Annual Seminar on Diagnosis of Forecasting & Data Assimilation Systems

Ocean Model Diagnostics

(helping us to understand SST variability)

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Featuring work of NOCS colleagues :
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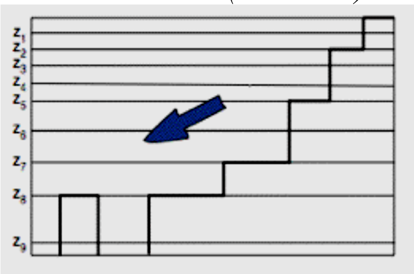
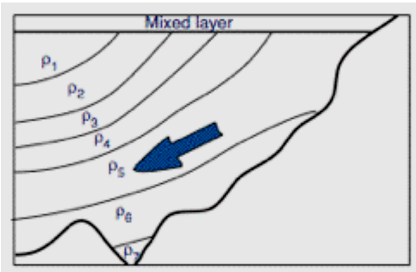
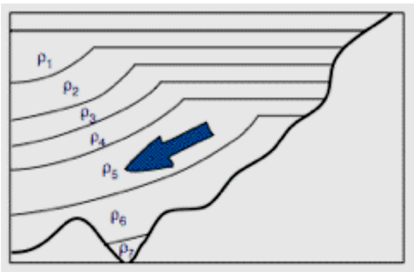
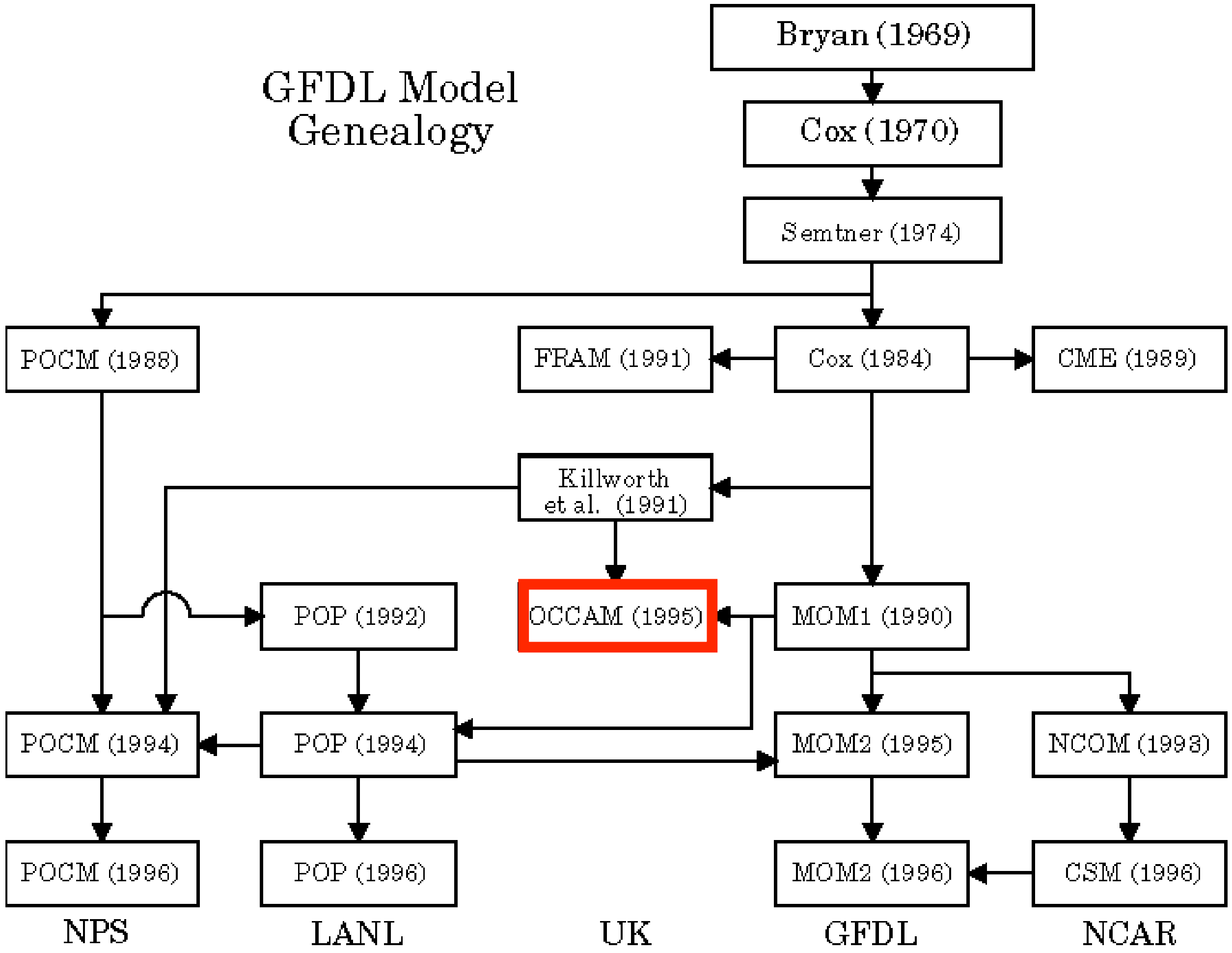
Outline

1. ***Ocean GCMs & Diagnostics - brief overview***
2. SST variability – Cause or Effect?
3. More/new observations & better ocean models - yielding new insights
4. The varying Meridional Overturning Circulation
5. The re-emergence story so far & where next?
6. Systematic ocean model error & SST - resolve eddies or refine parameterizations?
7. Summary & Conclusions

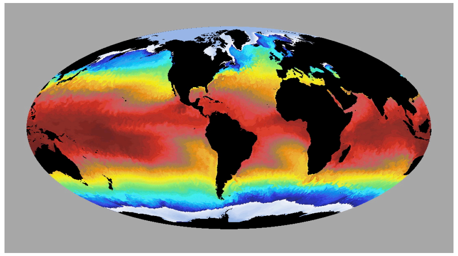
Ocean GCMs (1) : Choice of Vertical Coordinate

VERTICAL COORDINATES	Main Advantages	Main Disadvantages
z-coordinates *(HadCM3)* 	-Good vertical resolutions in the upper ocean. -Horizontal pressure gradient can be easily represented in an accurate manner. -Equation of state for ocean water can be accurately represented in a straightforward manner.	-Too much diffusion as flow crosses coordinate surfaces. -Excessive diapycnal mixing (this may gave adverse consequence in long-term climate simulations).
Isopycnical coordinates *(MICOM)* 	-Better representations of near-adiabatic flows along sloping isopycnal such as the Equatorial undercurrents (*Megann and New, 2001*), and deep western boundary currents. -Absence of spurious of dense waters at sill overflows (*Roberts et al., 1996*). -Preservation of water properties more faithfully over long time and length scales.	-Poor vertical resolution in weakly stratified regions (i.e. in high latitudes). -Imprecisely detrainment from the mixed layer.
Hybrid coordinates *(HYCOM)* 	Hybrid-coordinate should in principle combine the advantages of both model types without the weaknesses of either, i.e.: -Better resolution in weakly stratified regions. -Good vertical resolution in upper ocean. -Well controlled diffusion in ocean interior (T and S are preserved over long timescales)	

Ocean GCMs (2) : The GFDL Genealogy (z-coordinates)



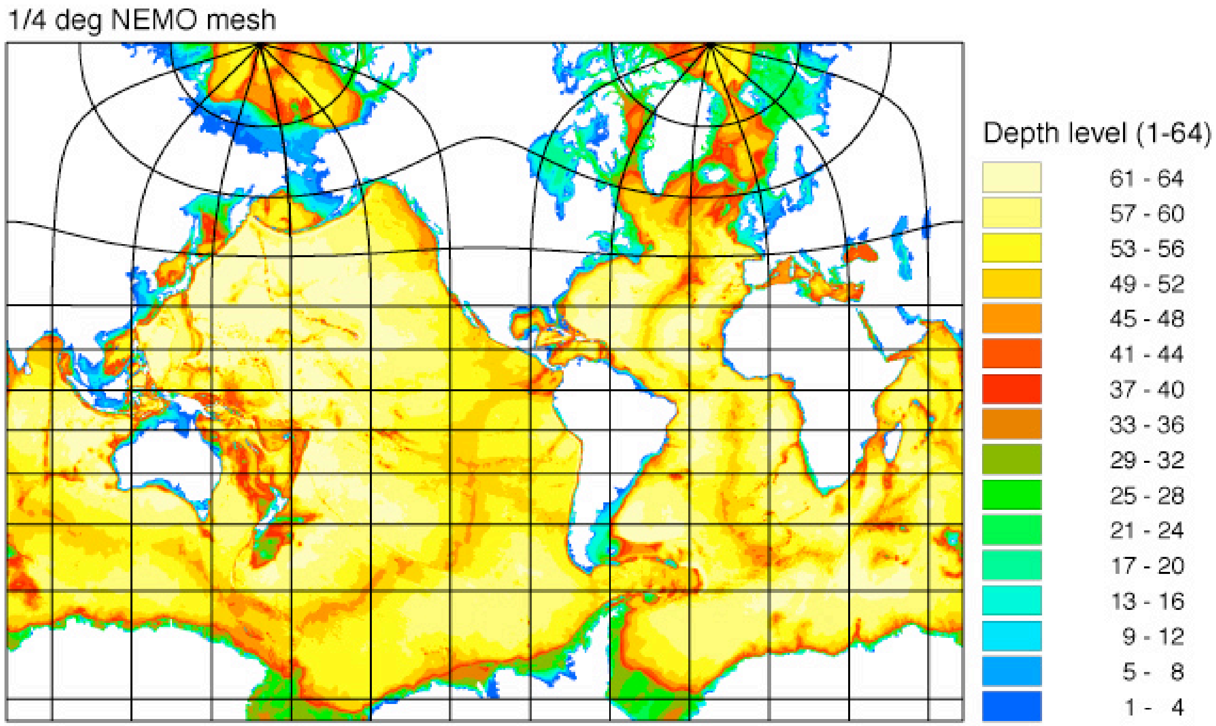
OCCAM 1/12°



1985-2006 hindcast

Ocean GCMs (3) : The Nucleus for European Modelling of the Oceans (NEMO)

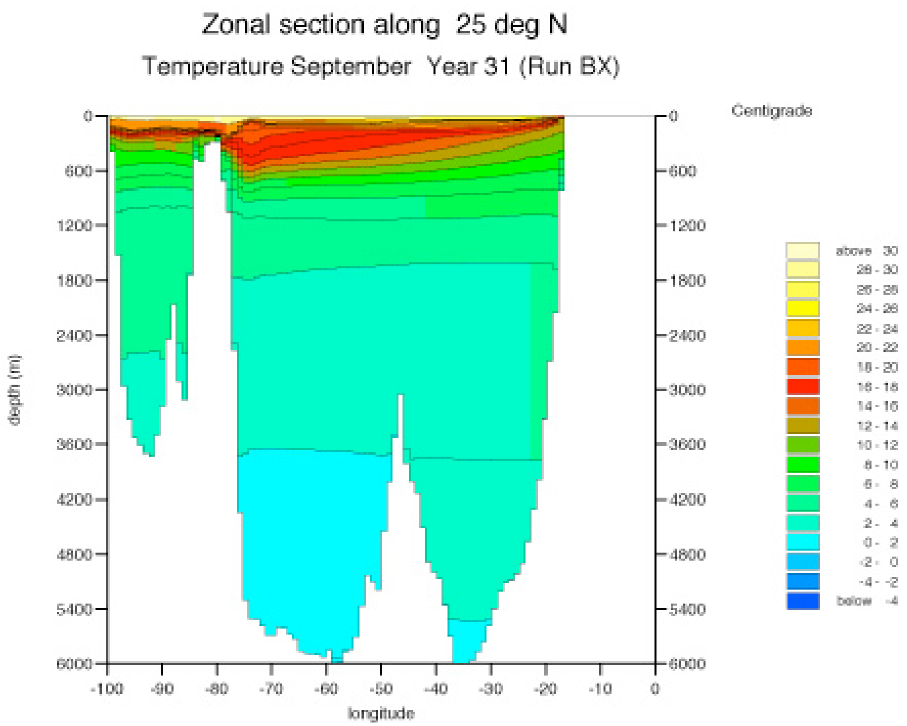
- Consortium between CNRS, Mercator-Ocean, UKMO & NERC (see http://www.nemo-ocean.eu/)
- Succeeded OCCAM at NOCS in 2007
- Used for series of 1958-2001 1/4° hindcasts



[lines of latitude per 15 deg, lines of longitude per 30 deg]

Ocean GCMs (4) : Layer and Hybrid Coordinates

- Isopycnic Interior + Mixed Layer, e.g., Miami Isopycnic Coordinate Ocean Model (MICOM)



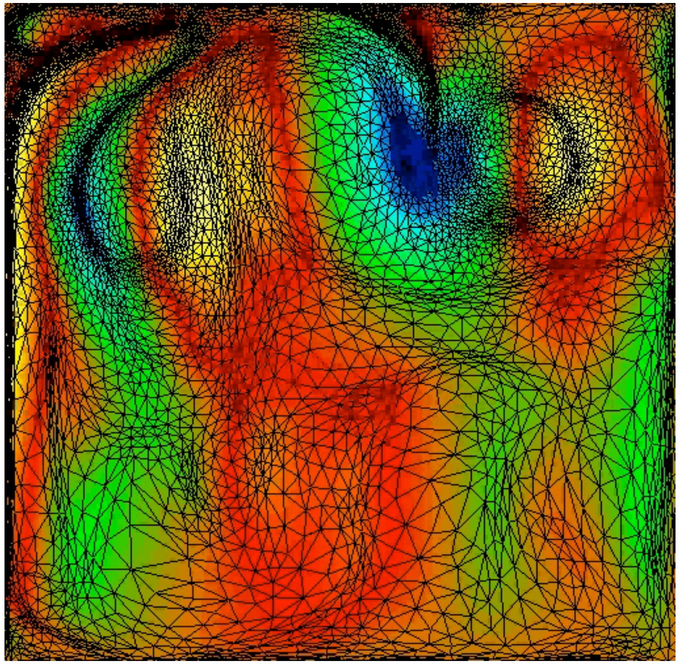
- Steeply sloping isopycnals near western boundary
- Supports western-intensified boundary current Gulf Stream)
- Gently sloping isopycnals across most of subtropical gyre
- Supports broad, weak “interior” circulation

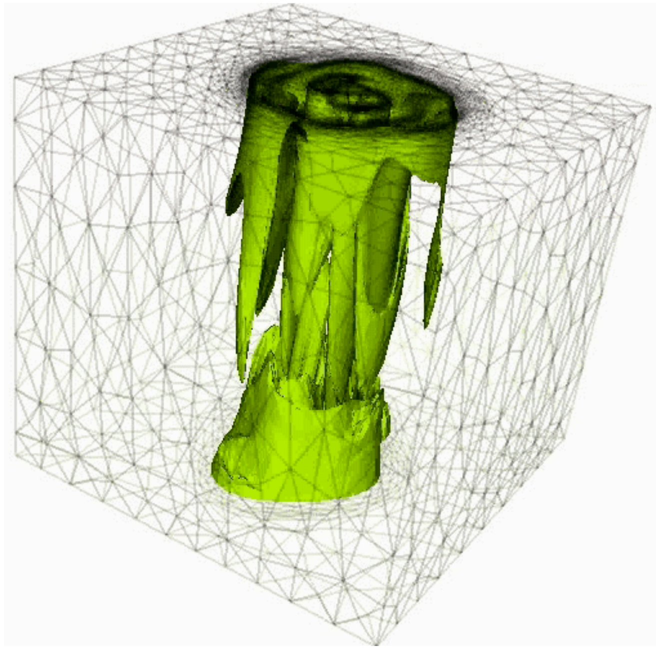
- Succeeded by the HYbrid Coordinate Ocean Model (HYCOM)

Ocean Models (5) : Unstructured, dynamic finite-element meshes - the future?

