Dynamics of upper ocean low-salinity waters in controlling winter convection, watermass transformation and spring blooms

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Helene Langehaug (Univ. of Bergen)
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Saattle 22 May 2011

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- **The list of extreme climate events in the subpolar Atlantic is long:**
  - **freshening** of the northern Atlantic (~1970s-1990s), e.g. Dickson *et al.Nature 2002)* **and increased Arctic outflow** (1970s and 1990s) and **increased Greenland melting**
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  - **slowing of the subpolar surface gyre** cyclonic gyre and associated variability of the deep circulation (1990s-2000s, *Hakkinen & Rhines Science 2004, Vẵge et Deep-Sea Res 2011, Dengler et al. GRL 2006, Han et al. GRL 2010.)*
  - **invasion of warm waters** from subtropics to subpolar Atlantic, Nordic Seas and associated change of general circulation (many authors, *e.g. Holliday et al. 2003, Hatun et al. Science 2004, Hakkinen & Rhines, JGR 2009, 2011)*

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- **atmospheric circulation variability** associated with high latitudes in recent decades (poleward shift of jet stream, blocking histories, storm tracks..) (e.g. *Woollings et al. Q.J.Royal Met. Soc. 2010)*
- **dislocation of fisheries, ecosystems**, birds, whales…*(many authors, e.g. Hatun et al. Prog. in Oceanogr. 2009, Laidre et al., Proc. Royal Soc. B, 2008)*

The Atlantic meridional overturning circulation (warm=red cold=black, purple

note the interlinked horizontal gyres, boundary currents and vertical circulation (sinking of dense waters, rising again far to the south)

In the upper ocean, low salinity waters flow from the Arctic, both east and west of Greenland

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3 decades of decrease in salinity of the subpolar gyre and Nordic Seas

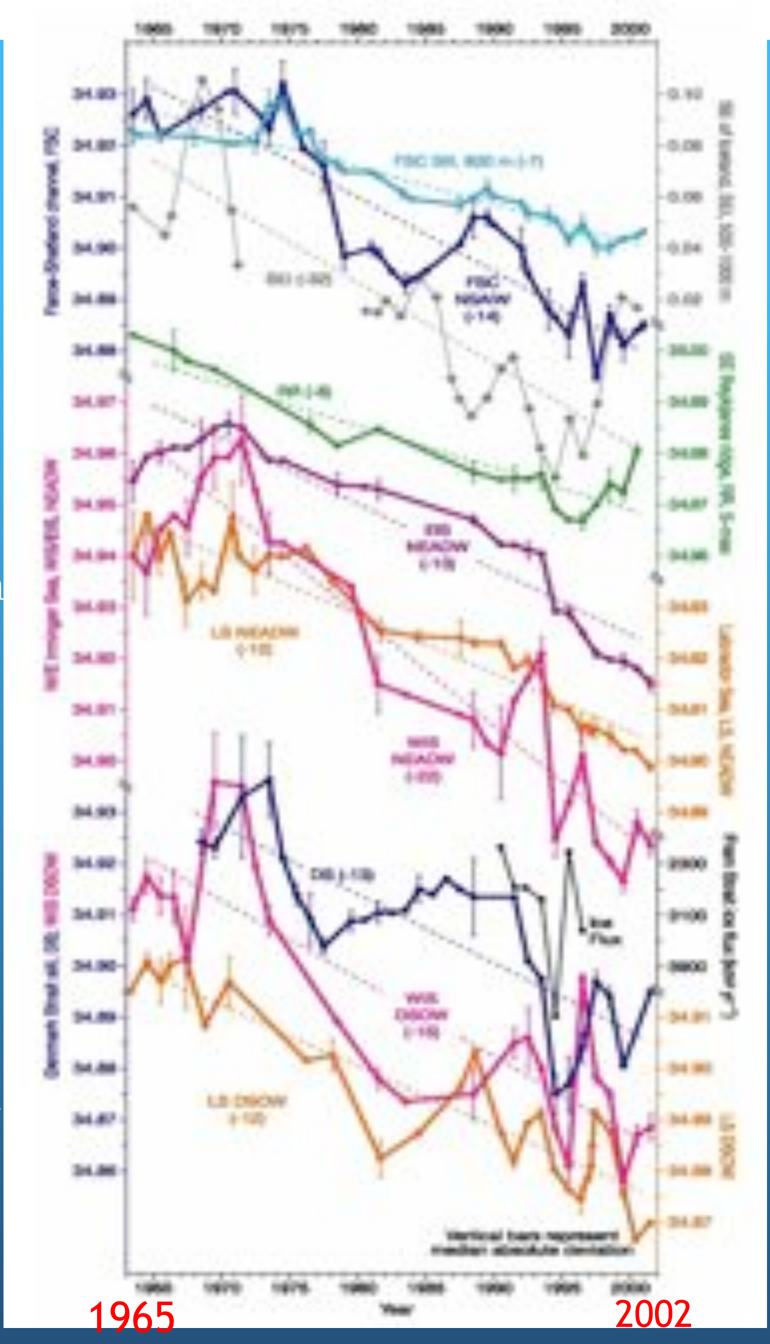
(here, the overflows, gyre and Labrador Sea from 1960 – 2002)

Fram Strait

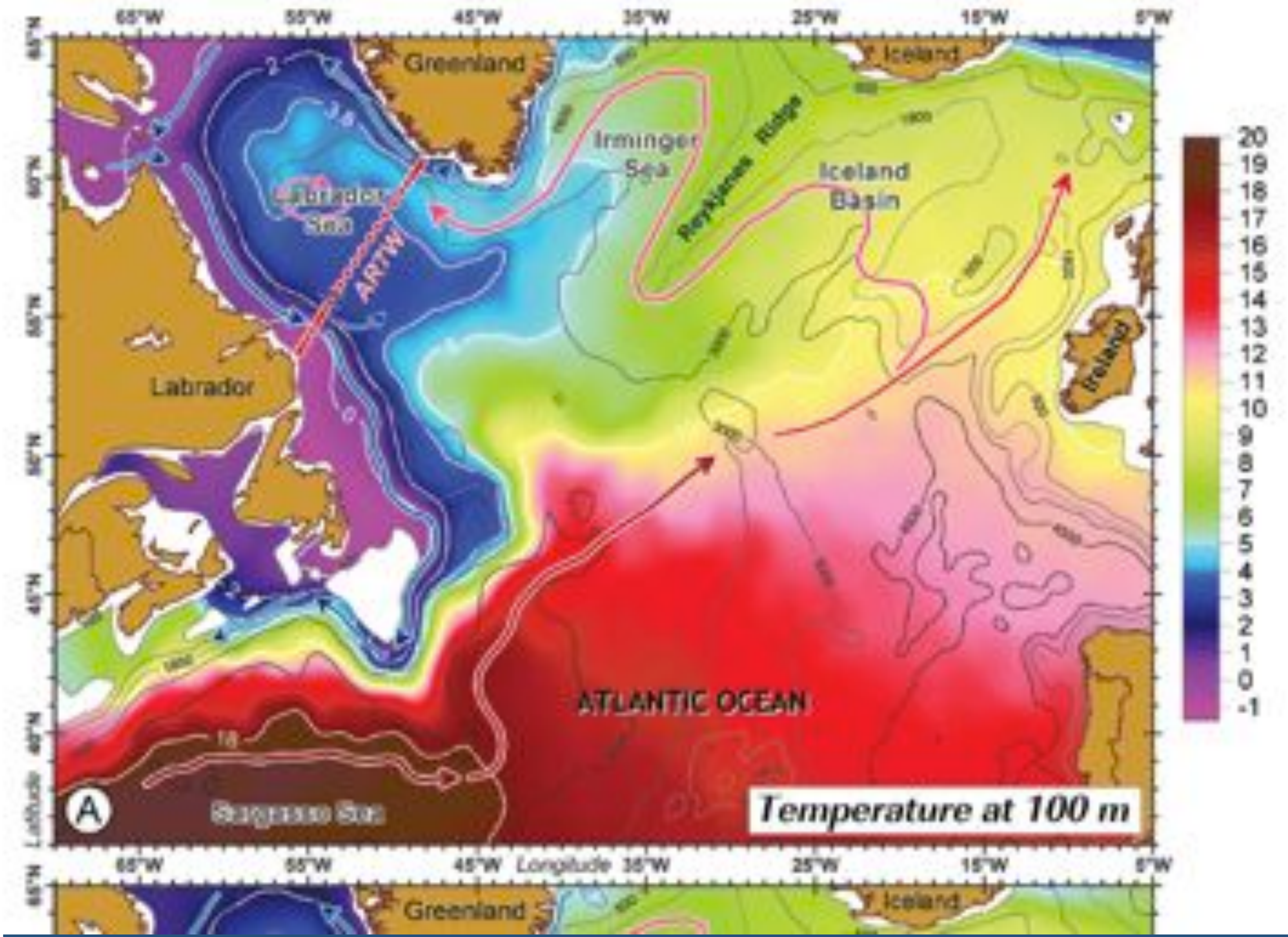
Iceland Basin

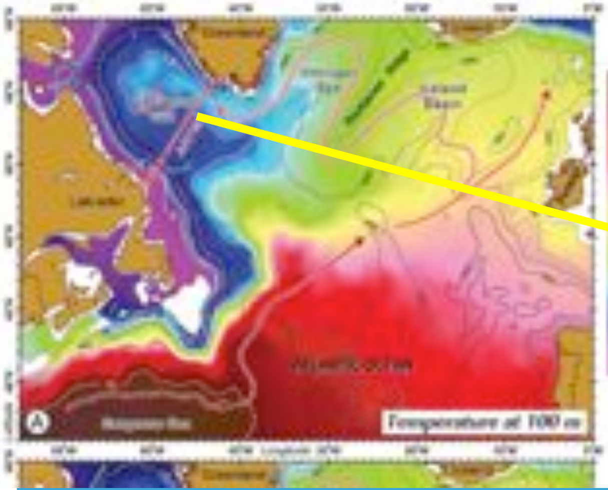
Denmark Strait

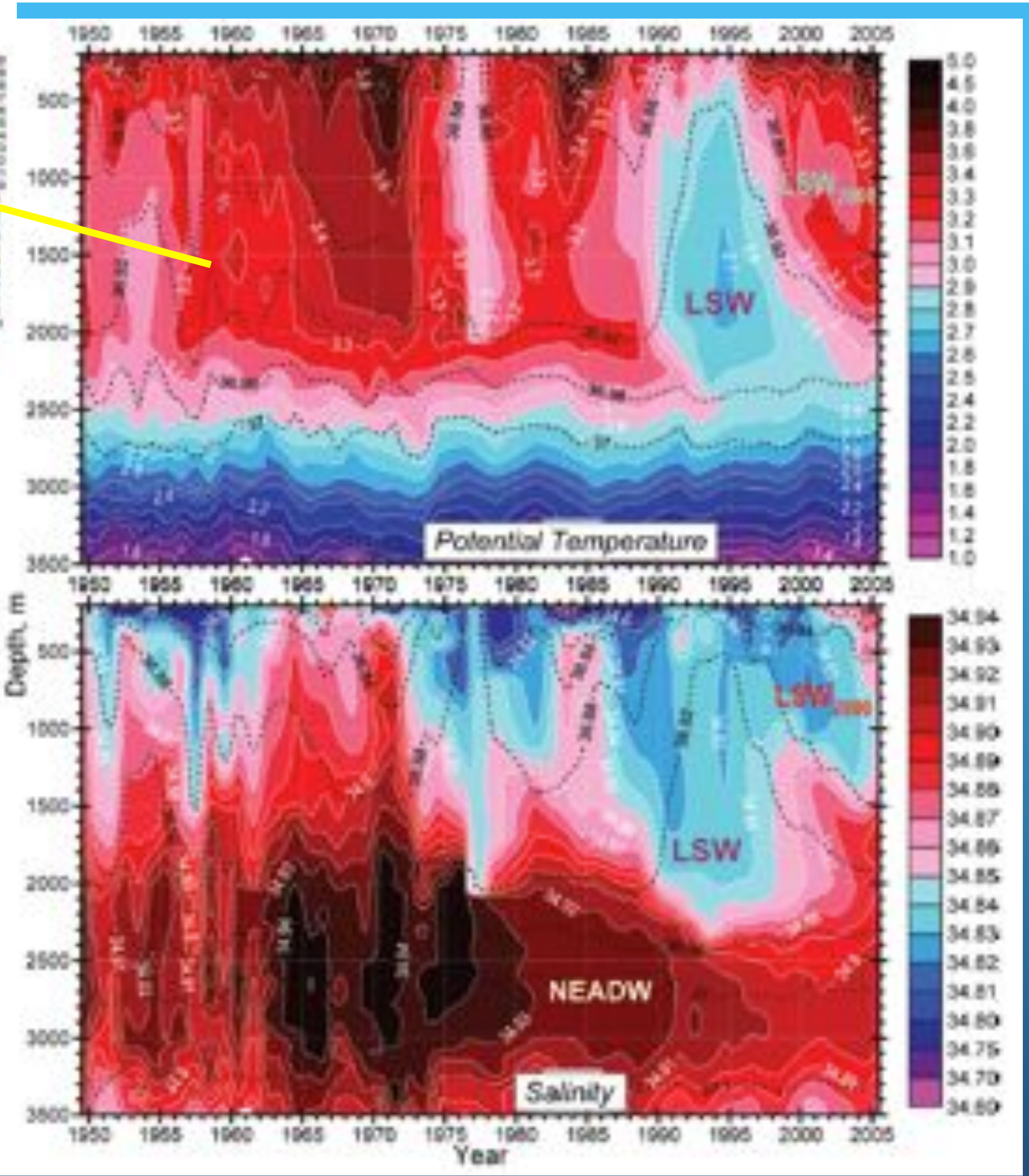
Labrador Sea



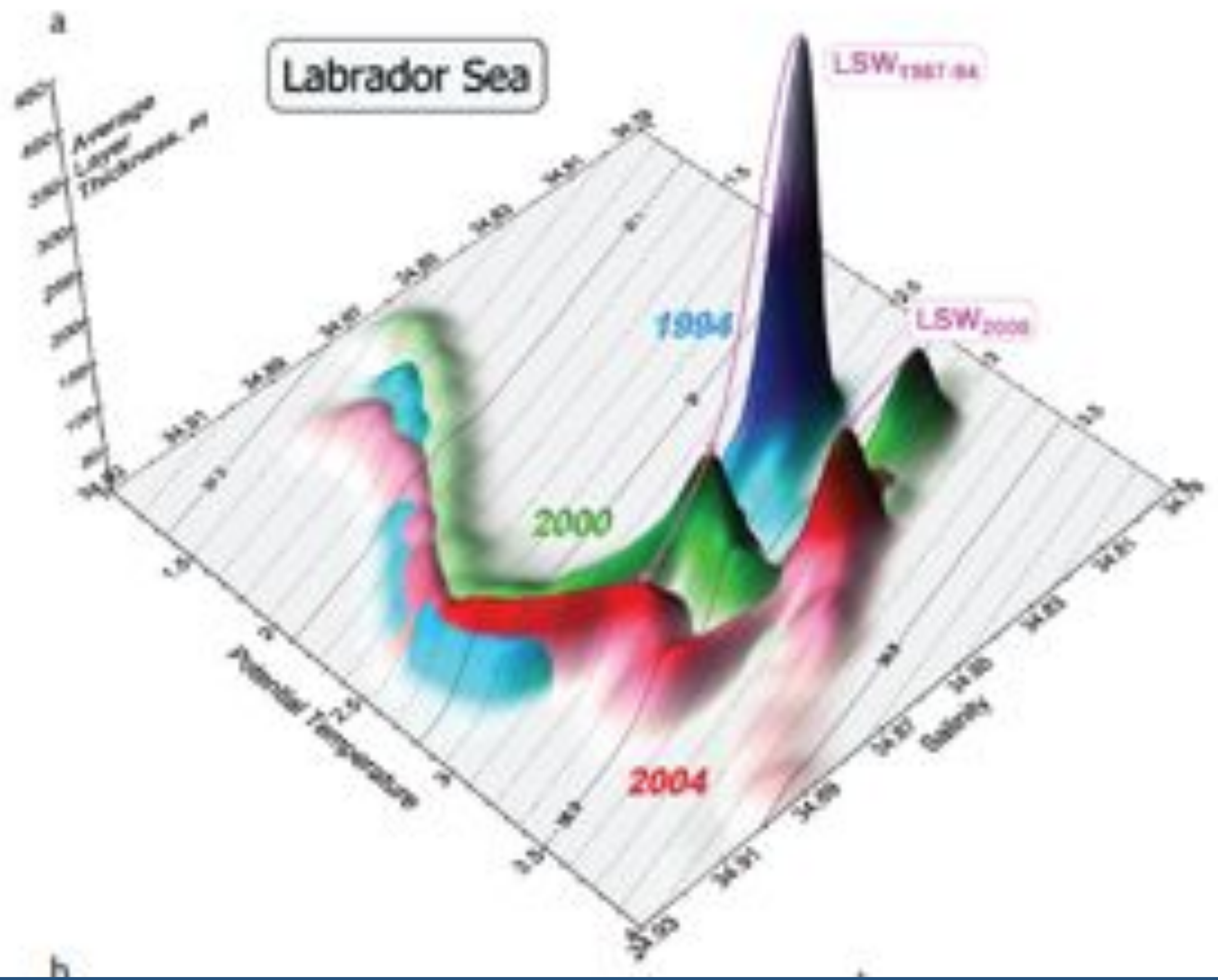
Dickson, Yashayaev, Meincke, Turrell, Dye and Holfort, Nature 2002


65°W
55°W
45°W
35°W
25°W
15°W
5°W
65°N
60°N
55°N
50°N
45°N
40°N
Latitude
Longitude
Greenland
Iceland
Irminger Sea
Reykjanes Ridge
Iceland Basin
Labrador Sea
ARTW
Labrador
Ireland
ATLANTIC OCEAN
Sargasso Sea
A
Temperature at 100 m
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1





