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UNIVERSITY OF SOUTHAMPTON AND NATURAL ENVIRONMENT RESEARCH COUNCIL

Recent warming and changes of circulation in the North Atlantic

- simulated with eddy-permitting & eddy-resolving models

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(+ contributions by Graham Quartly, Lisa Redbourn, Julian Jacquin)

Effects of Climate Change on the World's Oceans, Gijon, 19 - 23 May 2008

Prologue: Impacts are important, but the ocean is not a passive participant, so we may also consider:

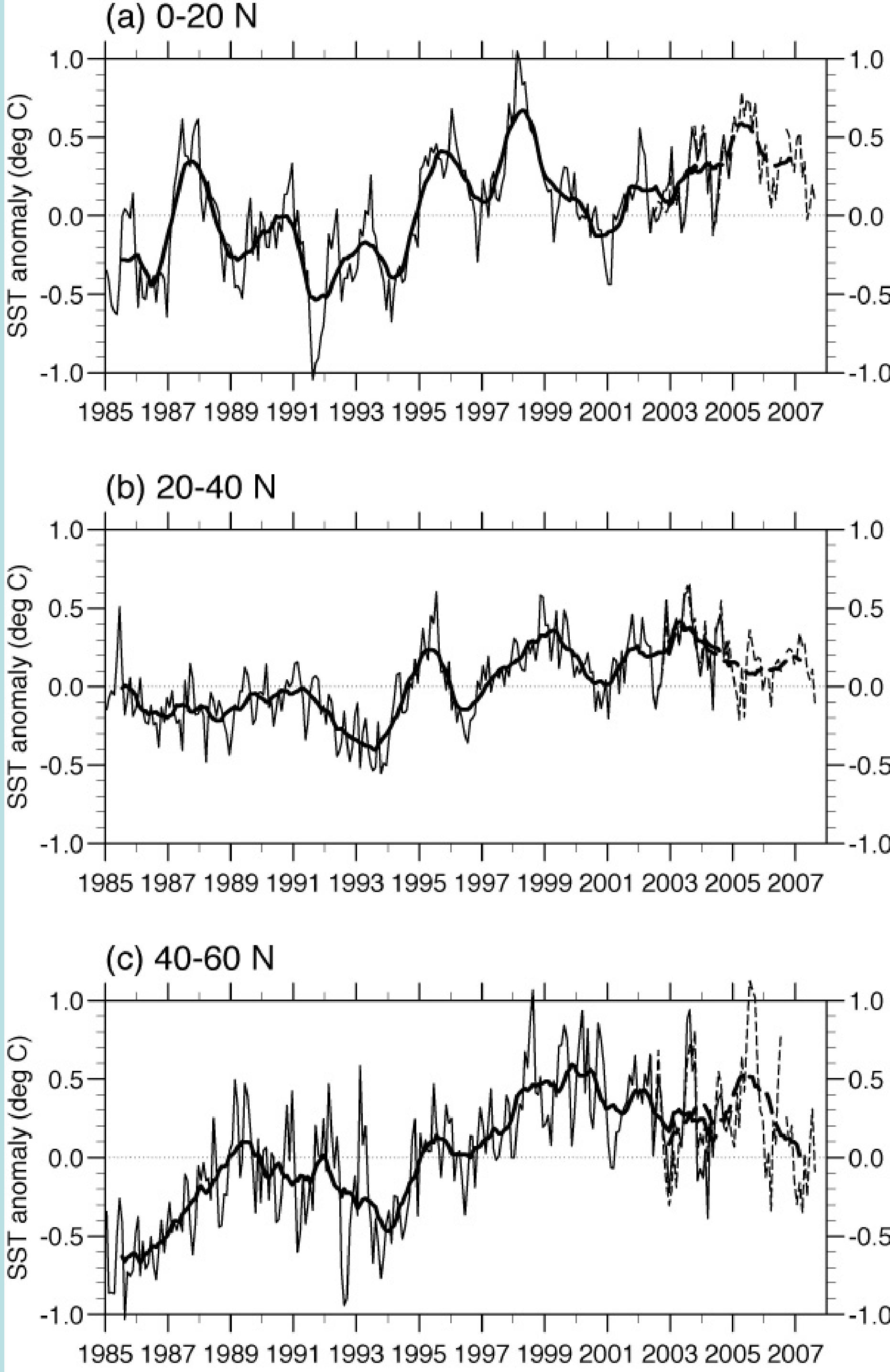
"Effect of the World's Oceans on Climate Change"