- Free up the 3-D mesh to evolve in space and time
- High resolution only when & where you need it …
- Preliminary results of Imperial College Ocean Model (ICOM)

Horizontal mesh in idealized basin



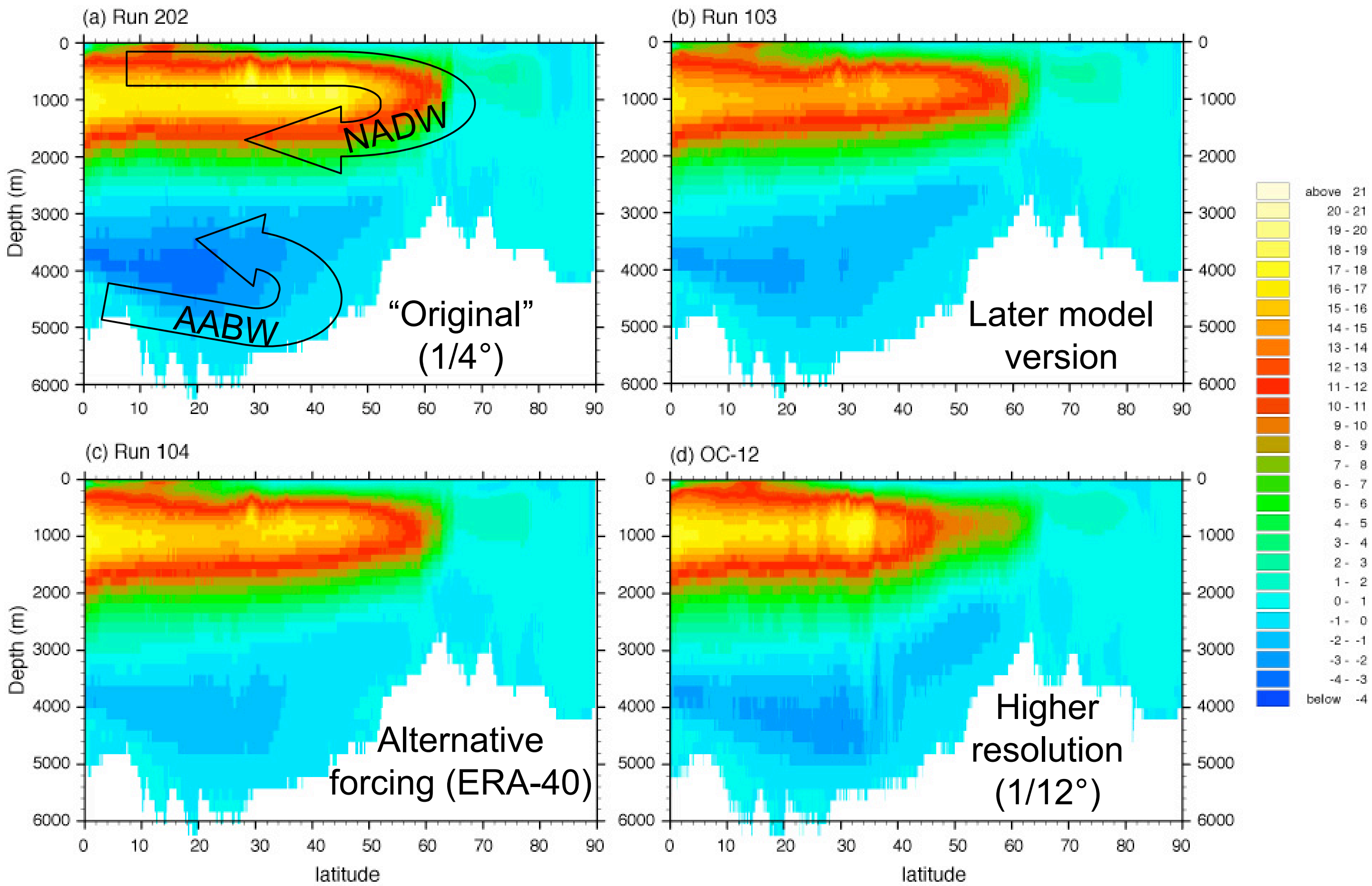


3-D visualization of convective event
[figures courtesy of ICOM]

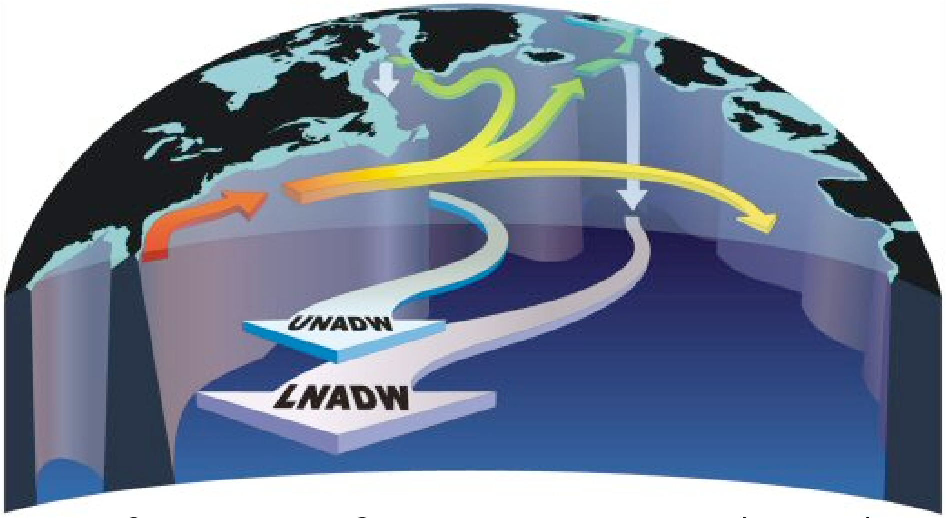
Diagnostics (1) : Meridional Overturning Circulation

- Meridional streamfunction at depth z, latitude θ, $\psi(\theta,z) = \int_{surface}^{z} \int_{east}^{west} v(\theta)dxdz$

e.g., Atlantic Overturning in 1/4° and 1/12° versions of OCCAM (Marsh et al., 2009)

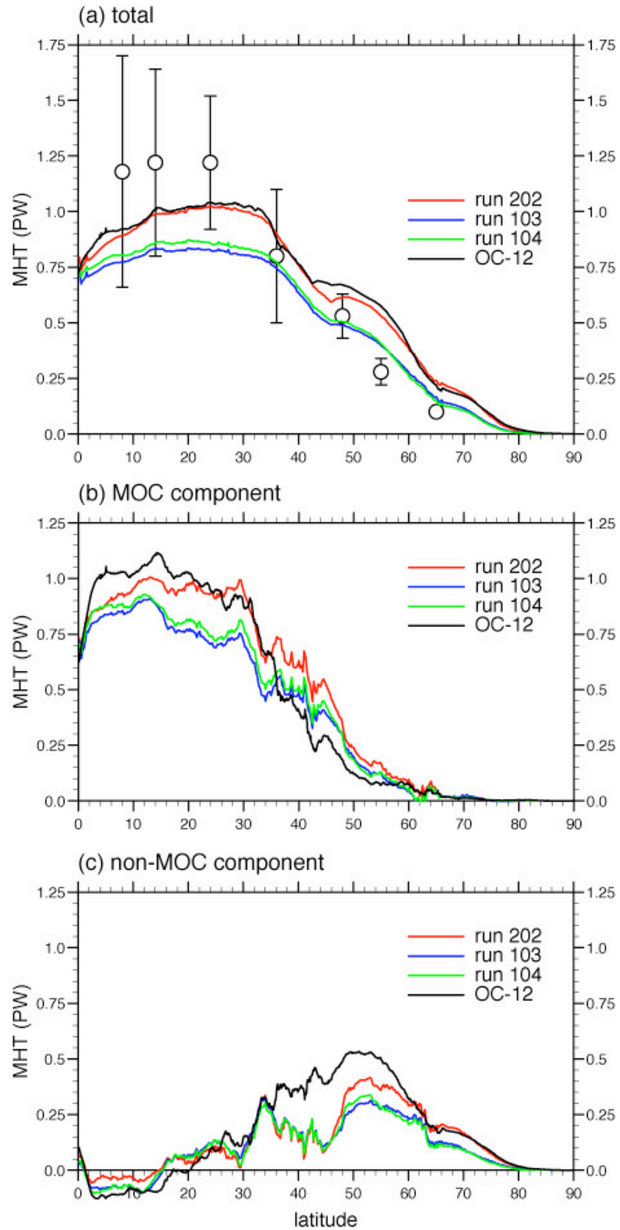


Diagnostics (2) : Heat Transports, decomposed into Components



The Subtropical Gyre conveys warm (cooler) water north (south) in the west (east)

The MOC carries warm (cold) water north (south) in the upper (lower) layer

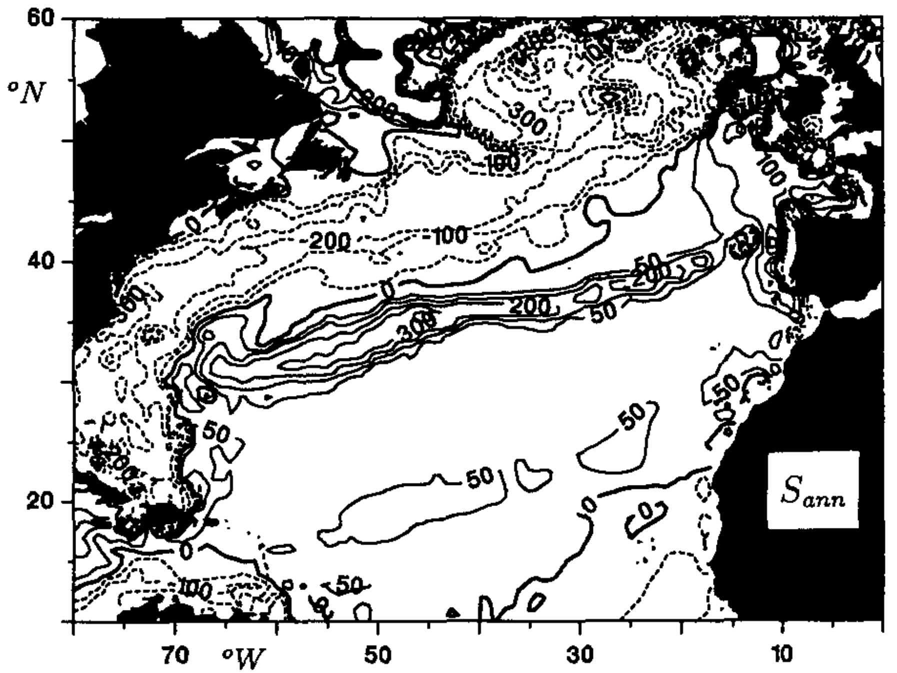


- e.g., Atlantic Meridional Heat Transport in 1/4° and 1/12° versions of OCCAM, decomposed into MOC and non-MOC parts (Marsh et al., 2009)

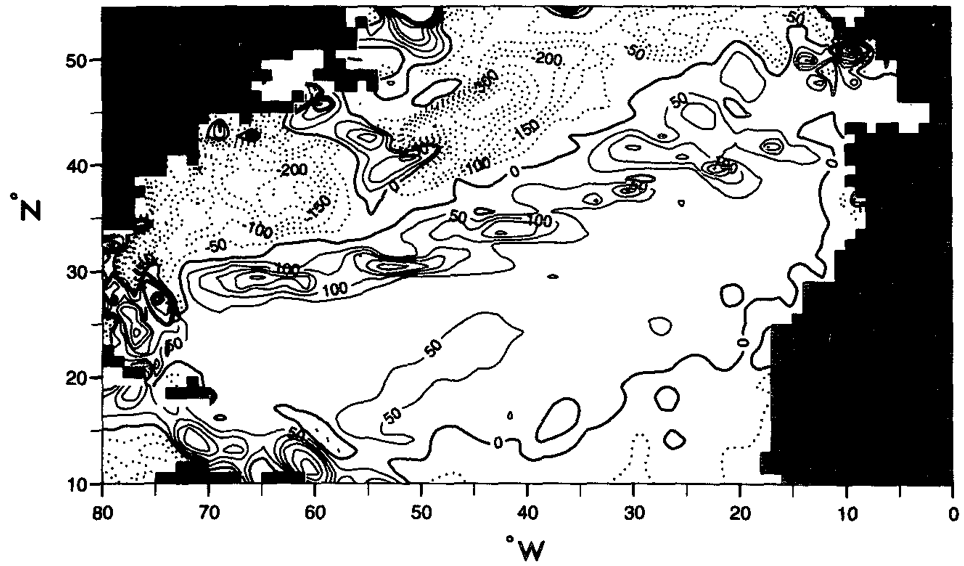
Diagnostics (3) : Annual Subduction rates

➢ Annual Subduction rate (m/year), $S_{ann} = \dfrac{1}{\tau_{year}} \int_{W1}^{W2} \left(u_h . \nabla h + w_h \right) dt$

[W1/W2 = Winter 1,2; h = mixed layer depth, W1; u_h = horiz. vel. at h ; w_h = vertical vel. at h]



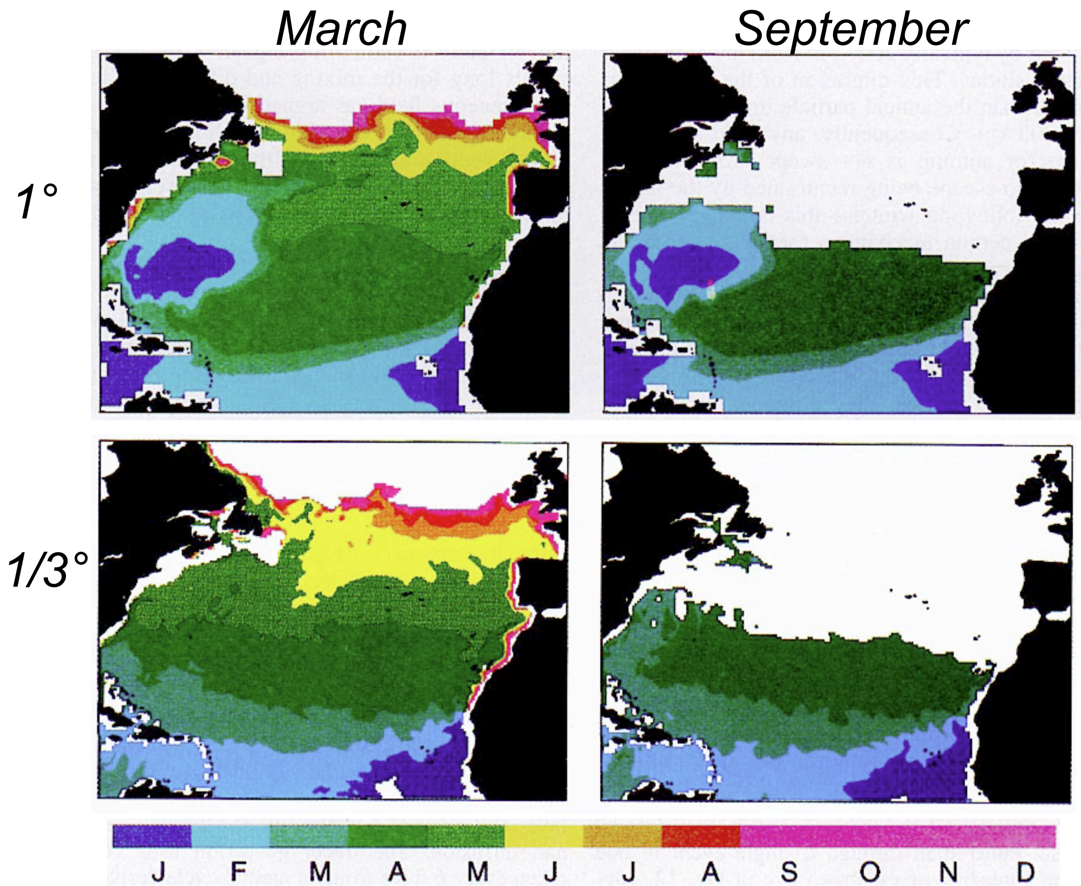
1° CME ocean model (Williams et al. 1995)



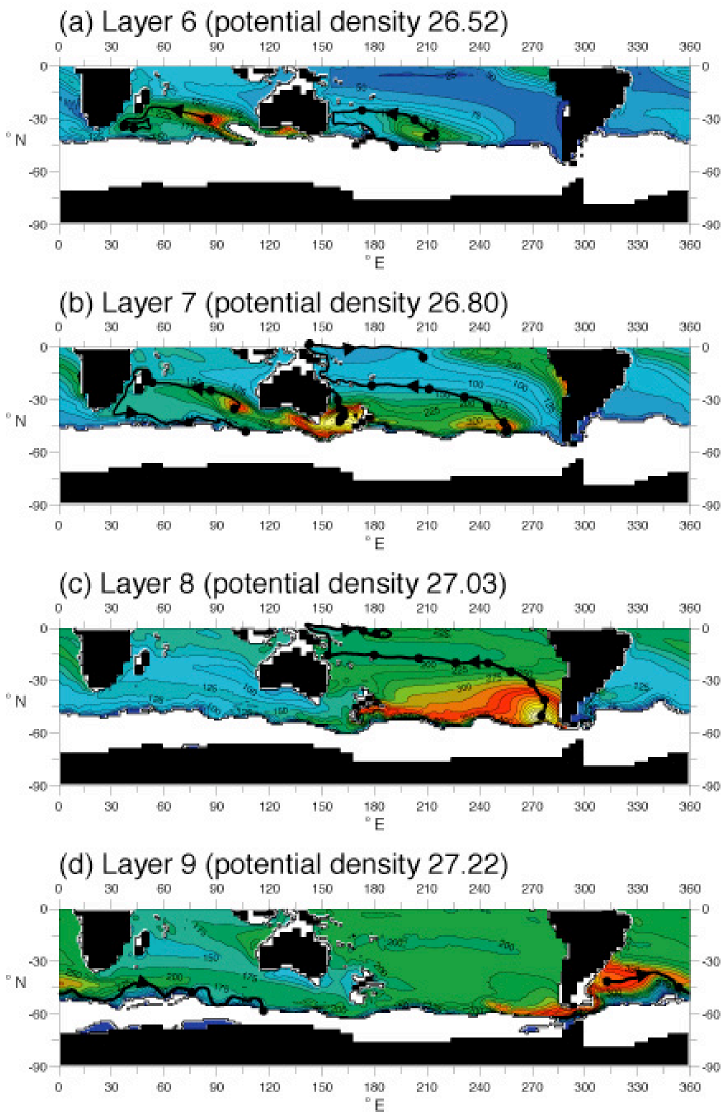
1° MICOM (New et al. 1995)

Diagnostics (4) : Patterns/Tracers of Thermocline Ventilation

- Spreading of “date tracer” on mode water isopycnal (σ_θ = 26.5) in CME model, non-eddy-resolving & eddy-permitting (Williams et al. 1995):

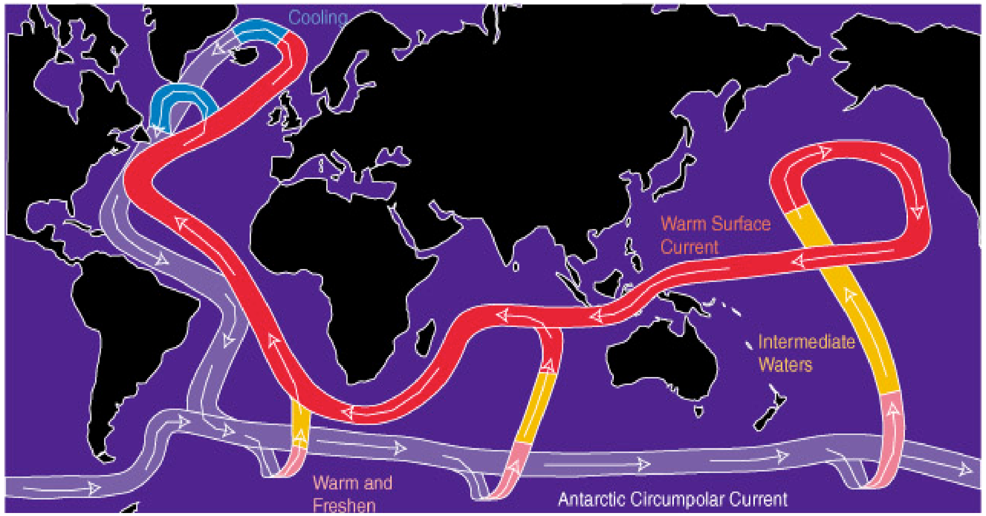


SAMW and AAIW layers in Southern Ocean of GIM:

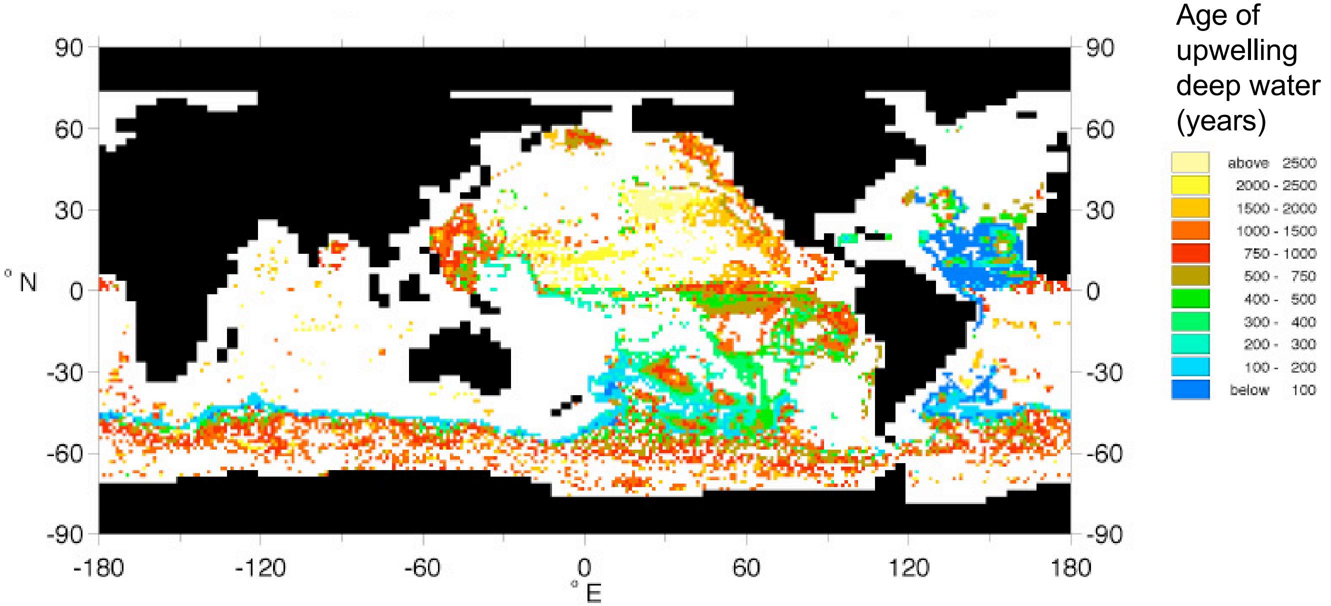


1.25° MICOM (Marsh et al. 2000)

Diagnostics (5) : Off-line particle trajectories



Observations and theory suggest a global “Conveyor Belt”, integral to stable climate over the last ~10,000 years



Based on offline trajectory analysis, it is clear that the model Conveyor timescales exceed 1000 years (Marsh & Megann 2002, Oc. Mod.)

