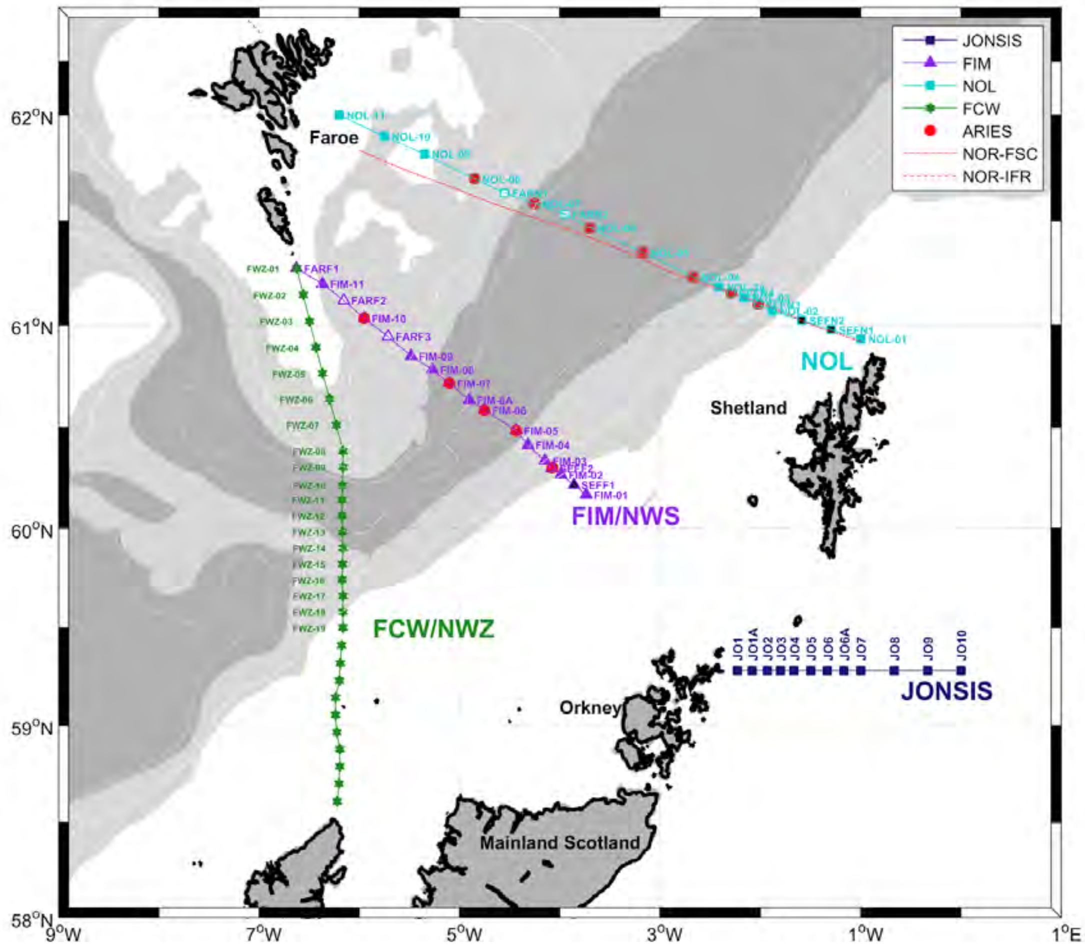
(1993 – 2018)



Faroe Bank Channel transport
(1995 – 2018)



Monitoring by Marine Scotland Science



Projects:

- Blue-Action
- AtlantOS
- MyCoast
- Scottish Government core funding

Main research fields:

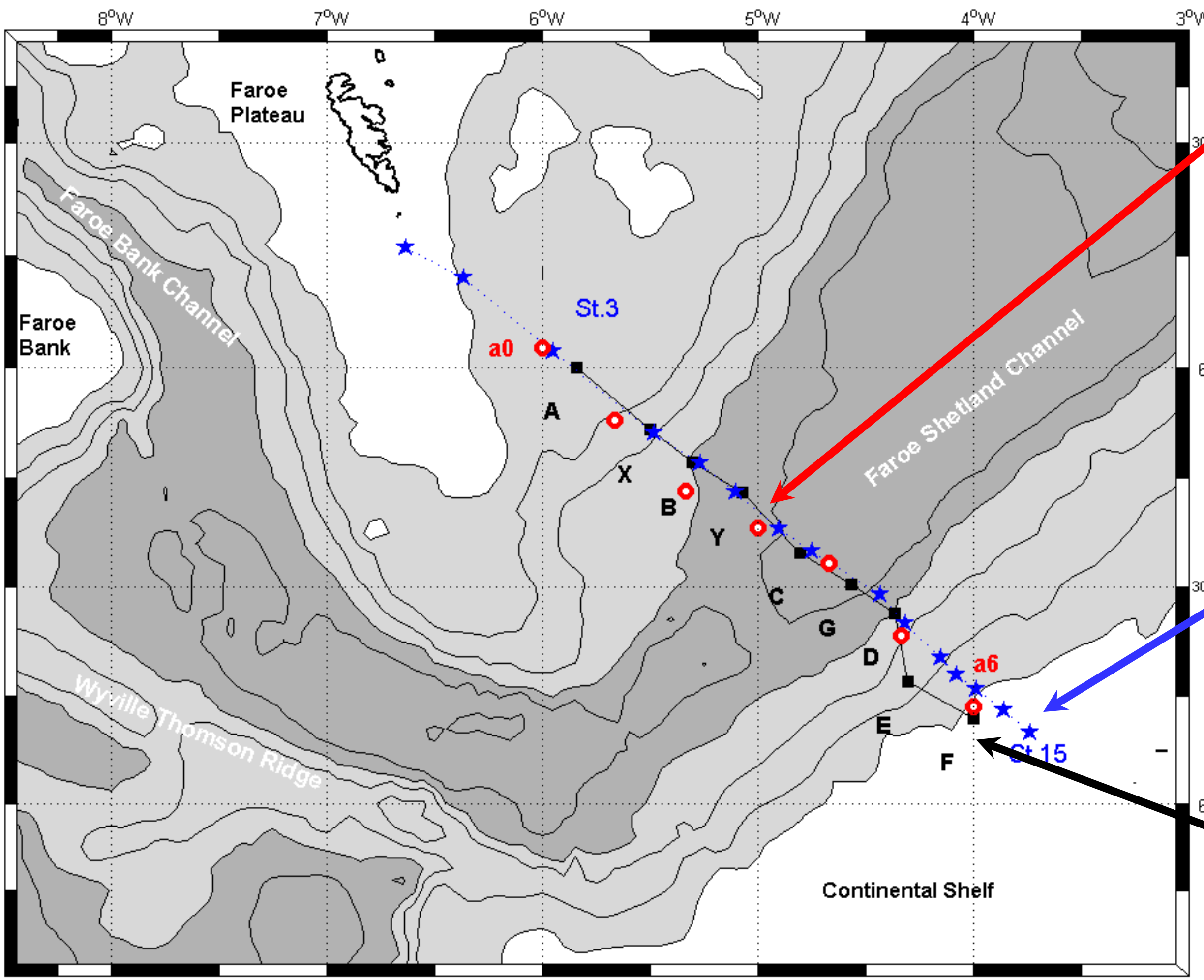
- Faroe-Shetland Channel
- Northern North Sea
- Circulation and water mass indicators to feed into national and international assessments of prevailing oceanographic conditions

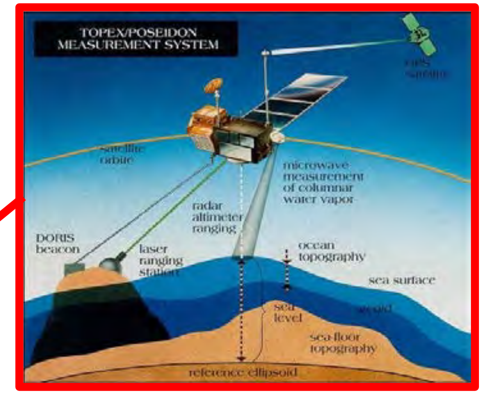
Observations:

- Standard sections
- ADCPs in Faroe Shetland Channel (with HAV) (> 20yrs)
- Other observations:
  - Fair Isle Gap inflow

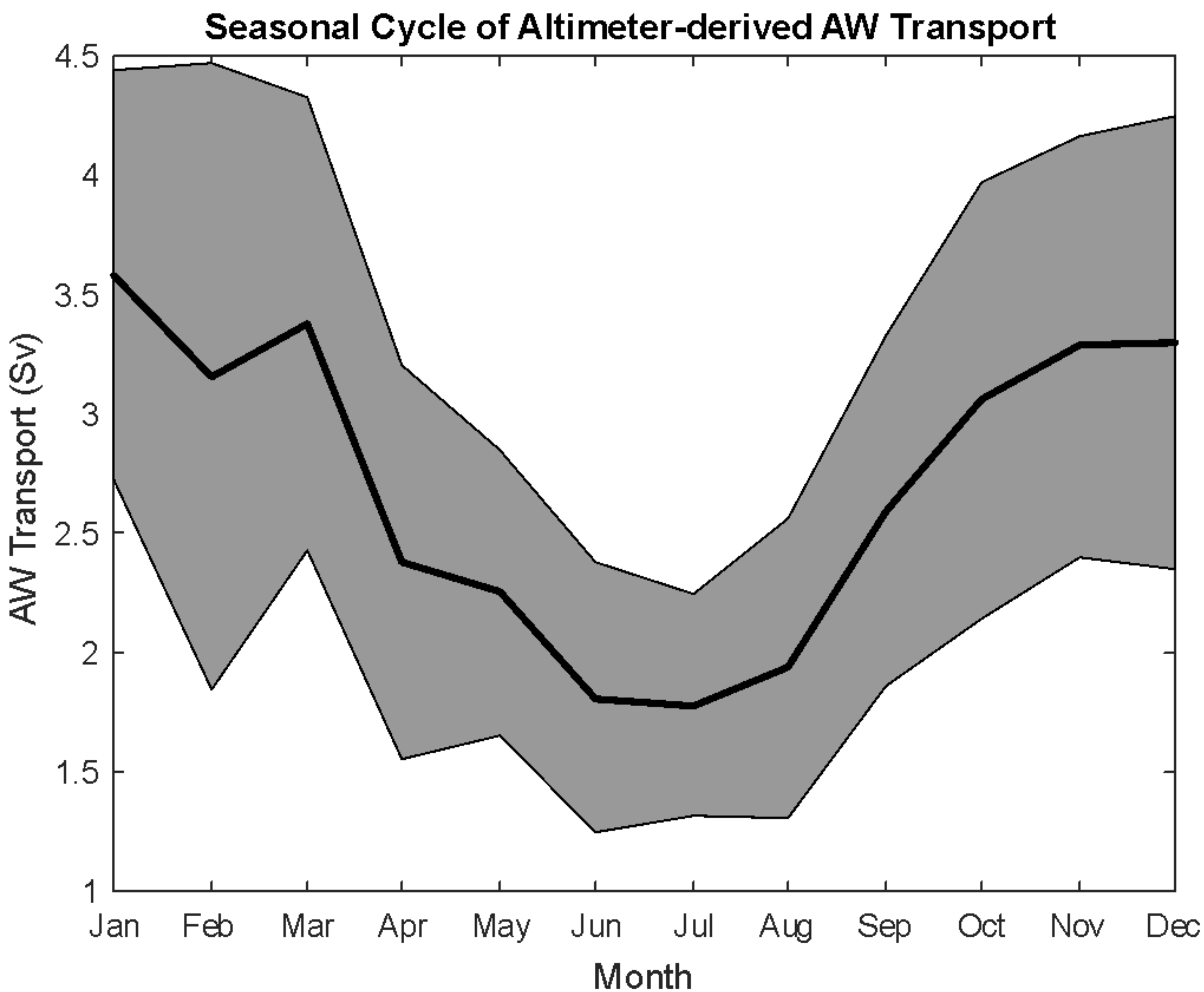
Observing Circulation in the FSC

Berx et al. (2013) Ocean Science 9: 639-654





AW Volume Transport – Derived from altimetry



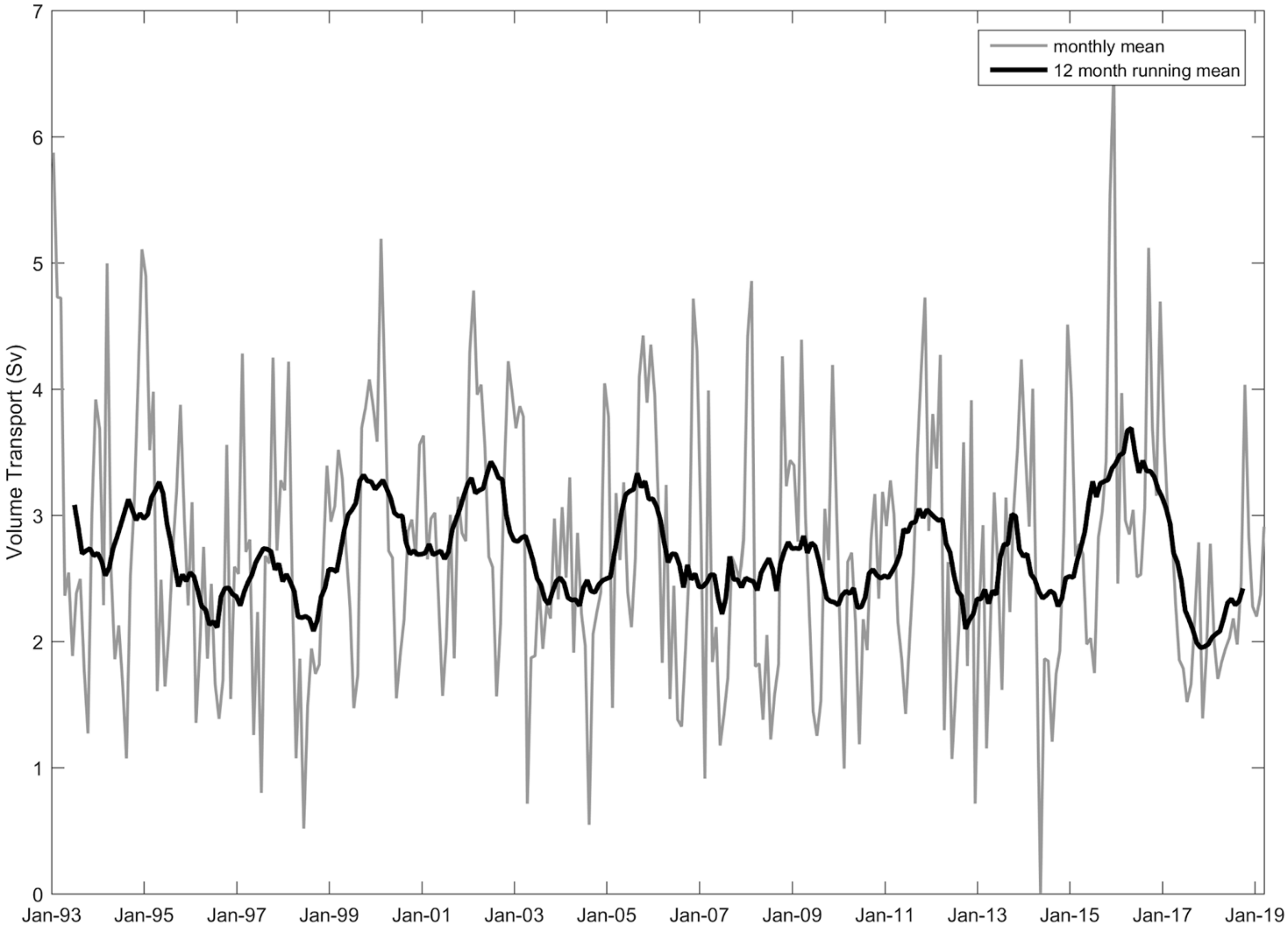
Seasonal amplitude of Atlantic water transport in FSC ~ 0.7-0.9 Sv

This is **~ 25%** of the average transport

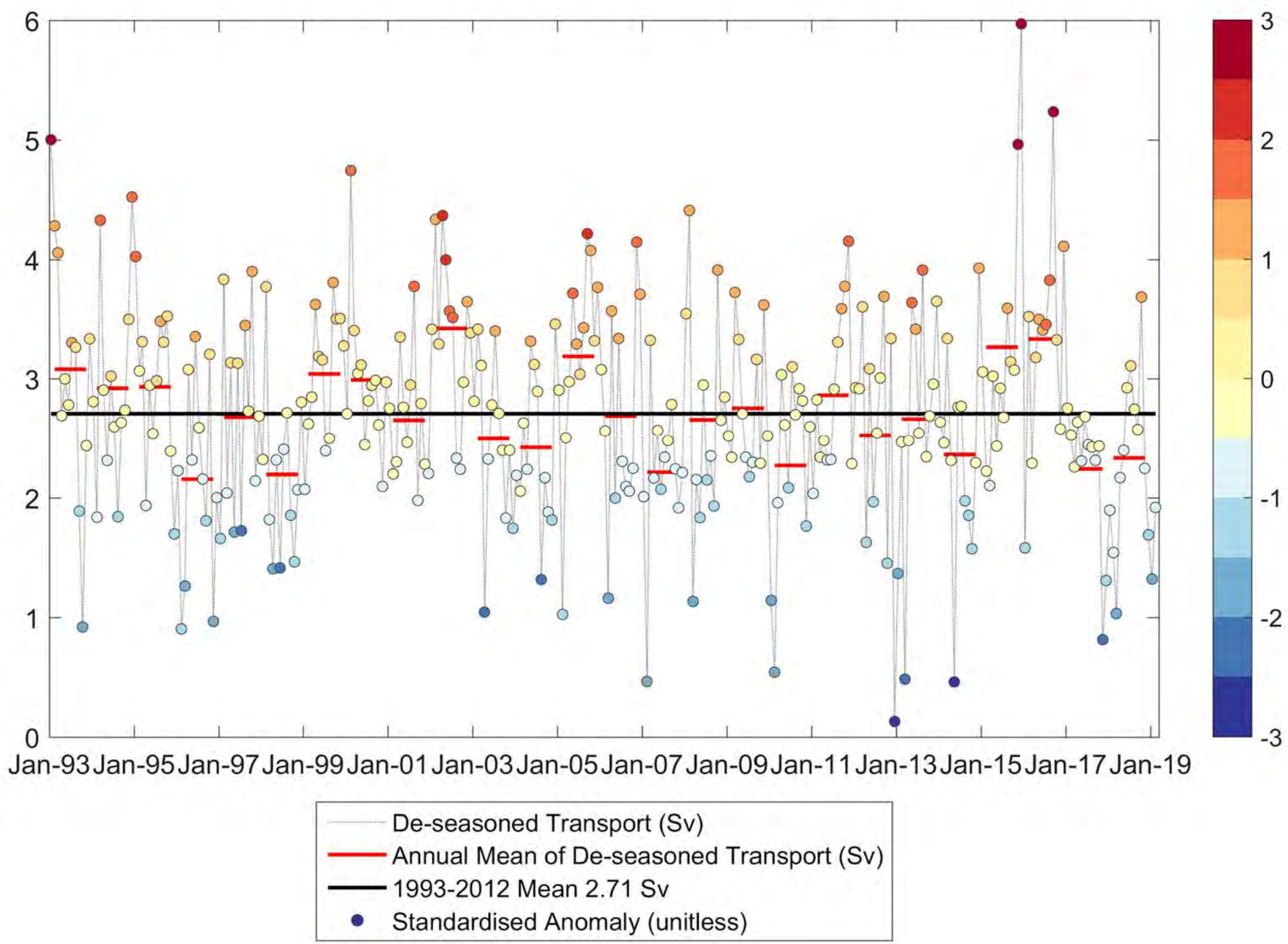
Maximum transport in winter-time, lowest transport in summer.

Different amplitude based on calculation method (see Berx et al., 2013)

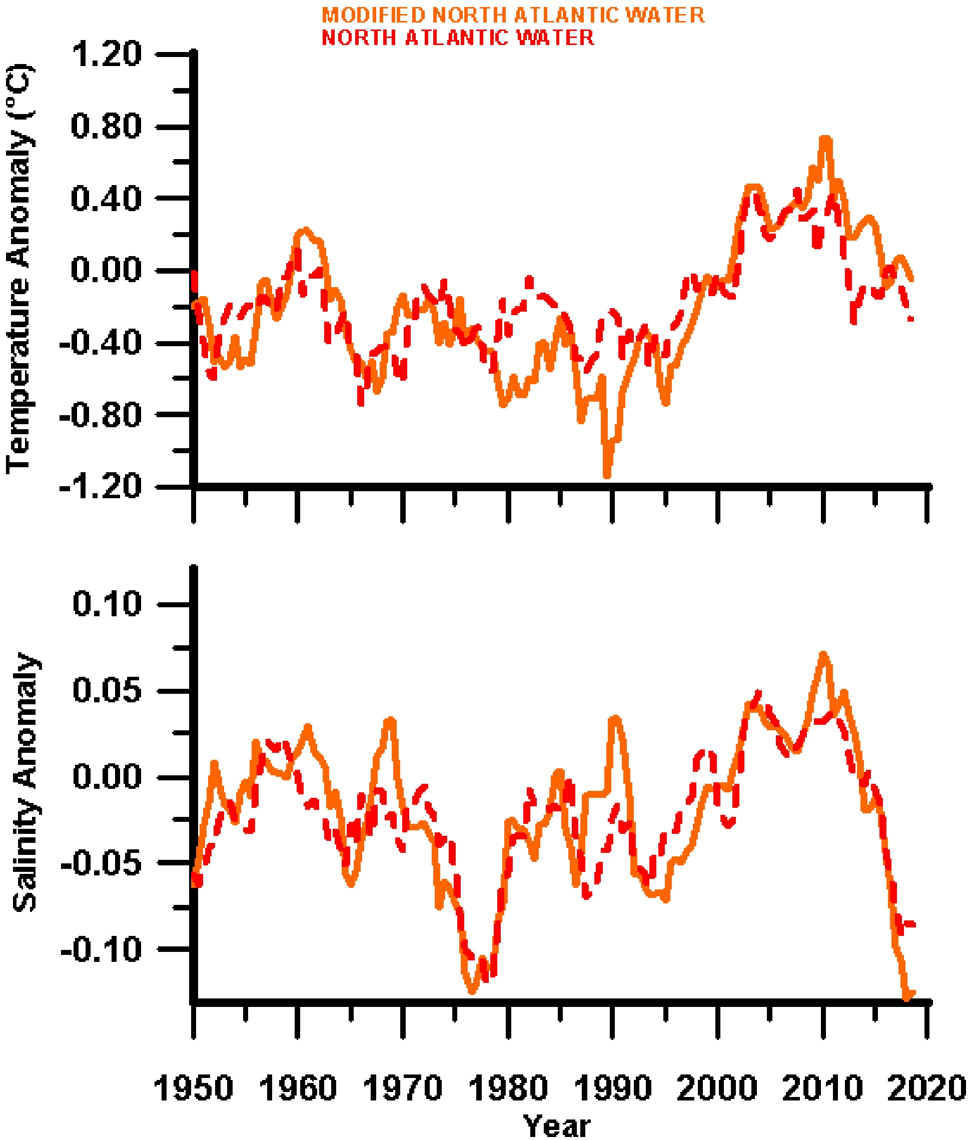
AW Volume Transport (1993-2018)

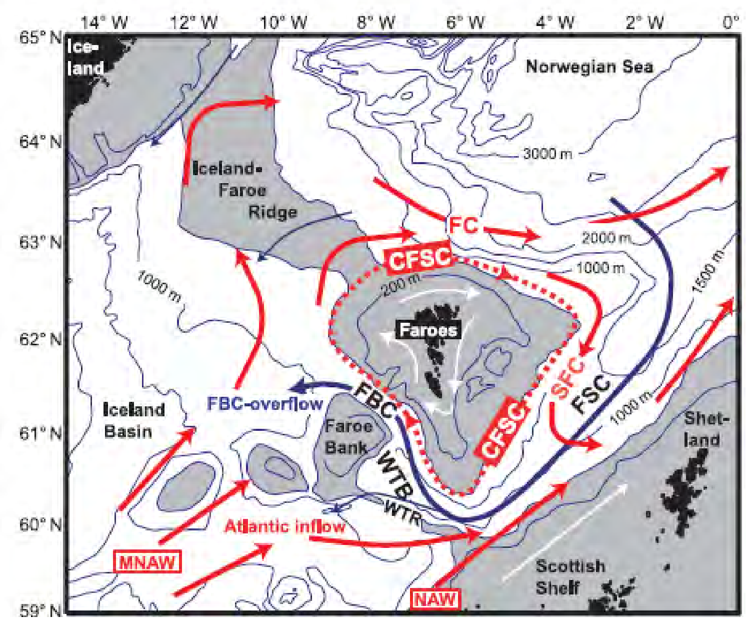


AW Volume Transport & Anomalies (ref. 1993-2012)



Variability in AW core properties

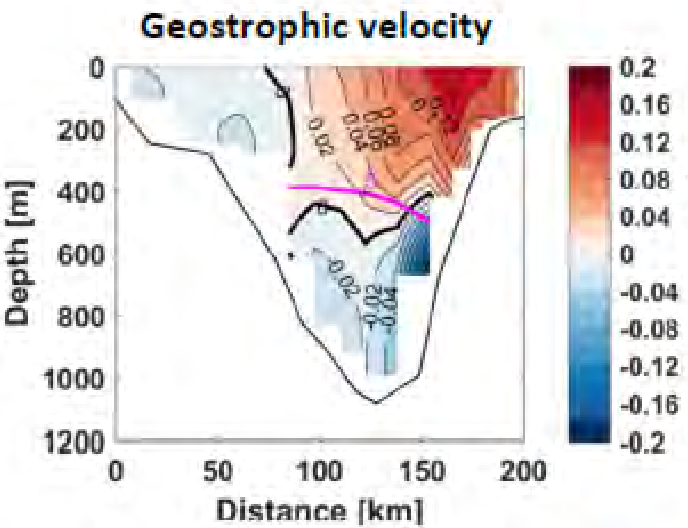


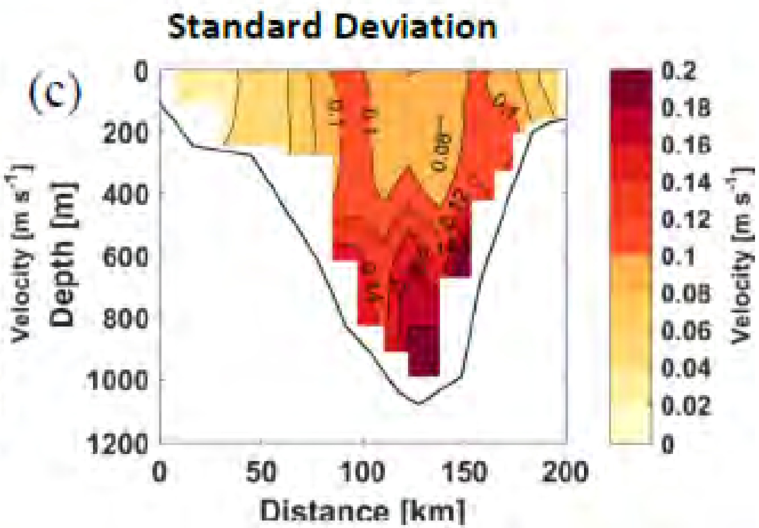


Hansen et al., 2017, Ocean Science

Towards a time series of temperature and salt transport

- Work undertaken by Kamila Walicka as part of PhD
- Working on updating method to estimate volume, temperature and salinity transport from the FSC sections and altimetry.
- Determining the relationships between the basin-scale forcing, climate indices, the structure of Atlantic Water in the FSC, and the temperature and salt fluxes obtained above. Currently working on investigating these linkages within the Viking20 model before revisiting observational datasets.

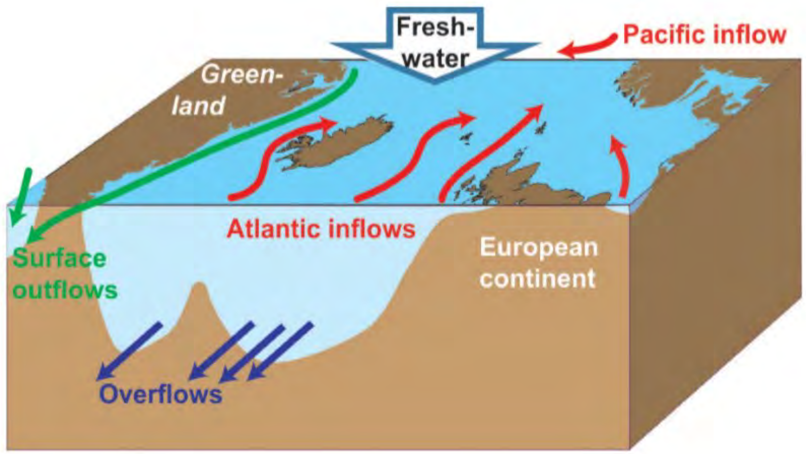


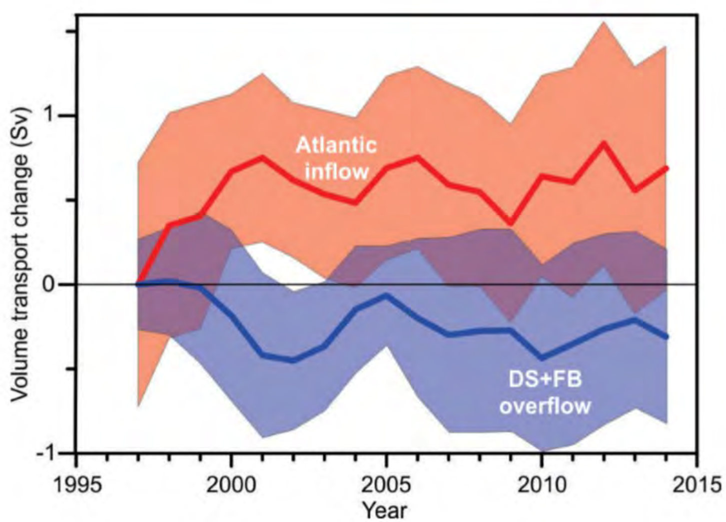


University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

SCOTTISH ASSOCIATION for MARINE SCIENCE

Arctic Mediterranean Exchanges

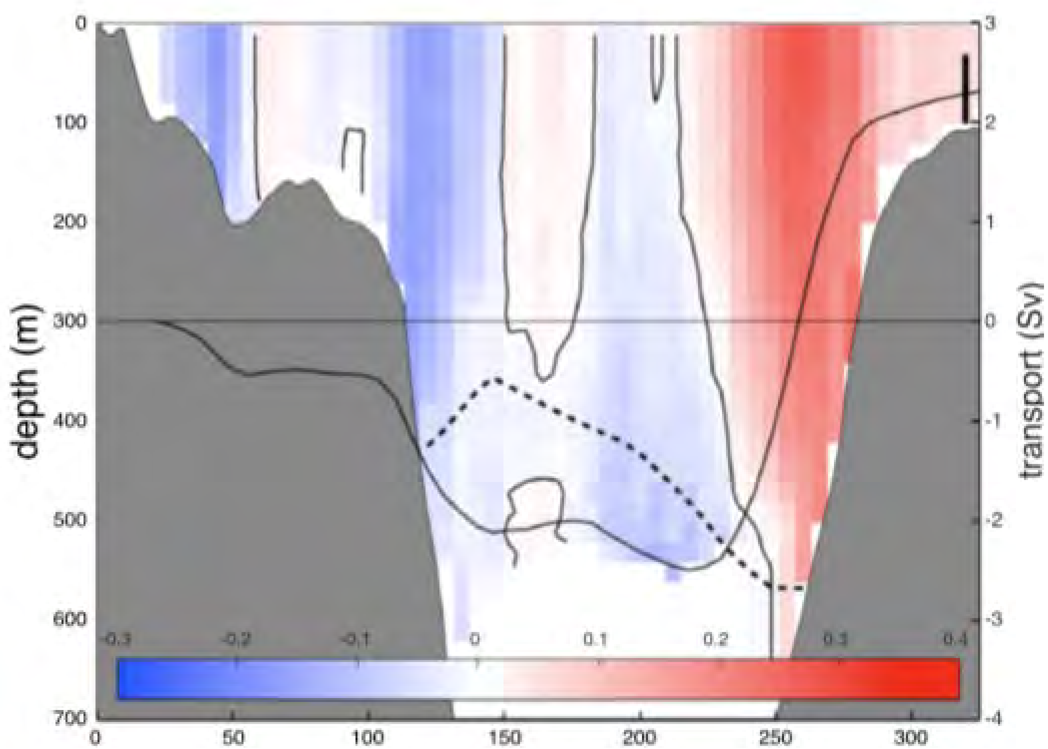




- Combination of the various branches shows consistent picture of the total Arctic Mediterranean exchanges.
- The five oceanic inflow branches and the two main overflow branches most likely do give a good representation of the long-term variations of the AM exchanges.
- The AM exchanges as a whole are not likely to have weakened during the two decades from the mid-1990s to the mid-2010s.
- This is reassuring given the global changes observed, but it is no guarantee of future stability.
- Efforts should be made to maintain the established monitoring systems and preferably expand them.

Østerhus et al. (2019) Ocean Sci.

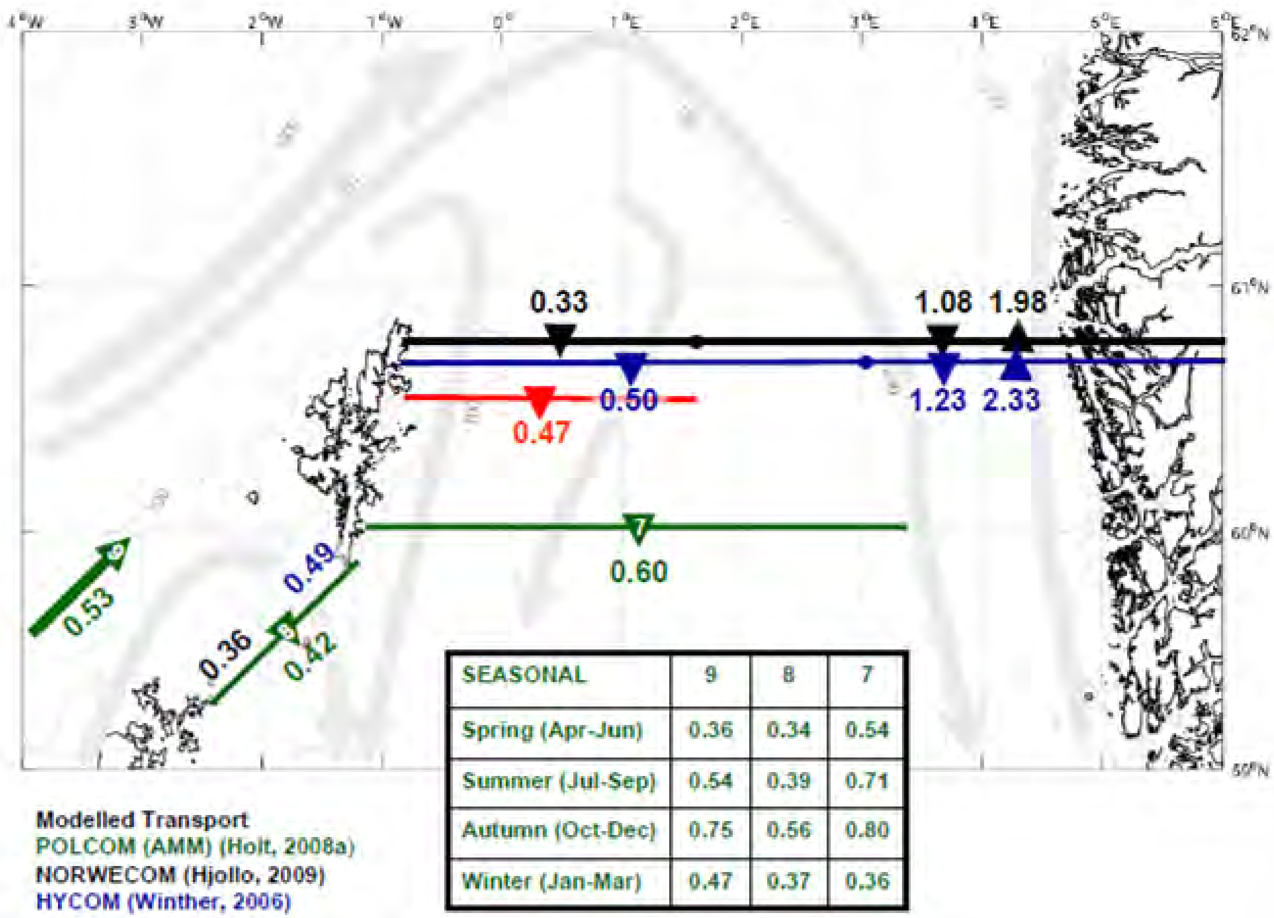
Deep Jet (in the FSC)



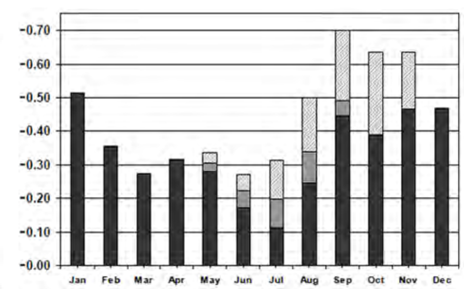
Rossby et al. (2018) JGR-O

- The deep jet is banked up on the slope beneath the Shetland slope current.
- The negative velocities close to the Shetland slope current is an indication of this deep current since the current is bottom-intensified
- Currently further analysing this feature

Inflows of AW in the Northern North Sea
East Shetland Atlantic Inflow

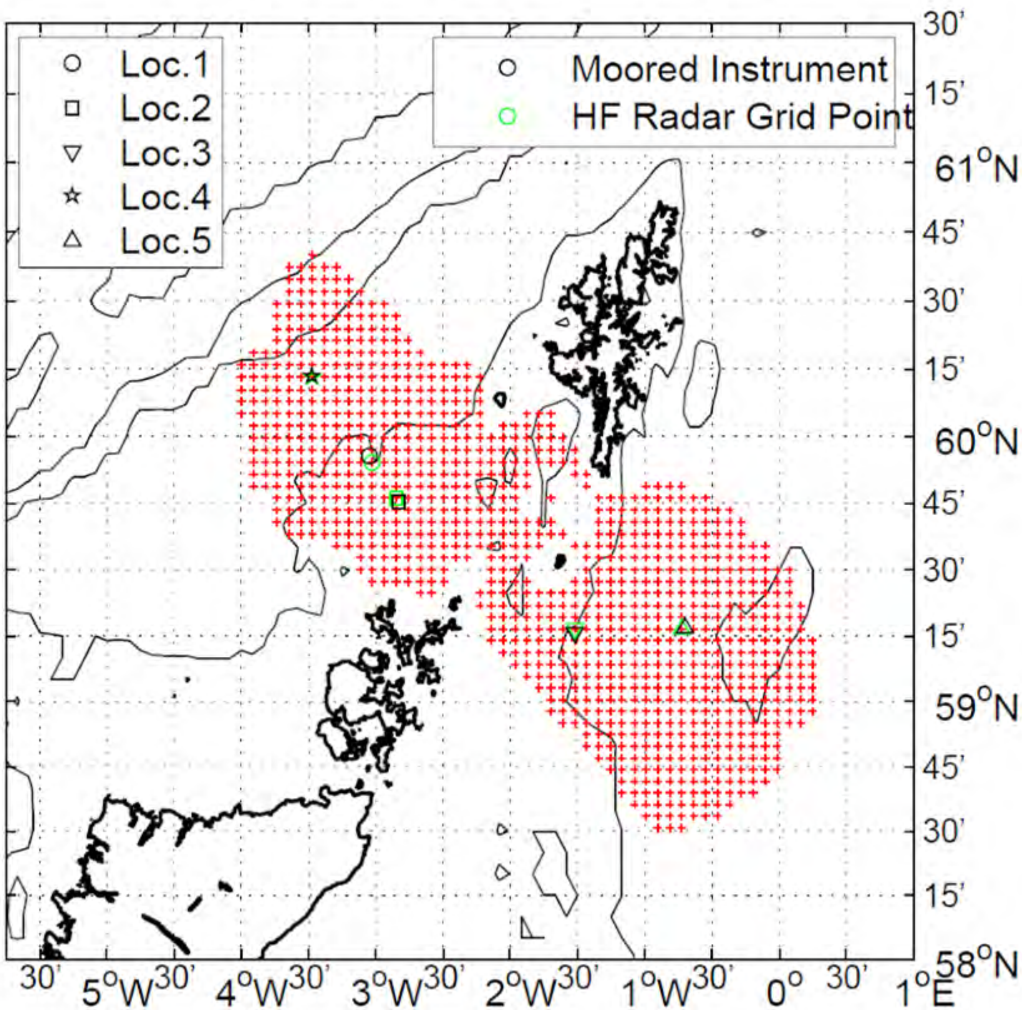


SEASONAL	9	8	7
Spring (Apr-Jun)	0.36	0.34	0.54
Summer (Jul-Sep)	0.54	0.39	0.71
Autumn (Oct-Dec)	0.75	0.56	0.80
Winter (Jan-Mar)	0.47	0.37	0.36



Hughes, S.L. (2014) Inflow of Atlantic Water to the North Sea: Seasonal Variability on the East Shetland Shelf. PhD Thesis. University of Aberdeen, Aberdeen.

Inflows of AW in the Northern North Sea
Fair Isle Gap - The Brahan Project



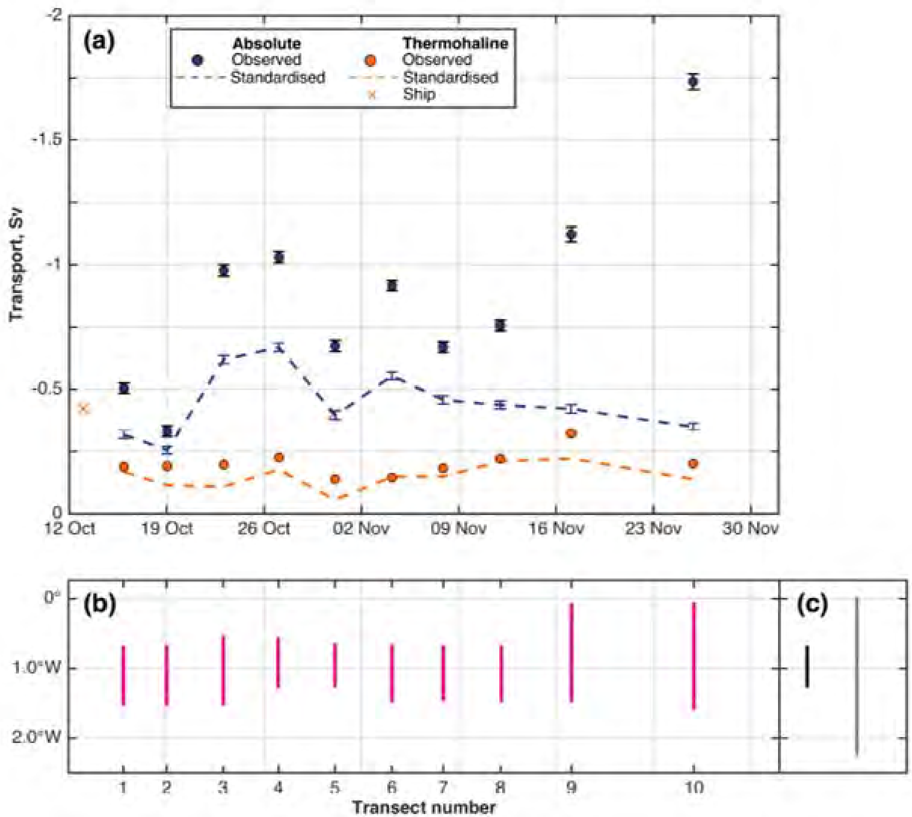
The Brahan Project:

- **Deployment of 2 High Frequency Radar sites across the Fair Isle Gap**
- **Coincident mooring deployments of profiling & single point current meters**
- **Ocean glider deployment along the JONSIS section**

Two PhD Projects:

- **Peter Sheehan (2019) Forcing and variability of northwestern inflows into the northern North Sea. PhD Thesis. University of East Anglia.**
- **Matteo Marasco (in progress) Vertical Structure and Coherence in a tidally energetic channel.**

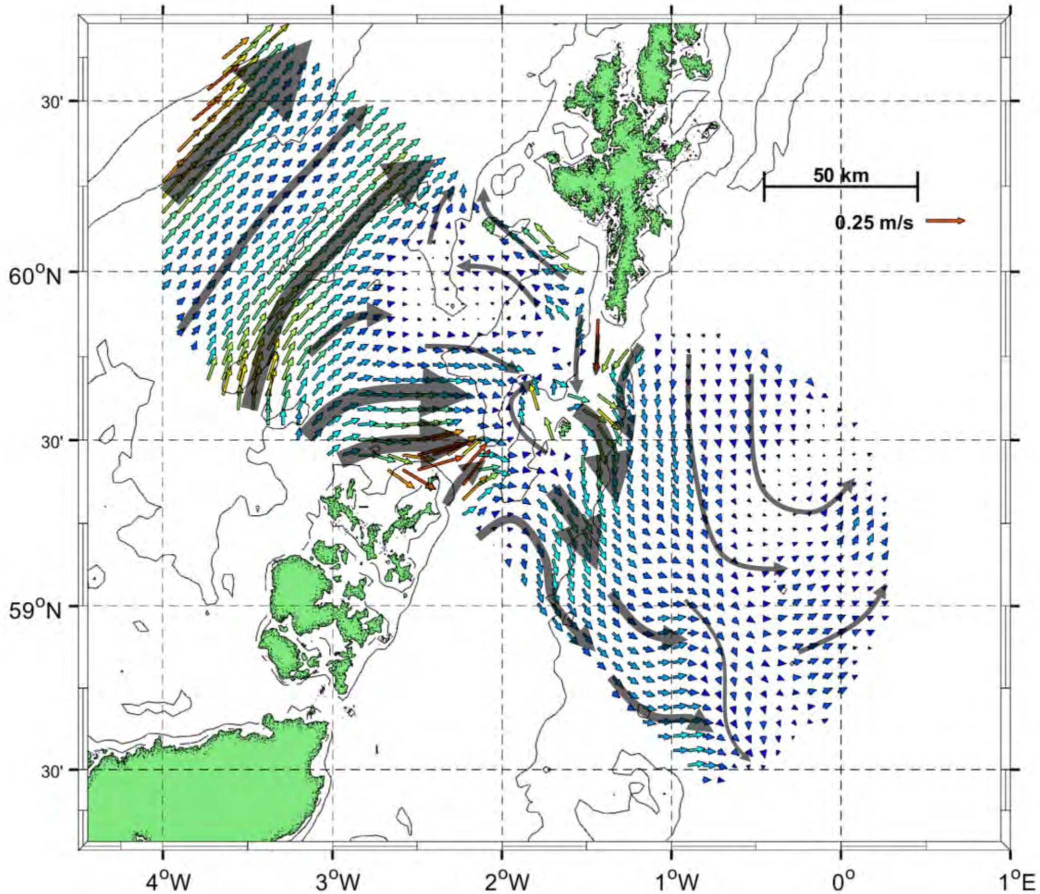
Inflows of AW in the Northern North Sea JONSIS section - glider-derived transports

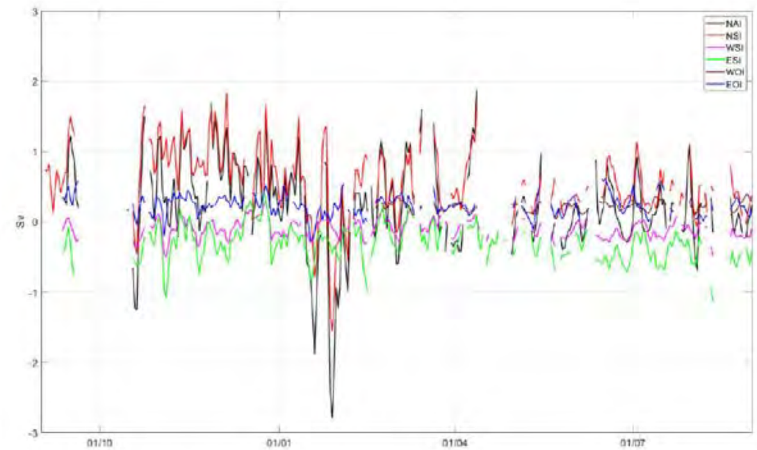


- Glider deployments used to estimate tidal currents and the tidal mixing front dynamics in the region
- Analysis of historic time series of JONSIS hydrography to investigate the baroclinic transport in the region
- Using glider dive-average currents to obtain absolute transport

Peter Sheehan (2019) Forcing and variability of northwestern inflows into the northern North Sea. PhD Thesis. University of East Anglia.