Outline

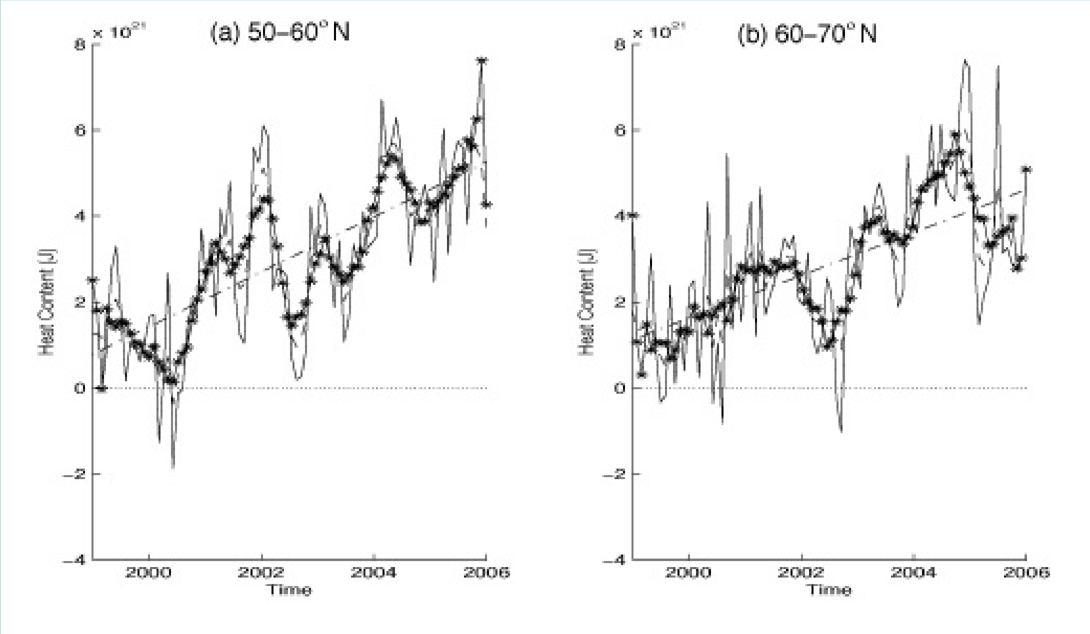
1. Observed Warming - brief background
2. OCCAM hindcasting - brief background
3. Patterns of surface warming since the 1980s, in the North Atlantic
4. Role of anomalous surface fluxes vs. anomalous ocean heat transport
5. Anomalous ocean heat transport: meridional overturning circulation (MOC) vs. "non-MOC" (gyres, eddies)
6. Summary & Future Developments

North Atlantic surface warming since 1985: satellite measurements (Pathfinder, AMSR)

- monthly anomalies (relative to means over hindcast 1985-2003 reference period)
- considered in three zones
- revealing strong interannual variability in the tropics, strong decadal variability in mid-latitudes
- … and warming trends



North Atlantic sub-surface warming since 1999 revealed by measurements from Argo floats



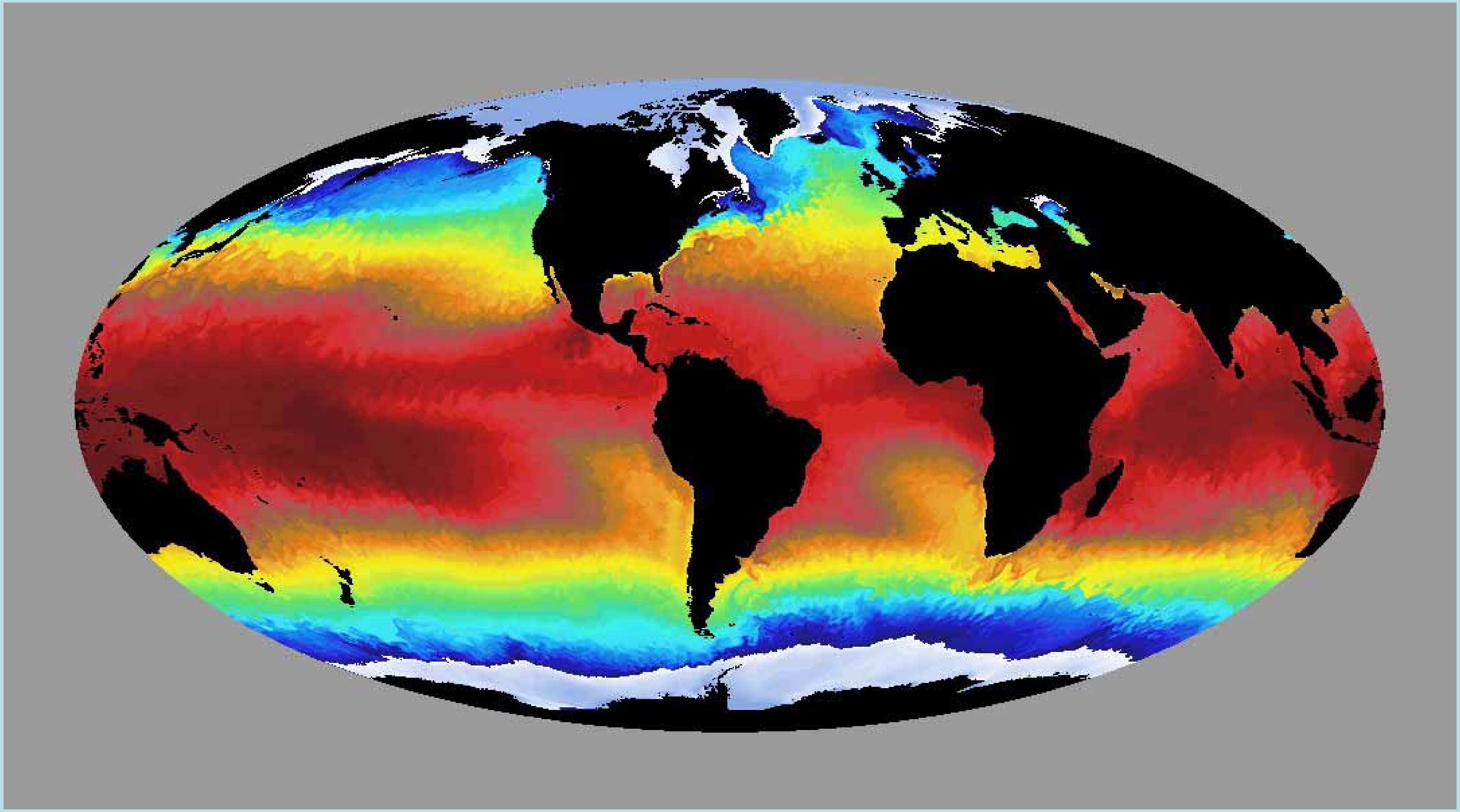
[courtesy of Vladimir Ivchenko - see Ivchenko et al., 2006, GRL]