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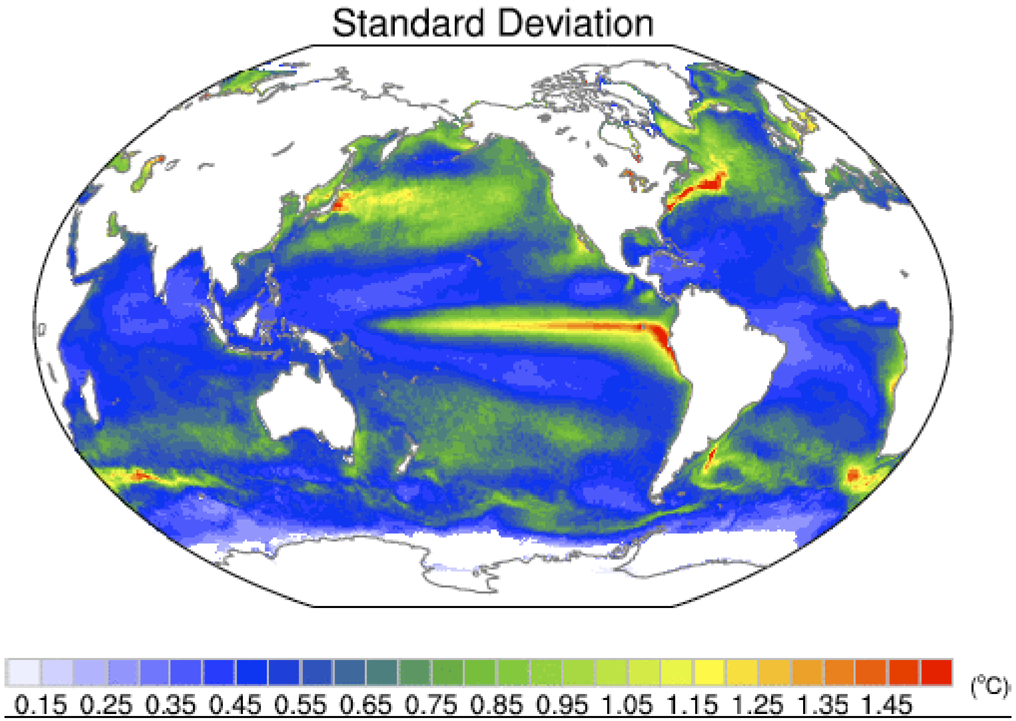
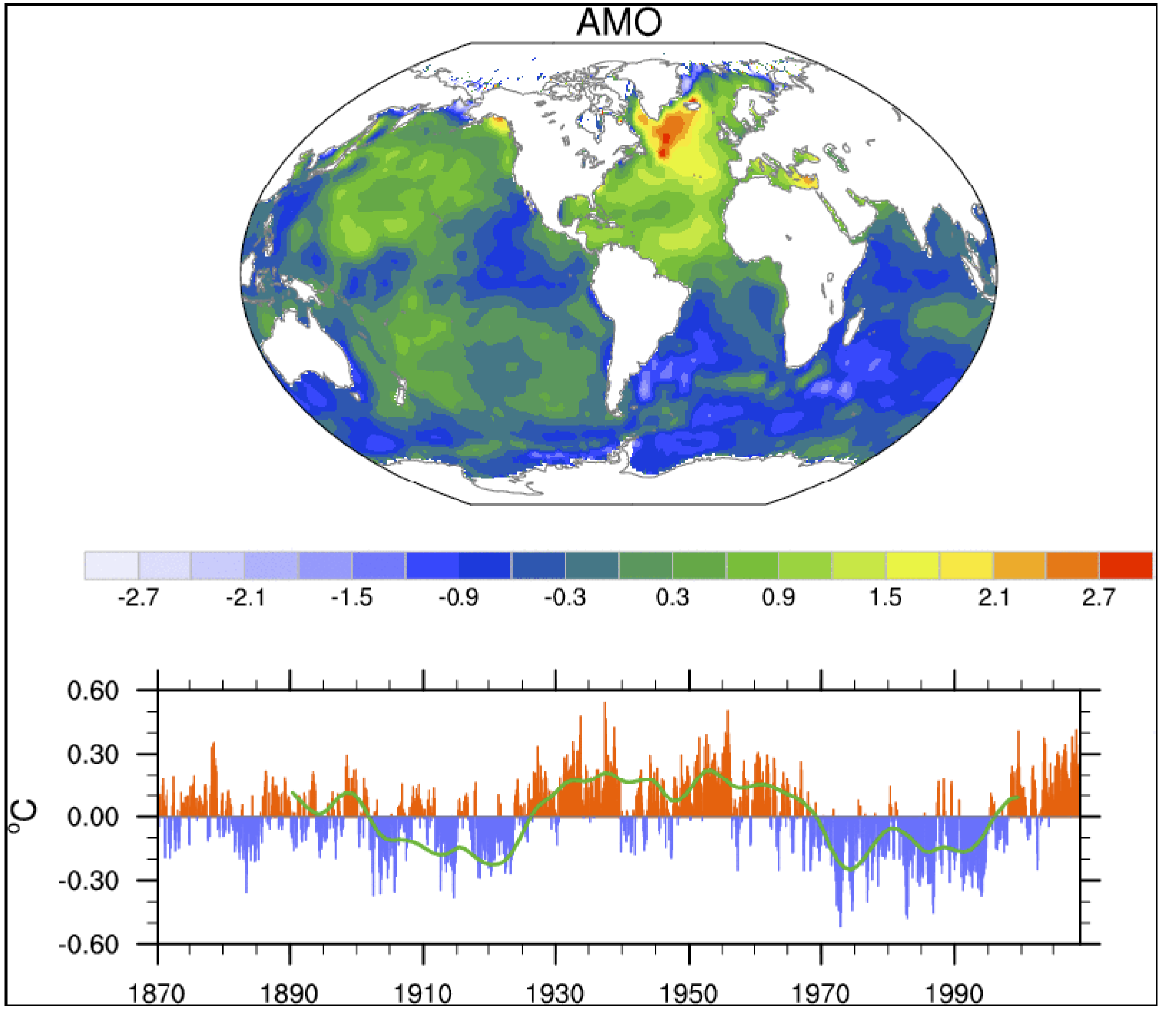
Long-term mean SST distribution from satellite passive microwave measurements during 1982-2008



From "Sea Surface Temperature Variability: Patterns and Mechanisms"
Clara Deser, Michael A. Alexander, Shang-Ping Xie and Adam S. Phillips
Submitted to *Annual Review of Marine Sciences, Vol. 2* (April 30, 2009)

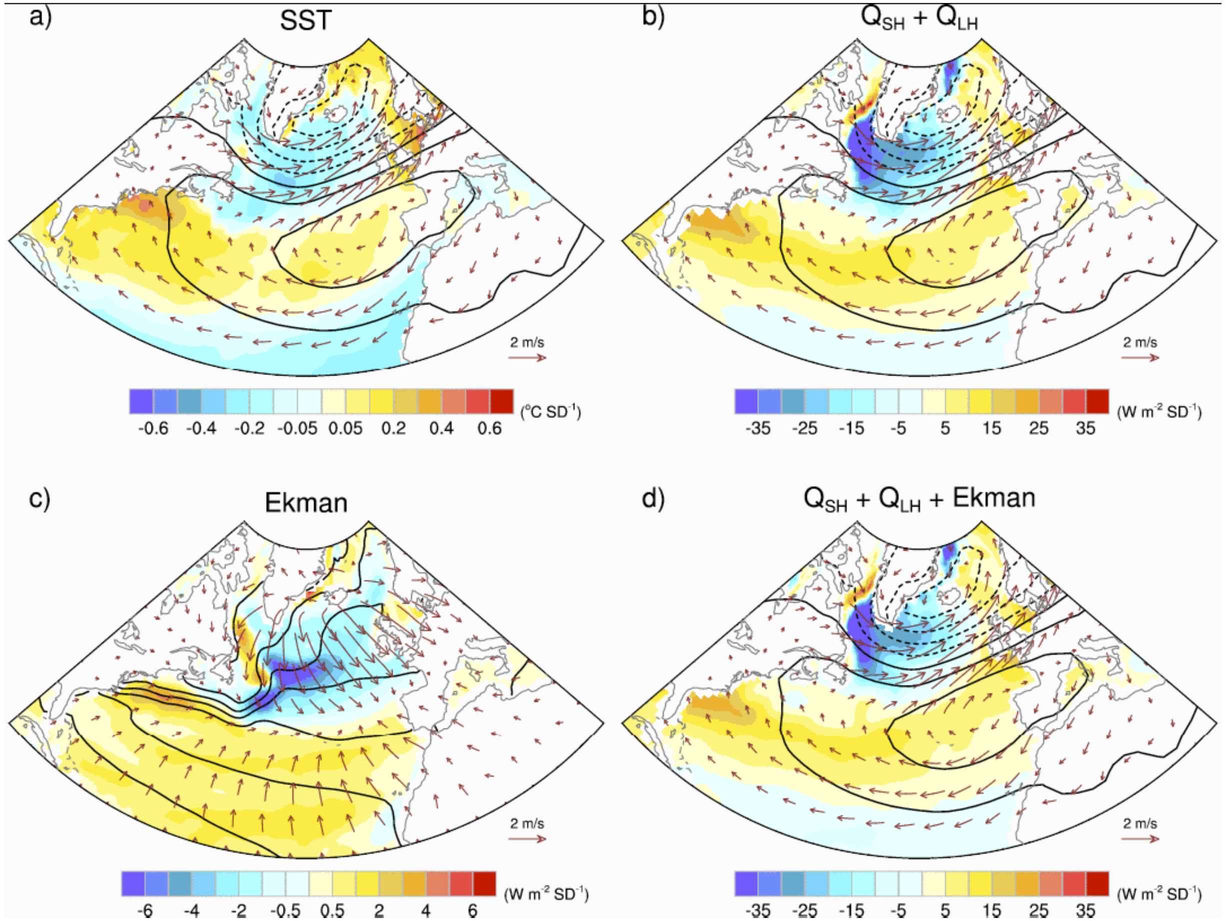
SST variability: AMO Cause?



Atlantic Multidecadal Oscillation. (Top) Regression pattern of monthly SST anomalies upon the North Atlantic SST Index, based on the HadISST data set during 1870-2008. (Bottom) The North Atlantic SST Index, defined as the average monthly SST anomaly over the North Atlantic (0°- 70°N).

From Deser et al. (2009)

SST variability: NAO Effect?



Anomaly patterns associated with a +1 standard deviation departure of the North Atlantic Oscillation (NAO) Index during winter (December-March). (a) SST (shading), SLP (contours) and surface wind (vectors). (b) Sensible plus latent energy flux (shading), SLP (contours) and surface wind (vectors). (c) Ekman heat transport expressed as an equivalent surface energy flux (shading), long-term mean SST (contours) and Ekman currents (vectors). (d) Sum of the sensible, latent and Ekman energy fluxes (shading), SLP (contours) and surface wind (vectors). The SLP contour interval is 1 hPa, with negative values dashed.

From Deser et al. (2009)

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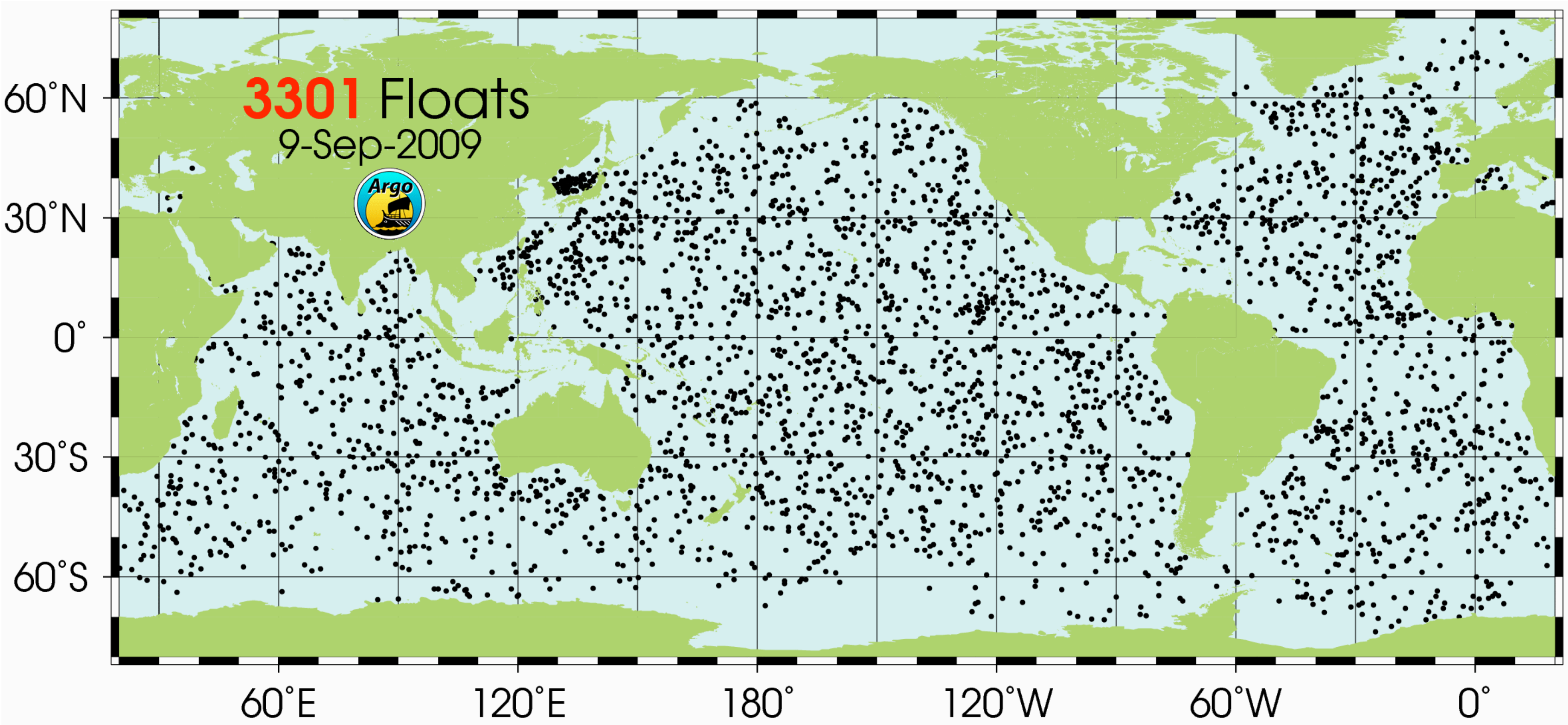
SST and sub-surface variability

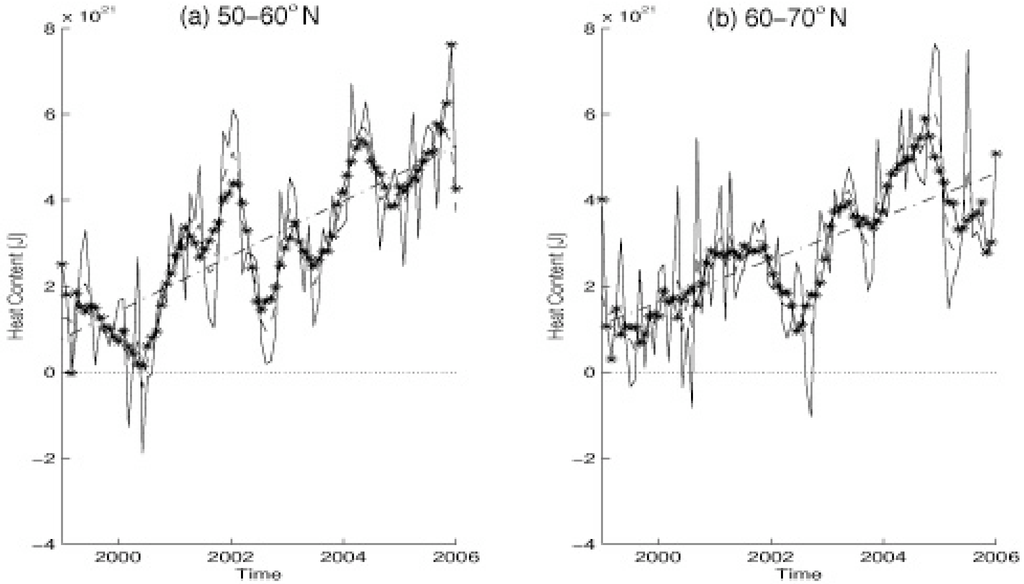
The Argo Revolution: now >3000 floats



(See http://www.argo.ucsd.edu/)