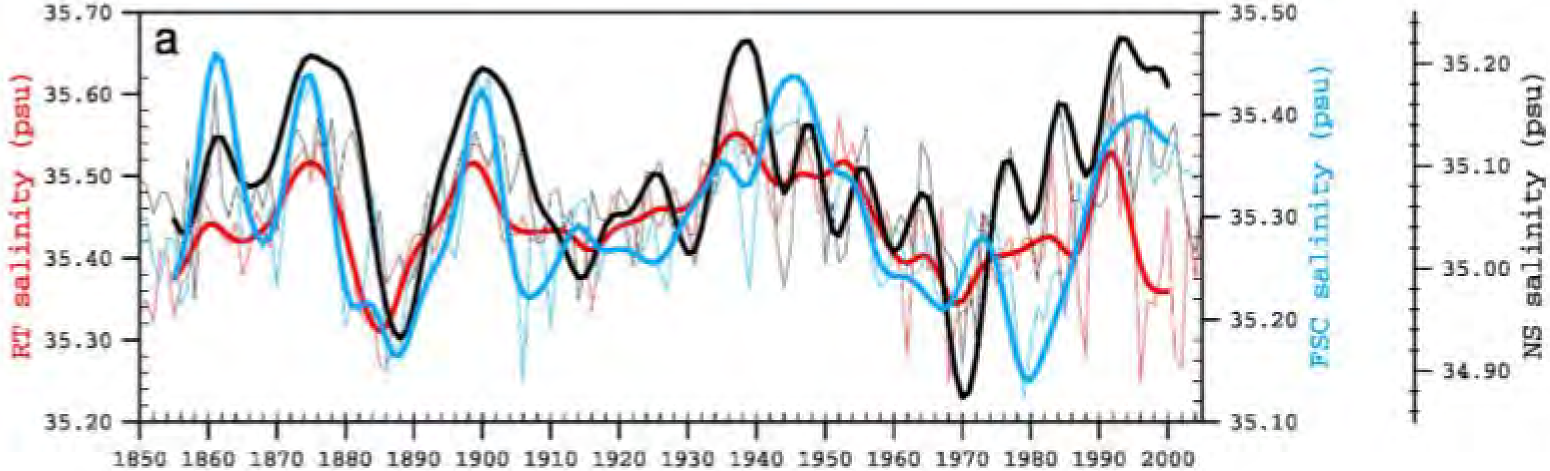
Inflows of AW in the Northern North Sea
Fair Isle Gap - The Brahan Project



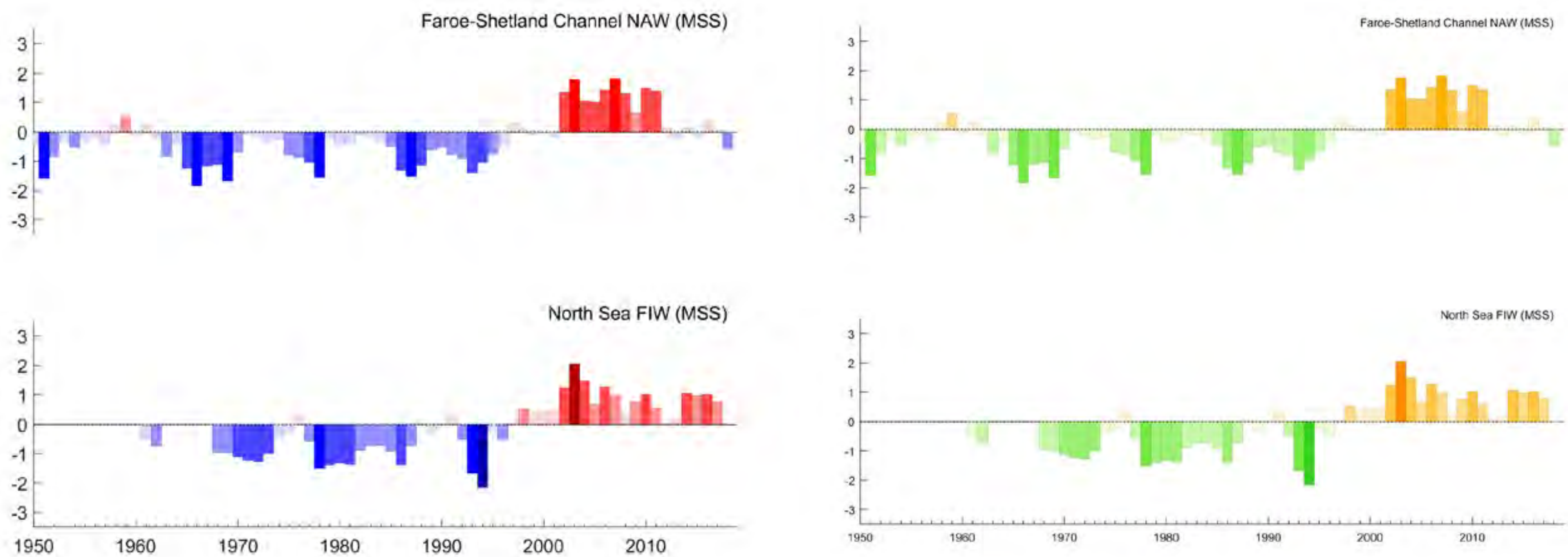


- Time series of volume transport compares well with previous estimates from observations and numerical models
- Opportunity to study further the mechanisms behind the variability (incl. flow reversal)
- Oct. 2019 deployment of two profiling current meters in the FIG
- Plans to further explore the topographic steering W of Orkney Isles

Role of the sub-polar North Atlantic in North Sea properties and circulation



Koul et al. (2019) JGR-O



Havstovan has received funding from:

The Danish Energy Agency as part of
the Arctic Climate Support Programme

The Blue-Action project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727852

Thank you

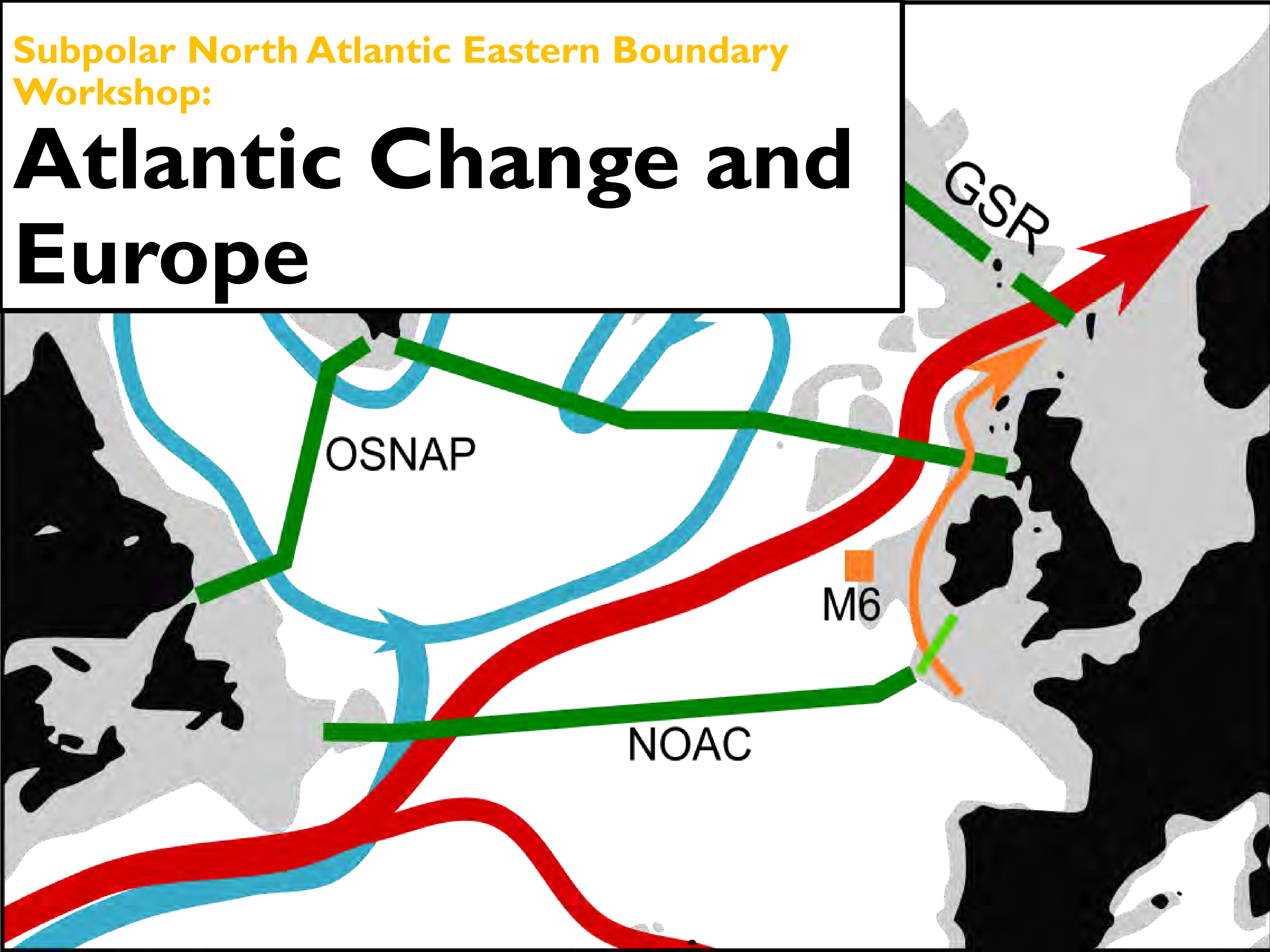
For questions/collaborations, please email b.berx@marlab.ac.uk

The Blue-Action project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727852

This work received funding from the MASTS pooling initiative (The Marine Alliance for Science and Technology for Scotland) and their support is gratefully acknowledged. MASTS is funded by the Scottish Funding Council (grant reference HR09011) and contributing institutions.

Subpolar North Atlantic Eastern Boundary Workshop:

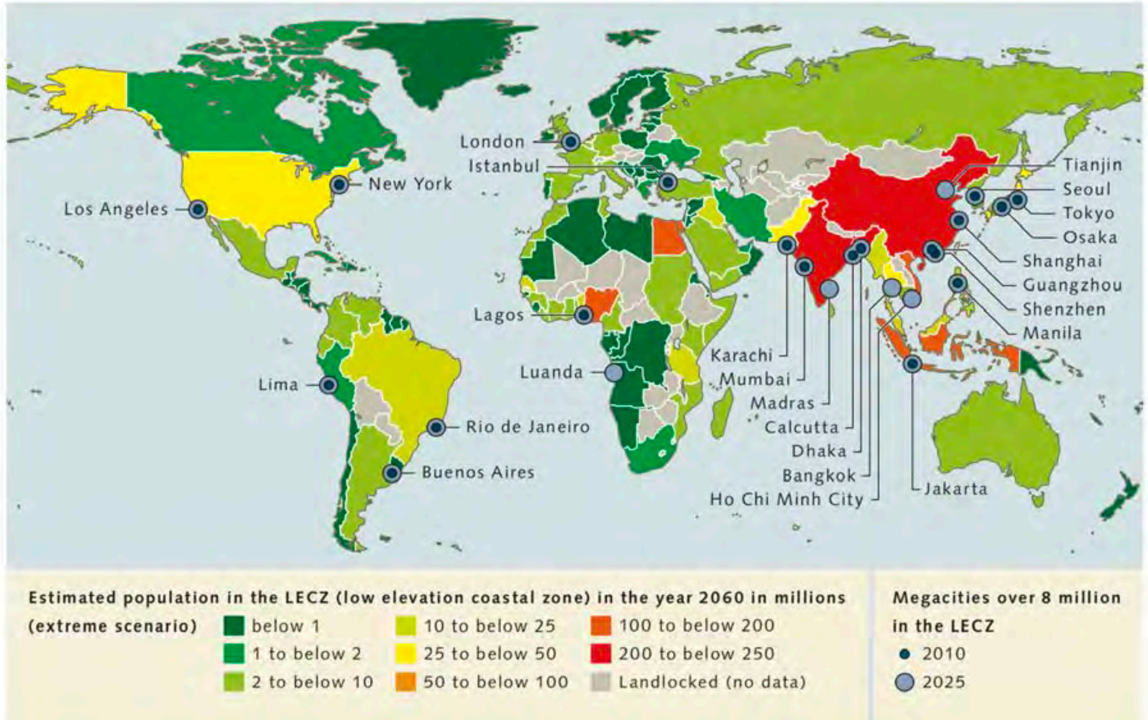
Atlantic Change and Europe



SROCC: Atlantic Circulation Change

- Special Report on Oceans and Cryosphere was the first IPCC report to acknowledge an observed decline in AMOC

- What could be the large societal impacts of this?



London
Istanbul
New York
Los Angeles
Lagos
Luanda
Lima
Rio de Janeiro
Buenos Aires
Tianjin
Seoul
Tokyo
Osaka
Shanghai
Guangzhou
Shenzhen
Manila
Karachi
Mumbai
Madras
Calcutta
Dhaka
Bangkok
Ho Chi Minh City
Jakarta
Estimated population in the LECZ (low elevation coastal zone) in the year 2060 in millions (extreme scenario)
below 1
1 to below 2
2 to below 10
10 to below 25
25 to below 50
50 to below 100
100 to below 200
200 to below 250
Landlocked (no data)
Megacities over 8 million in the LECZ
2010
2025

Population of current megacities (millions)
2015 | 2030
Population of future megacities (millions)
2015 | 2030
Moscow, Russia 12.1 | 12.2
Chengdu, China 7.6 | 10.1
Chongqing, China 13.3 | 17.3
Beijing, China 20.3 | 27.7
Delhi, India 25.7 | 36
Paris, France 10.8 | 11.8
Shanghai, China 23.7 | 30.7
London, UK 10.3 | 11.4
Lahore, Pakistan 8.7 | 13
New York, USA 18.5 | 19.8
Ahmedabad, India 7.3 | 10.5
Tokyo, Japan 38 | 37.1
Los Angeles, USA 12.3 | 13.2
Cairo, Egypt 18,7 | 24.5
Mexico City, Mexico 21 | 23.8
Manila, Philippines 12.9 | 16.7
Karachi, Pakistan 16.6 | 24.8
Lagos, Nigeria 13.1 | 24.2
Bogotá, Colombia 9.7 | 11.9
Mumbai, India 21 | 27.8
Kinshasa, Congo 11.5 | 20
Jakarta, Indonesia 10.3 | 13.8
Rio de Janeiro, Brazil 12.9 | 14.1
Hyderabad, India 8.9 | 12.7
Luanda, Angola 5.5 | 10.4
Bangkok, Thailand 9.2 | 11.5
São Paulo, Brazil 21 | 23.4
Johannesburg, South Africa 9.7 | 11.9
Ho Chi Minh City, Vietnam 7.3 | 10.2
Buenos Aires, Argentina 15.1 | 16.9

The EU Blue Economy

Ocean Wealth	Employment (%)	Profit (%)
Tourism	54	32
Ports and Shipping	28	38
Fisheries	14	12
Mining	4	18

source: The EU Blue Economy Report 2019

Total Employment: 4 million people
Total Profit: EUR 74.3 billion

Emerging areas include offshore renewables, biotechnology, desalination, (defence)
Also: Carbon capture and pollution cleanup (noted in Atlas of Ocean Wealth, Spalding et al.)

Blue Solutions

Table ES-1. Summary of Global Mitigation Potential Offered by Each Area of Ocean-based Climate Action

AREAS OF OCEAN-BASED CLIMATE ACTION	2030 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)	2050 MITIGATION POTENTIAL ($GTCO_2E$/YEAR)
1. Ocean-based renewable energy	0.18–0.25	0.76–5.40
2. Ocean-based transport	0.24 – 0.47	0.9 – 1.80
3. Coastal and marine ecosystems	0.32–0.89	0.50–1.38
4. Fisheries, aquaculture, and dietary shifts	0.34–0.94	0.48–1.24
5. Carbon storage in the seabed (Action in this Area Requires Further Research Prior to Implementation at Scale)	0.25–1.0	0.50–2.0
Total	1.32–3.54	3.14–11.82
Total percentage contribution to closing emissions gap (1.5°C pathway)	4–12 %	6–21%
Total percentage contribution to closing emissions gap (2°C pathway)	7–19%	7–25%

source: The Ocean as a Solution to Climate Change. Hoegh-Guldberg and co-authors

Pre-Publication Project · [illegible] · 08.08.2019

Changes in Ocean Circulation: Implications for Europe

This study looks in more detail at the potential implications for Europe of major changes in ocean circulation arising from global warming. This follows on from the initial identification of this issue in the EASAC 2018 extreme weather update, and will focus on the changes to the Atlantic Meridional Overturning Circulation (AMOC) and potential impacts via mechanisms such as changes to weather patterns and sealevel rise. The expert group has been established and had its first meeting in May 2019. The project is expected to be completed by the end of 2019 or early 2020.

European Academies
easac
Science Advisory Council

Working Group

1. Tor Eldevik, Geophysical Institute & Bjerknes Centre, Univ Bergen – Chair
2. Leif Anderson, University of Gothenburg, Sweden
3. Henrique Cabral, University of Lisbon, Portugal - **Remote**
4. Frederic Dias, University College Dublin, Ireland
5. Marta Estrada, Institute of Marine Sciences, Spain
6. Bogi Hansen, Havstovan Faroe Marine Research Institute, Faroe Islands
7. Gerard McCarthy, Maynooth University, Ireland
8. Tim Palmer, University of Oxford, UK - **Remote**
9. Erik Van Sebille, Utrecht University, Netherlands
10. Petteri Uotila, University of Helsinki, Finland
11. Lars Walløe, EASAC Chair of Environment Programme, Univ Oslo,Norway

EASAC secretariat: Nina Hobbhahn, scientific policy officer SAPEA

Bjerknes Centre: Beatriz Balino, Senior adviser

WG apologies

- Jean Marie Beckers, Universtié de Liège, Belgium
- Jean Paul Duplessy & Julie Deshayes, CNRS, France
- Lars H. Smedsrud, Geophysical Institute & Bjerknes Centre, Univ Bergen
- Martin Visbeck, GEOMAR, Helmholtz Centre for Ocean Research Kiel, Germany

Atlantic Change and Europe

1. Sea Level

2. Storminess

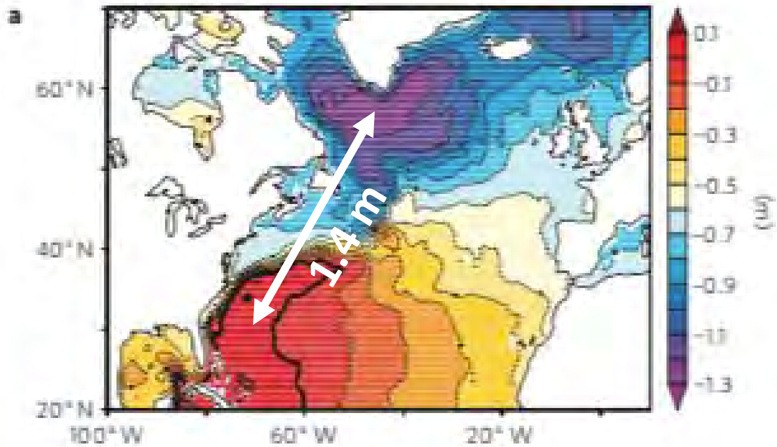
3. Fisheries

4. Predictability

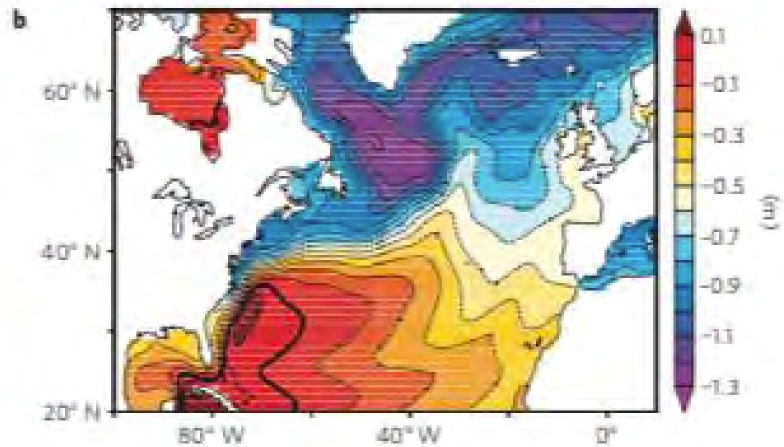
Atlantic Change and Europe

1. Sea Level
2. Storminess
3. Fisheries
4. Predictability

Sea Level and Atlantic Circulation



Observed (satellite) dynamic sea level

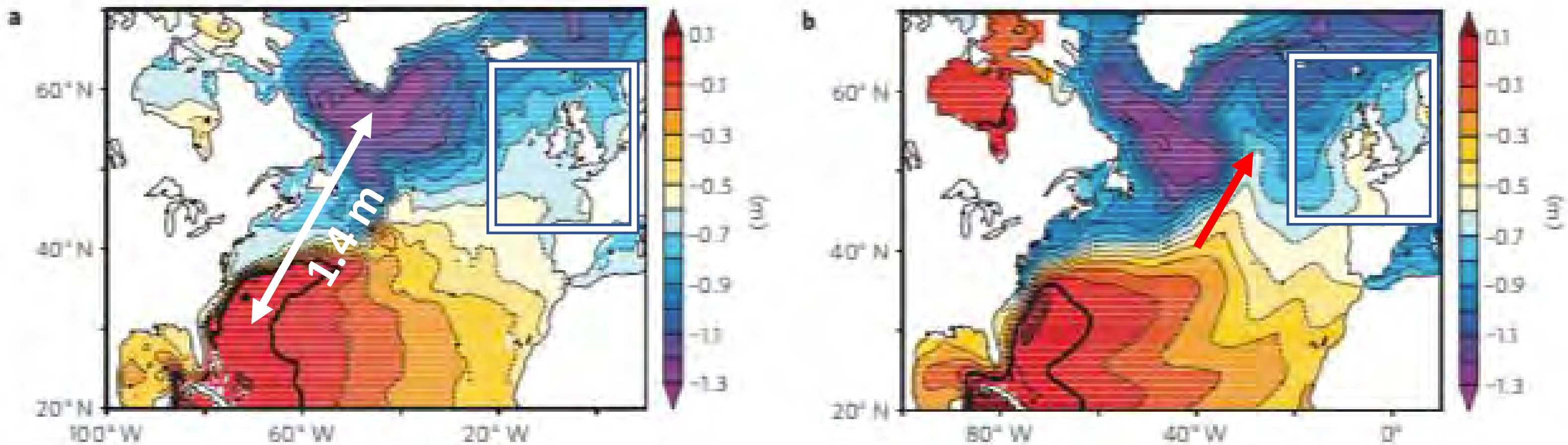


GFDL simulation of dynamic sea level

- Meridional gradient (approx. 1.4 m peak-to-trough in western Atlantic is reproduced in climate models

Yin, J., Schlesinger, M. E., & Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, *2*(4), 262.

Sea Level and Atlantic Circulation

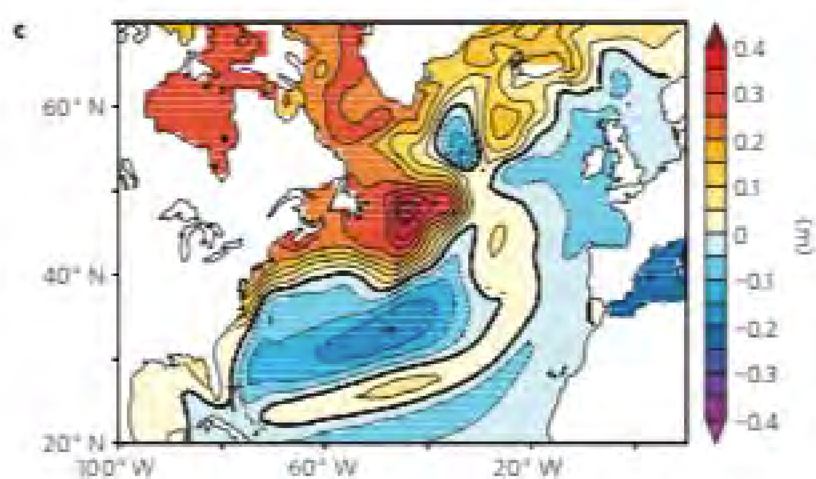


Observed (satellite) dynamic sea level GFDL simulation of dynamic sea level

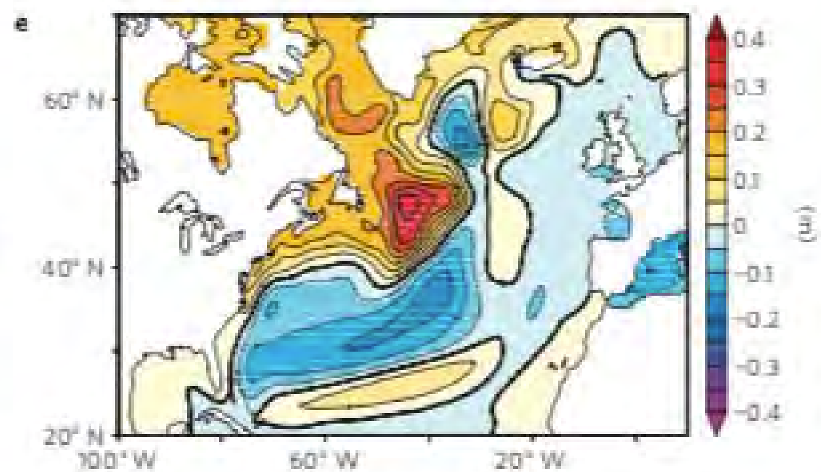
- Meridional gradient (approx. 1.4 m peak-to-trough in western Atlantic is consistently and accurately reproduced in climate models
- Dynamic sea level around European shelf is less consistent and accurate, with problems simulating the pathway of the North Atlantic Current consistent

Yin, J., Schlesinger, M. E., & Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, *2*(4), 262.

Sea Level and Atlantic Circulation



A2 emissions scenario (~RCP8.5)



B1 emissions scenario (~RCP 4.5)

- Meridional gradient in western Atlantic responds to a decline in overturning. This is consistent in CMIP5 models e.g. Little et al. 2019.
- Eastern boundary response is much more uncertain due to differing pathways of ocean currents in models. Also note European response of 0.1 m max.

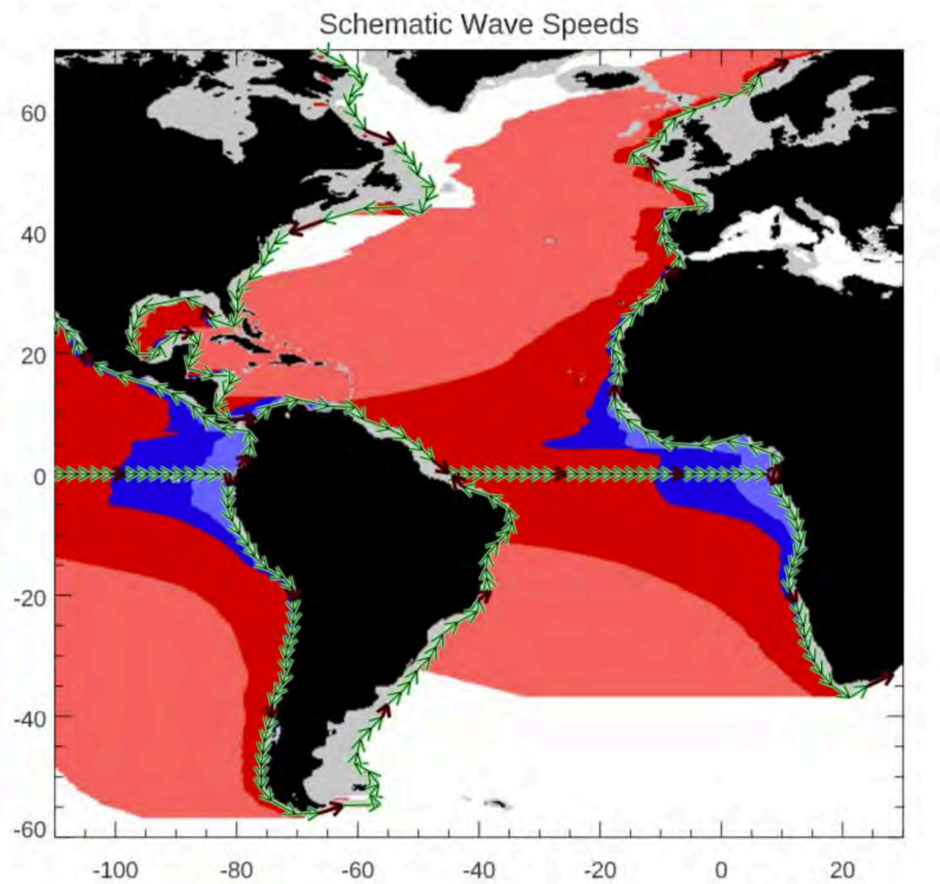
Yin, J., Schlesinger, M. E., & Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. *Nature Geoscience*, *2*(4), 262.

The Relationship Between US East Coast Sea Level and the Atlantic Meridional Overturning Circulation: A Review
CM Little, et al. - Journal of Geophysical Research: Oceans, 2019

Eastern Boundary Response

Most of the action in terms of large sea level response to AMOC decline happens on the west. The mechanisms of how the sea level signal is transmitted is complex.

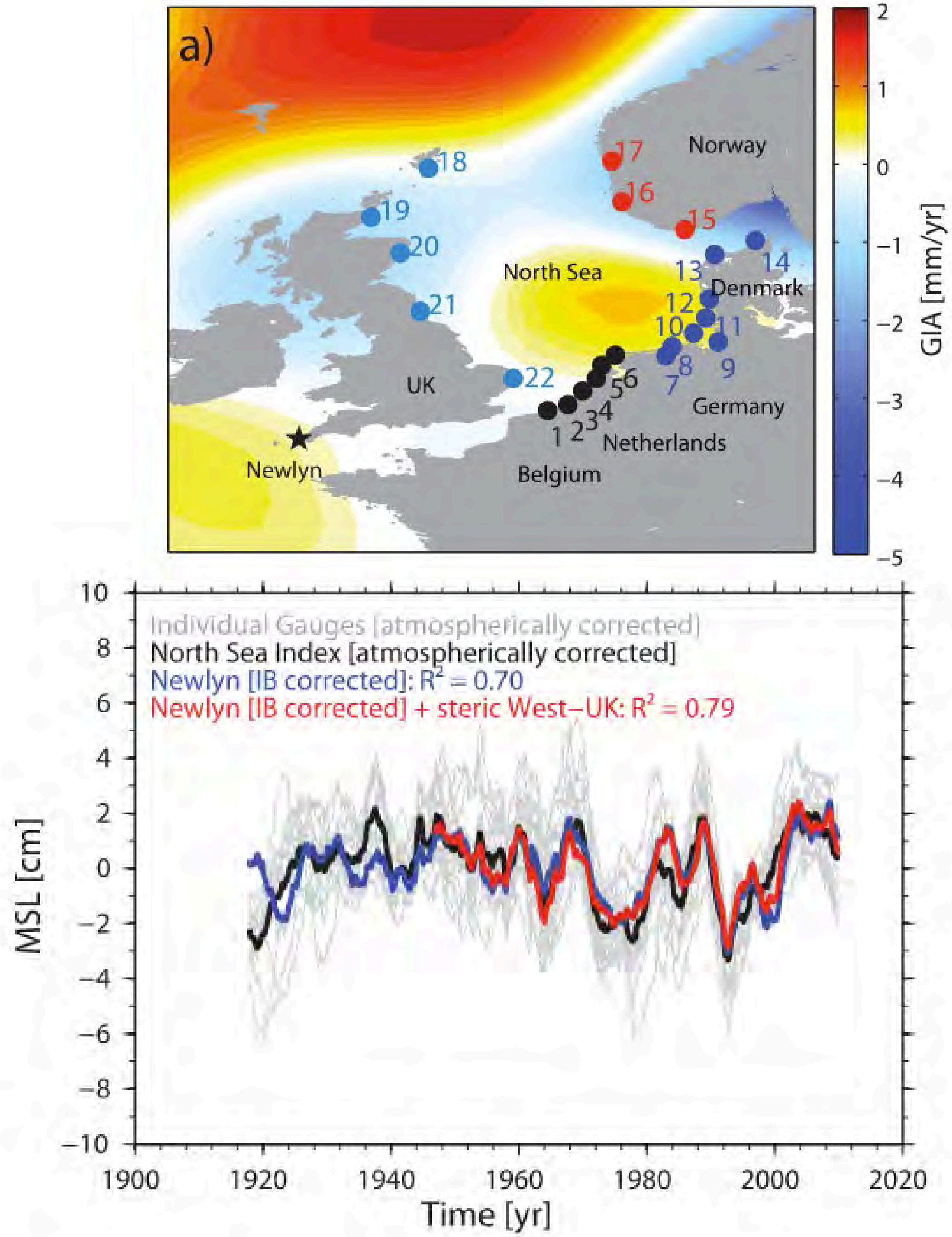
Eastern boundary dynamics can be/are simpler and driven by local winds or coastally trapped waves travel poleward (equatorial origin)



Hughes, C. W., Fukumori, I., Griffies, S. M., Huthnance, J. M., Minobe, S., Spence, P., ... & Wise, A. (2019). Sea Level and the Role of Coastal Trapped Waves in Mediating the Influence of the Open Ocean on the Coast. *Surveys in Geophysics*, 1-26.

Eastern Boundary Response

This paradigm is borne out in studies of European tide gauges. Dangendorf et al. (2014) note that **North Sea** tide gauges dominated by inverse barometer fluctuations and Norwegian/UK gauges by longshore wind. Remote forcing from the south (i.e. CTW) is also identified.



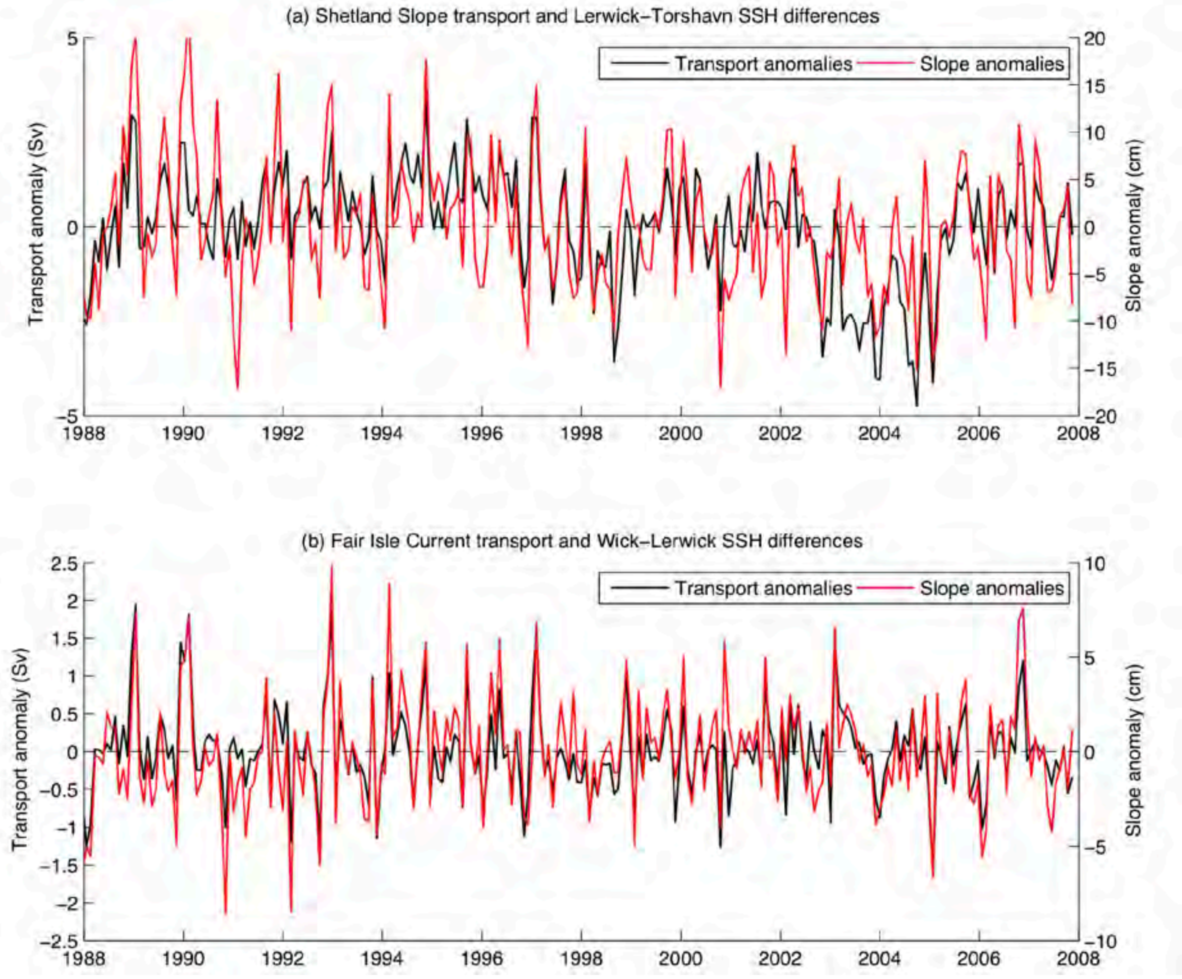
Dangendorf, Soenke, et al. "Mean sea level variability in the North Sea: Processes and implications." *Journal of Geophysical Research: Oceans* 119.10 (2014).

So where does that leave us?

How much are fluctuations of European coastal sea level driven by fluctuations in Atlantic circulation?

Understanding this can help isolate long term trends or accelerations, identify spatial patterns associated with other impacts etc.

Marsh, R., Haigh, I. D., Cunningham, S. A., Inall, M. E., Porter, M., & Moat, B. I. (2017). Large-scale forcing of the European Slope Current and associated inflows to the North Sea. *Ocean Science*, *13*(2), 315-335.



Atlantic Change and Europe

1. Sea Level

2. Storminess

3. Fisheries

4. Predictability

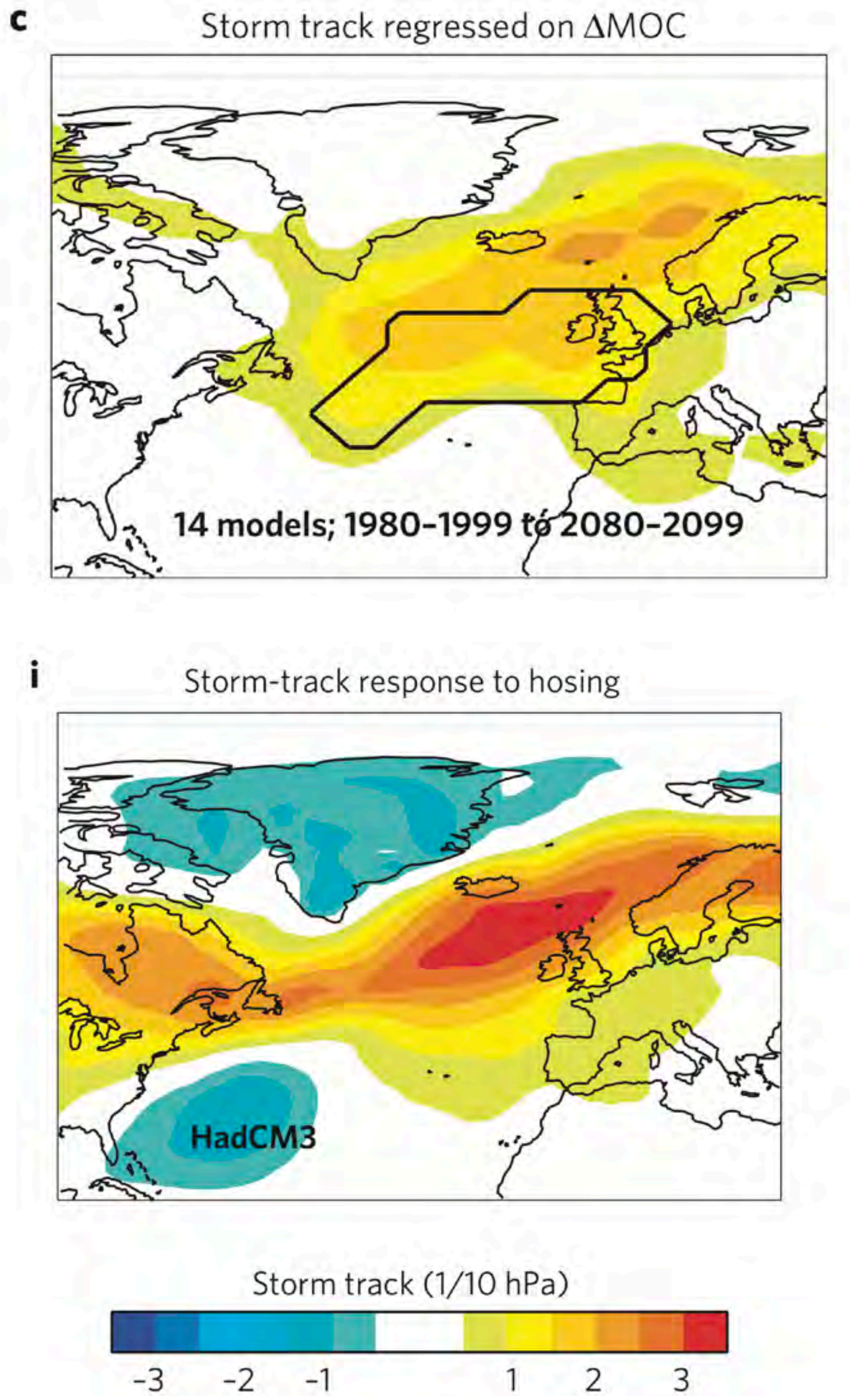
IPCC and storminess

- Weakening of the storm track in response to reduced equator to pole temperature gradient
- Paradigm of ‘less storms but more intense’

AMOC and storminess

A different trajectory to this paradigm arises from examining the impact of the AMOC on the storm track

A more intense and eastward shifted storm track results from a reduction in the AMOC.

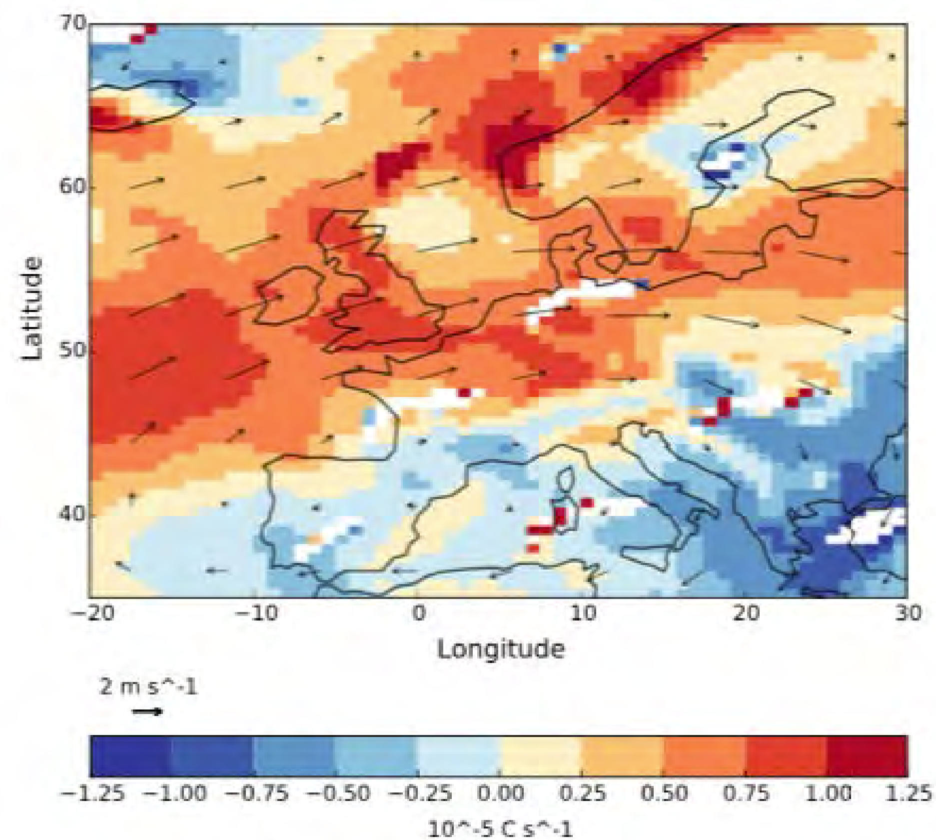


Woollings, T., Gregory, J. M., Pinto, J. G., Reyers, M., & Brayshaw, D. J. (2012). Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. *Nature Geoscience*, *5*(5), 313.

AMOC and storminess

A different trajectory to this paradigm arises from examining the impact of the AMOC on the storm track

A more intense and eastward shifted winter storm track results from a reduction in the AMOC.



Winter anomalies in thermal advection in case of AMOC collapse vs. control

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate dynamics*, *45*(11-12), 3299-3316.

AMOC and storminess

- Whether NW Europe has stormier winters in future in store appears to depend on the future trajectory of the Atlantic (e.g. Woolings et al., 2012; Gervais et al., 2019)
- Seasonality is important and differing impacts occur in different seasons (e.g. Haarasma et al., 2015)
- The influence of the tropics and Arctic sea ice may also play a role and may be dominant

Impacts of the North Atlantic Warming Hole in Future Climate Projections: Mean Atmospheric Circulation and the North Atlantic Jet
Gervais et al., 2019, J. Climate

Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes
Haarasma et al., ERL, 2015

Atlantic Change and Europe

1. Sea Level

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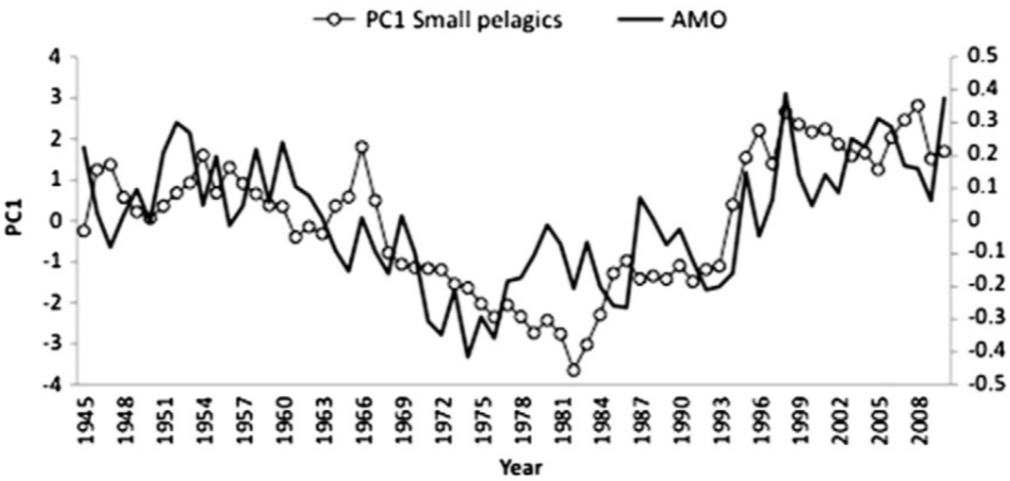
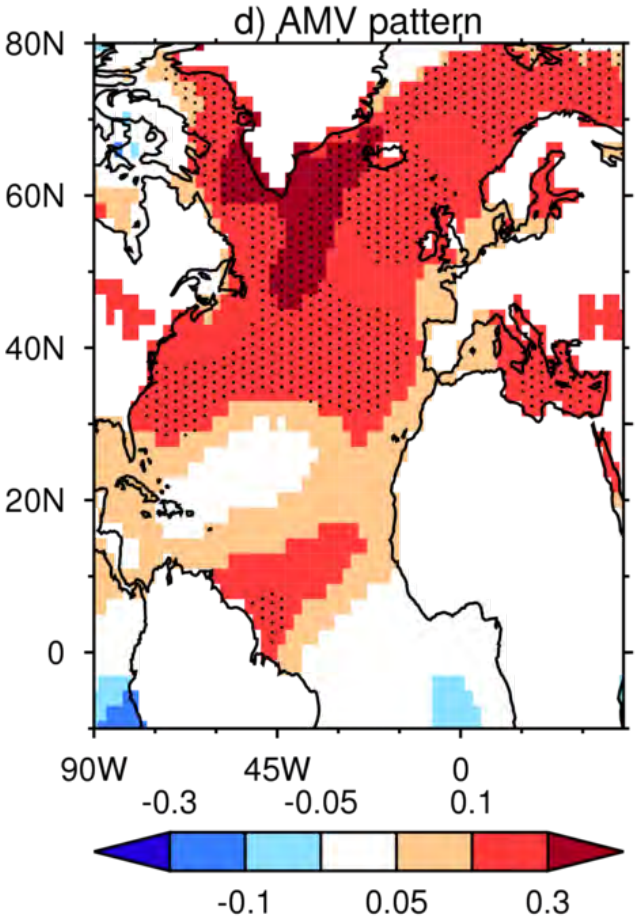
Changes to Pelagic Fish Distributions





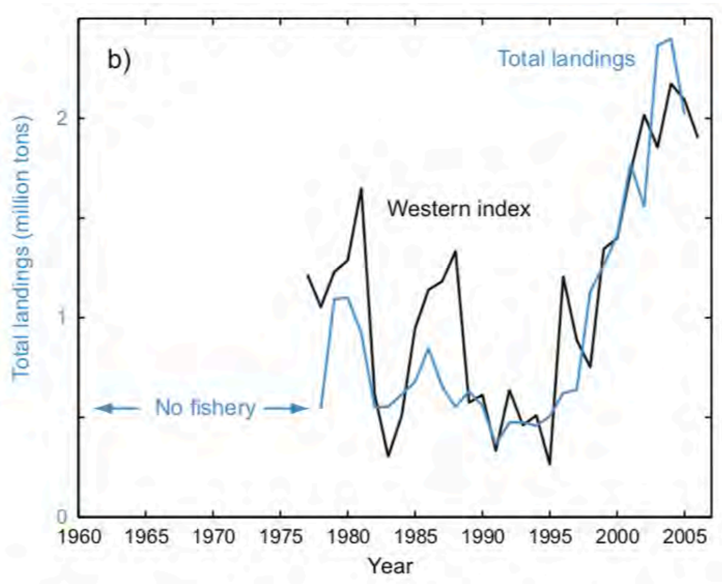
Atlantic Multidecadal Variability is a major feature of North Atlantic climate. A leading hypothesis is that it is controlled by fluctuations in AMOC strength.

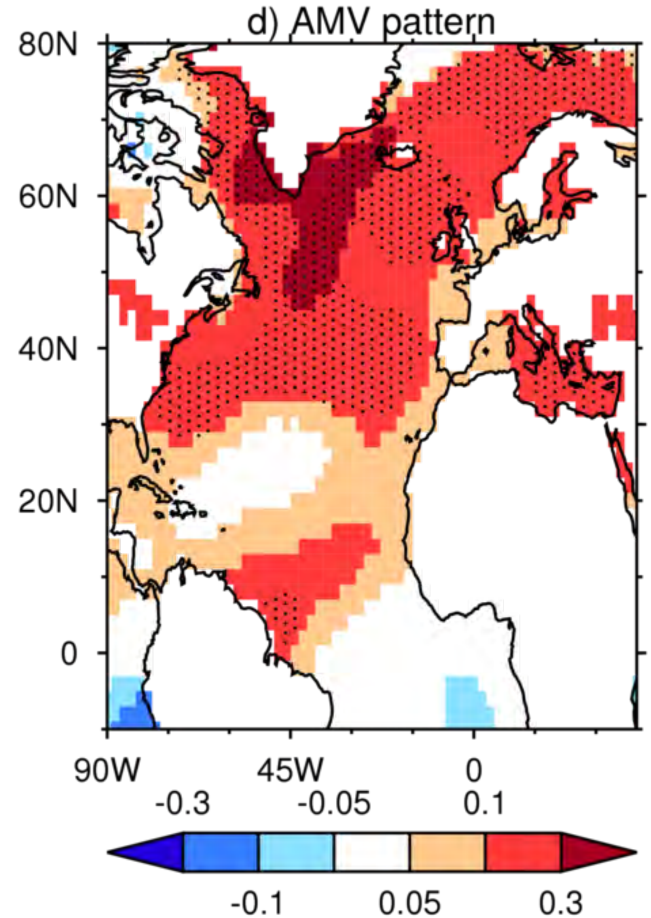
Phases of the AMV are linked to the distribution of certain fisheries.