- 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
- In global & longer term contexts: over 1955-98, warming of the upper 3km of the Atlantic accounts for ***~44% of heat gain by the entire Earth System*** (atmosphere, oceans, soils, ice) - extrapolating from Levitus et al. (2005)

The Ocean Circulation & Climate Advanced Model (OCCAM, 1995-2007)

- OCCAM projects provided huge amounts of data for extensive analysis of key processes in ocean circulation
- Crowning achievement of OCCAM: hindcast of World Ocean at 1/12° resolution (< 10 km gridcell dimensions), truly resolving eddies equatorward of ~50°
- OCCAM analysis highlights: Antarctic Circumpolar Current; Agulhas Retroflection; Indonesian Throughflow
- OCCAM superceded by models in a new framework: Nucleus for European Modeling of the Ocean (NEMO)

The World Ocean of OCCAM

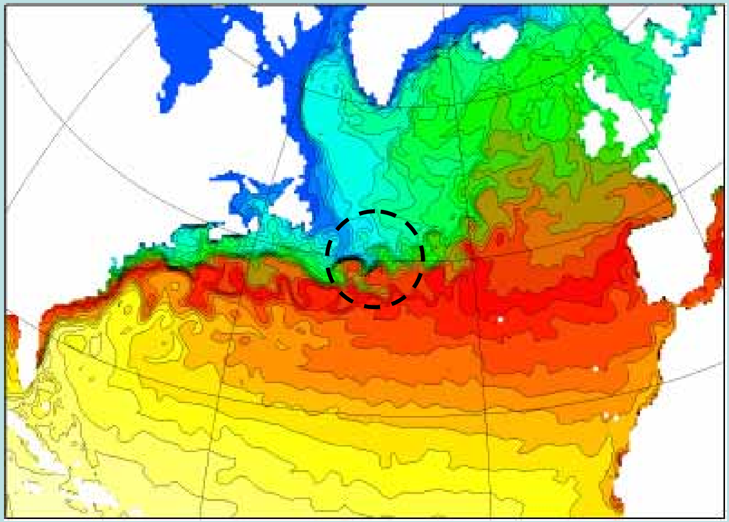


… is actually 2 models joined together at the Atlantic Equator & connected at the Bering Strait (Pacific-Arctic)

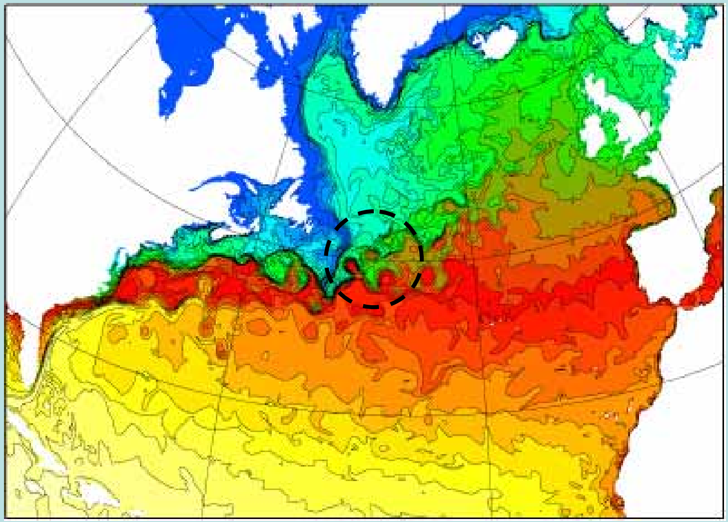
- Subsequently results from Atlantic/Arctic sector today …

OCCAM: 1/4° & 1/12° simulations, 1985-2004

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



OC-4



OC-12

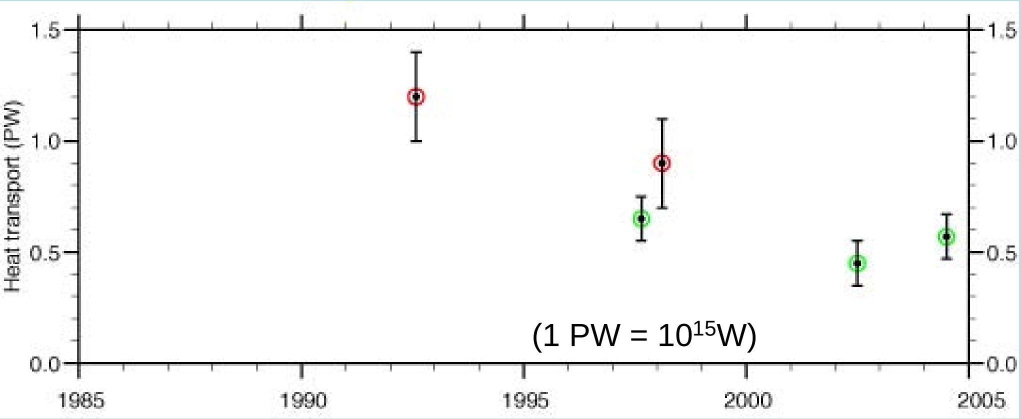
Compared to OC-4, OC-12 has:

- Narrower Boundary Currents (Gulf Stream, subpolar gyre)
- More Correct SST field (especially “Northwest Corner”)
- “Proper” Eddies & Eddy Fluxes (e.g., Lee et al. 2007)

Confronting OCCAM with Observations

- Recent changes in AMOC & Heat Transports (Marsh et al. 2005, GRL)

Observed oceanic heat transport across hydrographic sections 26ºN, Spain-Greenland

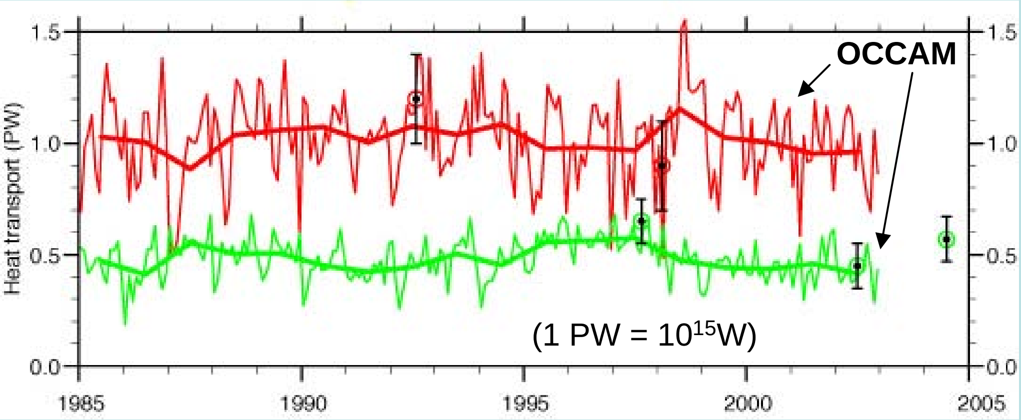


- **Only a few estimates of heat transport - how representative of recent changes?**

Confronting OCCAM with Observations

❑ Recent changes in AMOC & Heat Transports (Marsh et al. 2005, GRL)

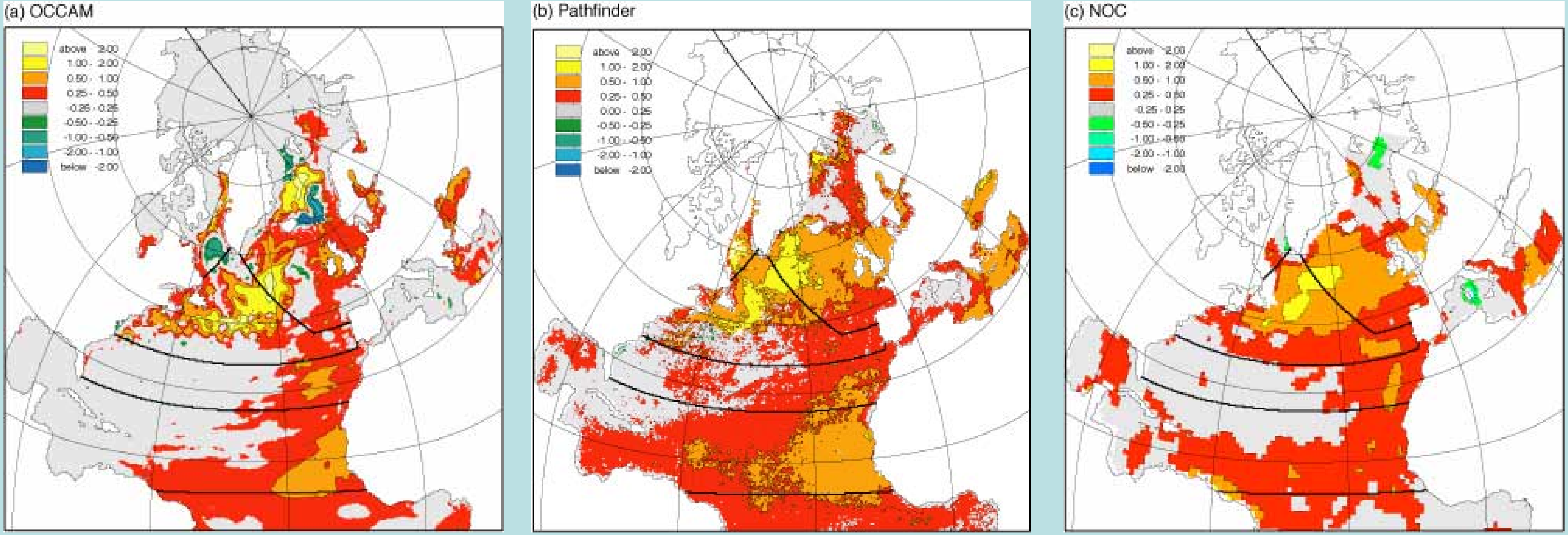
Observed oceanic heat transport across hydrographic sections 26ºN, Spain-Greenland



