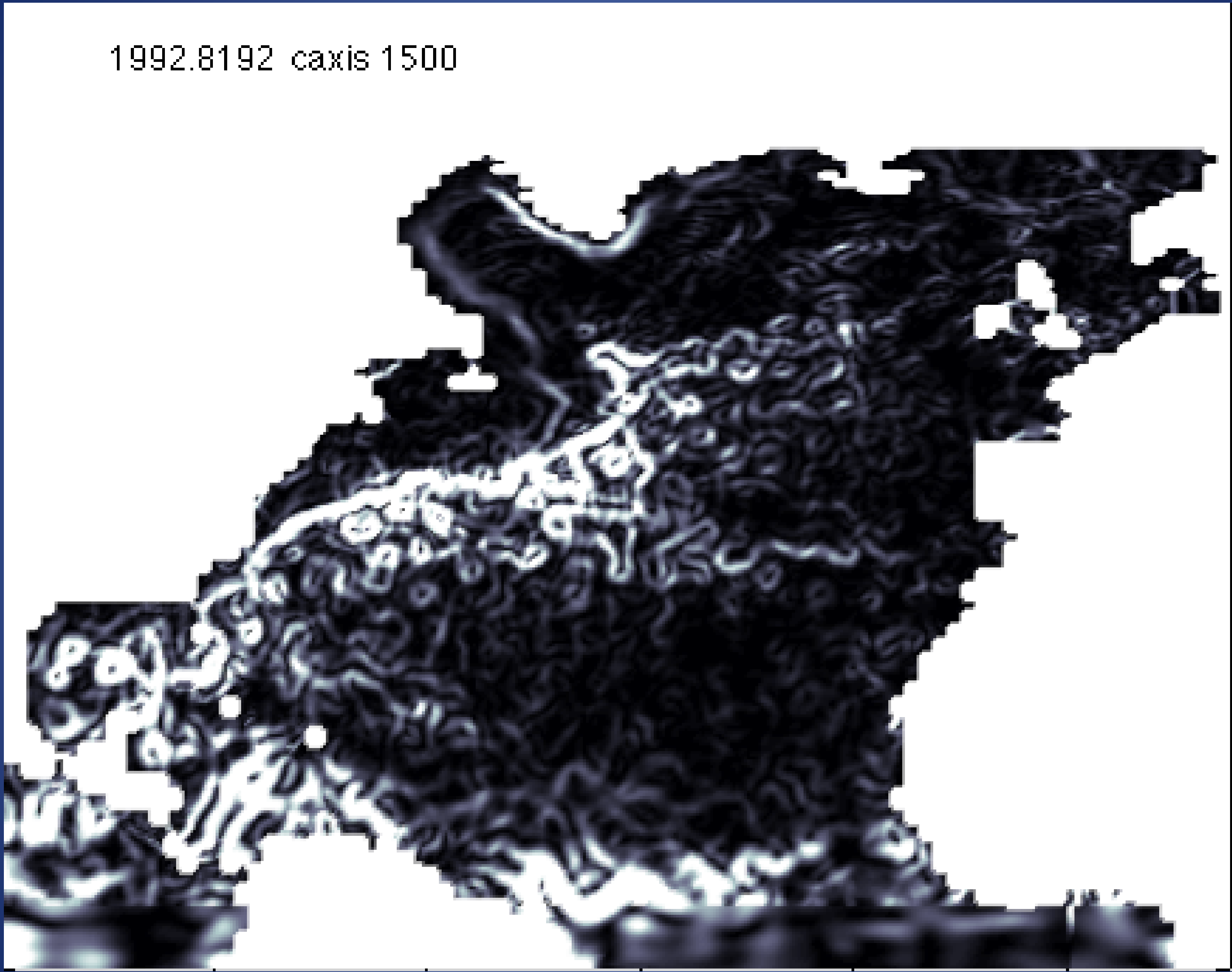
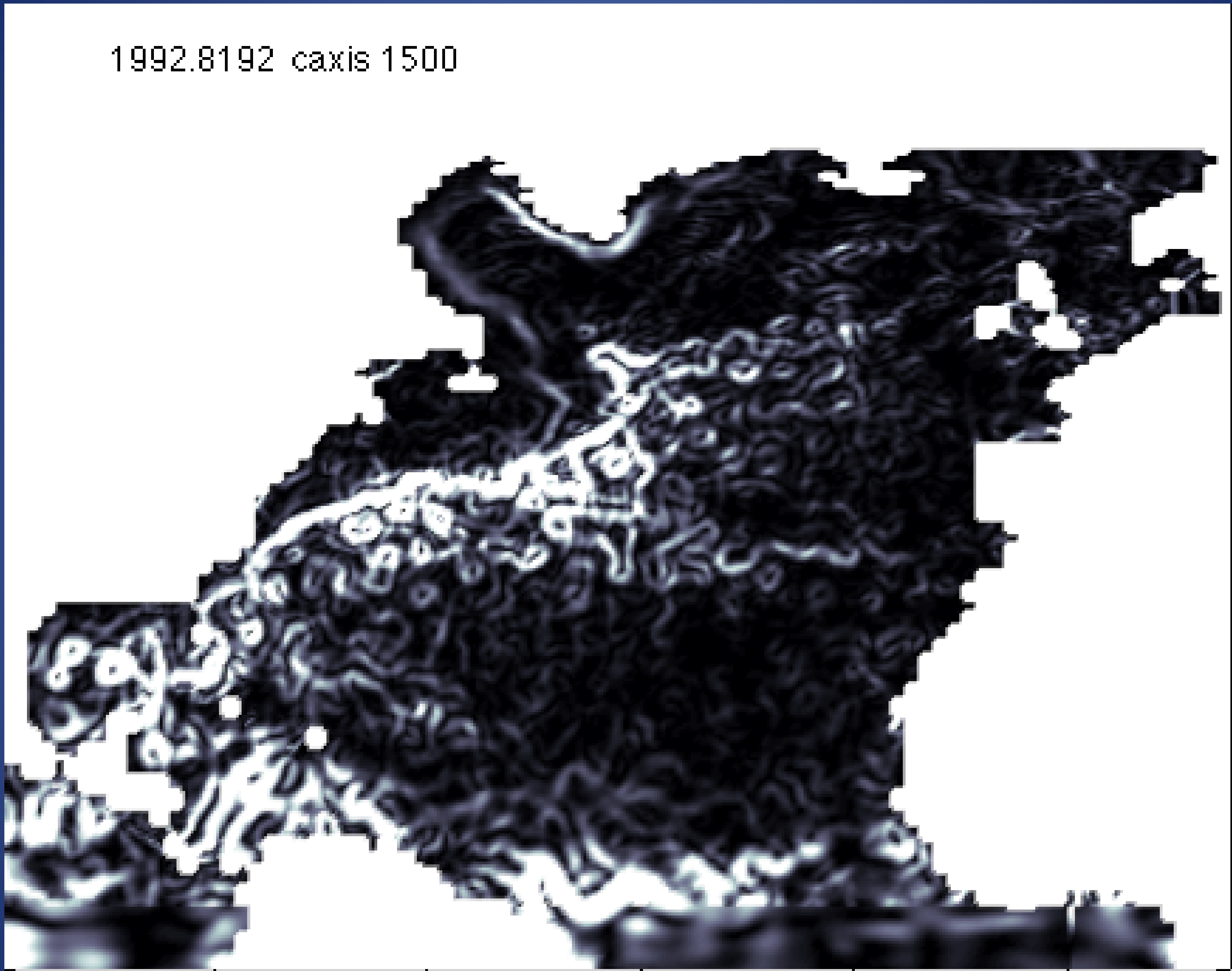

1992.8192 caxis 1500


1992.8192 caxis 400


1992.8192 caxis 1500


1992.8192 caxis 400

LINKING THE SUBTROPICAL AND SUPOLAR OCEANS: EXCHANGE IN THE NORTH ATLANTIC

(ATMOSPHERIC FORCING, SSH STRUCTURE, CARBON, AMOC, AMV)

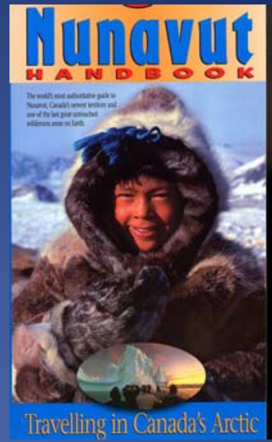
Sirpa Häkkinen (1) and Peter B. Rhines (2)

(1) NASA Goddard Space Flight Center, Code 614.2, Greenbelt, MD 20771

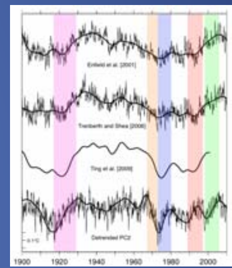
(2) University of Washington, Seattle, PO Box 357940, WA 98195

THANKS TO JIM CARTON FOR SODA ASSIMILATION DATA AND JPL FOR ECCO DATA

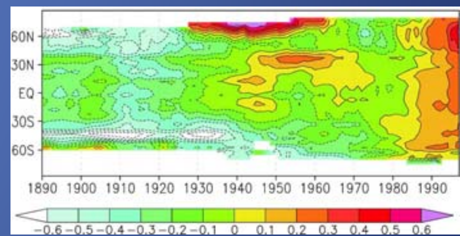
Why are we interested in the subpolar zone, especially in the N Atlantic?



people and ecosystems and natural resources: all are on the move.

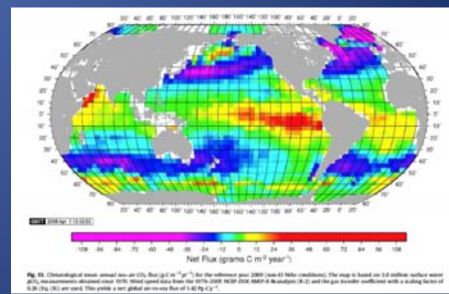


concentrated sector of the global climate system's meridional heat flux/fresh water flux
in both ocean and atmosphere
'headwaters' of the AMOC



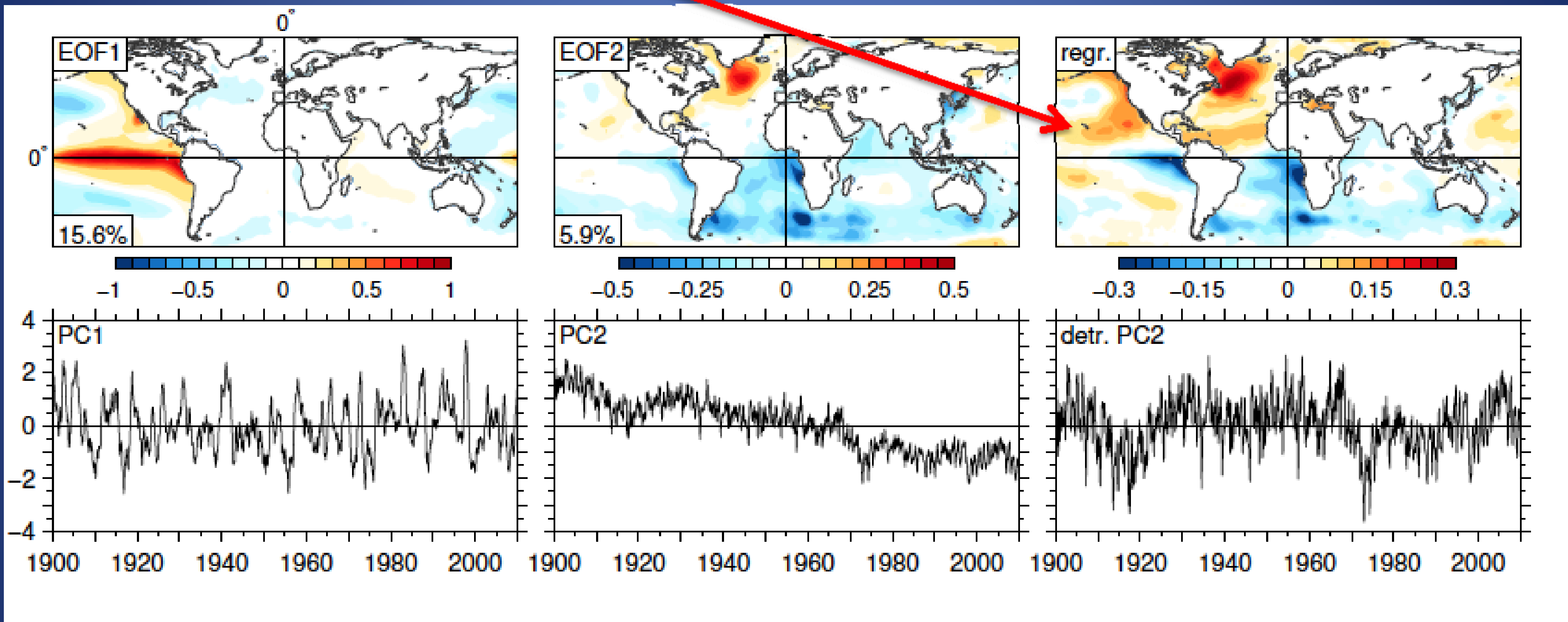
center of variabiity: decadal, multidecadal
Arctic rim is where cryosphere change may have greatest impact

leading edge of global warming yet with dynamical cycles producing extended cold periods