Alheit, J., Licandro, P., Coombs, S., & Garcia, A. Girá ldez, A., Santamarıa, MTG, Slotte, A., et al. 2014. Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. *Journal of Marine Systems*, *131*, 21-35.

Sutton, R. T, McCarthy, G. D., Robson, J., Sinha, B., Archibald, A., and Gray, L. J. (2018) Atlantic Multi-decadal Variability and the UK ACSIS Programme *BAMS*

Changes to Pelagic Fish Distributions





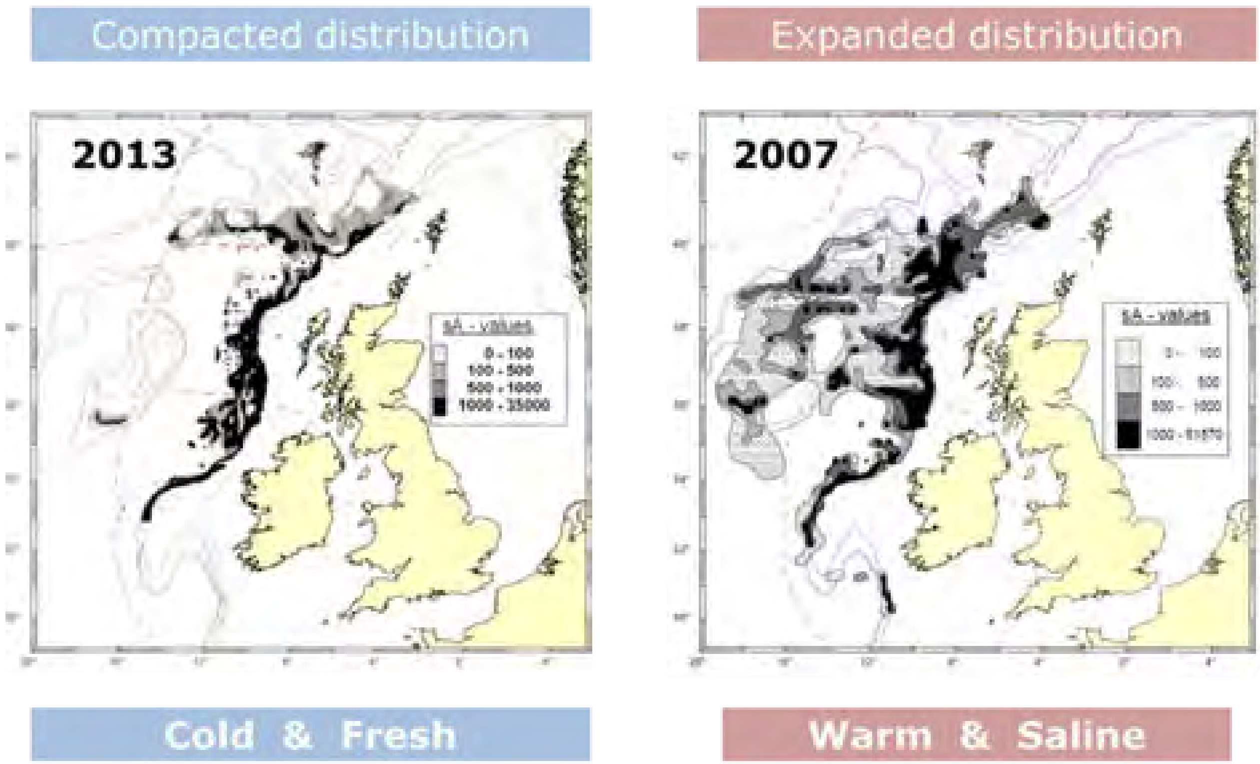
Atlantic Multidecadal Variability is a major feature of North Atlantic climate. A leading hypothesis is that it is controlled by fluctuations in AMOC strength.

Phases of the AMV are linked to the distribution of certain fisheries e.g. blue whiting.

Hátún, H., Payne, M. R., Beaugrand, G., Reid, P. C., Sandø, A. B., Drange, H., ... & Bloch, D. (2009). Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography*, *80*(3-4), 149-162.

Sutton, R. T, McCarthy, G. D., Robson, J., Sinha, B., Archibald, A., and Gray, L. J. (2018) Atlantic Multi-decadal Variability and the UK ACSIS Programme *BAMS*

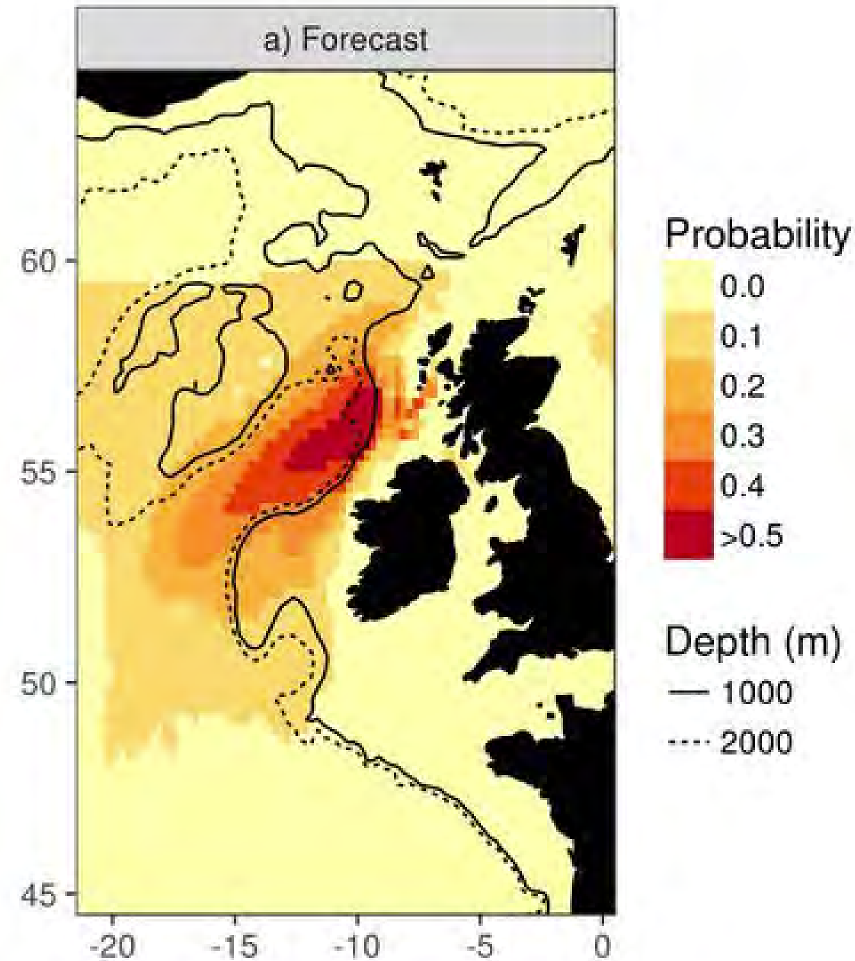
Changes to Blue Whiting Distribution



Blue whiting is a pelagic fish, about 30 cm long.
Its abundance and distribution is dependent on ocean properties, especially salinity

https://rpubs.com/markpayne/WGS2D_01_blue_whiting_spawning

Forecasts of Blue Whiting Distribution

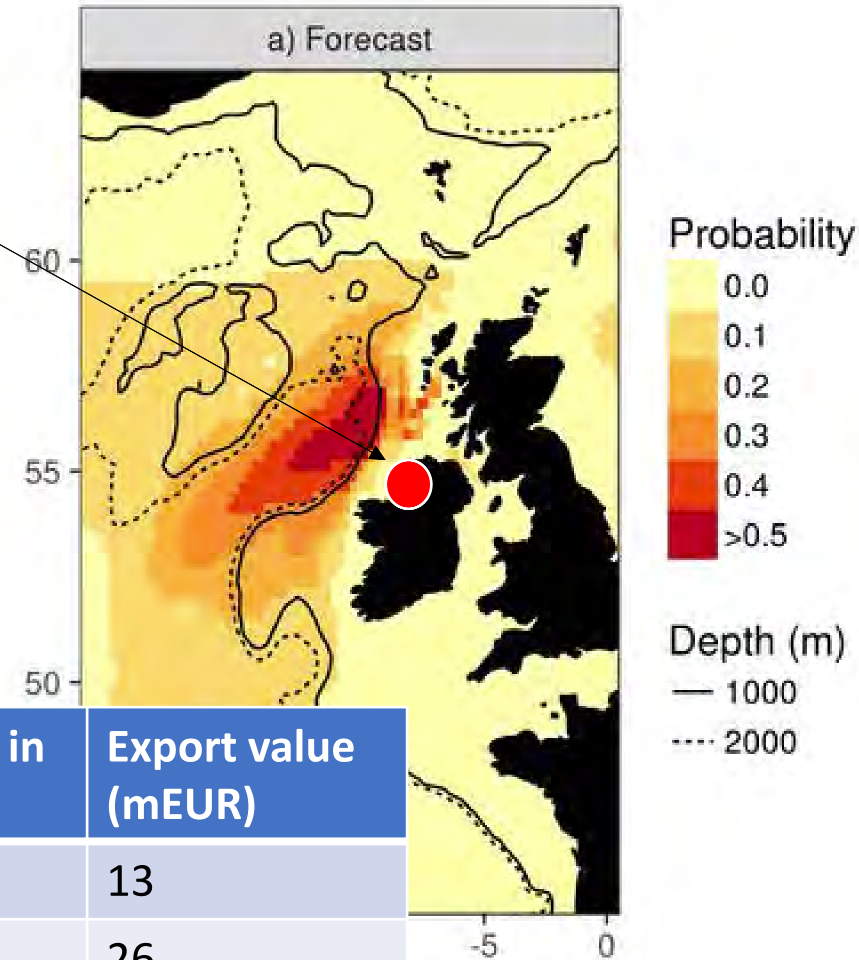


https://rpubs.com/markpayne/WGS2D_01_blue_whiting_spawning

Forecasts of Blue Whiting Distribution

Killybegs in Donegal is Ireland's largest fishing port.

Blue Whiting has been a large growth stock in recent years.



Blue Whiting	Landings (tonne)	% increase in landings	Export value (mEUR)
2017	44600	20	13
2018	49900	9	26

source: BIM, The Business of Seafood, 2018, 2019

https://rpubs.com/markpayne/WGS2D_01_blue_whiting_spawning

Atlantic Change and Europe

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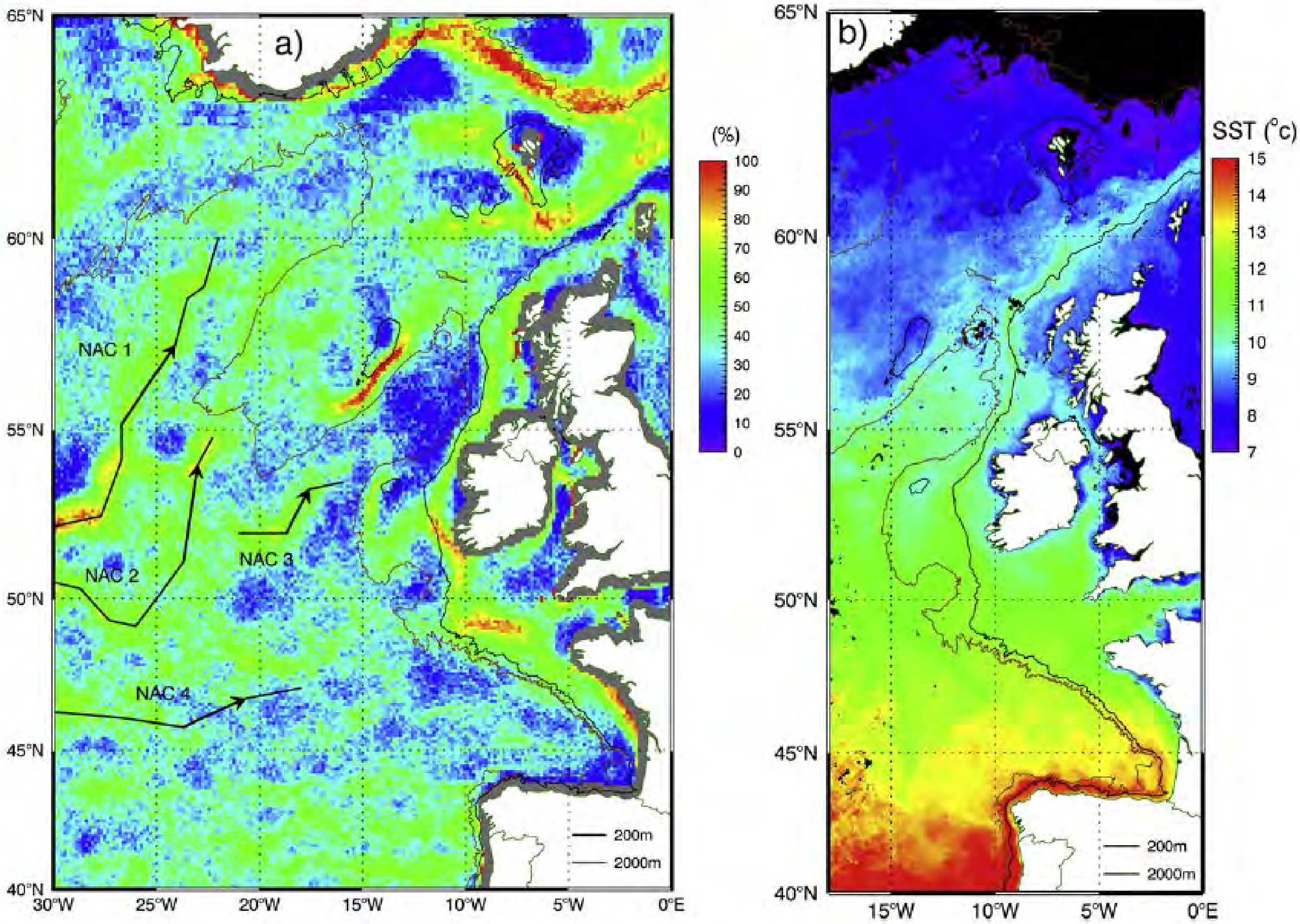
Predictability

- The North Atlantic is most predictable region on the planet on decadal timescales
- In meteorology, a key motivation for the maintenance of observing infrastructure is improvement of forecasts. Can we generate enough support to use the same arguments here?

The NW European Slope Current

W. Xu et al. / Remote Sensing of Environment 162 (2015) 196–207



Winter Front climatology

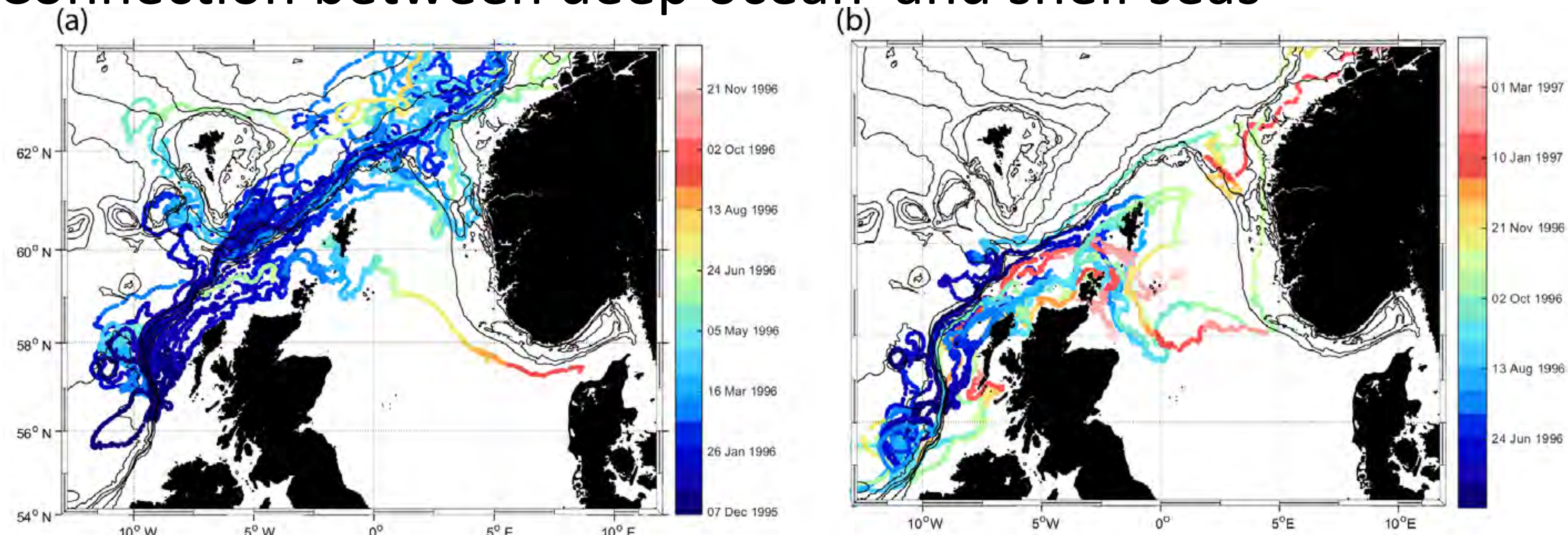
Jan 1996 SST

(Xu et al, 2015)

European Slope Current – Lagrangian Observations

Pathway of warm saline water (modified Atlantic Water) to Nordic Seas

Connection between deep ocean and shelf seas

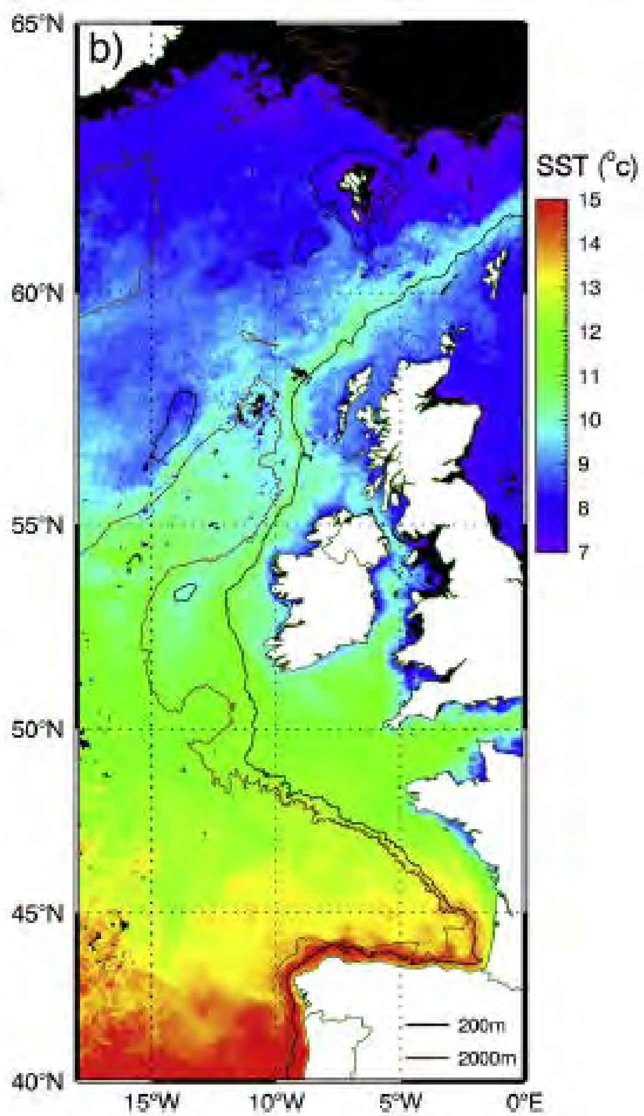


(Marsh et al, 2017)

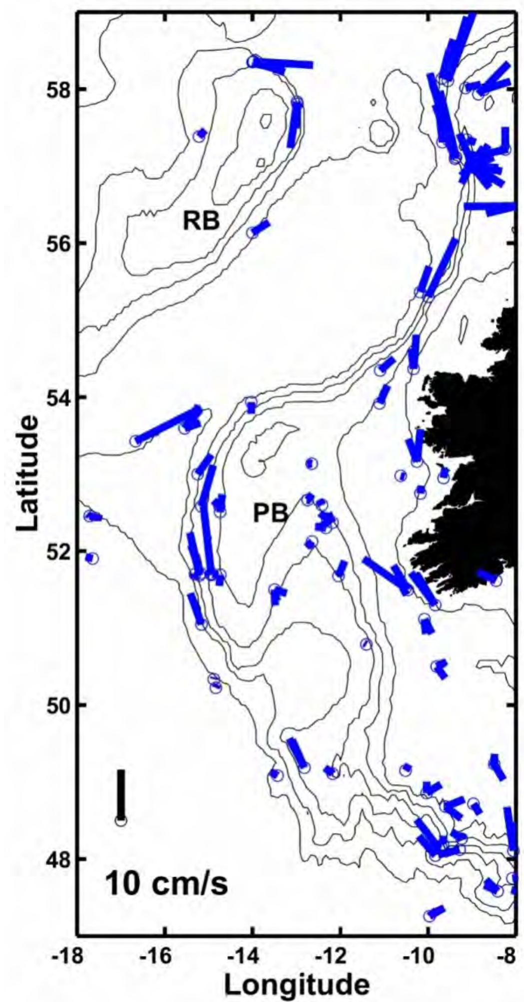
Much of the previous drifter data comes from N Rockall Trough deployments (N of Ireland)

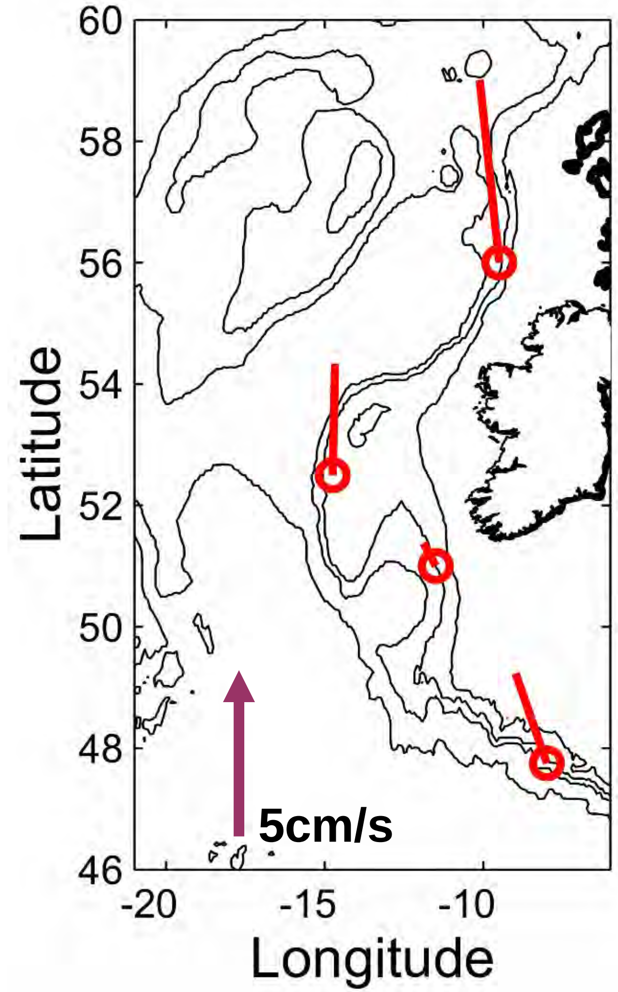
FASTNEt deployments in Biscay went south so linkage from S-N not really observed in Lagrangian measurements

European Slope Current – Eulerian Observations



Measured mean residual flows (mid/upper water column) for current meter data going back to mid 70s (at least 2months data)





Generating force

Density gradients – [poleward decline of dynamic height]

Wind stress – both feeding current from deep ocean and direct forcing

Theoretical consideration (Huthnance)

Current approx. -

$(g/2) * (H/k) * \Delta D/dy * [(h/H) * (1-h/H)]$

↑ Ocean frictional decay (H/k)

↑ Dyn Ht Gradient (ΔD/dy)

↑ Depth h Ocean Depth H

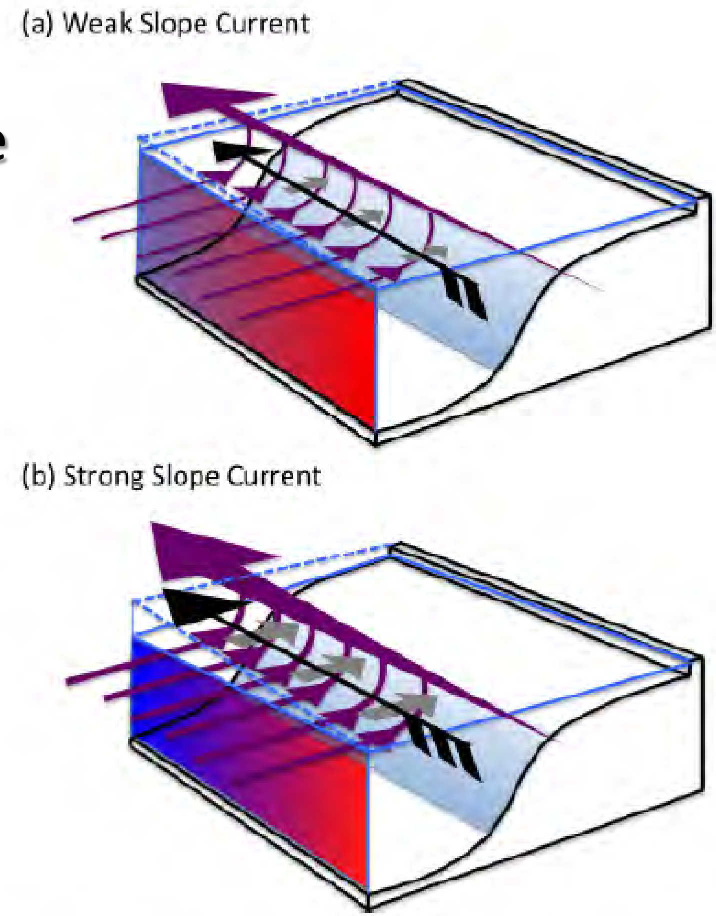
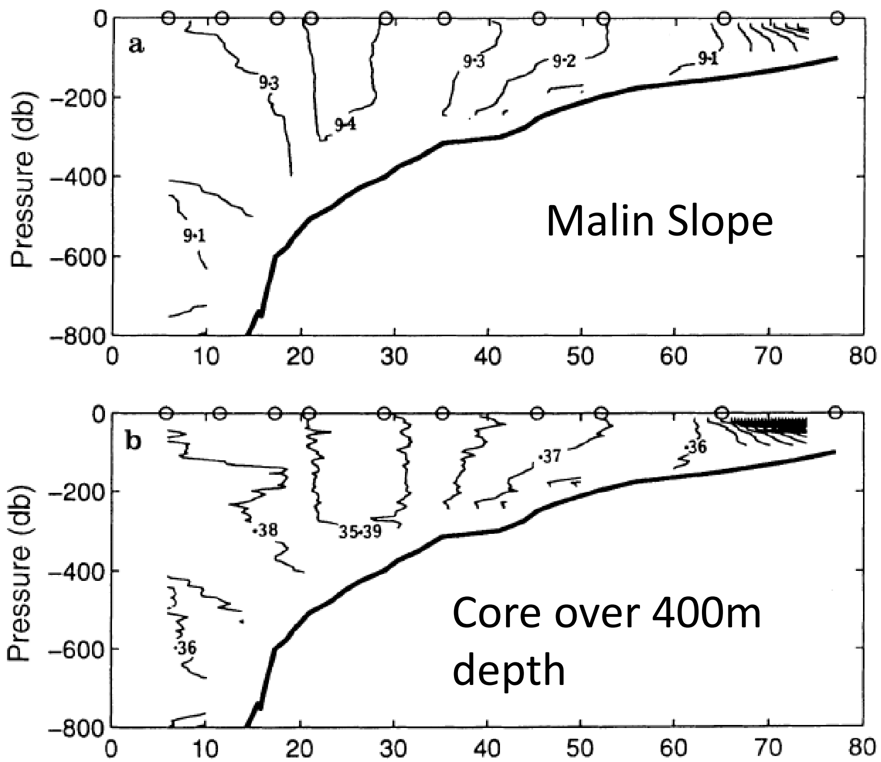


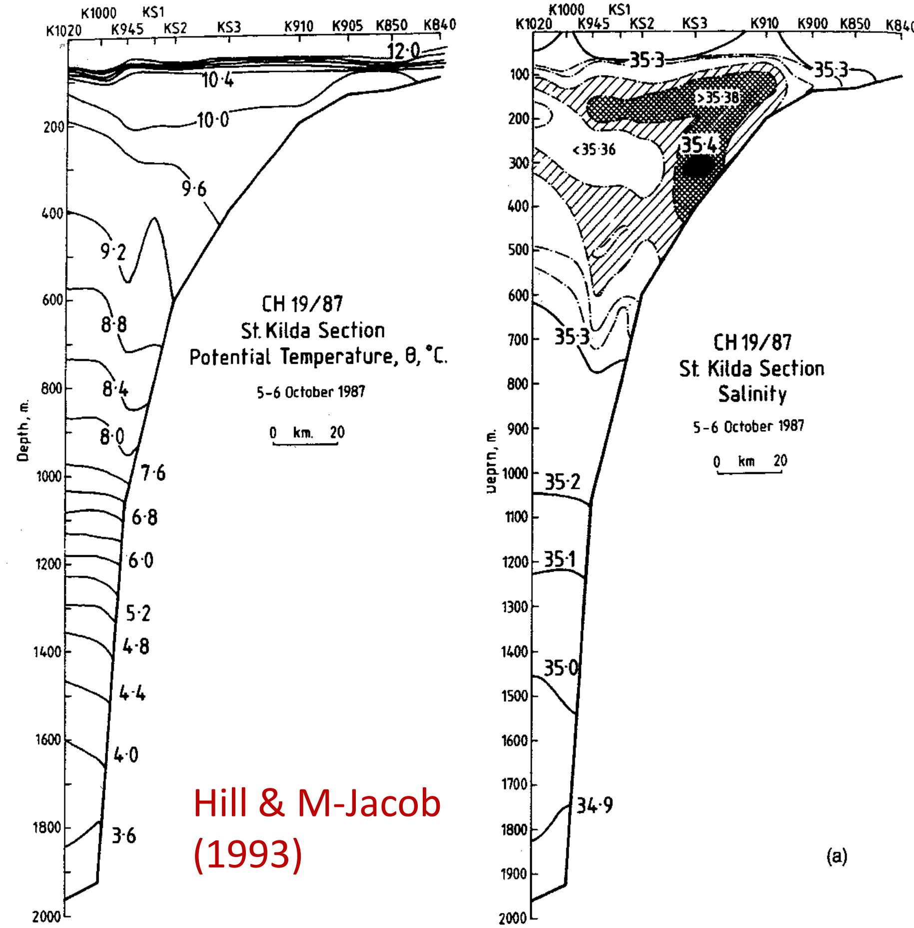
Figure 16. Schematics showing density gradients (shaded red to pale or dark blue), eastward geostrophic inflow, wind forcing (black alongshore arrow), Ekman transports (grey onshore arrows) and sea surface slopes at an idealized eastern boundary, associated with (**a**) weak and (**b**) strong Slope Current transport.

Current Core max at mid continental slope

(Marsh et al, 2017)



White and Bowyer, (1998)

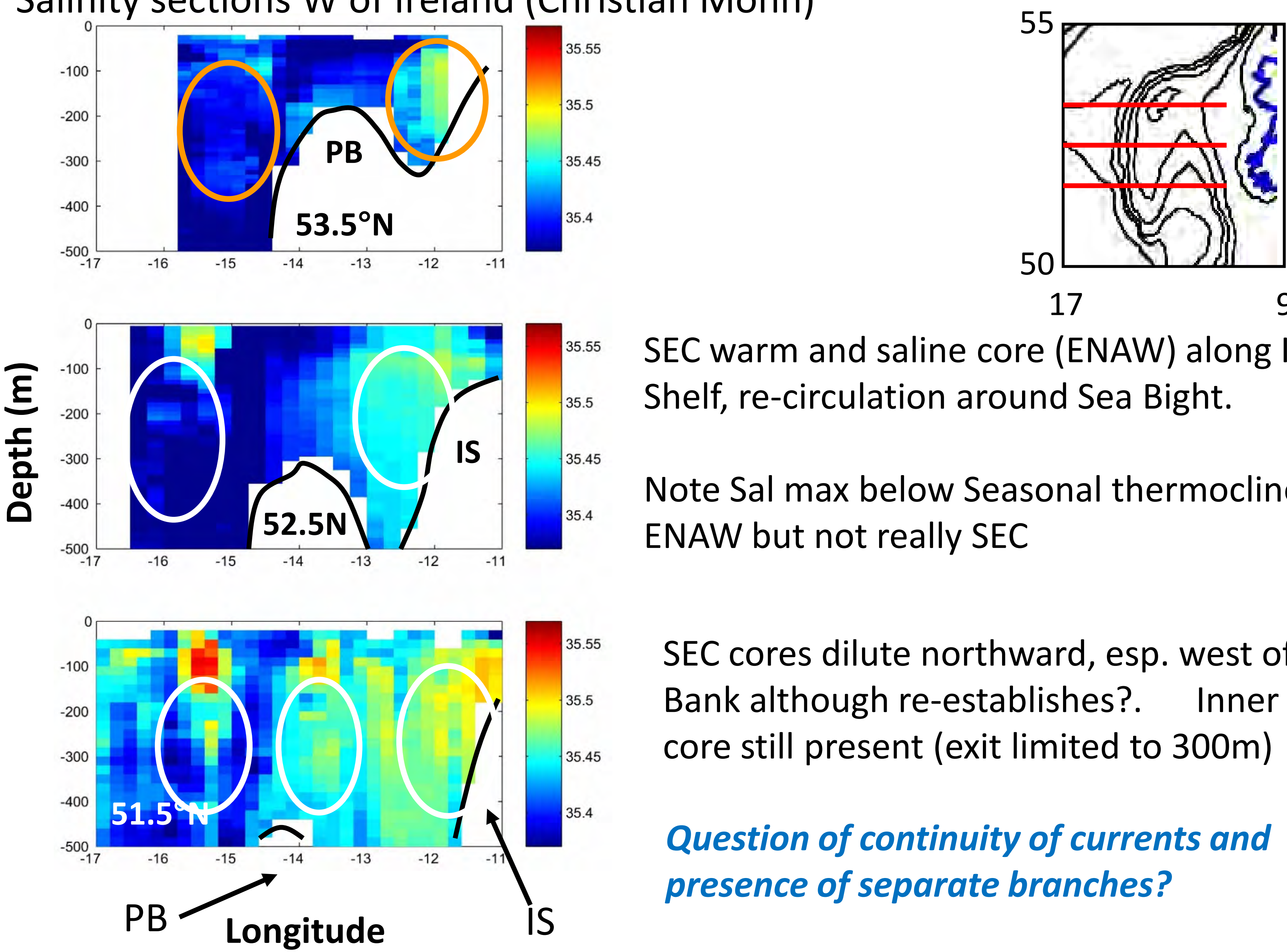


Hill & M-Jacob (1993)

One feature of flow is its core/filament nature –

Maybe hard to estimate full current with hydrographic sections even with moderate station separation

Salinity sections W of Ireland (Christian Mohn)



SEC warm and saline core (ENAW) along Irish Shelf, re-circulation around Sea Bight.

Note Sal max below Seasonal thermocline – ENAW but not really SEC

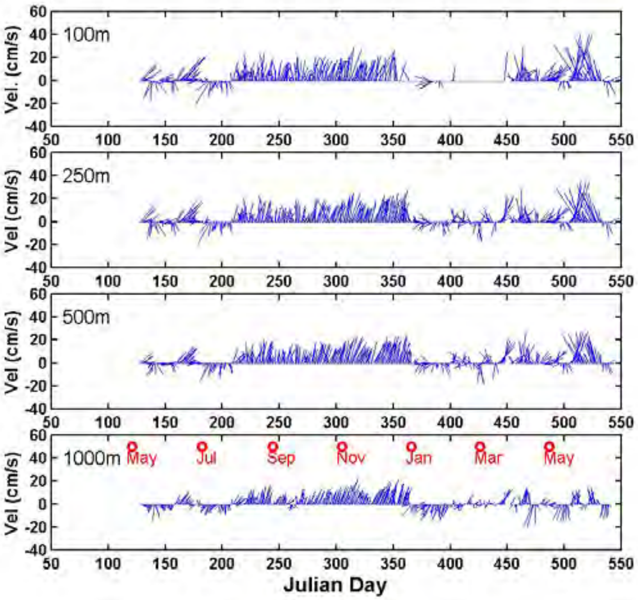
SEC cores dilute northward, esp. west of P Bank although re-establishes?. Inner core still present (exit limited to 300m)

Question of continuity of currents and presence of separate branches?

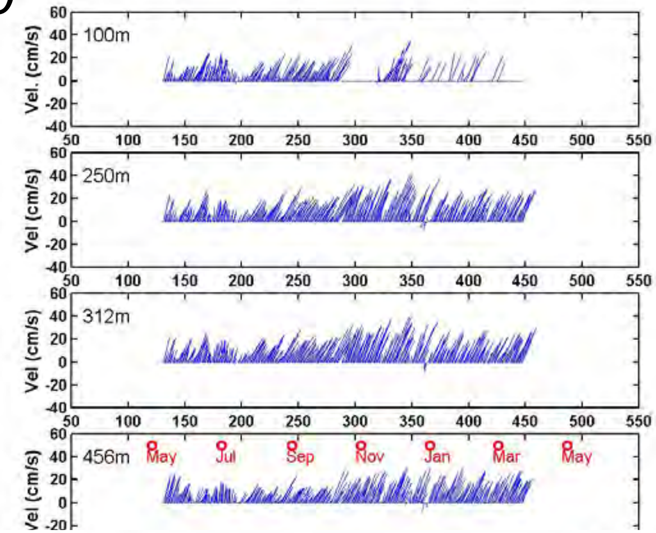
EXAMPLE TIMESERIES

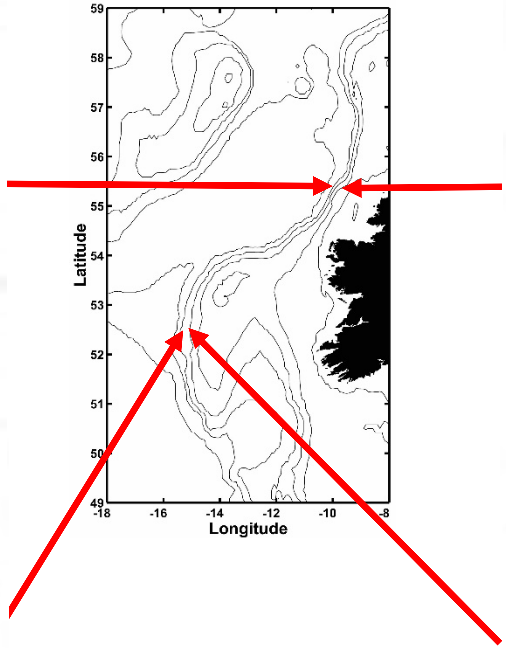
May1999 - May2000

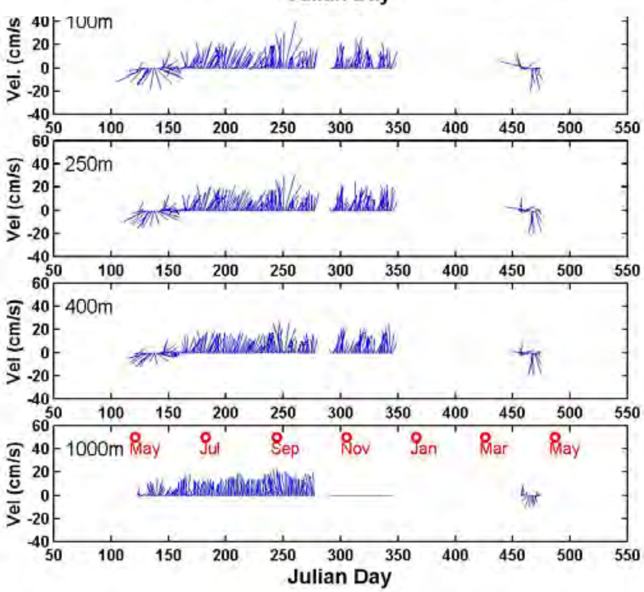
Malin 1250m WD



Malin 500m WD



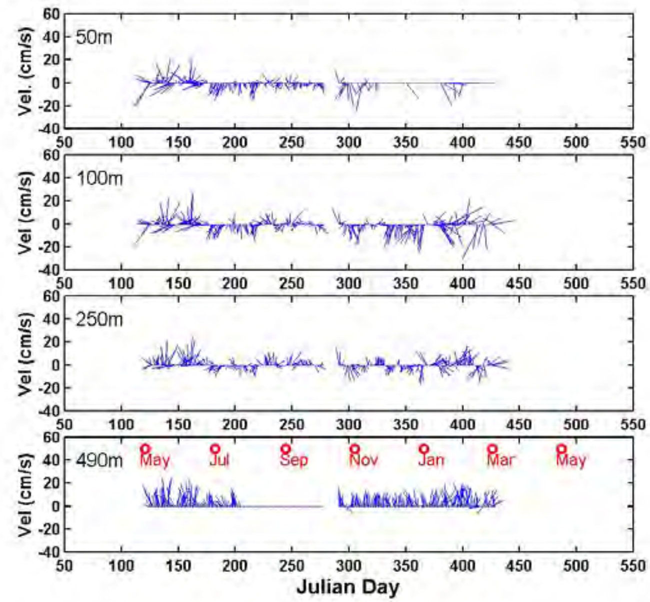




W Porcupine Bank

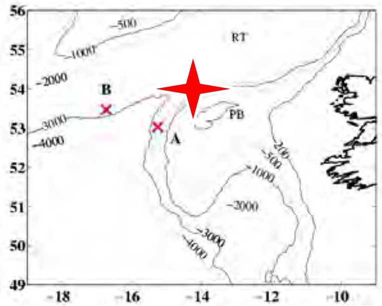
1250m

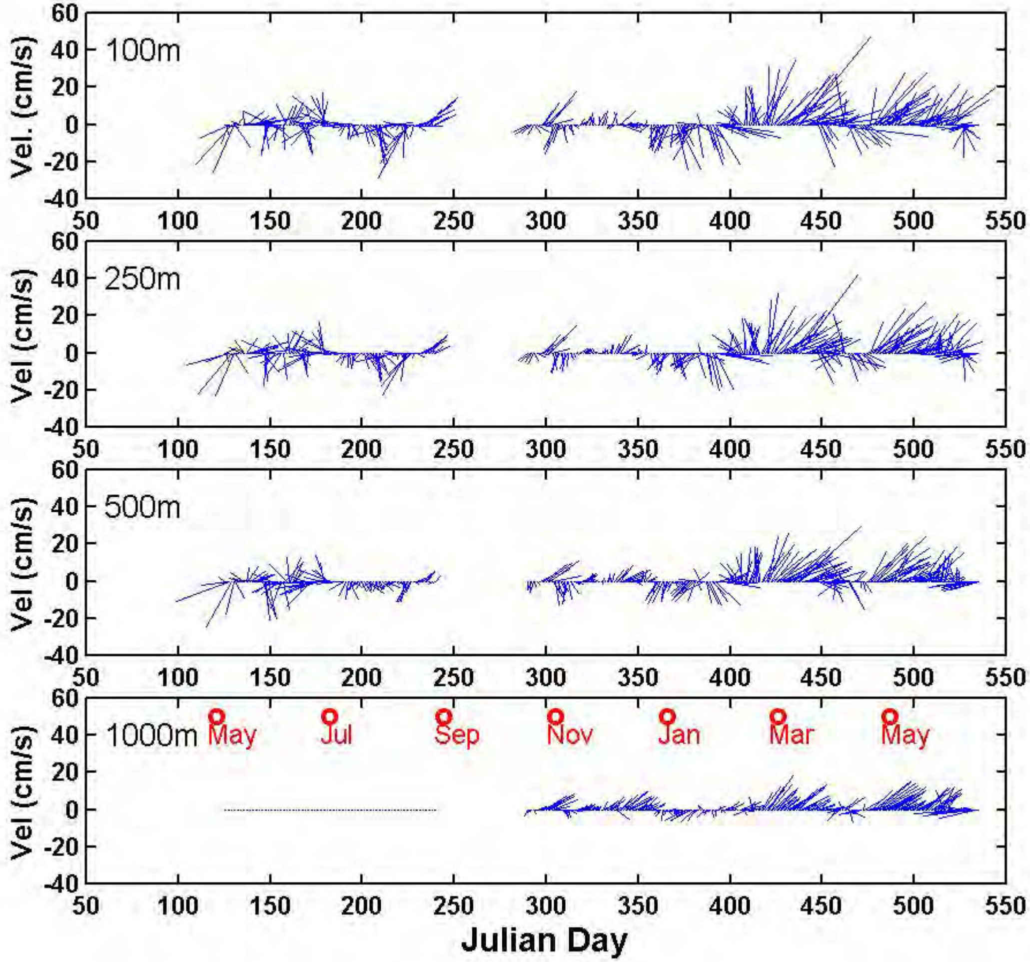
500m

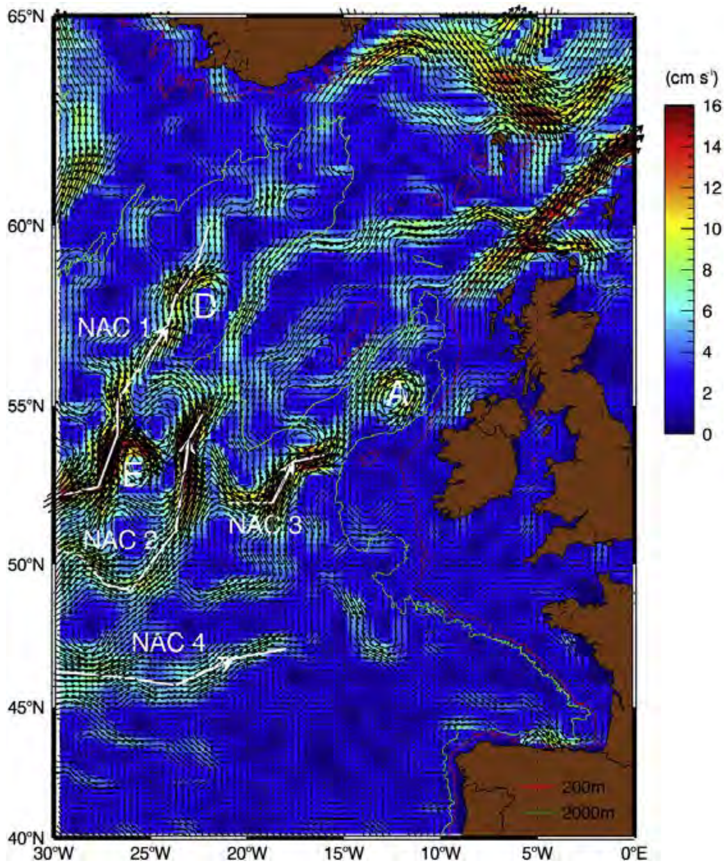


N Porcupine Bank, 1250m water depth May 1999 – May 2000

Unpublished (commercial) data



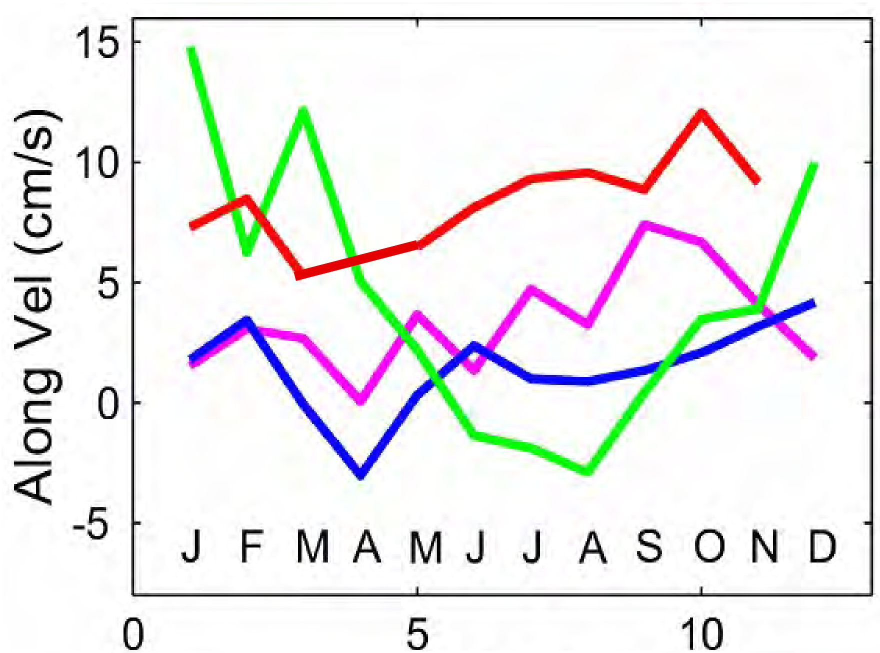


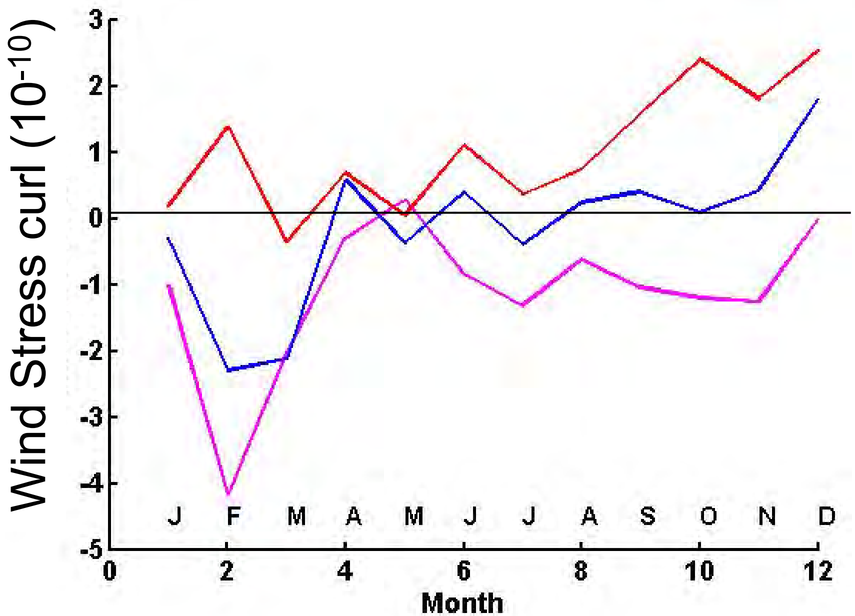


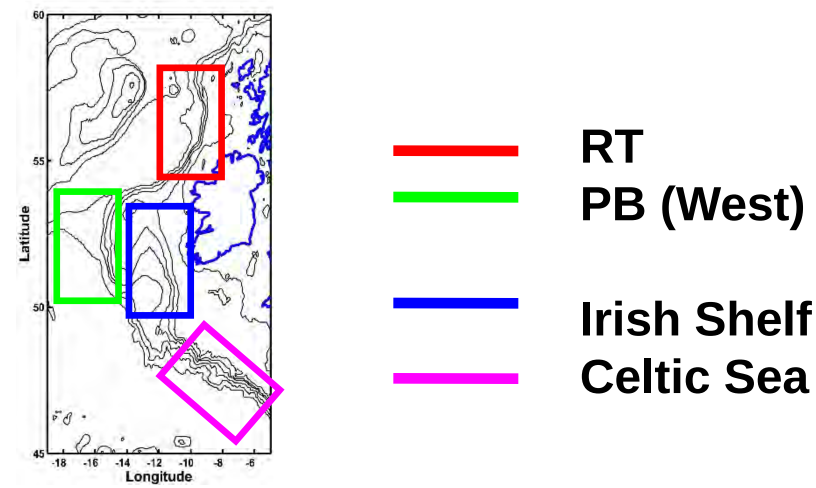
Xu et al. (2015)

Influence of mesoscale eddies on the variability (and instability) in the slope current?