❑ **OCCAM time series reveal considerable variability in ocean heat transport, encompassing recent estimates**

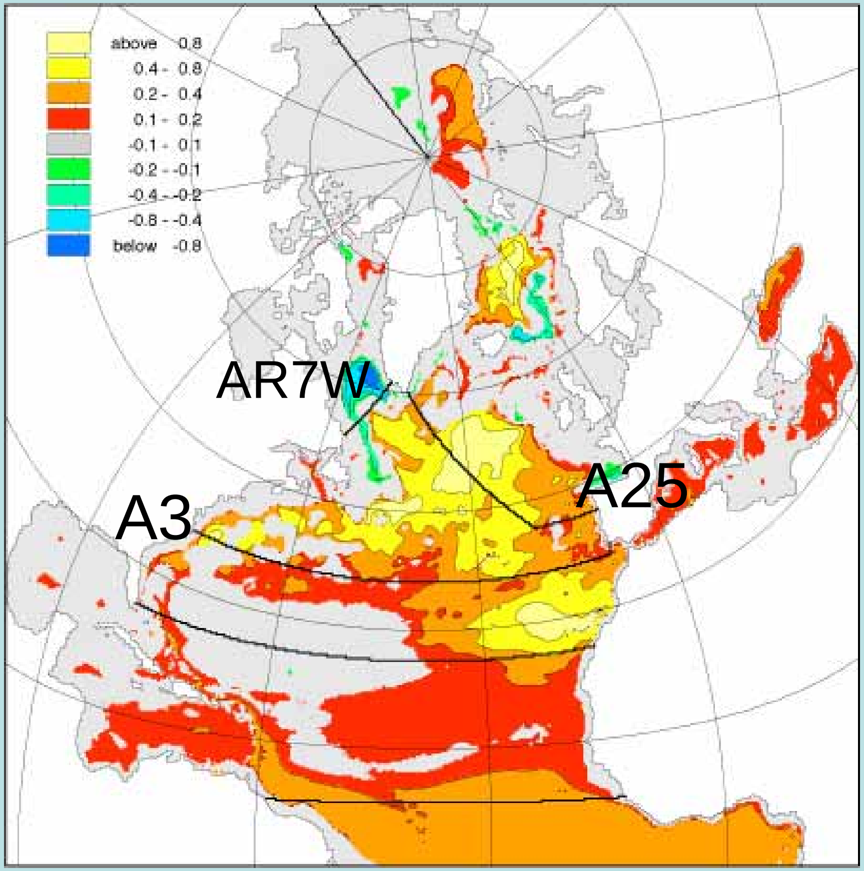
Recent Atlantic warming: Significantly non-zero SST change simulated in OC-4, observed by satellites (Pathfinder) & in situ (NOC)

Composite changes - 1995-2003 mean minus 1985-94 mean



- OC-4 simulates observed warming in Tropics, Mid-latitudes
- Analysis of OC-4 confirms the extent to which SST increases are the surface expression of increasing Ocean Heat Content …

Significant trend in OC-4 Ocean Heat Content (OHC, GJ m^{-2} $year^{-1}$), 1985-2003