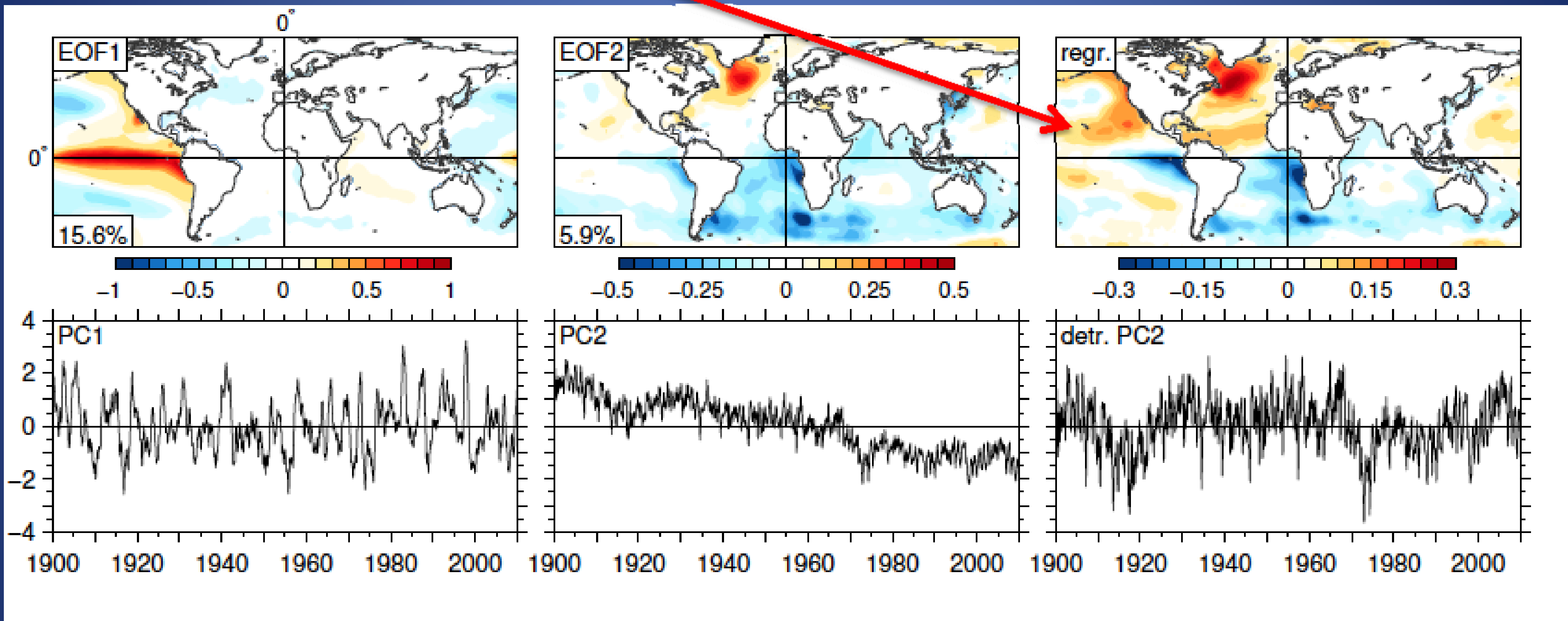


strongest carbon uptake of any oceanic region

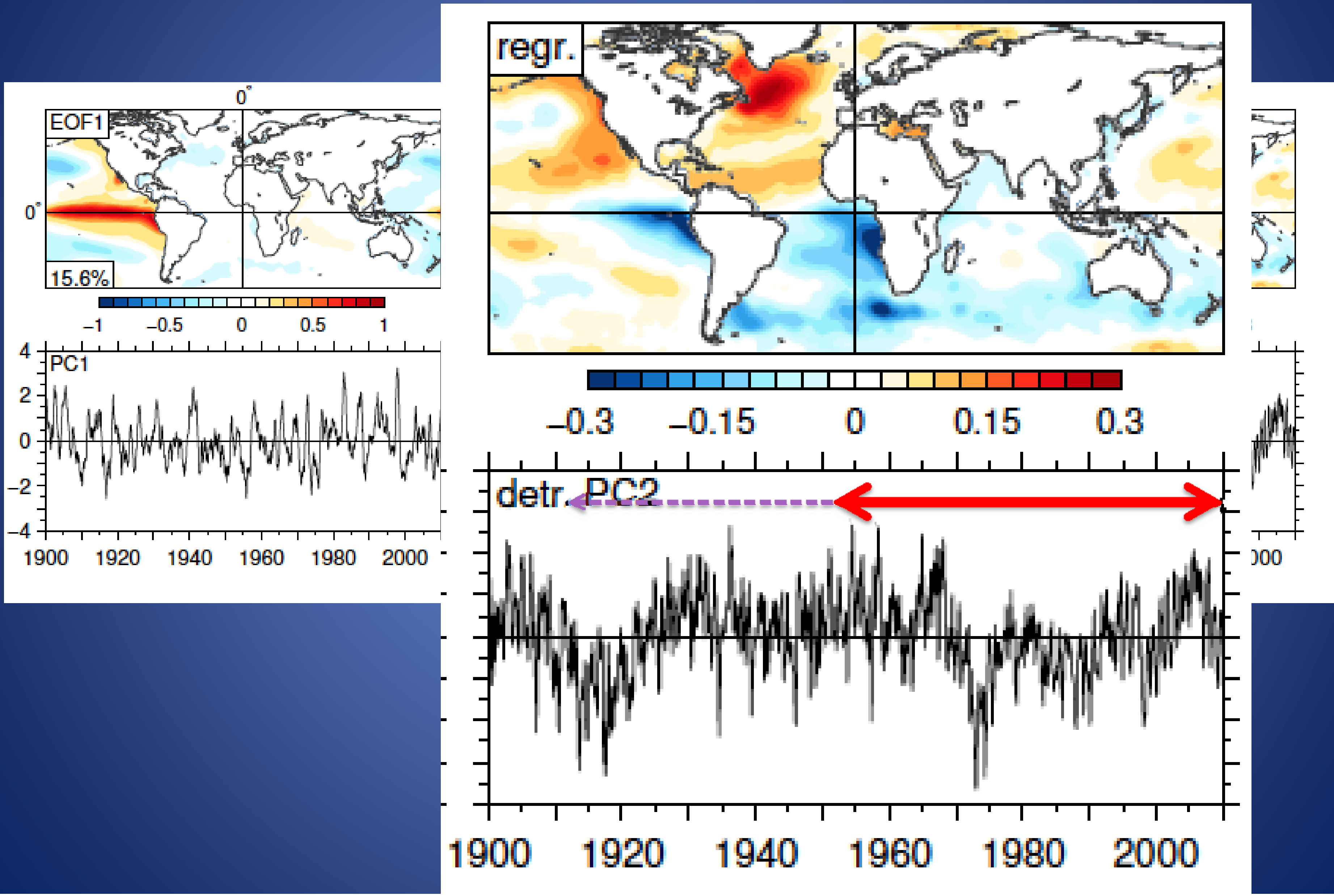
Wallace & Smoliak 2010 AMV: COWL or MOC dynamics?
detrended SST EOF-2 is a typical AMO/AMV timeseries (right)



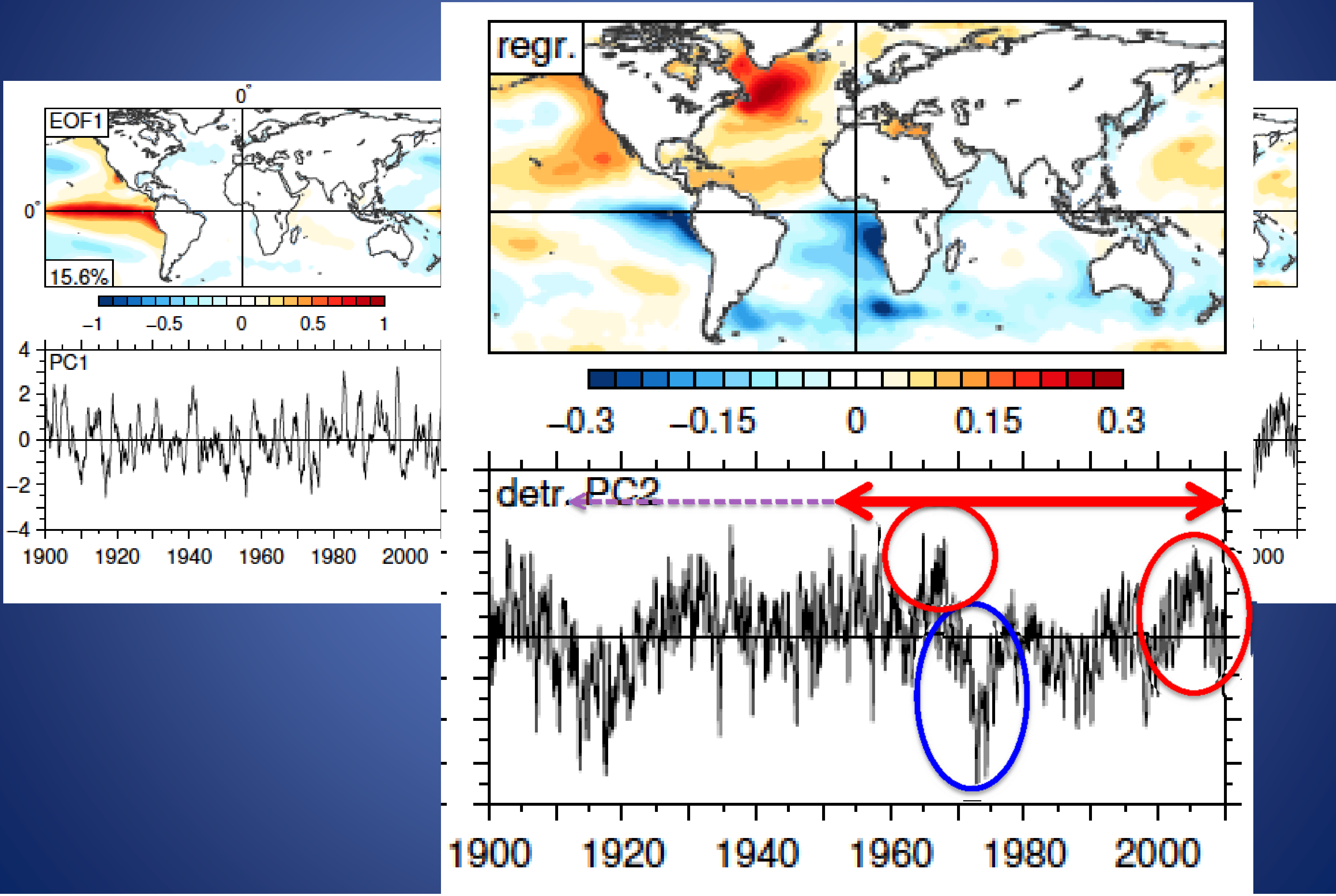
Wallace & Smoliak 2010 AMV: COWL or MOC dynamics?
detrended SST EOF-2 is a typical AMO/AMV timeseries (right)



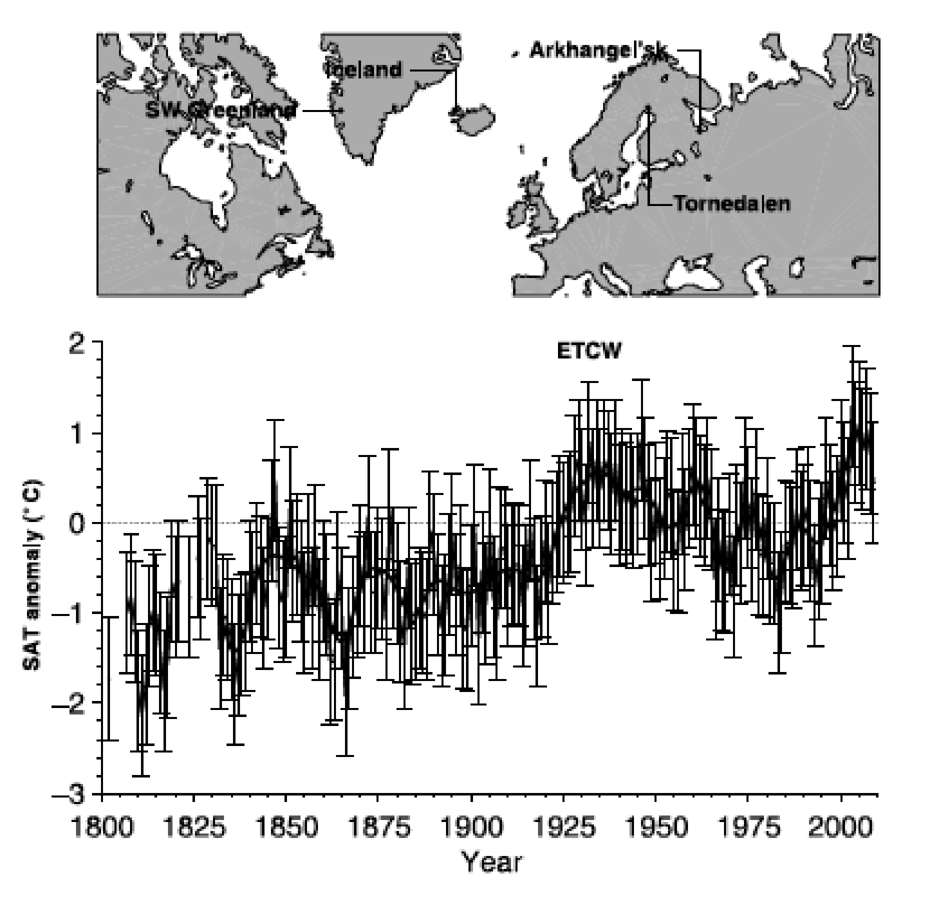
Wallace & Smoliak 2010 AMV: COWL or MOC dynamics?