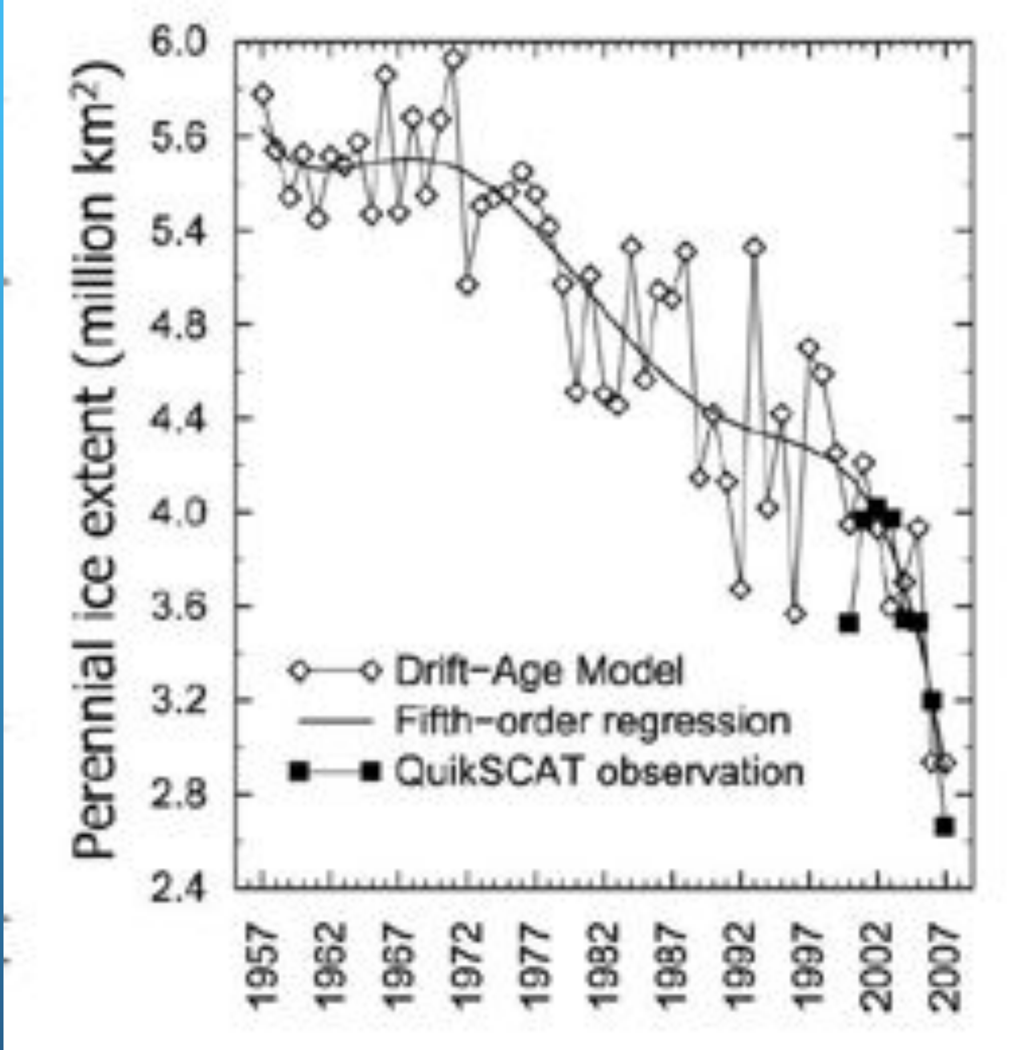
Yashayaev 2005
Oceanography

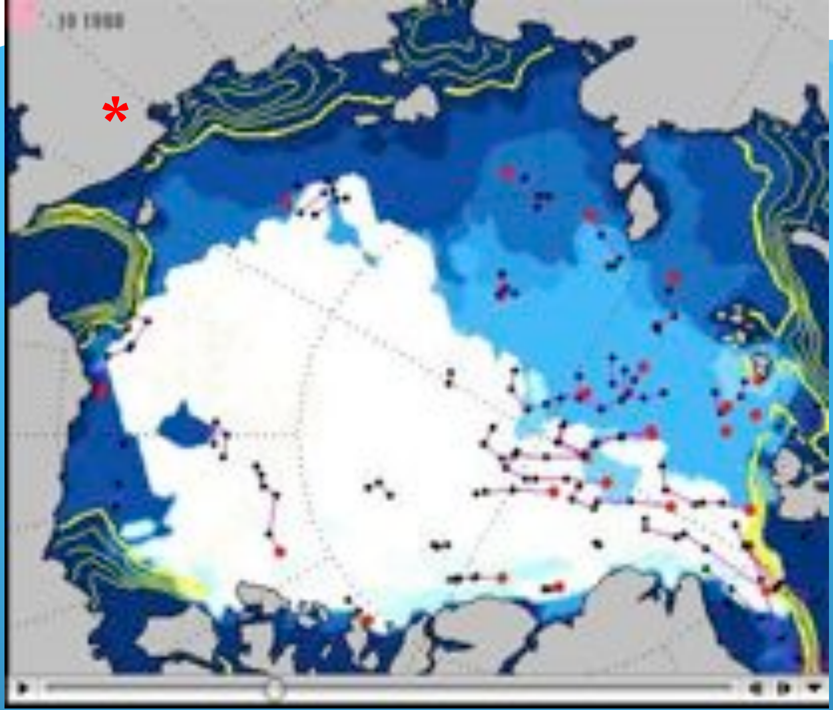

a
Labrador Sea
Average Layer Thickness, m
LSW1987-94
LSW2000
1994
2000
2004
Potential Temperature
1.5
2
2.5
3
3.5
Salinity
34.93
34.91
34.89
34.87
34.85
34.83
34.81
b

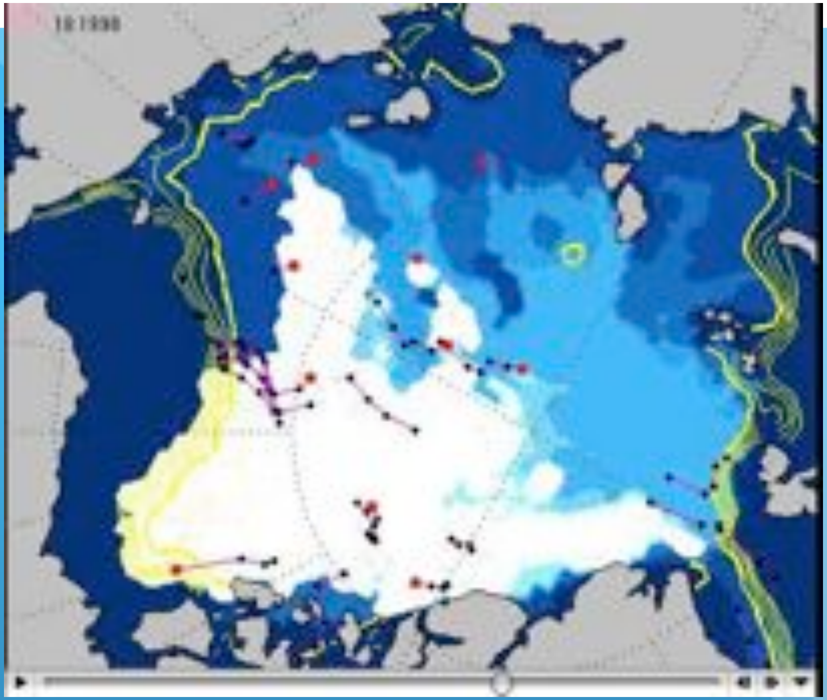
Relevant to the near-surface outflow of low-salinity water,

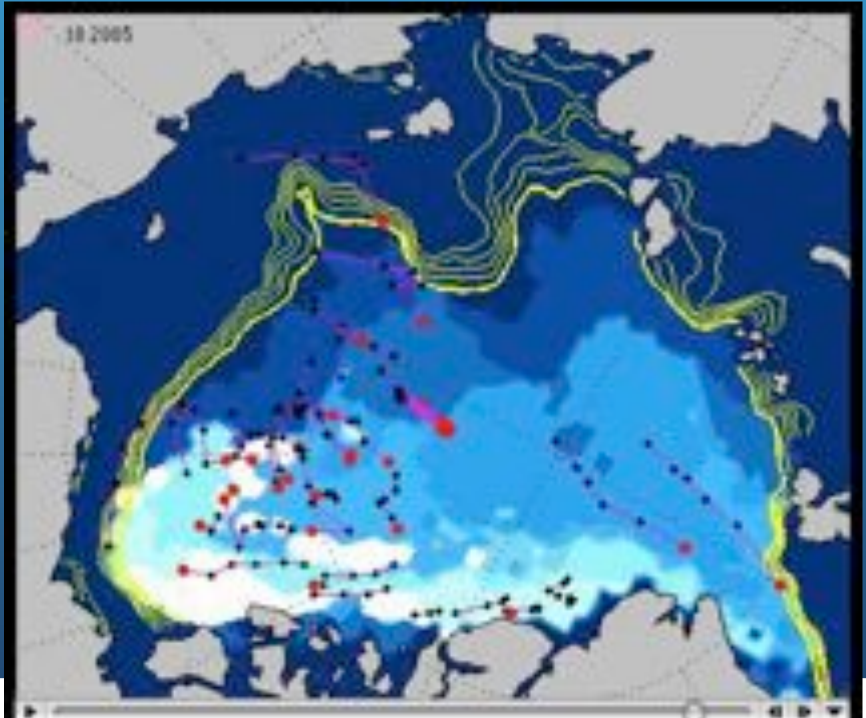
perennial (multi-year) ice cover in the Arctic Ocean, 1957-2007: ice thickness video reconstructed from icebuoys and winds: http://seaice.apl.washington.edu/

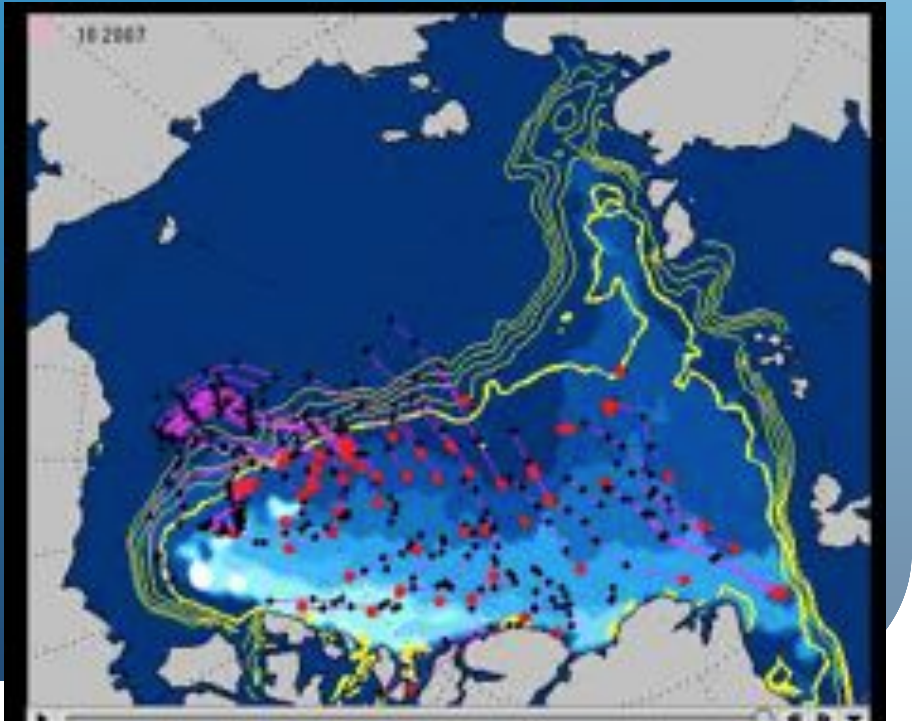
Ignatius Rigor, GRL 2007



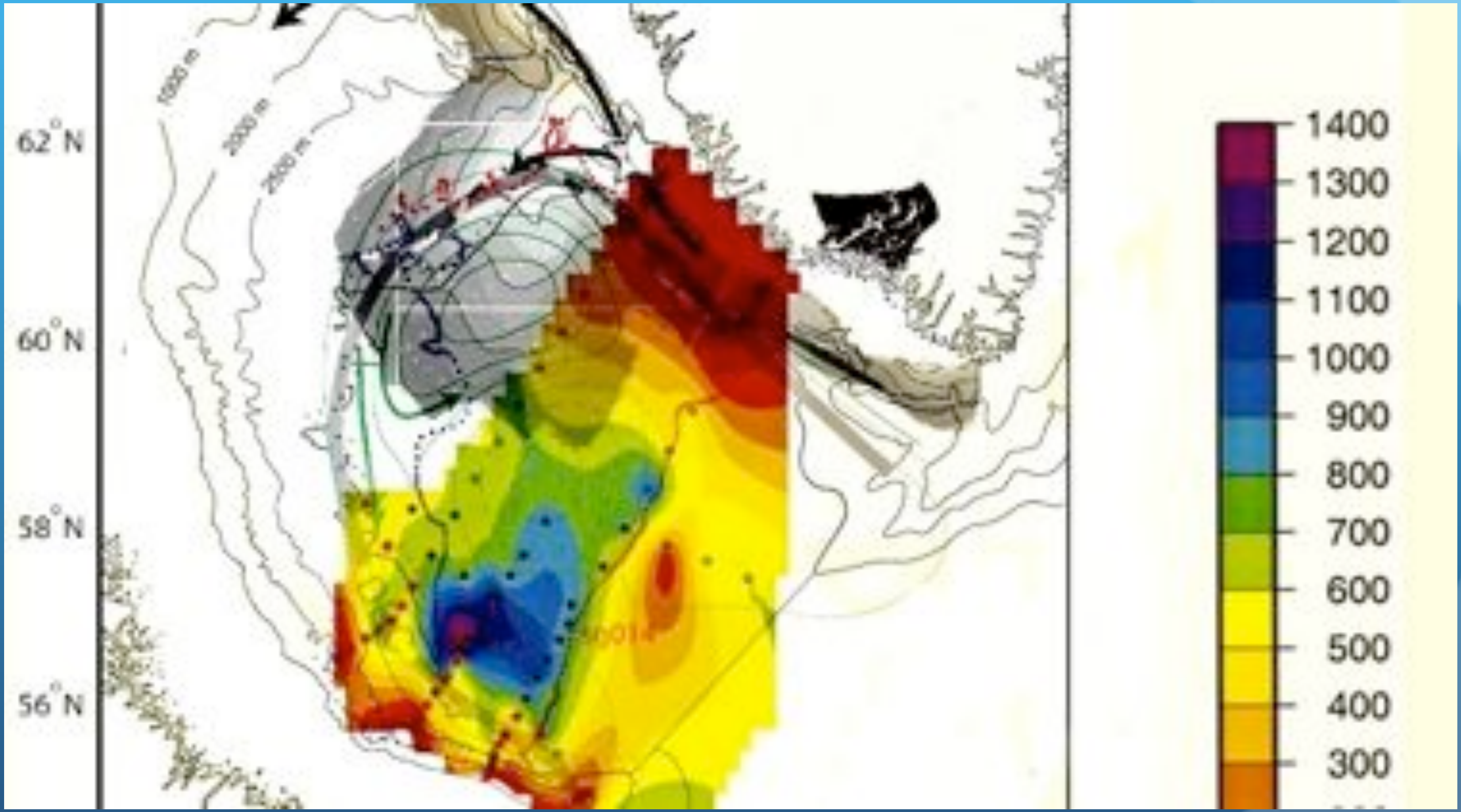

10 1988


10 1998


10 2005


10 2007

Hatun et al 2007 JPO: site of deep convection from Pickart et al. 2002.JPO controlled by the plume of FW from west Greenland boundary current/shelf



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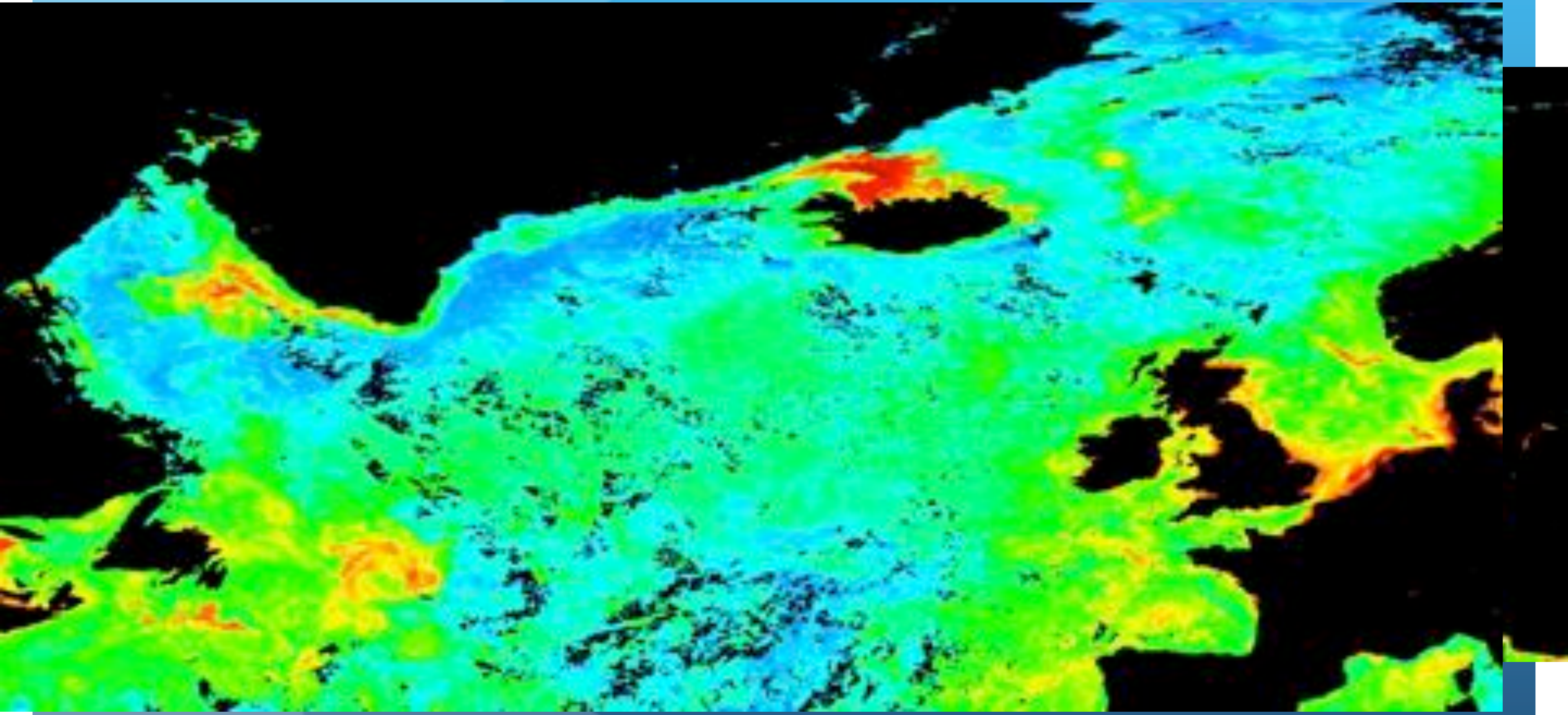
Connections with upper ocean biology

Spring bloom, Labrador Sea

(Frajka-Williams et al., Deep-Sea Res. 2009, 2010)

SeaWiFS satellite: oceanic surface phytoplankton
2005 days 91-120



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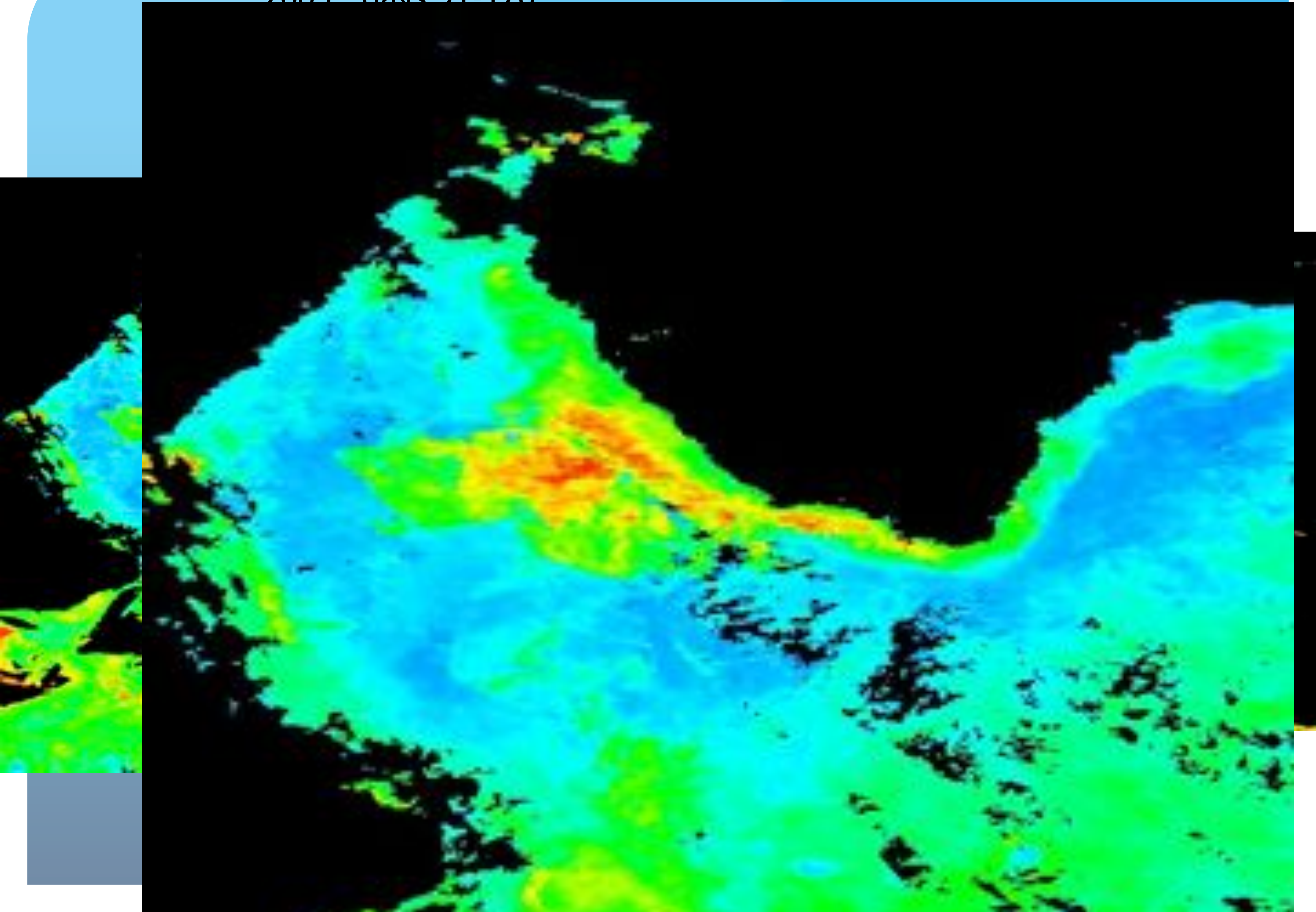