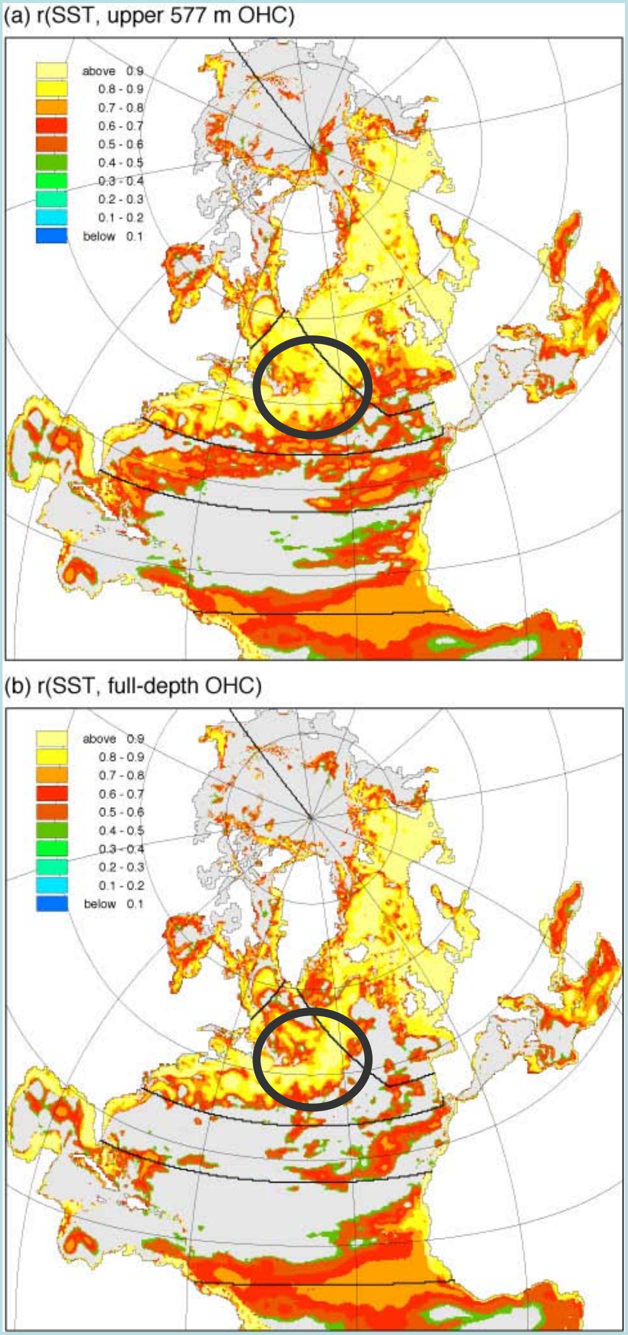


- almost entirely in upper 1500m (layer-mean 1ºC warming in mid-lats)
- rate of warming in good agreement with Argo estimates

Point-wise correlation coefficients between annual-mean OHC and annual-mean SST

• Correlations persist to great depth at mid and high latitudes, also in the eastern Tropics

• Highly significant correlations (r > 0.9) coincide with regions of strongest SST increase in Mid-latitudes

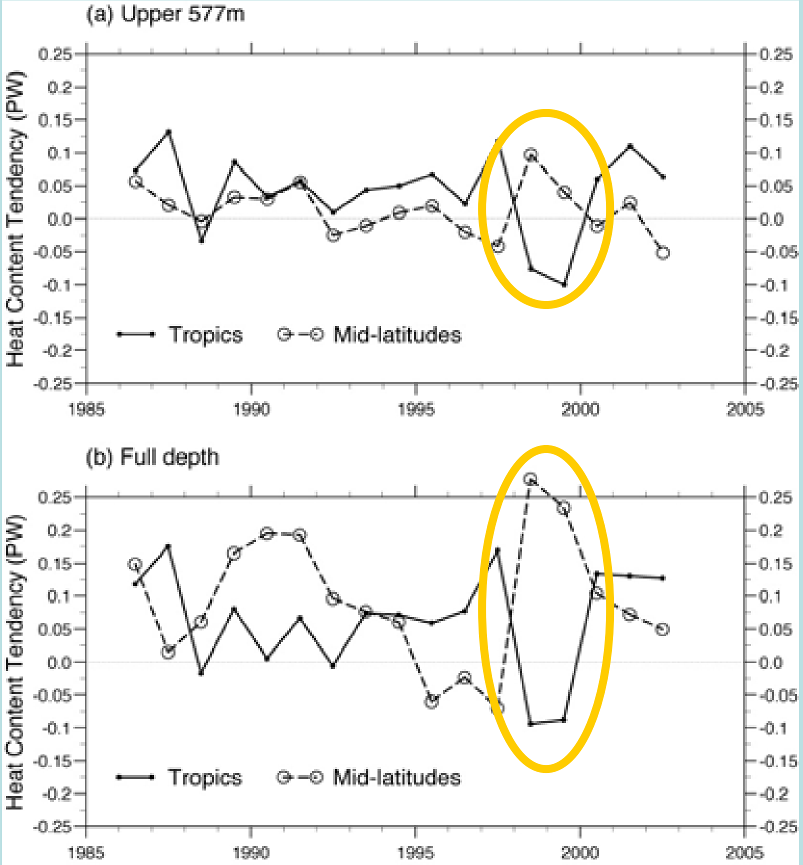


Annual tendency in OC-4 Heat Content, Q_{tend} (units PW = 10^{15} W): Tropics & Mid-latitudes

- Tendencies generally positive - i.e., long-term warming

- Much of full-depth heating in upper few hundred metres

- Some anti-correlation, notably in late 1990s, between Tropics & Mid-latitudes - suggests role for meridional heat transport?