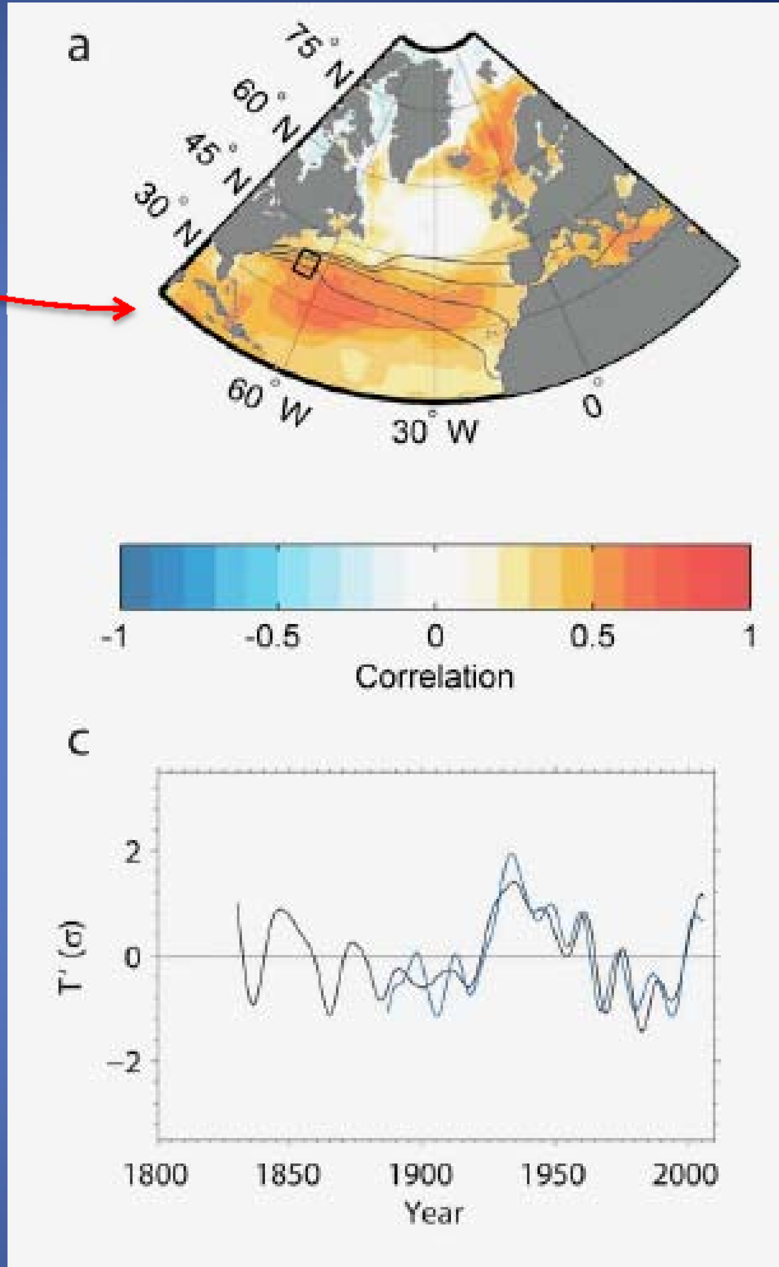


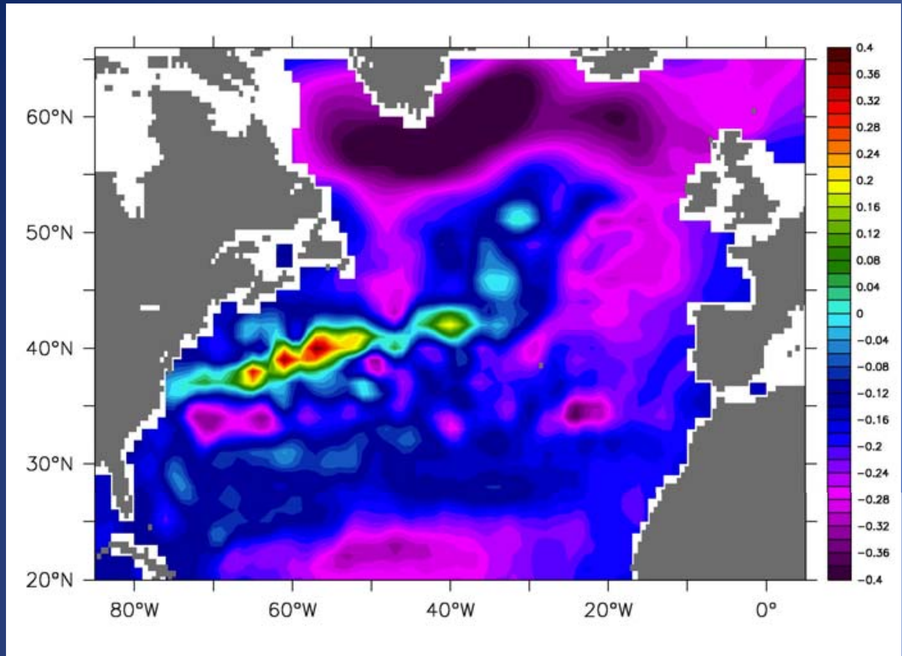
Wallace & Smoliak 2010 AMV: COWL or MOC dynamics?

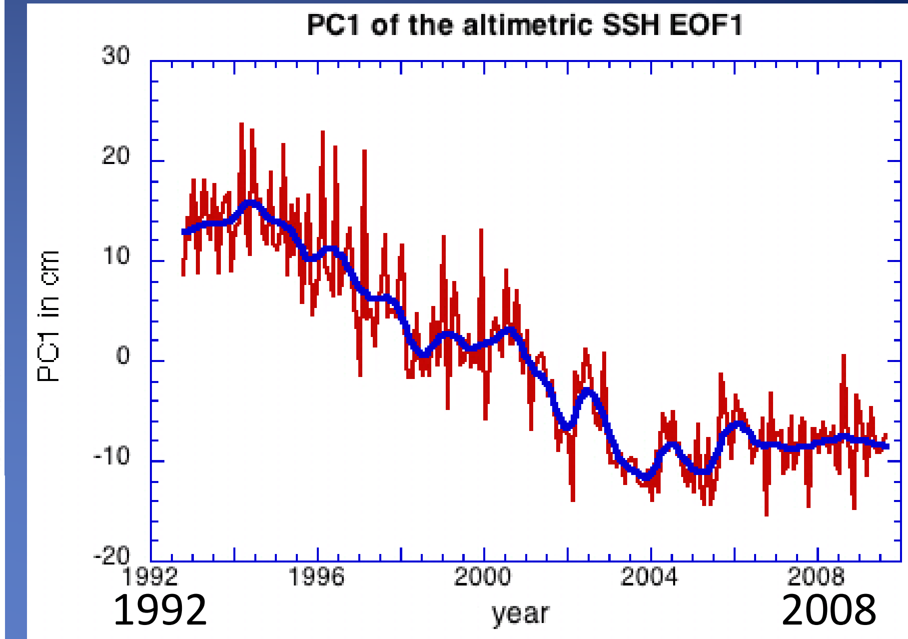


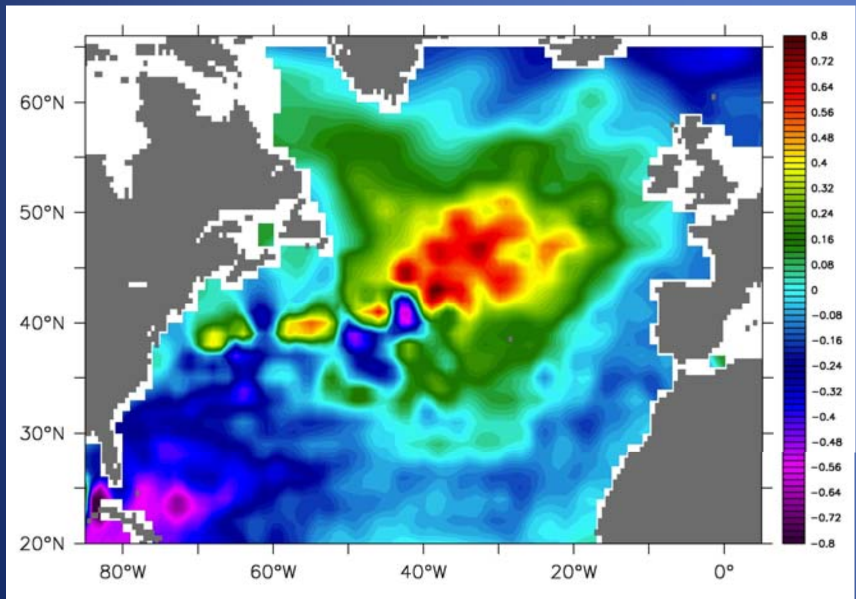
Wood, Overland, Jonnson & Smoliak GRL 2010: subarctic air temperature index regressed on SST

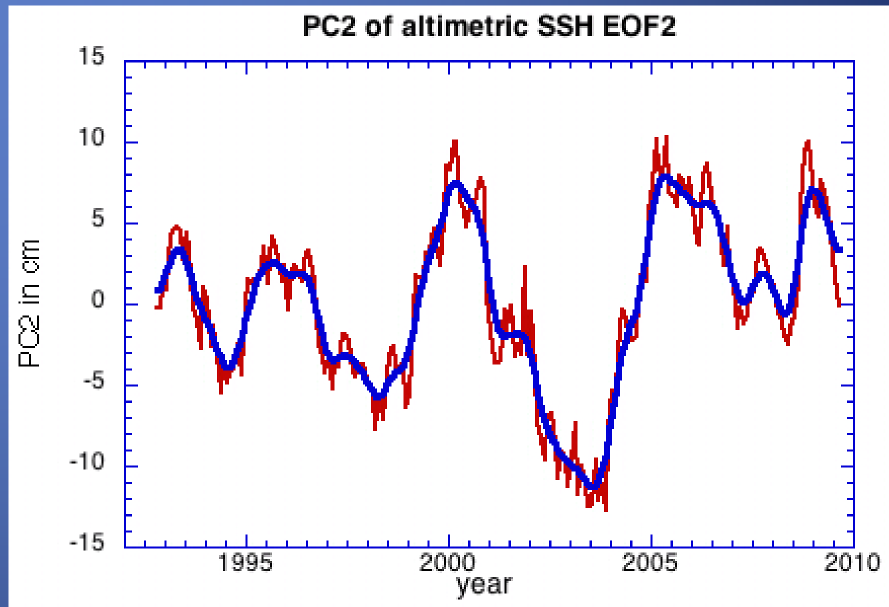





60°N
50°N
40°N
30°N
20°N
80°W
60°W
40°W
20°W
0°
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
-0.04
-0.08
-0.12
-0.16
-0.2
-0.24
-0.28
-0.32
-0.36
-0.4


PC1 of the altimetric SSH EOF1
PC1 in cm
30
20
10
0
-10
-20
1992
1996
2000
2004
2008
year
1992
2008


60°N
50°N
40°N
30°N
20°N
80°W
60°W
40°W
20°W
0°
0.8
0.72
0.64
0.56
0.48
0.4
0.32
0.24
0.16
0.08
0
-0.08
-0.16
-0.24
-0.32
-0.4
-0.48
-0.56
-0.64
-0.72
-0.8


PC2 of altimetric SSH EOF2
PC2 in cm
15
10
5
0
-5
-10
-15
1995
2000
2005
2010
year

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

▪ 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)

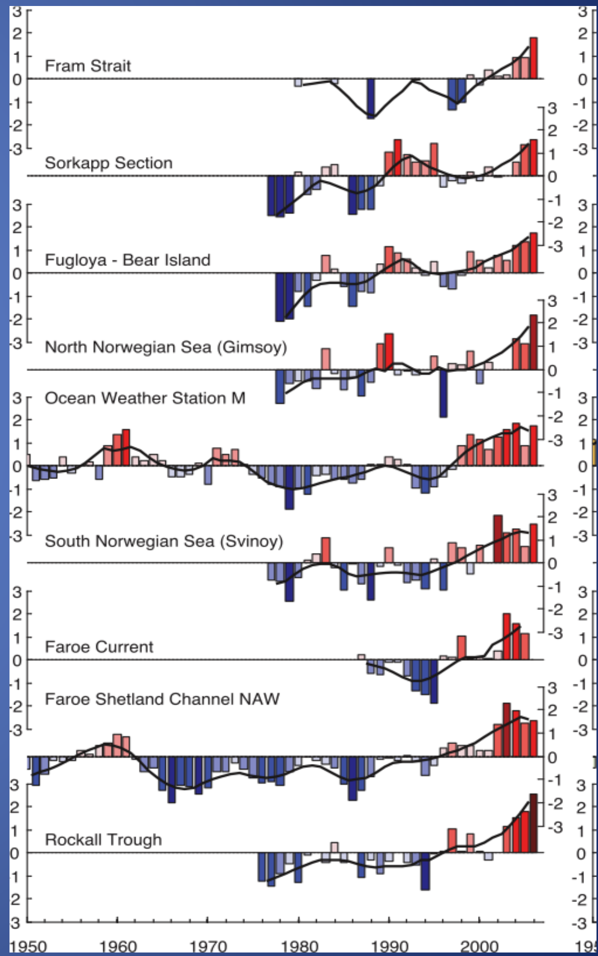
Cannot be explained by changes in surface heat and P-E fluxes