Seasonality & wind stress







55-60 N shelf edge – 30W

50-55 N shelf edge – 30W

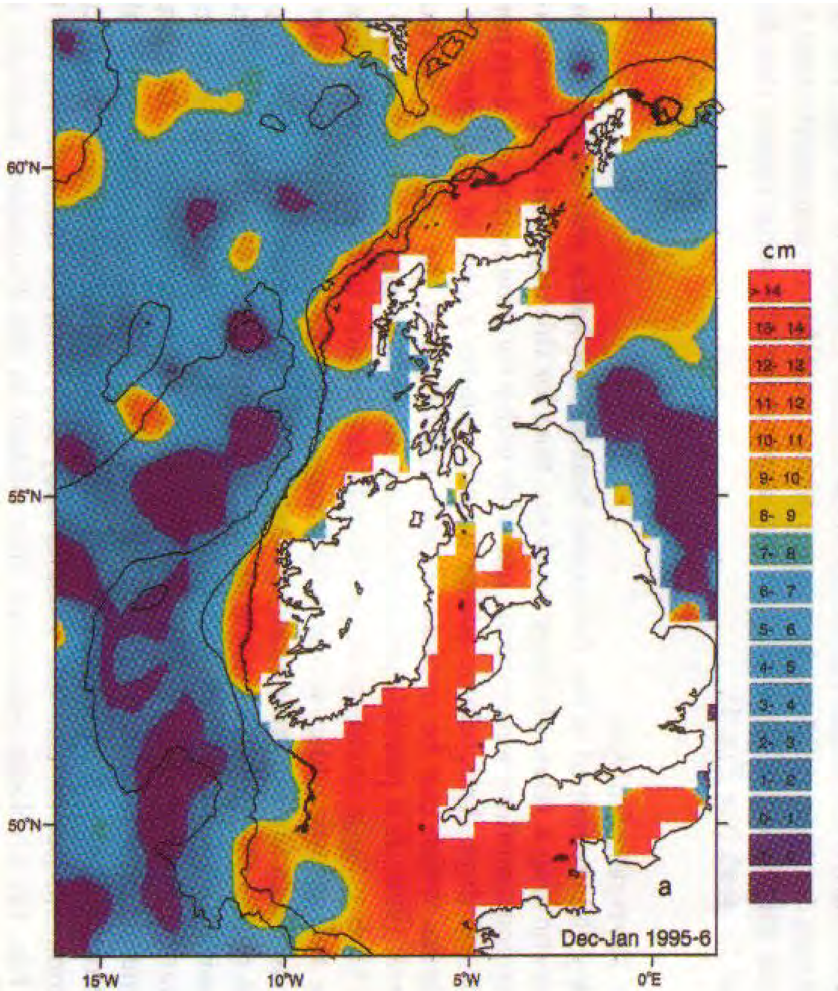
45-50 N shelf edge – 30W

Good relationship with RT, Celtic Sea / Irish Shelf seasonality (1-2 month lag) cf SOMA response (Pingree)

Not at Porcupine Bank

Continuous or not?

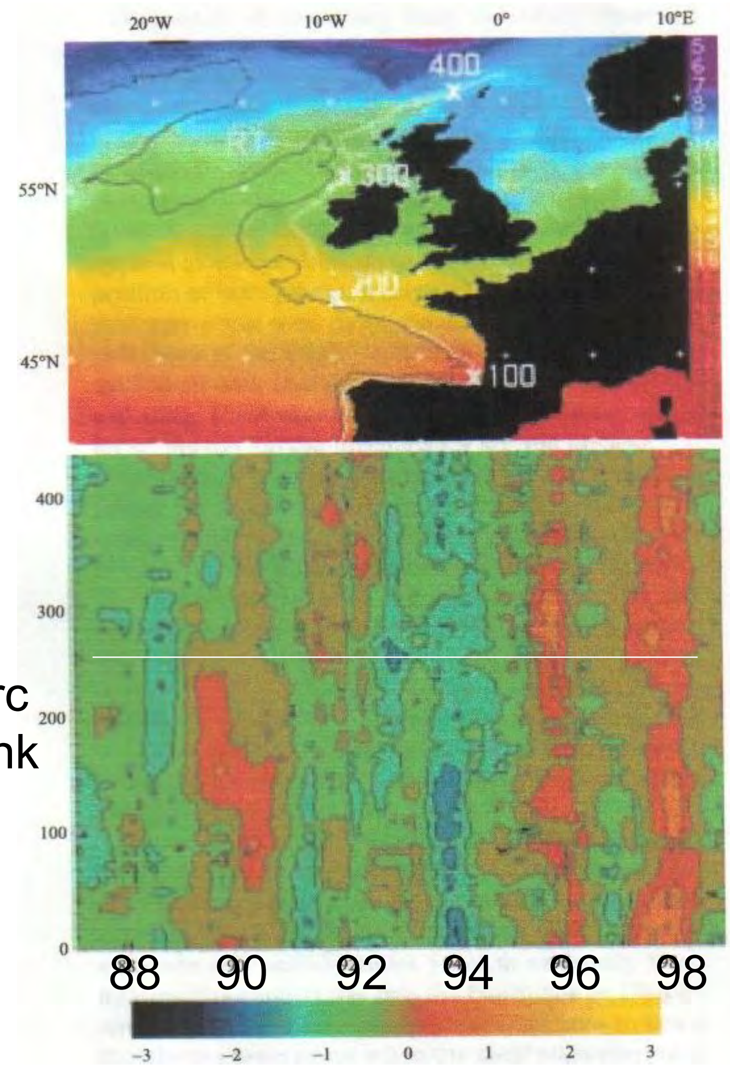
For



Robin Pingree's float deployed Winter 1996. Celtic Sea-Nordic

Against?

Lat
Porc
Bank

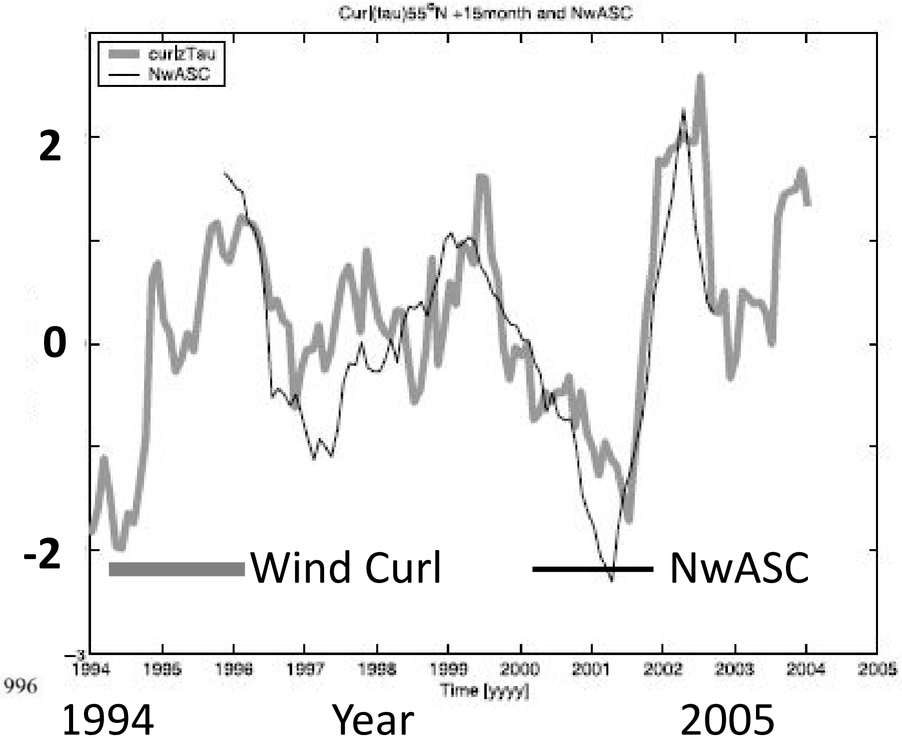


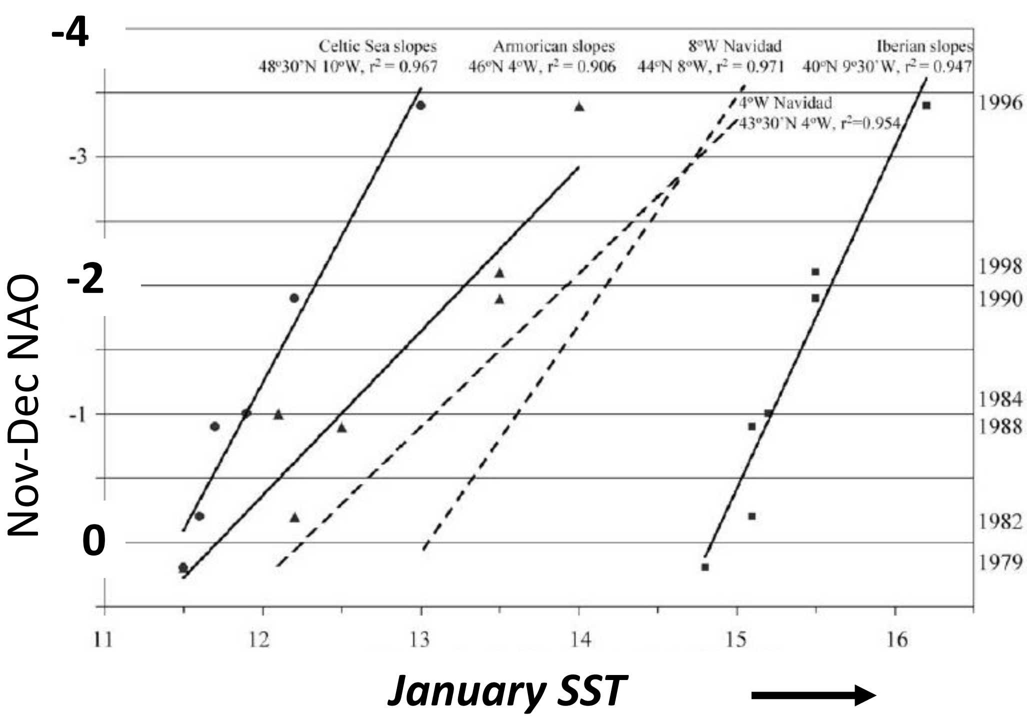
Read et al. (2001)

WIND STRESS

Relationship of Atlantic inflow into North & Norwegian seas with Atlantic Wind Stress curl (and NAO) becoming well appreciated

e.g. Orvik & Skagseth (2003) – Strong (0.8) correlation between zonally integrated wind stress curl at 55N and Norwegian Slope Current transport (NwASC) lagged at 15months



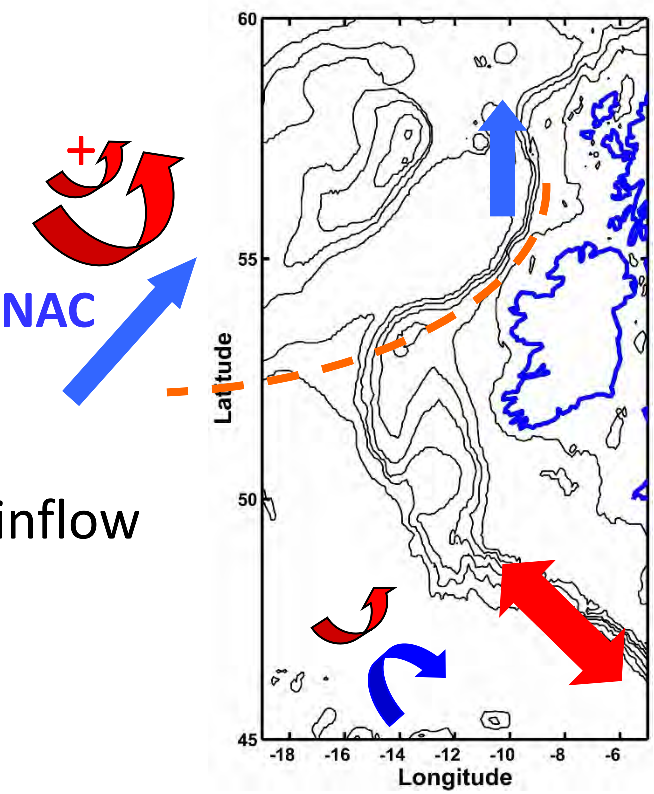


<u>Garcia-Soto et al. (2002)</u>

Low NAO = strong Navidad and SEC flow along the Bay of Biscay and Iberian margins

Possibly two separate regimes for SEC current north & south of Porcupine Bank

Zero wind stress curl passing close to Porcupine Bank likely important



NORTH

Gyre scale forcing controls the Atlantic fed inflow magnitude but always polewards

SOUTH

Modulated by the inter-gyre structure heavily modifies slope current magnitude/direction

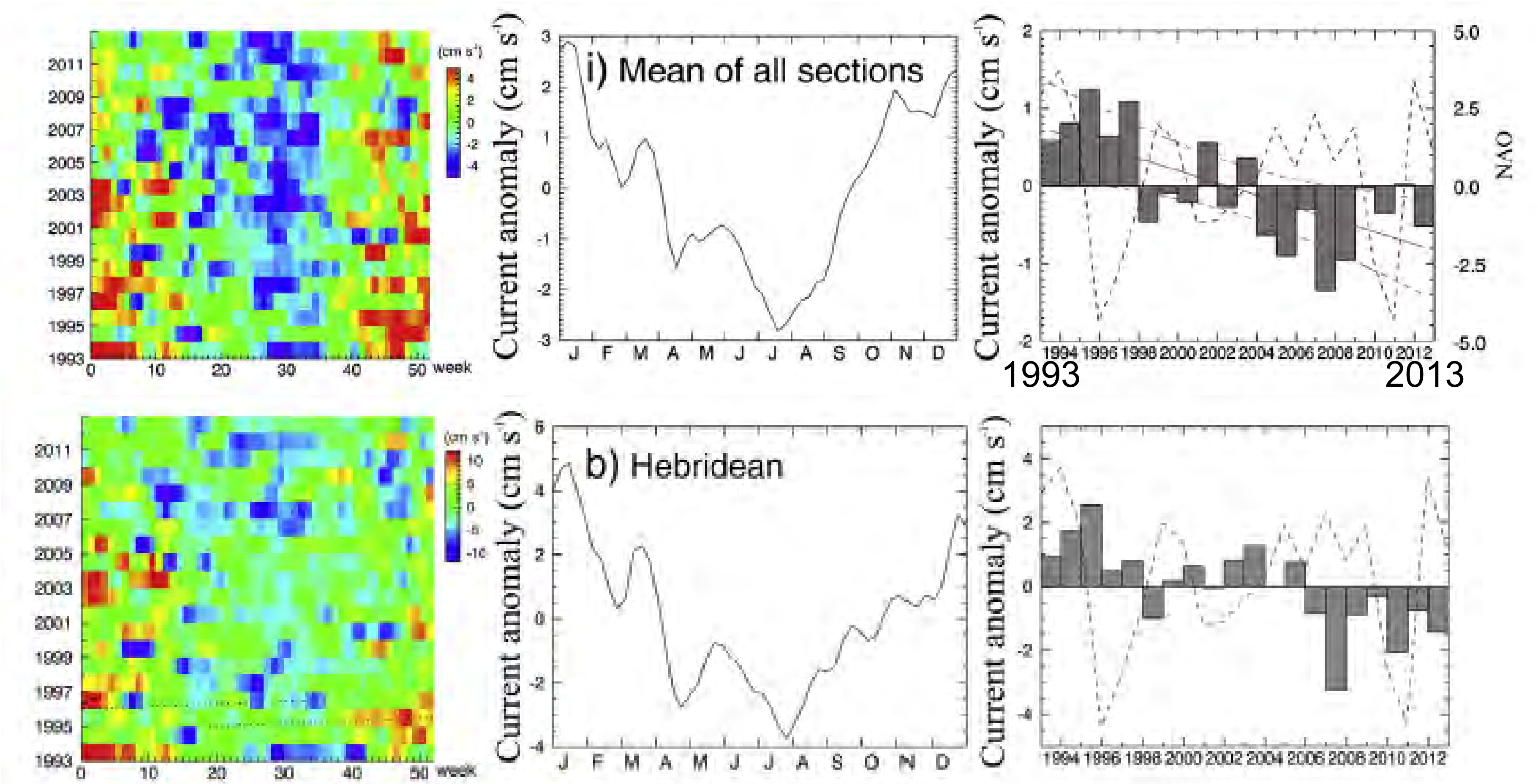
Probably has big influence for on-shelf excursions – additional heat , modulating the shelf sea frontal structures

Analysis of 20 years of Altimetry:

(i) Seasonal variability in Altimetry derived current anomaly,

(ii) Suggest a decreasing trend in slope current

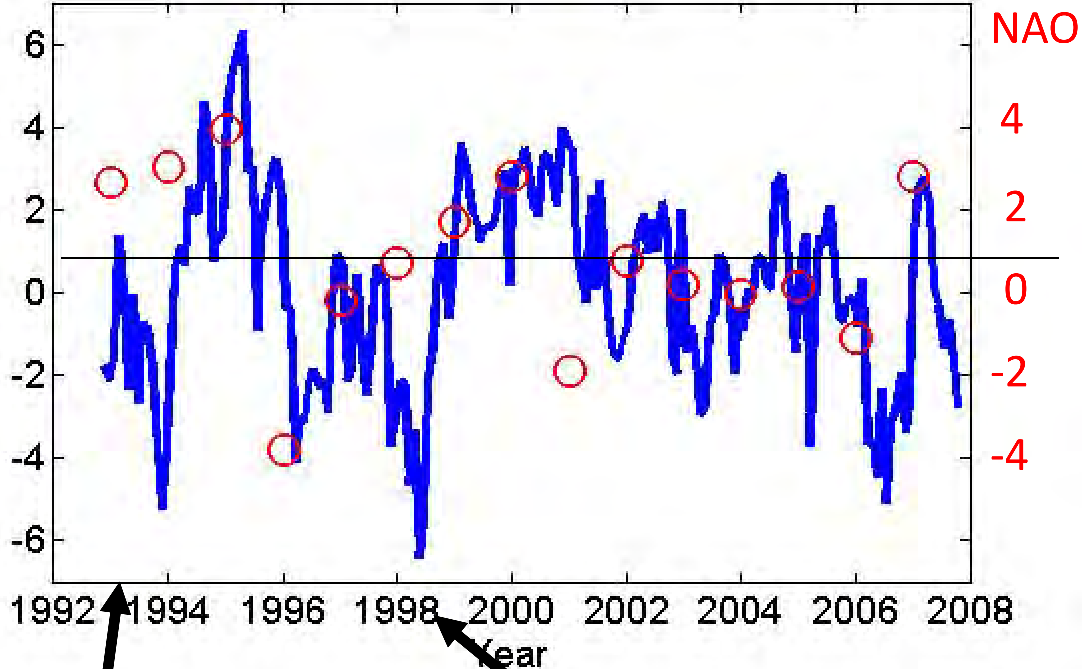
– **BUT is this a long period variation?**



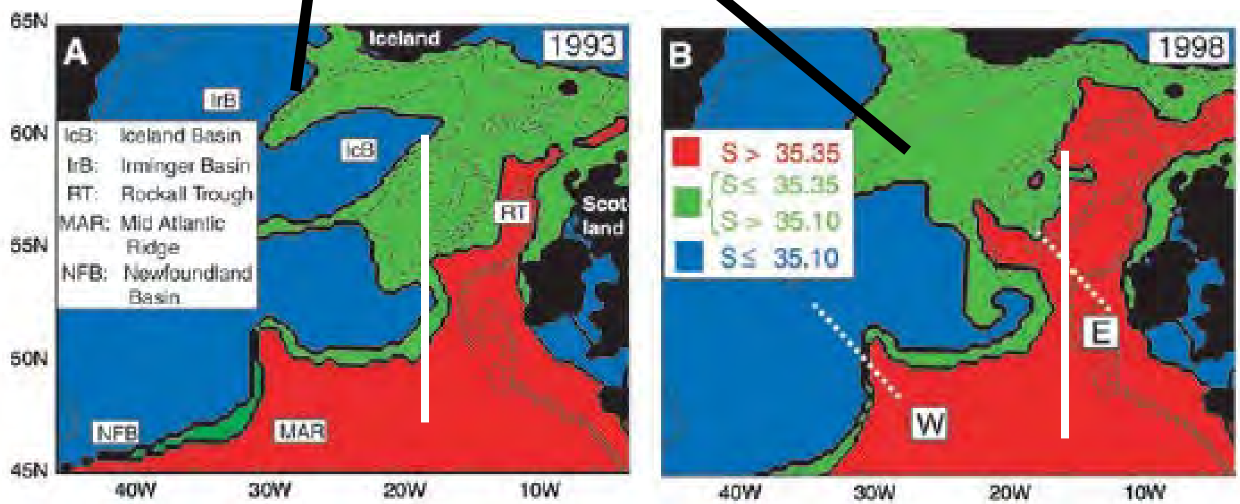
Xu et al., 2015, Remote Sensing Environment

Anomaly in Biscay-Rockall SSH difference

(-ve = flatter margin)

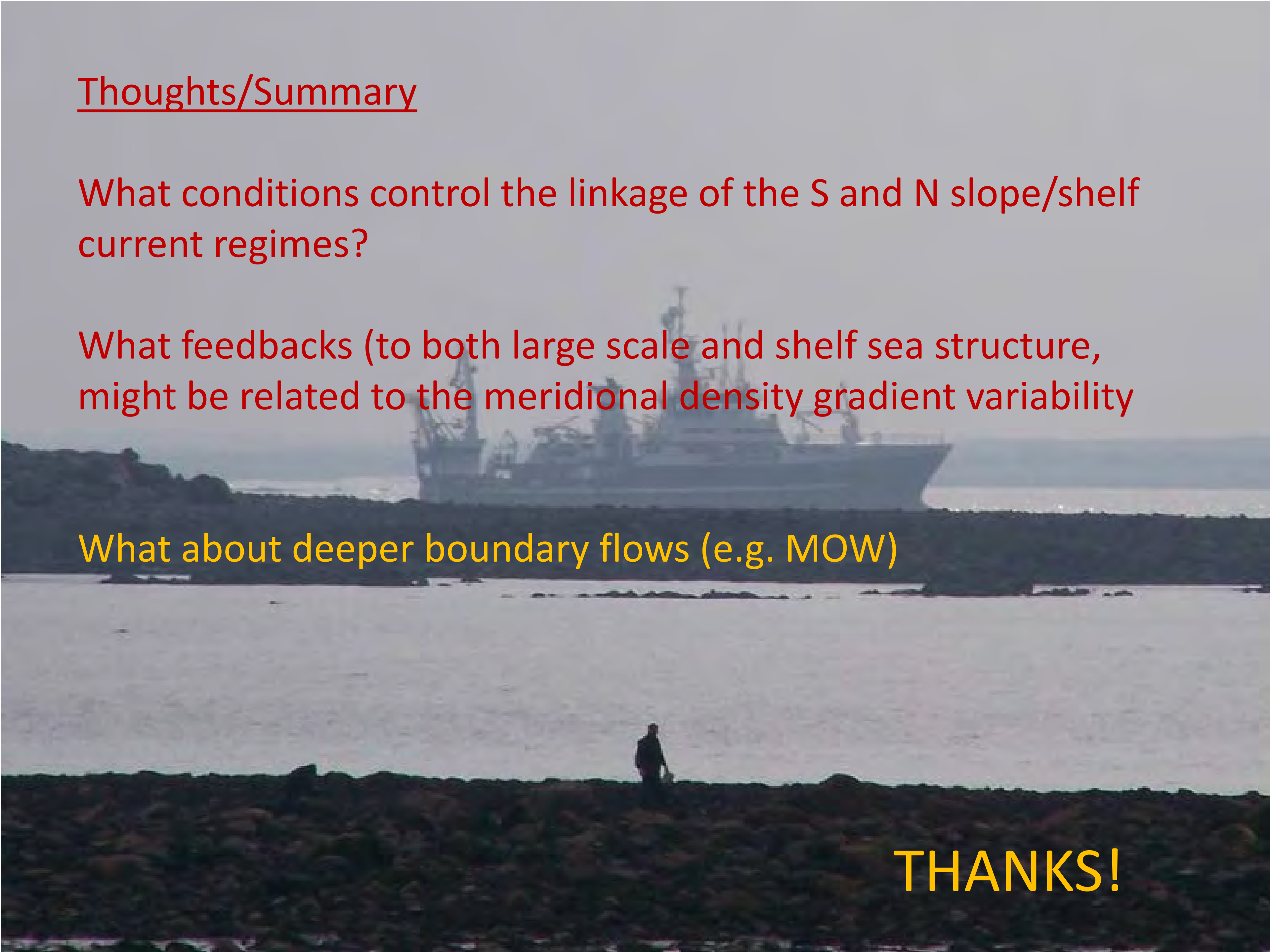


Larger meridional SSH gradient



Smaller meridional SSH gradient

Hatun et al. (2003)



Thoughts/Summary

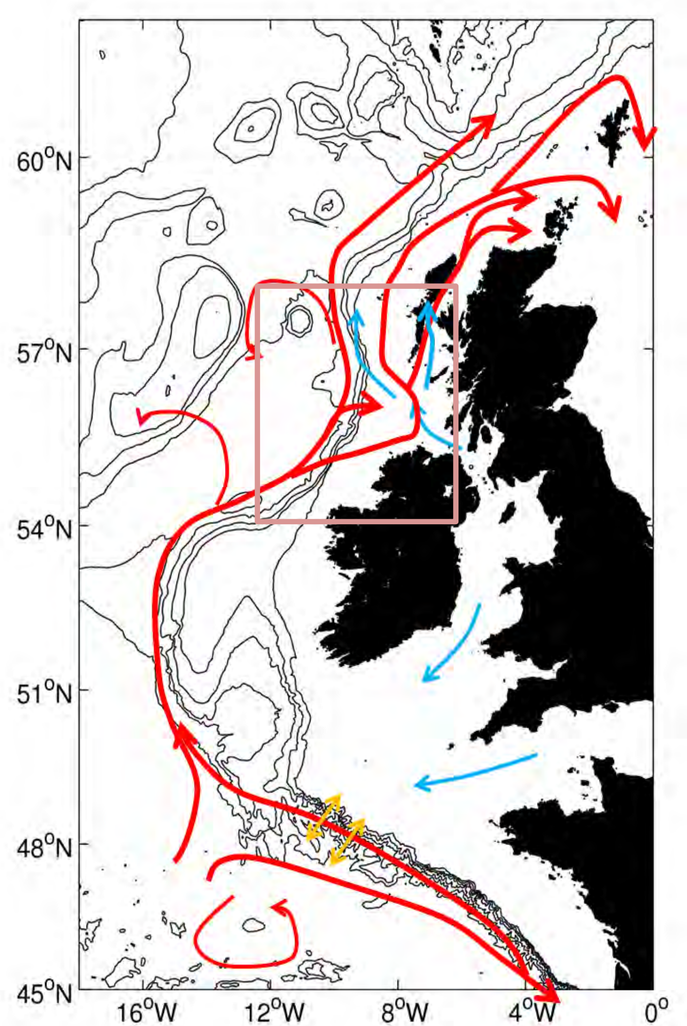
What conditions control the linkage of the S and N slope/shelf current regimes?

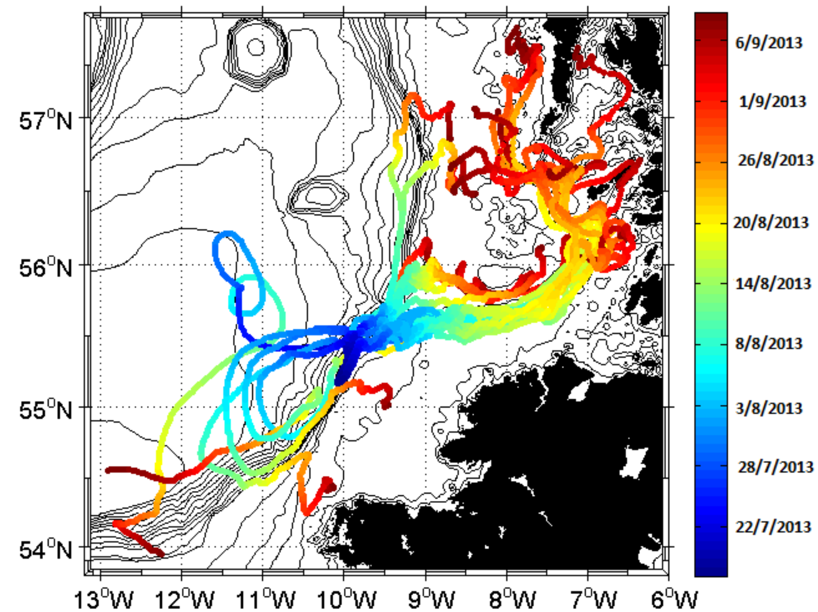
What feedbacks (to both large scale and shelf sea structure, might be related to the meridional density gradient variability

What about deeper boundary flows (e.g. MOW)

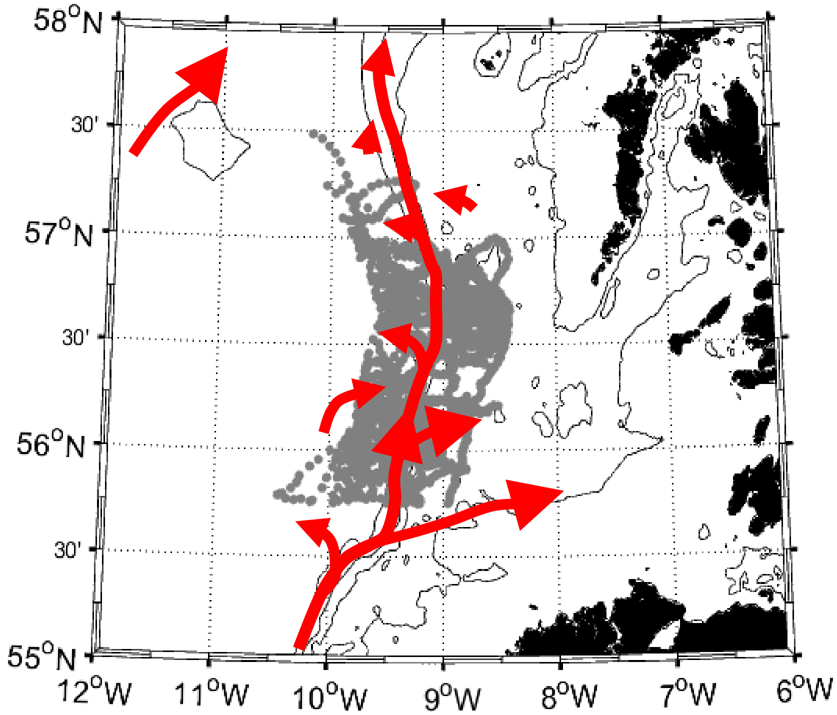
THANKS!

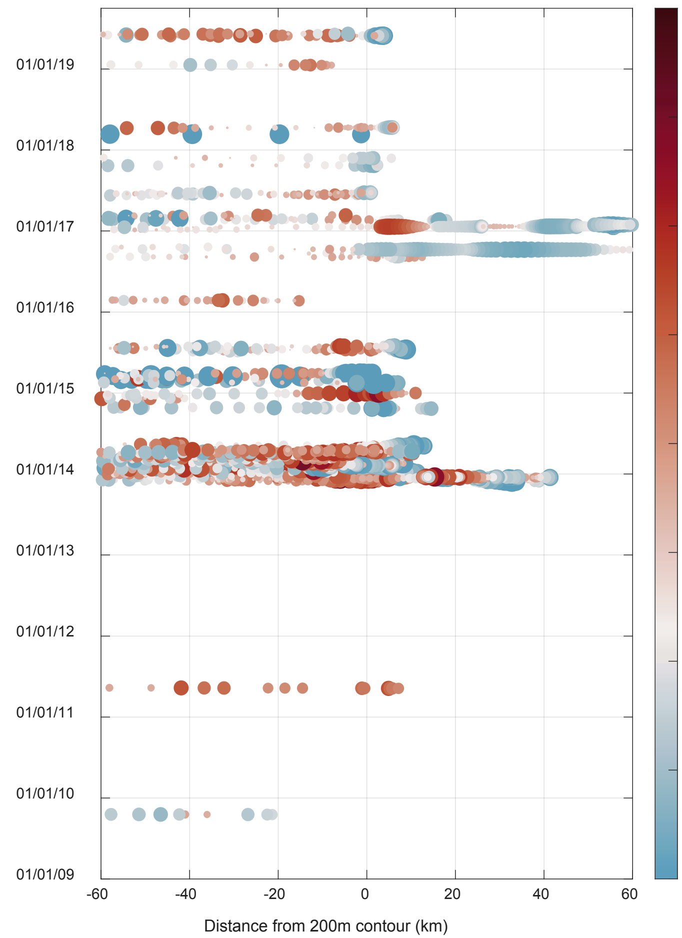
The European slope current (From a Malin Shelf perspective)





The Malin slope current

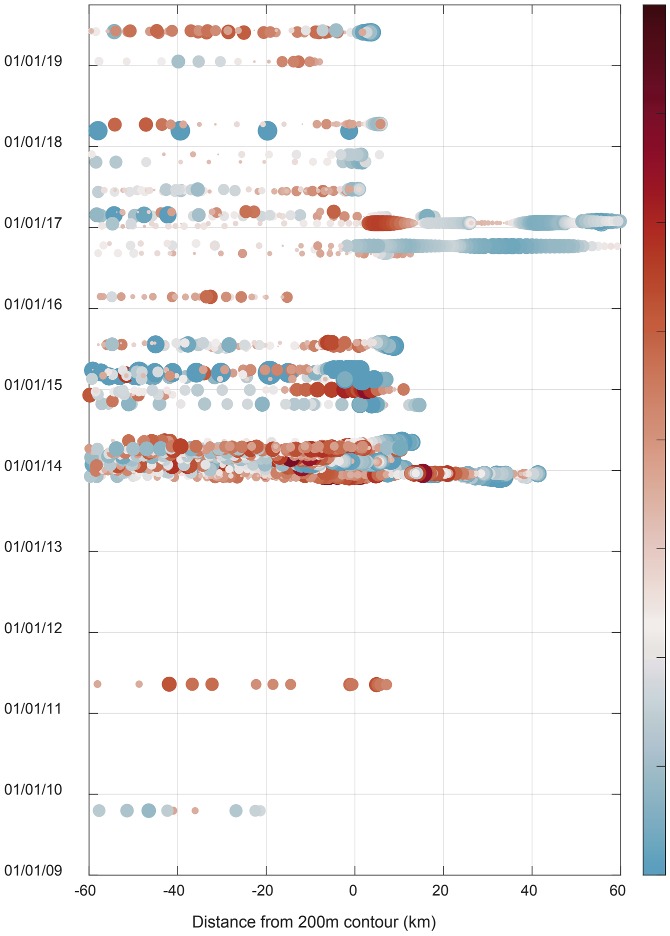




- The data have been cut down to those within 60 km of the 200 m contour, and those north of 55.75°N.
- The data have then been detided using the OSU TPXO model.

The Malin slope current

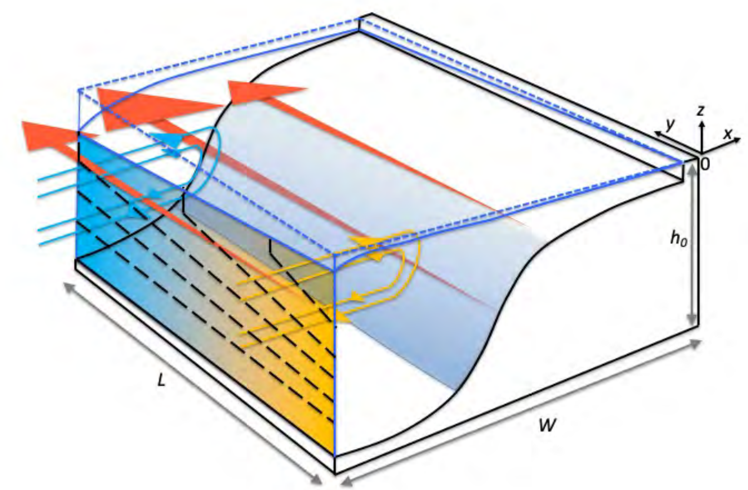
- The detided data have then been collapsed onto a single transect line and gridded into monthly transects.
- The gridding uses an optimal analysis scheme



Slope Current from Density Field

Consider a slope current in equilibrium
i.e. no temporal or along-slope evolution.

We are concerned only with large-scale, steady density/pressure gradients.



Can calculate velocity shear from thermal wind, just need bottom velocity:

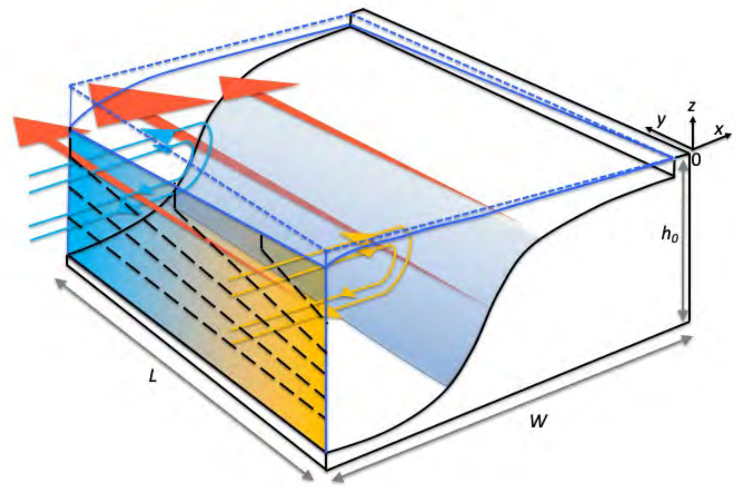
$$v = v_b - \frac{g}{f\rho_s}\int_{-h}^{z}\frac{\partial\rho}{\partial x}dz'$$

Slope Current from Density Field

$$\rho\left(\frac{\partial u}{\partial t} - fv\right) - \frac{\partial \tau^x}{\partial z} = -\frac{\partial p}{\partial x} = -g\rho_s\frac{\partial \eta}{\partial x} - g\int_z^\eta \frac{\partial \rho}{\partial x}dz' + NL_x \quad (1a)$$

$$\rho\left(\frac{\partial v}{\partial t} + fu\right) - \frac{\partial \tau^y}{\partial z} = -\frac{\partial p}{\partial y} = -g\rho_s\frac{\partial \eta}{\partial y} - g\int_z^\eta \frac{\partial \rho}{\partial y}dz' + NL_y \quad (1b)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$



Depth-integrate (2), and impose $\frac{\partial v}{\partial y} = 0$ to find:

$$\int_{-h}^{\eta} u dz = 0$$

Depth-integrate (1b), and impose $\frac{\partial v}{\partial t} = 0$ to find:

$$\frac{\partial \eta}{\partial y} = -\frac{1}{(h_0\rho_s)}\left(\int_{-h_0}^{0}\int_z^0 \frac{\partial \rho}{\partial y}\bigg|_{x=-W} dz'dz + \frac{\tau_{s0}^y}{g}\right)$$

Evaluated at oceanic boundary. Assume $\frac{\partial \eta}{\partial y}$ is constant in *x* and *y*, so this holds everywhere:

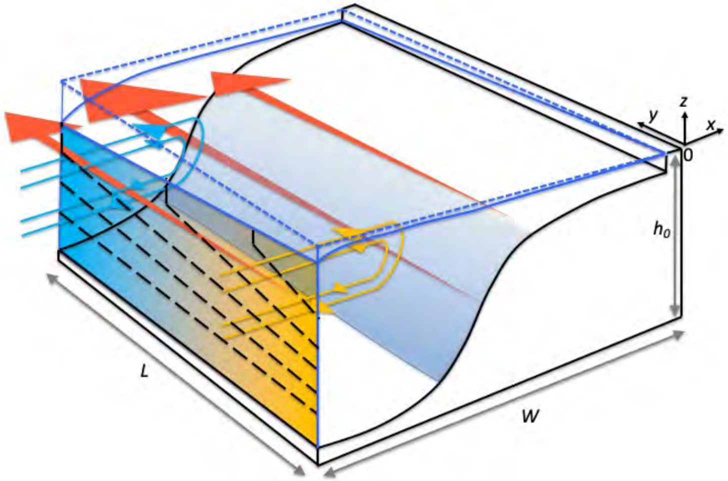
$$r\rho_s v_b = g\frac{h}{h_0}\int_{-h_0}^{0}\int_z^0 \frac{\partial \rho}{\partial y}\bigg|_{x=-W} dz'dz - g\int_{-h}^{0}\int_z^0 \frac{\partial \rho}{\partial y}dz'dz - \frac{h}{h_0}\tau_{s0}^y + \tau_s^y$$

✓

Slope Current from Density Field

Can calculate velocity shear from thermal wind, just need bottom velocity:

$$v = v_b - \frac{g}{f\rho_s}\int_{-h}^{z}\frac{\partial\rho}{\partial x}dz'$$



Linearise density field along-slope:

$$\rho = \rho_y(z)y + \rho_2(x,z)$$

Giving:

$$v = \frac{1}{\rho_s r}\left(g\frac{h}{h_0}\int_{-h_0}^{0}\int_{z}^{0}\rho_y(z')dz'dz - g\int_{-h}^{0}\int_{z}^{0}\rho_y(z')dz'dz - \frac{h}{h_0}\tau_{s0}^{y} + \tau_s^{y}\right)$$

$$-\frac{g}{f\rho_s}\int_{-h}^{z}\frac{\partial\rho_2}{\partial x}dz'$$

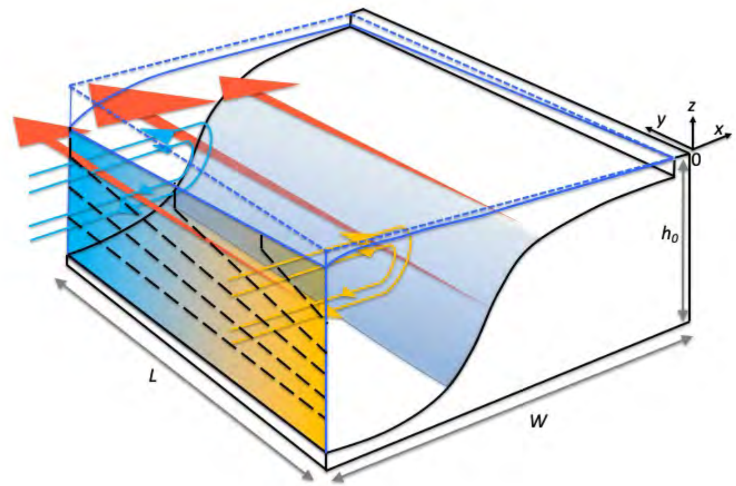
Slope Current from Density Field

Can calculate velocity shear from thermal wind, just need bottom velocity:

$$v = v_b - \frac{g}{f\rho_s}\int_{-h}^{z}\frac{\partial\rho}{\partial x}dz'$$

Linearise density field along-slope:

$$\rho = \rho_y(z)y + \rho_2(x,z)$$



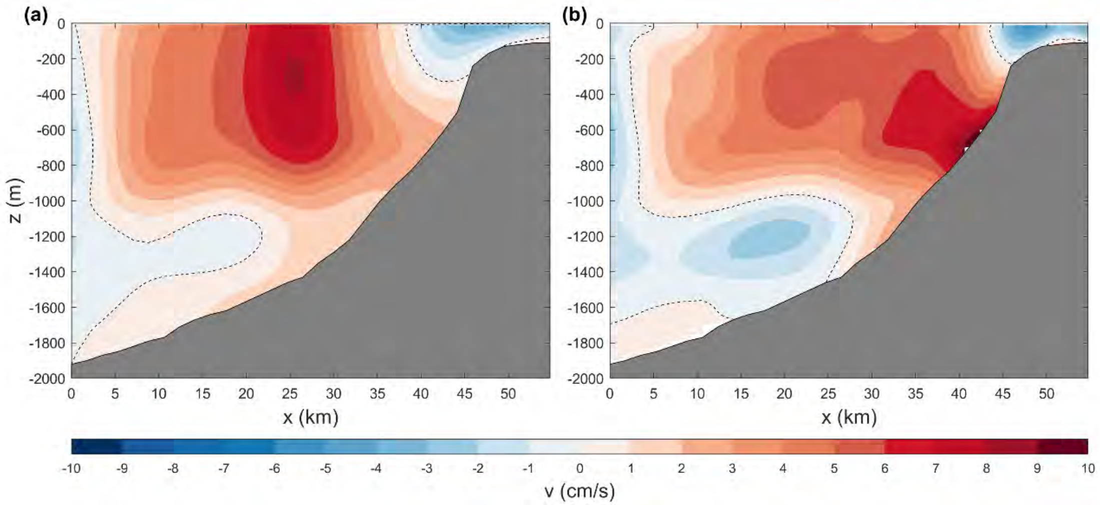
Giving:

$$v = \frac{1}{\rho_s r}\left(g\frac{h}{h_0}\int_{-h_0}^{0}\int_{z}^{0}\rho_y(z')dz'dz - g\int_{-h}^{0}\int_{z}^{0}\rho_y(z')dz'dz - \frac{h}{h_0}\tau_{s0}^{y} + \tau_s^{y}\right)$$

$$-\frac{g}{f\rho_s}\int_{-h}^{z}\frac{\partial\rho_2}{\partial x}dz'$$

Slope Current from Density Field

Initial comparison with AMM15 model:



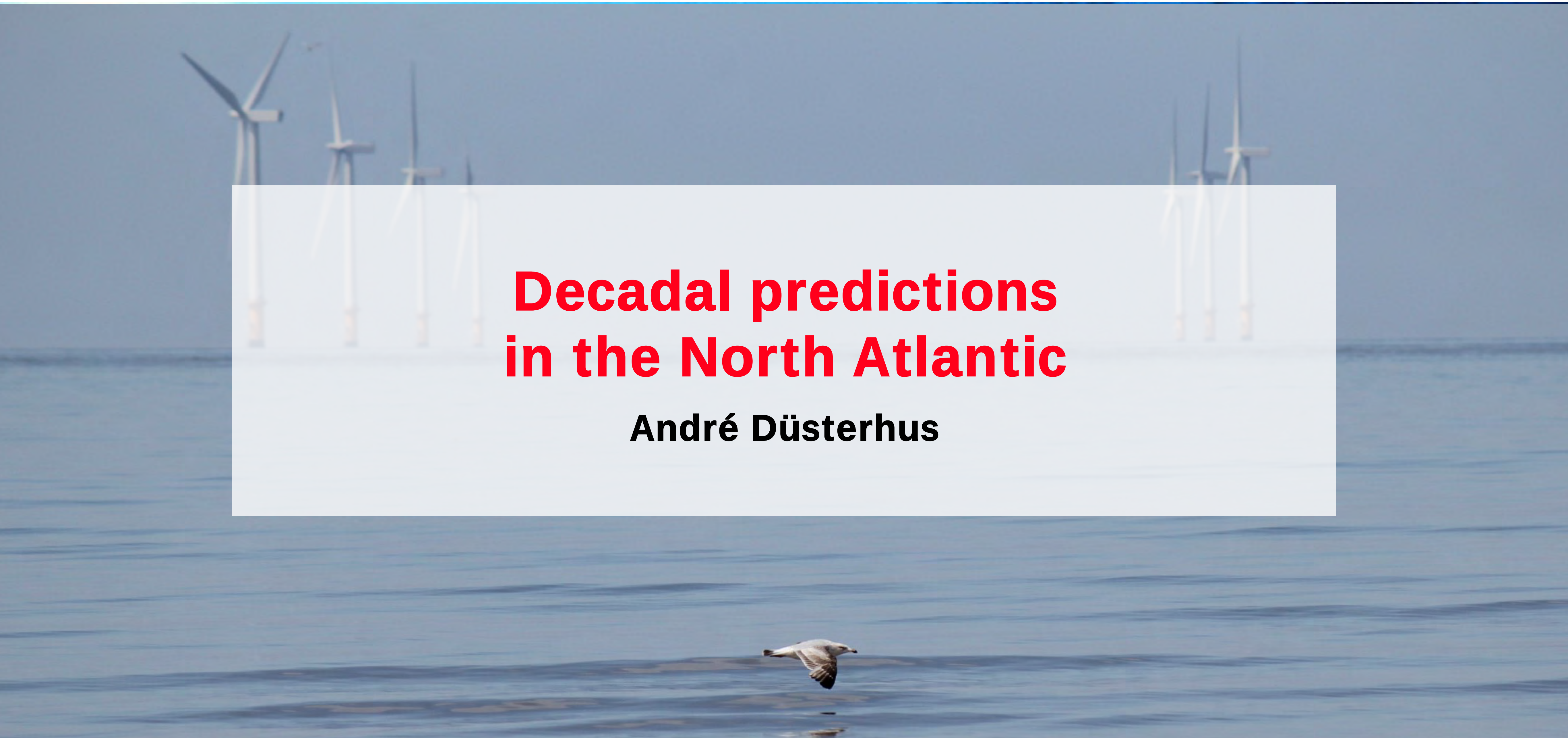
Still a work in progress! Looking at lateral smoothing to simulate viscosity.