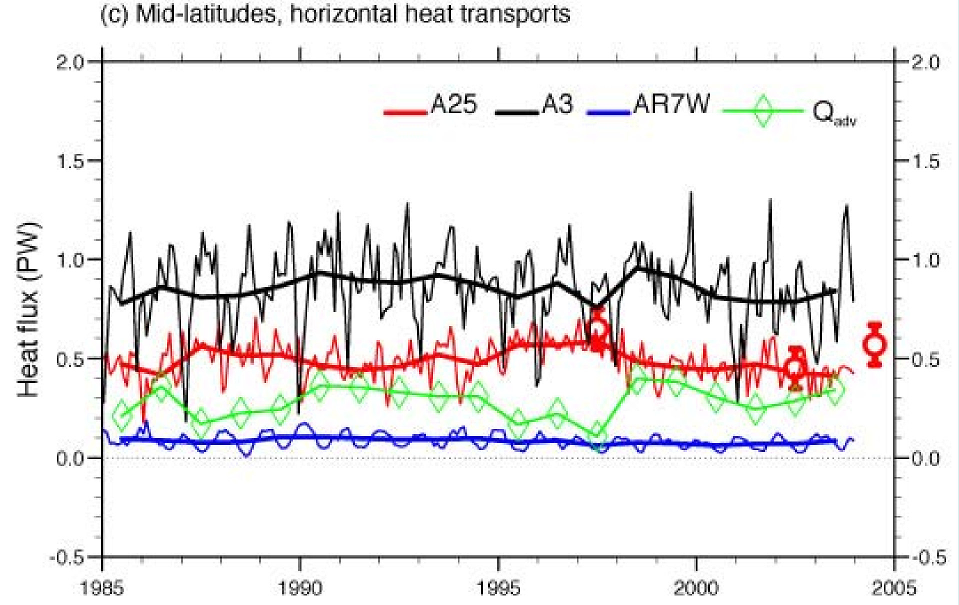


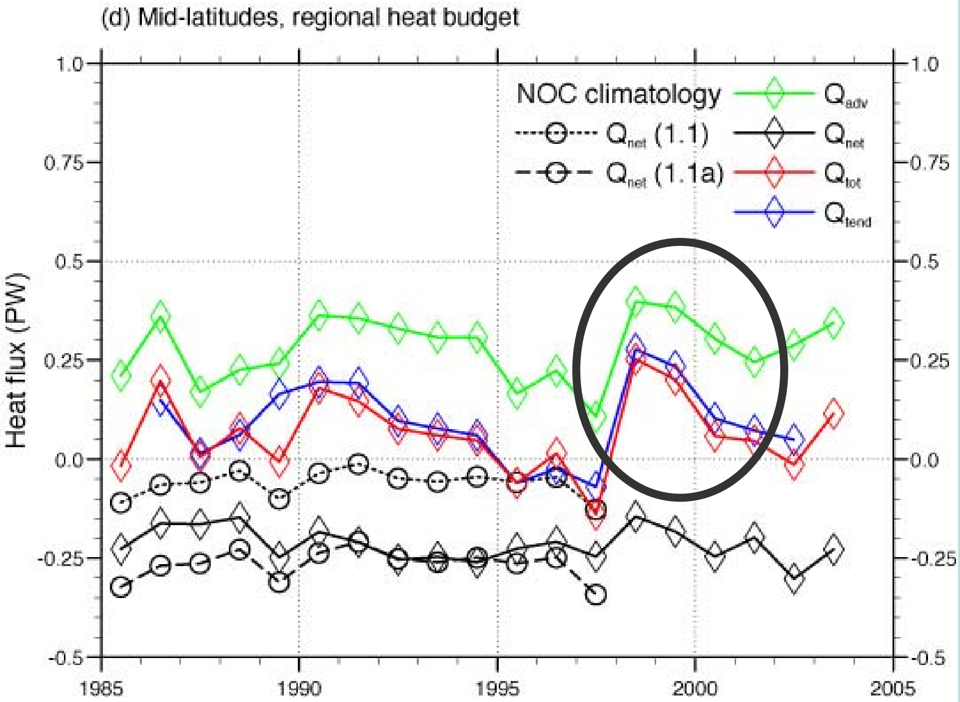
OC-4 Heat Budget: Mid-latitudes

- Q_{net} (OC-4) ≈ Q_{net} (NOC 1.1a), so model surface heat fluxes close to some of our best observations

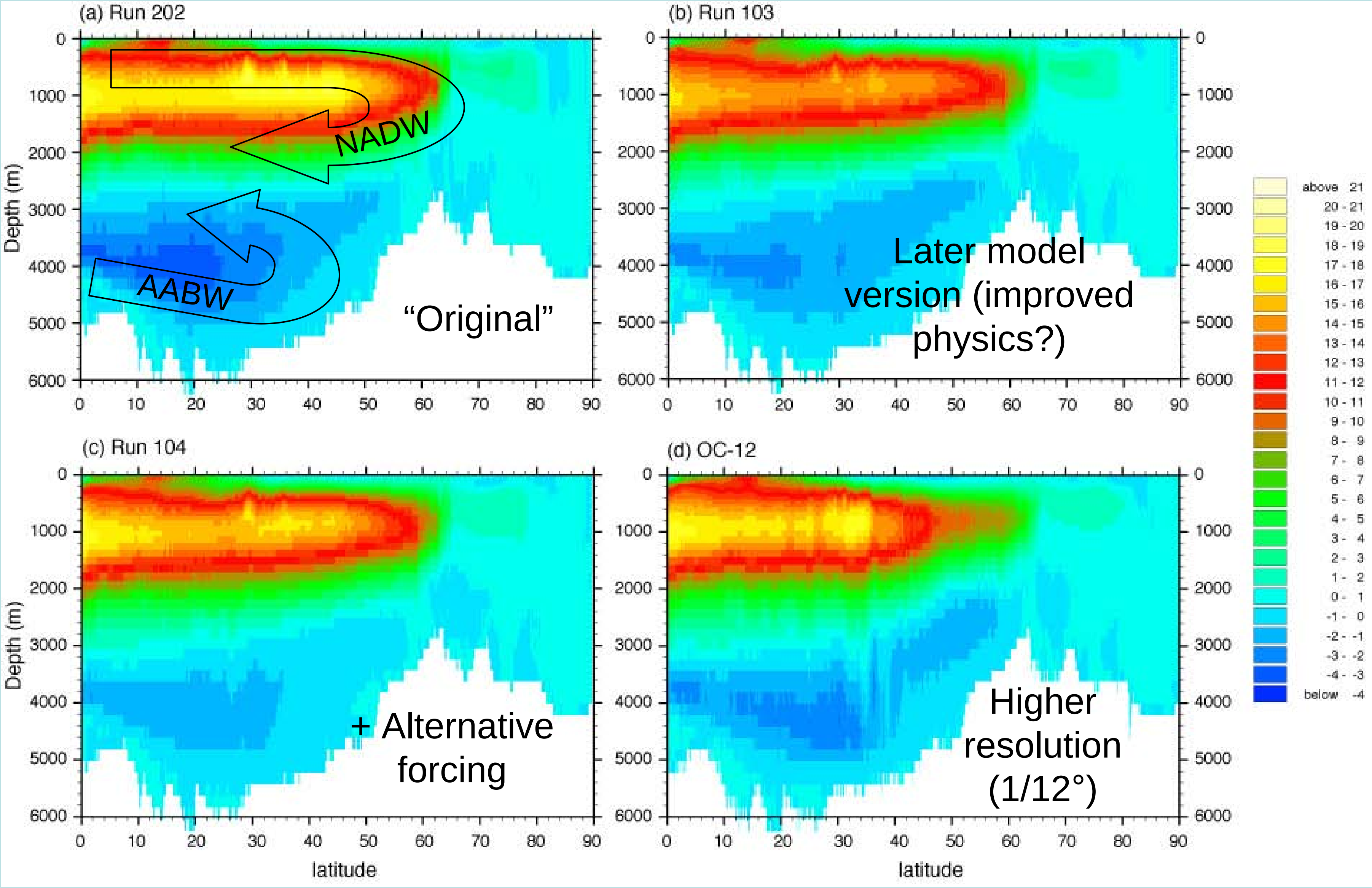
- Advection supplies heat (> 0), Surface Fluxes remove heat (< 0)