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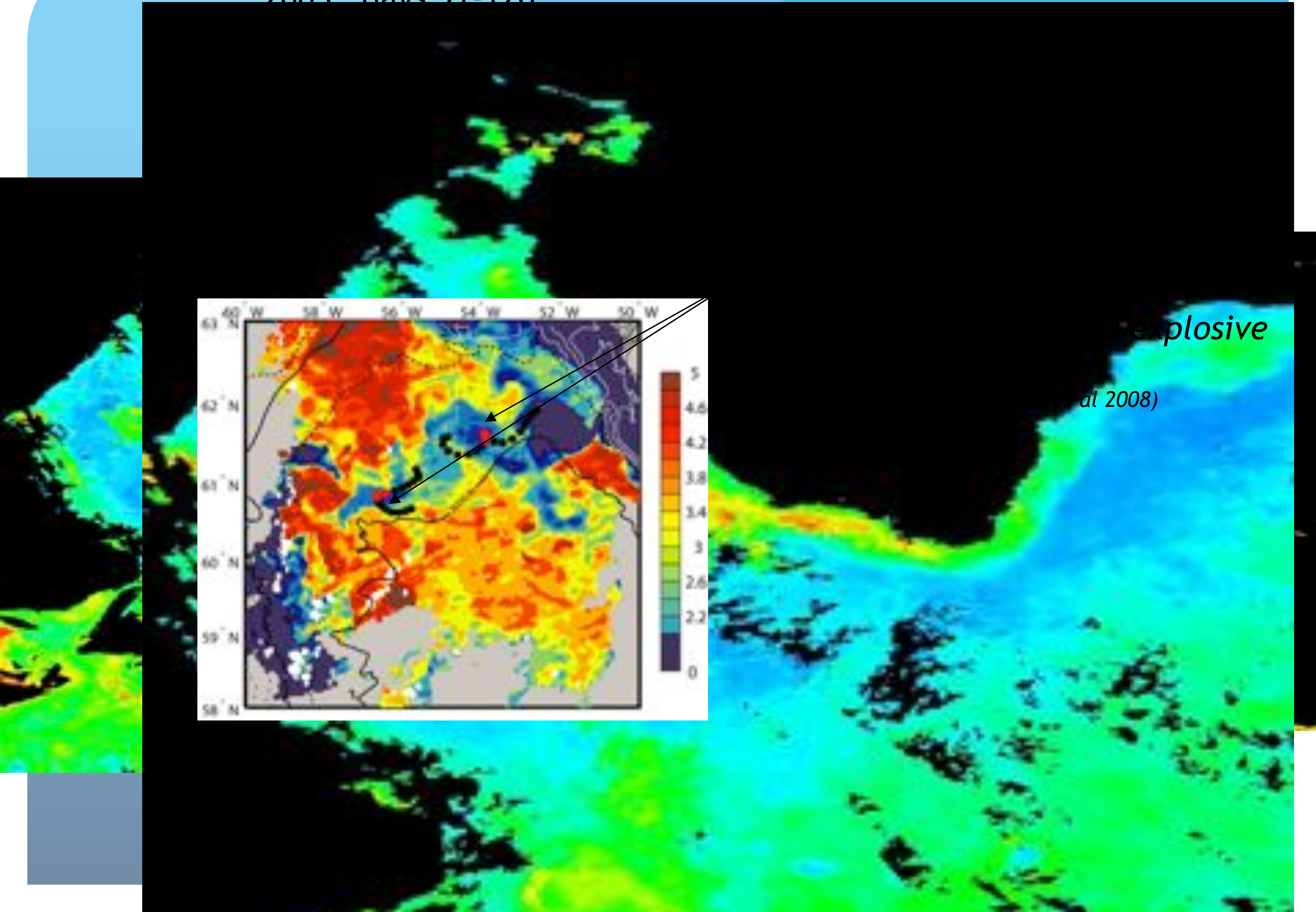


xplosive

al 2008)

Seaglider: 1.8 m long (+ antenna), 52 kg.
range ~ 5000 km, power consumption ½ Watt
Lithium battery pack: 10MJ + ~ 3 Kwh

Low salinity surface waters flowing from near the coast of Greenland, and from local run-off, and sea ice melt produce a buoyant 'blanket' over the ocean which stabilizes the water column.

{ *Steffen (Hydrolog. Processes 2009)*
estimates that Greenland runoff + ice calving is now ~ 3 times bigger than in recent decades ~ 786 km^3 yr^{-1} contributing 0.7 mm yr^{-1} to global sea level rise…roughly 25%
…and 17% of the FW input to the Greenland Sea
(4700 km^3 yr^{-1} coming from the Arctic).}

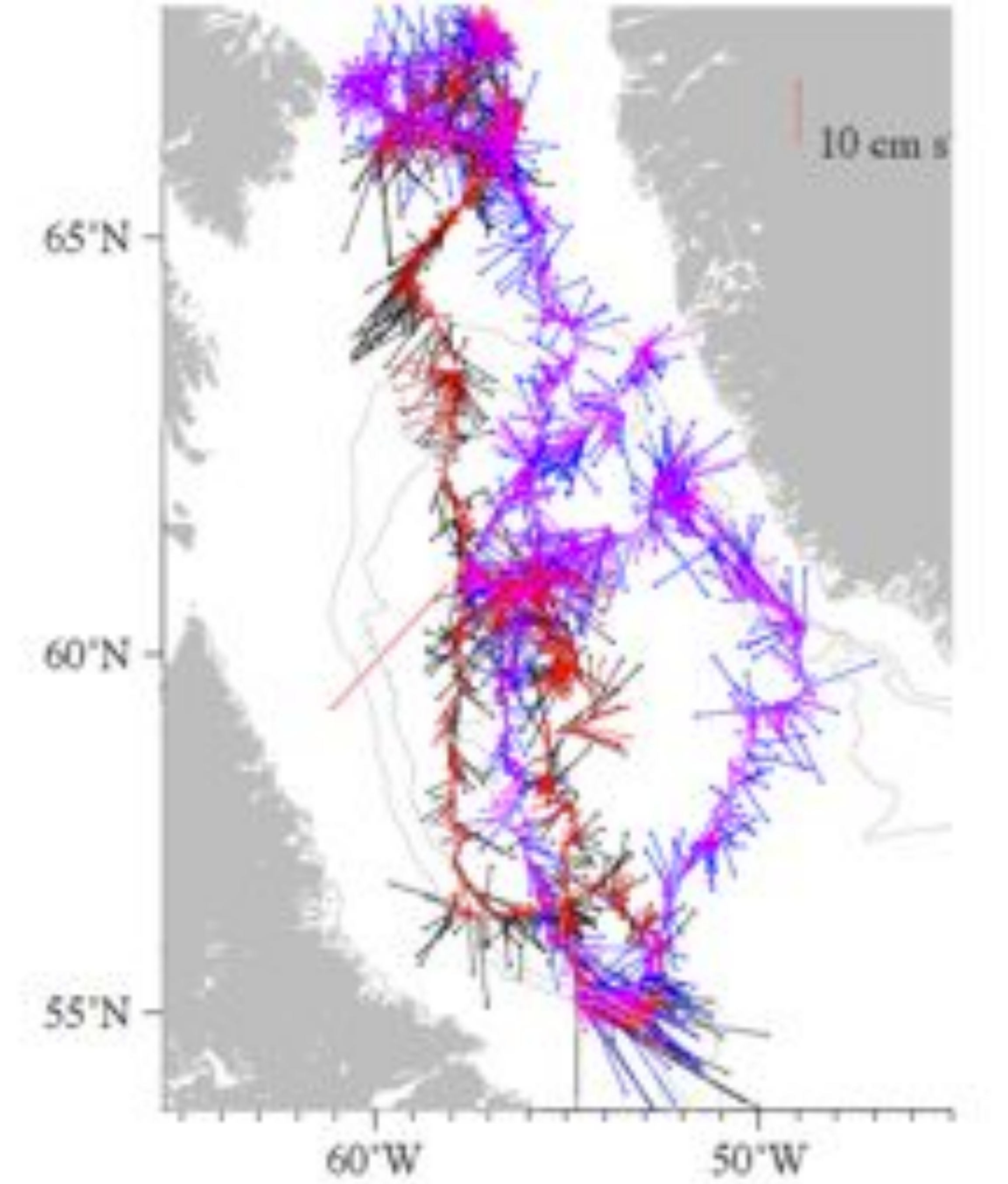
Plankton can happily remain in the sunshine, and their growth initiates an intense growth of zooplankton (*Calanus finmarchicus* especially), all the way to large animals and birds.

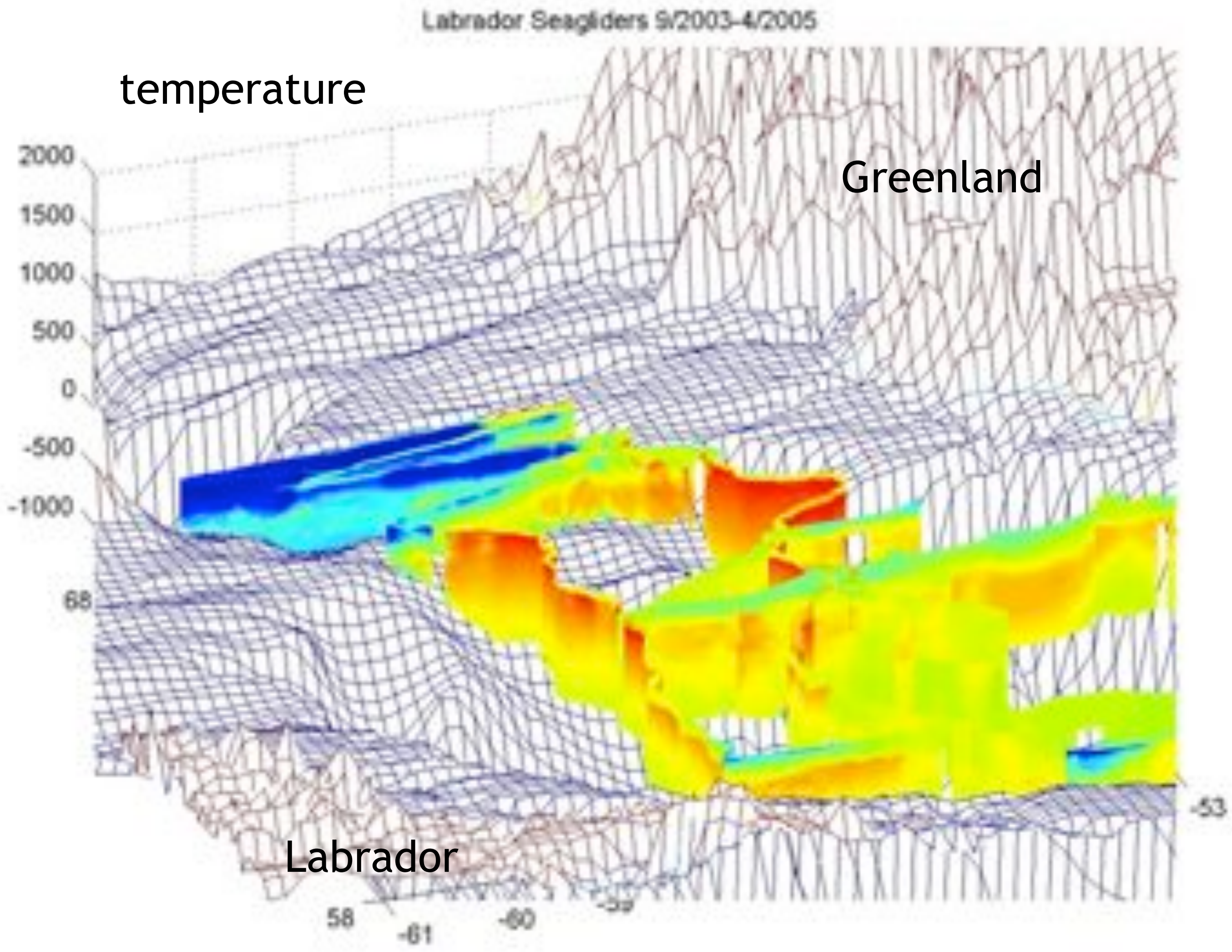
➔This is the dominant spring bloom in the northwest Atlantic

*

Seaglider sections, from the latter part of the first major deep-sea deployment of the Seaglider, 2003-2005

(depth-averaged velocity vectors (blue or red) and surface current vectors purple or black)

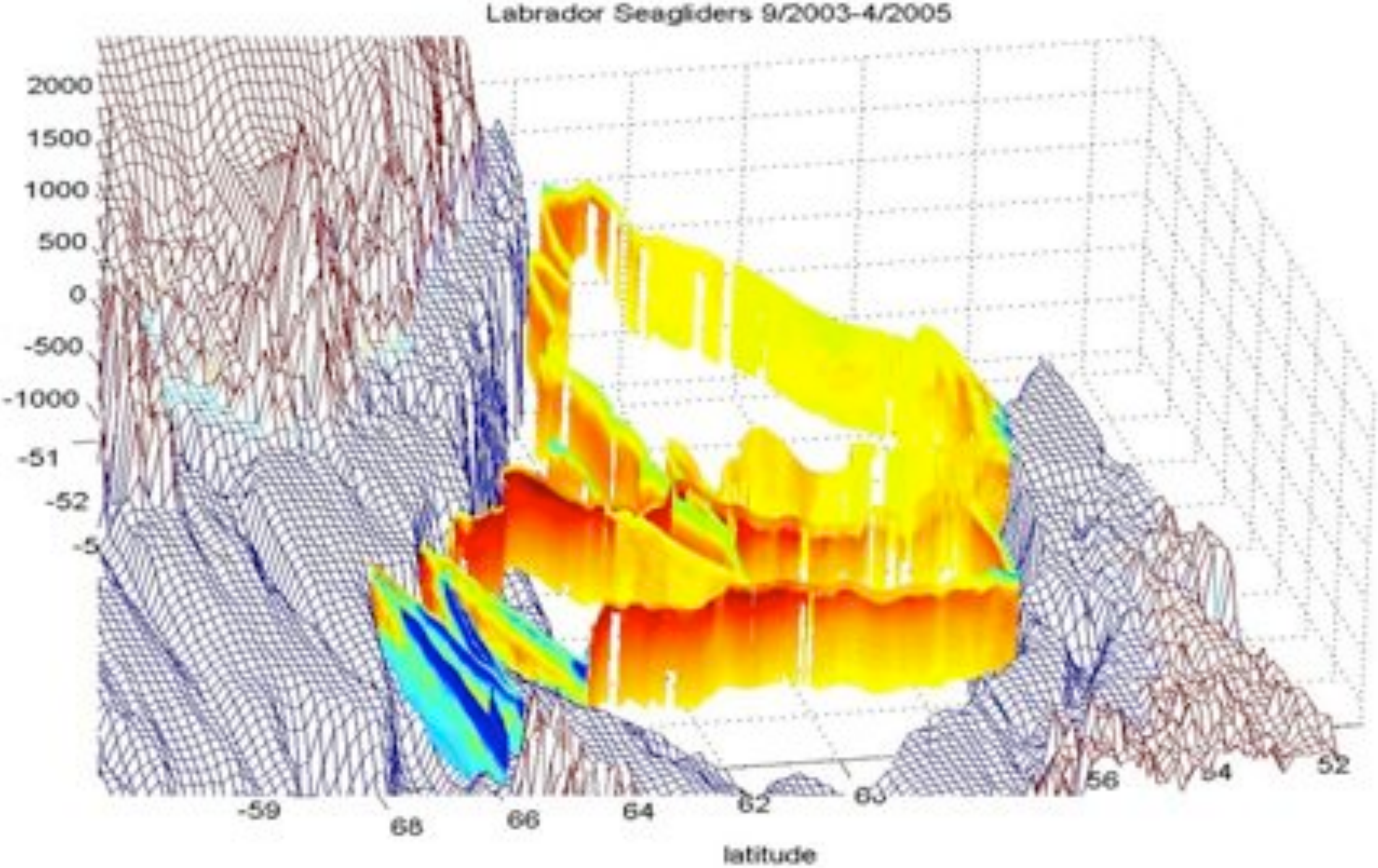




temperature

Greenland

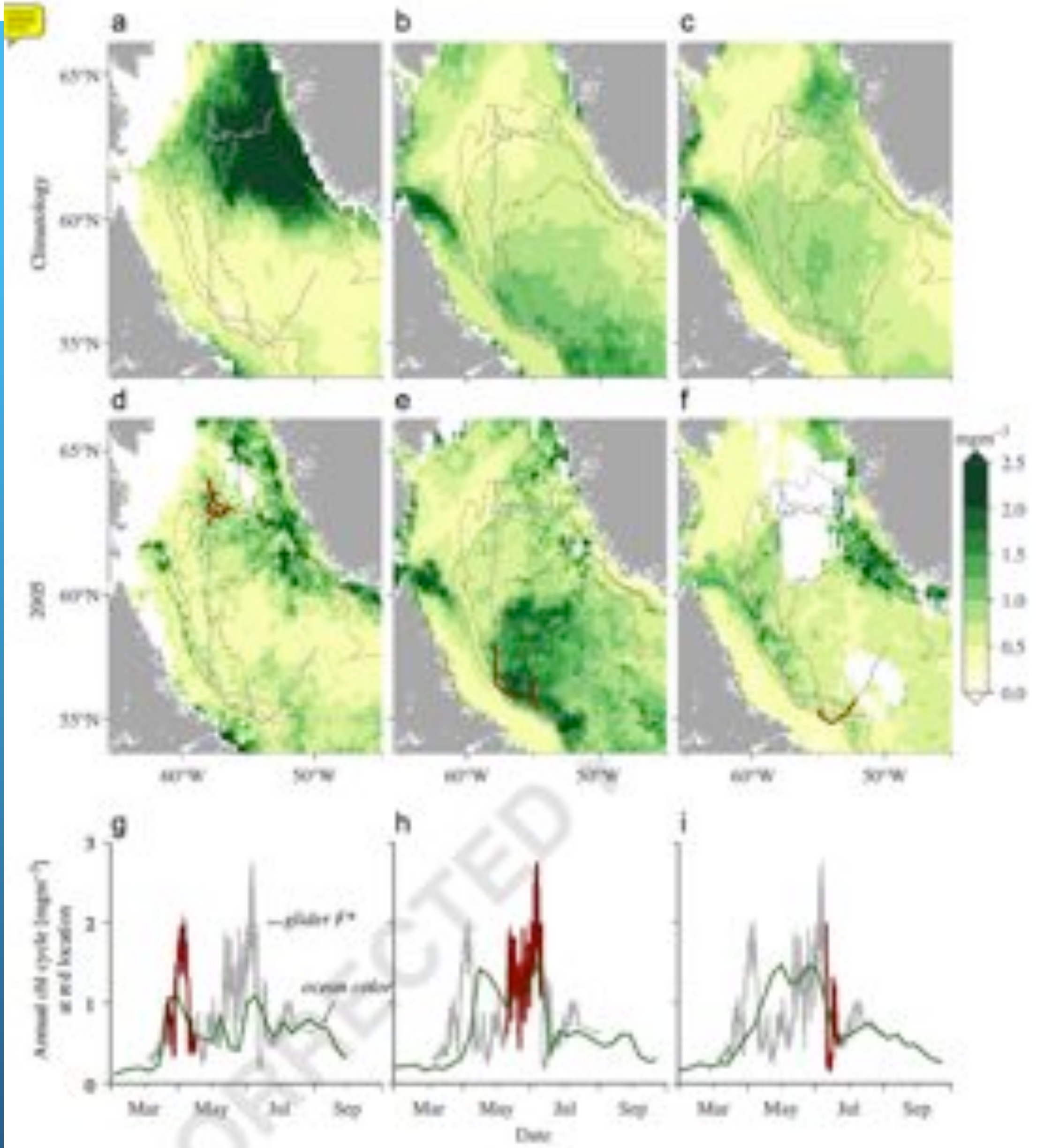
Labrador


Labrador Seagliders 9/2003-4/2005
2000
1500
1000
500
0
-500
-1000
-51
-52
-5
-59
68
66
64
62
63
56
54
52
latitude

climatology
of spring bloom
from SeaWiFS
ocean color

2005 bloom with
Seagldier tracks
superimposed:

April, June and July



5. Comparison of climatological and 2005 surface chlorophyll (rows 1: a–c and 2: d–f) with glider track marked in gray), and glider chlorophyll
surements in the top 20 m with SeaWiFS chlorophyll annual cycle (row 3: g–i). The three time periods for each column are roughly one month long
correspond to the glider location highlighted in red in row 2. In this way, the spatial pattern of chlorophyll while the glider made a single track of
surements is revealed. For the annual cycles in row 3, SeaWiFS chlorophyll (green) is from the location in row 2, allowing a direct comparison
een Seaglider measurements and SeaWiFS where the Seaglider chlorophyll is highlighted in red. Row 3 shows when the Seaglider measured
rophyll relative to the local bloom timing. From (g) the glider observations during this region and time were during the local peak and decline of the
n. From (h) the glider observed a secondary peak for this region. From (i) the glider made observations after the local peak bloom had declined. (For
rpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Close up of offshore plume of fresh near-surface water in Labrador Sea: *(Frajka-Williams& Rhines DSR 2009, 2010)*