Glider work can help calibrate formulation (e.g. tune *r*).

We hope to use this to understand the dynamics of the observed seasonality.

Maynooth University
National University of Ireland Maynooth

cen



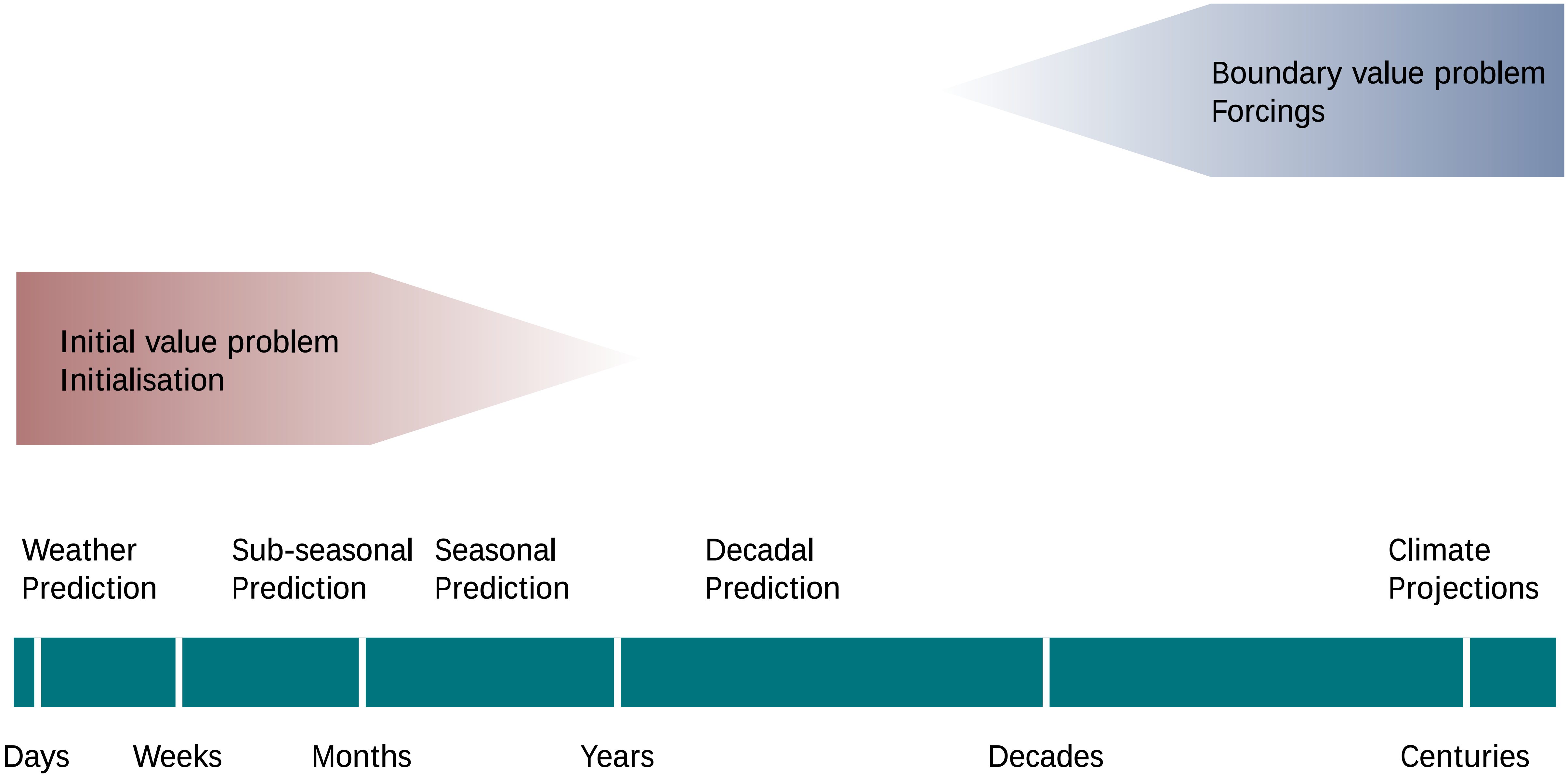
Decadal predictions in the North Atlantic

André Düsterhus

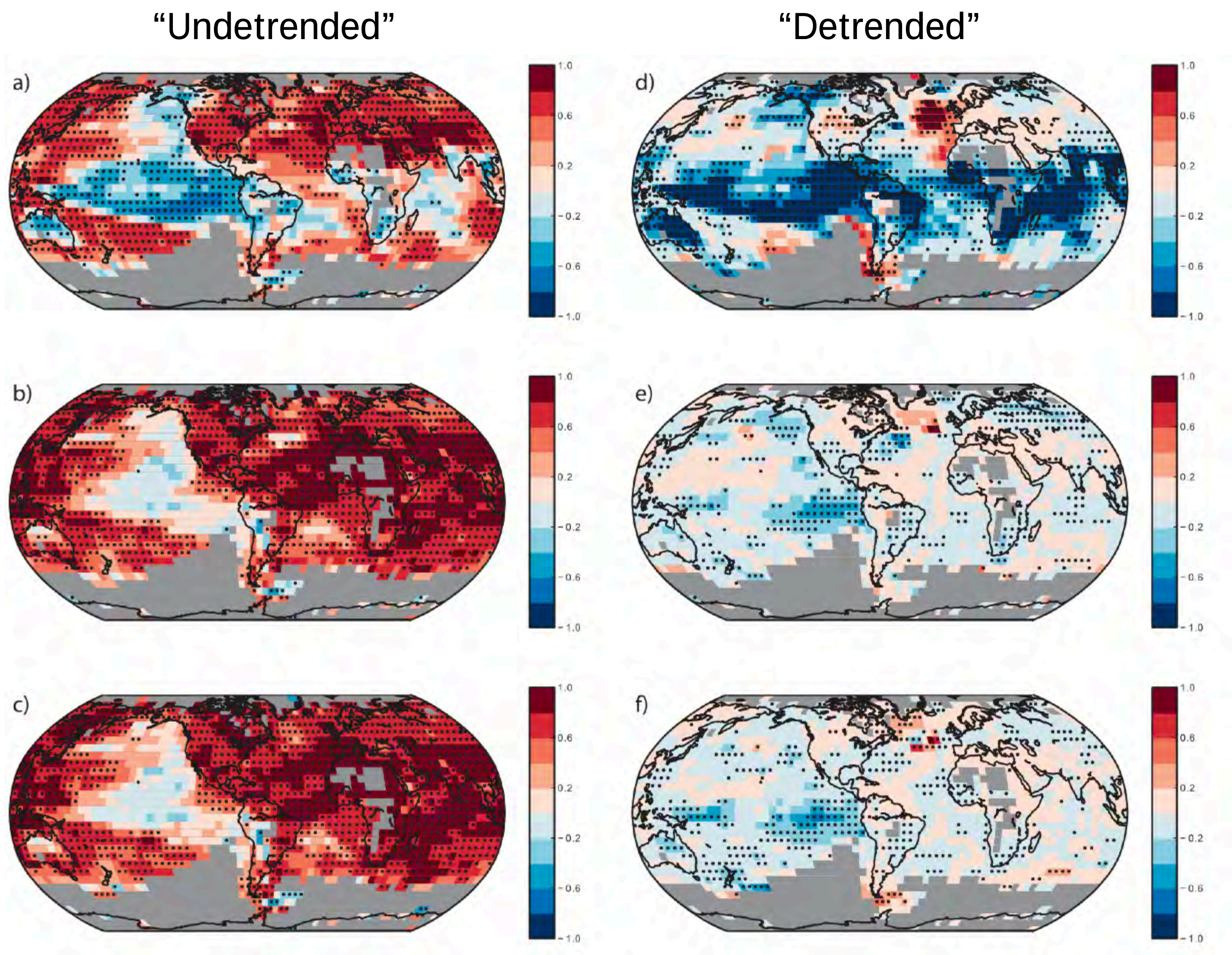
andre.duesterhus@mu.ie

Workshop on Eastern North Atlantic 2019
Edinburgh, 14th October 2019

Predictions



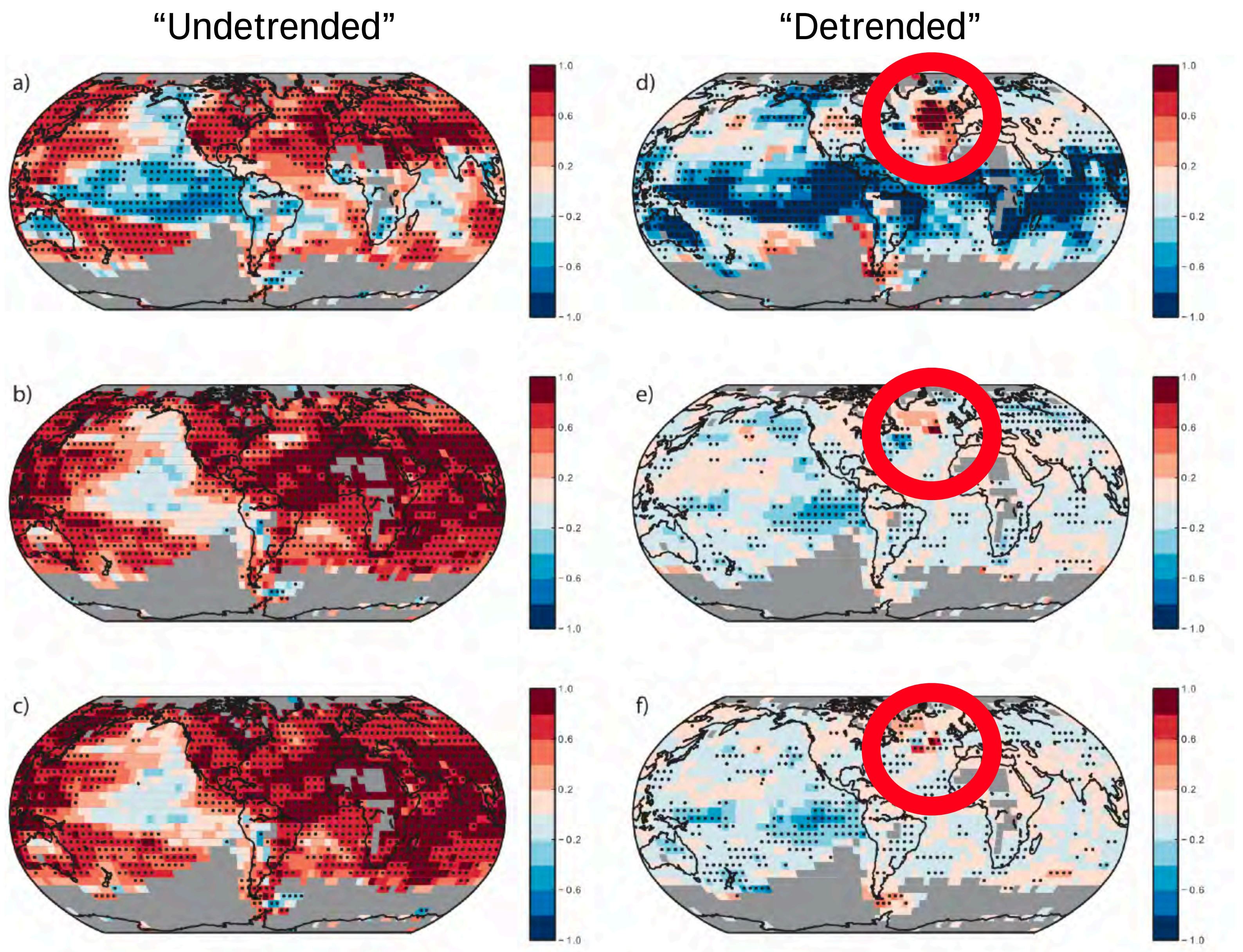
Decadal Prediction



MPI-ESM-LR; 1961-2012; initialisation each January; 2 to 5 years; 3, 10, 15 members

Marotzke et al. (2016)

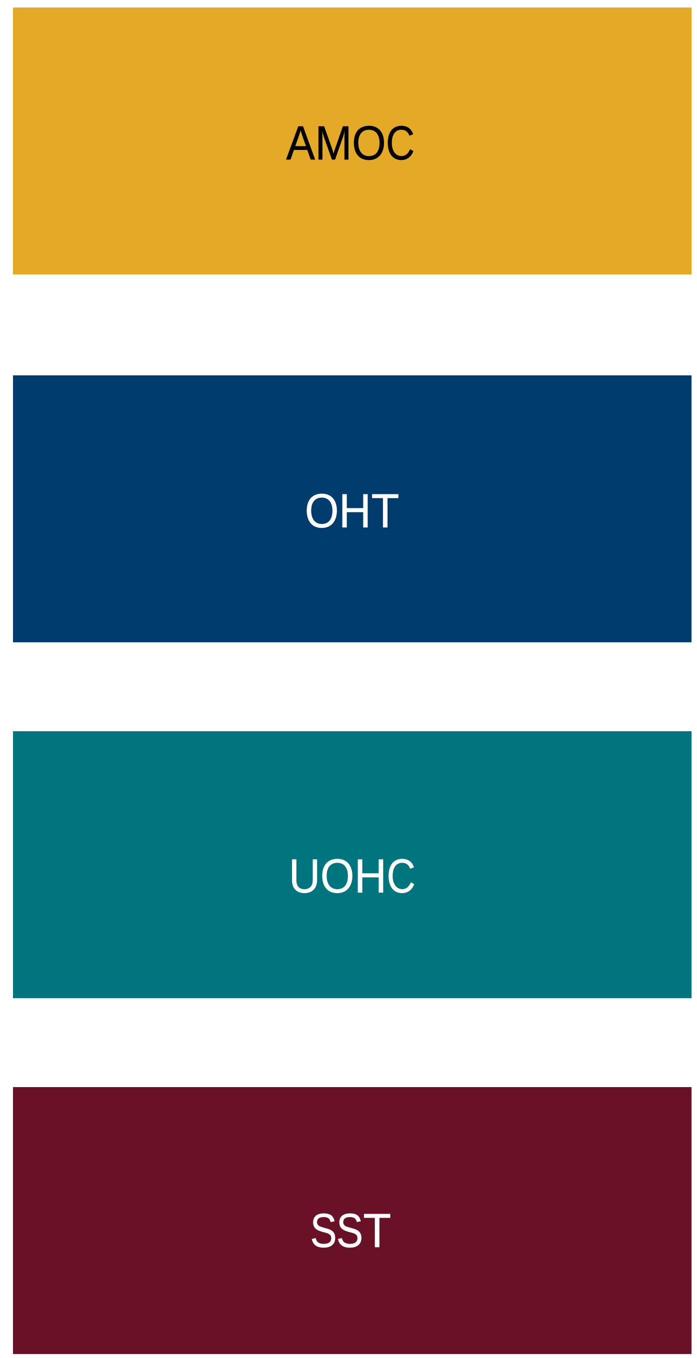
Decadal Prediction



MPI-ESM-LR; 1961-2012; initialisation each January; 2 to 5 years; 3, 10, 15 members

Marotzke et al. (2016)

Simplified mechanism

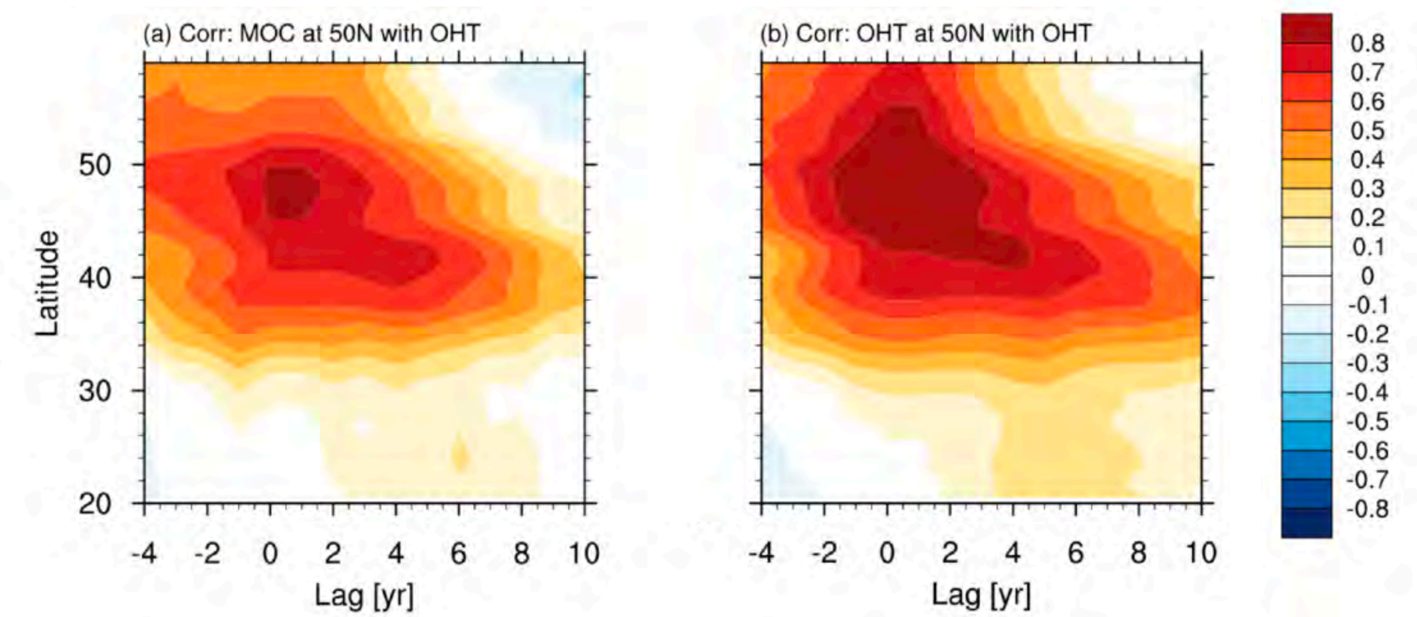


What links do we “observe” in models

AMOC to OHT

AMOC

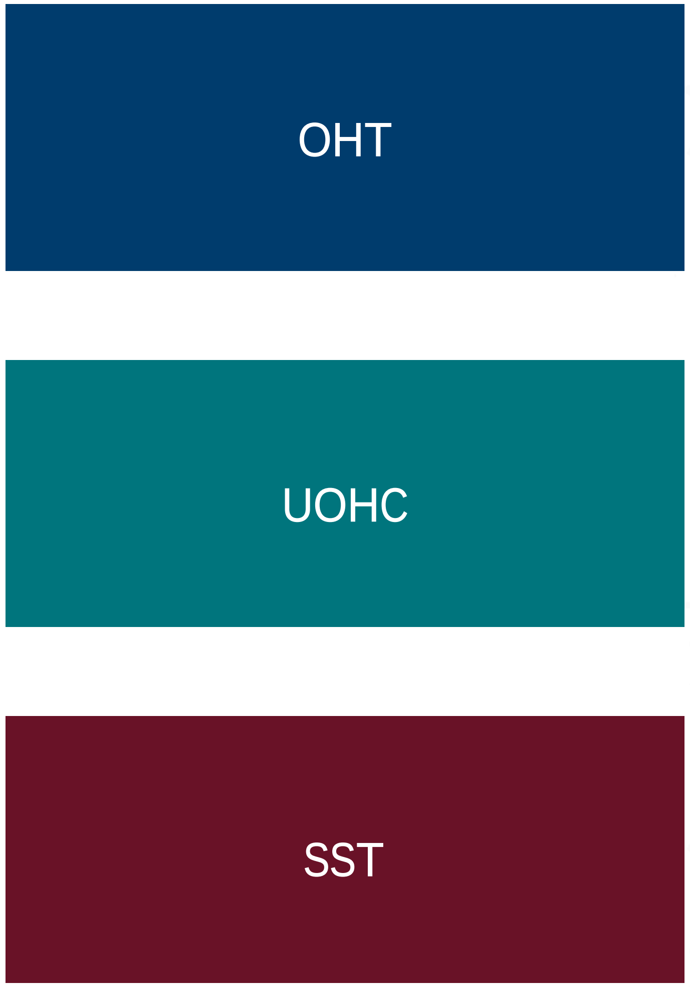
OHT

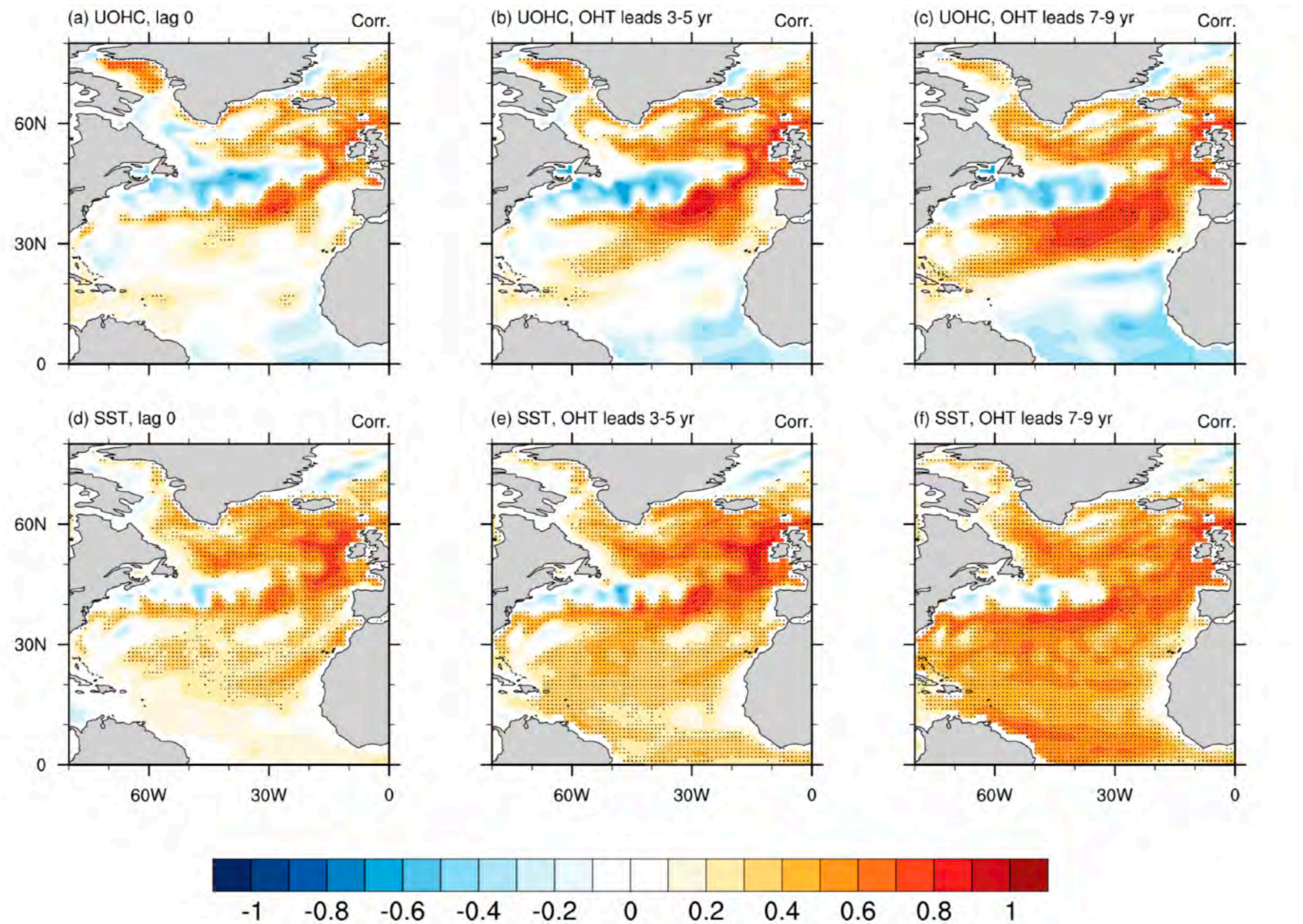


MOC at 50°N allows understanding of OHT over many years

Borchert et al. (2018)

OHT to UOHC / SST





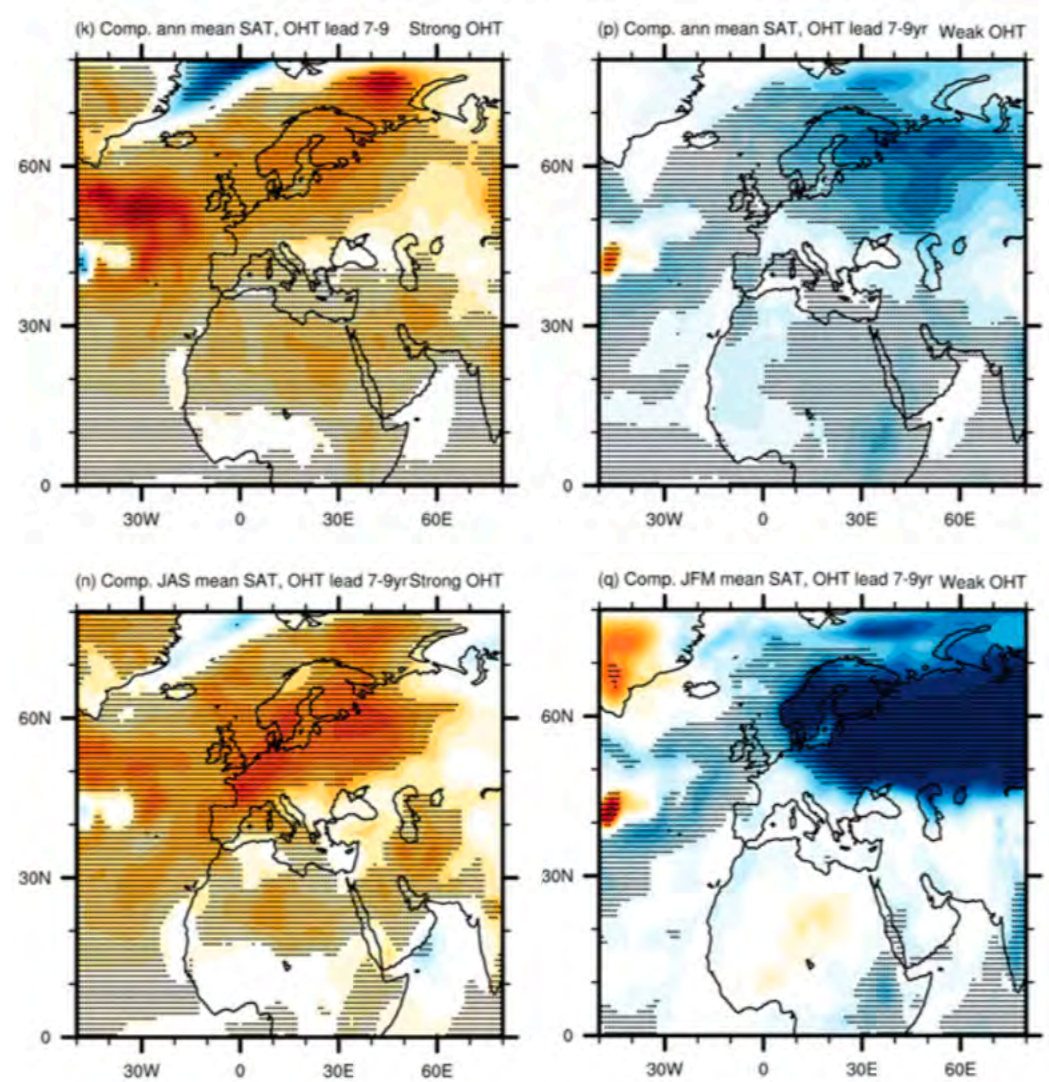
OHT understanding at 50°N allows UOHC/SST understanding in the North Atlantic

Borchert et al. (2018)

Consequence for European Temperatures

Strong OHT all year

Weak OHT all year



Strong OHT Summer (JAS)

Weak OHT Winter (JFM)

OHT understanding at 50°N allows Temperature understanding over Europe 7-9 years ahead

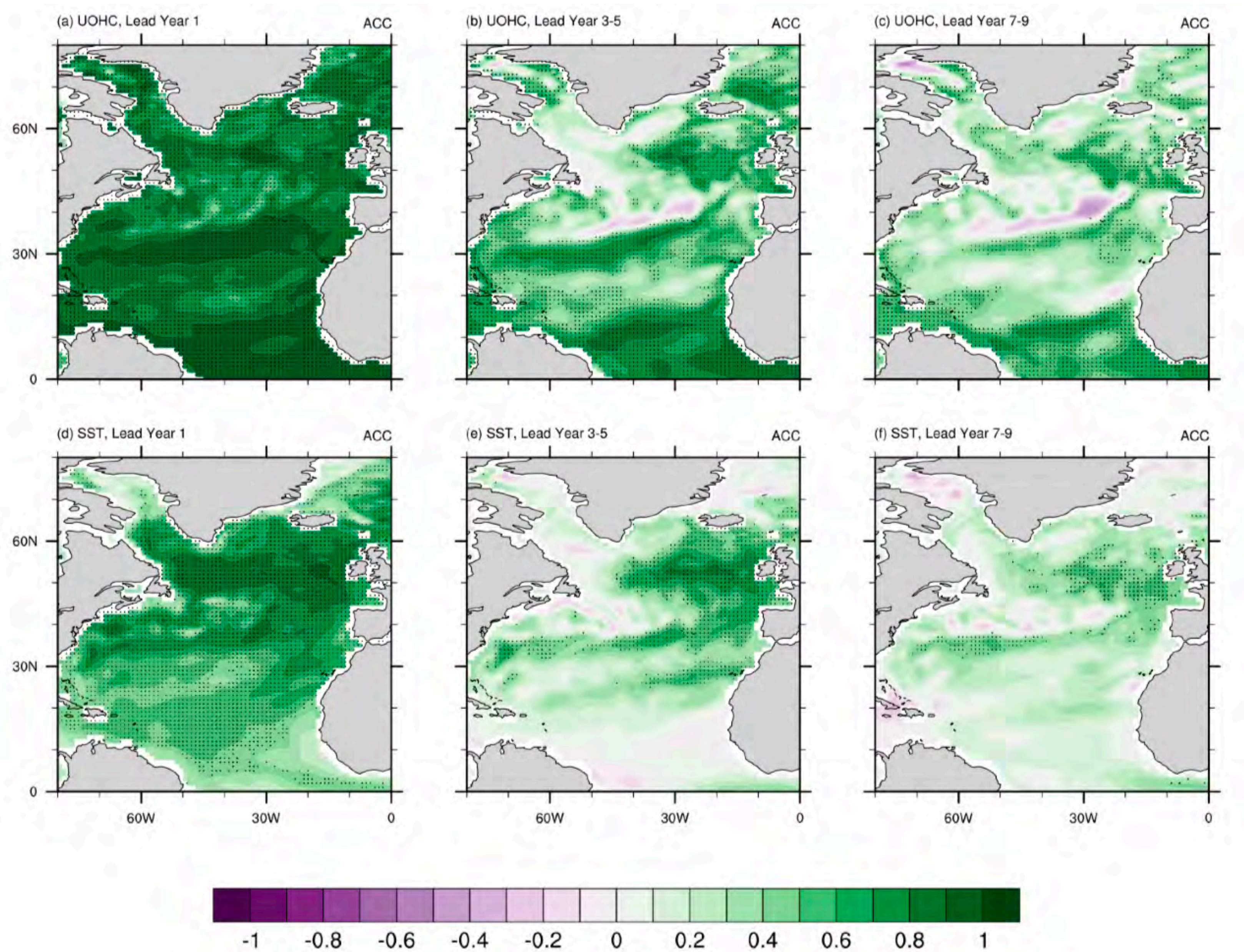
Borchert et al. (2018)

What predictability do we have in models

UOHC/SST predictability

UOHC

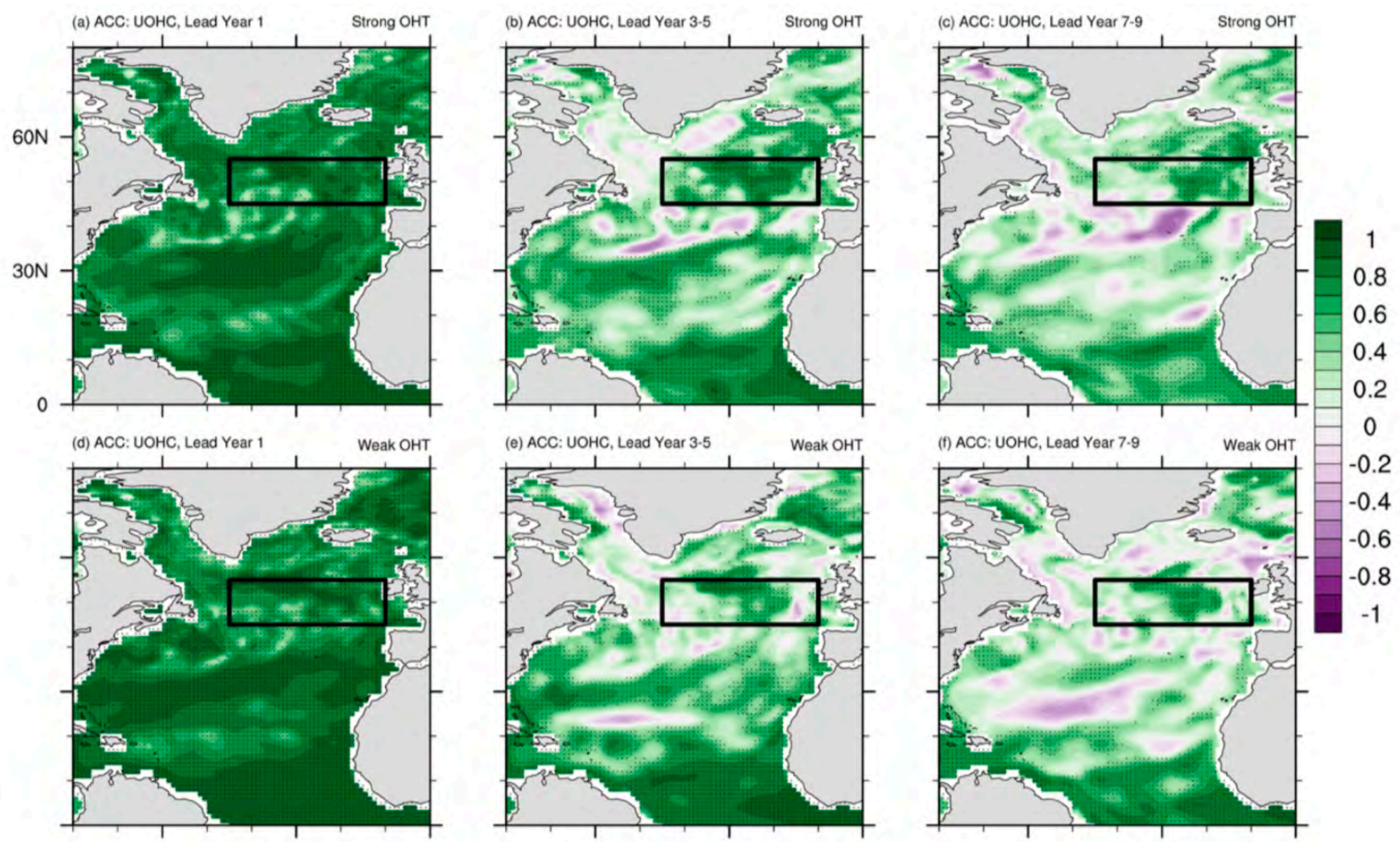
SST



Predictability exists, but only in North Eastern Atlantic

Borchert et al. (2018)

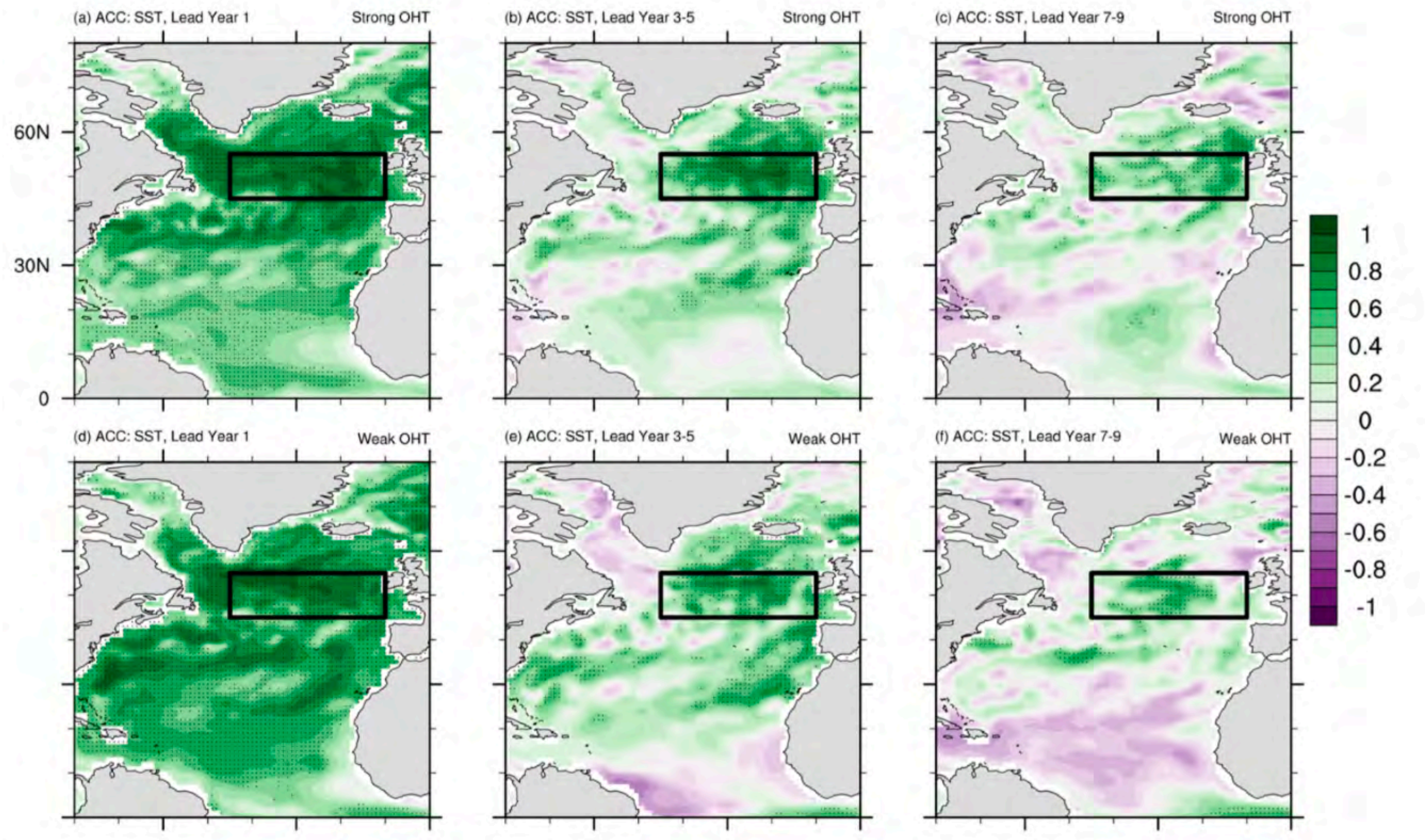
UOHC in strong/weak OHT years



Starting conditions determine prediction success

Borchert et al. (2018)

SST in strong/weak OHT years



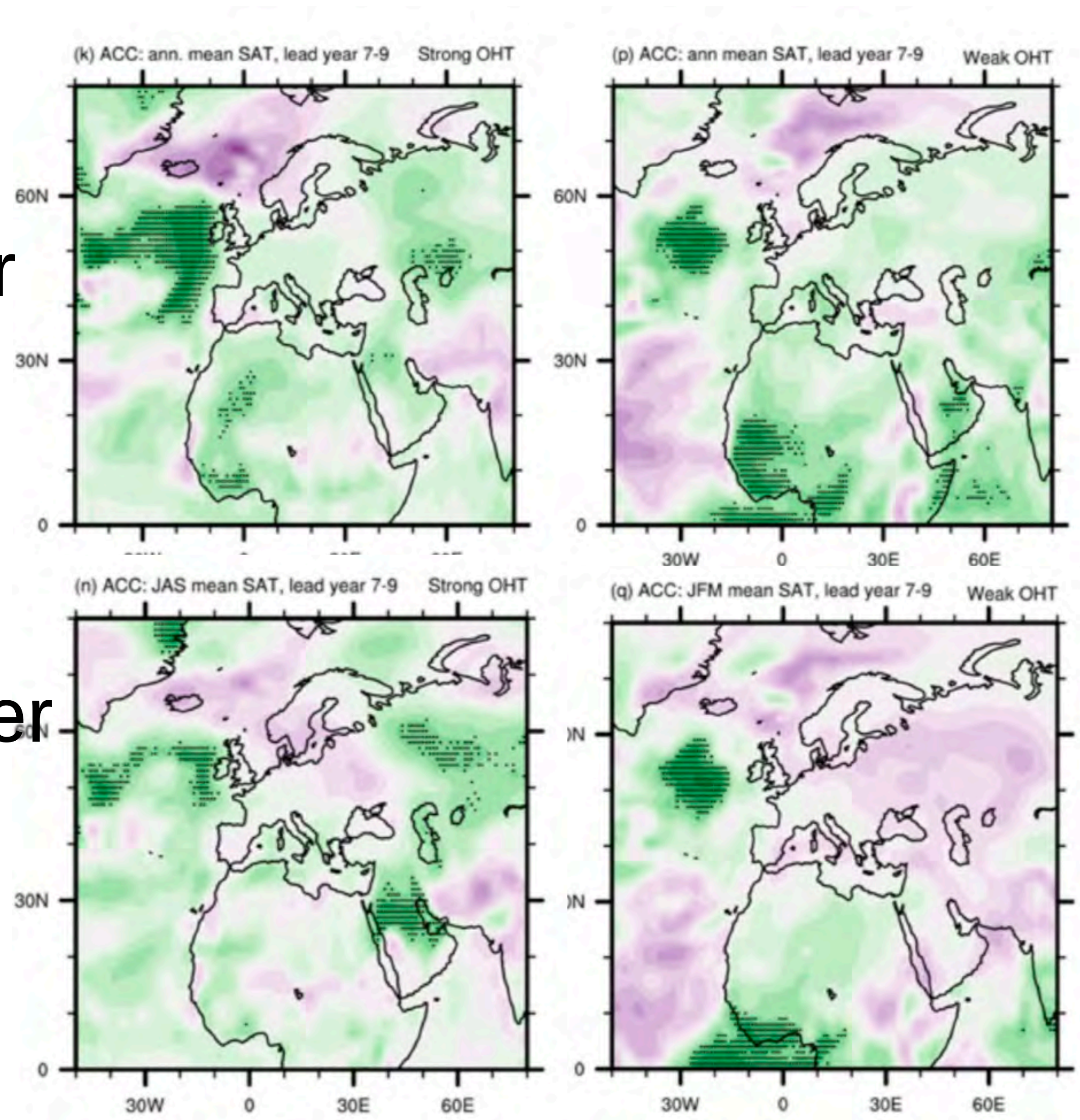
Link UOHC/SST still given

Borchert et al. (2018)

Predictability over Europe

Strong OHT all year

Weak OHT all year



Strong OHT Summer (JAS)

Weak OHT Winter (JFM)

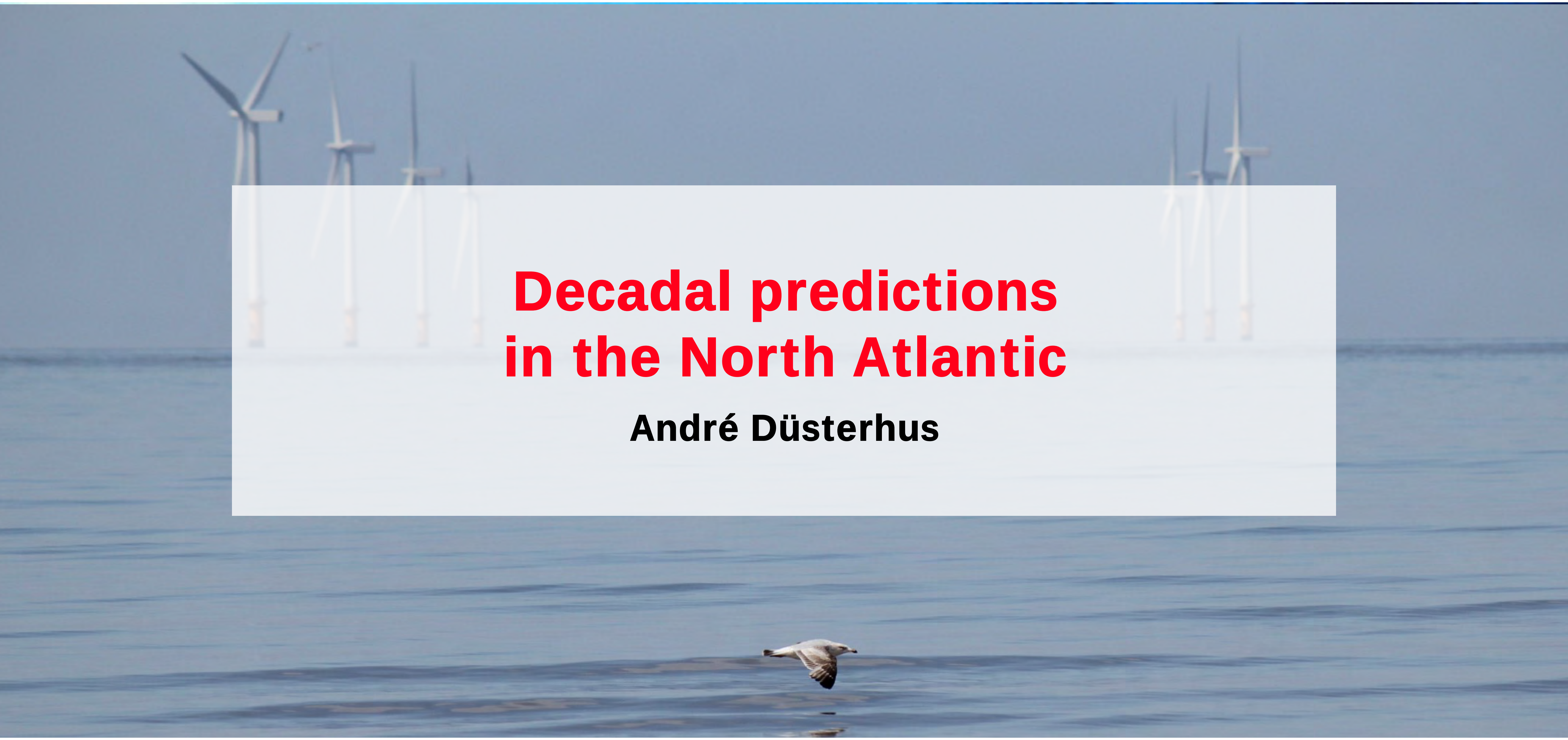
No predictability over Europe

Borchert et al. (2018)

Summary

- Understanding of AMOC at ~50°N helps us to understand SST and T2m variability of NA and Europe
- Caveat: Small number of runs
- Further story: Knowledge of the OHT-Phase at 50°N helps understanding the skill of individual predictions of AMV

-> L. Borchert, Thu, 10.20h & Borchert et al. (accepted)



Decadal predictions in the North Atlantic

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Workshop on Eastern North Atlantic 2019
Edinburgh, 14th October 2019

Large-scale forcing of the European Slope Current and associated inflows to the North Sea

Bob Marsh, University of Southampton

Workshop on Subpolar North Atlantic Eastern Boundary

University of Edinburgh,

14 October 2019

Themes

- Some Slope Current theory
- Variable Slope Current transport and density forcing in a global ORCA12 (1/12 deg) hindcast, 1988-2007
- ARIANE trajectory software used to trace provenance and fate of Slope Current water
- Distinguishing cold and warm provenance of the Slope Current, and changes over time
- Changing provenance of Slope Current related to larger scale changes in ocean re-analysis (GODAS)
- Additional analysis of tide gauge data north of Scotland
- Links to biology – some ongoing work

Slope Current dynamics

Modelled (left) and followed by drogued drifters (right):

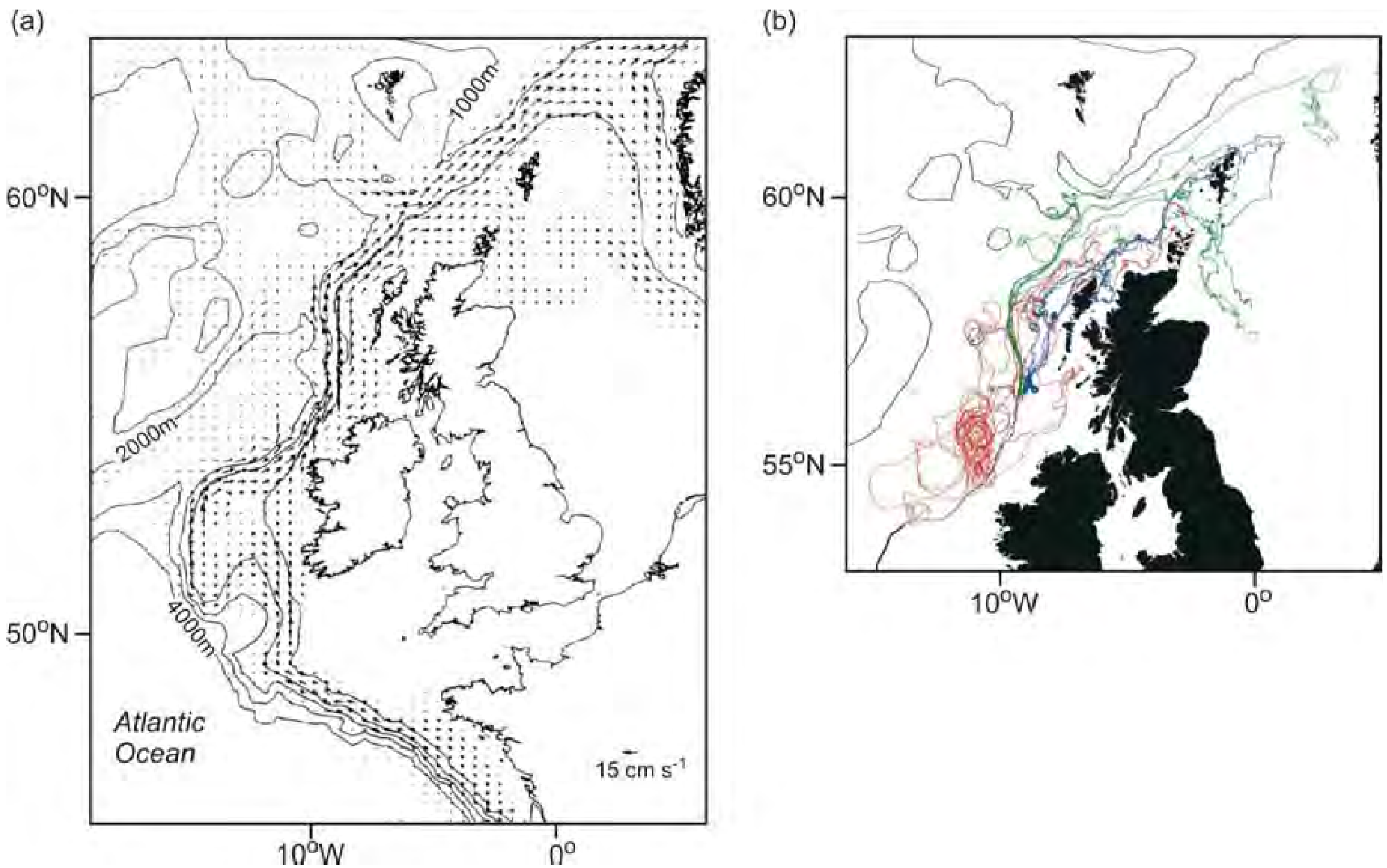


Figure 10.4 in Simpson & Sharples (2012)

Forcing of Slope Currents (1)

Key driver of the Slope Current is the meridional density gradient, common to both hemispheres as water gets denser moving polewards (primarily due to falling temperature).