▪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)

Holliday et al. GRL 2008

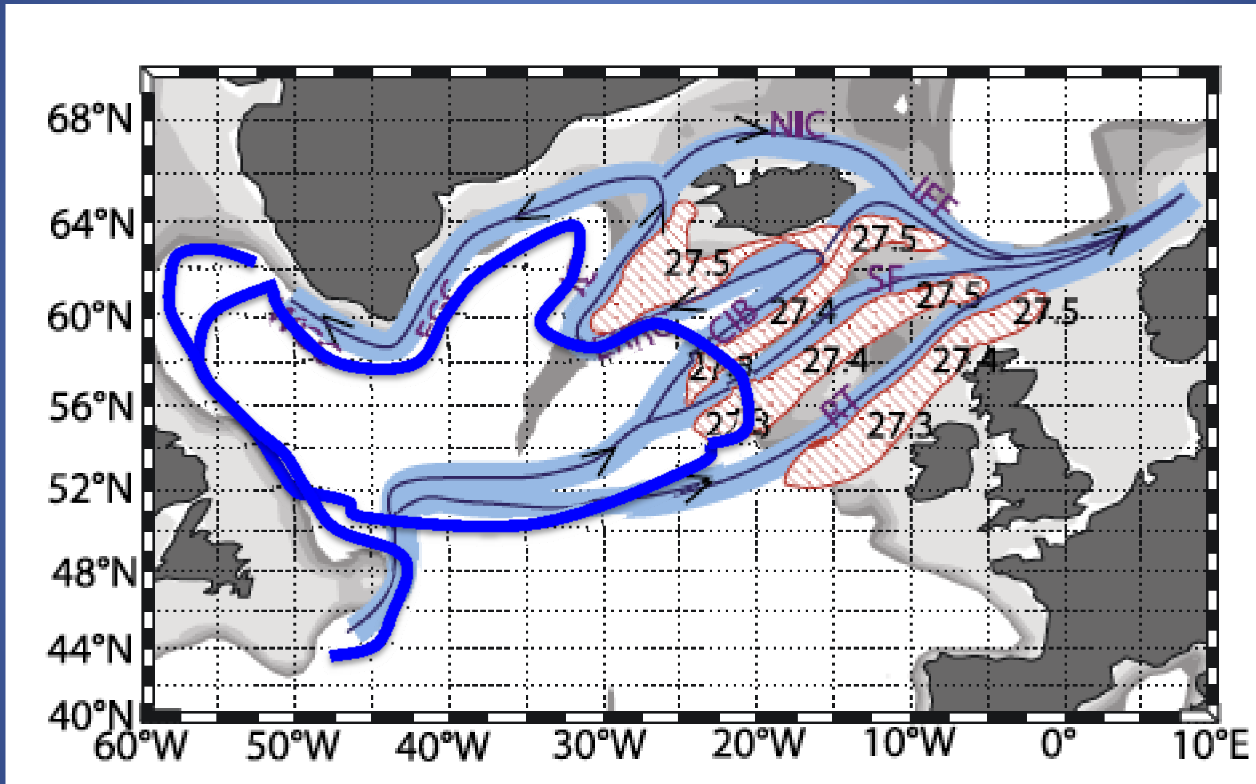
TEMPERATURE



1950 2000

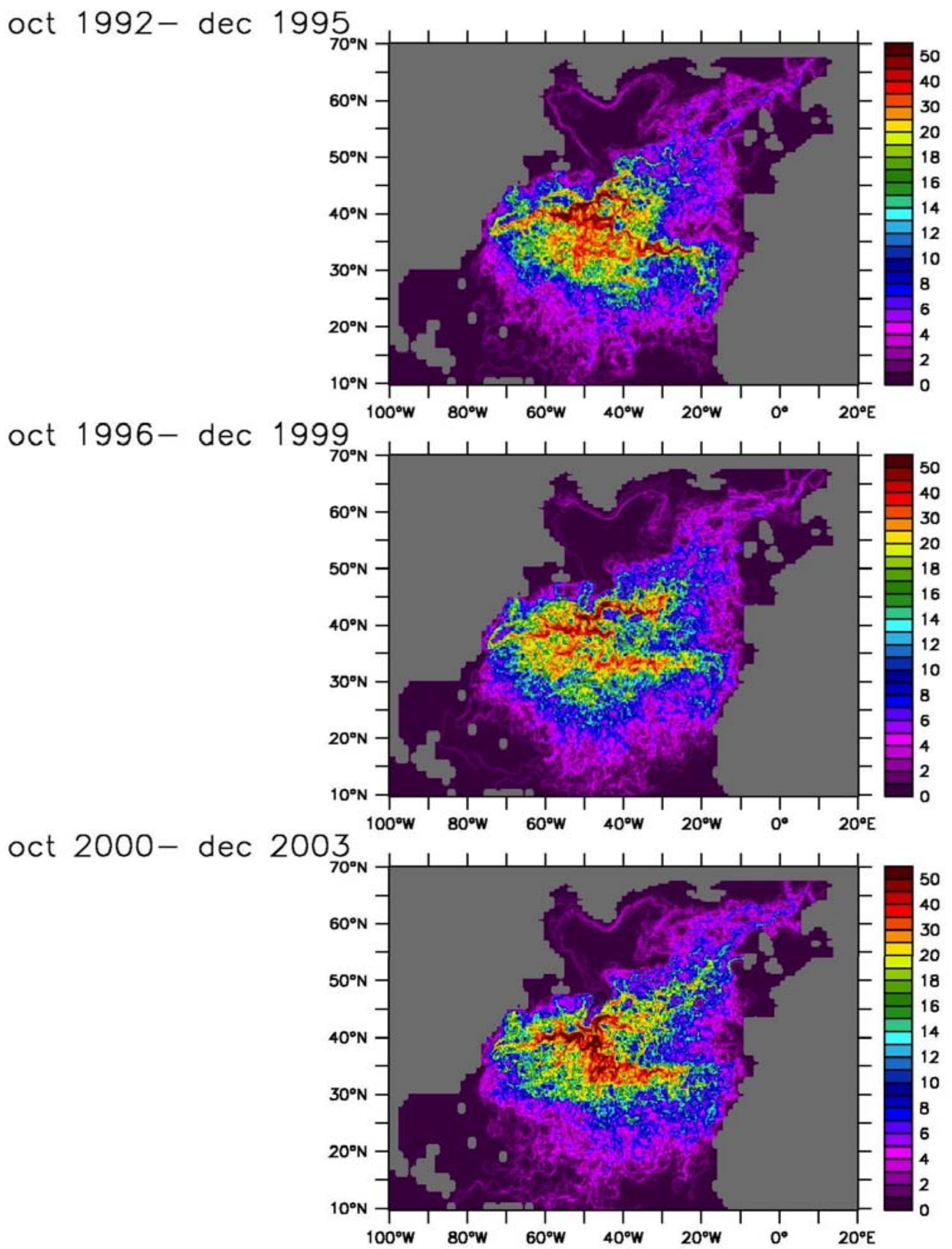
The cyclonic subpolar gyre competes with the overlying warm, saline northeastward transport to the Nordic Seas

Brambilla & Talley, JGR 2008

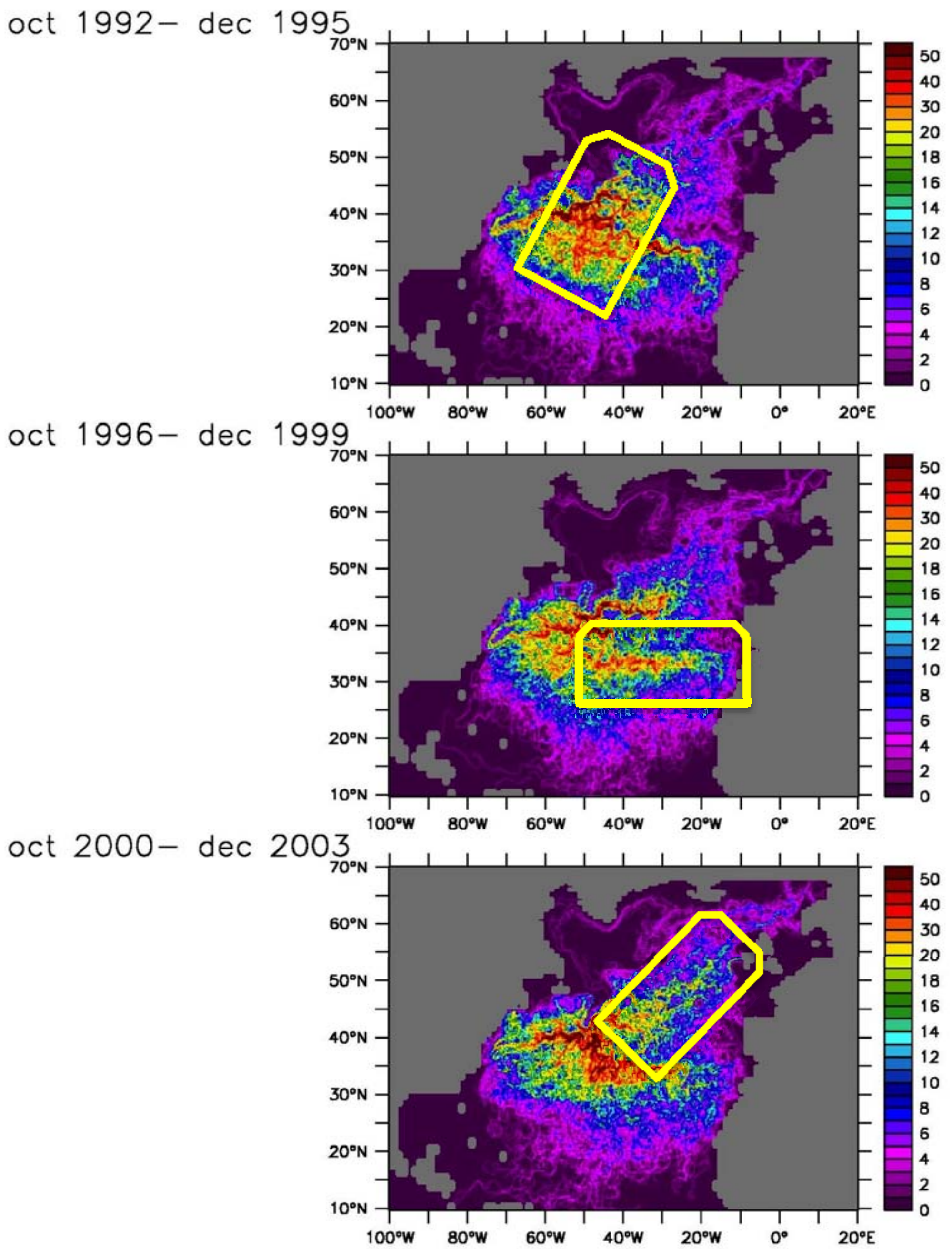


Along these paths air/sea interaction and lateral/diapycnal stirring creates Deep cooling (subpolar mode waters, SPMWs) and also mixing with warm eastern Atlantic waters

Synthetic surface drifters launched in AVISO/OSCAR altimetric surface currents the Gulf Stream region show episodes of warm, saline penetration northward, notable during the 2000s.



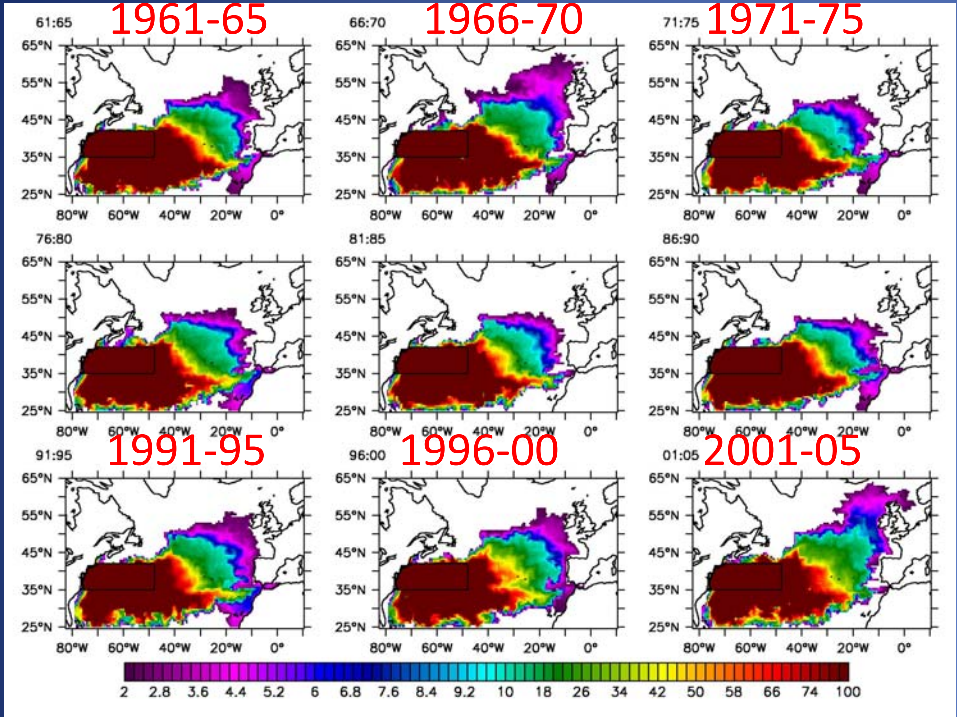
Synthetic surface drifters launched in AVISO/OSCAR altimetric surface currents the Gulf Stream region show episodes of warm, saline penetration northward, notable during the 2000s.