Lengthening time series from Argo floats

North Atlantic sub-surface warming, 1999-2006

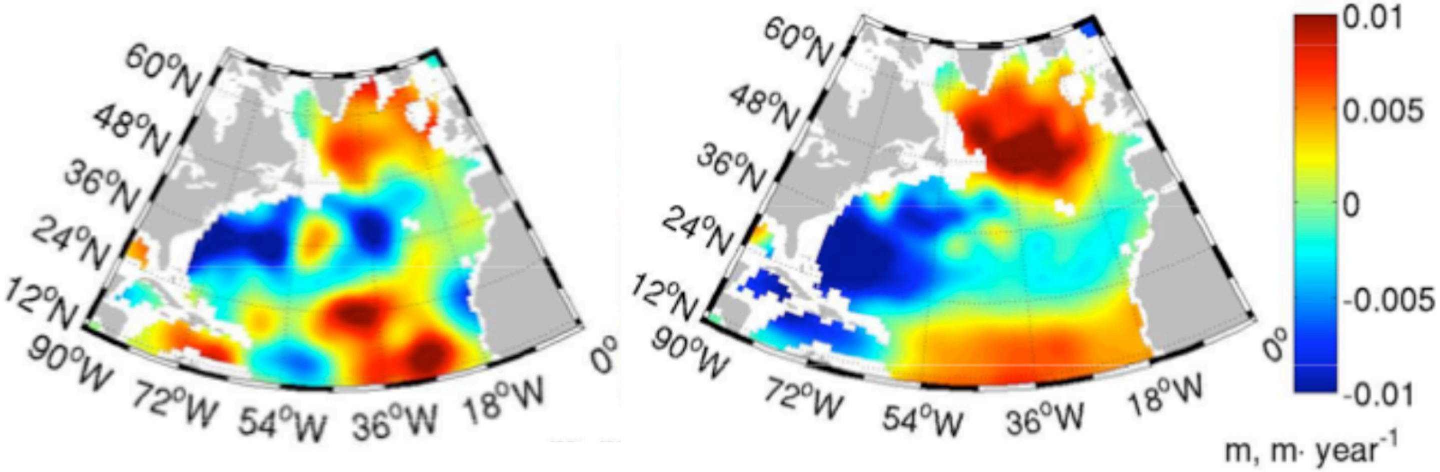


[Ivchenko et al., 2006, GRL]

- Argo data in 10° zones used to estimate heat content in upper 1500 m
- For two zones in particular, spanning 50-70°N (subpolar gyre), heat content increases strongly, by around 10^{21} J/year

Co-use of Argo and Altimetry data

Steric and sea surface height trends, 1999-2006



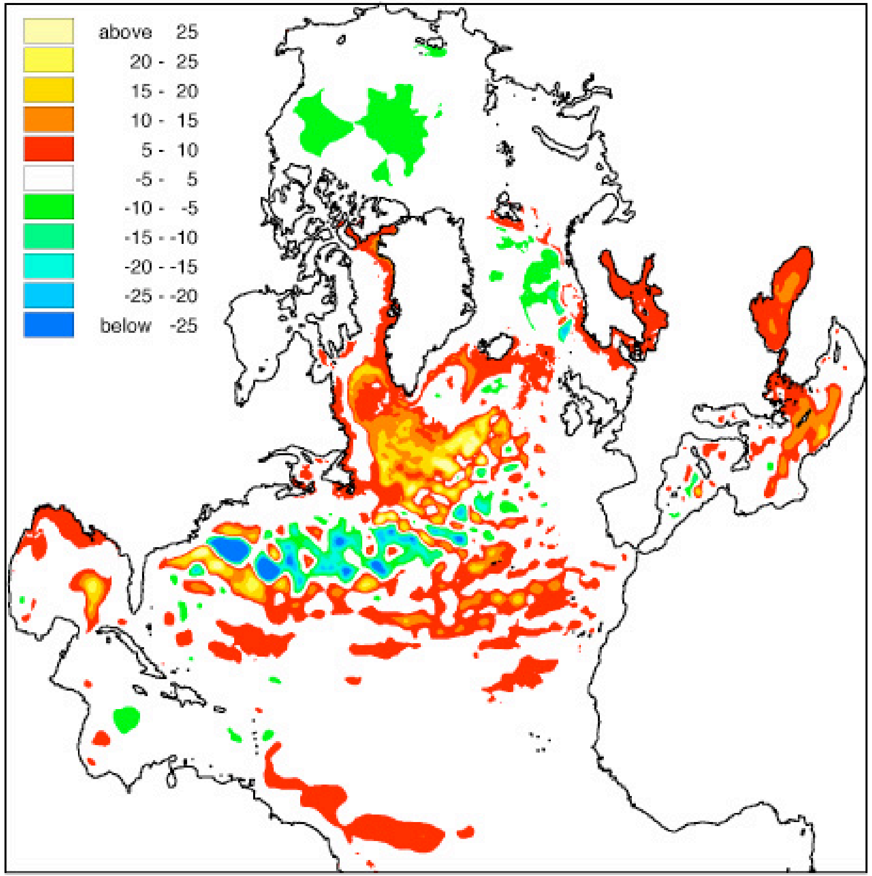
Trends (m year^{-1}) over 1999-2006: (left) steric height trend, computed from Argo data; (right) SSH trend, computed from altimetric data [from Ivchenko et al., 2008, JGR-Oceans]

- Good agreement between methods, i.e., sea level trend mainly ***steric***
- Implied warming and/or freshening of subpolar gyre

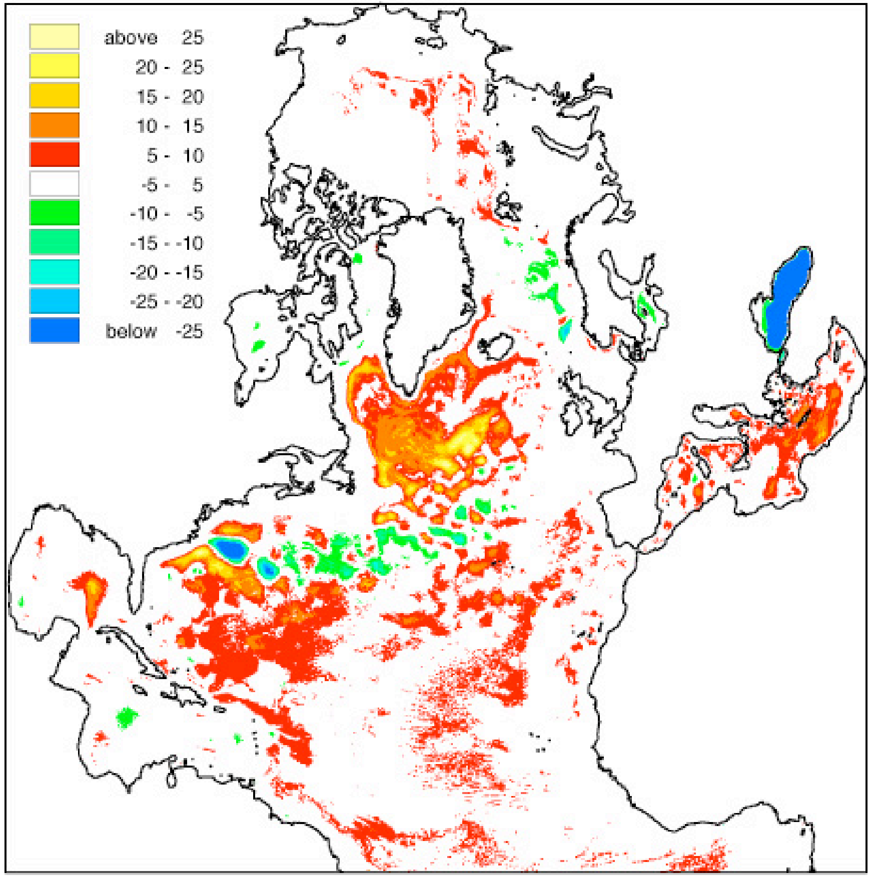
SSH change in the eddy-resolving OCCAM

Changes of Steric height, based on changes in temperature & salinity, from 1993 (start of *altimeter era*) to 2004, in OC-12 (1/12° OCCAM ocean model):

(a) sea surface height difference



(b) steric height difference

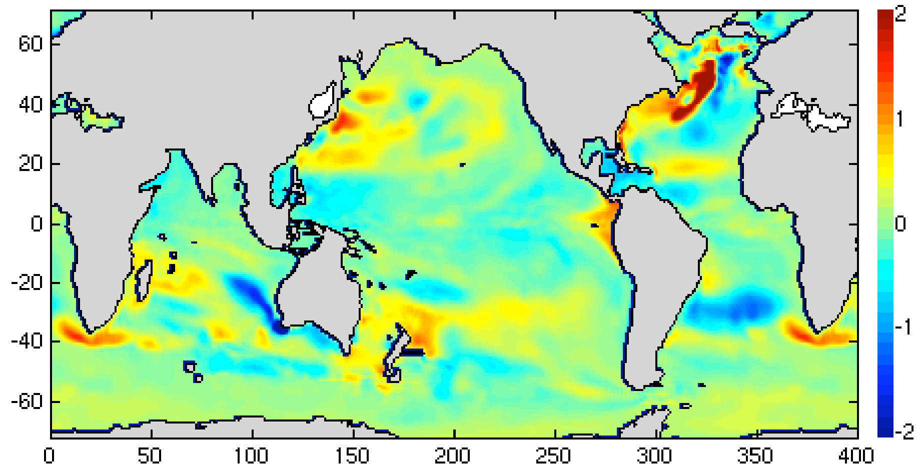


Assimilating 3-D observations - ECCO state estimation

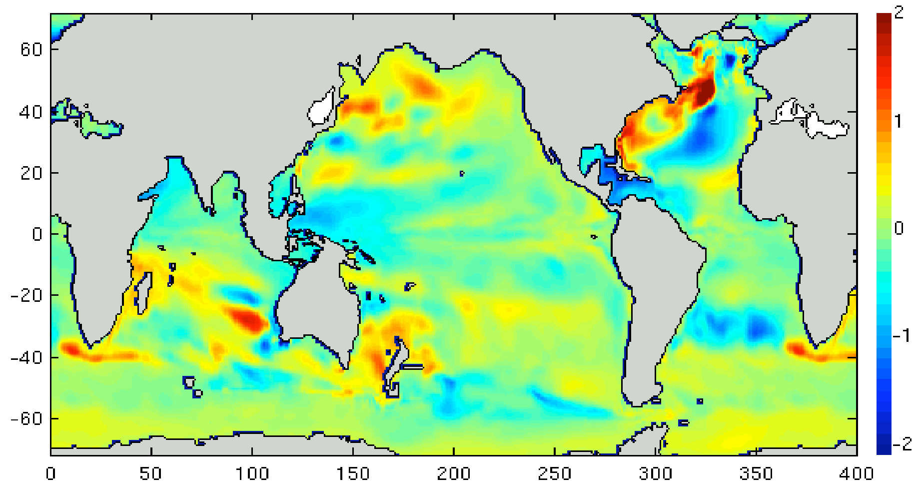
Temp. anomaly (°C) relative to average seasonal cycle at 500 m

see http://ecco.jpl.nasa.gov/external/index.php

29 July 2003:



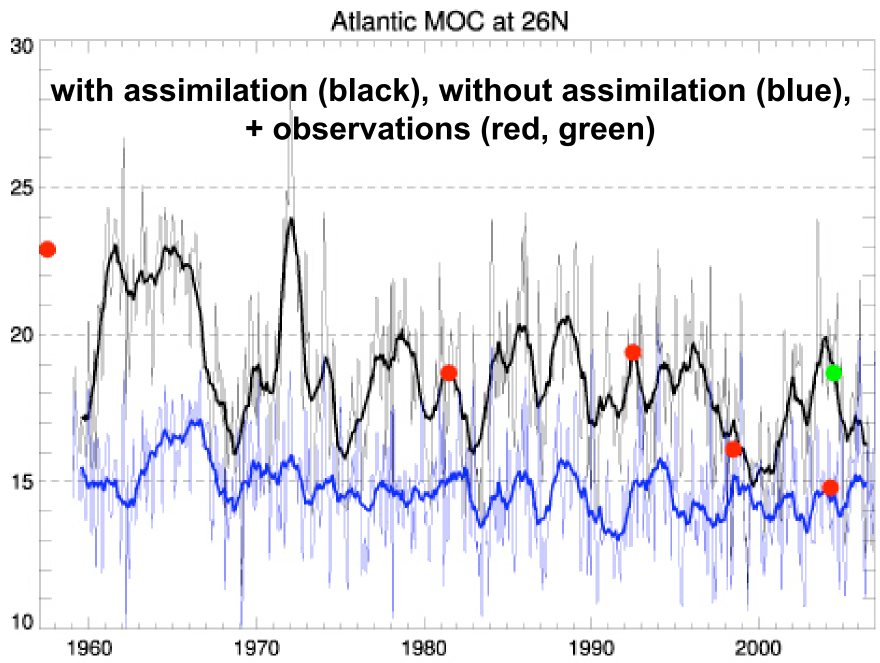
29 July 2009:



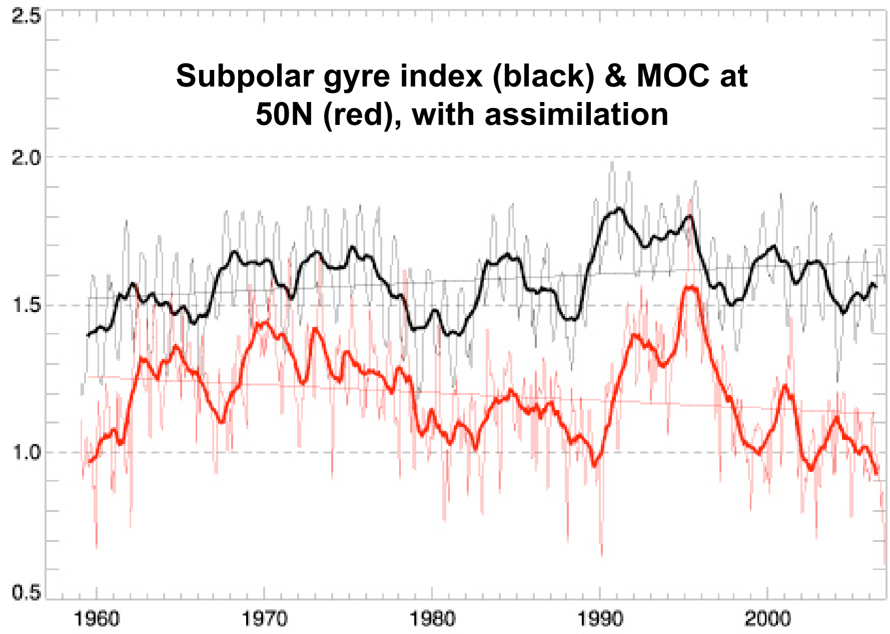
- Strong persistence of 500m temperature anomalies at sub-decadal timescales

- Related to slow variation in large-scale ocean circulation?