Accommodate this in the geostrophic momentum balance.

First consider the x-momentum equation, using the hydrostatic balance, P = $\rho g(h+\eta)$, and noting that the zonal density gradient is zero, so the RHS simplifies to a zonal gradient in sea surface height (η), or the surface slope:

$$-fv = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} = -\frac{1}{\rho_o}\frac{\partial(\rho g(h+\eta))}{\partial x} = -\frac{g}{\rho_o}\frac{\partial(\rho h)}{\partial x} - \frac{g}{\rho_o}\rho\frac{\partial \eta}{\partial x}$$

(allow meridional density gradients only)

$$\Rightarrow -fv = -g\frac{\partial \eta}{\partial x} \qquad [\rho = \rho_o]$$

Now vertically integrate …

Forcing of Slope Currents (2)

$$\int_{-h}^{\eta}(-fv)\,dz = \int_{-h}^{\eta}\left(-g\frac{\partial\eta}{\partial x}\right)dz$$

$$\Rightarrow \boxed{-fV = -g\frac{\partial\eta}{\partial x}h}$$

where $$V = \int_{-h}^{\eta} v\,dz$$

[and assuming $h >> \eta$ for RHS integral]

Forcing of Slope Currents (3)

Now consider the y-momentum equation, following the same approach, but noting that the meridional density gradient is non-zero, so the RHS now includes an extra term:

$$fu = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} = -\frac{1}{\rho_o}\frac{\partial(\rho g(h+\eta))}{\partial y} = -\frac{g}{\rho_o}\frac{\partial(\rho h)}{\partial y} - g\frac{\partial \eta}{\partial y}$$

Vertically integrate again …

$$\int_{-h}^{\eta}(fu)dz = \int_{-h}^{\eta}\left(-\frac{g}{\rho_o}\frac{\partial \rho}{\partial y}h\right)dz + \int_{-h}^{\eta}\left(-g\frac{\partial \eta}{\partial y}\right)dz$$

$$\Rightarrow \boxed{fU = -\frac{g}{2\rho_o}\frac{\partial \rho}{\partial y}h^2 - g\frac{\partial \eta}{\partial y}h}$$

where $U = \int_{-h}^{\eta} u\,dz$

Forcing of Slope Currents (4)

So the governing momentum balance is an equation pair:

$$-fV = -g\frac{\partial \eta}{\partial x}h \qquad (1)$$

$$fU = -\frac{g}{2\rho_o}\frac{\partial \rho}{\partial y}h^2 - g\frac{\partial \eta}{\partial y}h \qquad (2)$$

Need one further equation to progress – vertically-integrated continuity of volume:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad (3)$$

Forcing of Slope Currents (5)

Now take ∂/∂y (1), ∂/∂x (2), and substitute into (3) ….

$$-f\frac{\partial V}{\partial y} = -gh\frac{\partial}{\partial y}\left(\frac{\partial \eta}{\partial x}\right) - g\frac{\partial \eta}{\partial x}\frac{\partial h}{\partial y}$$

$$f\frac{\partial U}{\partial x} = -\frac{g}{2\rho_o}\frac{\partial}{\partial x}\left(\frac{\partial \rho}{\partial y}\right)h^2 - \frac{g}{2\rho_o}\left(\frac{\partial \rho}{\partial y}\right)\frac{\partial (h^2)}{\partial x} - gh\frac{\partial}{\partial x}\left(\frac{\partial \eta}{\partial y}\right) - g\frac{\partial \eta}{\partial y}\frac{\partial h}{\partial x}$$

(no x-variation of density y-gradient)

(term cancels)

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \Rightarrow -\frac{g}{2\rho_o}\frac{\partial}{\partial x}\left(\frac{\partial \rho}{\partial y}\right)h^2 - \frac{g}{2\rho_o}\frac{\partial \rho}{\partial y}2h\frac{\partial h}{\partial x} - gh\frac{\partial}{\partial x}\left(\frac{\partial \eta}{\partial y}\right) - g\frac{\partial \eta}{\partial y}\frac{\partial h}{\partial x}$$

$$+gh\frac{\partial}{\partial y}\left(\frac{\partial \eta}{\partial x}\right) + g\frac{\partial \eta}{\partial x}\frac{\partial h}{\partial y} = 0 \Rightarrow \boxed{\frac{\partial \eta}{\partial y} = -\frac{h}{\rho}\frac{\partial \rho}{\partial y}}$$

(term cancels) (no y-variation of h)

Forcing of Slope Currents (6)

Taking this key relation, we distinguish between the shelf (depth h = h_s) and the deep ocean (h = H)

Shelf: $$\left(\frac{\partial \eta}{\partial y}\right)_{h_s} = -\frac{h_s}{\rho}\frac{\partial \rho}{\partial y} \qquad (4)$$

Deep ocean: $$\left(\frac{\partial \eta}{\partial y}\right)_{H} = -\frac{H}{\rho}\frac{\partial \rho}{\partial y} \qquad (5)$$

Since $H \gg h_s$, the downward slope with latitude will be greater over the deep ocean, so ***the difference between sea surface height over the shelf and that over the ocean increases with latitude*** …

Schematic of Slope Current forcing and structure

- Cross-shelf (zonal) density gradients set up, increasing towards the pole
- Along-slope meridional flow, $V(x,y)$, therefore increases towards the pole
- Meridional density gradients support zonal geostrophic currents, U, in deep ocean
- SC is thus “fed from the west”

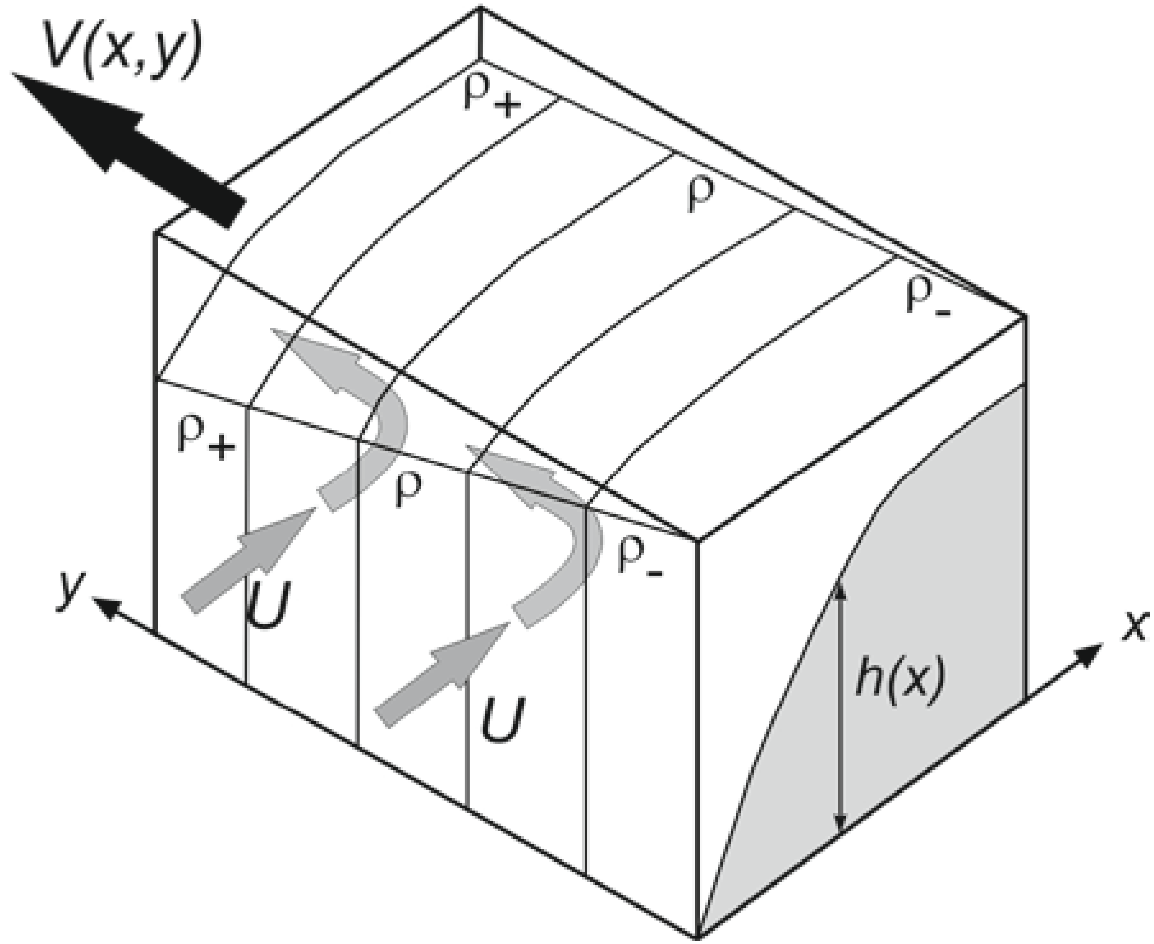


Figure 10.5 in Simpson & Sharples

Estimating inflow that sustains the Slope Current

This cross-slope height difference will result in a geostrophic current parallel to the isobaths.

At the same time, the momentum balance in the meridional direction implies a geostrophic transport in deep water towards the slope, predicted by (5) substituted in (2):

$$U = \frac{gH^2}{2\rho_o f}\frac{\partial\rho}{\partial y}$$

As the flow reaches the slope, it turns to the north and joins the meridional current which is increasing with latitude as the zonal difference in height increases (see previous schematic)

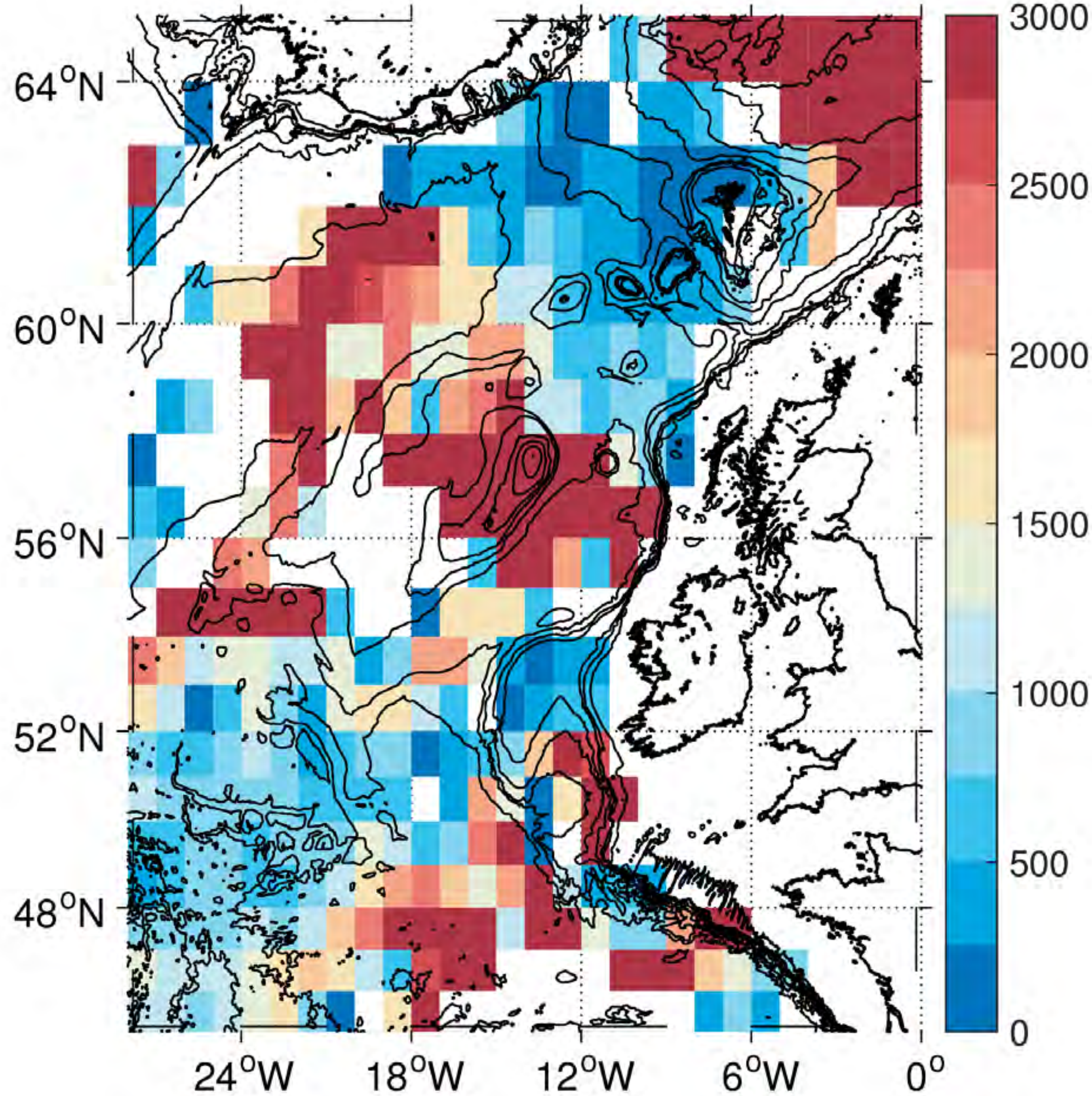
Testing the theory with altimetry and hydrography

From (5):

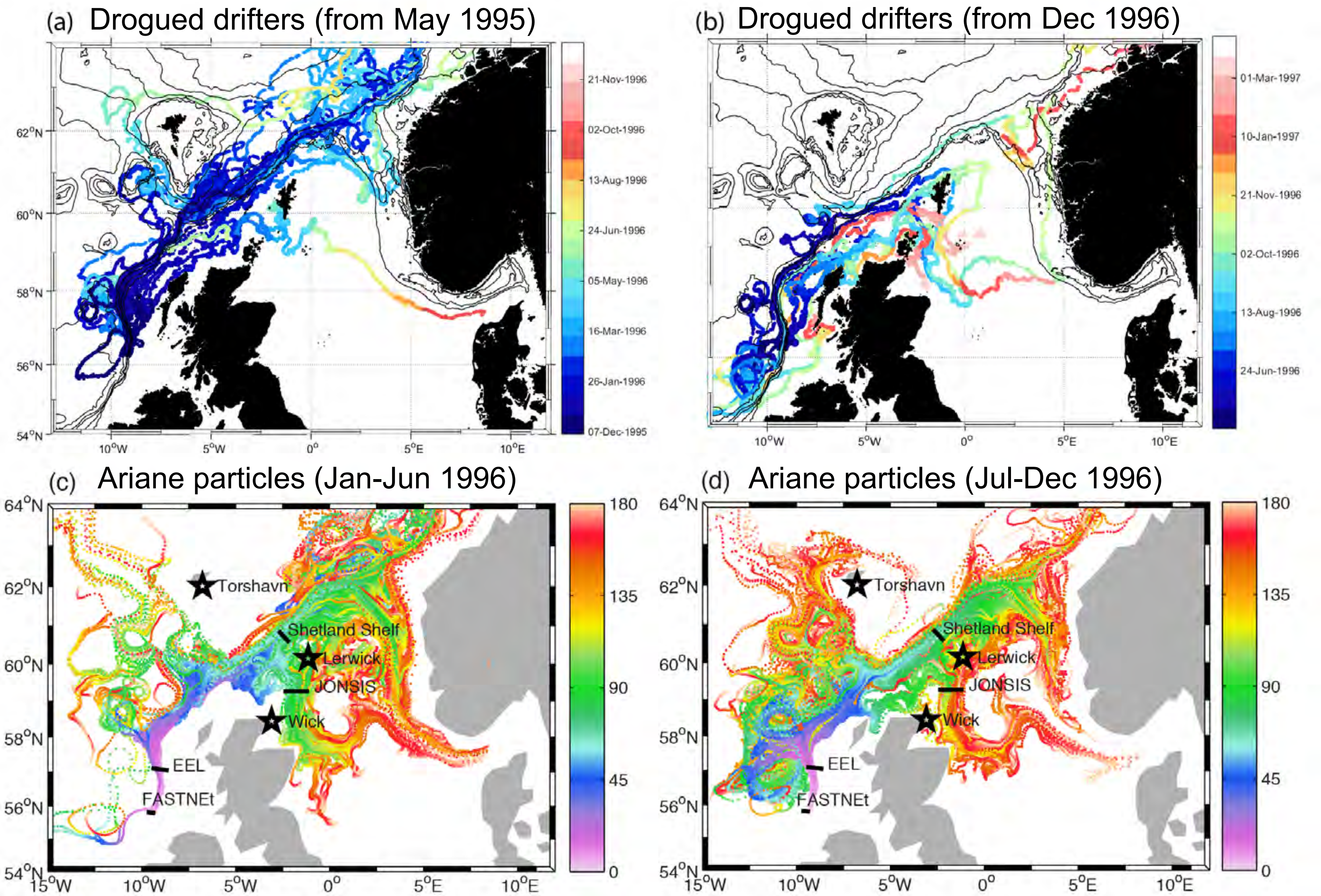
$$\left(\frac{\partial \eta}{\partial y}\right)_H = -\frac{H}{\rho}\frac{\partial \rho}{\partial y}$$

$$\Rightarrow H = \frac{1}{\rho_0}\frac{(\partial \eta / \partial y)}{(\partial \rho / \partial y)}$$

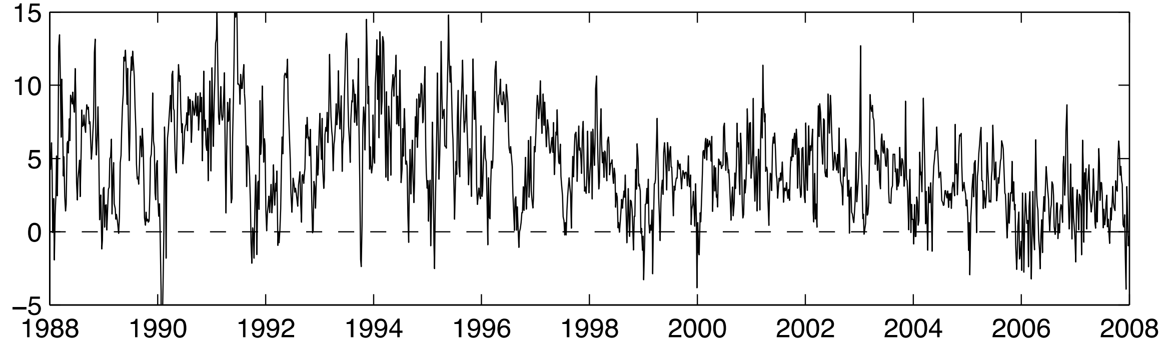
Given climatological surface height and density gradients, we calculate H in the range 500-3000 m across much of the SC inflow region



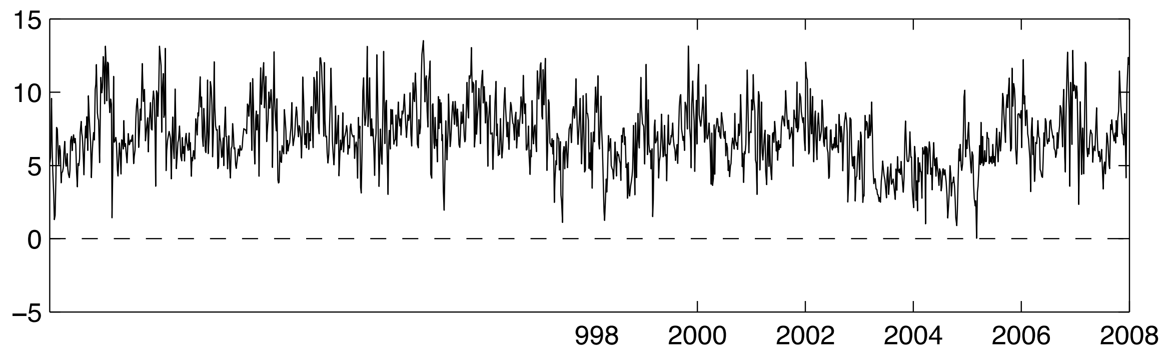
Observed and simulated Slope Current trajectories



Slope Current transport across three sections in ORCA12

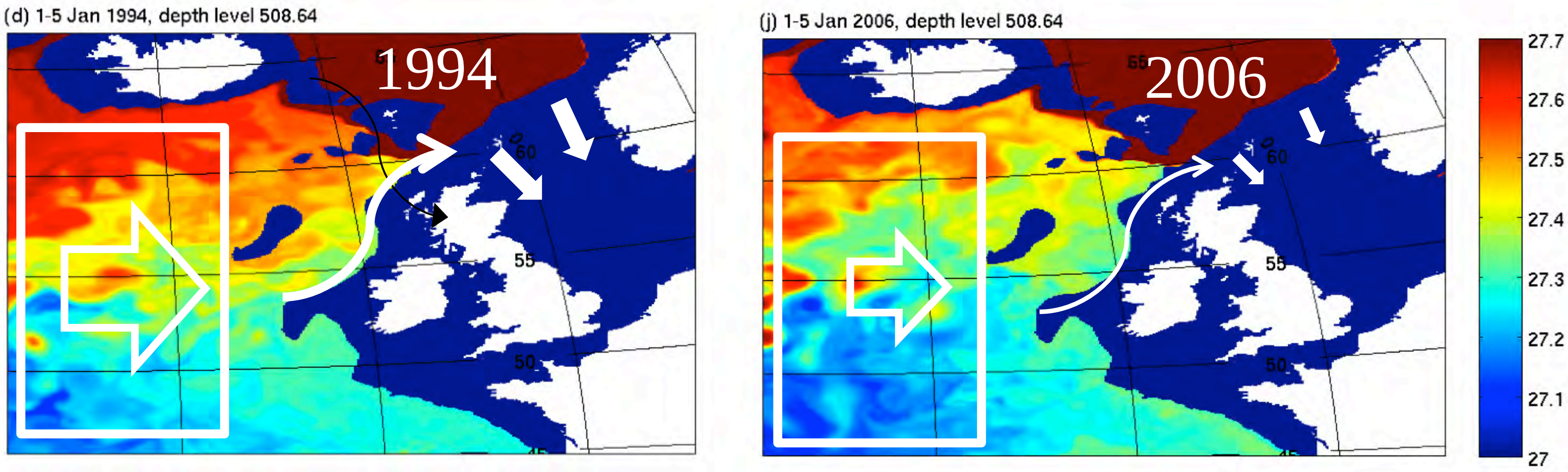


- Stronger transports during the first half of the records
- Switch to weaker transports around 1996-98
- Some seasonal cycles (stronger transports in winter)



Meridional density gradients underwent major decline around 1996-98, linked to extensive SPG warming at that time ...

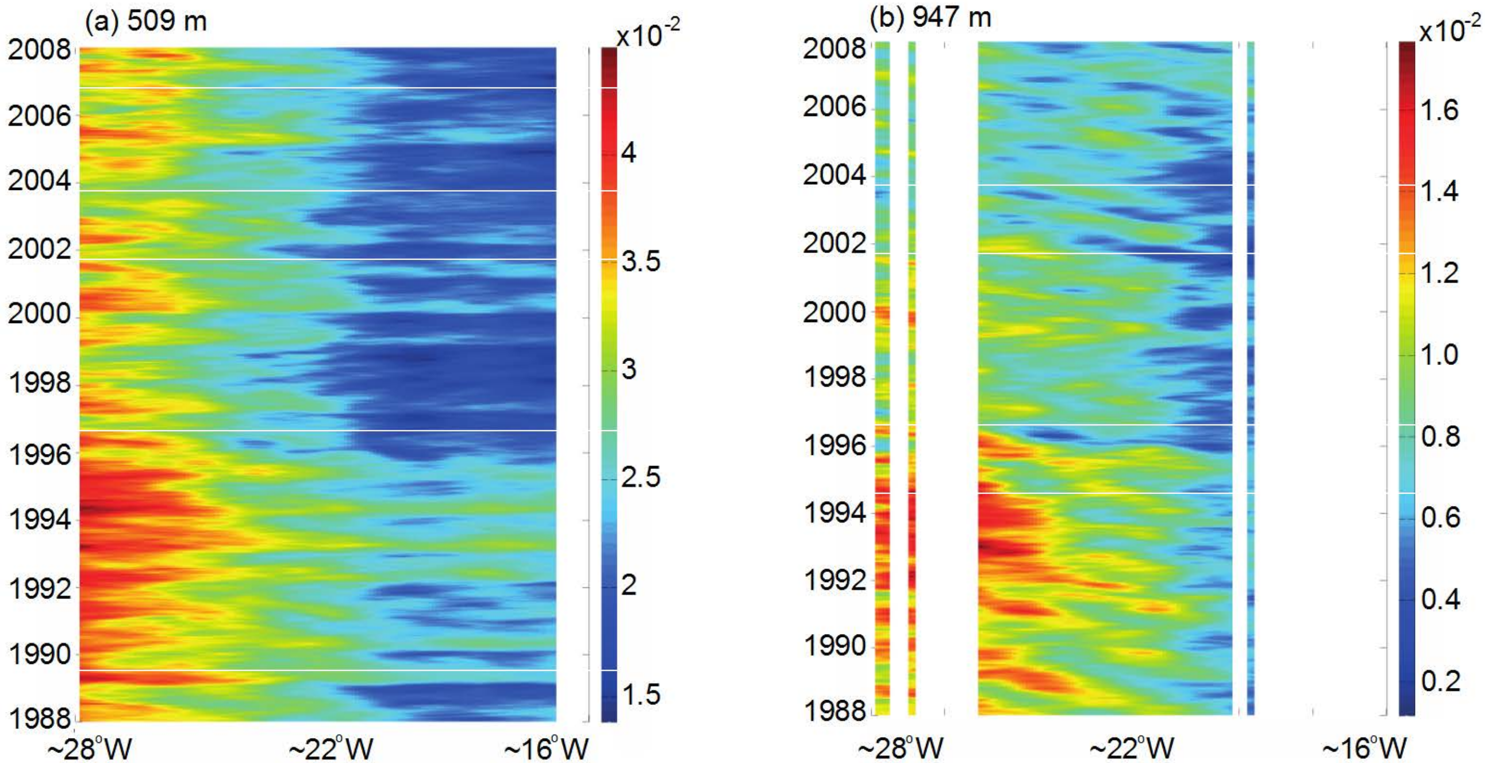
Reduction of $d\rho/dy$ across eastern SPG: snapshots of σ_0 at 500 m in 1994 and 2006



Proposed sequence of events:

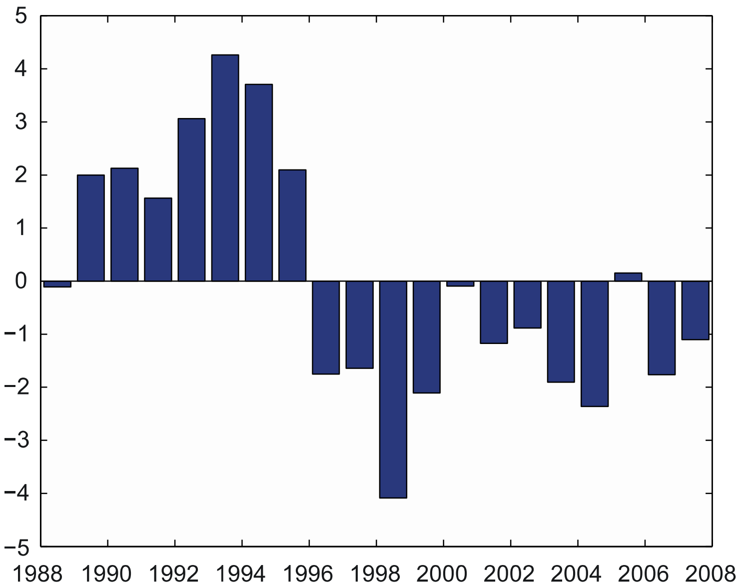
- Meridional density gradients weakened
- Geostrophic inflow weakened
- Slope Current weakened

Hofmuller plots of dρ/dy trend (regressed 45-62°N) in the eastern SPG longitude range 16-28° W, over 1988-2007



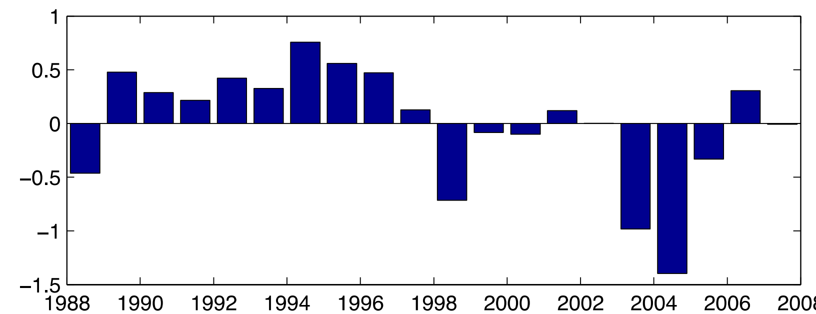
- Note that meridional density gradients weakened across the region after around 1996

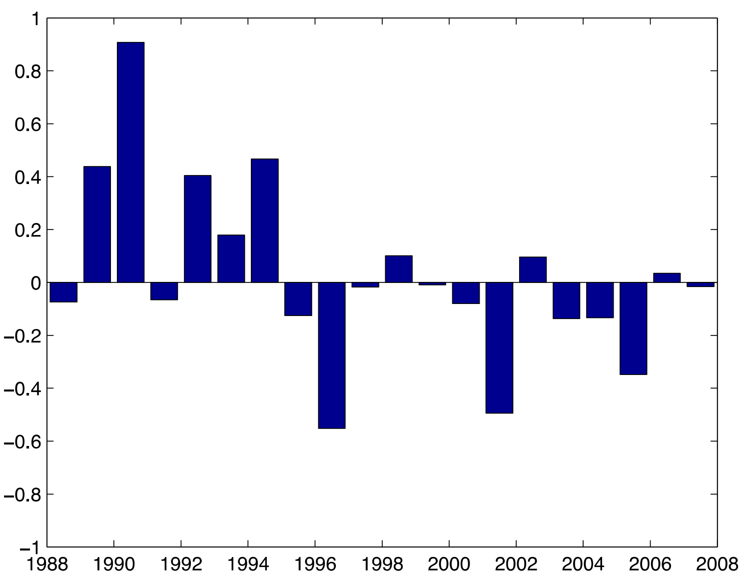
Large-scale drivers of Slope Current transport, 1988-2007



Dominant density forcing

$$\frac{\partial \rho}{\partial y}$$



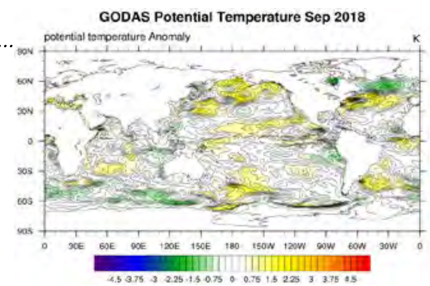


Complemented by wind forcing

$$\frac{\partial \rho}{\partial s} = \frac{A}{hHg}\left|\tau^{s}\right|$$

Extend study with ocean re-analysis, GODAS:

NCEP Global Ocean Data Assimilation System (GODAS)



Brief Description:

- High Resolution Multi-level ocean analysis from NCEP *More Details...*

Temporal Coverage:

- Monthly values for 1980/01 - 2018/09 .

Spatial Coverage:

- 0.333 degree latitude x 1.0 degree longitude global grid (418x360).
- 74.5S - 64.5N, 0.5E - 359.5E.
- 74.0S - 65.0N, 1.0E - 360.0E.

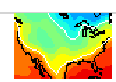
Levels:

- 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 165, 175, 185, 195, 205, 215, 225, 238, 262, 303, 366, 459, 584, 747, 949, 1193, 1479, 1807, 2174, 2579, 3016, 3483, 3972, 4478 m depth.
- 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 231, 250, 282, 334, 412, 521, 665, 848, 1071, 1336, 1643, 1990, 2376, 2797, 3249, 3727, 4225, 4736 m depth (for geometric vertical velocity only).
- Sea Surface

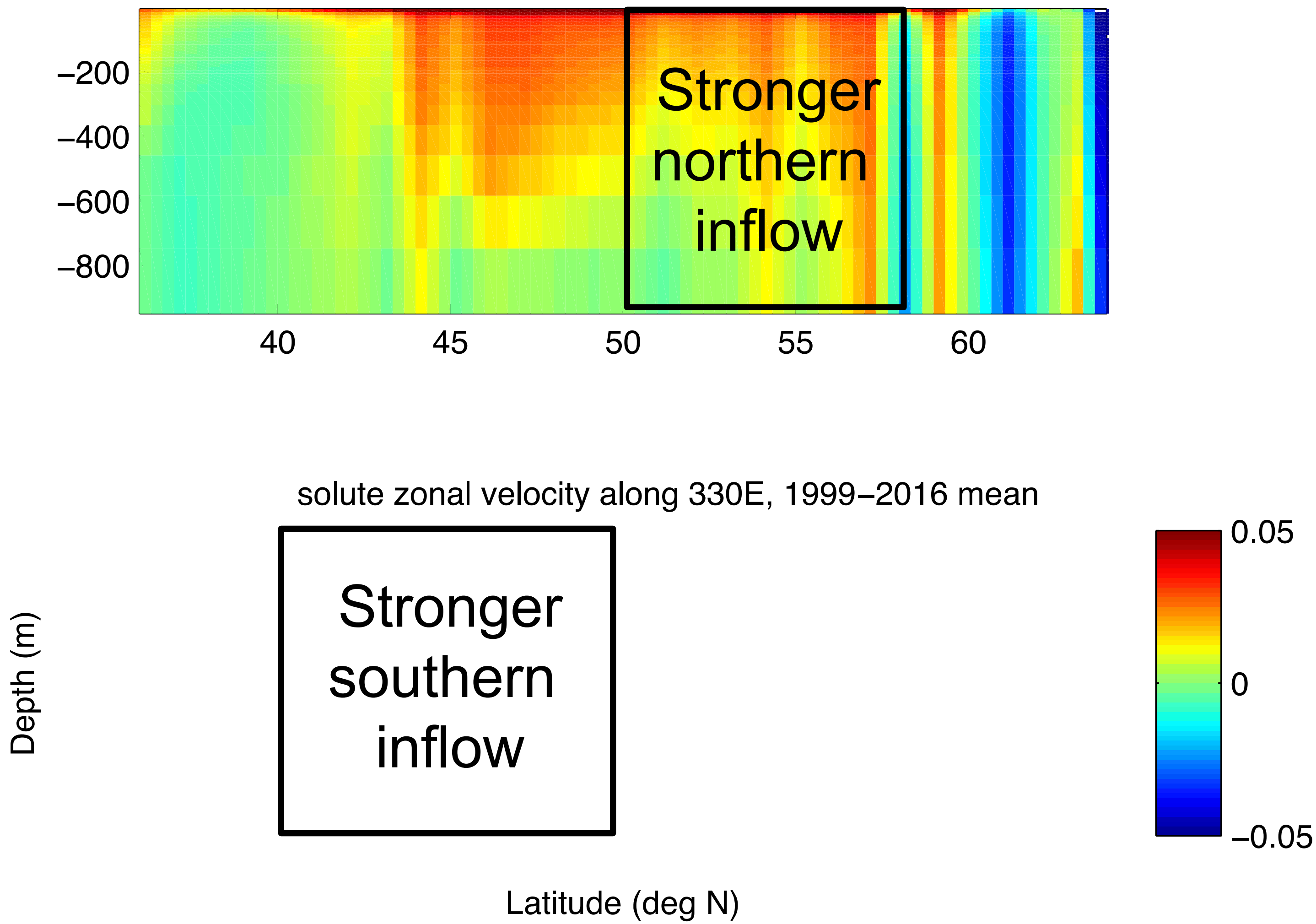
Update Schedule:

- Static

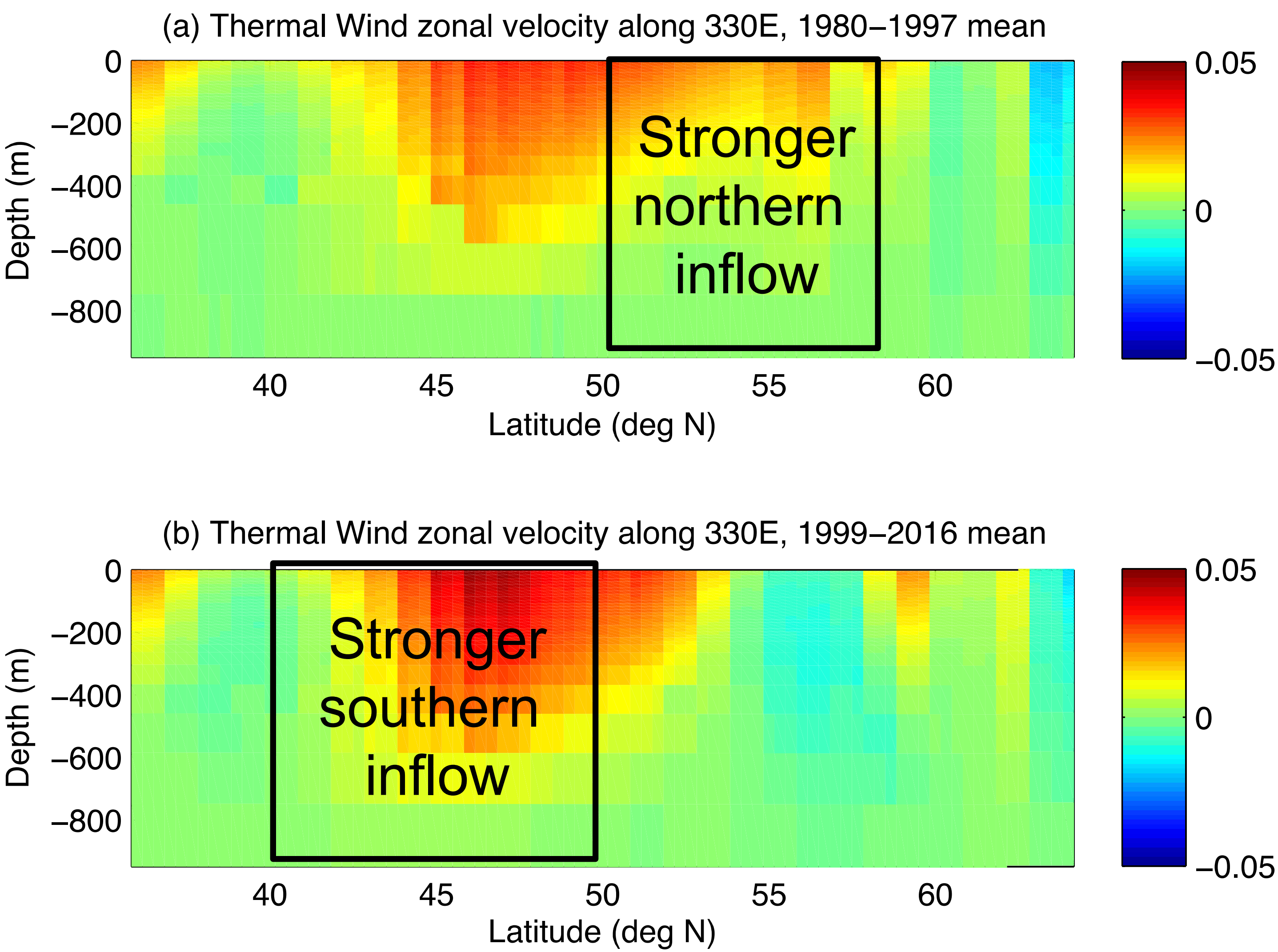
Download/Plot Data:

Variable	Statistic	Level	Download File	Create Plot/Subset
Total downward heat flux at surface	Monthly Mean	Surface	List of thflx.*.nc files (/psd/cgi-bin/db_search/DBSearch.pl? Dataset=NCEP+GODAS&Variable=total+downward+heat+flux+at+surface&group=0&submit=Search)	 (/psd/cgi-bin/db_search/DBSearch.pl? Dataset=NCEP+GODAS&Variable=total+downward+heat+flux+at+surface&group=0&submit=