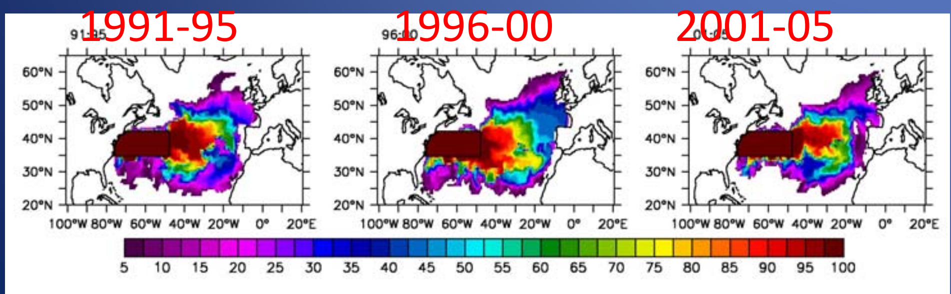
TRACER ADVECTION IN THE 15M 5-YEAR AVERAGE VELOCITY FIELD

SODA VELOCITY DATA:

TRACER KEPT CONSTANT IN THE GS BOX (left),

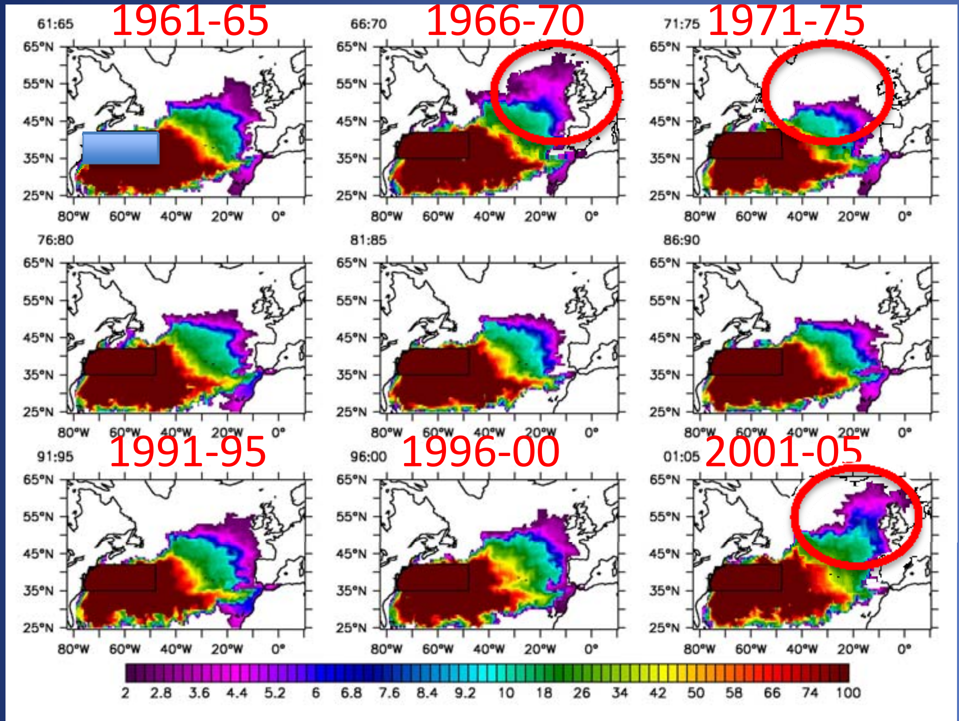


TRACER IN THE SURFACE DRIFTER VELOCITY FIELD

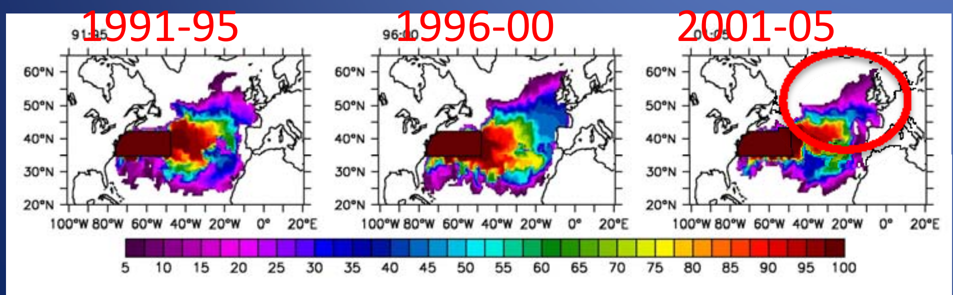


TRACER ADVECTION IN THE 15M 5-YEAR AVERAGE VELOCITY FIELD

SODA VELOCITY DATA:
TRACER KEPT CONSTANT IN THE GS BOX (left),



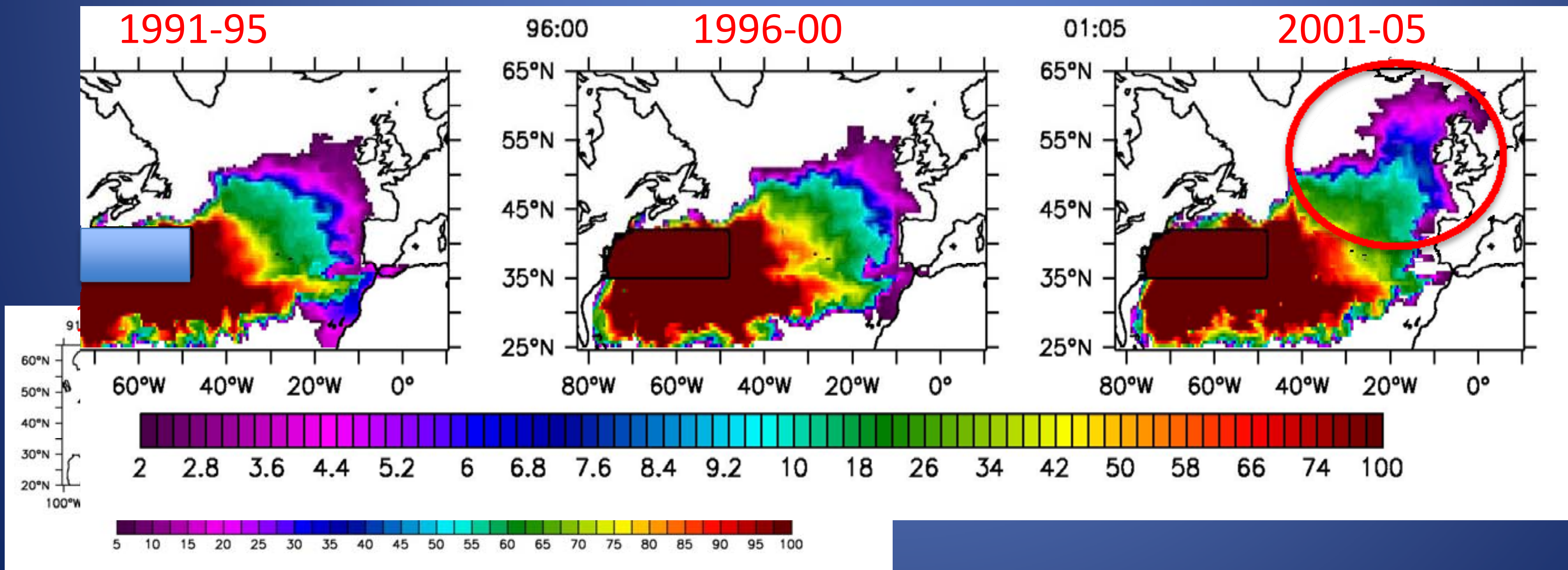
TRACER IN THE SURFACE DRIFTER VELOCITY FIELD



TRACER ADVECTION IN THE 15M 5-YEAR AVERAGE VELOCITY FIELD

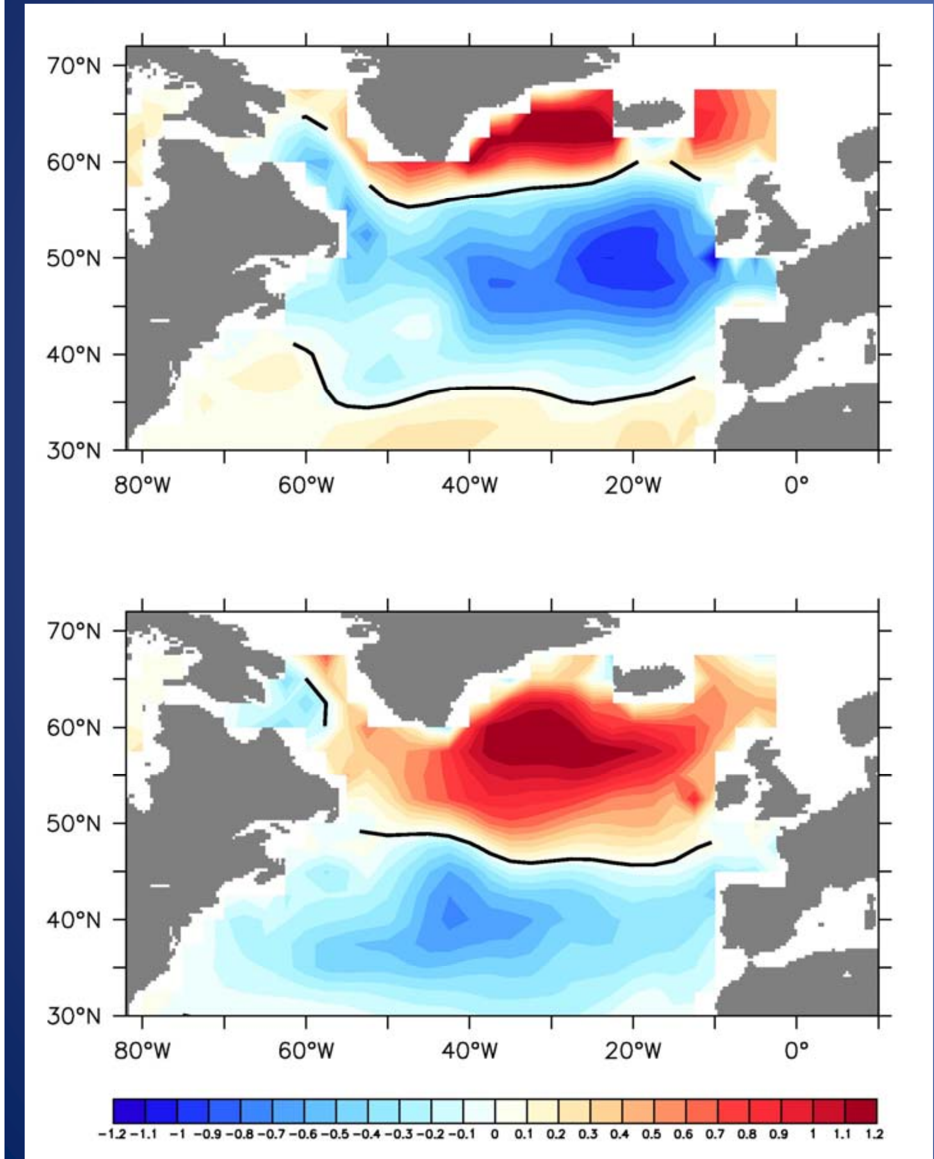
SODA VELOCITY DATA:
TRACER KEPT CONSTANT IN THE GS BOX (left),