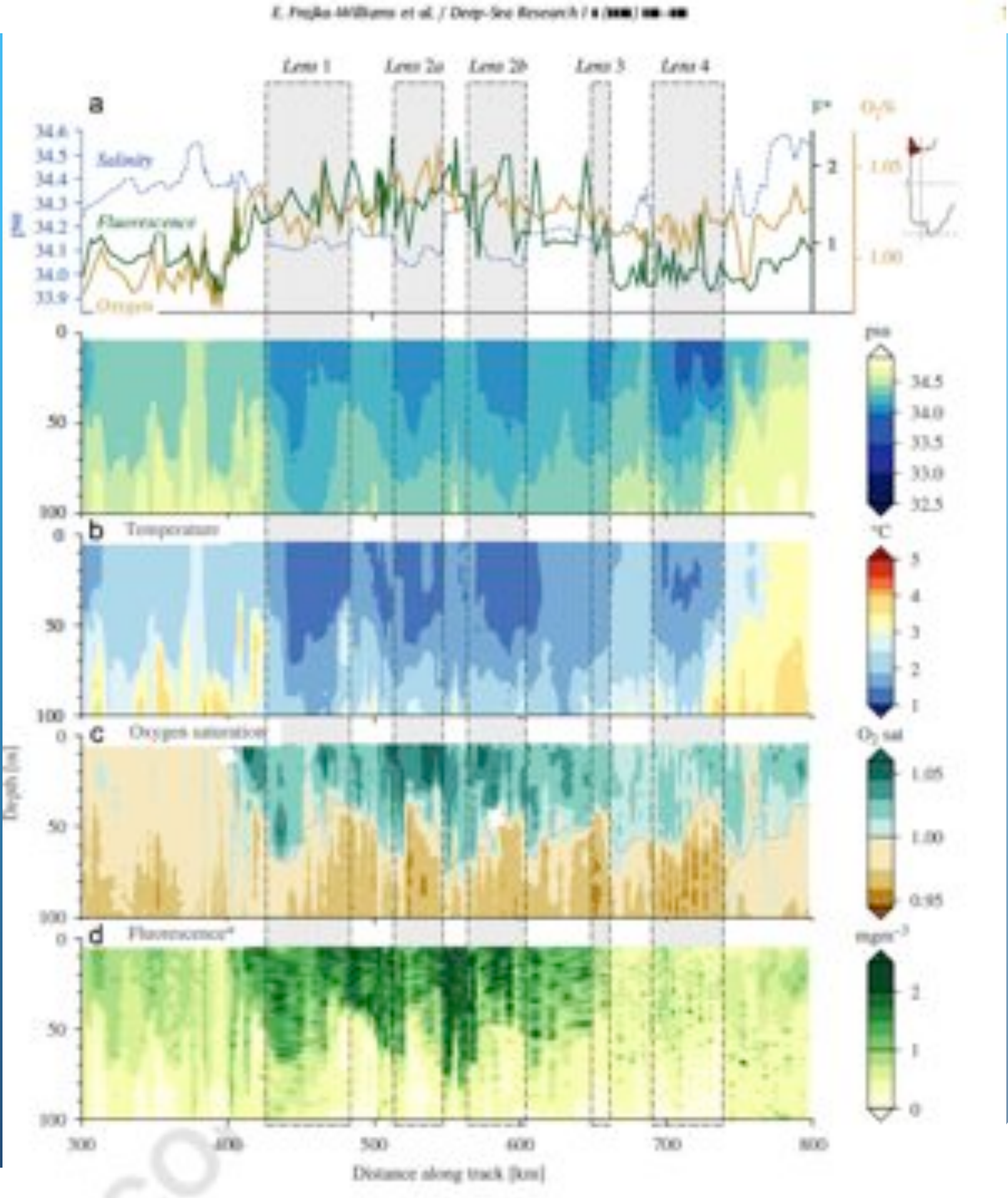
sections 0-100m

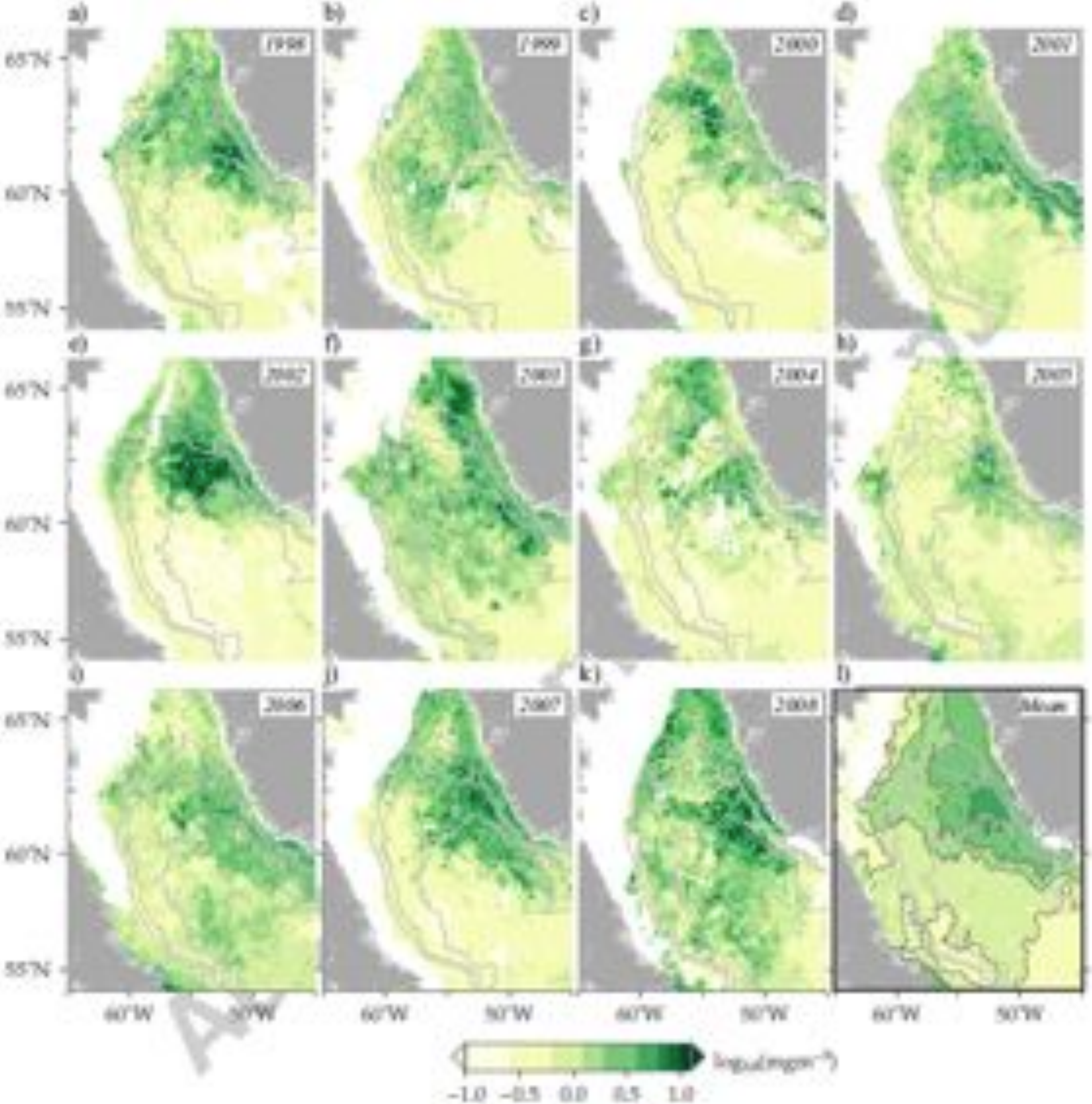
S

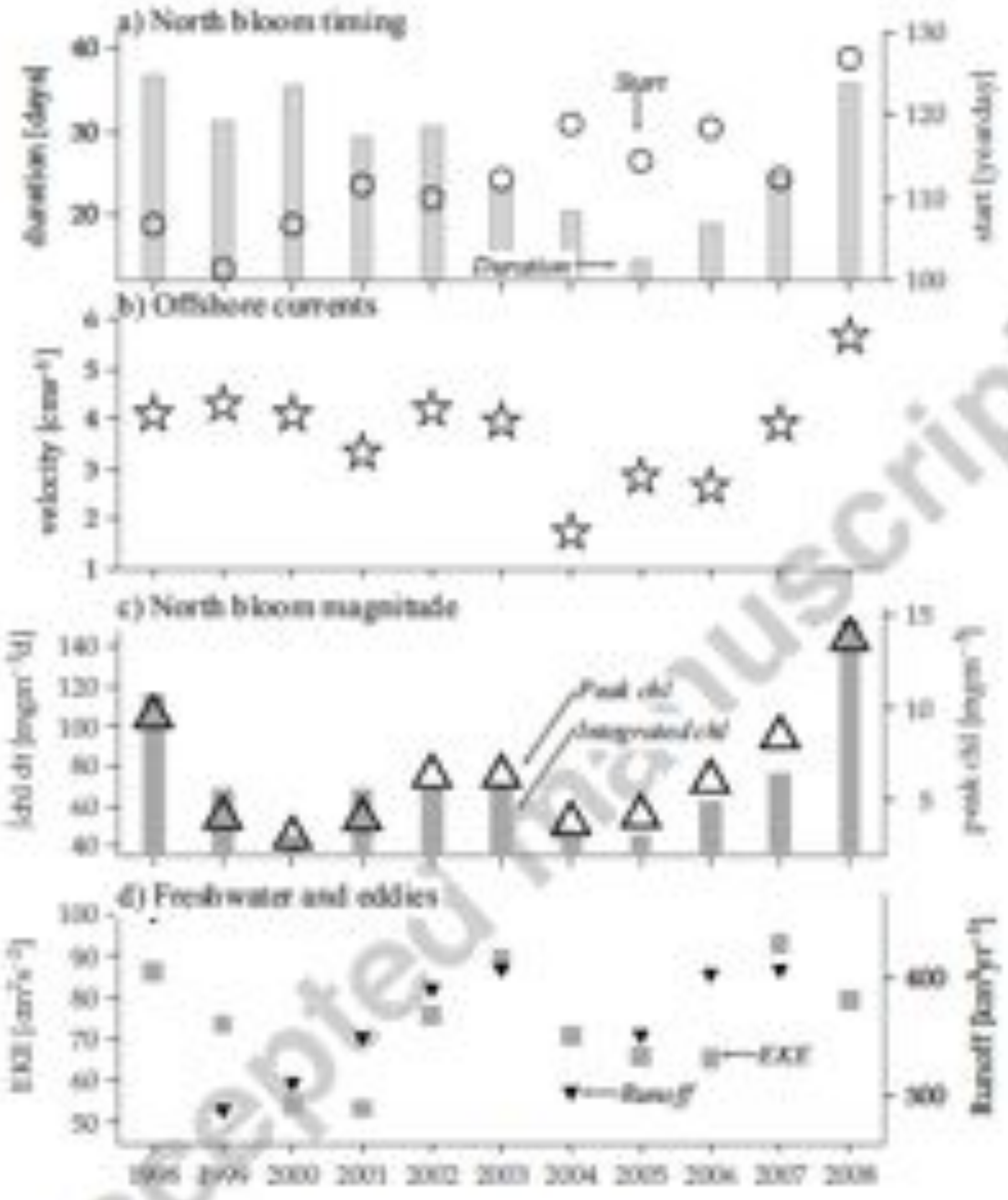
T

O_2

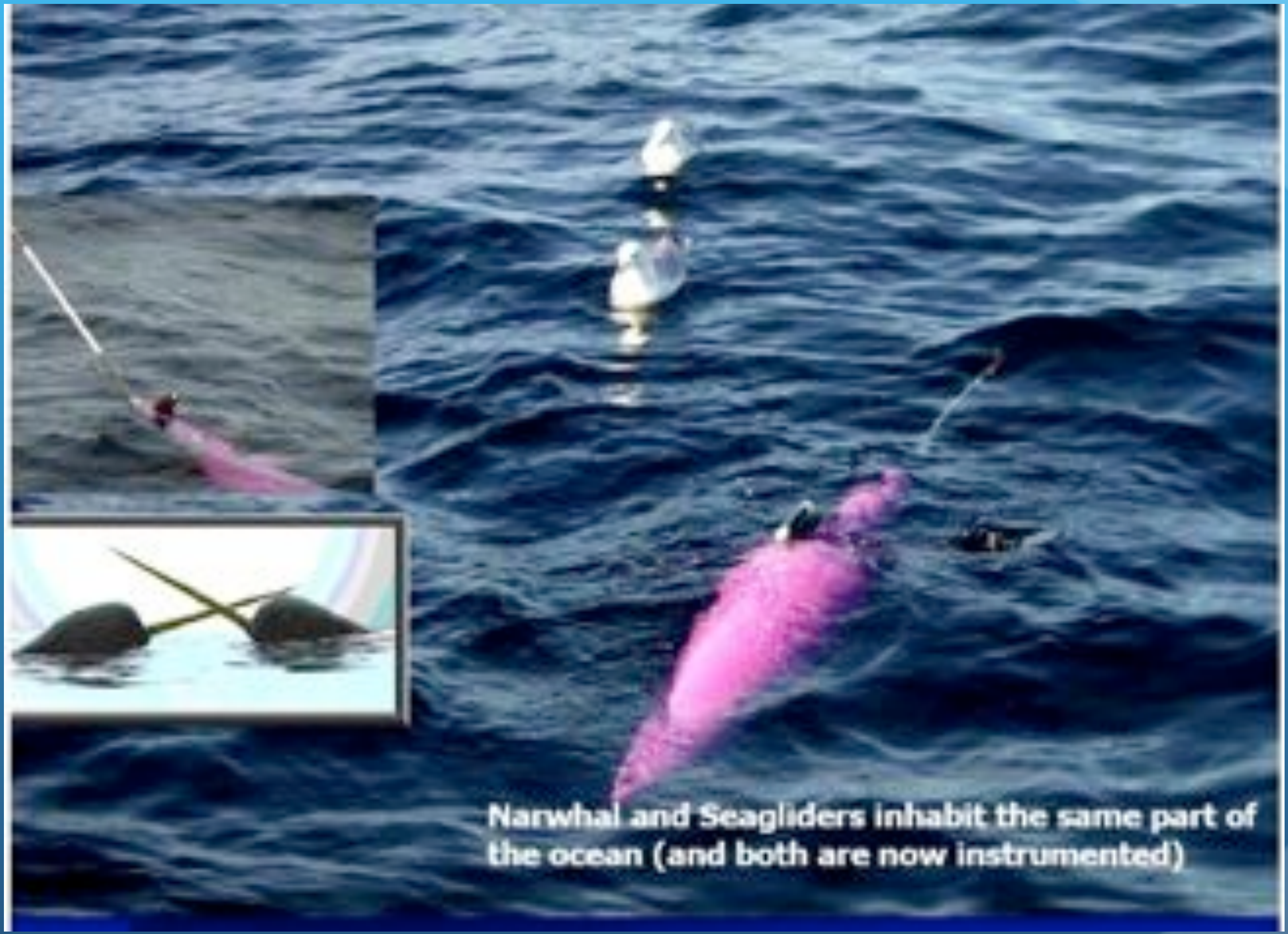
Fluorescence




a)
1998
b)
1999
c)
2000
d)
2001
e)
2002
f)
2003
g)
2004
h)
2005
i)
2006
j)
2007
k)
2008
l)
Mean
65°N
60°N
55°N
60°W
50°W
log10(chl mg m⁻³)
−1.0
−0.5
0.0
0.5
1.0



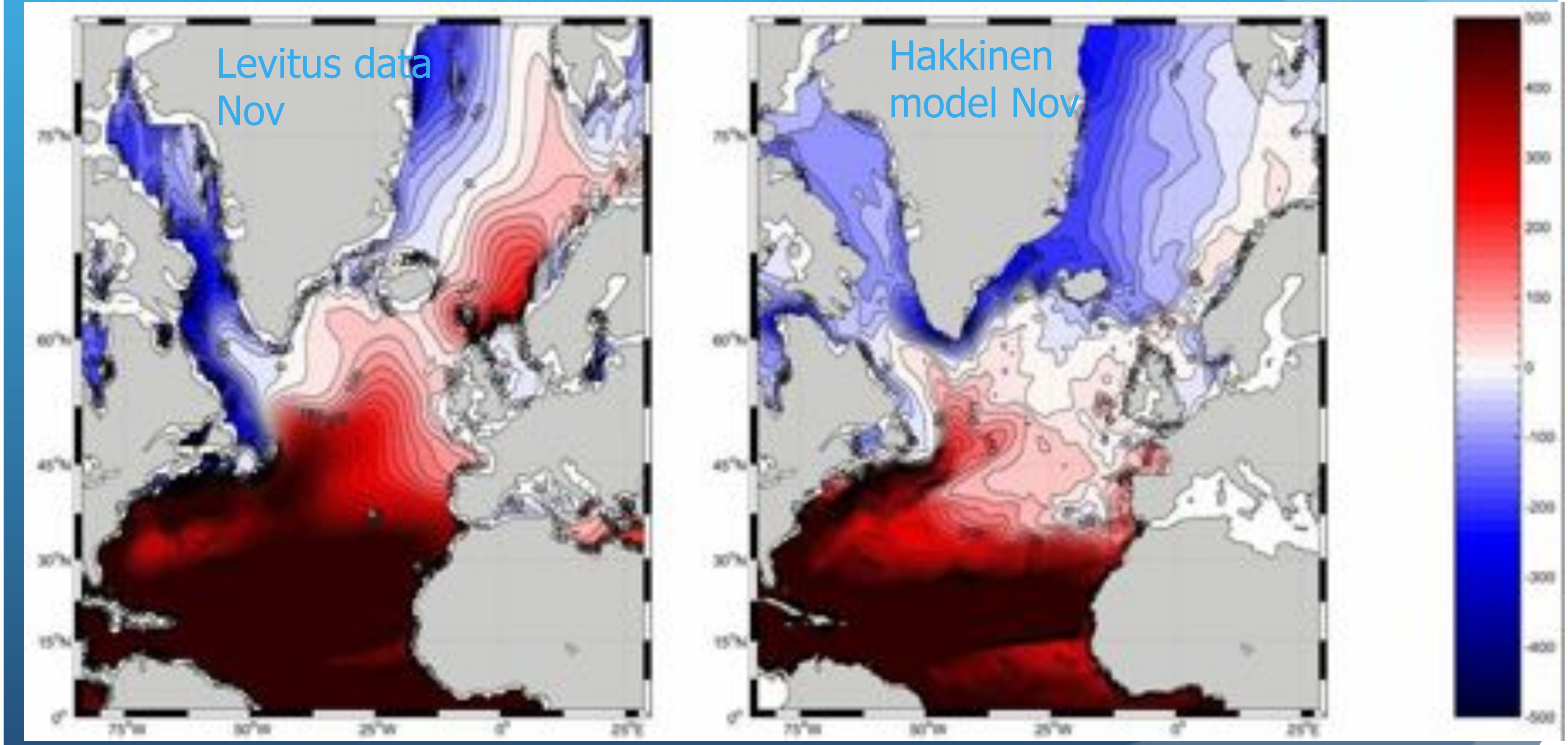
10: Measures of bloom and physical variability in the north region, defined



Narwhal and Seagliders inhabit the same part of the ocean (and both are now instrumented)

Buoyancy barrier to convection: 0-500m *difference* between thermal and haline components of dynamic height (blue: salinity wins, red: temp wins) ….. Fresh-water buoyancy resists heat-flux driven convection

(Bailey et al Climate Dyn 2005)