U. Reading/ECMWF ocean re-analysis, 1959-2006 - past changes of large-scale circulation (Balmaseda et al. 2007)



(Fig. 1, Balmaseda et al. 2007)



(Fig. 3, Balmaseda et al. 2007)

- Assimilation gives better agreement with occasional MOC estimates
- Decline of Subpolar gyre in 1990s consistent with observations

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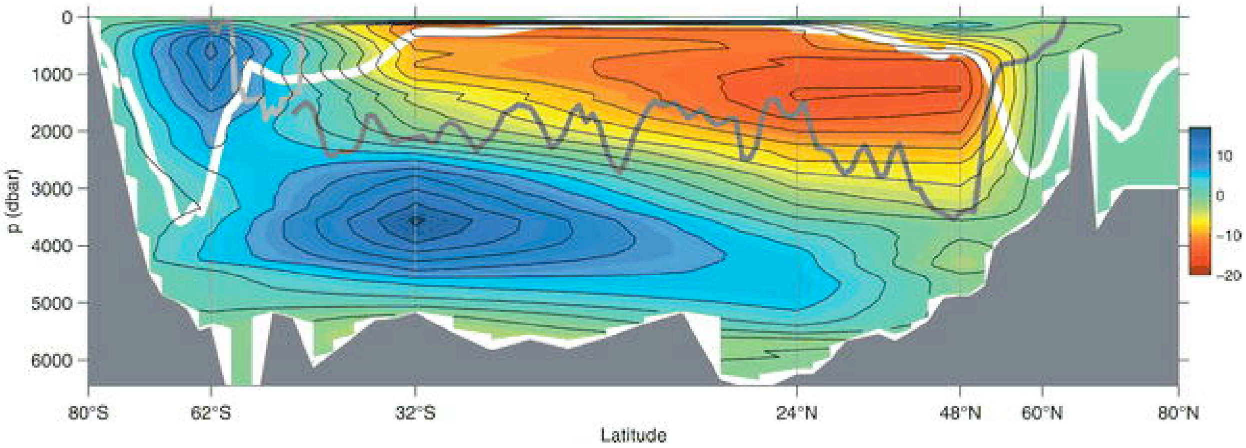
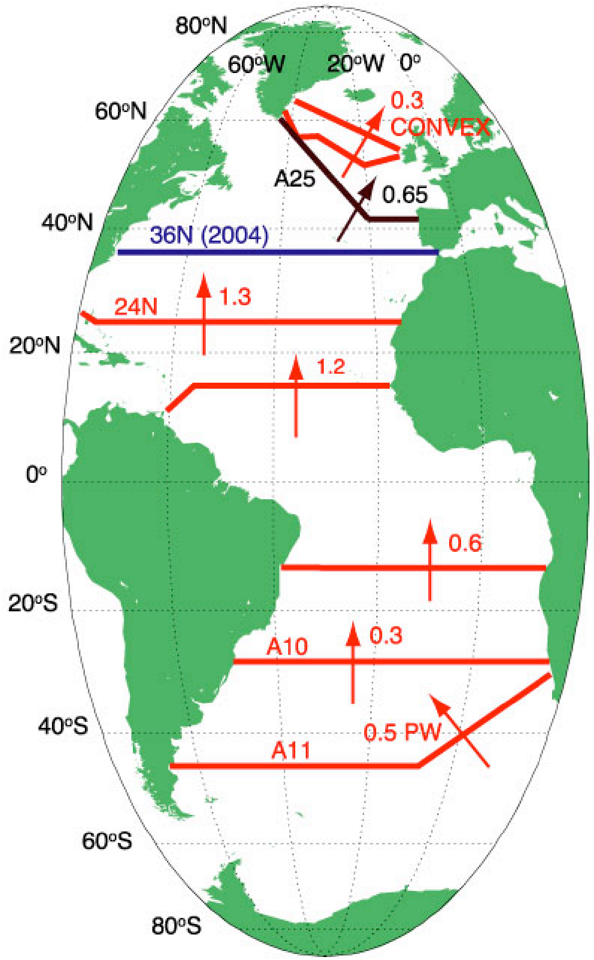
The Meridional Overturning Circulation (MOC) & Climate

Decade-mean (1990s) global MOC streamfunction based on hydrographic section data & estimated with inverse methods (Lumpkin & Speer 2007):

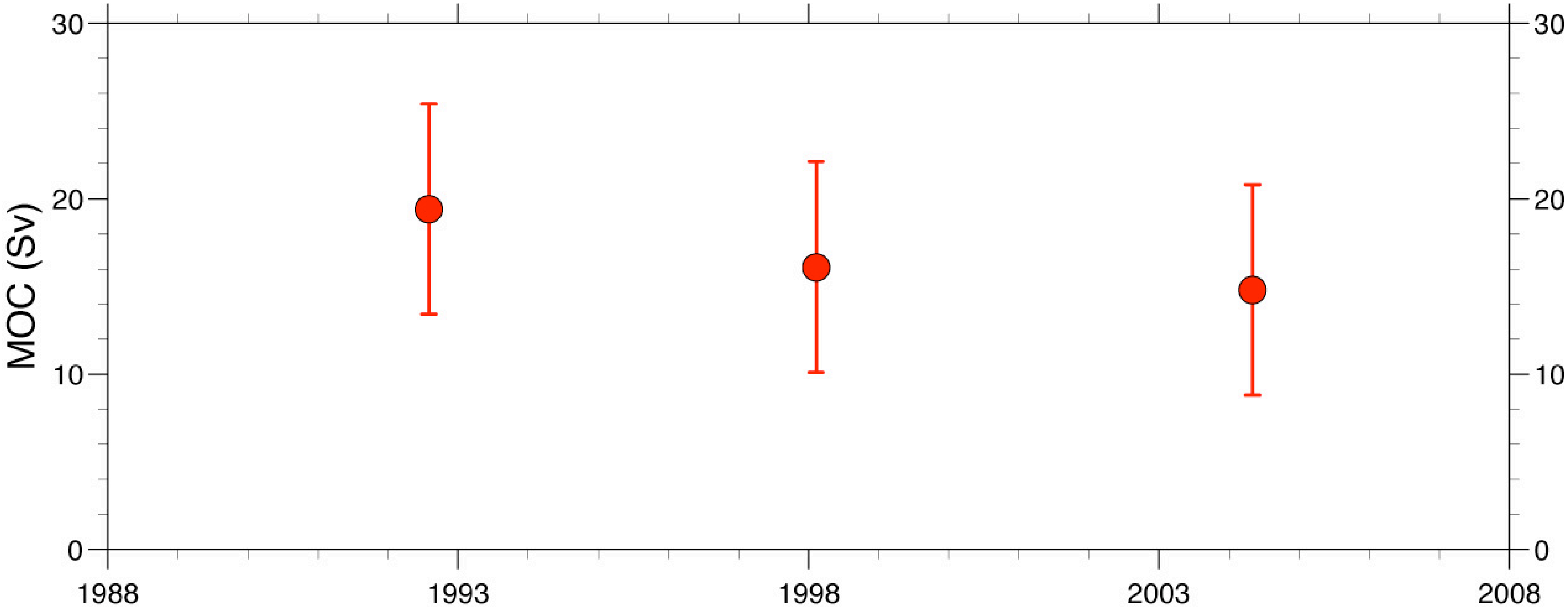


- Positive cell occupying 40°S-60°N, 0-3000 m dominated by Atlantic MOC, strength ~20 Sv (1 Sv = 10^6 m^3s^{-1})
- Associated with MOC is substantial poleward heat transport 0.3-1.3 PW, previously assumed rather stable …

Summary of heat transport estimates for selected Atlantic WOCE sections (updated from Bryden and Imawaki 2001)



The Atlantic MOC at 26°N - last 20 years



Occasional hydrographic sections, as of 2004 (Bryden et al. 2005)

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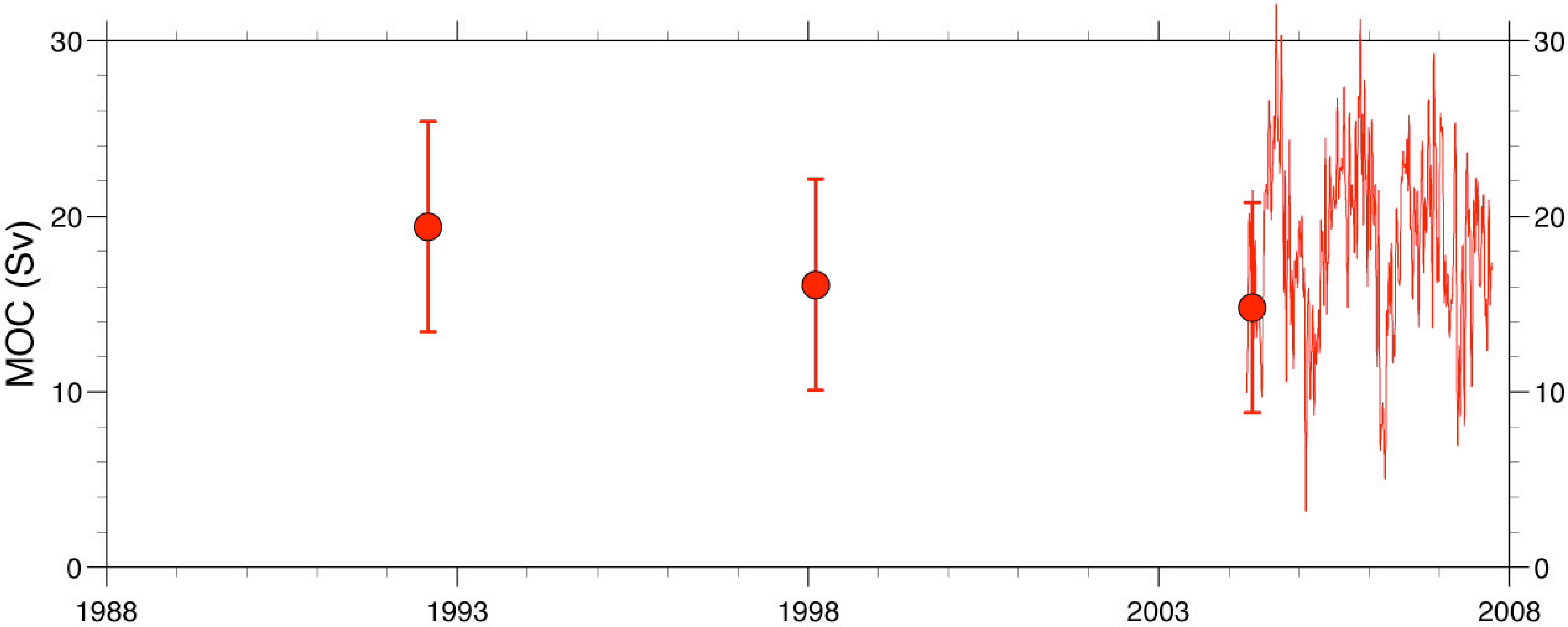
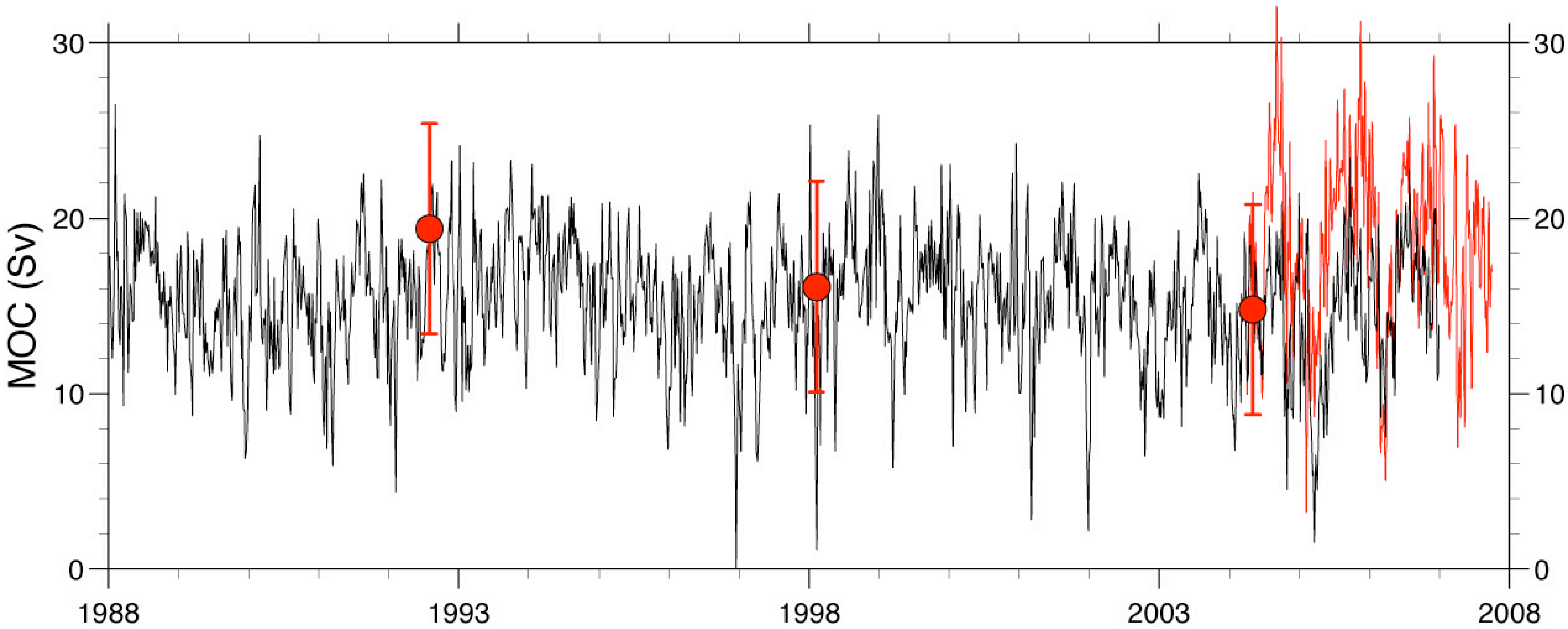


Occasional hydrographic sections, as of 2004 (Bryden et al. 2005)

+ RAPID monitoring since April 2004 (twice daily)

The Atlantic MOC at 26°N - last 20 years



Occasional hydrographic sections, as of 2004 (Bryden et al. 2005)

+ RAPID monitoring since April 2004 (twice daily)

+ 1/12° OCCAM (5-day averages), 1988-2006

The lengthening MOC time series at 26°N

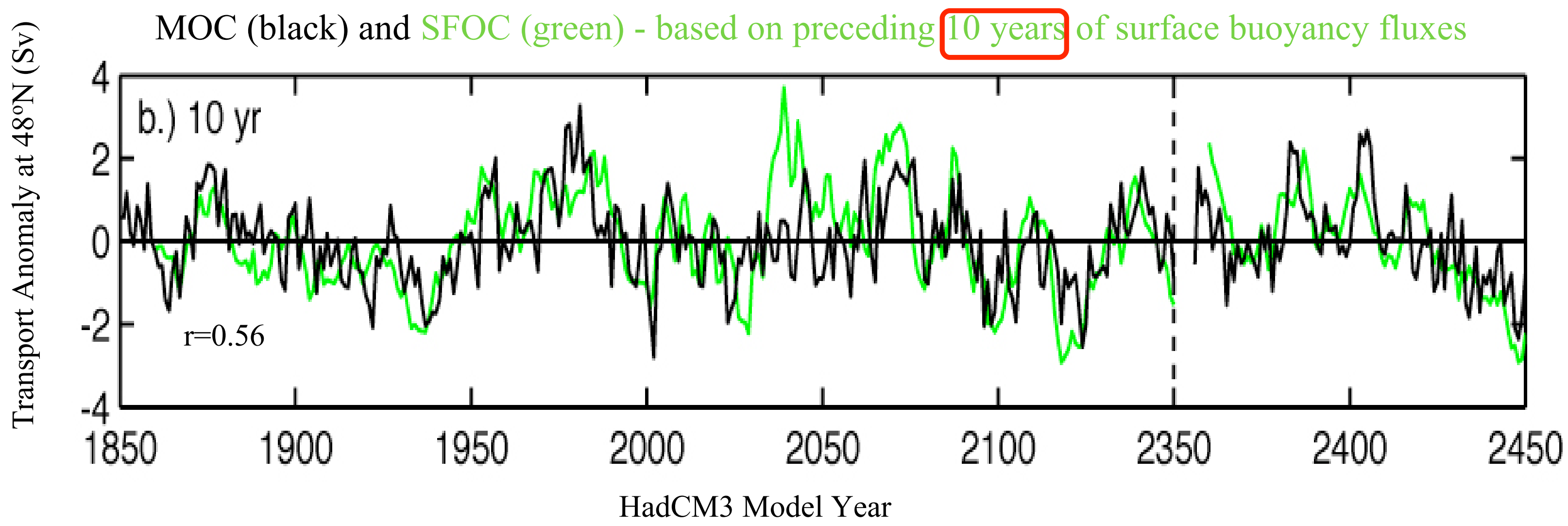
- Periodically extended by 6 months, 6-12 months behind real time
- A seasonal cycle emerges for 2004-07
- Overlapping simulation with truly eddy-resolving ocean model (OCCAM)
- Promising signs of model-observation agreement, and evidence that seasonality is sporadic, with trends dominating in earlier periods (e.g., 1994-97)
- Prospects for data telemetry & real-time MOC
- Emerging applications of the data, such as apparent link between MOC at 26°N and remote SST variability (Hirschi, pers. comm.)

The MOC at 26°N : next steps

- Establish extent of MOC influence on SST (early evidence is promising)
- Identify mechanisms: likely Ekman effects, but possible influences from fluctuations in other modes of transport (full-depth variability)
- Analyse OCCAM 1/12° simulation (2004-06 overlap) for MOC influence on SST north/south of 26°N
- But what about MOC variability elsewhere, on longer timescales?

Prospects for forecasting the MOC north of 26°N

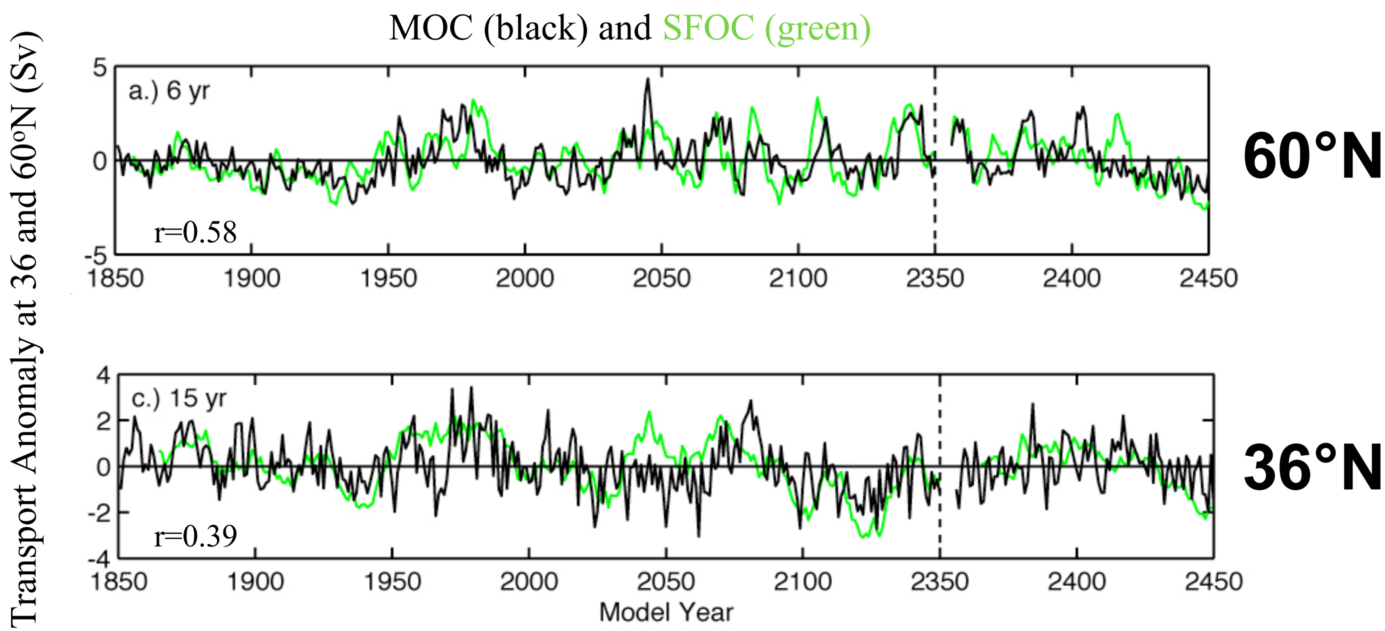
- Developing method of Marsh (2000) for diagnosing the “surface-forced overturning circulation” (SFOC) based on water mass transformation theory - using 3 climate models (HadCM3, GFDL, Bergen Climate Model)
- Surface forced estimates of MOC at 48°N in good agreement with full MOC in models for earlier 300-year period - e.g., HadCM3