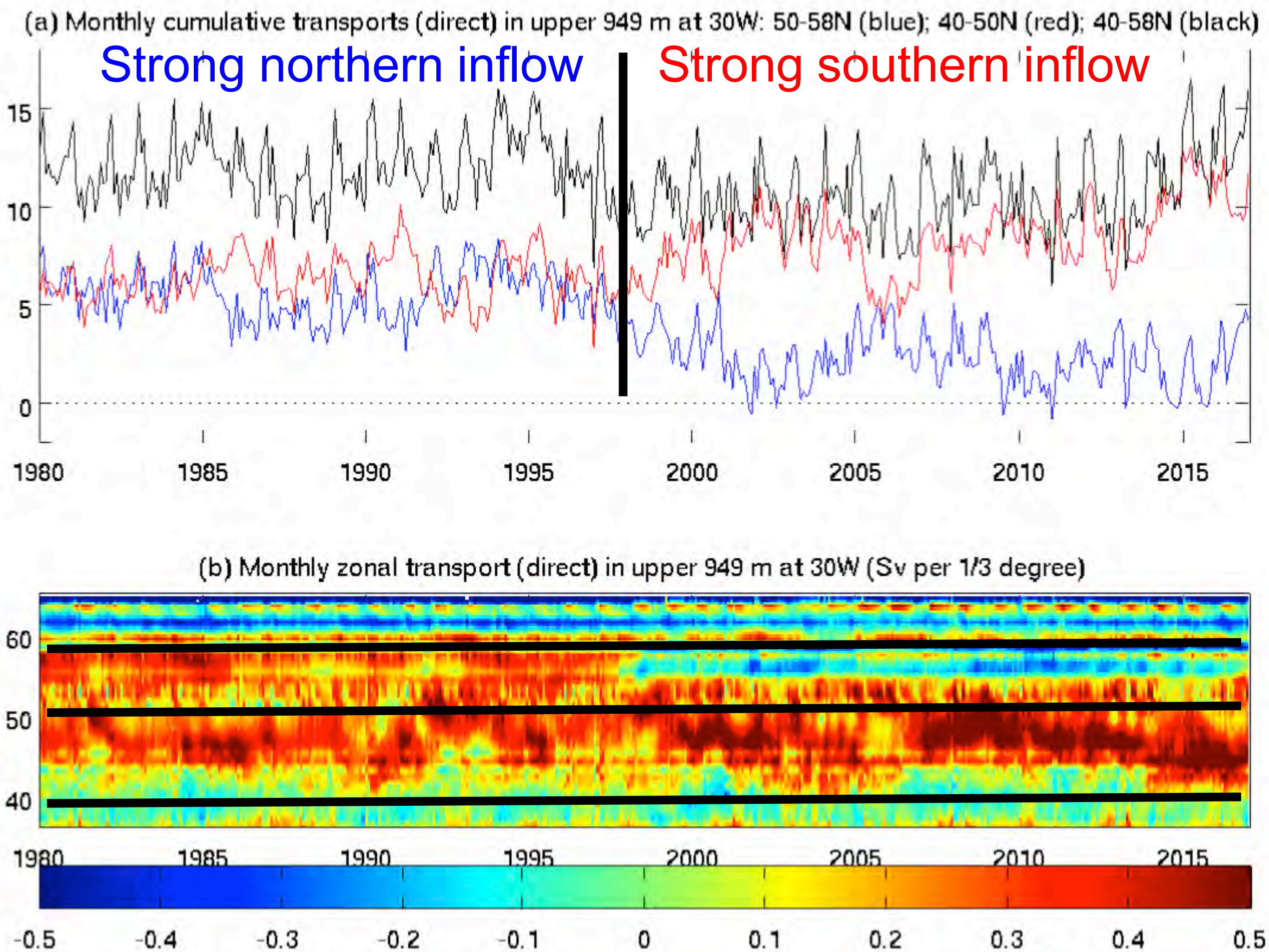
GODAS currents at 30°W - absolute



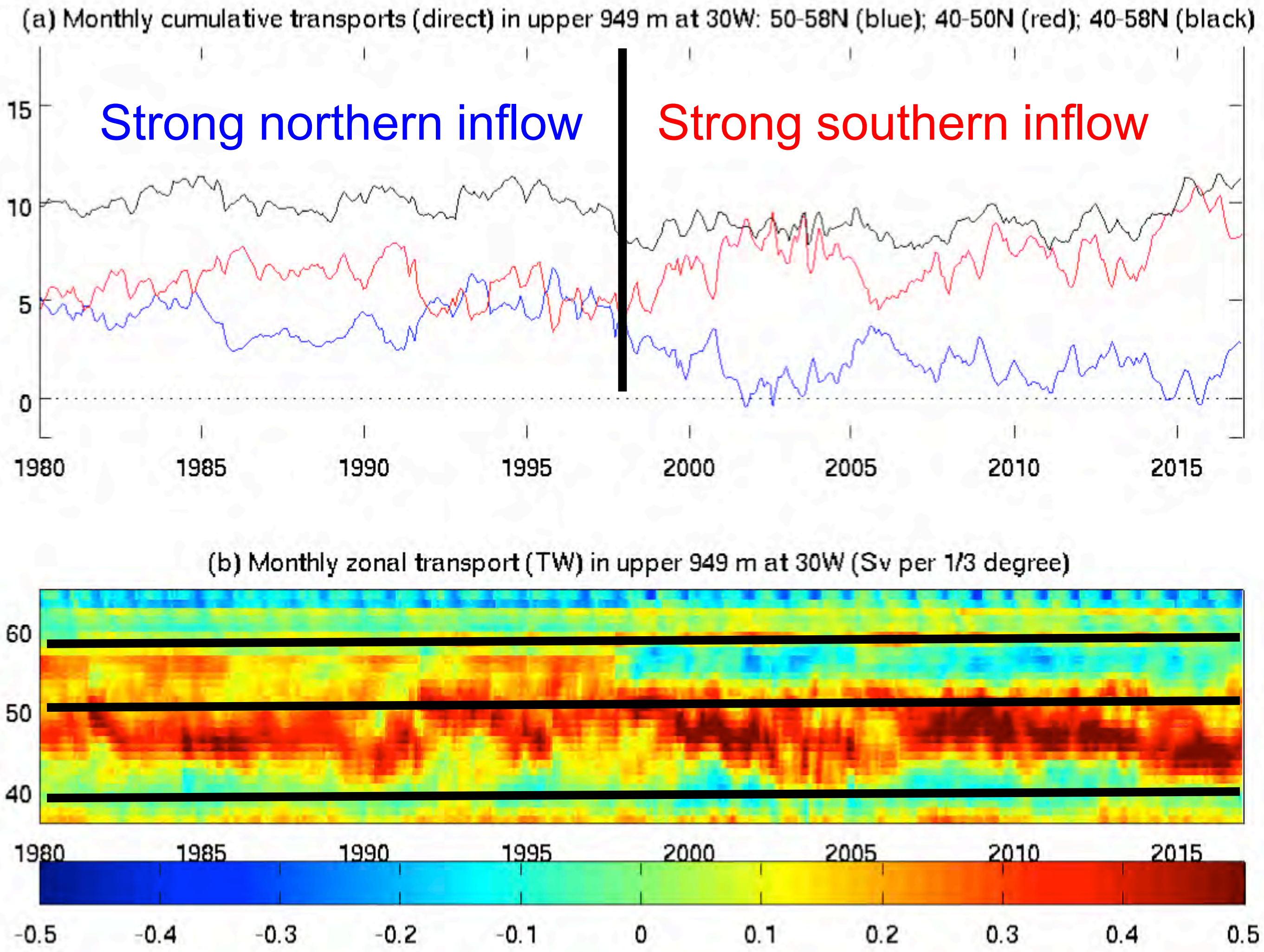
GODAS currents at 30°W – thermal wind



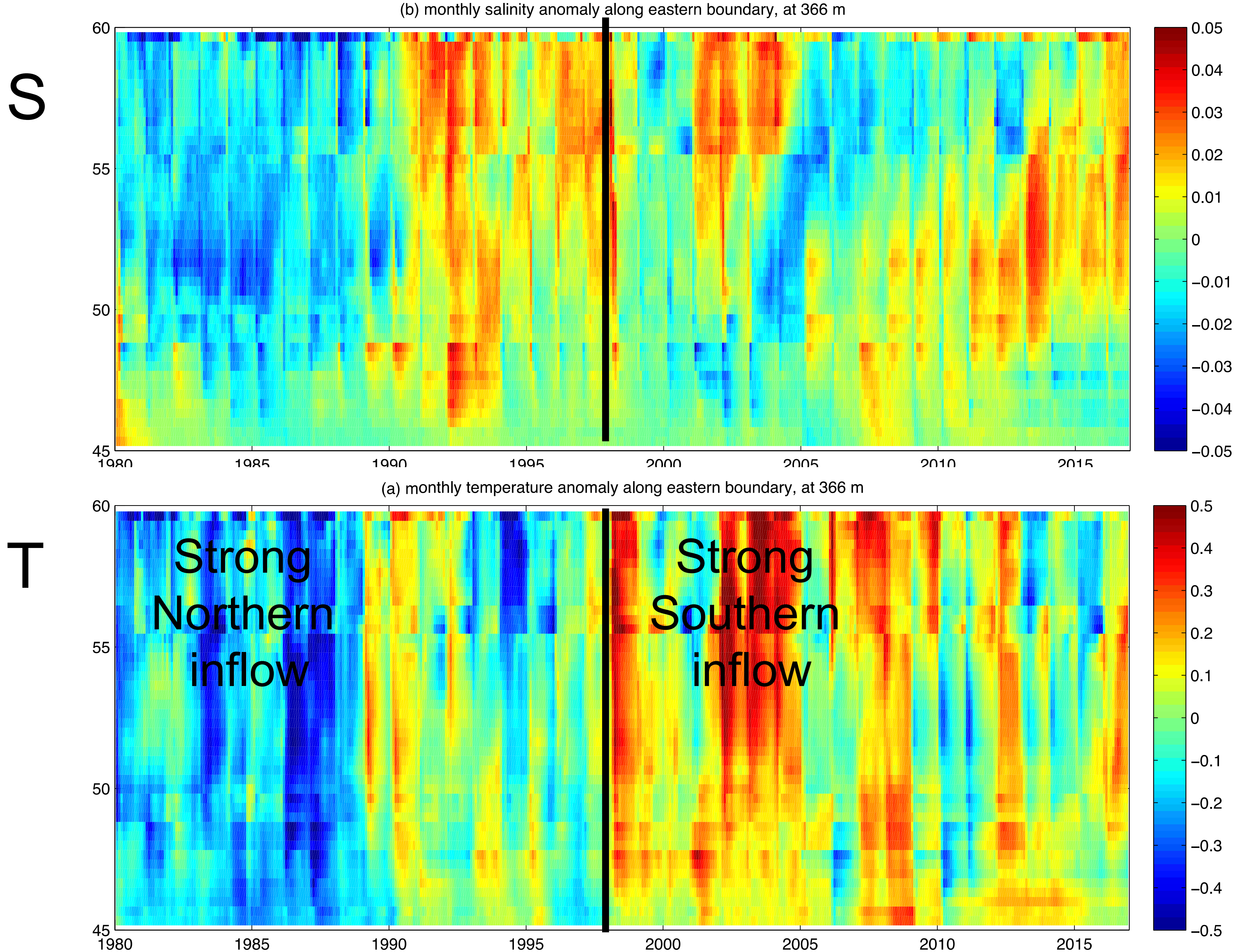
GODAS transports at 30°W - direct



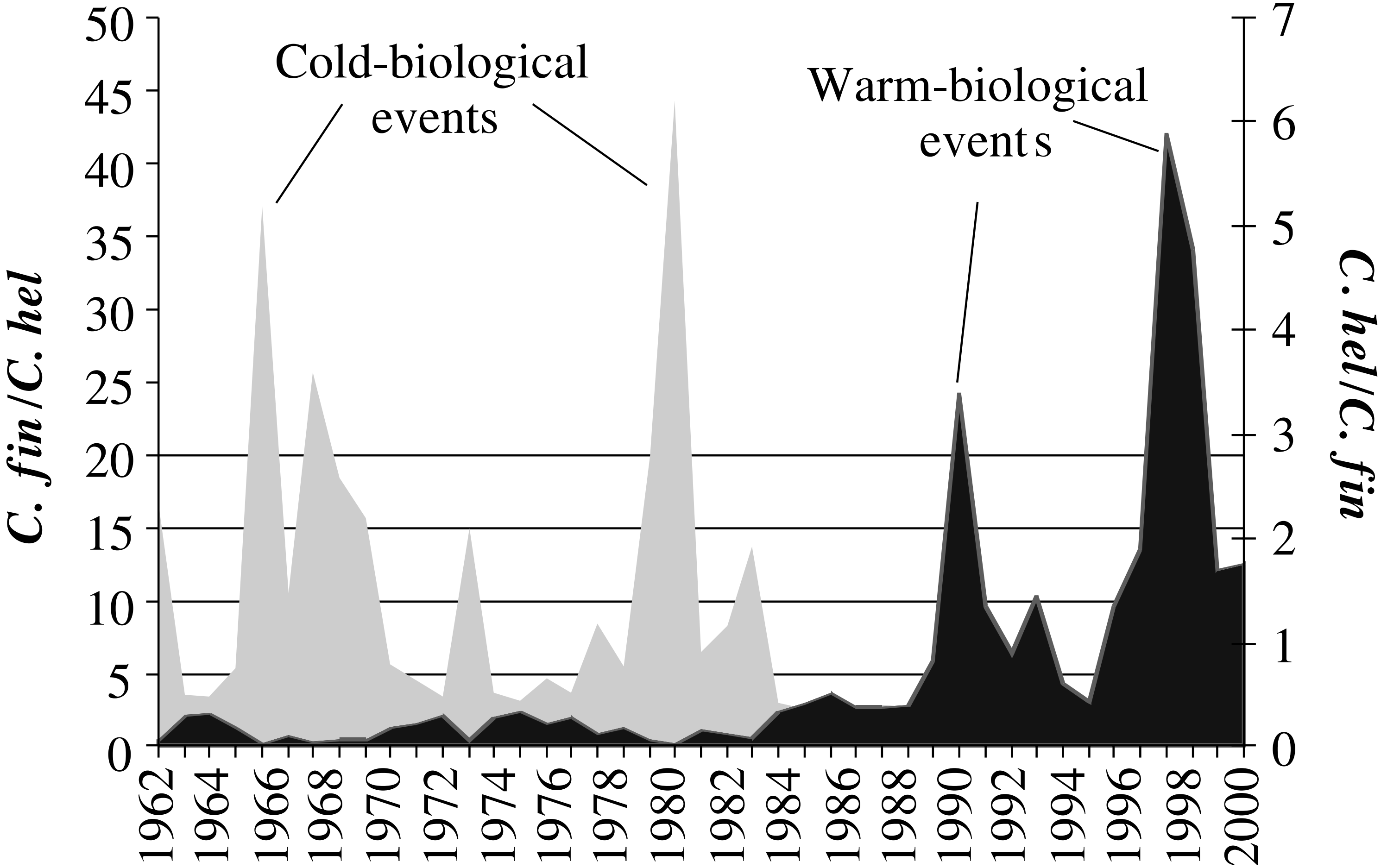
GODAS transports at 30°W – thermal wind

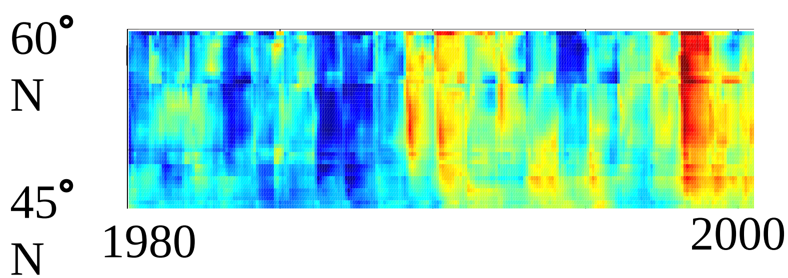


GODAS hydrography at eastern boundary



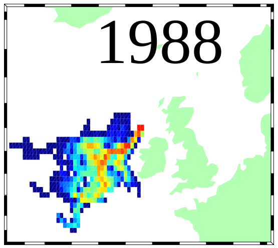
Likely consequences for shelf edge ecosystems and neighbouring shelf seas – e.g. Fig. 3 in Reid et al. (2003)





Back-traced particle density, 1988-2007

1988

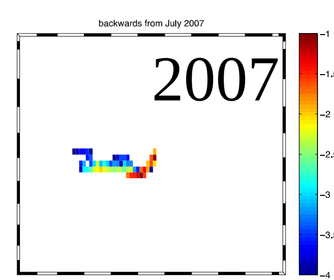


1989 1990 1991 1992

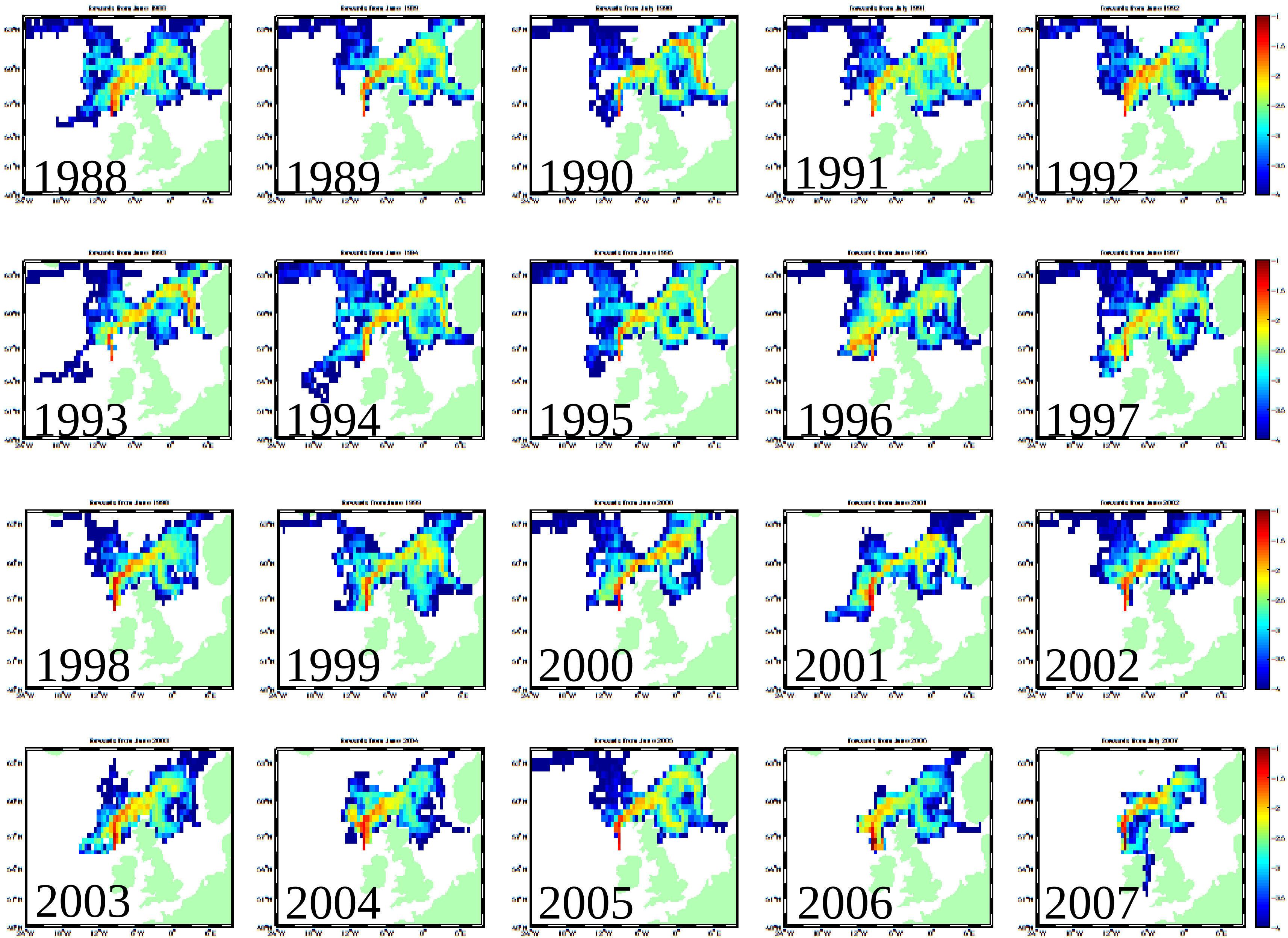
1993 1994 1995 1996 1997

1998 1999 2000 2001 2002

2003 2004 2005 2006 2007



Forward-tracked particle density, 1988-2007



Continuous Plankton Recorder data reveal "sub-tropicalization" of North Sea over the last 60 years

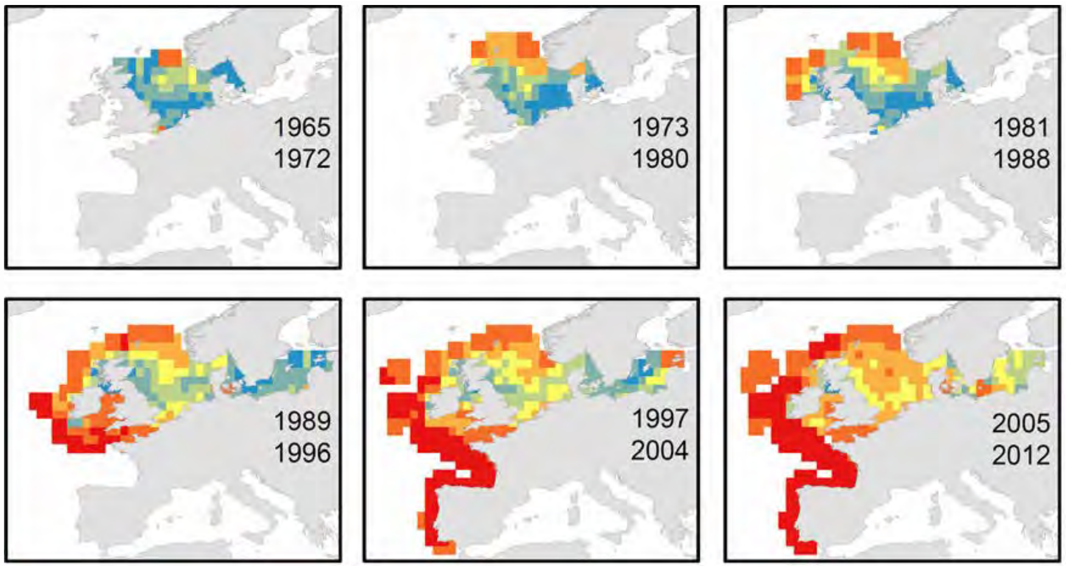
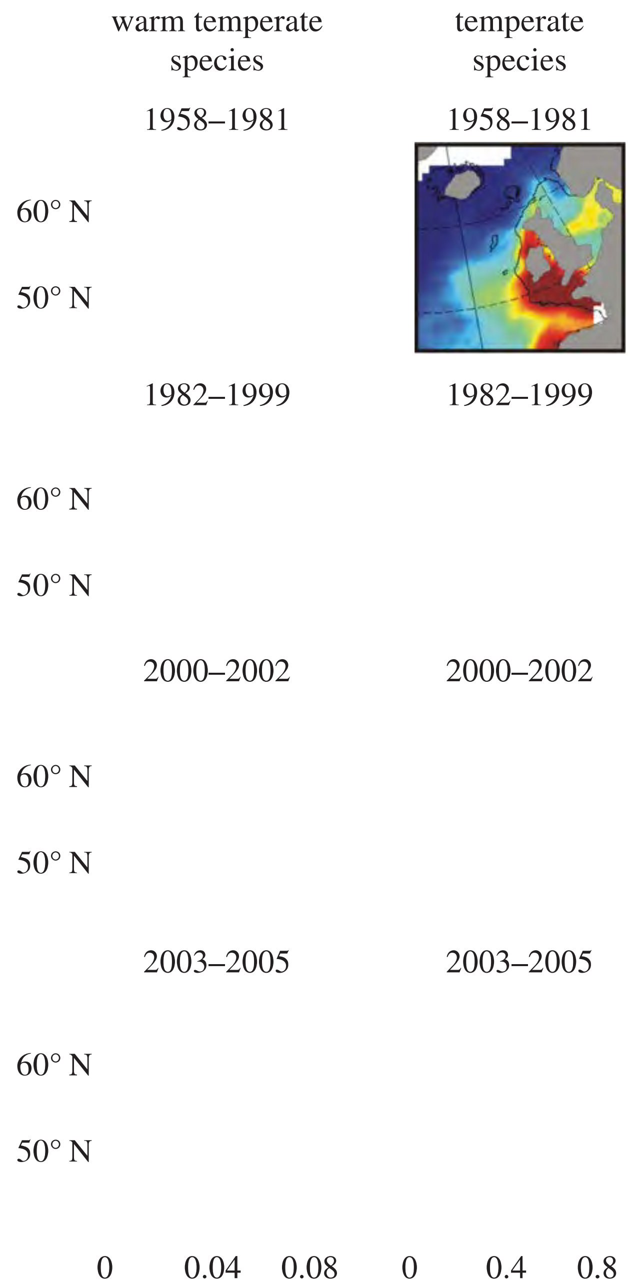


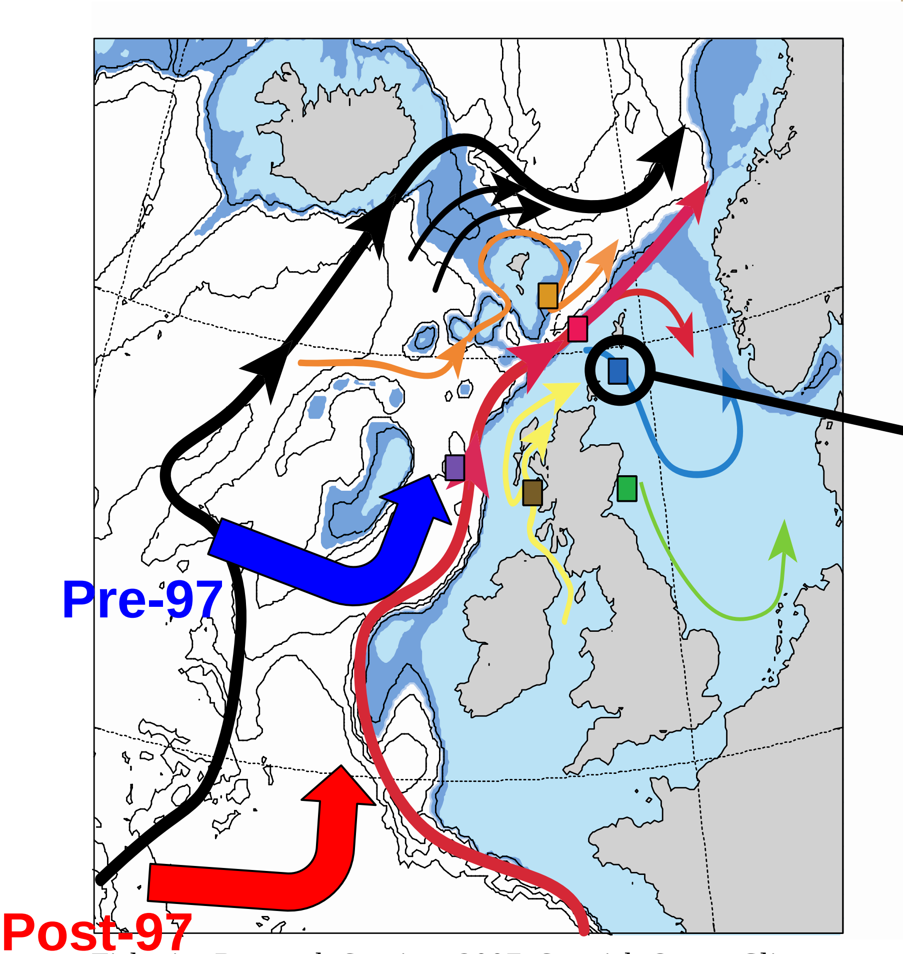
Fig. 2a in Montero-Serra et al. (2015) – community-level changes of pelagic fish (six species): red cells dominated by warm-water southern species; blue cells dominated by cold-water northern species

The focus have been on local (North Sea) warming, but advection is likely important



in Beaugrand et al. (2009)

Local changes at Fair Isle – gateway to the North Sea



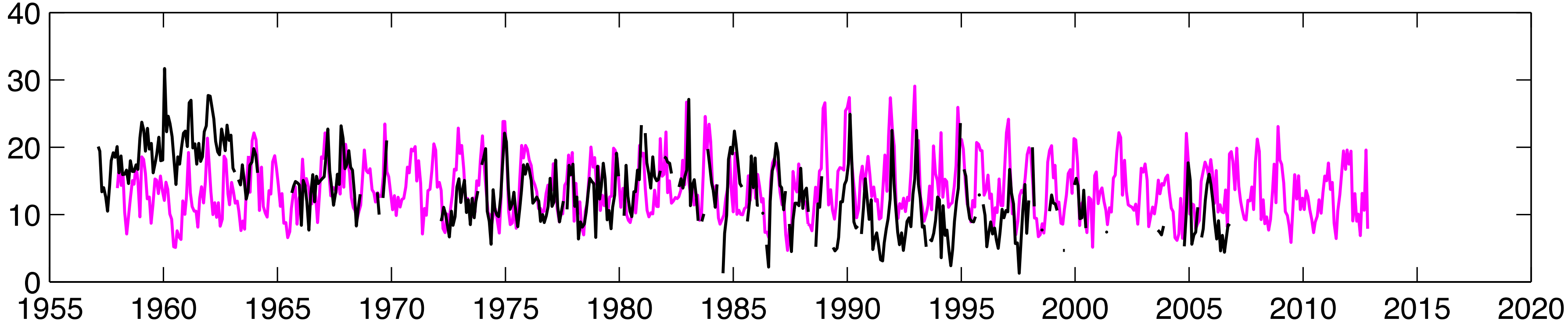
Fisheries Research Services 2007. Scottish Ocean Climate Status Report 2004 and 2005. Hughes S.L. (ed.) Aberdeen

Subtropical species arriving in recent years

Fair Isle Marine Environment & Tourism Initiative

(http://www.fimeti.org.uk/monitoringclimatechange.asp)

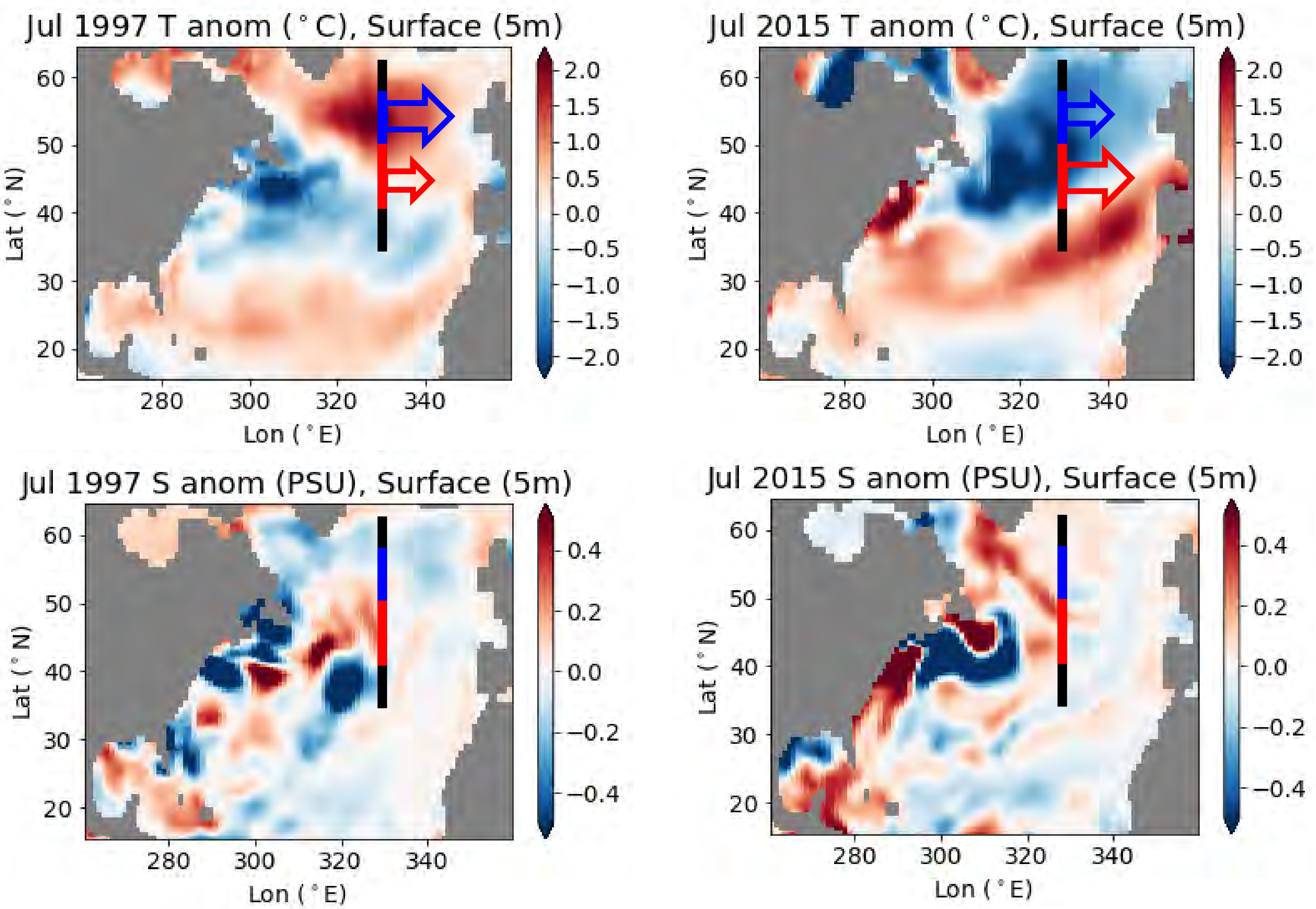
Sea level signatures of variable Slope Current transport and North Sea inflow



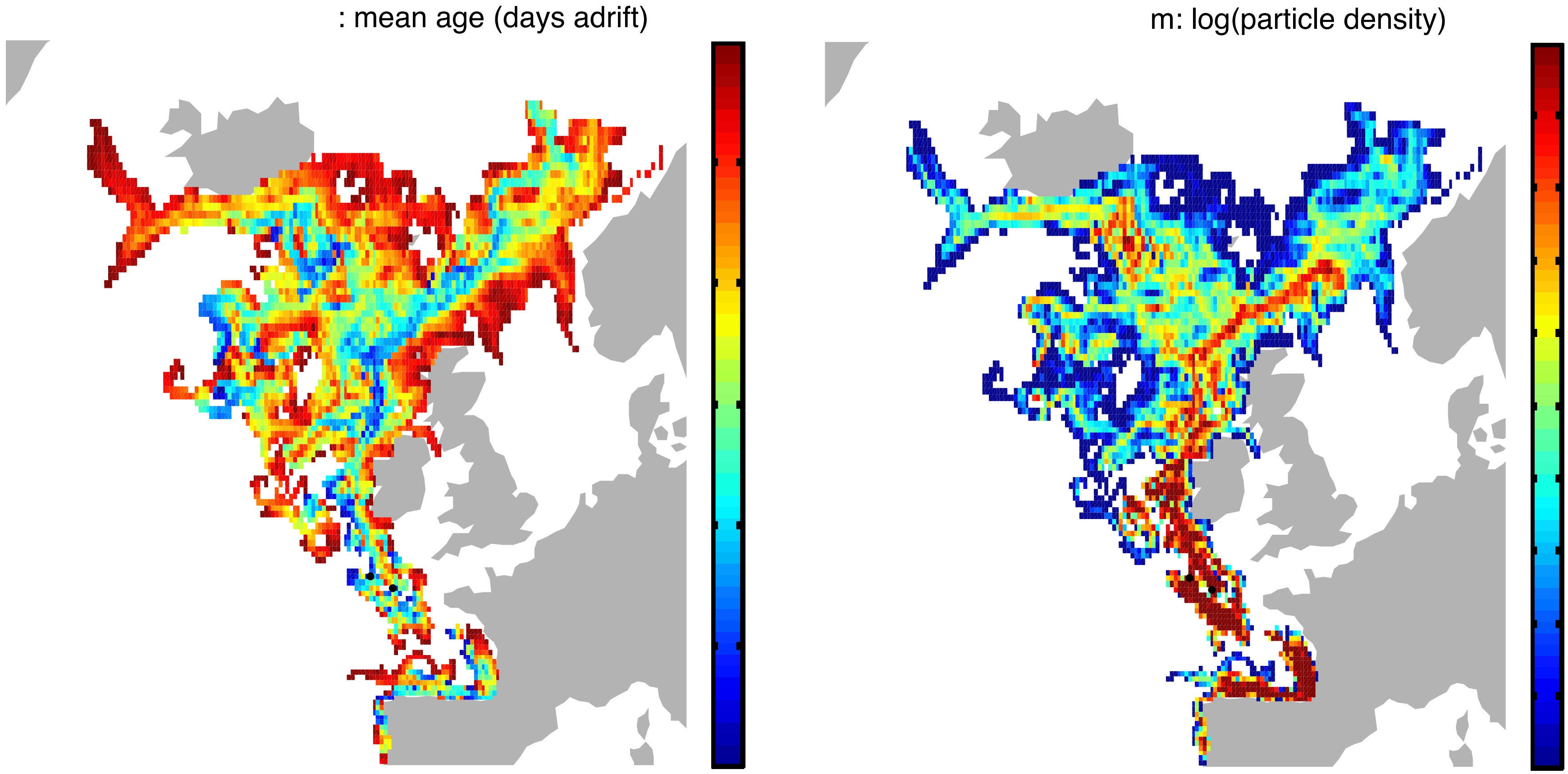
ack); ORCA12 (mauve)

- Seeking historical metrics for Slope Current transport (Lerwick – Torshavn) and North Sea inflow (Wick-Lerwick) – barotropic parts

Changing Atlantic influences on northwest European shelf seas (PhD student Matt Clark)



Habitat transitions in marine fishes - expanding the otolith toolkit (PhD student Olivia Chou)



- Starting with spawning and drift of mackerel along shelf break

Paper

Marsh, R., Haigh, I. D., Cunningham, S. A., Inall, M. E., Porter, M., and B. I. Moat (2017). Large-scale forcing of the European Slope Current and associated inflows to the North Sea, Ocean Science, in press.

Acknowledgements

Support from the Scottish Association for Marine Science (SAMS) via a 2013 Research Bursary, “Variability, Forcing and Impacts of Shelf Edge Exchange”

Nested models on the shelf at the Marine Institute

Tomasz Dabrowski, *Marine Institute, Ireland*

Current team members:

- Kieran Lyons
- Hazem Nagy
- Joseph McGovern
- Diego Pereiro
- Achref Othmani

Workshop on Subpolar North Atlantic Eastern Boundary *14 Oct 2019, Edinburgh*

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The Marine Institute was set up under the Marine Institute Act 1991:

“to undertake, to coordinate, to promote and to assist in marine research and development and to provide such services related to research and development, that in the opinion of the Institute, will promote economic development and create employment and protect the marine environment.”

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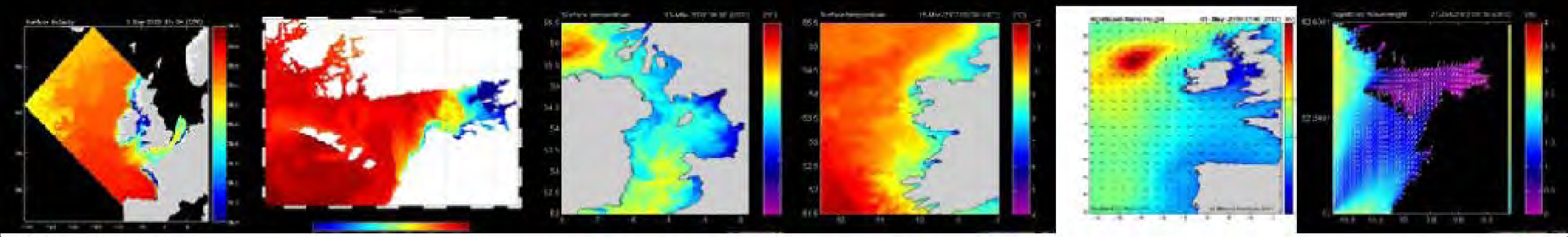
Ocean Modelling



Type of models:

- Hydrodynamics (*ROMS*)
- Waves (*SWAN*)
- Biogeochemistry (formerly Fennel et al. 2006, currently *PISCES*, as part of CMEMS)
- Shellfish (*DEB*)
- Oil spill (*OILTRANS*)
- Particle tracking (*Ichtyop*)

Downstream services:

- Aquaculture (carrying capacity, HABs, fish larvae transport, disease spread, siting, weather windows, IMTA)
- Fisheries (egg and larvae transport, climatology maps)
- Oil pollution
- Storm surges (on request)
- Search and rescue
- Leisure (sailing)
- New projects starting in the areas of MSFD and marine litter
- Wave energy

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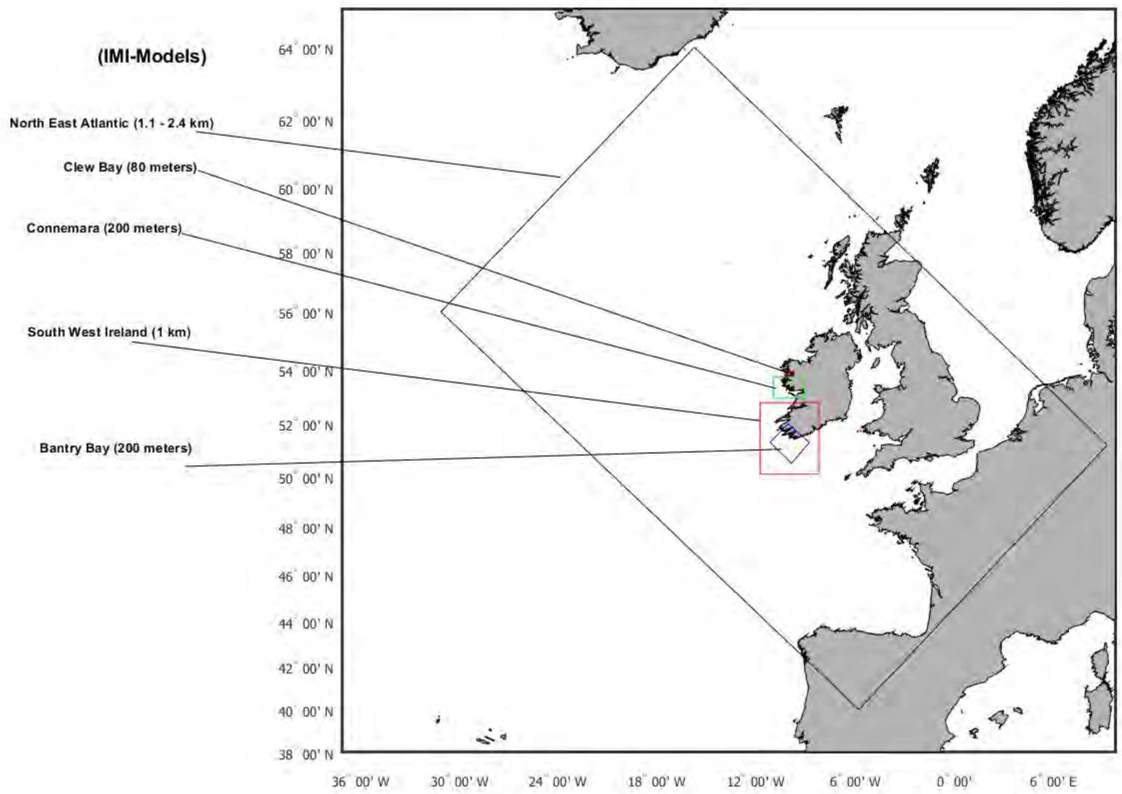
Operational models – ROMS (archive 2012 -)

Model name	North East Atlantic
Model code	ROMS 3.7

Ocean (ROMS 3.7)



http://milas.marine.ie/thredds/catalog.html

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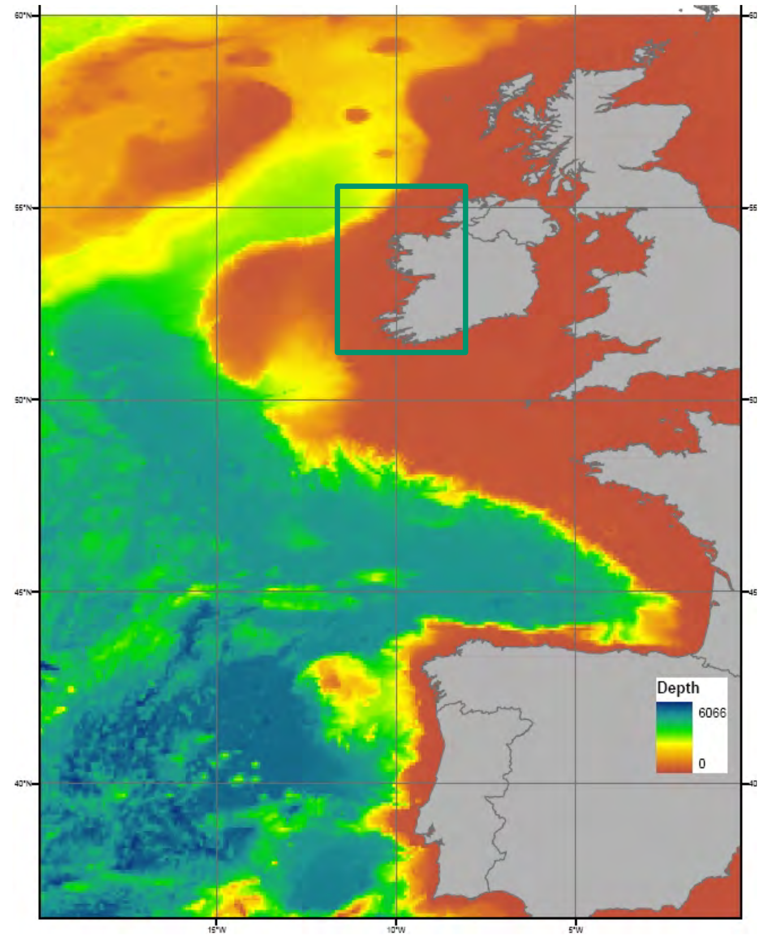
Operational models - SWAN

Waves (SWAN)

Model code	SWAN
Model Grid	Rectangular 0.025°
Bathymetry	GEBCO & INFOMAR
Forcing	• 3-Hourly GFS 0.25° • FNMOC Wave Watch III
Forecast Period	+6 days (daily)
Hindcast Period	-7 days (weekly)
Output	• significant wave height, wave period, wave spectra • @ 3 hrs spatially • 20 stations @ 0.5hr
Other Domains	West Coast 0.004° (non-operational)



R&D:

- Funded PhD student in wave-current interactions (at UCD)
- new coastal model for all Ireland using unstructured mesh (SWAN (or WW3))

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CMEMS technical « internal » Framework: building blocks

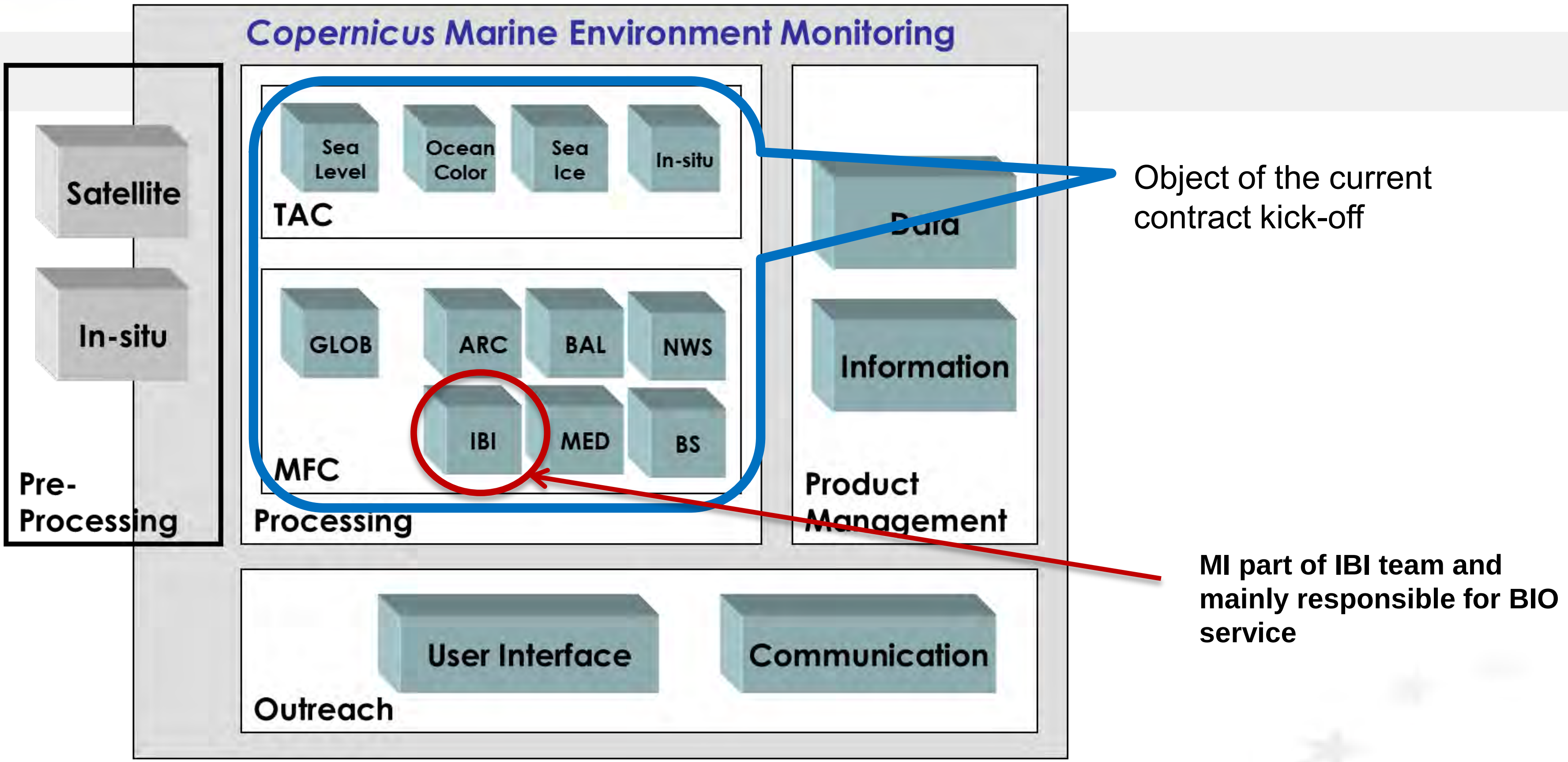
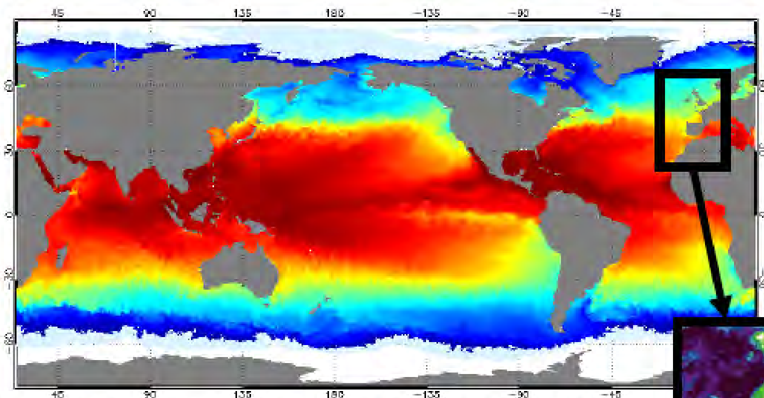


Figure 1: System overview of *Copernicus* Marine Environment monitoring service chain as presented by the European Commission to the GMES/Copernicus User Forum.