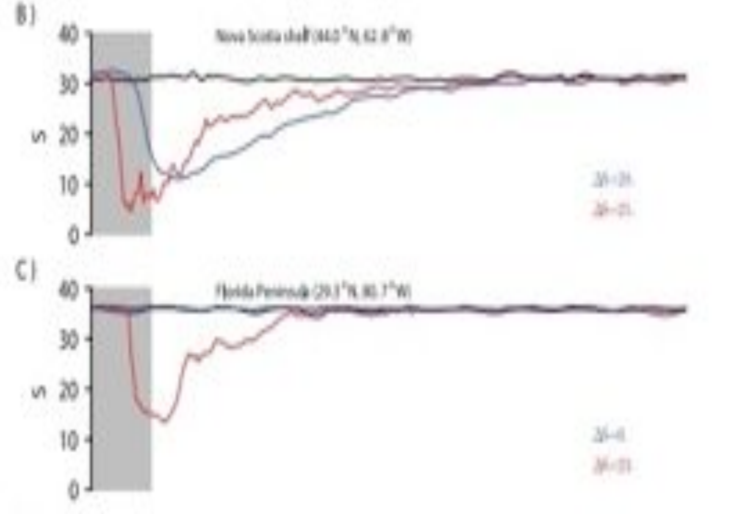


Bailey, Rhines+Häkkinen J Clim subm 2003

Condron & Winsor GRL 2011

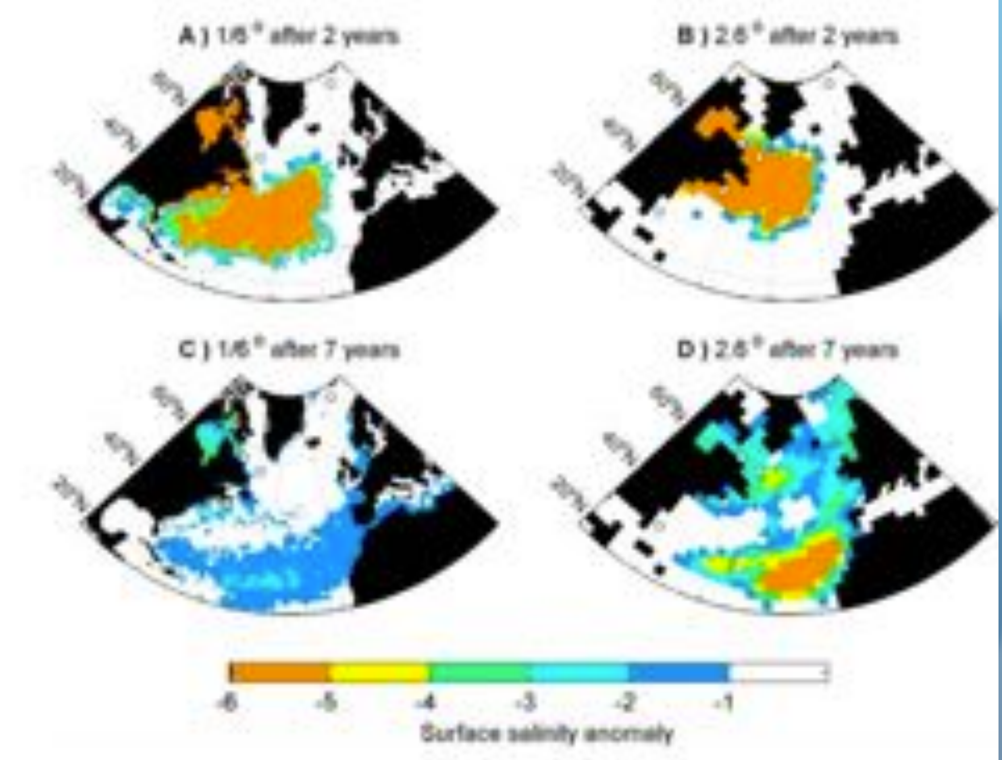
Fresh water plume flowing down N Atlantic coastline following 8.2 Kyr Lake Agassiz event….

showing dependence of buoyant upper-ocean fresh-water on model resolution



1/6^0 resolution model (red) vs. 2.6^0 coarse resolution model (grey)

163,000 km^3 FW released with strongest cooling in 10,000 years over N Atlantic, here modeled as 5 Sverdrups for 1 year



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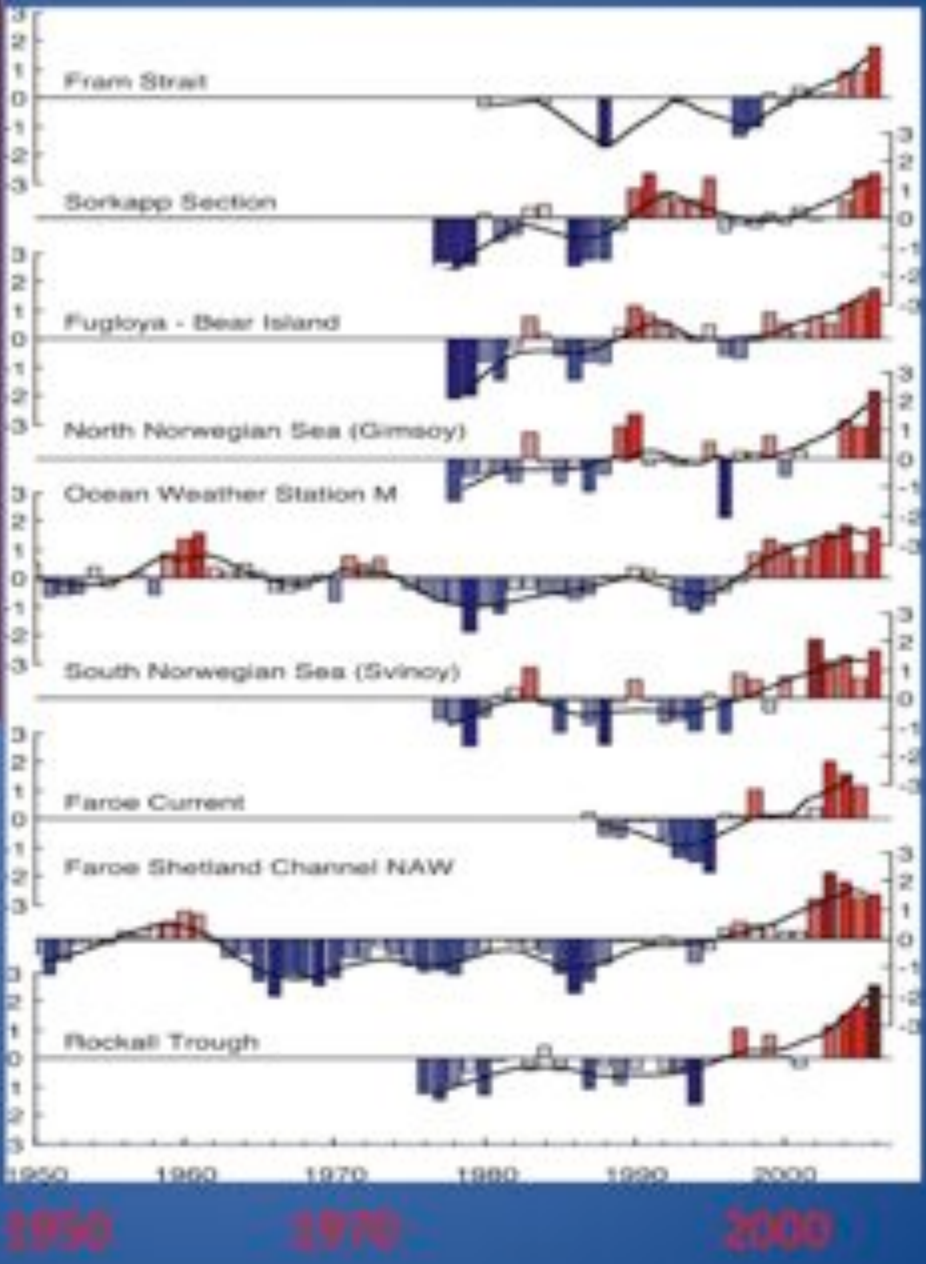
Increasing salinity and temperature of the Atlantic flow in the channels leading to the Nordic Seas since 1996 with a steep increase since 2002 (Holliday et al 2008)

- Cannot be explained by local changes in atmospheric forcing (surface heat and P-E fluxes)

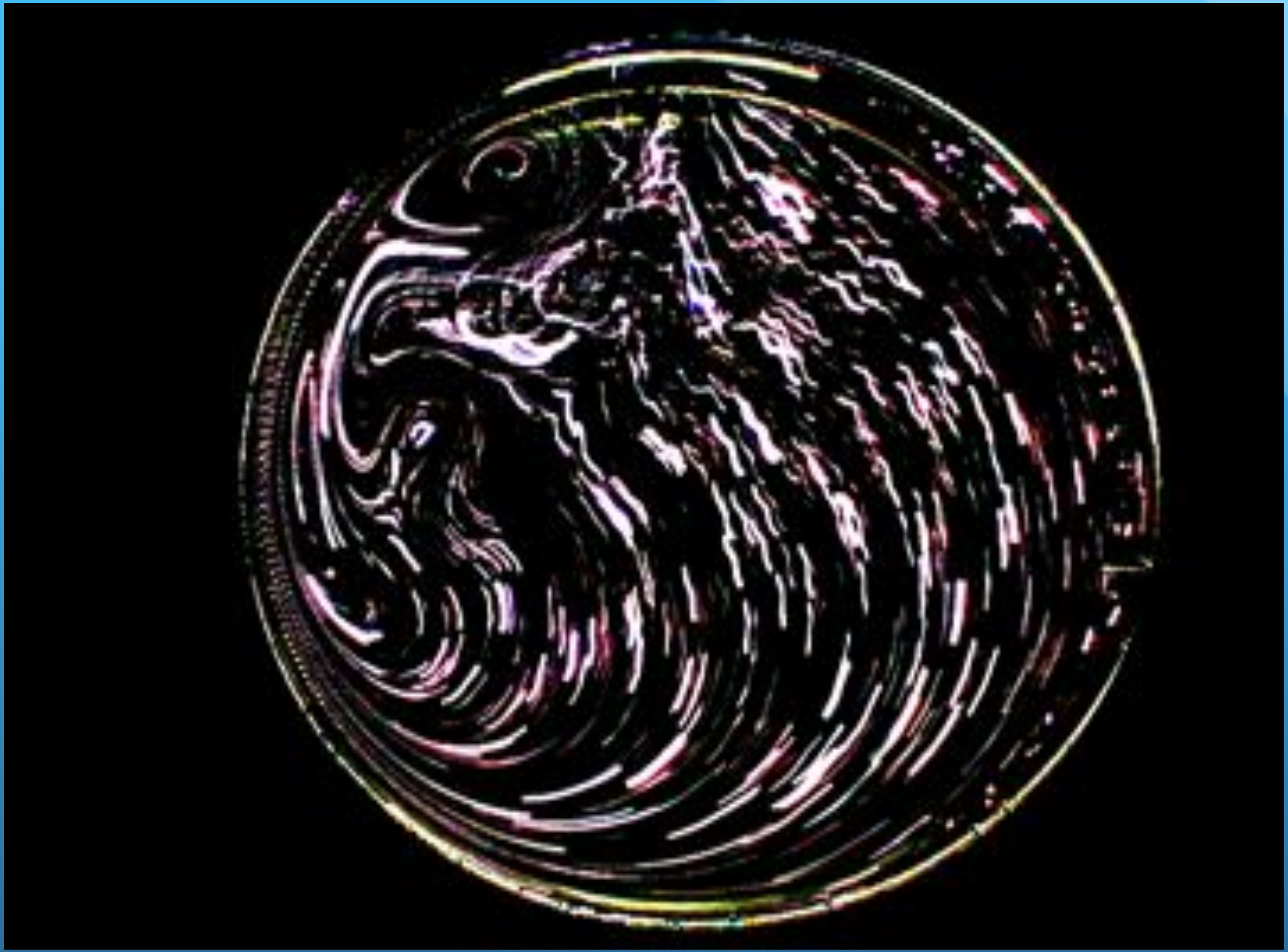
Holliday et al. GRL 2008



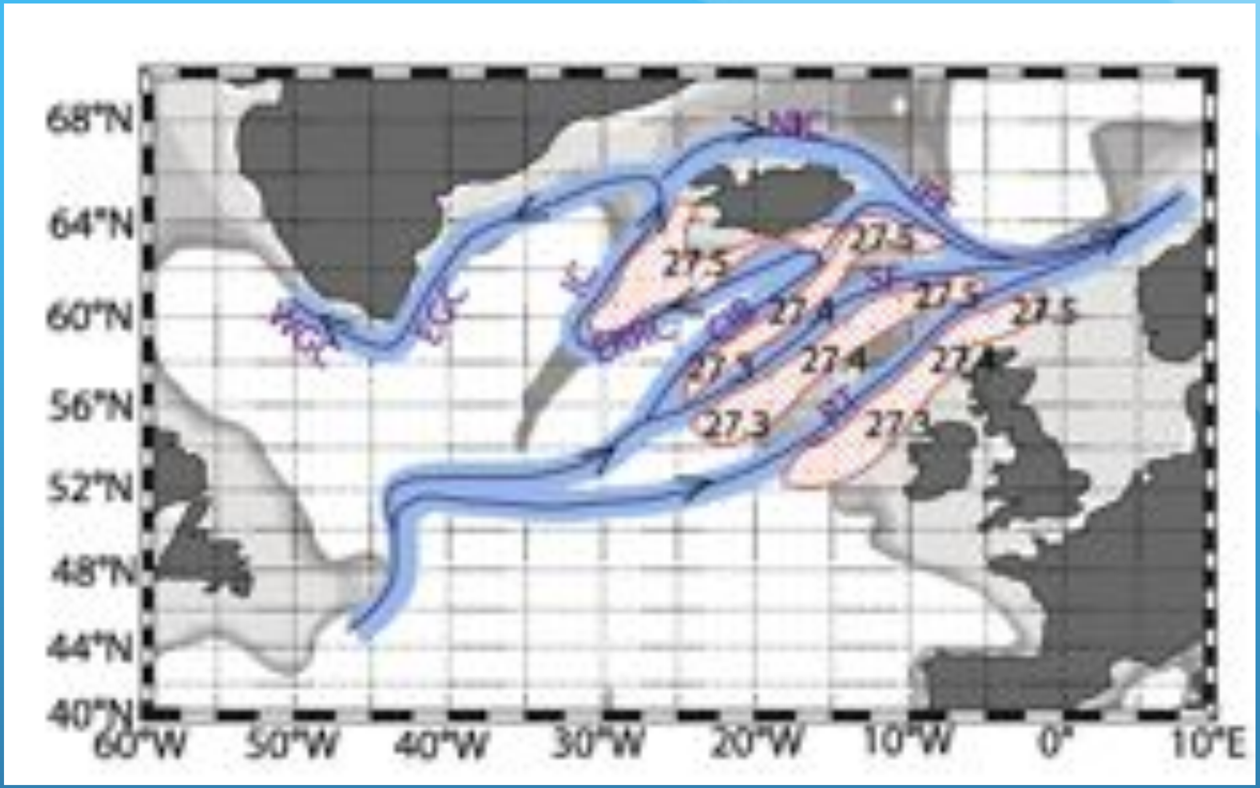
Relevant to the northward flow of Atlantic Water, the subpolar gyre and subtropical gyres have complex, variable exchange properties

- Satellite altimetry provides nearly 20 years of surface circulation dynamics for the world ocean. Here we have plotted surface kinetic energy density to bring out smaller scale features: the animations are available at www.ocean.washington.edu/research/gfd

The integrity of these small nonlinear Rossby waves, 'MODE-' mesoscale eddies and boundary currents has stood up to numerous ground-truth observations, including the Rossby *Oleander* sections of the Gulf Stream and individual eddy events observed *in situ* and with altimetery.



AVISO kinetic energy density-surface currents



Warm-water pathway northward from subtropics to subpolar gyre, and into Nordic Seas with approx winter outcrop densities (*Brambilla & Talley JGR 2008*)

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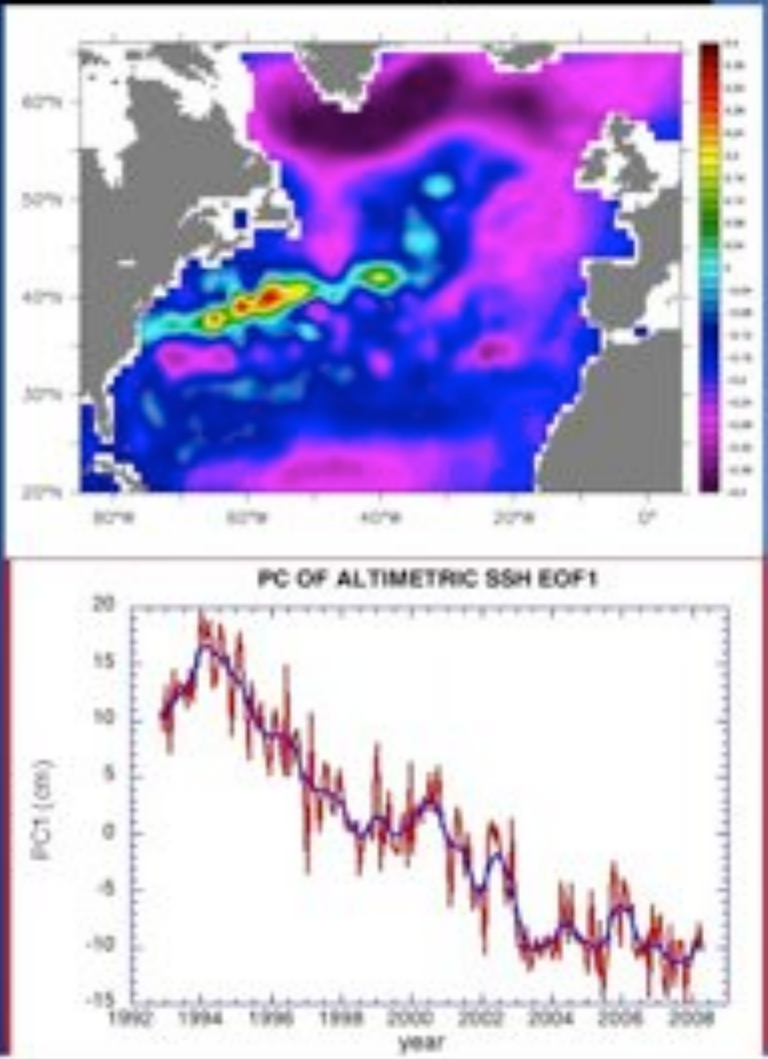
BACKGROUND

Update of Häkkinen and Rhines (*Science, 2004*): EOF 1 of the altimetric sea-surface height



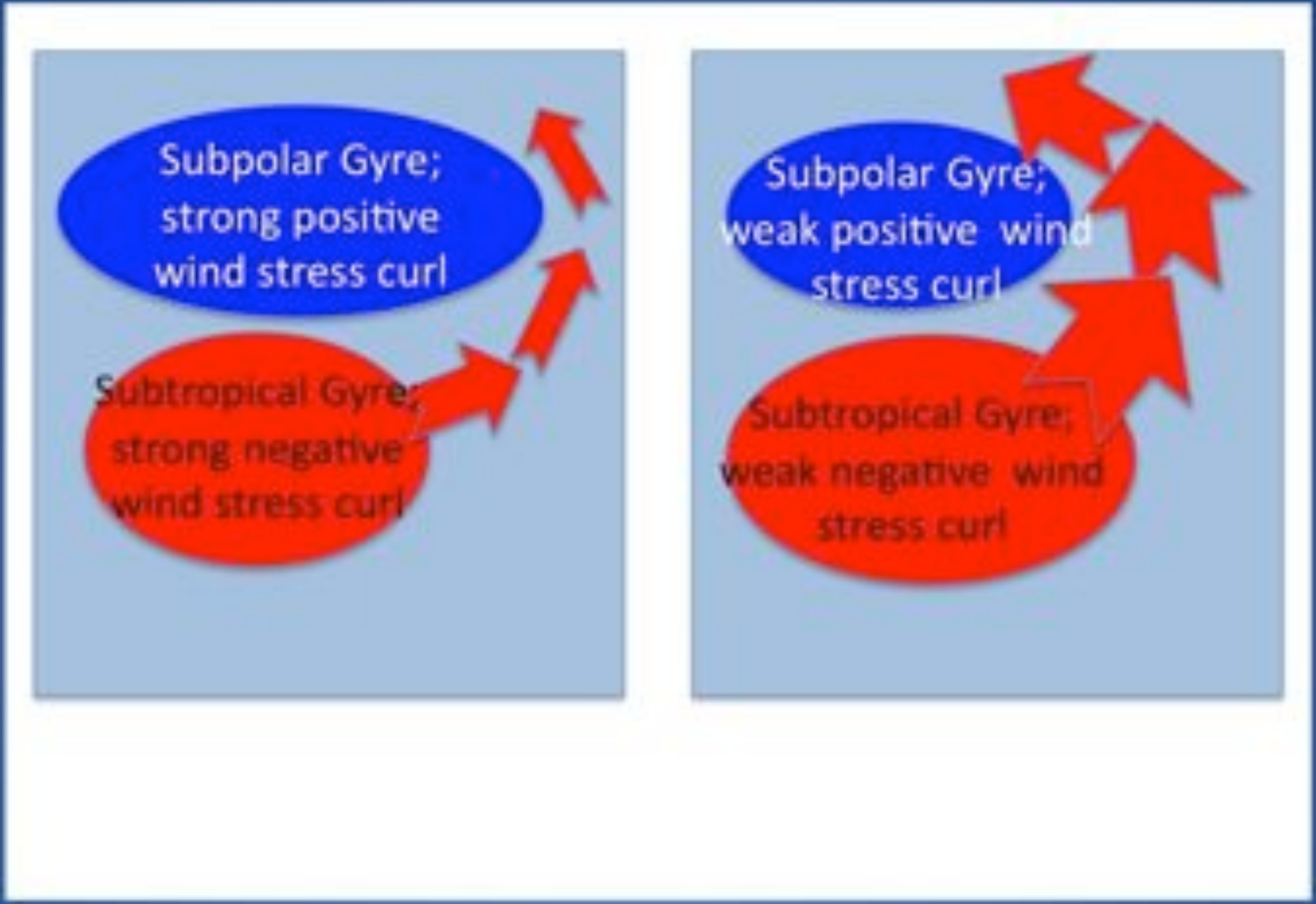
- WEAKENING and SHRINKING SUBPOLAR GYRE - FROM ALTIMETRY (*Hakkinen & Rhines* Science 2004) -> WESTWARD SHIFT OF THE SUBPOLAR FRONT (*Bersch* 2002; *Hatun et al.*, Science 2005)

- EXPANSION AND WEAKENING OF THE SUBTROPICAL GYRE FROM SATELLITE ALTIMETRY AND SEAWIFS (*McClain et al* 2004, *Polvina et al.* 2008)

- NO SUBTROPICAL SURFACE DRIFTERS ENTERED SUBPOLAR GYRE BEFORE 2002 (*Brambilla & Talley*, JPO 2006)
  BUT THEY DID SO AFTER 2001 (*Hakkinen & Rhines*, JGR 2009)

- CHANGES IN THE UPPER LIMB OF THE AMOC ?