Grist, Josey & Marsh (2009); Josey, Grist & Marsh (in press)

Latitude-dependence of past-averaging interval

- Good agreement at 60°N with shorter 6-year past averaging interval



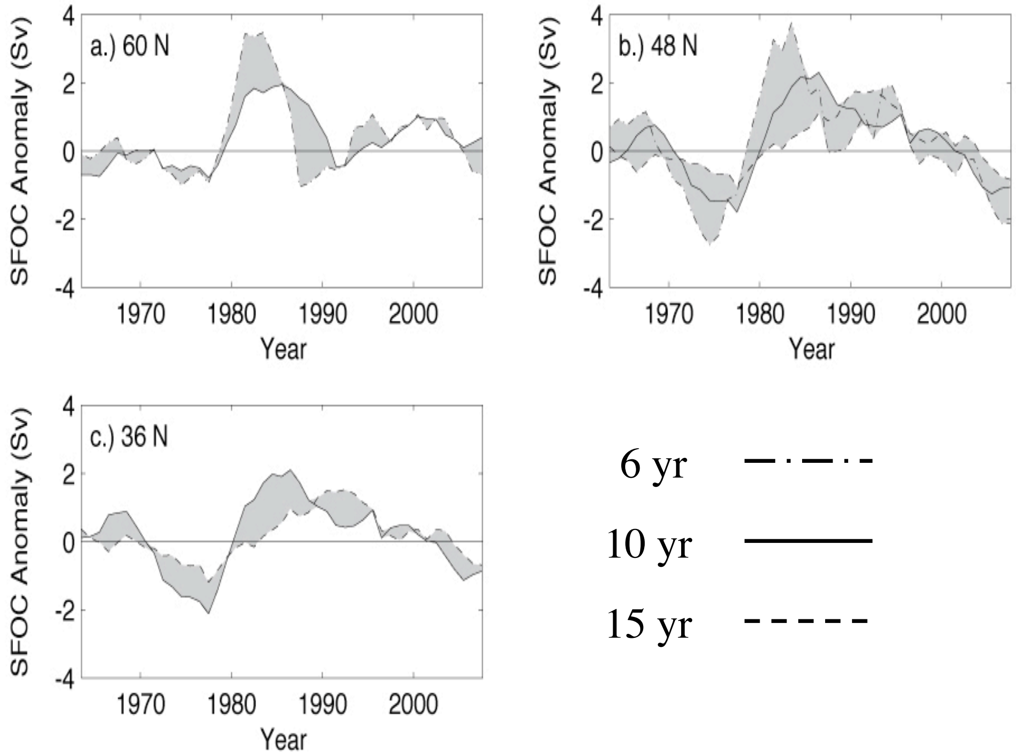
- Some skill at 36°N with longer 15-year interval but method breaks down at lower latitudes

- Improve agreement if Ekman term (i.e., wind forcing) included?

Estimating MOC Variability over last 40 years

- **NCEP used with various past-averaging intervals to estimate MOC variability from 1965-2008**

- Variability at 60 & 48˚N noticeably different
- Implies surface forcing between these latitudes significantly modifies SFOC
- Variability at 48 & 36˚N is broadly similar
- Overall : AMOC peaked around 1990, subsequently declined - part of Atlantic Multi-decadal Oscillation?



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SST re-emergence : the story so far

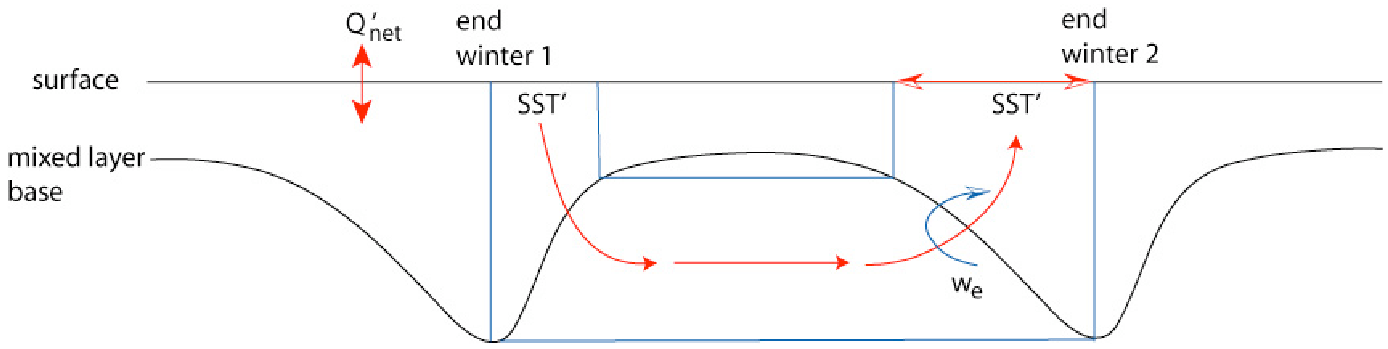
- Developing literature on mechanisms/impacts:

Namias & Born (1970, 1974)
Alexander & Deser (1995)
Alexander, Deser & Timlin (1999)
Alexander, Timlin & Scott (2001)
Junge & Haine (2001)
Timlin, Alexander & Deser (2002)
Deser, Alexander & Timlin (2003)
De Coëtlogon & Frankignoul (2003)
Zhao and Haine (2005)
Hanawa & Sugimoto (2004, 2007)
Sugimoto & Hanawa (2005)
Cassou, Deser & Alexander (2007)
Ciasto & Thompson (2009)

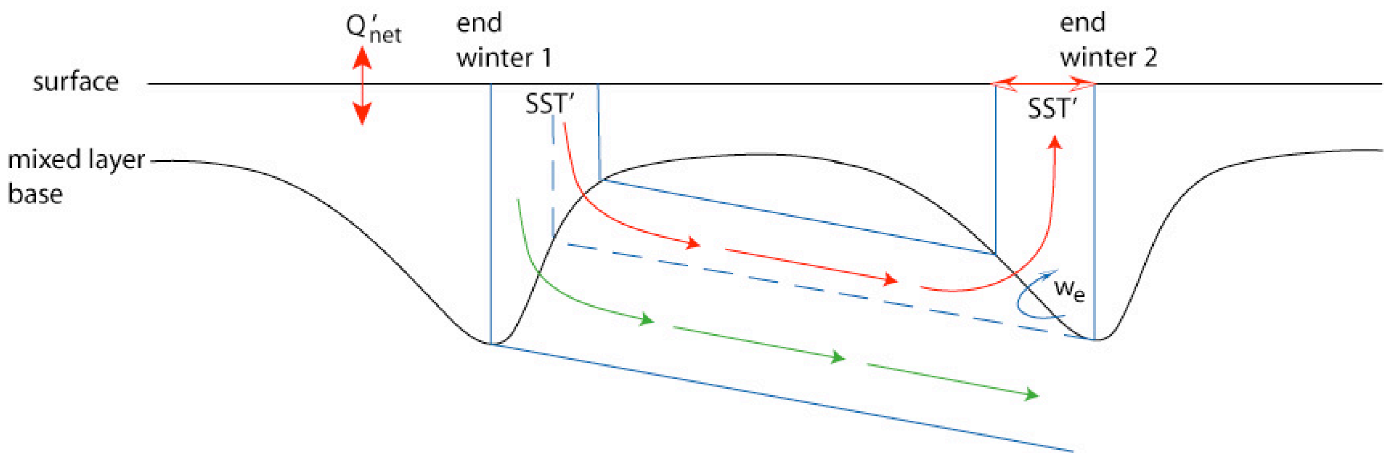
- Statistical evidence (e.g., Rodwell & Folland 2002) motivates ongoing search for physical mechanisms & representation in forecast models

SST re-emergence : concepts (1)

"Full" re-emergence (as in Alexander & Deser 1995)



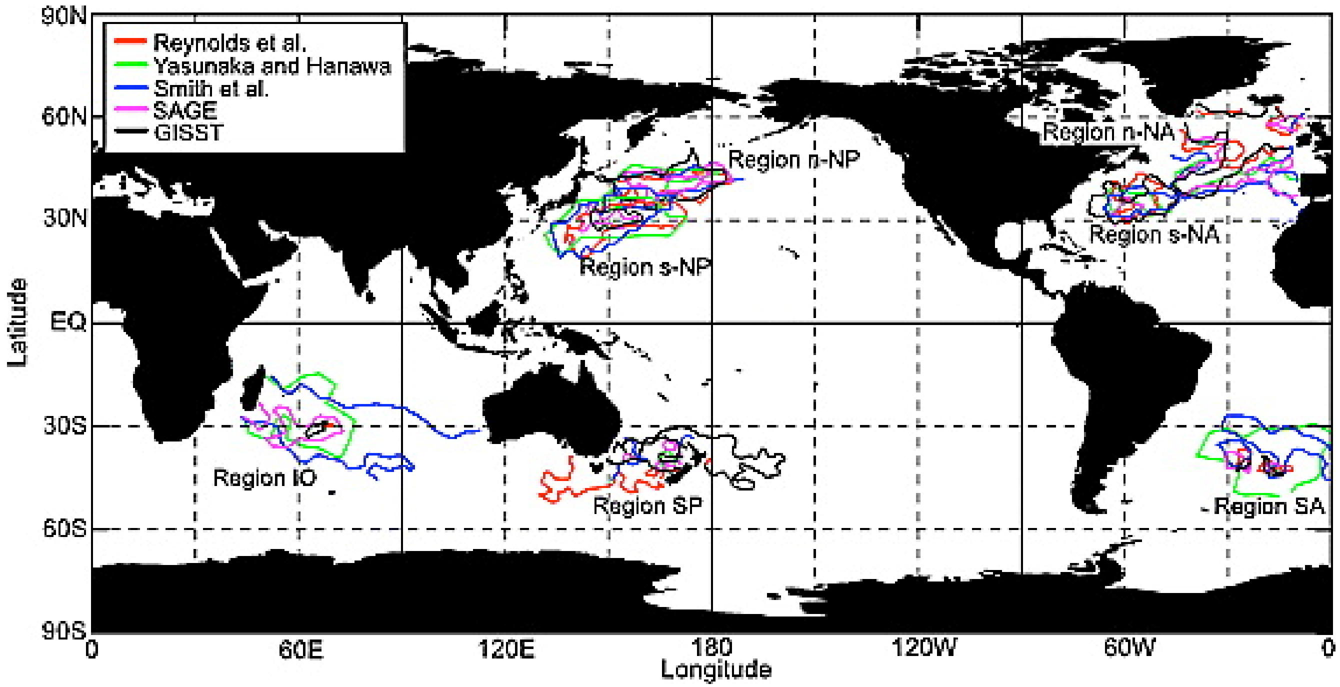
Limited re-emergence - accounting for asymmetry of heating/cooling & downward motion (e.g., Ekman pumping in subtropical gyre)



National Oceanography Centre, Southampton
UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

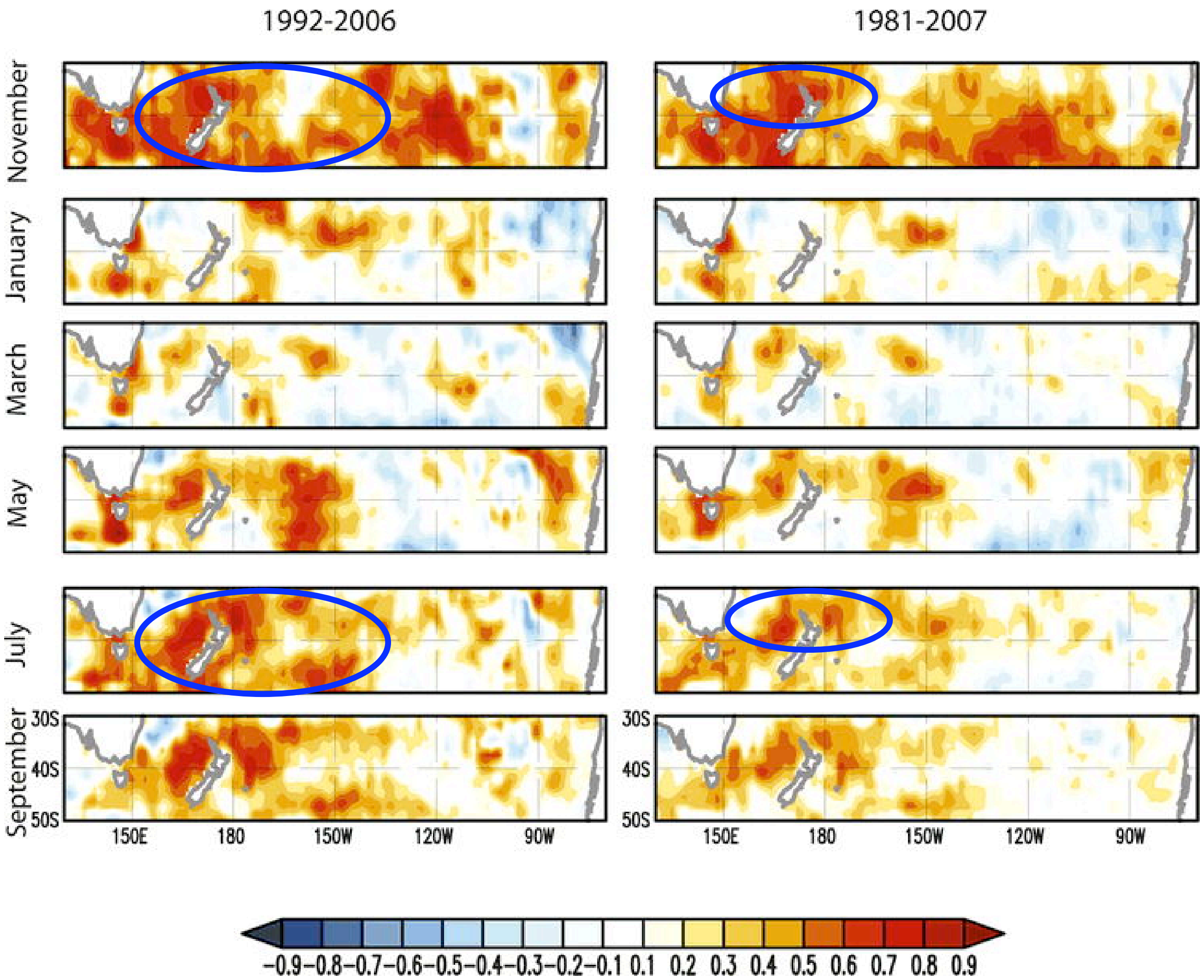
Re-emergence “hot-spots” in the World Ocean : Evidence from Observations

Hanawa & Sugimoto (2004)



Re-emergence areas detected by lag correlation analysis using five SST datasets (contours bound areas where lag correlations exceed 99% significance level)

Re-emergence in the South Pacific : More Observations



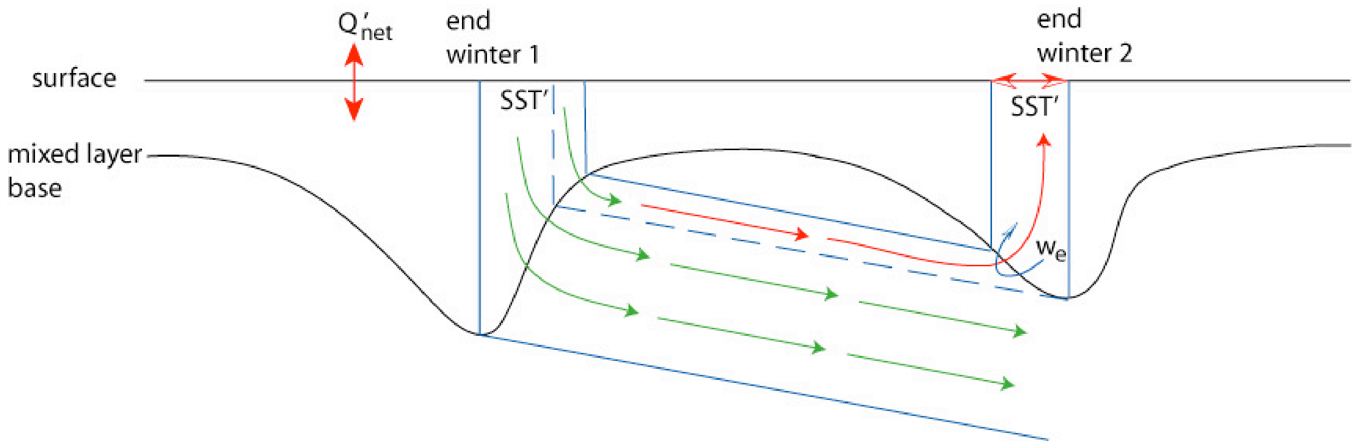
Correlations between SST anomalies in Sept & subsequent months [from Ciasto and Thompson, 2009]

Strongest re-emergence evident in SW Pacific, around New Zealand

Less discernible in SE Pacific (due to strong subduction there?)