TRACER IN THE SURFACE DRIFTER VELOCITY FIELD



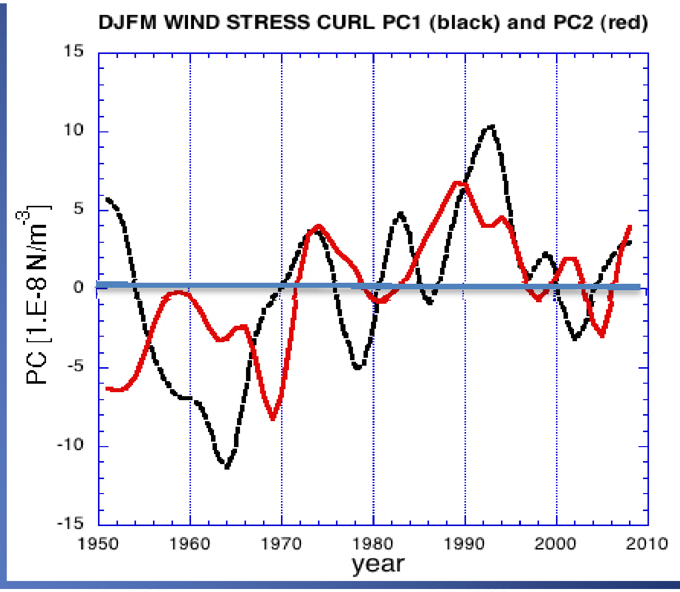
DJFM WIND STRESS CURL VARIABILITY

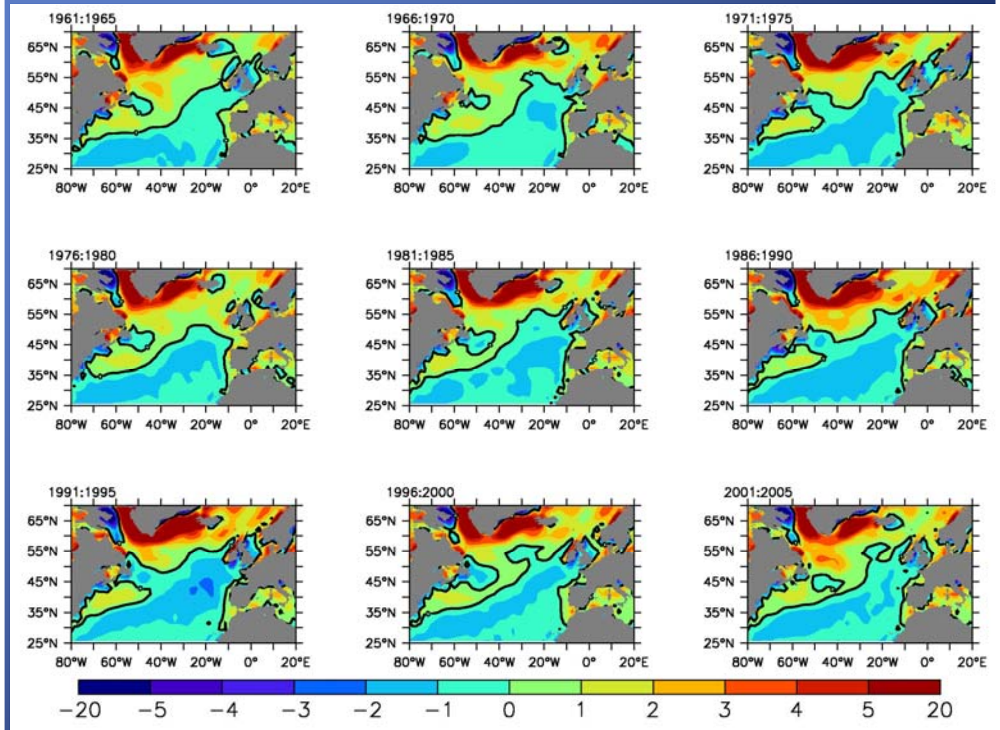
EOF1 (24%) and EOF2 (16%)

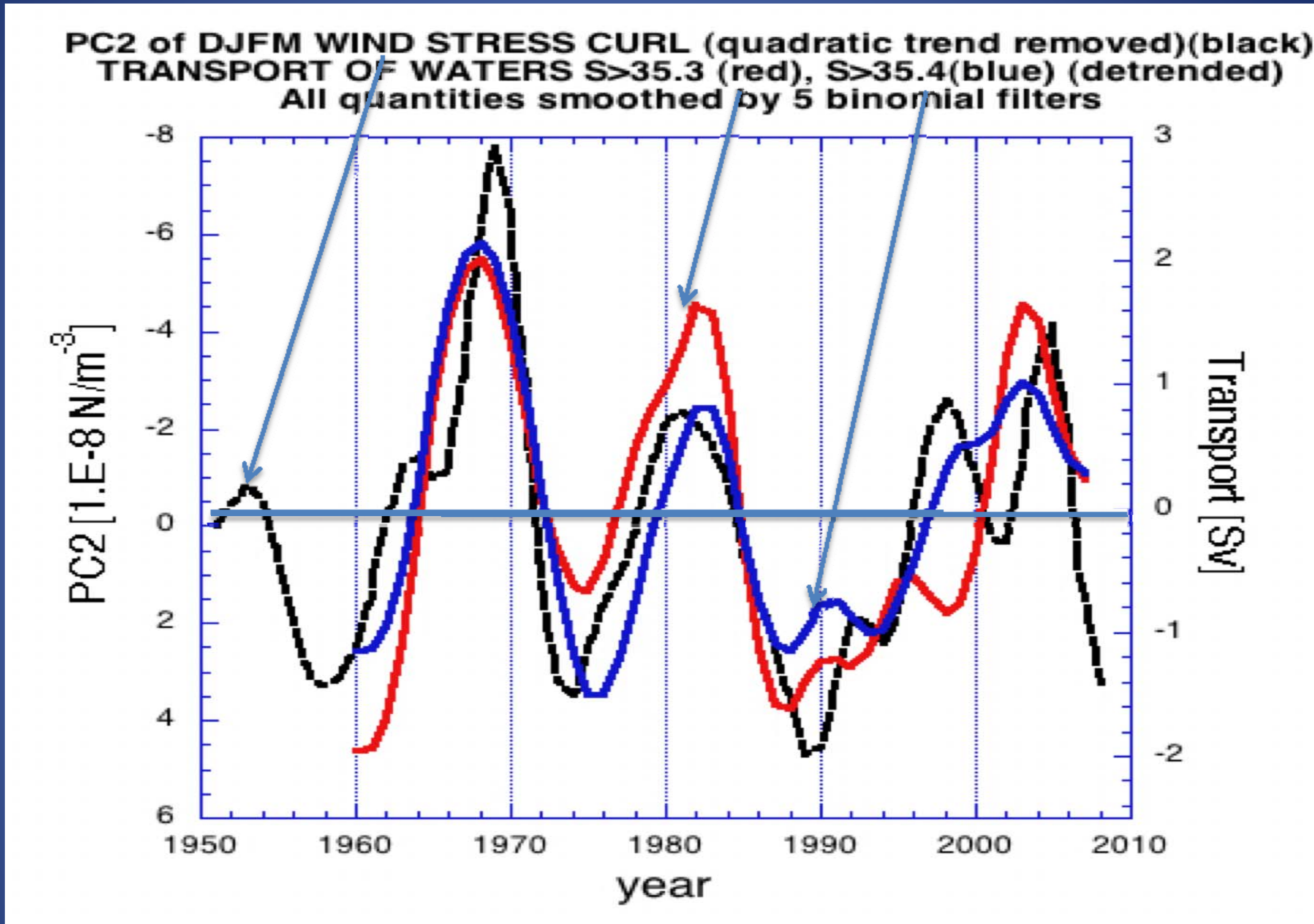


PCs (right)

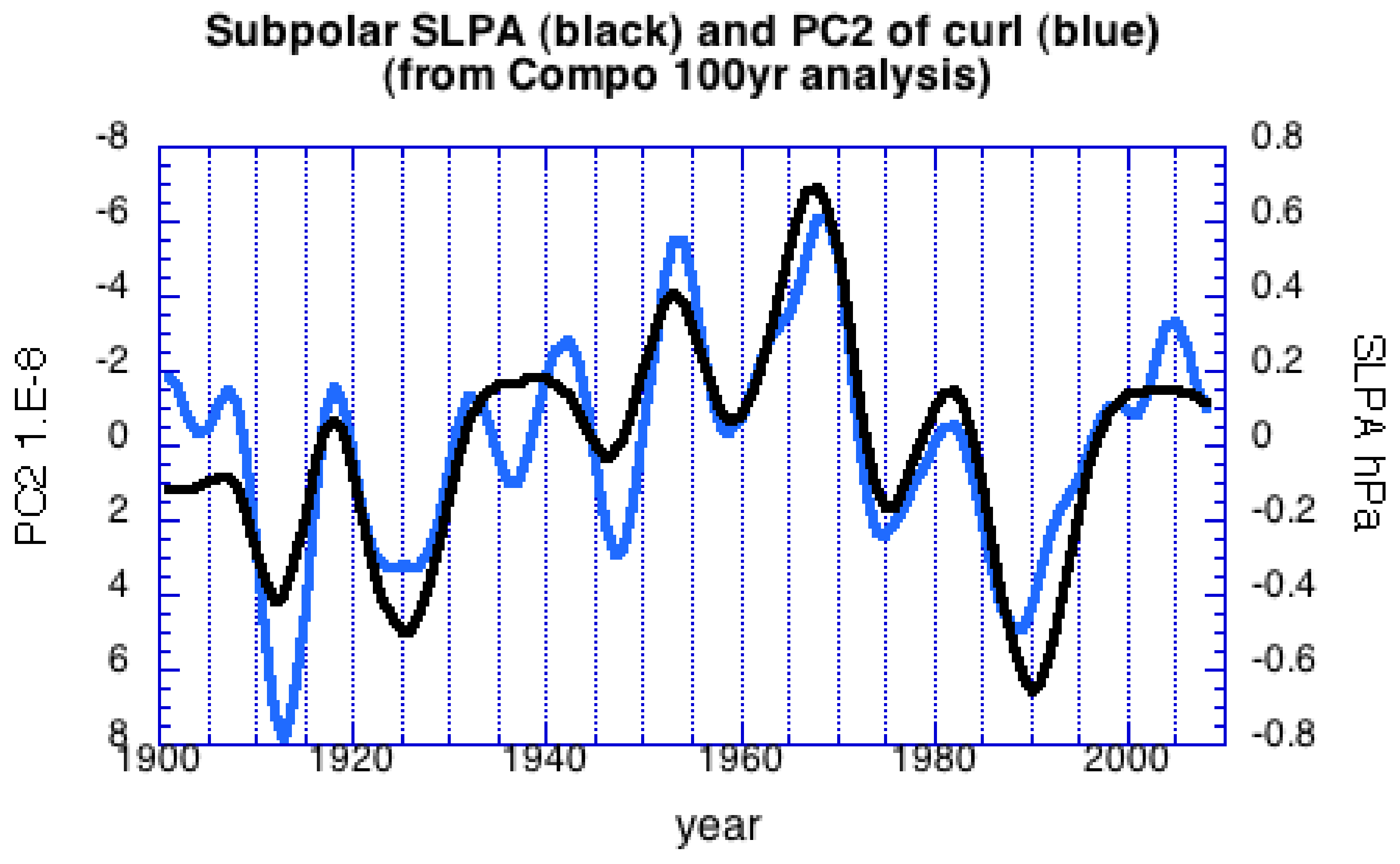
DJFM CURL FIELDS FROM NCEP (below)