- EARLIER EVENTS ?



Subpolar Gyre; strong positive wind stress curl
Subtropical Gyre; strong negative wind stress curl
Subpolar Gyre; weak positive wind stress curl
Subtropical Gyre; weak negative wind stress curl

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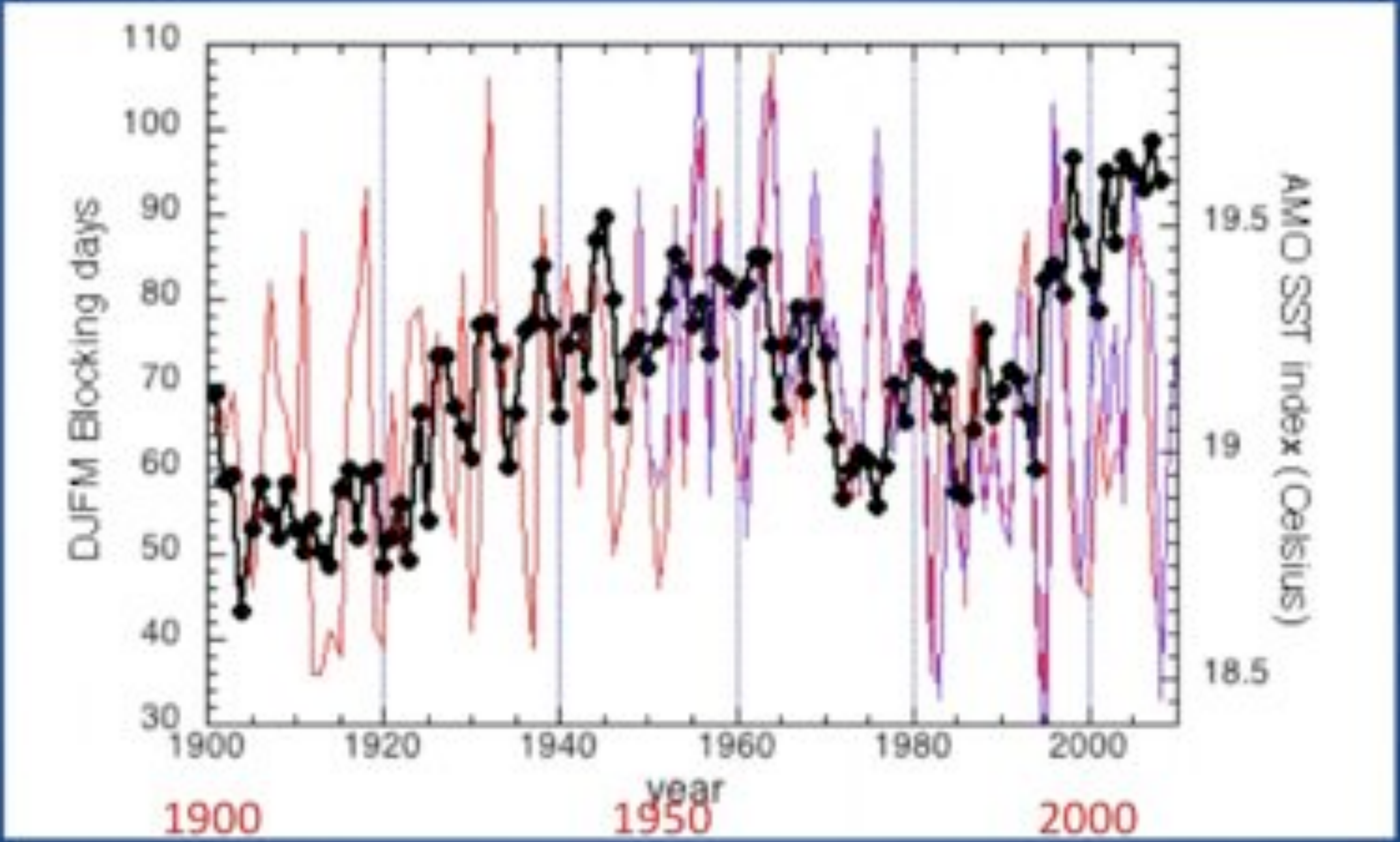
- **atmospheric circulation variability** associated with high latitudes in recent decades (poleward shift of jet stream, blocking histories, storm tracks..) (e.g. *Woollings et al. Q.J.Royal Met. Soc. 2010)*

- **dislocation of fisheries, ecosystems**, birds, whales…*(many authors, e.g. Hatun et al. Prog. in Oceanogr. 2009, Laidre et al., Proc. Royal Soc. B, 2008)*

We see in the northern Atlantic episodes of variability over decades and also over the much longer, century time-scale

(AMO index of subpolar sea-surface temperature in black)



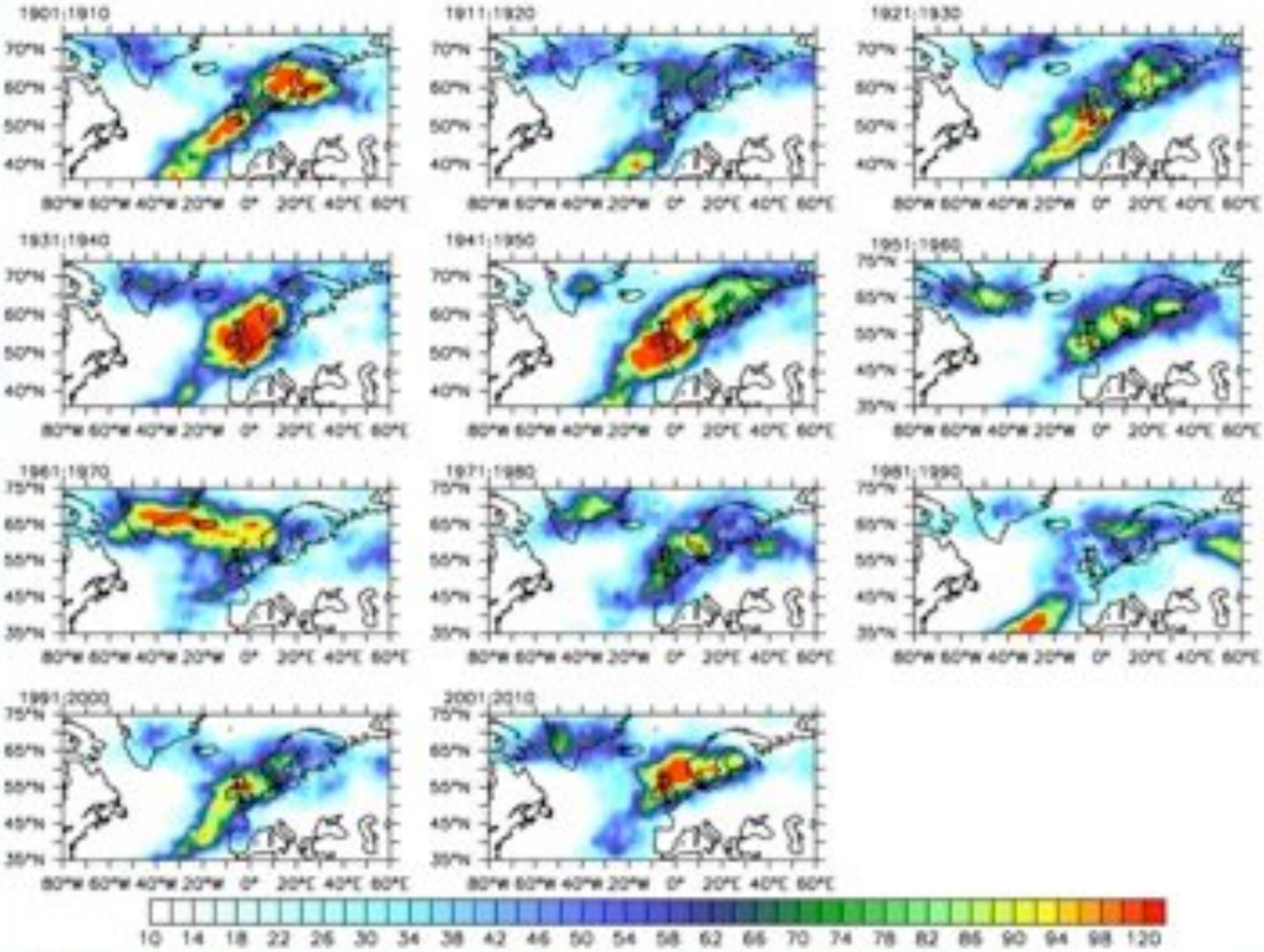
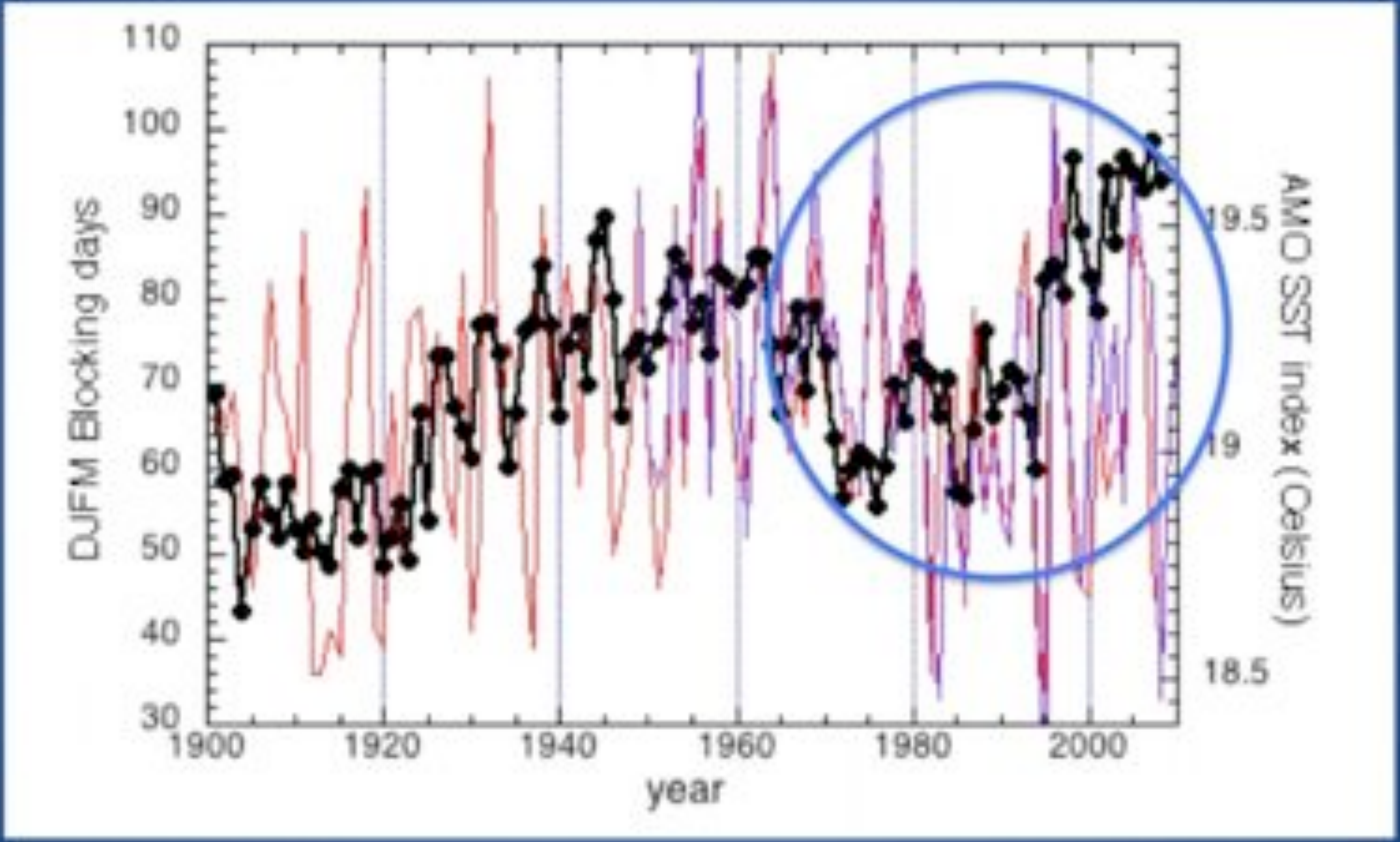


Fig 2. Blocking days by decade: 1901-1950 from the 20th century reanalysis, 1951-2010 from NCEP/NCAR Compo et al. Reanalysis.

We had begun to track the past 50 years using satellite altimetry (which records the surface ocean circulation variability in great detail) : episodes of warm subtropical waters invade the Arctic and subpolar latitudes



Hatun et al. 2005

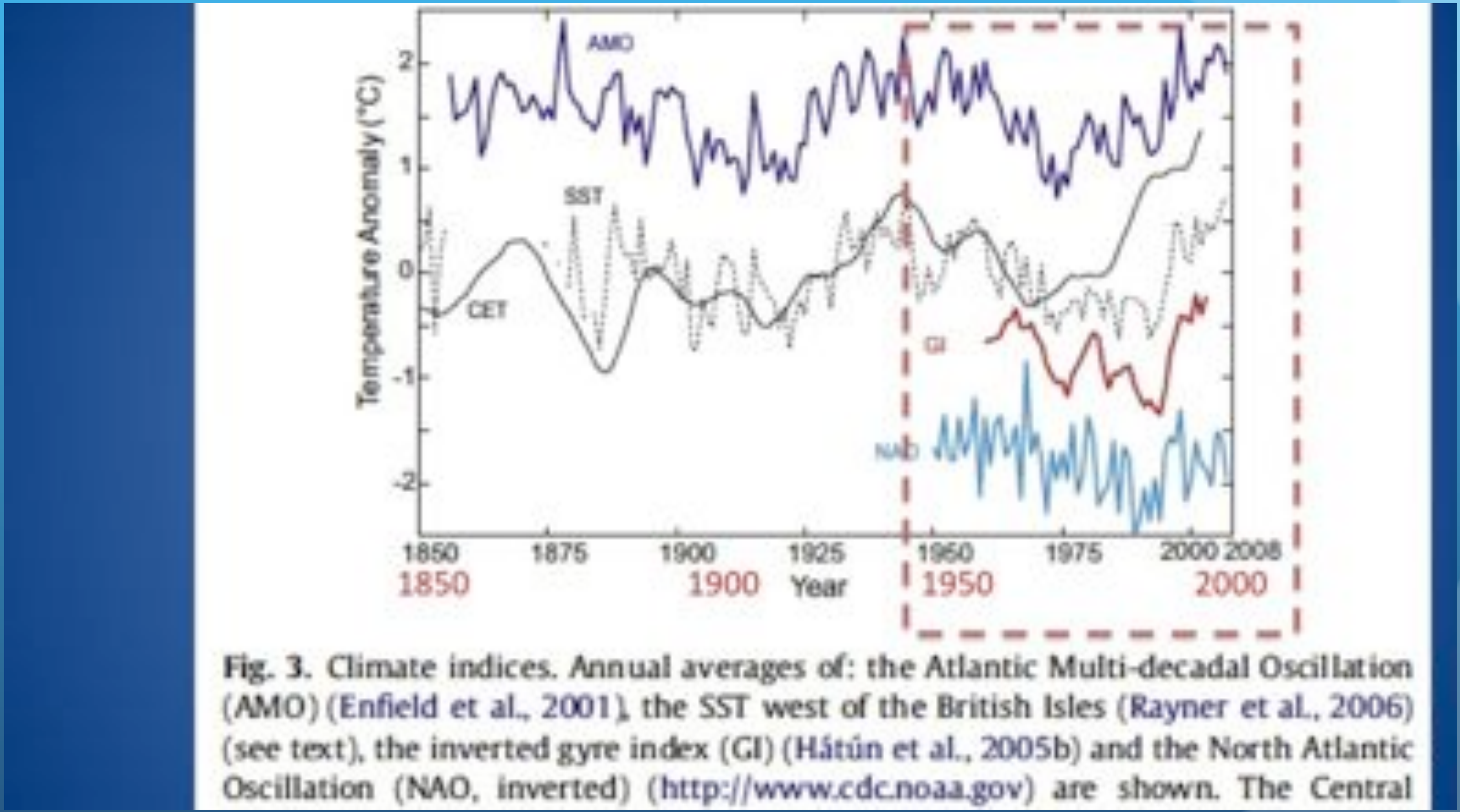


Fig. 3. Climate indices. Annual averages of: the Atlantic Multi-decadal Oscillation (AMO) (Enfield et al., 2001), the SST west of the British Isles (Rayner et al., 2006) (see text), the inverted gyre index (GI) (Hátún et al., 2005b) and the North Atlantic Oscillation (NAO, inverted) (http://www.cdc.noaa.gov) are shown. The Central

The following slide shows the combination of two variability modes that seem to describe the atmospheric sea-level pressure behavior (from *Woollings, Hannachi & Hoskins, Q J Royal Met Soc 2010*). The figure shows various combinations of the NAO and East Atlantic Pattern, which together can describe the lack of stationarity of the NAO by itself: systems move east and west as well as north and south. This is very similar to our two EOFs for the (different) field of wind-stress curl that is actively driving the ocean. Similar decompostions have been suggested by *Hurrell & Deser J Mar. Systems 2010*), where they name the 4 extreme modes: NAO+, NAO- , Atlantic Ridge and Blocking.