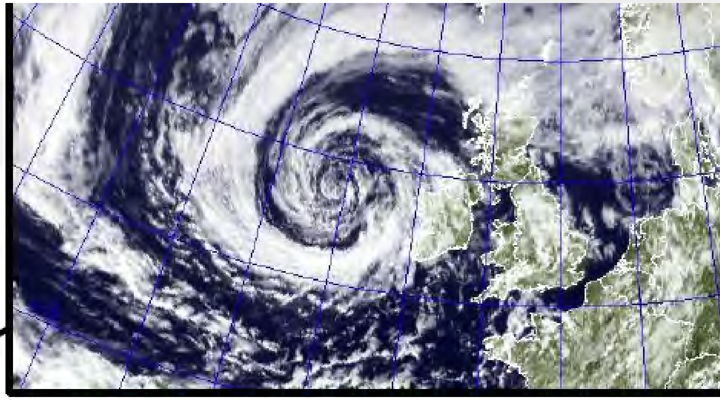
From the Technical Annex of the Delegation Agreement between the EU and Mercator Ocean

BIO Forecast

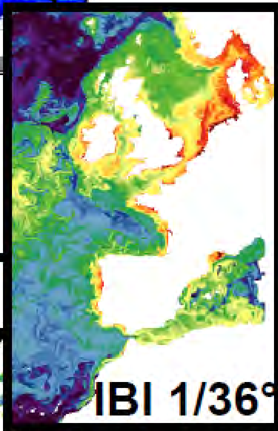
Physics



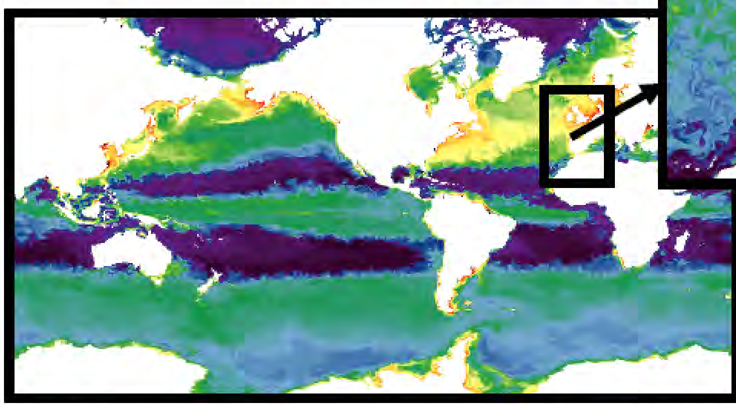
Global forecasting system at 1/12°
(PSY4, Mercator Ocean, Copernicus)



ECMWF (3h)



Biogeochemistry



Operational System:
NEMO-PISCES 3.6
1/36°, 50 vertical levels
PISCES: coupled **«online»** with the physics

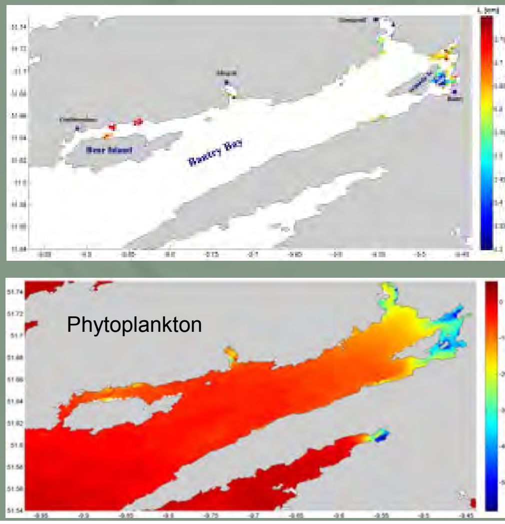
Near real Time in progress:
de 03/2013 → real time

Set in operations in 2016

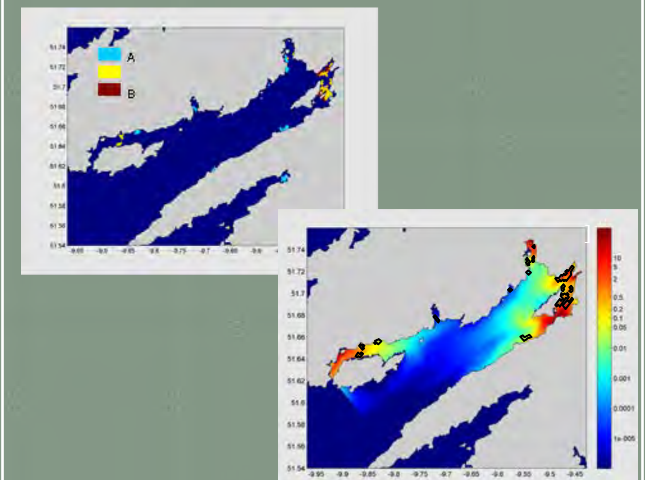
Global forecasting system at 1/4° (BIOMER, Mercator Ocean, Copernicus)

Modelling for Aquaculture and Fisheries

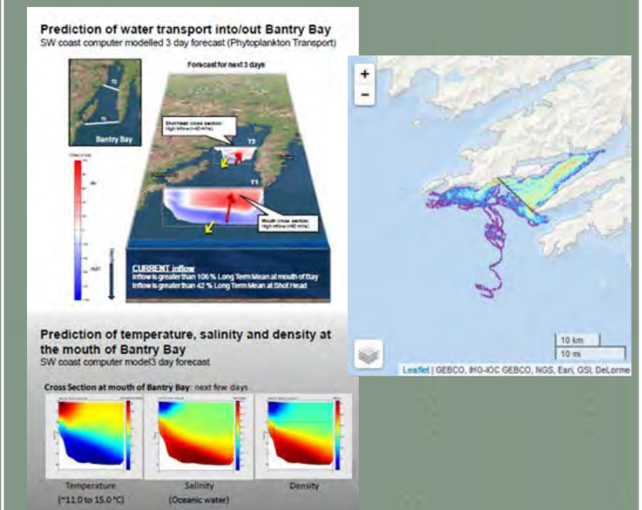
Shellfish growth & carrying capacity



Shellfish microbial contamination

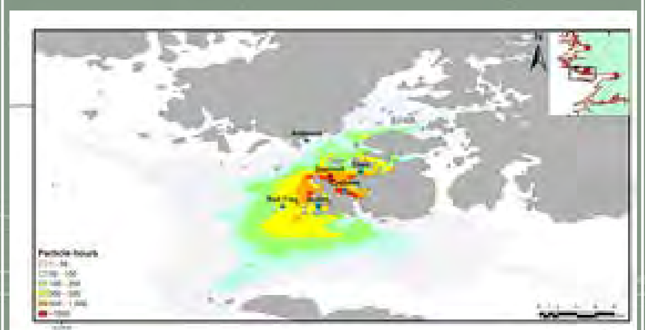


HAB warning

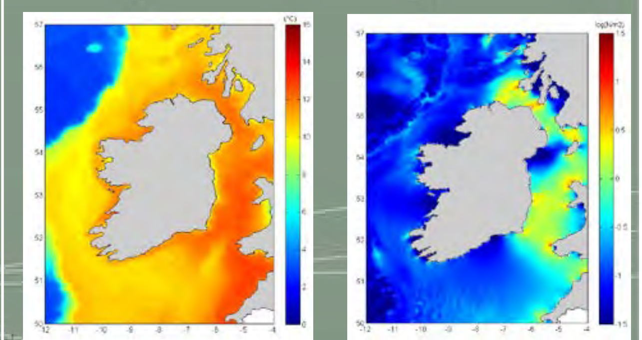


Offshore aquaculture (maritime spatial planning)

Cross-contamination of farms (e.g. sea lice)



Products for fisheries (e.g. long-term means, anomalies)

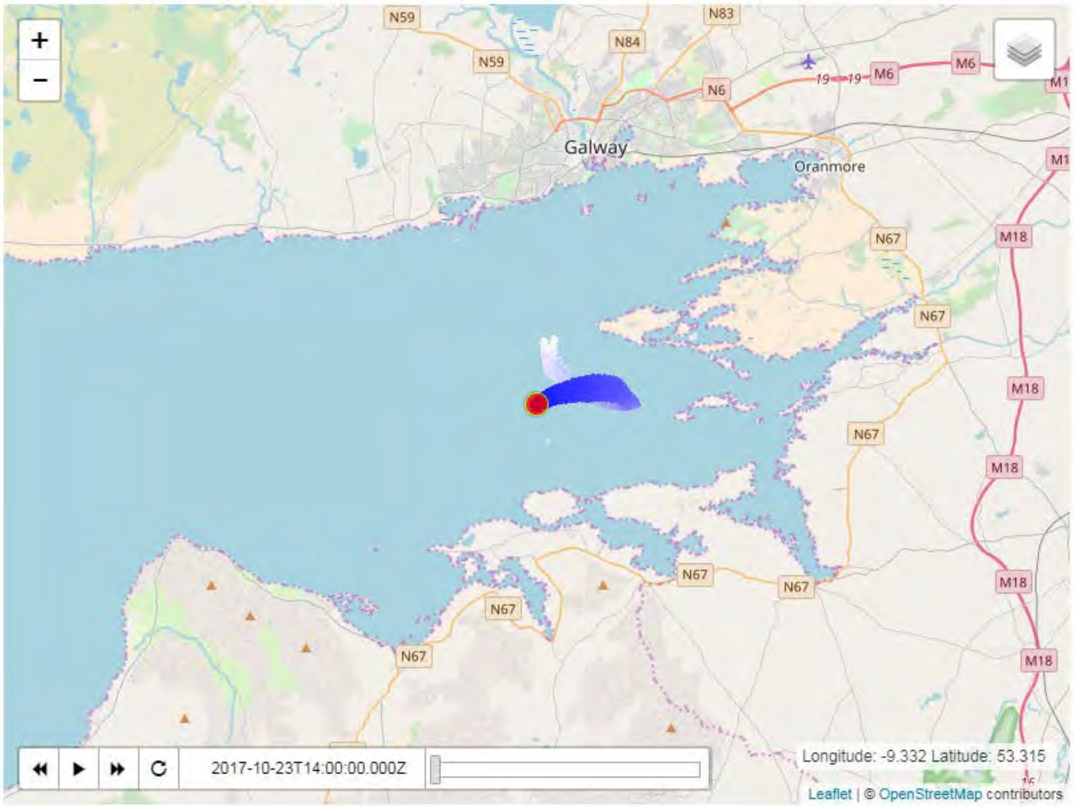


Search and rescue – web app

ADRIFT

Marine Institute predicted sea surface tracking.

Project 2017-10-23 14:00 (click to rename)



Project Details

Created	2017-10-23T16:21:32Z
Start	2017-10-23T14:00:00+00:00Z
End	2017-10-24T02:00:00+00:00Z
Location	53.1949271207, -9.0795135498
Radius	250
Particles	1000
Model	connemara_his

Current Display

UTC Time	2017-10-23T14:00:00.000Z
Local Time	Mon Oct 23 2017 15:00:00 GMT+0100 (GMT Daylight Time)

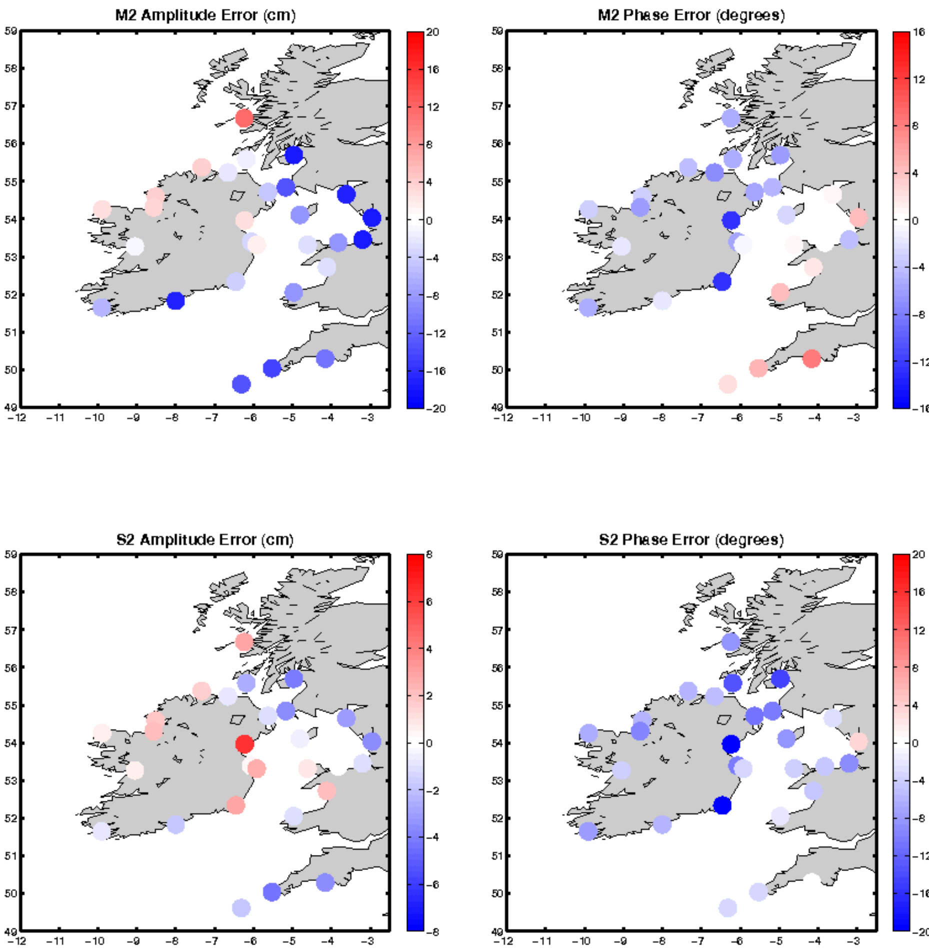
Downloads

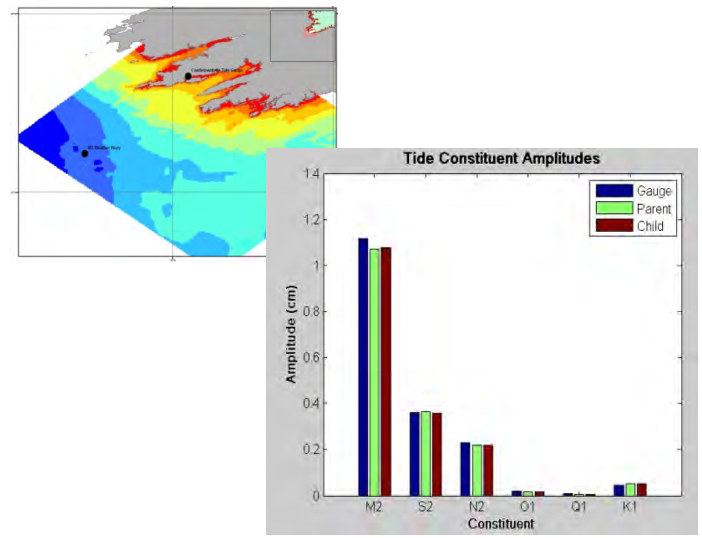
Generated NetCDF File

Also frequent requests by An Garda Síochánna (forensic investigations)

NE Atl model validation

Tides





	Mean Amp (cm)	Amp Ratio	Phase Error (deg)
M2	149	0.98	-2.4
S2	51	1.01	-7.2
N2	29	0.98	-17.9
K1	10	1.09	5.6
O1	8	0.84	-3.9
Q1	3	0.90	9.9

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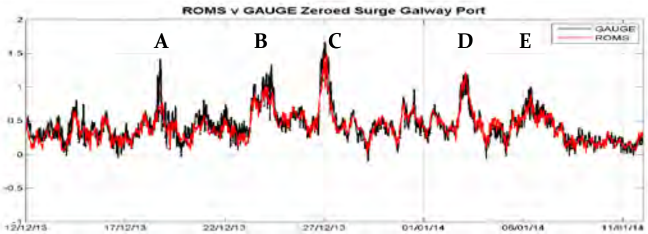
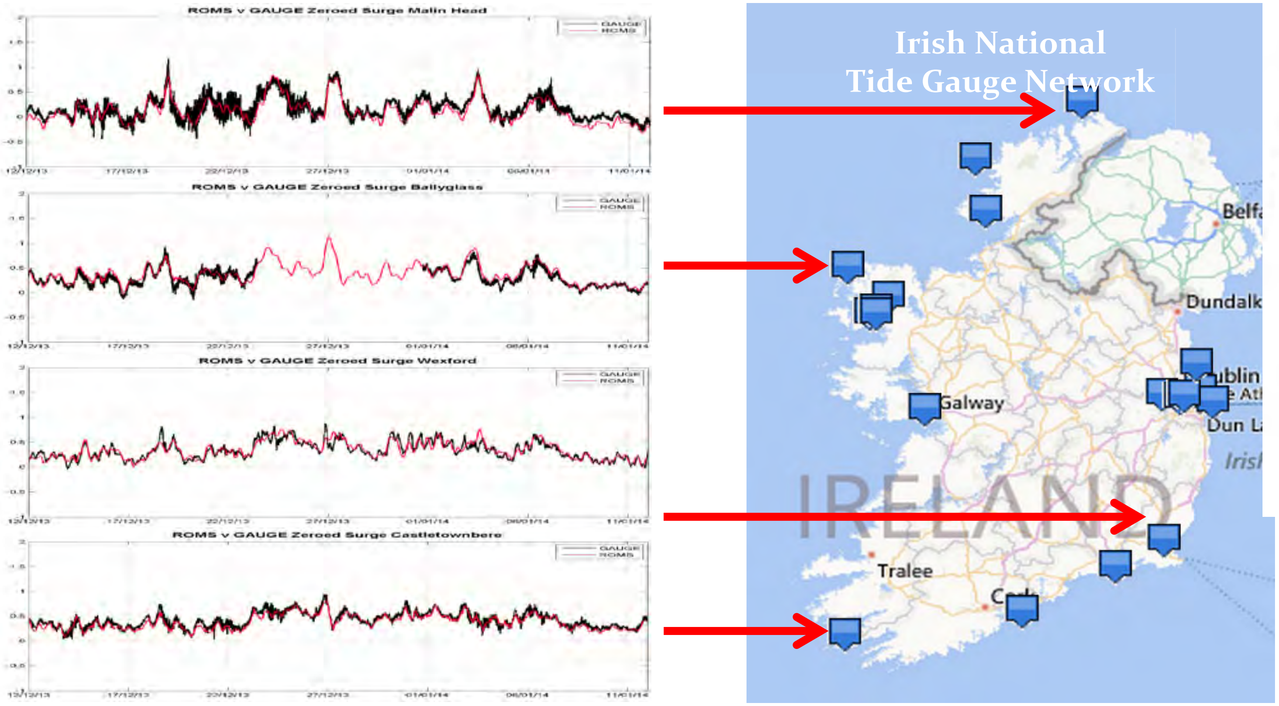
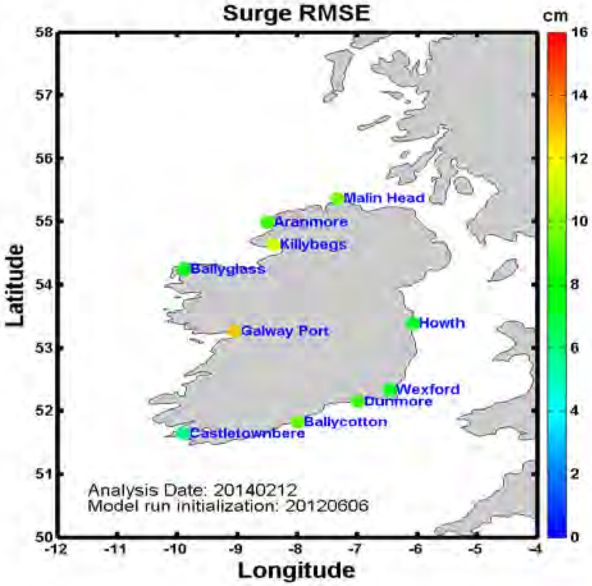
NE Atl model validation

Surges



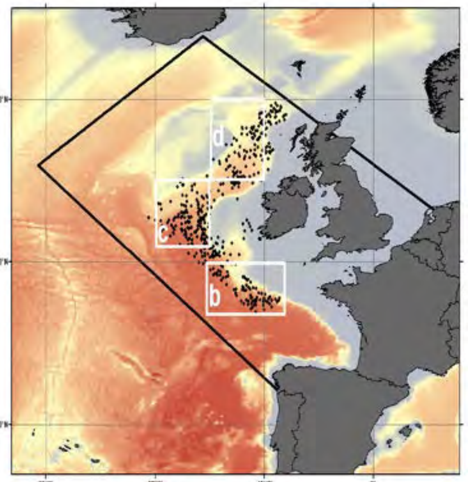
Modelled Surge v Galway Port Gauge

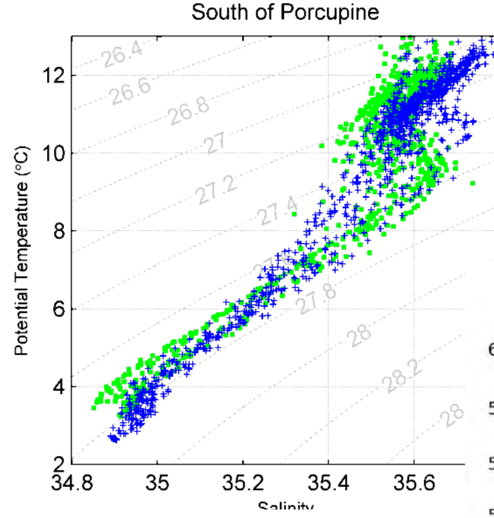


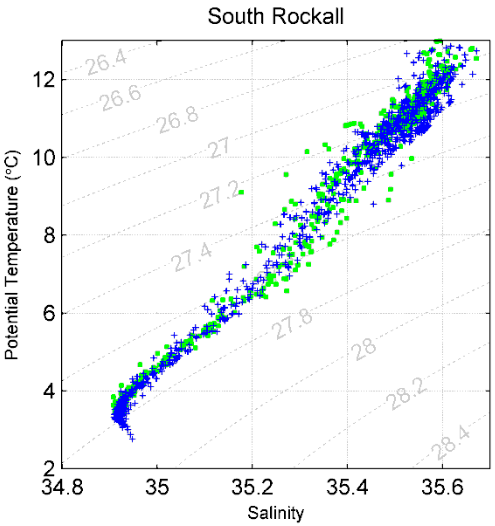


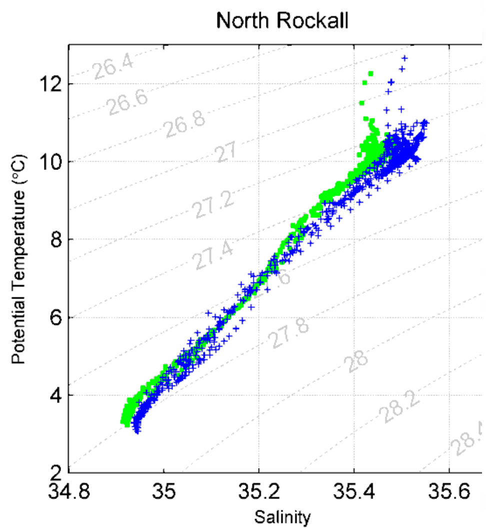
NE Atl model validation

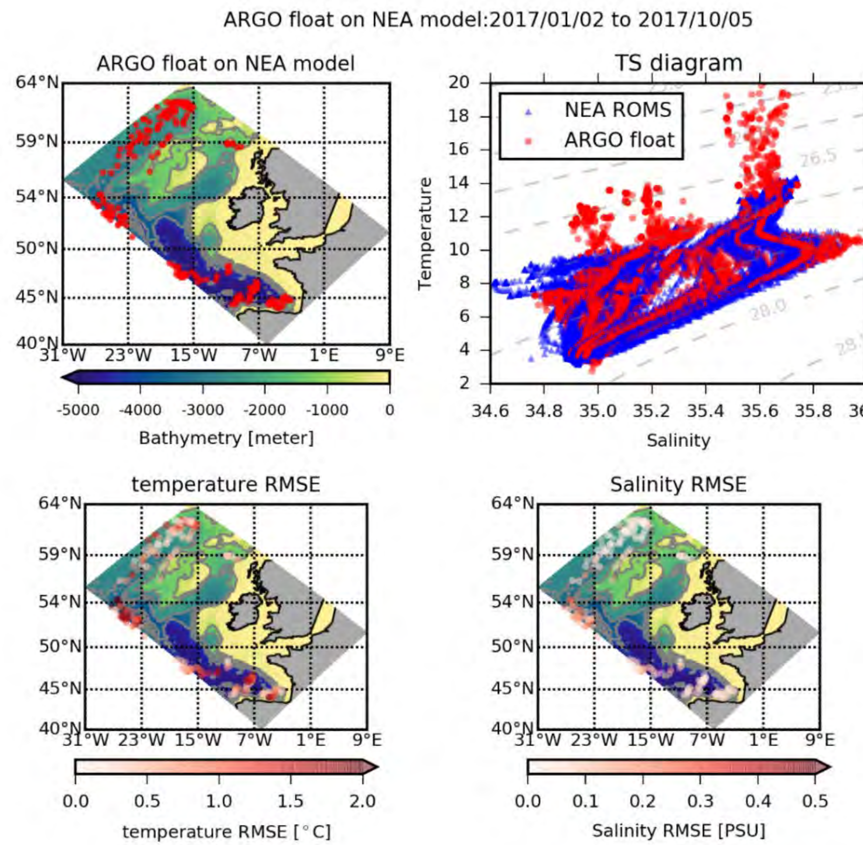
TS profiles (Argo floats, 474 profiles)





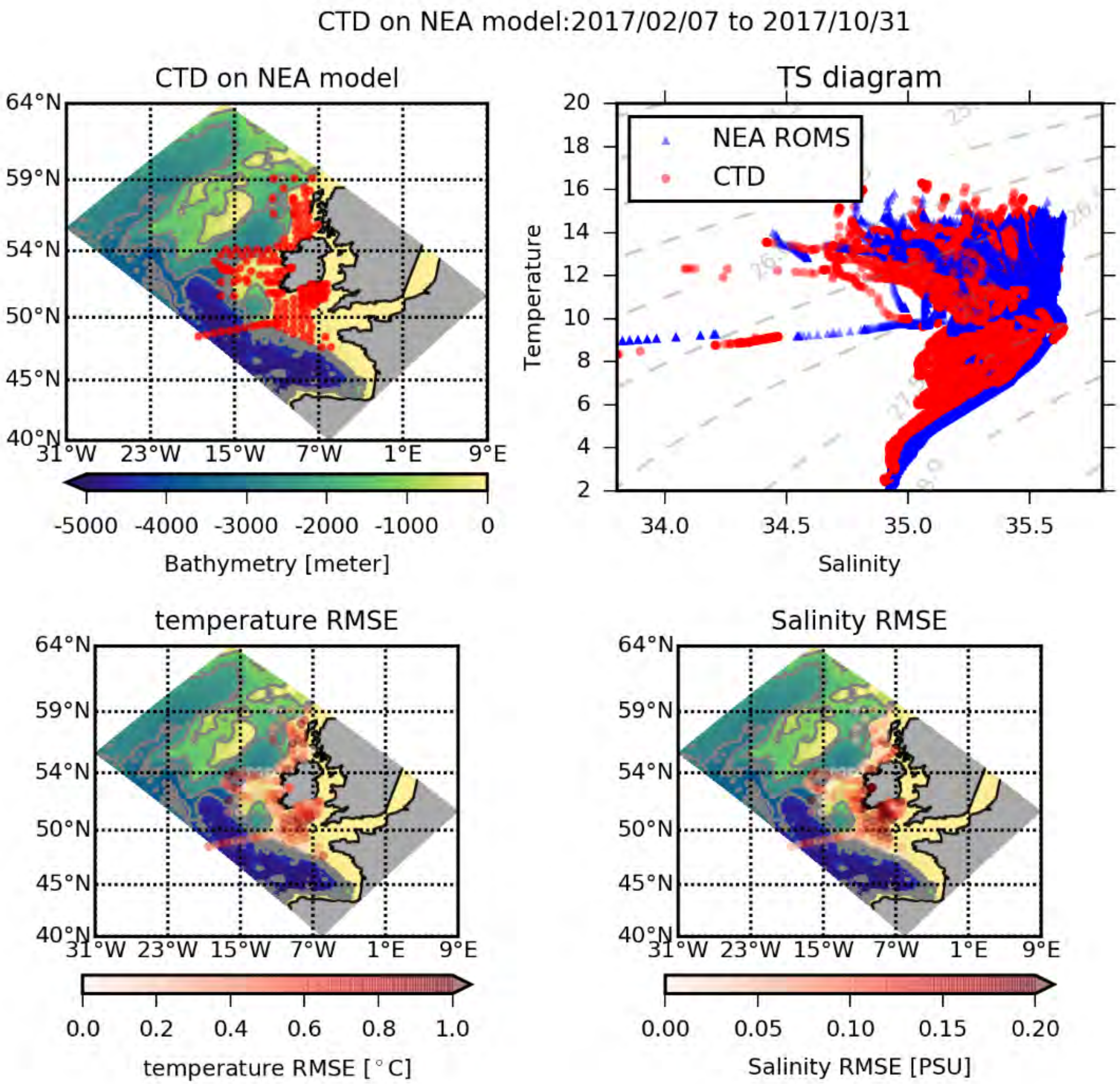






NE Atl model validation

CTD profiles (from MI)

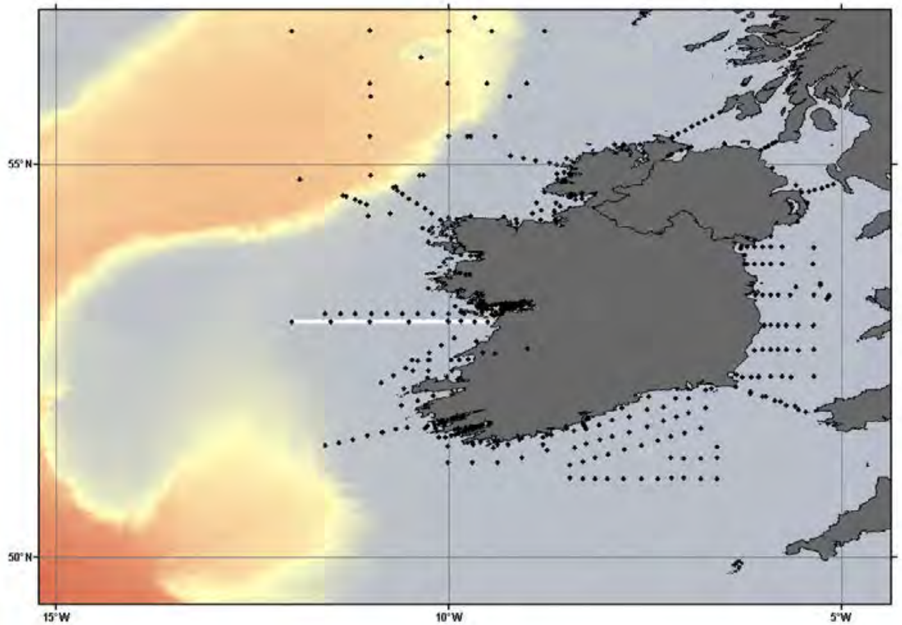


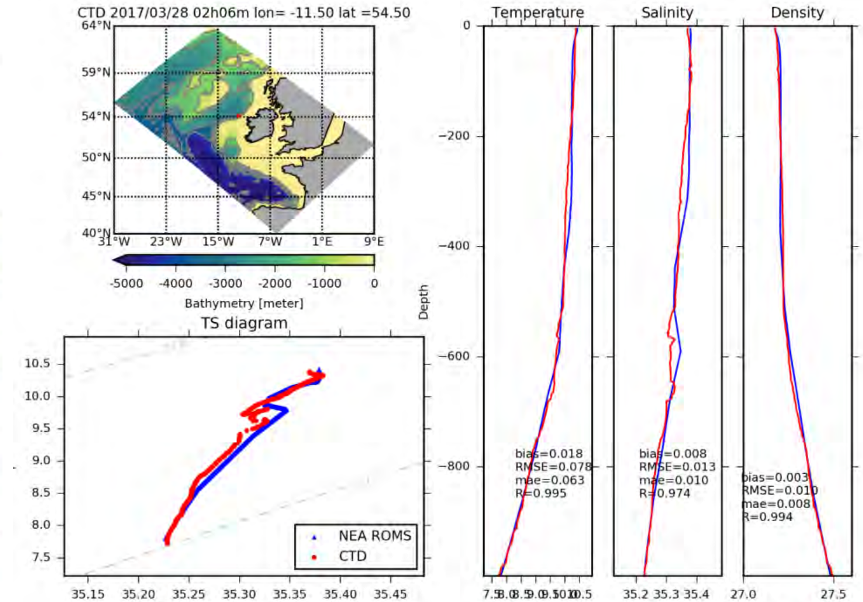
- Figure shows the comparison of the salinity and temperature between NEA model and CTD MI data collected during 2017

- The NEA model correctly reproduces the water masses around Ireland. Seems to have less error to the north of Ireland compared to the Celtic Sea

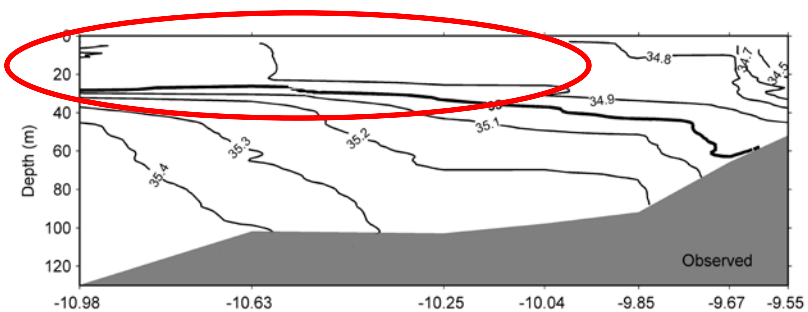
NE Atl model validation

CTD profile to the west of Galway Bay – August 2012

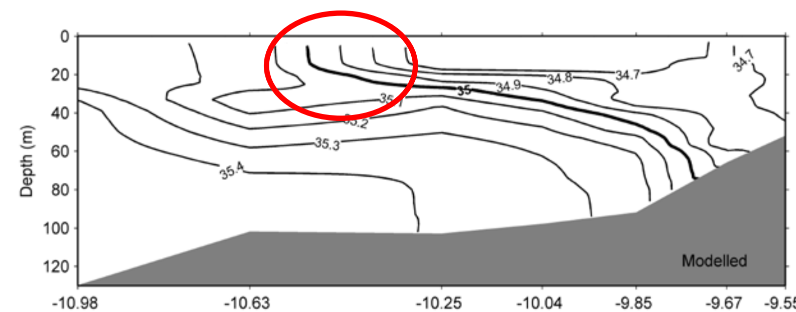




CTD



Model



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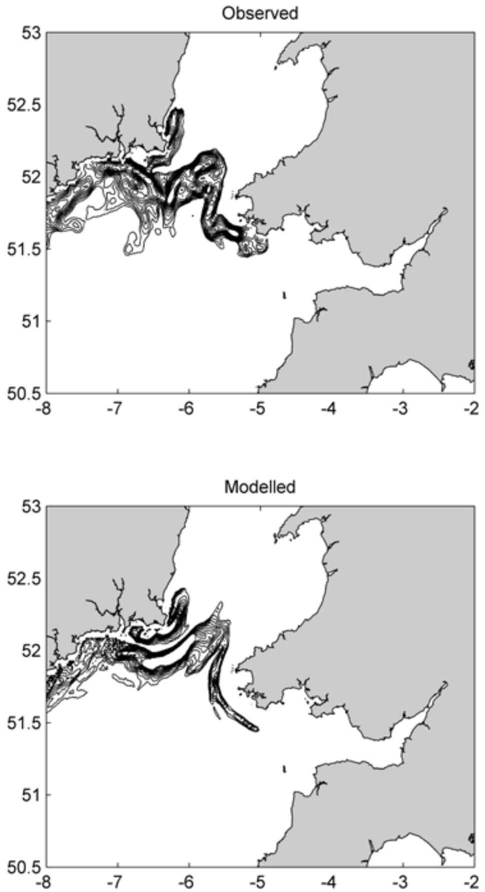
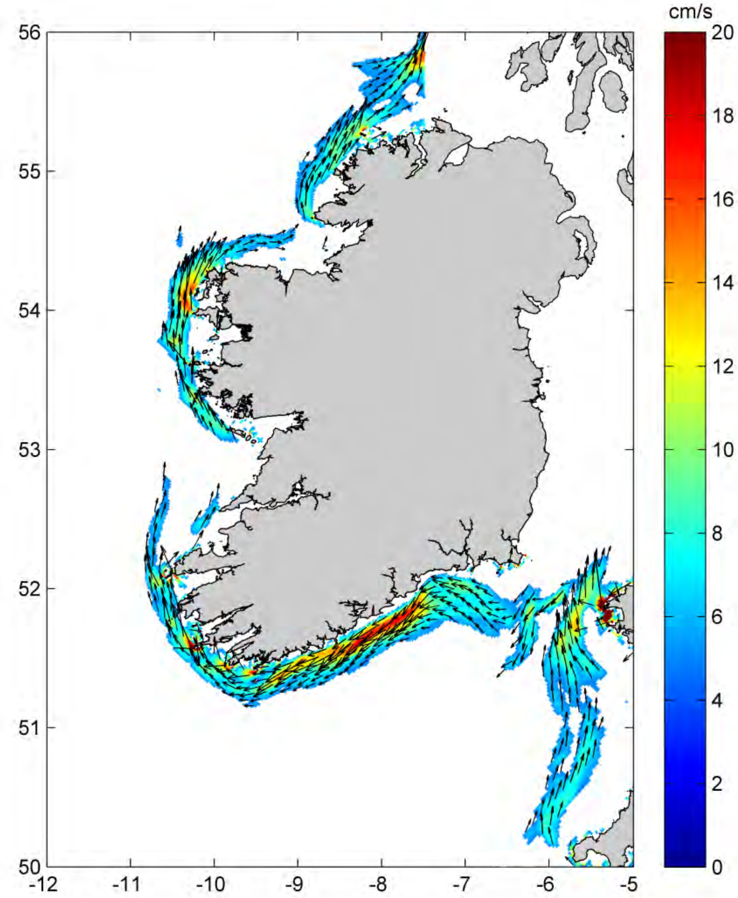
Rivers in the model are 'daily climatologies' !

NE Atl model validation

Position of the Celtic Sea front

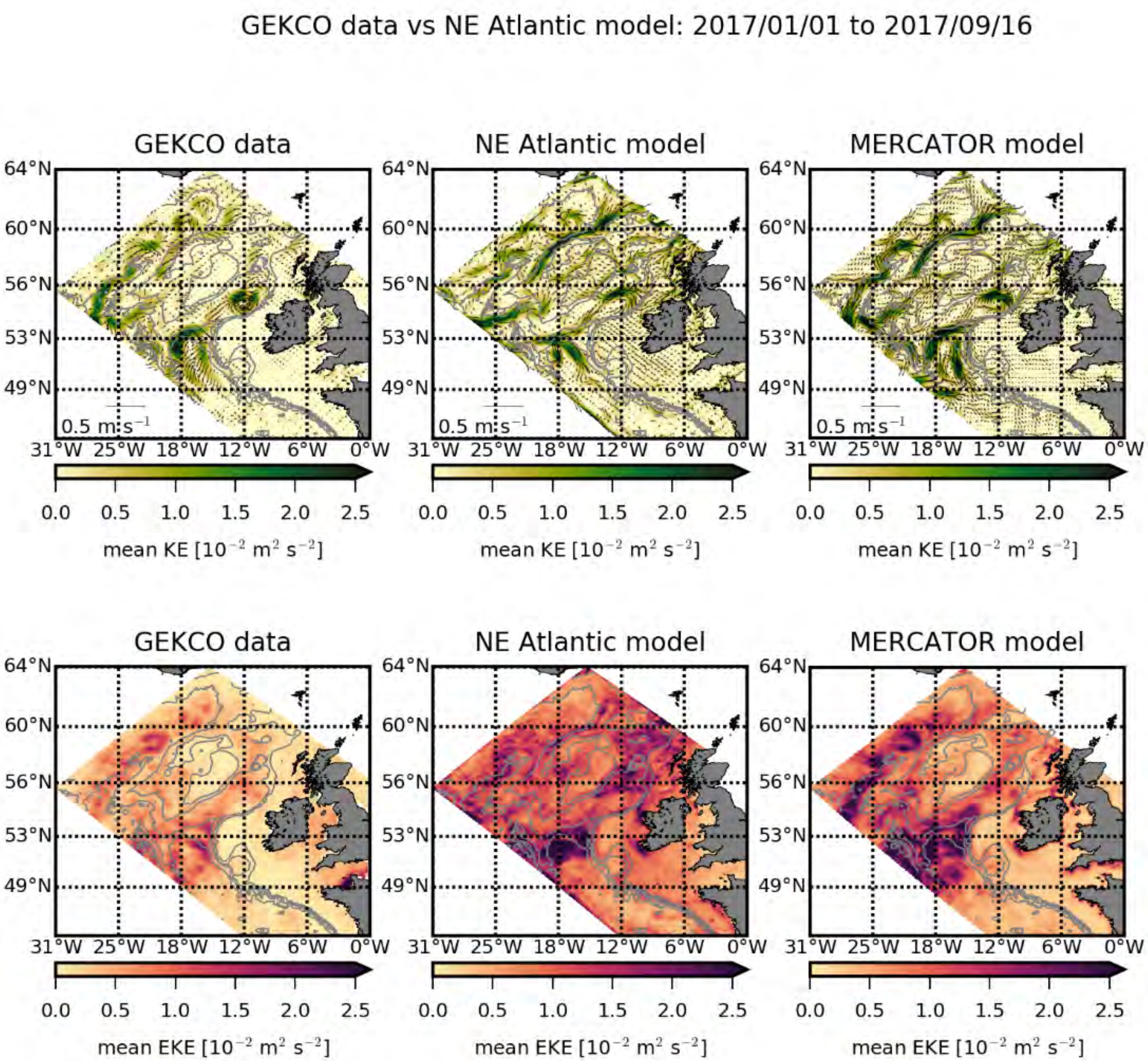


Expression of Irish Coastal Current



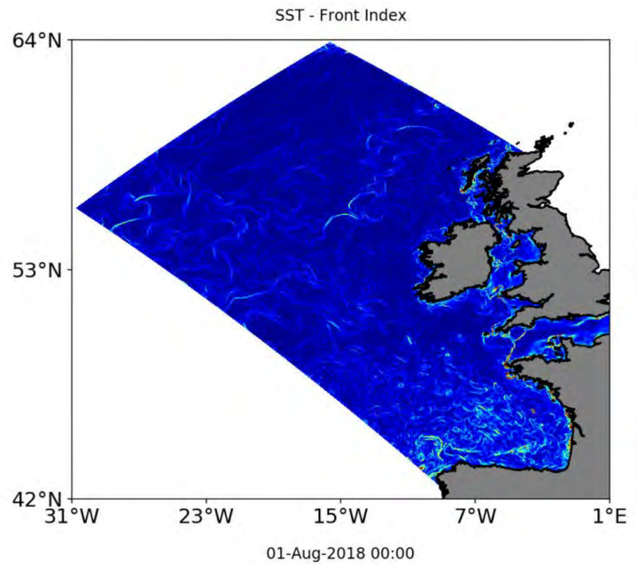
NE Atl model validation

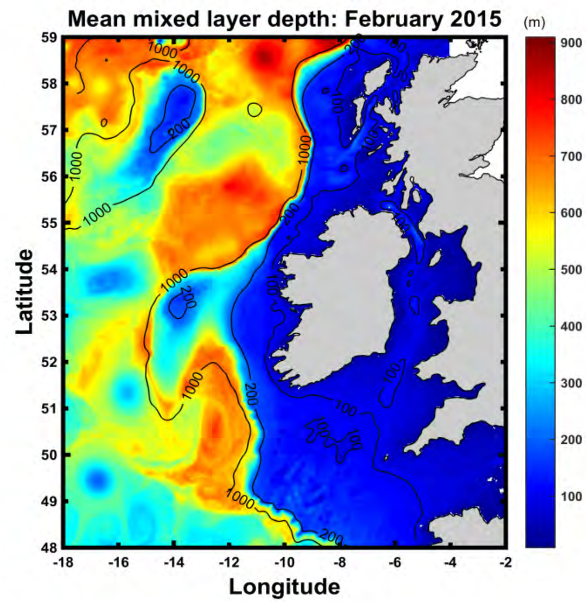
Kinetic energy

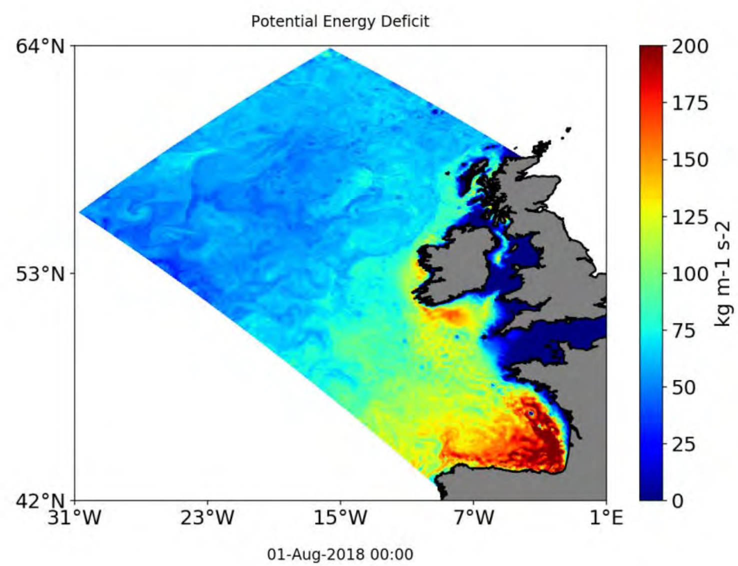


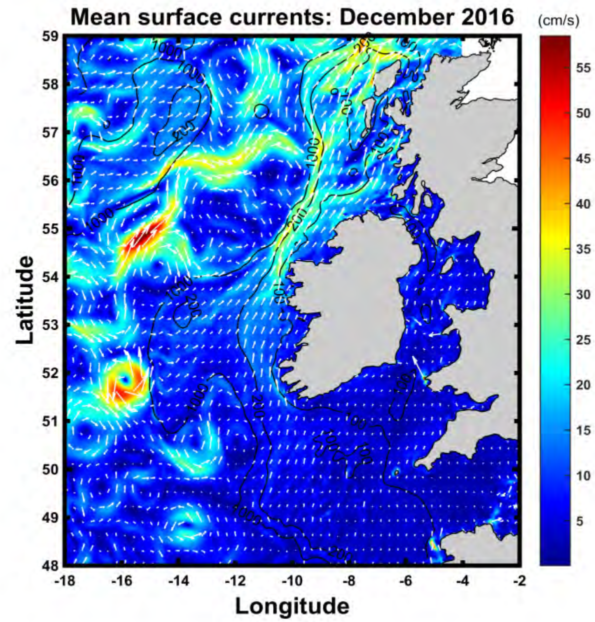
- MKE and EKE calculated from geostrophic current from altimetry GEKCO data and surface current from NEA and MERCATOR models.
- The variability in NEA and MERCATOR models are highest than GEKCO

Some indices being developed for various EU projects









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Room for improvement – *Data assimilation*

MI are funding a **PostDoc Fellowship** in DA to the MI models. Submitted proposals are under review.

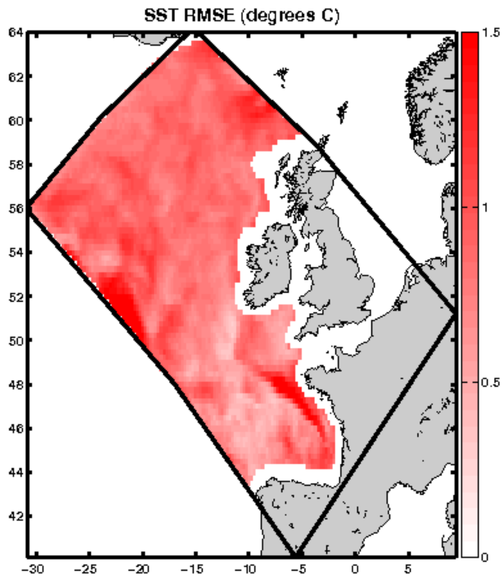
Currently, we have simple Newtonian nudging in the model:

- T & S along the boundaries $t_{i,j,k} = t_{i,j,k} + dt * T_{nudgcof} * (tclm_{i,j,k} - t_{i,j,k})$
- SST at surface $Shflx_{i,j} = Shflx_{i,j} + dQdt_{i,j} * (T_{i,j} - sst_{i,j})$

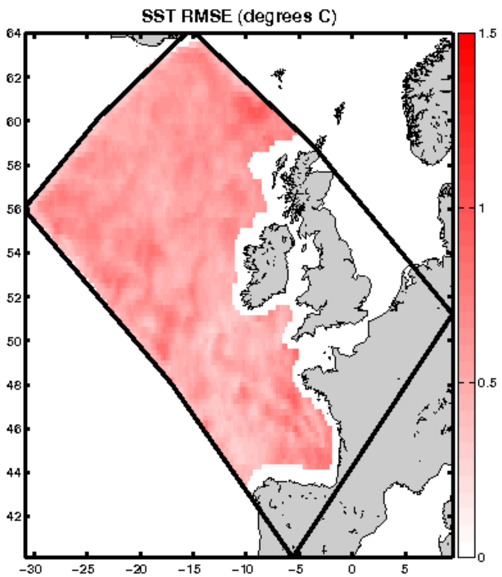
TS Argo profiles improvement

	Original Model Configuration		Model with nudging	
	Mean Error	RMSE	Mean Error	RMSE
Temperature (C)	-0.14	0.85	-0.05	0.70
Salinity	-0.01	0.105	0.0003	0.074

Without nudging



With nudging



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Room for improvement – *River discharges*

We are Associated Partnerts in the Copernicus LAMBDA project developing watershed models for predicting freshwater inputs

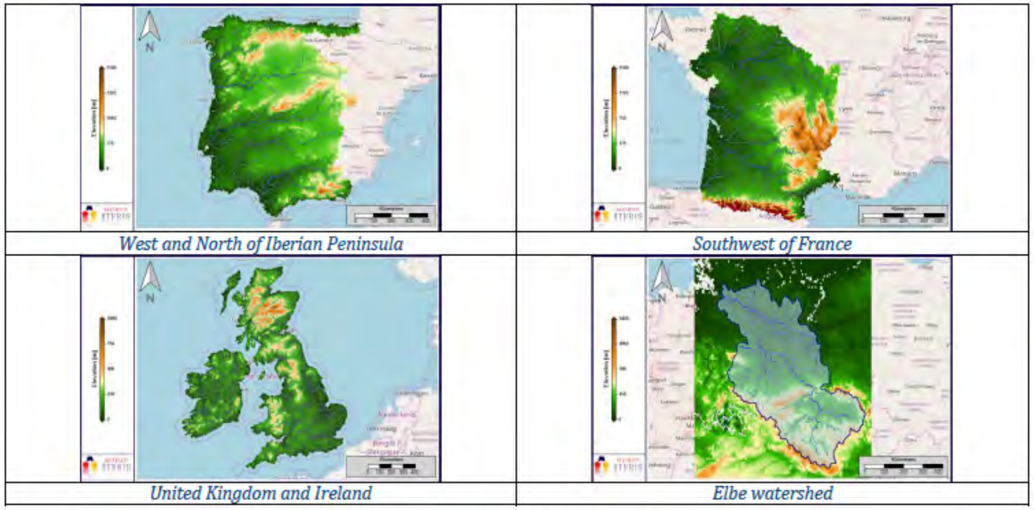
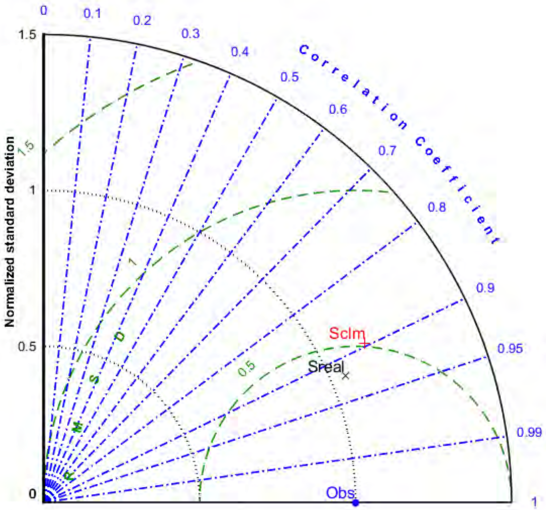
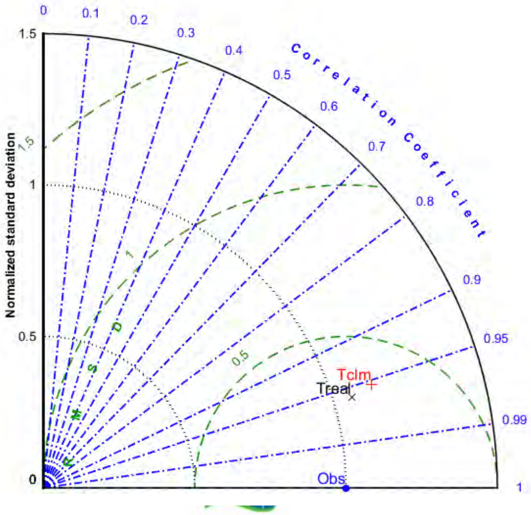


Figure 1 – LAMBDA project watershed modelled domains.

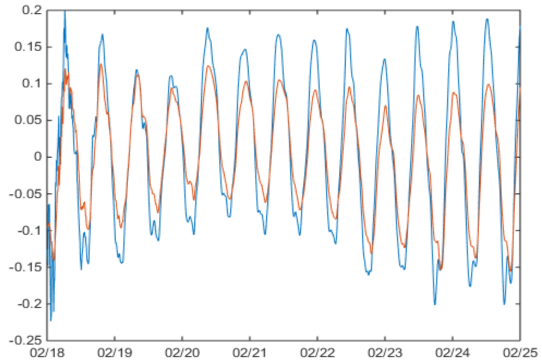
‘Real’ vs. ‘clim’ river discharges tested for 2009 -2011 period. Taylor diagrams show T & S validation against Hadley EN3 CTDs on the shelf





Selected other R&D

- Wave – current interactions: PhD fellowship funded at UCD (coastal scale model 'Connemara', ROMS + SWAN or WW3)



- R&D of coastal scale models includes:
  - Wetting-drying (implemented in 'Connemara')
  - 2-way nesting (implemented in Kenmare Harbour, ongoing work for Galway Bay)
  - Review atmospheric forcing (e.g. use of Met Eireann's forecasts)
  - Climate runs of SW Ireland model to include RCP 8.5 and 4.5

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Thank you

http://www.marine.ie/Home/site-area/data-services/marine-forecasts/marine-forecasts