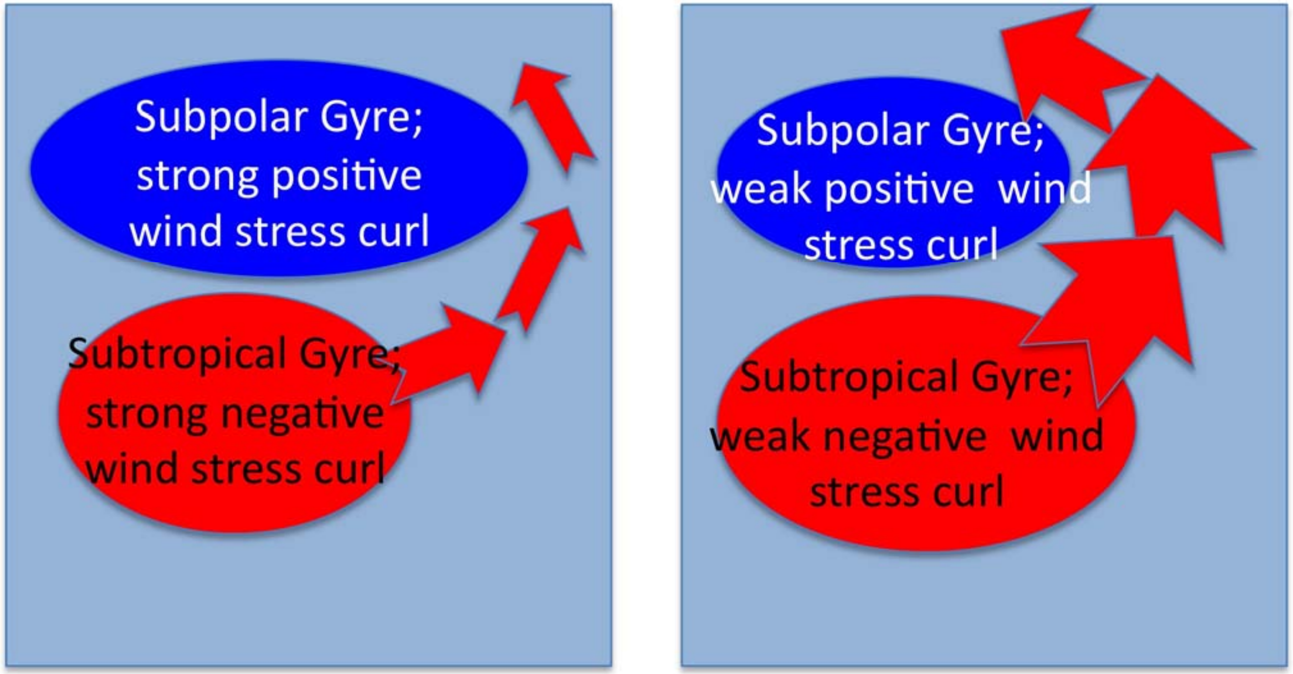




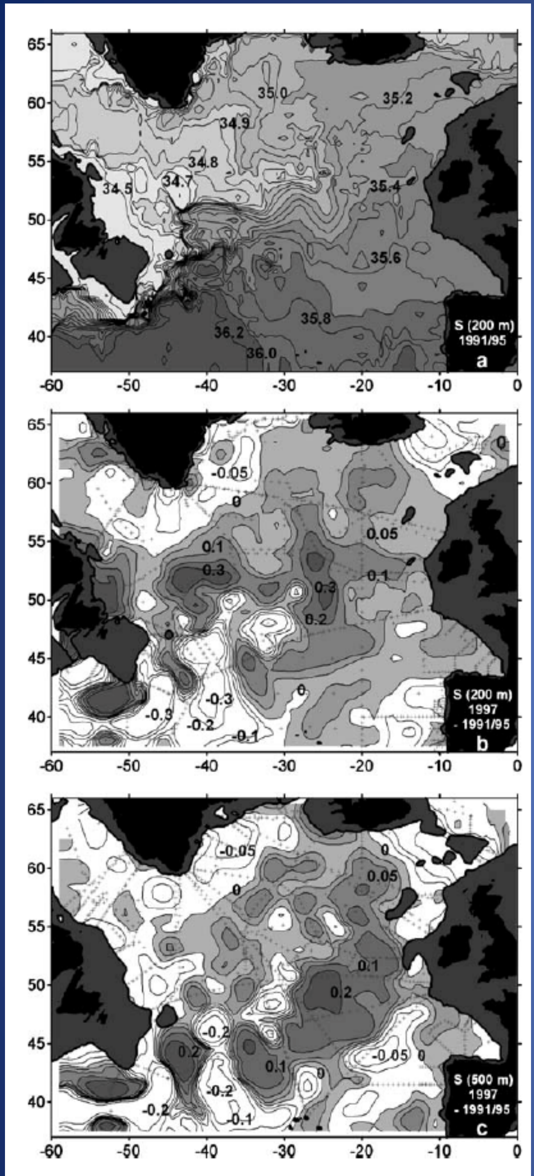
MAXIMUM TRANSPORT WHEN SUBTROPICAL AND SUBPOLAR CURL ANOMALIES ARE ASSOCIATED WITH THE WEAKENED GYRES



Subpolar SLPA (black) and PC2 of curl (blue)
(from Compo 100yr analysis)
-8
-6
-4
-2
0
2
4
6
8
PC2 1.E-8
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
SLPA hPa
1900
1920
1940
1960
1980
2000
year


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

The warm, saline signal extends to great depth (>500m)



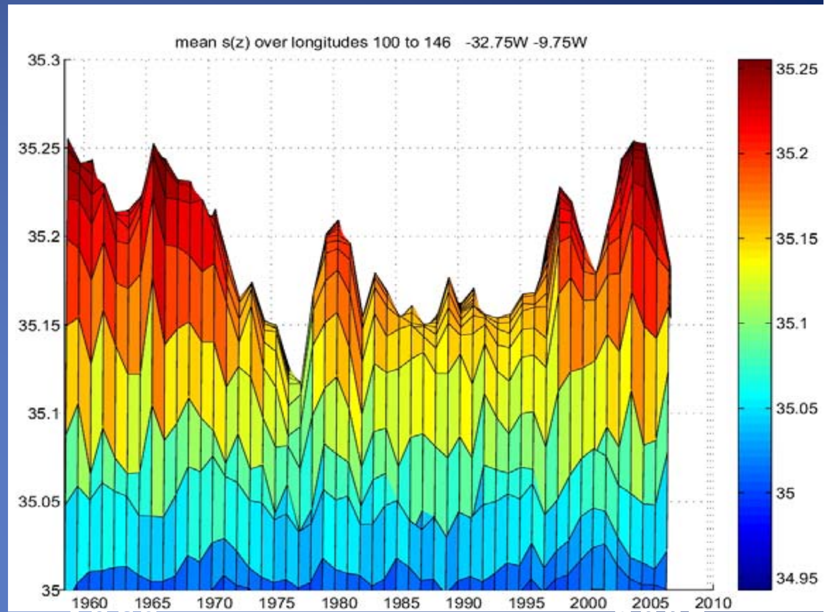
S 200m
1991-95

S 200m
1997-(1991-95)

S 500m
1997-
(1991-95)

Bersch, Yashayaev, Koltermann OD2007

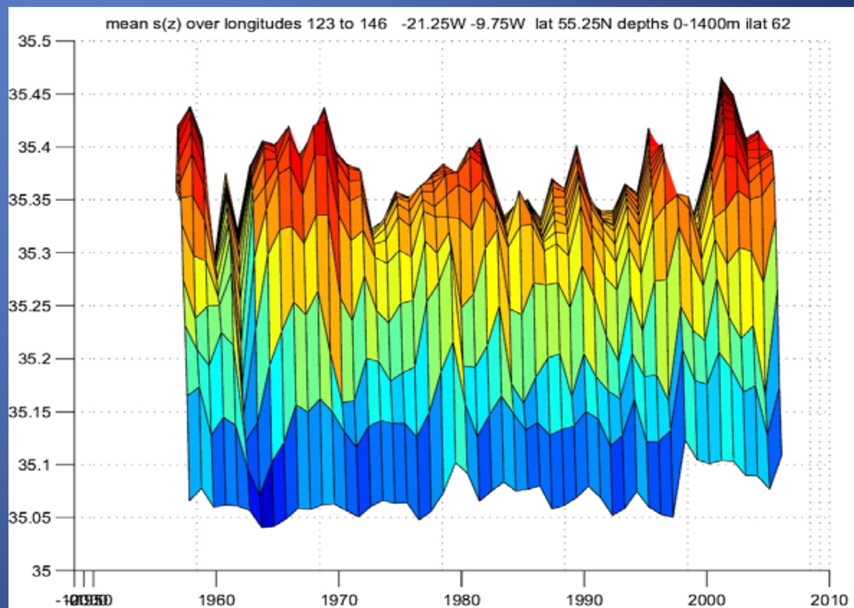
60N



1960

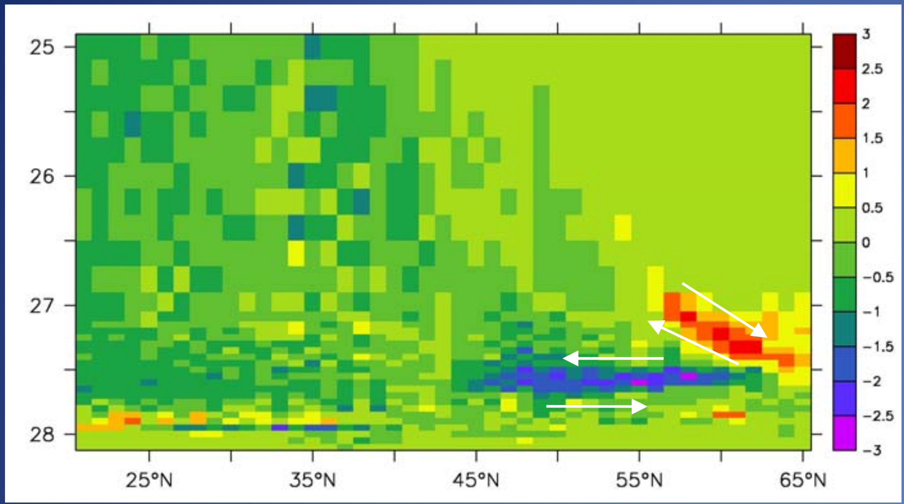
2005

55N

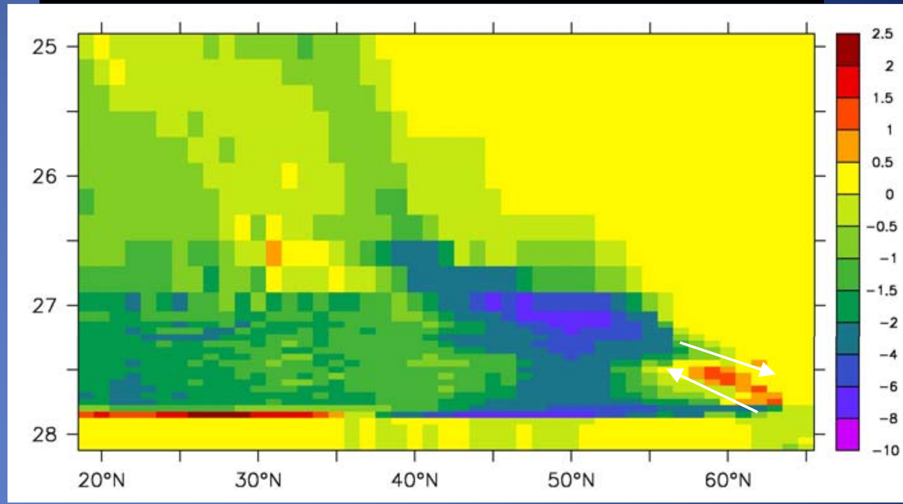


AMOC CHANGE IN DENSITY SPACE [2001-2007] - [1994-2000]