A distinction in the new work is that wind-stress curl is differentiated, and squared quantity which can be more spatially concentrated than high- and low- SLP systems

*

Woollings Hannachi & Hoskins QJRoyal Met Soc 2010

500HPa height field

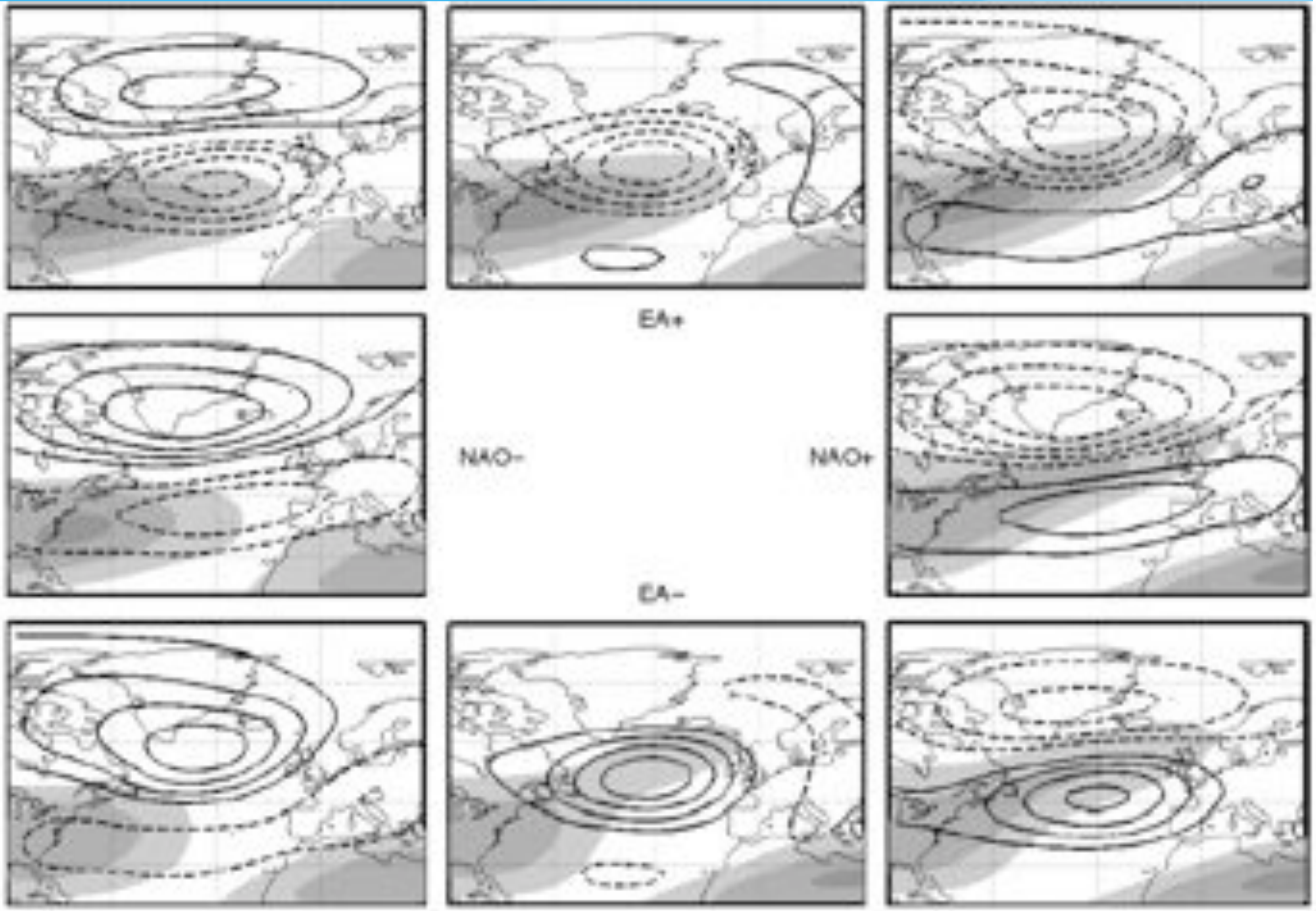
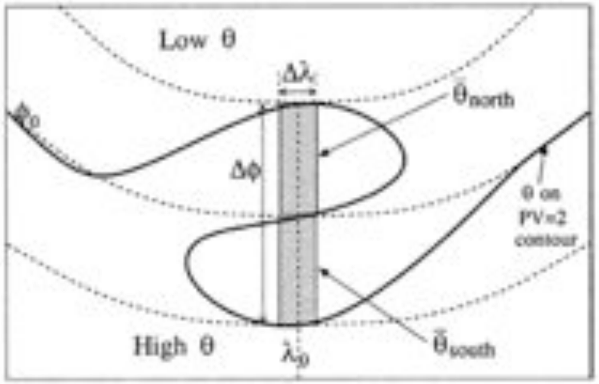
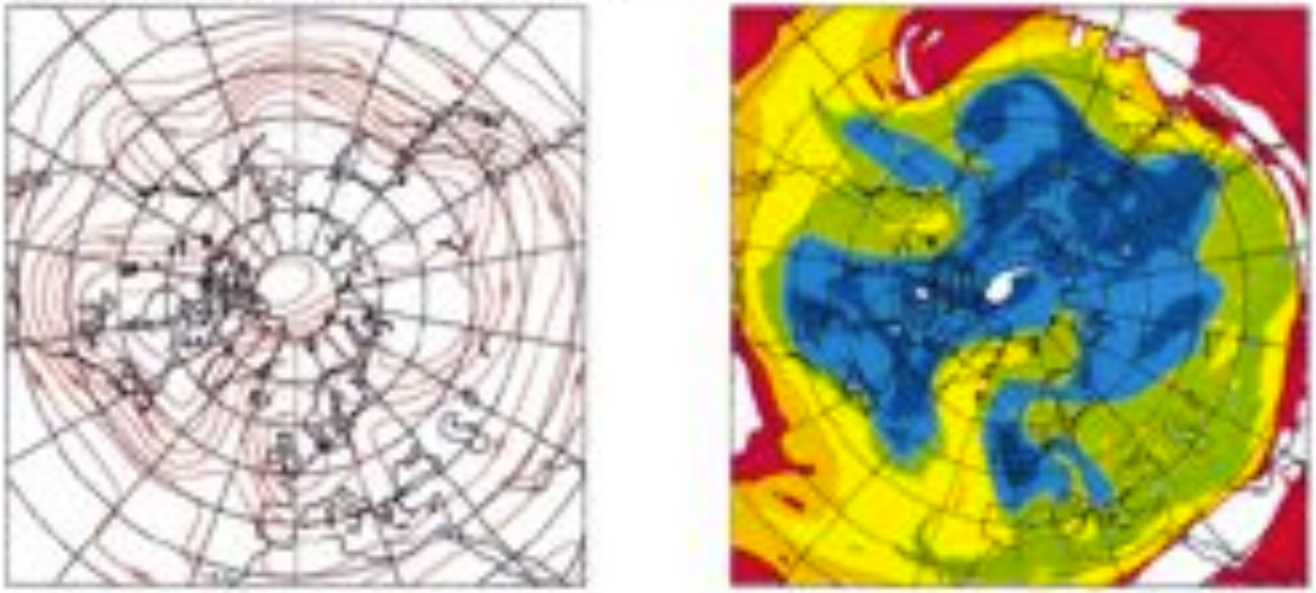


Figure 10. Summary of the circulation at different locations in NAO/EA space. The horizontal axis of the grid of plots is the NAO and the vertical the EA. Z500 anomalies are contoured every 20 m per standard deviation of the principal component time series, and 300 hPa zonal wind is shaded 10 m s^{-1} starting at 20 m s^{-1}. The corner plots are given by adding the respective NAO and EA maps and scaling by $1/\sqrt{2}$.

Blocking over Europe (when the meridional temperature gradient reverses, warm air north of cold air, often in an anticyclone that may persist 4 to 10 days (*Pelley & Hoskins, JAS 2003)*)



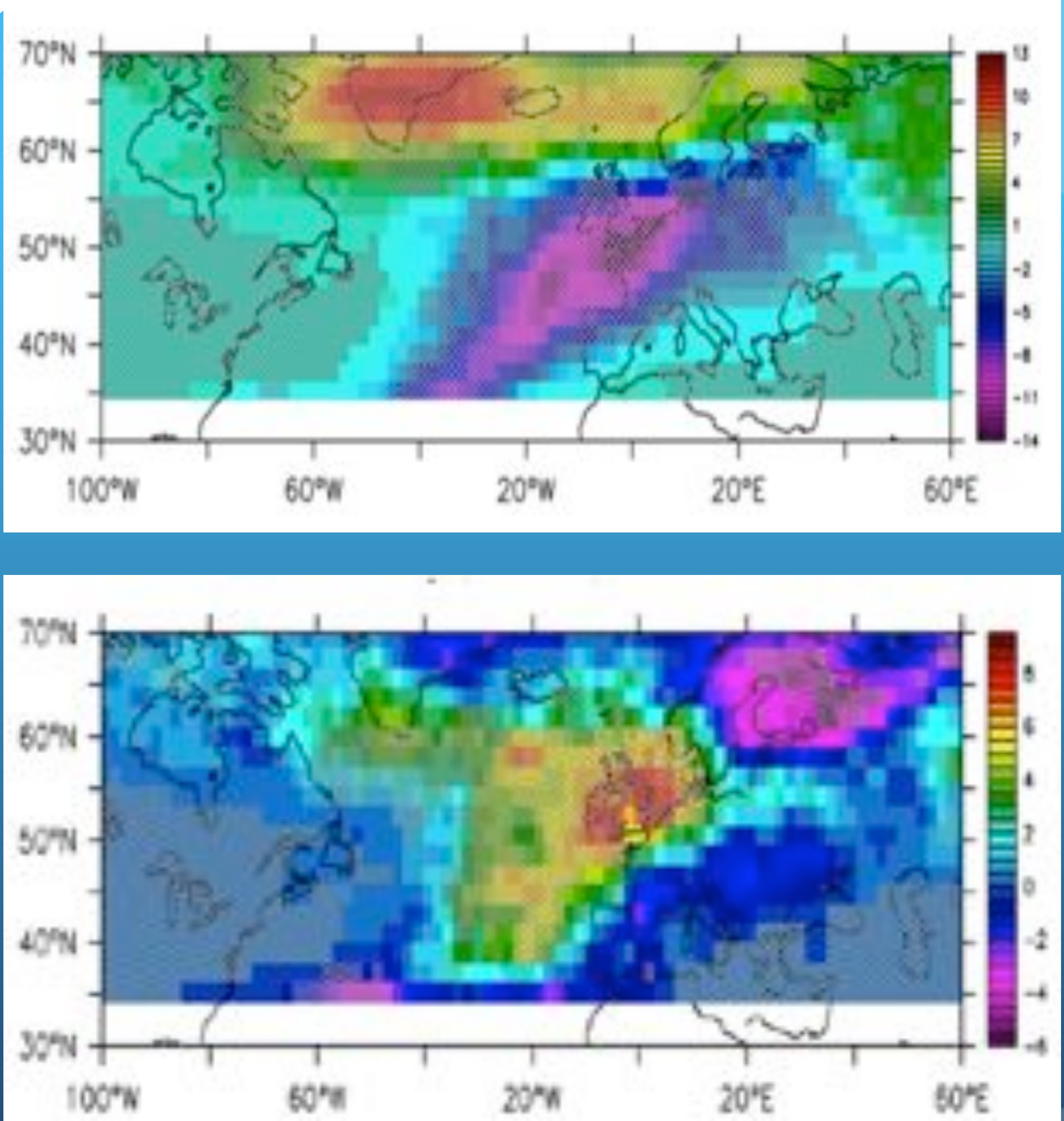
20 November 2000 (Euro-Atlantic dipole block, 19–24



A key aspect of blocking is its location east and west. Blocking occurs over Europe and over Greenland, with the Euro-bloc

more frequent (see *Tyrlis & Hoskins, J Atmos Sci 2008).*

The next slide shows that our two EOFs of wind-stress curl correspond, respectively, to Greenland and European sector blocking events. Woollings has associated the Greenland anticyclonic blocks sitting over Greenland with NAO- : the negative NAO pattern in which the high latitude 'eddy-driven' jet stream moves southward and nearly merges with thesubtropical 'Hadley-cell' jet stream.



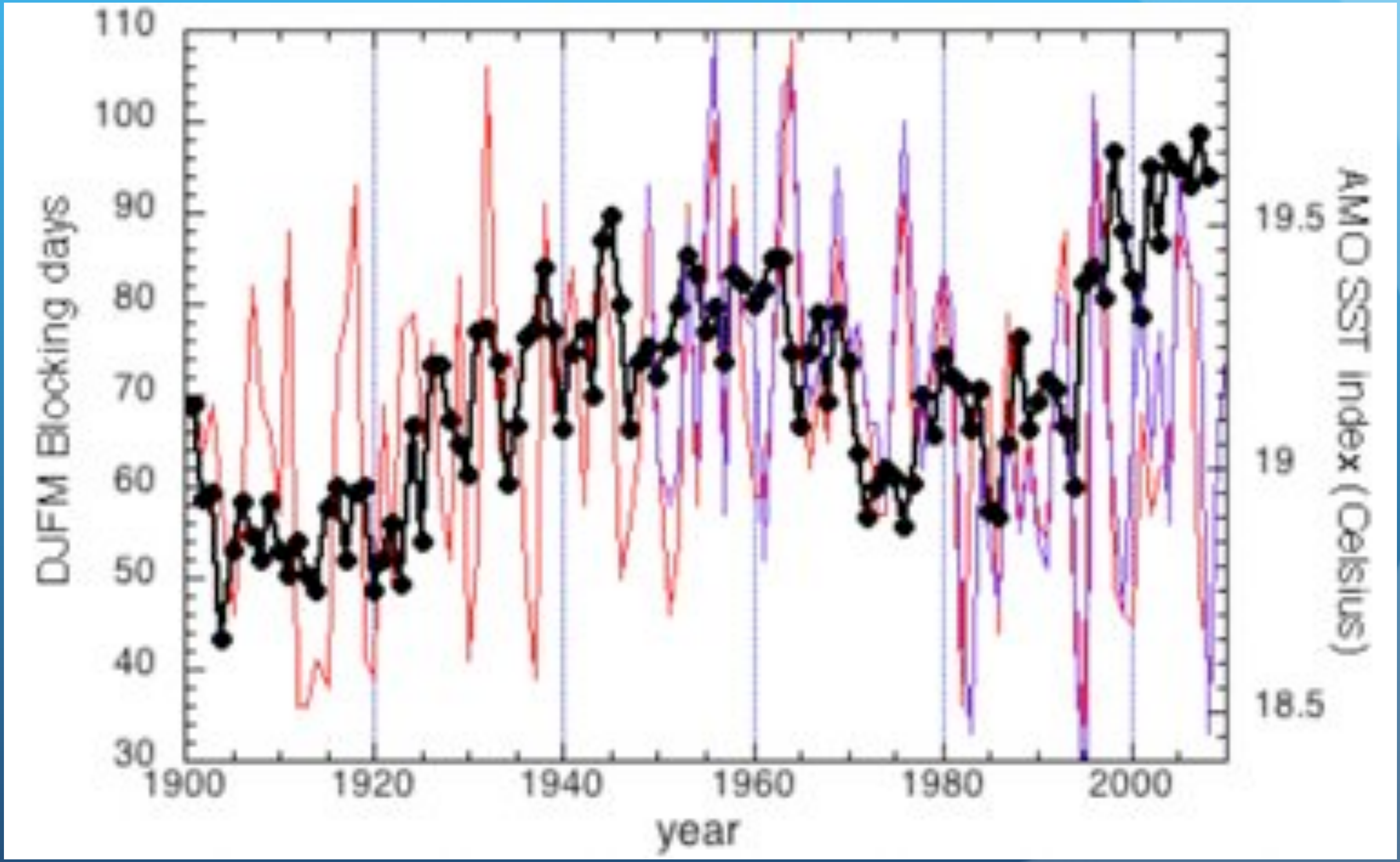
The two EOFs contribute these patterns of blocking (frequency of blocking days),

PC1 over Greenland and PC2 over Europe

Quite surprisingly, we find from the 20th C. reanalysis at NCAR by *Compo et al. (Q J. Royal Met. Soc. 2011*) that blocking, though describing typically 4- to 10-day duration blocking episodes, varies strongly over decade-to-century timescales, following closely the Atlantic Multidecadal Variabilty (AMV) (or AMO the ”….Oscillation”).

The AMV is a measure of warm episodes in northern Atlantic SST after removal of the long-term trend.

AMO time series (showing warm subpolar gyre periods (black) and blocking index for N Atlantic based on new NCAR analysis of 20th C sea level pressure (*Campo et al 2011*).



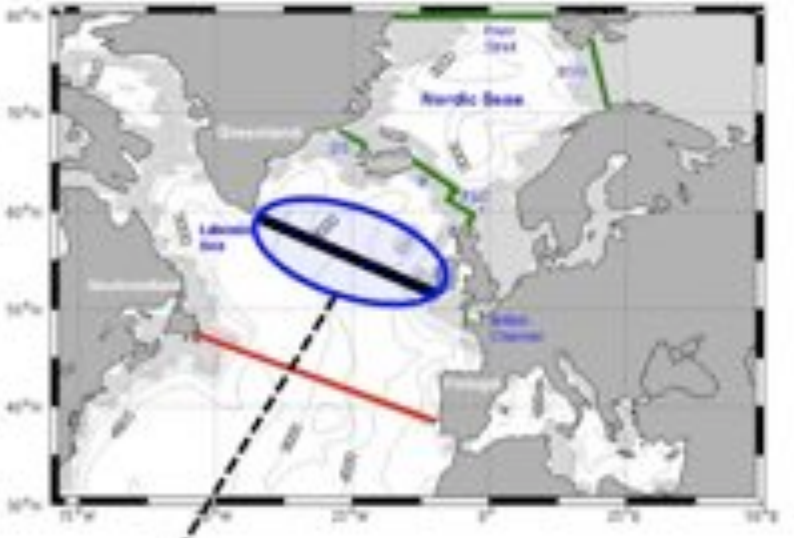
Displaying transport across (roughly) east-west sections on the Θ/S plane gives a portrait of the meridional flux of mass, heat and fresh-water anomaly (given by the respective 0th and 1st moments of these diagrams. Integrating them along potential density curves gives the overturning streamfuntion, and differencing adjacent sections gives the sum of internal watermass formation and external air/sea flux of heat and freshwater.

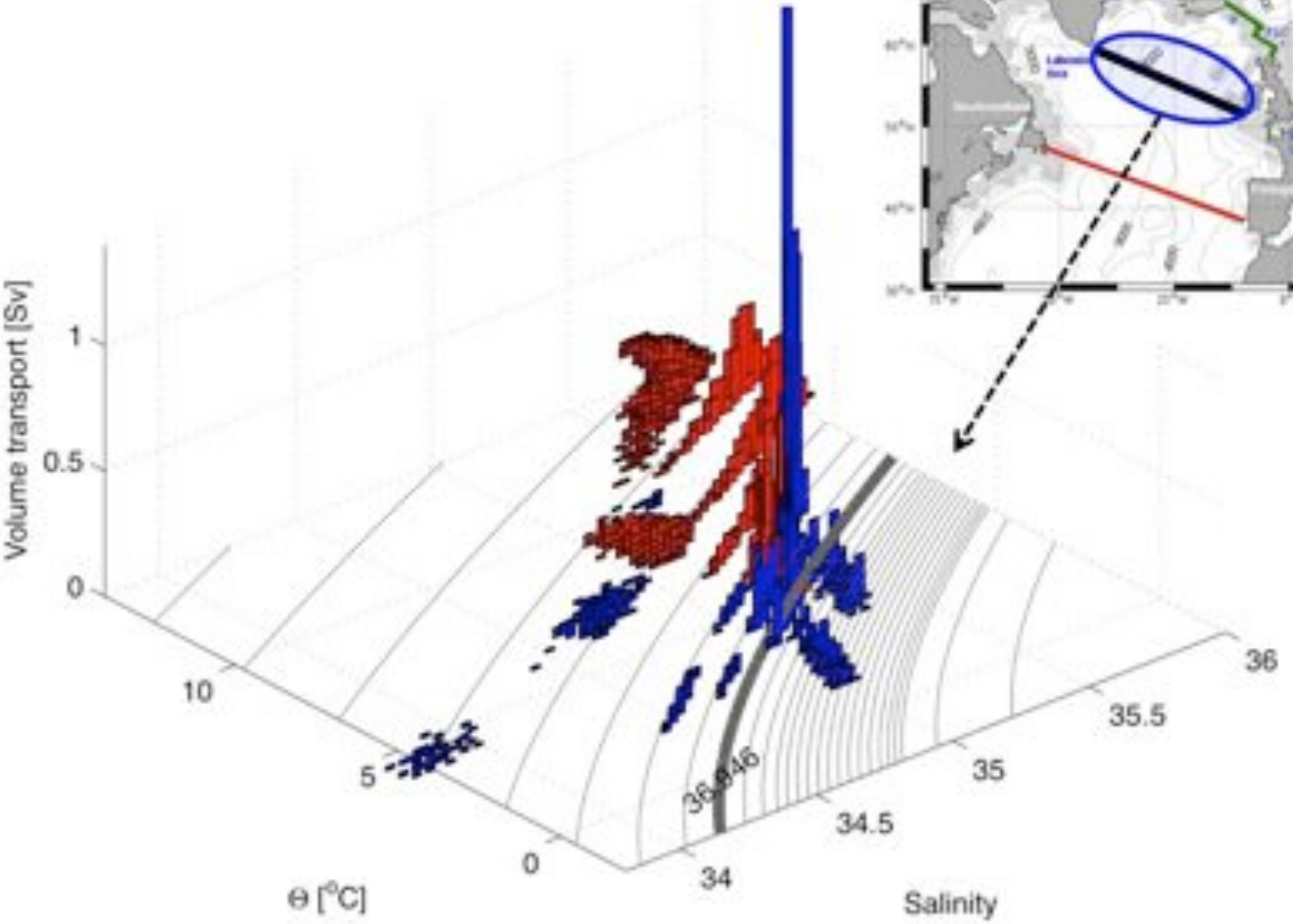
RED = northward transport
BLUE = southward transport

Note that the mixed layer can have any density, hence appearing as a cloud of points whereas the MICOM isopycnal layers confine the transport to constant potential density (σ_2-) curves.