SST re-emergence : concepts (2)

Further limited re-emergence - accounting for subduction (advection)

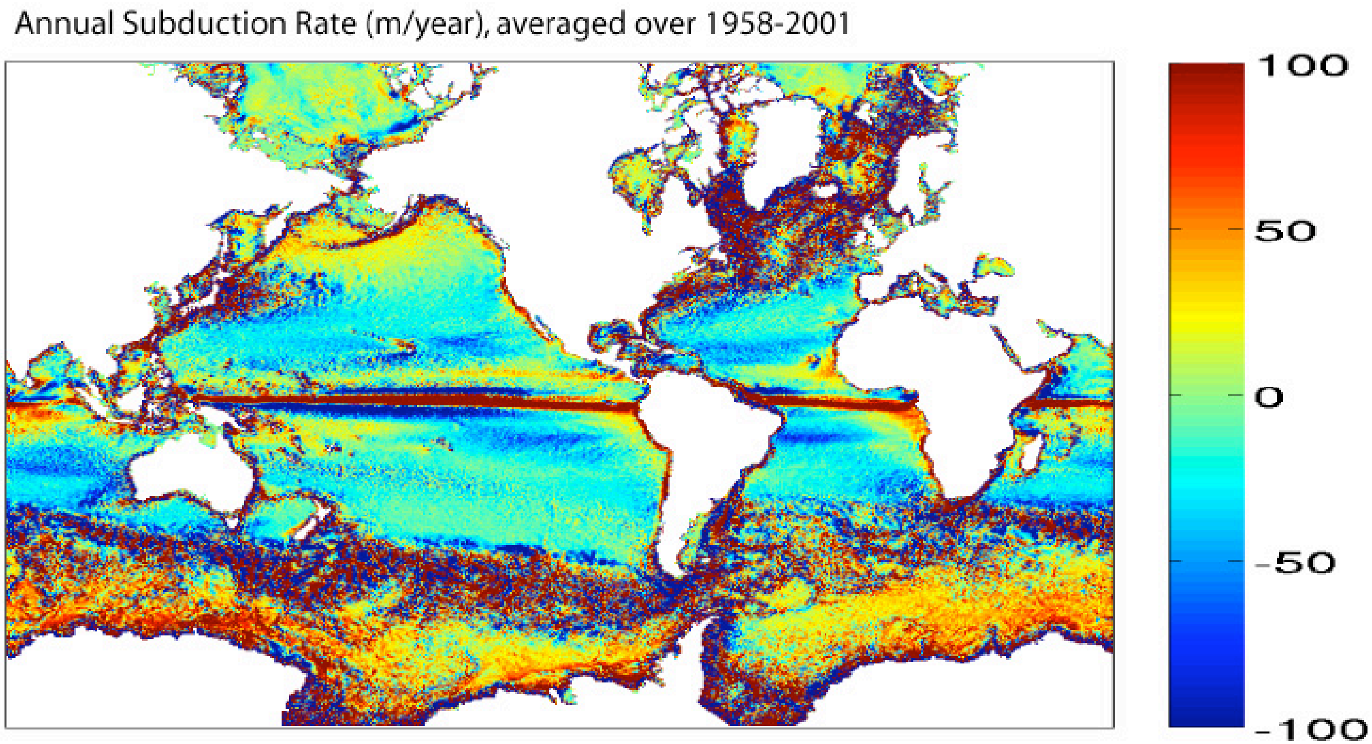


- MLD in winter 2 < MLD in winter 1 - due to advection away from region of deep winter mixing and/or interannual variation of winter MLD

- Recall annual Subduction rate (m/year), $S_{ann} = \frac{1}{\tau_{year}} \int_{W1}^{W2} \left(u_h . \nabla h + w_h \right) dt$

- Re-emergence further diminished through horizontal & vertical mixing

Subduction/Obduction from/to the Thermocline in 1/4° NEMO hindcast



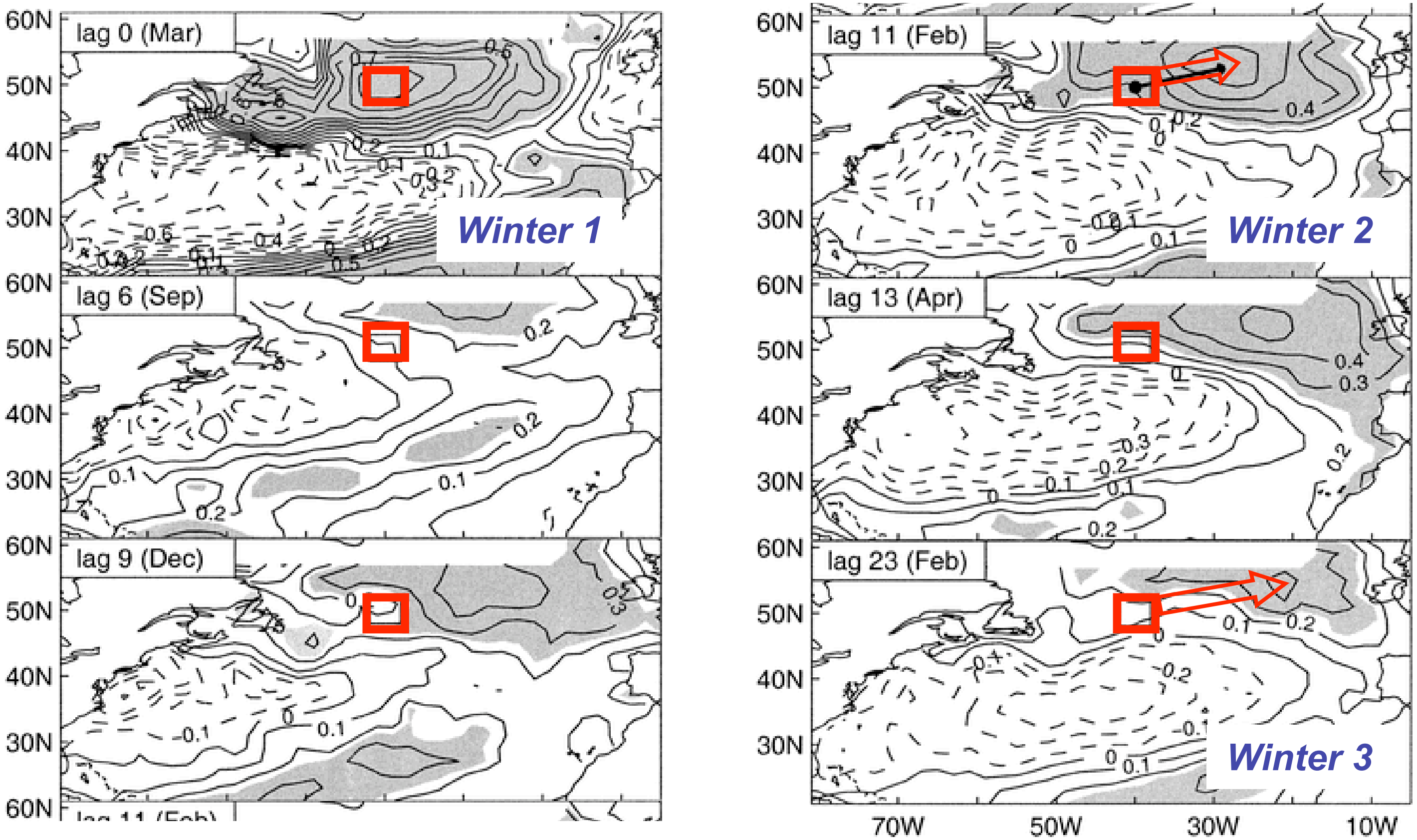
Obduction complements seasonal re-emergence with older anomalies

Subduction reduces the extent of re-emergence

Figure courtesy Sarah Taws (PhD CASE student with Met Office, Seasonal Forecasting Group)

Remote Re-emergence : Observational Evidence (1)

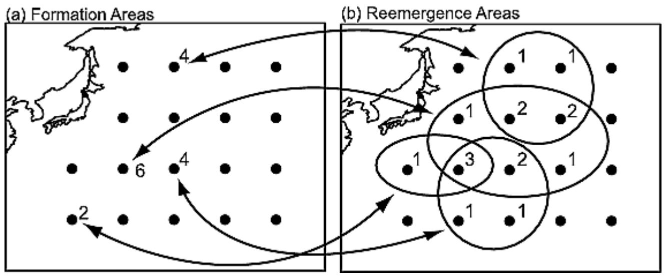
Evidence that strong advection leads to "remote re-emergence" along the path of the Gulf Stream (de Coëtlogon & Frankignoul 2003):



Seasonal cross correlations at selected lags between a reference time series (av. Mar SST in red square) and SST anomalies at each grid-point

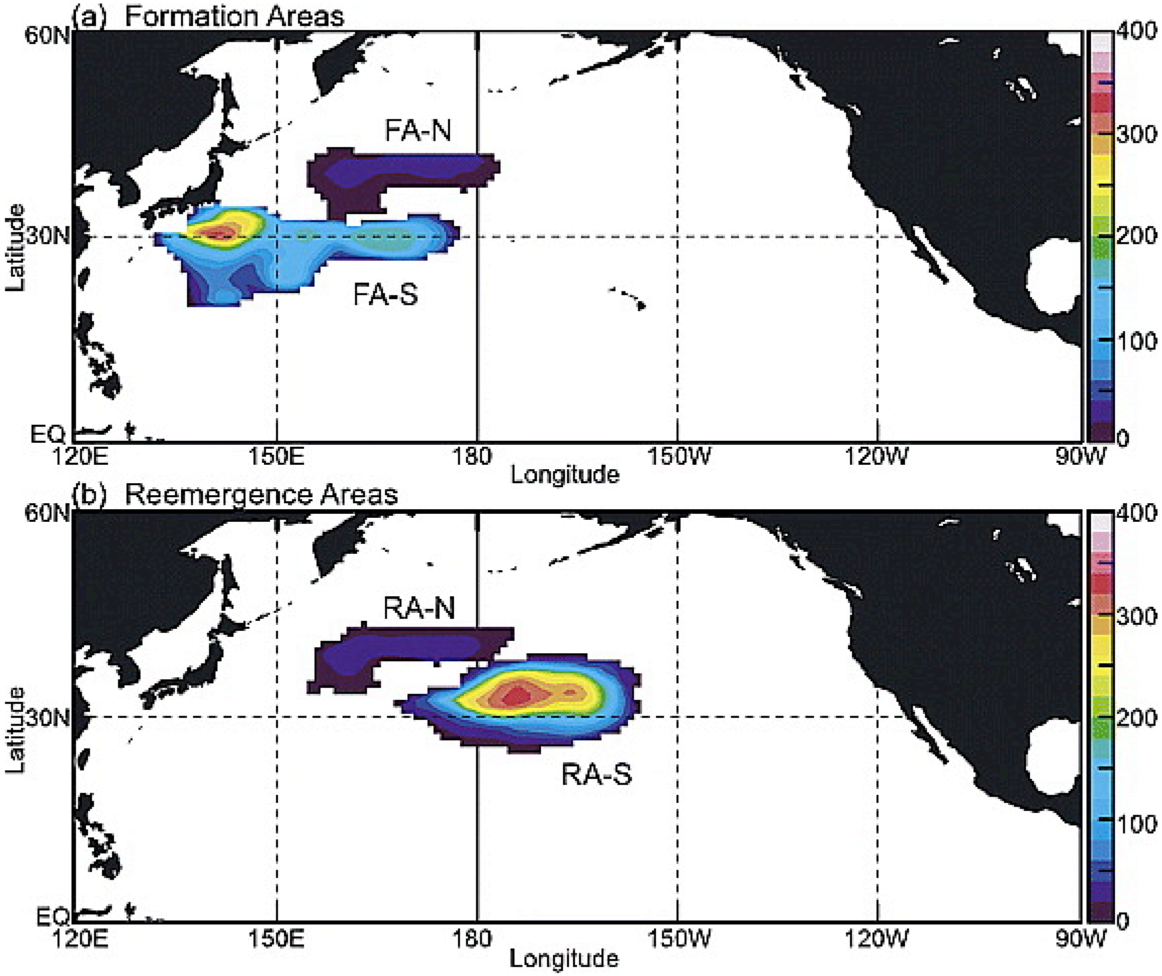
Remote Re-emergence : Observational Evidence (2)

… and along the path of the Kuro Shio (Sugimoto & Hanawa 2005):



- 1-year lag correlations (r_{lag}) are taken between all grid points in (a) and (b)
- formation and re-emergence areas (FA & RA) detected by counting number of cases where r_{lag} exceeds threshold

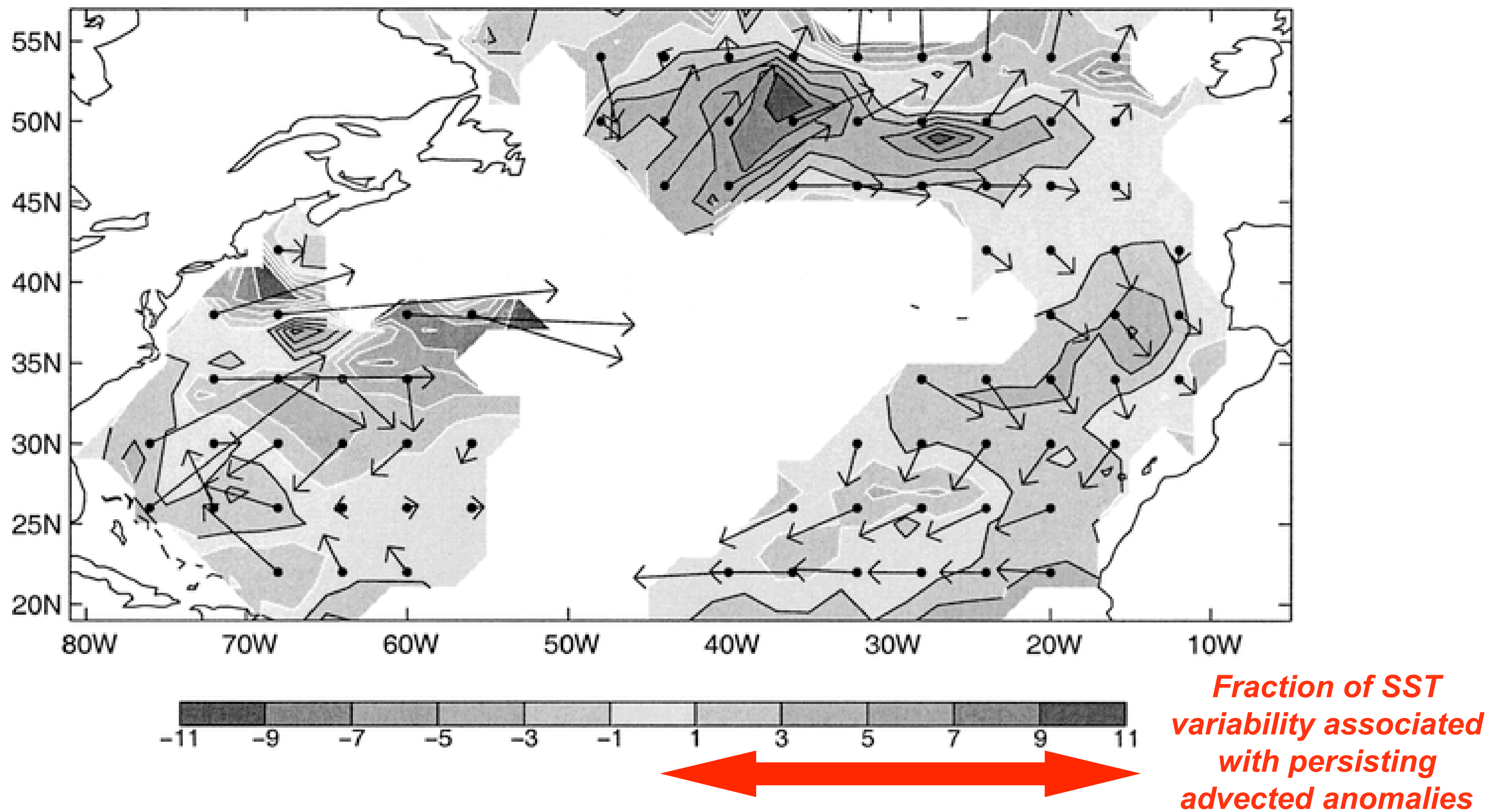
- Two distinct patches of remote re-emergence correspond to two types of "mode water"



Counted number of cases where r > conditional threshold (0.6-0.7)

Remote Re-emergence : Model Analysis

"Quasi-Lagrangian" approach with MITgcm (de Coëtlogon & Frankignoul 2003):



Increase/decrease in e-folding timescale of recurrent SST anomalies (persistence) when estimated along MITgcm displacement, compared to local SST

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3. More/new observations + better ocean models = new insights
4. The varying Meridional Overturning Circulation
5. The re-emergence story so far & where next?
6. ***Systematic ocean model error - resolve eddies or refine parameterizations?***
7. Summary & Conclusions

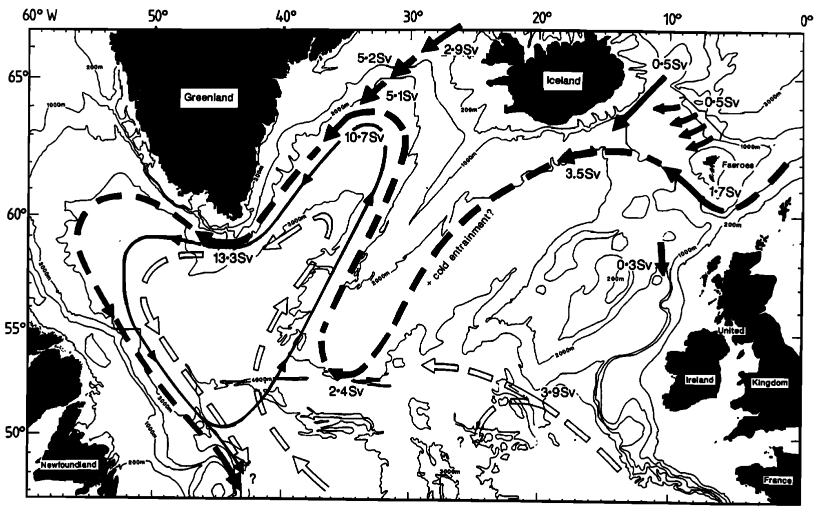
National Oceanography Centre, Southampton
UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

Outstanding Problems & Challenges

In spite of much progress & success in ocean modelling, specific problems are associated with some processes:

1) Overflows

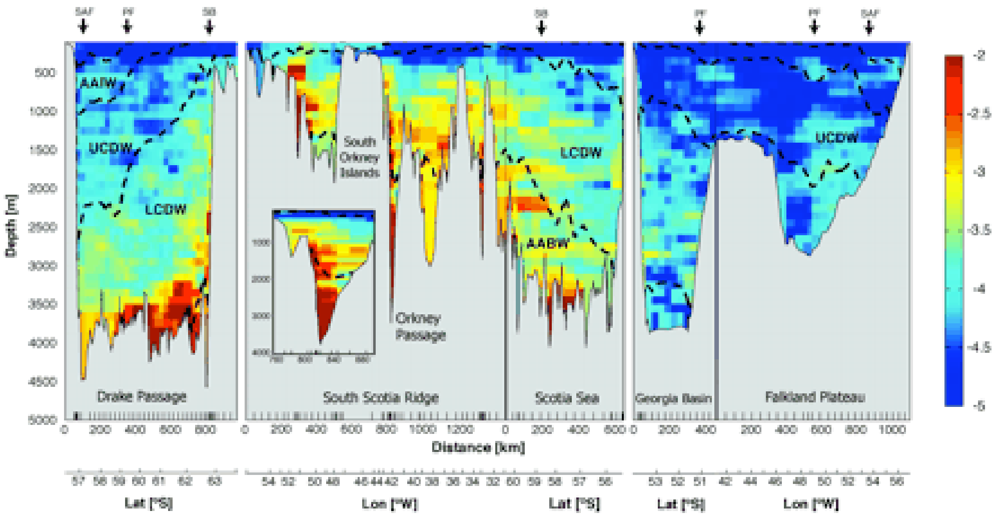
e.g., in North Atlantic



[from Dickson & Brown, 1994]