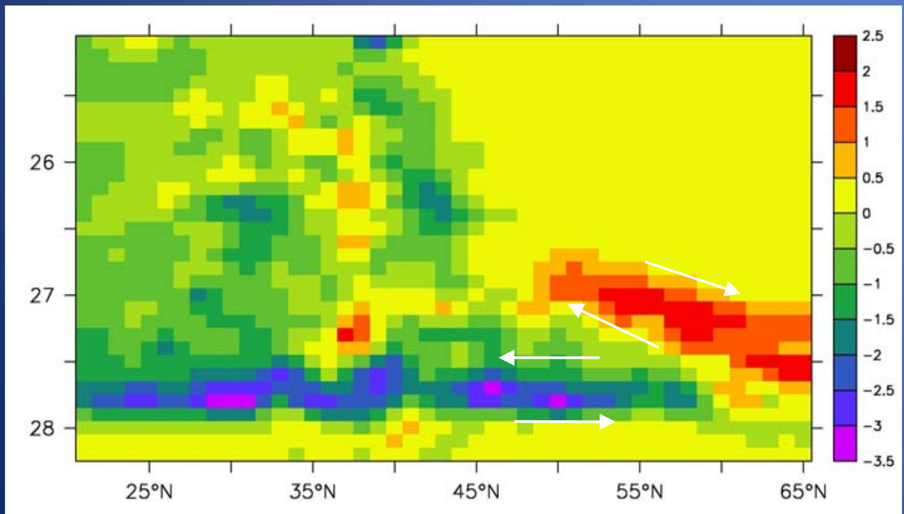
PROGNOSTIC POM



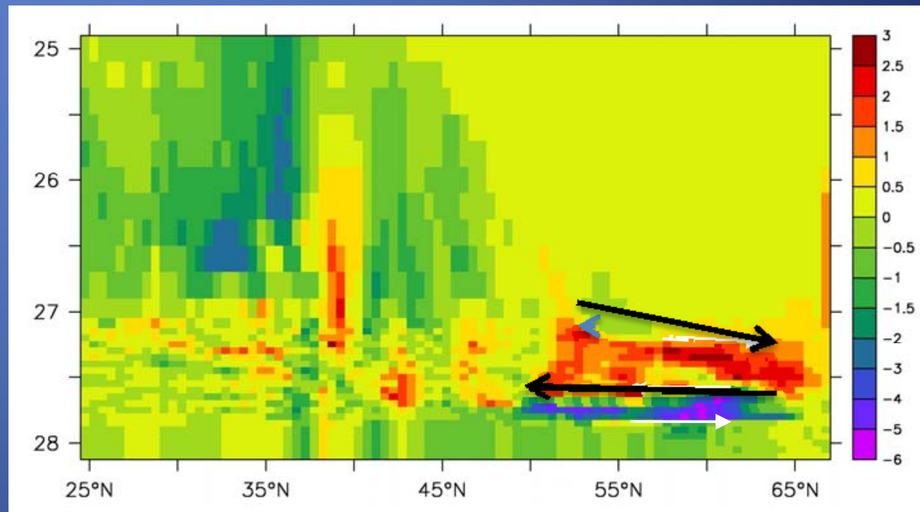
STATE ESTIMATION- ECCO-KF



PROGNOSTIC POM-Z



STATE ESTIMATION- SODA



Units are Sv

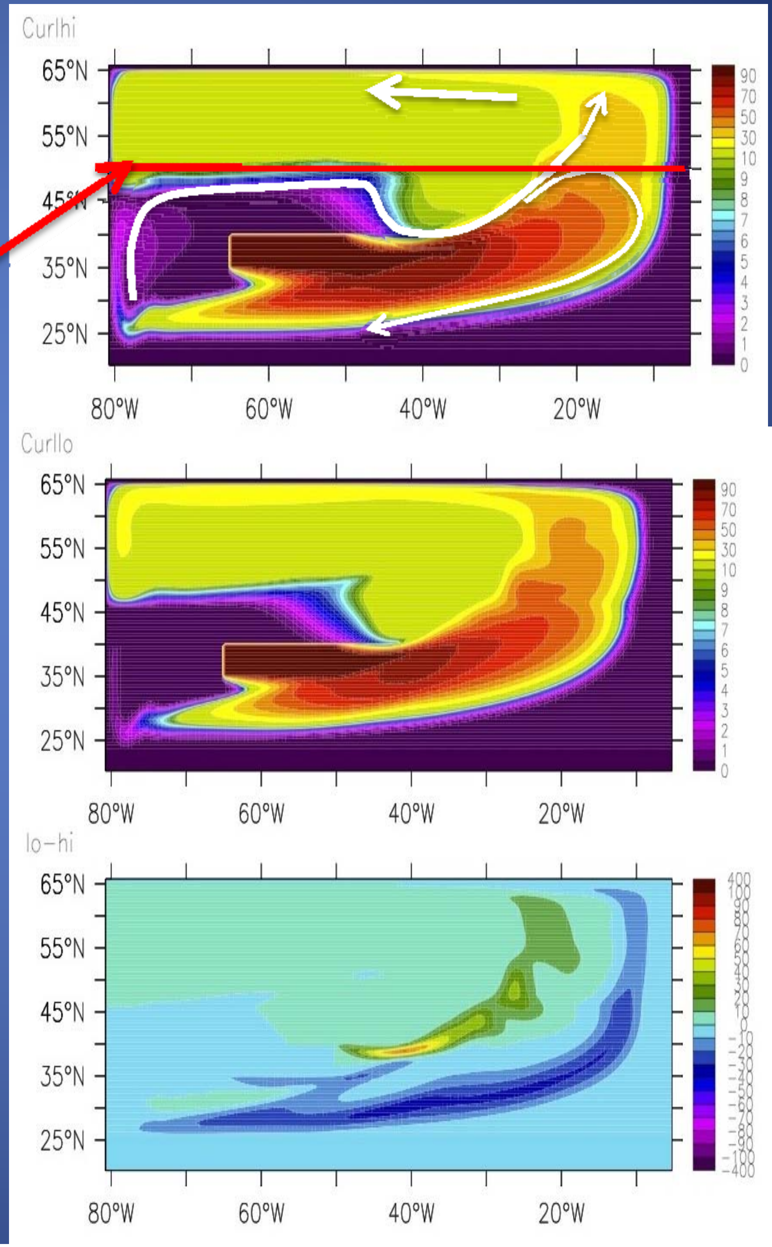
the basic dynamics of intergyre exchange appears in a 2-layer isopycnal model: cold water outcrops in the north, forcing warm water to flow northward and join the subpolar gyre HIM model…
see *Huang & Flierl JPO 1987*

strong
wind-curl

zero-curl line

weak
wind-curl

difference



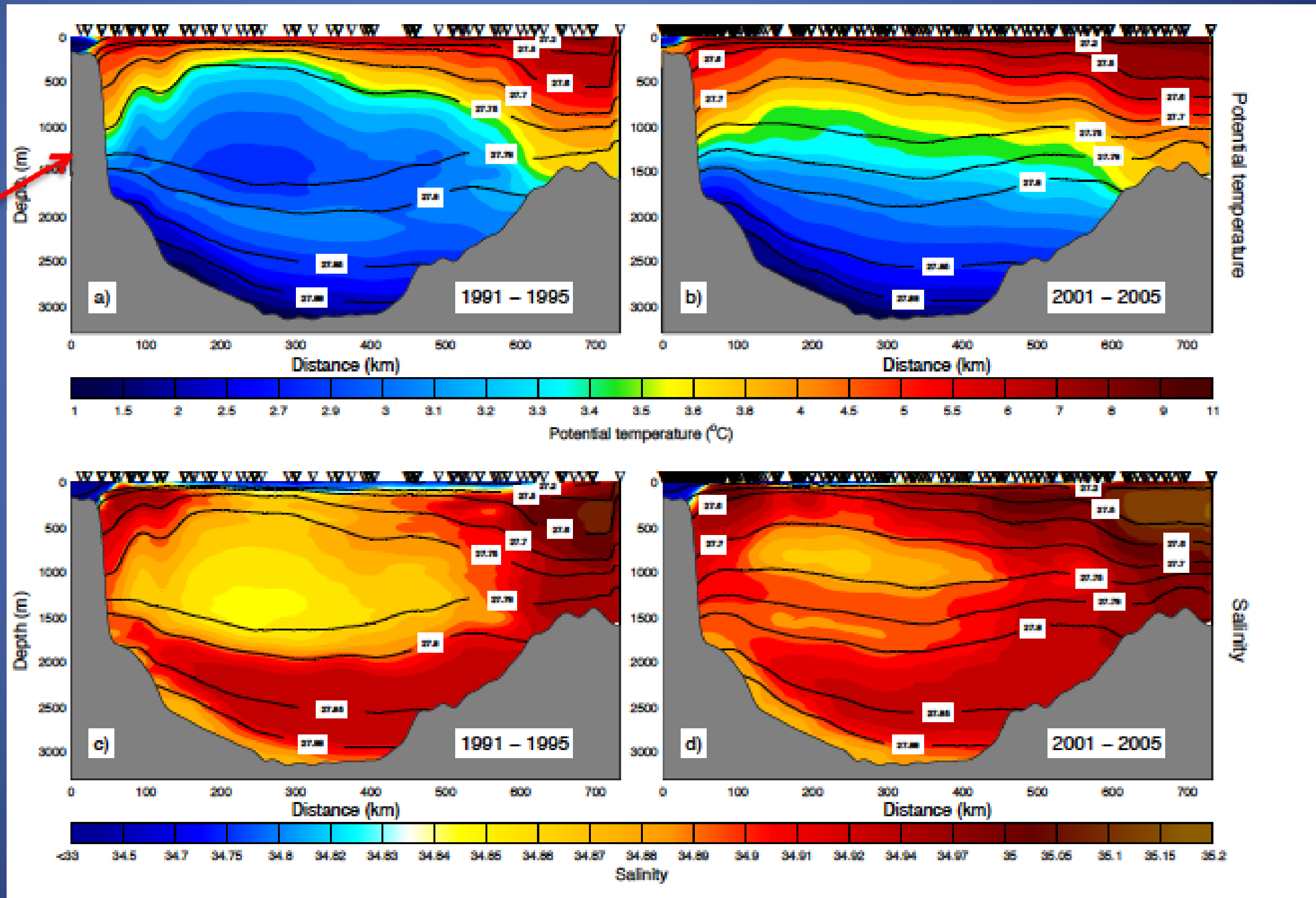
tracer released in subtropical gyre penetrates northward into the subpolar gyre even with strictly zonal wind-stress; outcropping of cold layer forces transport from subtropics to subpolar gyre

This is just the beginning of the story…of the web of interactions between global climate and ocean circulation in the high latitudes. While the mean-state ocean has always been acknowledged as an active partner with the atmosphere, its role as active through *extratropical variability* is relatively new.

AMO, AMV, AMOC are 3 dimensional circulations, with complex subsurface structure. Example:

Subsurface *in situ* observations of the Irminger Sea near the max of subpolar Atlantic variability (ships' ctd, adcp, tracers, Seagliders) describe the 3-dimensional fields connecting with satellite altimetry, SST and ocean color. *Vage, Pickart et al, DSR 2010*

Greenland



velocity transect across Irminger gyre: *Vage, Pickart, et . DSR 2010; Knutsen, Rossby et al GRL 2005*

AVISO altim

Nuka Arctica adcp

GRACE DOT

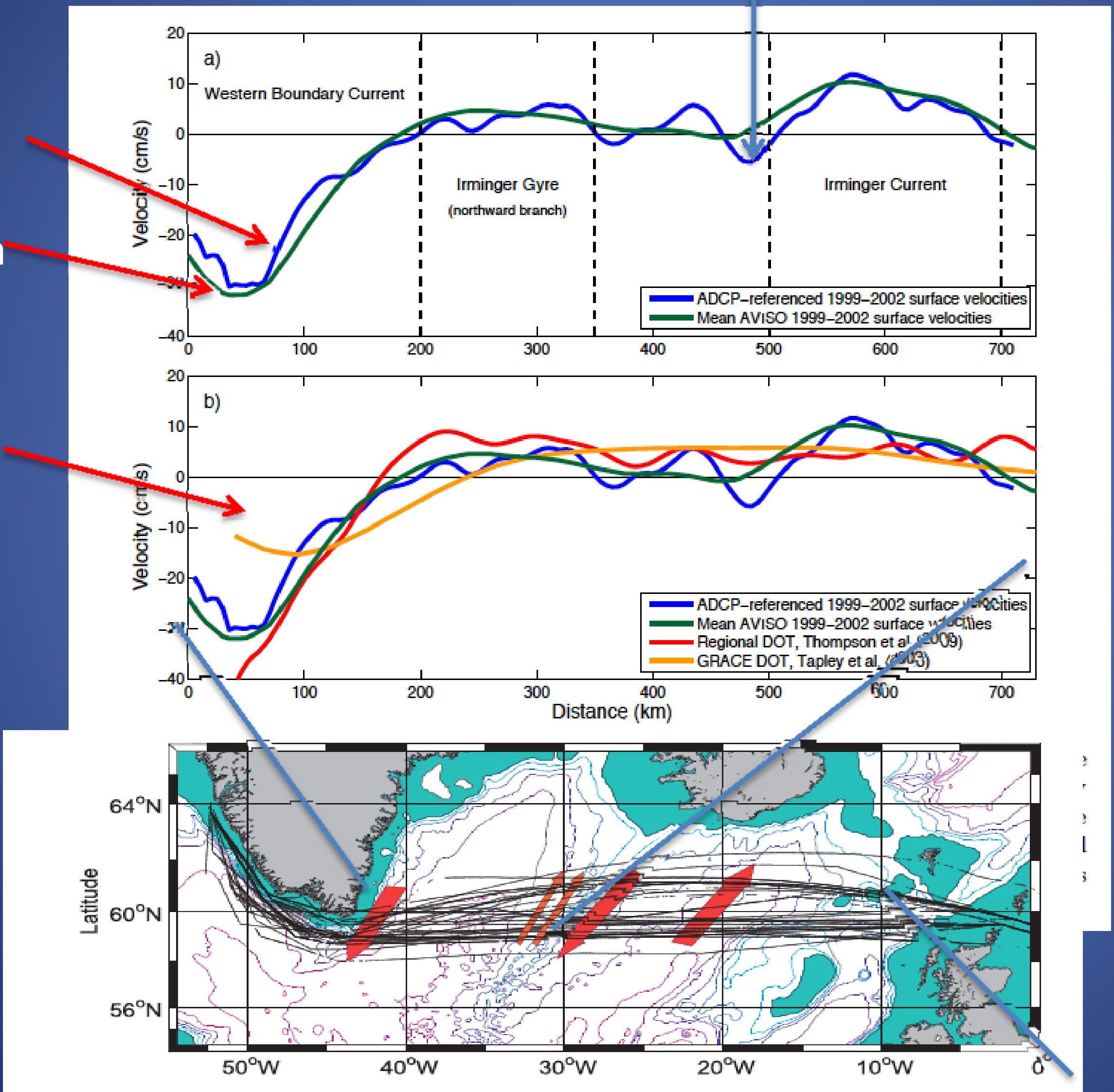


Figure 5: Nuka Arctica transects between 1999 and 2002, from Knutsen et al. (2005). The gre

In this example, the dense overflows of the AMOC interact with the warm, saline surface circulation through *barotropization* and turbulent entrainment. The 1960s and 2000s invasion of warm subtropical water to the subpolar gyre shows some continuity with the longer period Atlantic Multidecadal Variability (AMV)

Topographic control and pseudo-Taylor-columns are everywhere at high latitude (e.g., in the two-way circulation through the Charlie-Gibbs Fracture zone (*Bower & Van Appen, JPO 2008).*

At high latitude the altimetric sea-surface height differs from the baroclinic SSH derived from hydrography: the 'thermometer' versus the 'barotropic circulation gauge'. (And both differ from GRACE ocean mass variability (*Willis, Chambers & Nerem JGR 2008))*

In situ observations (e.g. *Vage et al. DSR 2010)* are beginning to show the mean and variable relationships between the subpolar gyre strength seen at the surface and key meridional overturning indices.

Meanwhile, new analyses of climate and circulation models are suggesting covariance structure of subtropical/subpolar communication, structure of AMOC and the construction of the shallow and deep AMOC branches (e.g. *Langehaug, Medhaug & Eldevik, 2011 preprint from Bergen Climate model).*

Summary

Penetration of subtropical waters northward to the subpolar gyre 'appears' as a **strengthened upper limb of the AMOC** after 2000 in the SODA model assimilation (has not happened since 1960s)

- unclear if the net upper layer transports have changed, clearly the sources of the North Atlantic Current have shifted towards more subtropical origin as confirmed by tracer simulations, satellite altimetry, sea-surface drifters, OSCAR surface currents (*Hakkinen & Rhines*, JGR 2009)

The forcing: The first two EOFs of wind stress curl correlated in broad terms with the three recent warming-high salinity periods in the NE Atlantic (1960s, 1980, 2000s)

-The first mode PC follows closely NAO-index, however the spatial pattern of the second mode resembles climatologic North-Atlantic SLP pattern

- The second mode appears as the modulation of the climatologic forcing pattern of the two gyres and hence dominates the gyre response such that weak gyres => strong warming of subpolar gyre.

Changes in the NAC source waters may not be of immediate significance to AMOC but can have a delayed effect in increasing water mass modification in the Nordic Seas as happened in the 1960s and early 1970s. These cycles appear to be part of the longer period AMO/AMV variability seen in recent SST historical analyses over 1900-2010 and longer.