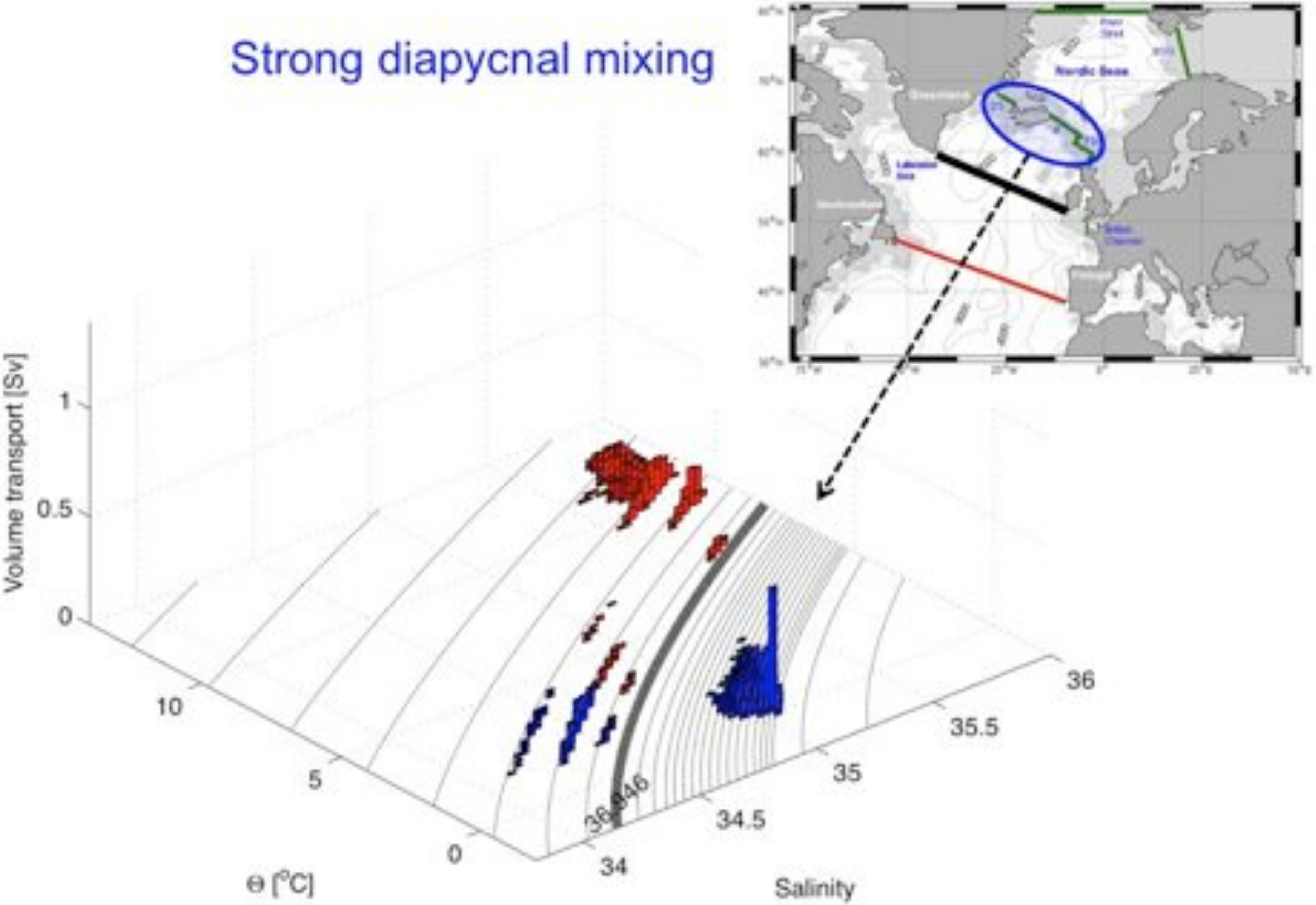
The two sections following show the great change in transport properties between the Cape Farewell/Ireland section and the Greenland-Scotland section.

Strong diapycnal mixing

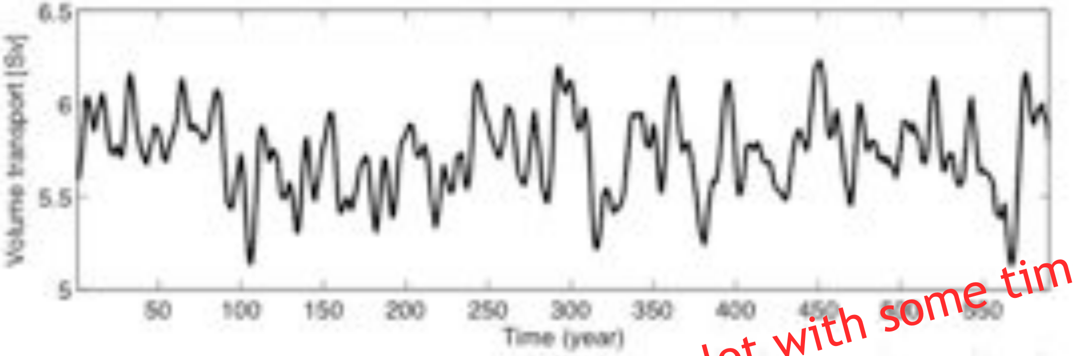




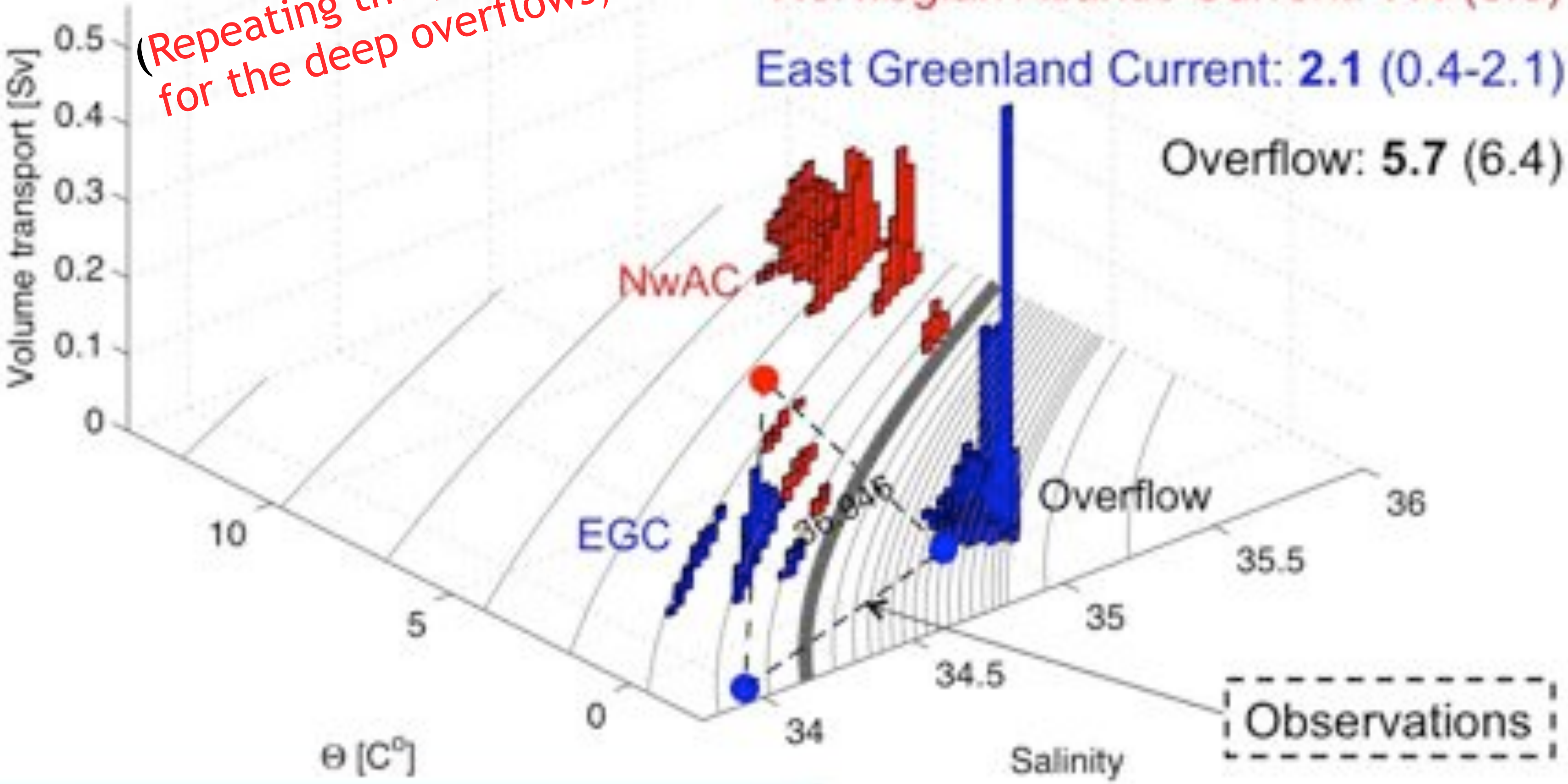
Strong diapycnal mixing



3. Nordic Seas Overflow



(Repeating the previous plot with some timeseries for the deep overflows):

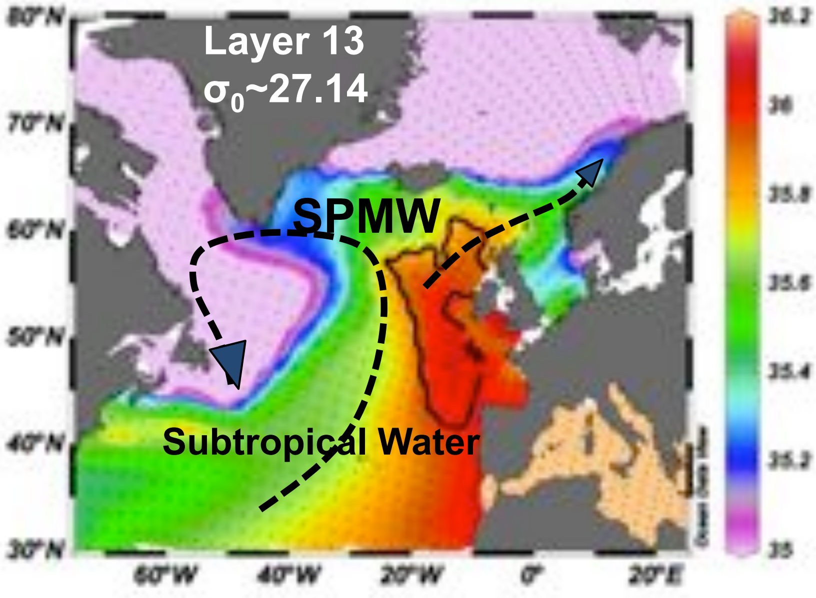


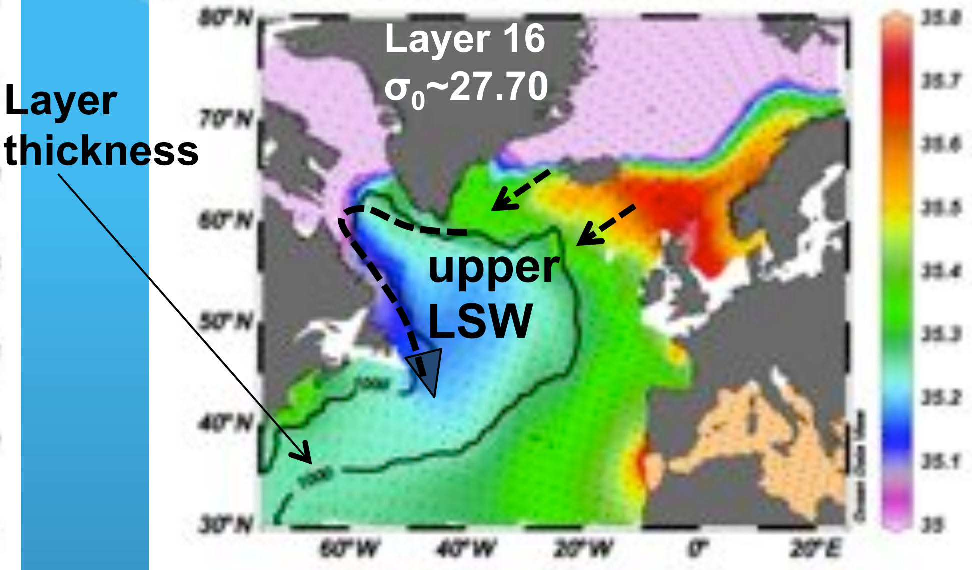
Norwegian Atlantic Current: **7.4** (8.5) Sv

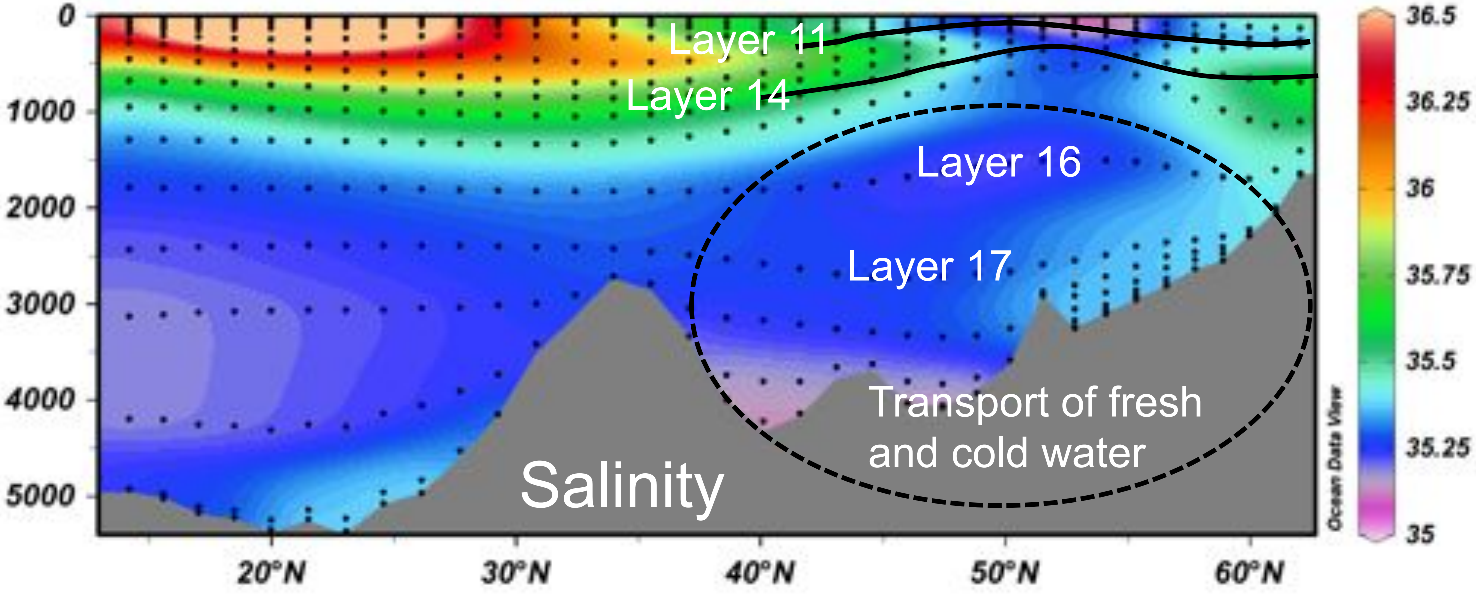
East Greenland Current: **2.1** (0.4-2.1) Sv

Overflow: **5.7** (6.4) Sv

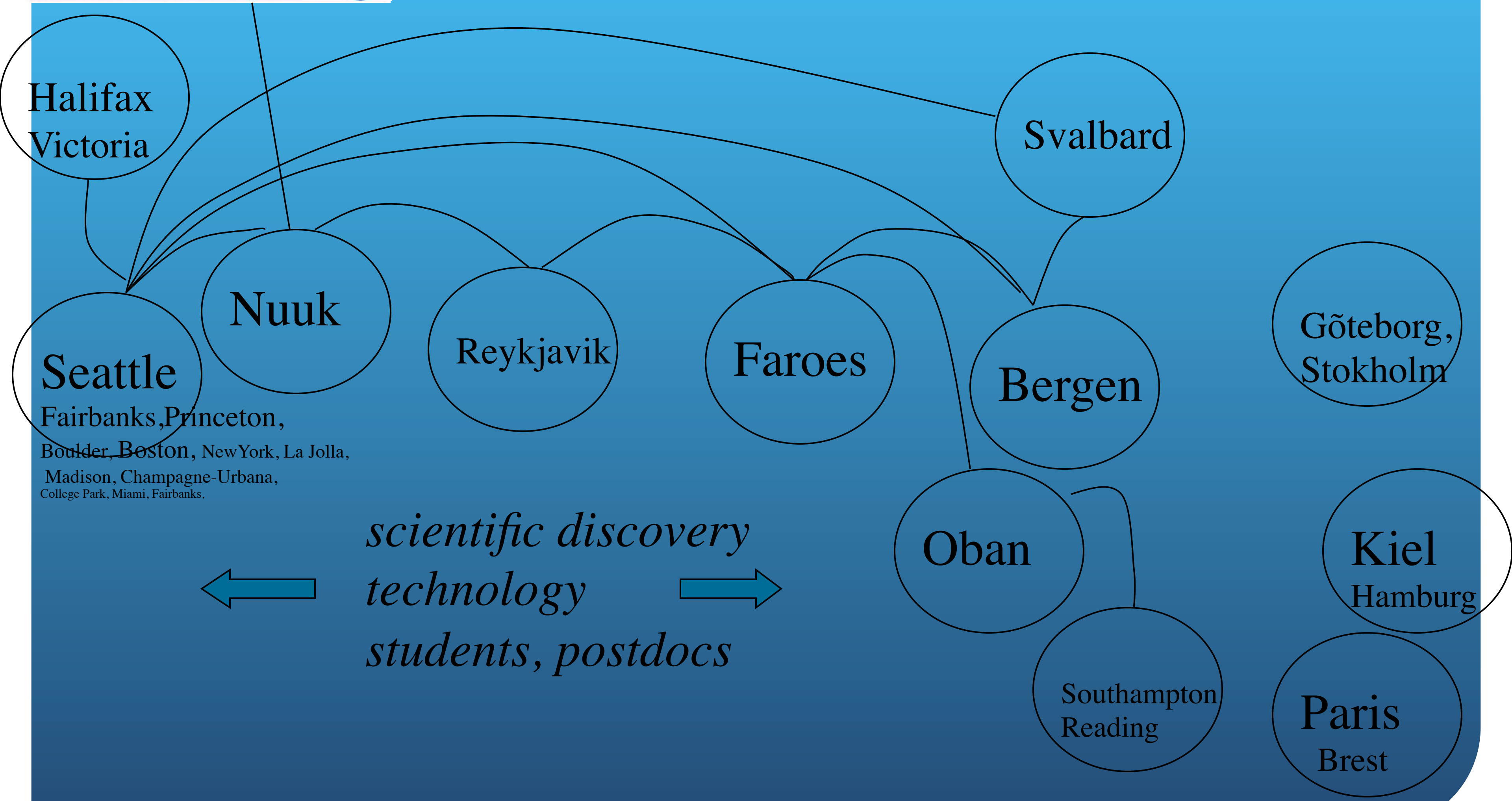
Observations from: Eldevik and Nilsen (2009), Olsen et al. (2008), Østerhus et al. (2005), Nilsson et al. (2008).


Layer 13
σ_0~27.14
SPMW
Subtropical Water
80°N
70°N
60°N
50°N
40°N
30°N
60°W
40°W
20°W
0°
20°E
36.2
36
35.8
35.6
35.4
35.2
35
Ocean Data View


Layer thickness
Layer 16
σ_0~27.70
upper LSW
1000
80°N
70°N
60°N
50°N
40°N
30°N
60°W
40°W
20°W
0°
20°E
35.8
35.7
35.6
35.5
35.4
35.3
35.2
35.1
35
Ocean Data View


0
1000
2000
3000
4000
5000
Layer 11
Layer 14
Layer 16
Layer 17
Transport of fresh and cold water
Salinity
20°N
30°N
40°N
50°N
60°N
36.5
36.25
36
35.75
35.5
35.25
35
Ocean Data View

some of the high-latitude network



Halifax
Victoria

Svalbard

Nuuk

Reykjavik

Faroes

Bergen

Gõteborg,
Stokholm

Seattle
Fairbanks,Princeton,
Boulder, Boston, NewYork, La Jolla,
Madison, Champagne-Urbana,
College Park, Miami, Fairbanks,

scientific discovery
technology
students, postdocs

Oban

Kiel
Hamburg

Southampton
Reading

Paris
Brest