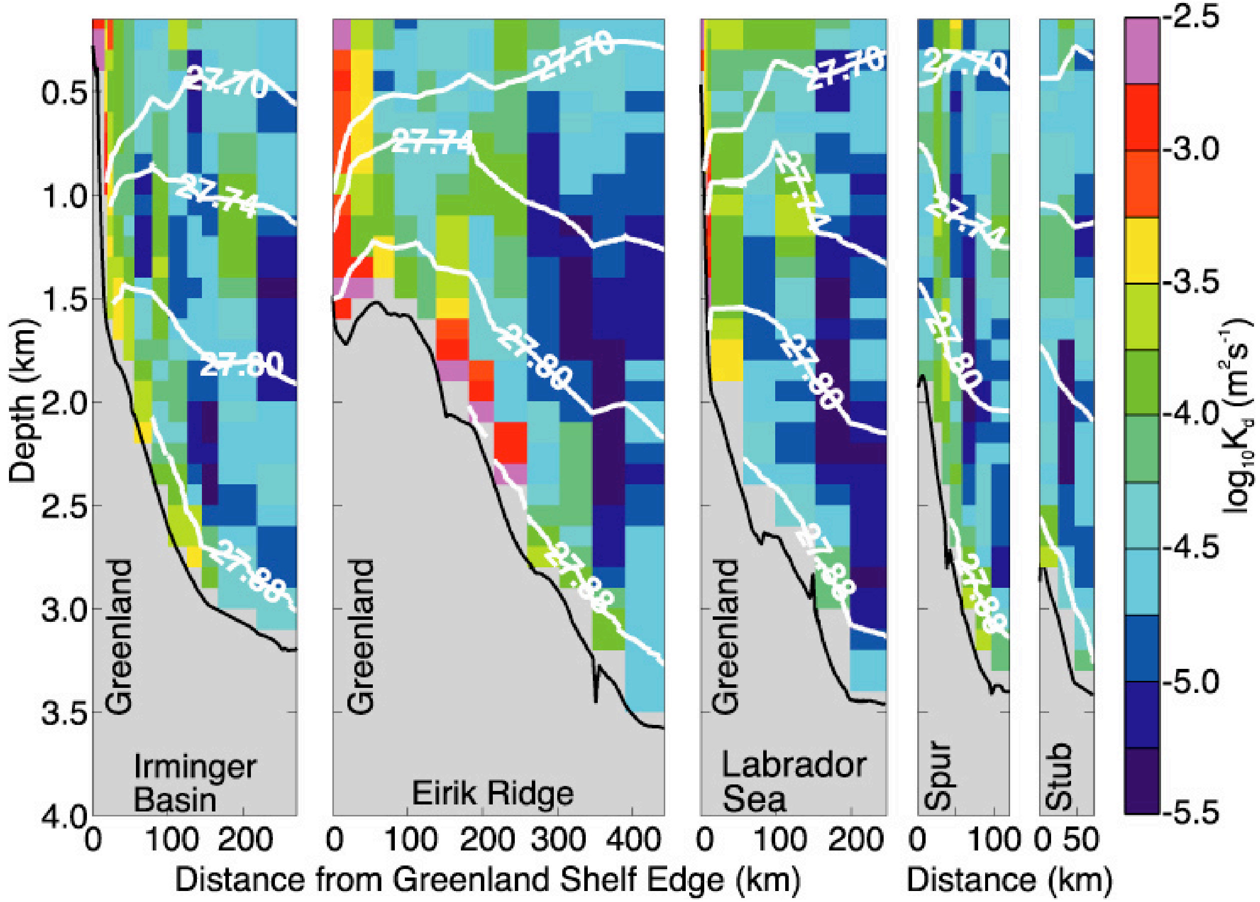
2) Deep mixing

e.g., in Southern Ocean



[from Naveira-Garabato et al., 2004, Nature]

& combining Overflows and Deep Mixing …



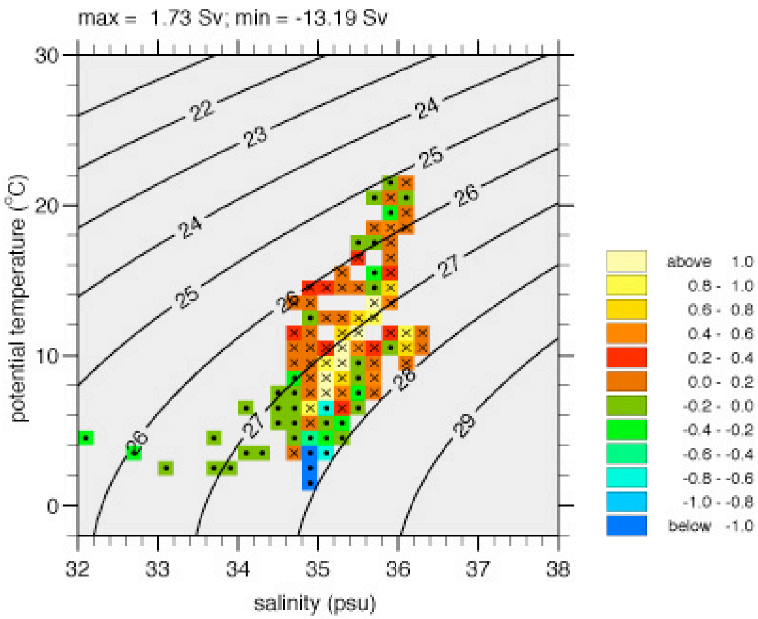
[Fig. 2, Lauderdale et al., 2008, GRL]

"Intensified turbulent mixing in the boundary current system of southern Greenland" (Lauderdale et al. 2008)

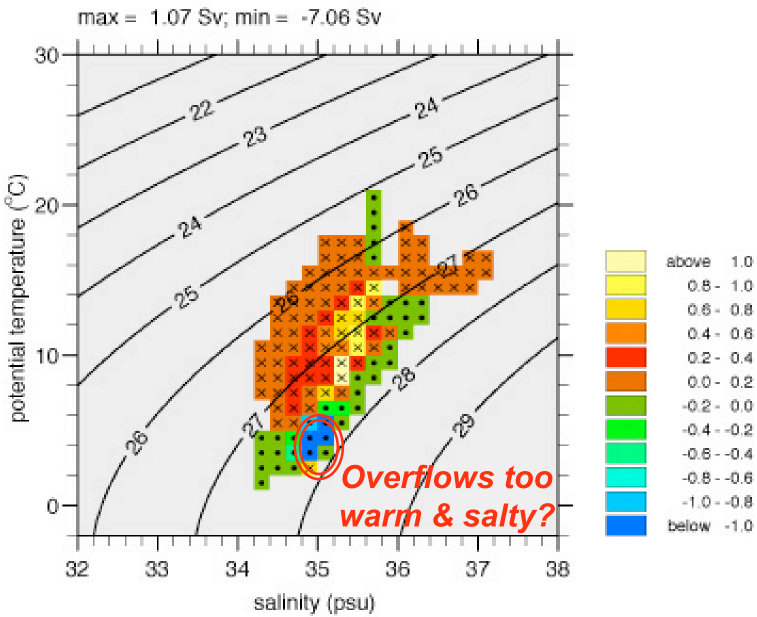
Example: Problems with Deep Overflows in OC-4

Northward transport across Spain-Greenland section, partitioned in (T,S):

(a) Observations (Aug 1997)



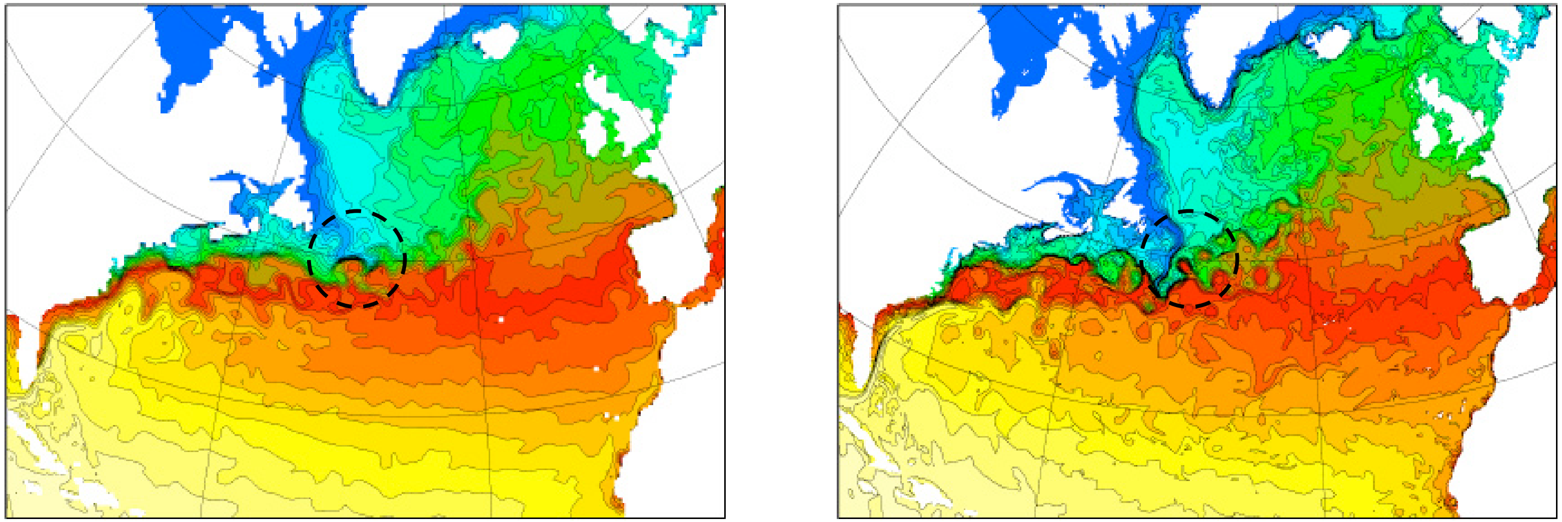
(b) OC-4 (Run 202)



- **Broadly correct simulation (right) of observed transport (left) across a wide range of T & S, southward transport in a much more limited range**
- **But the southward flow is at too high temperature and salinity …**
- **Due to misrepresentation of upstream processes in the deep overflows?**

To eddy resolution : the OCCAM experience

e.g., January 1989 Sea Surface Temperature in N. Atlantic



OC-4 **OC-12**

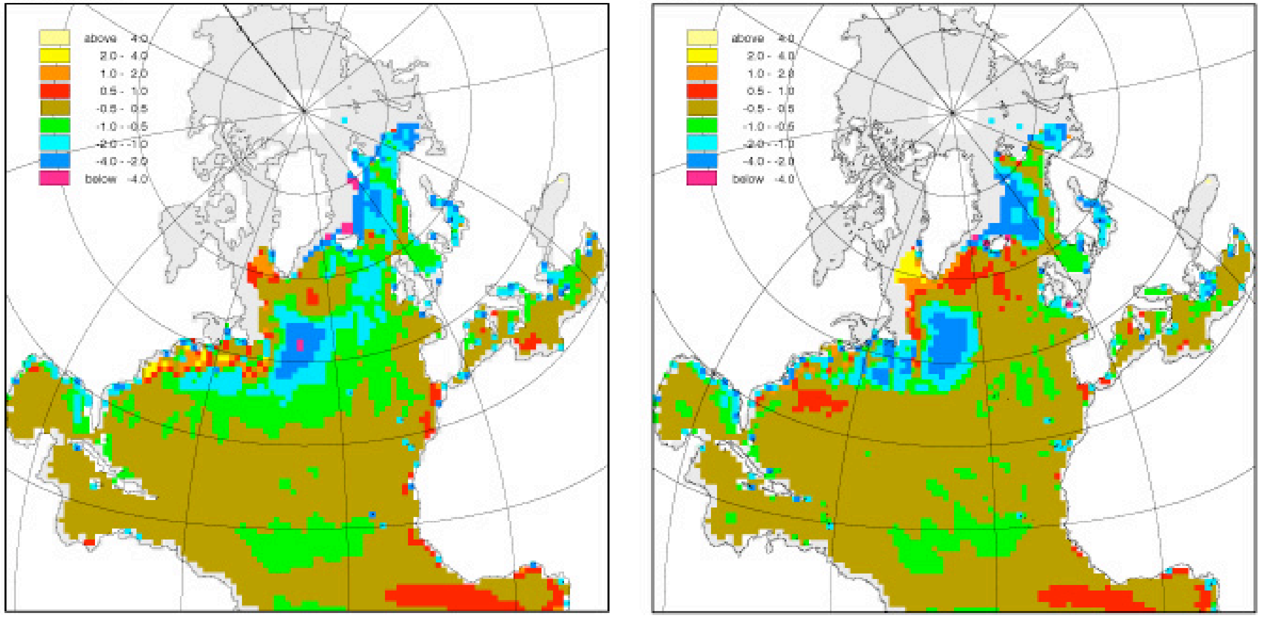
Compared to 1/4° version, 1/12° version of OCCAM has:

- Narrower Boundary Currents (Gulf Stream, subpolar gyre)
- More realistic Eddy Fluxes (e.g., Lee et al. 2007)
- More Correct SST field, with exception of “Northwest Corner”…

SST errors in eddy-permitting & eddy-resolving OCCAM

Reduce with increased resolution, from 1/4° to 1/12° →

… but persist in the "Northwest Corner"



from Marsh et al. 2009 (Ocean Modelling)

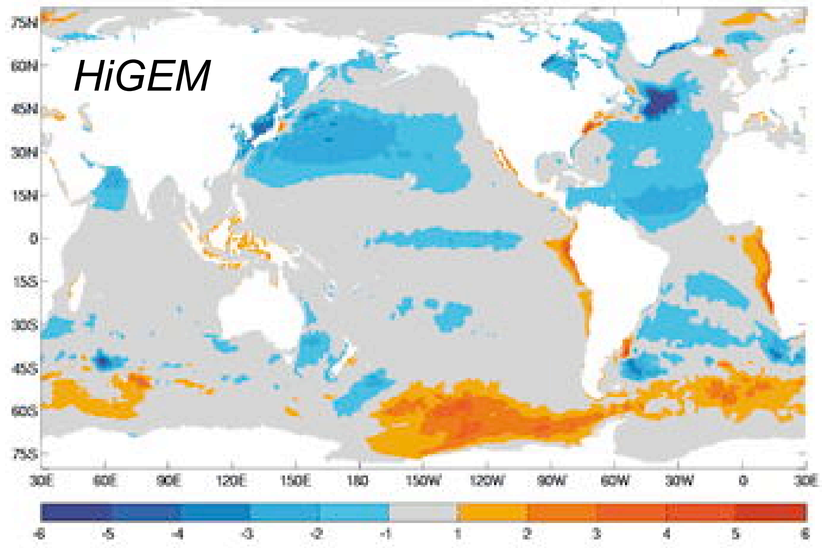
- Errors are Model SST minus NOCS SST (ship-based measurements)
- Smaller in eddy-resolving model

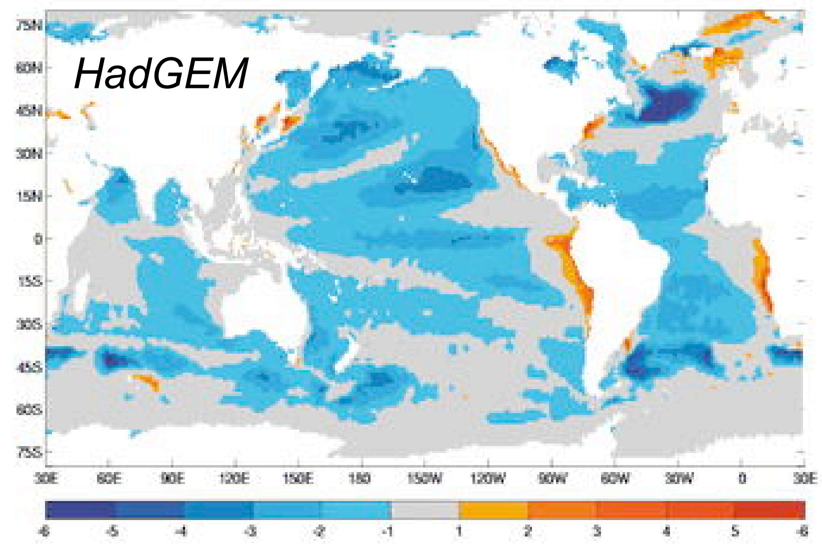
SST error reduction in a climate model with an eddy-permitting ocean

- Similar SST error reduction in the northwest Atlantic (among other places)

- comparing HadGEM, with a partially (low-latitude) eddy-permitting ocean to HiGEM, with a globally eddy-permitting ocean

[from Shaffrey et al. 2009]





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Summary (1)

Observations improve & grow:

- Better retrieval & interpretation of CTD & XBT data has provided clearer information on last 50 years - strong variability & Atlantic warming trend
- Satellite measurements since 1980s (SST), 1990s (SSH) provide lengthening time series of spatial patterns of changing upper ocean heat content
- Argo measurements since 1999 now allowing analyses of interannual variability in ocean inventories and transports
- MOC monitoring since April 2004

Summary (2)

Ocean Models:
- Reaching higher resolution (eddy-resolving)
- Becoming more realistic (through better physics, resolution)
- Promising advanced techniques (e.g., ICOM)

Key Processes/timescales:
- Seasonal-interannual timescale : re-emerging SST anomalies, shaped by advection, subduction, eddies
- Interannual-decadal timescales : changes in gyres, Ekman transport, overturning
- Seamless transition between all timescales?

Conclusions & Prospects

➢ Range of ocean model diagnostics (routine, novel) required to establish fidelity of models for operational use

➢ Much of observed SST variability (seasonal to decadal) potentially predictable with a variety of methods/models

➢ Lagrangian diagnostics bringing clearer link between SST variability & earlier remote SST anomalies - ***can do more?***

➢ But ocean models in forecast systems are perhaps too heavily parameterized - ***time for higher resolution?***