- annual net heating clearly linked to annual Q_{adv} anomalies, especially in late 1990s





Additional OCCAM hindcasts: Atlantic MOC



Meridional heat transport, OCCAM & observations

➢ Split Total as:

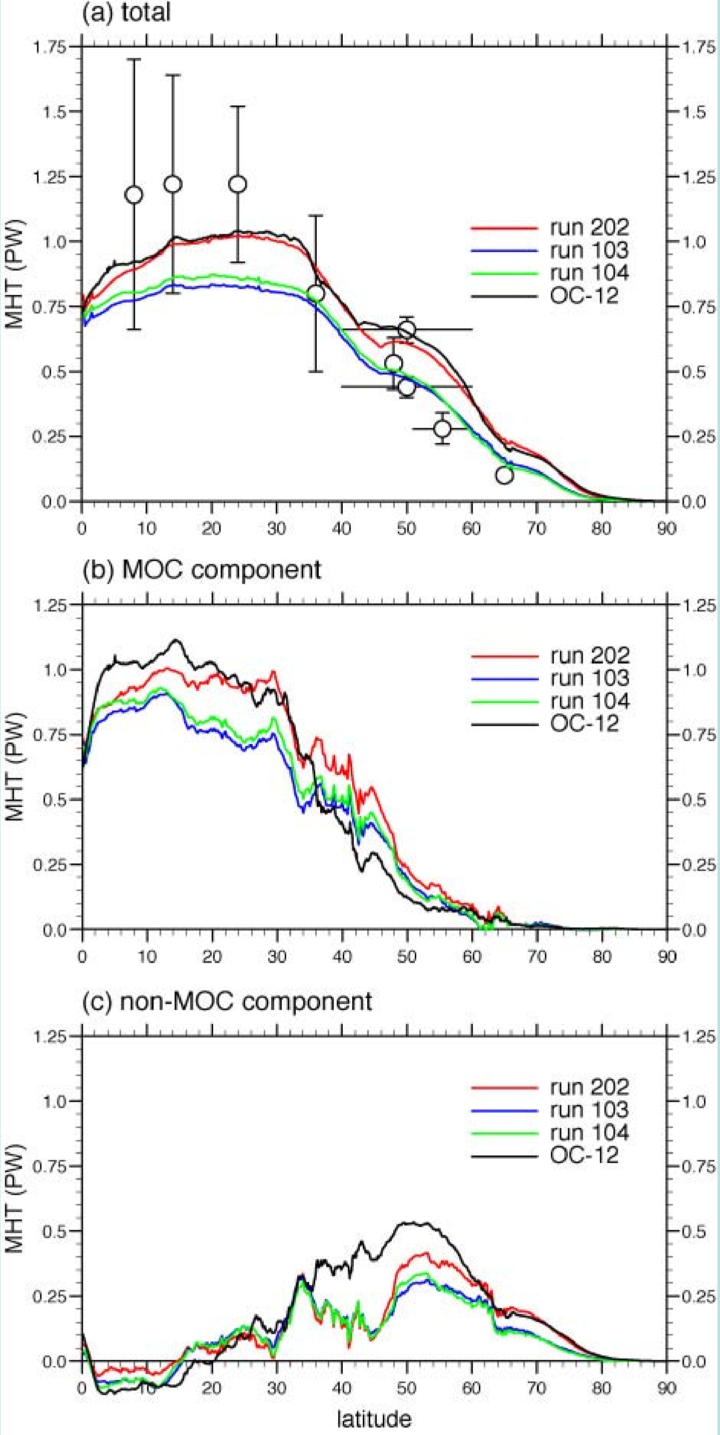
• MOC (warm upper branch; cold lower branch)

• non-MOC (gyres & eddies: cold western boundary current; warm eastern interior flow)

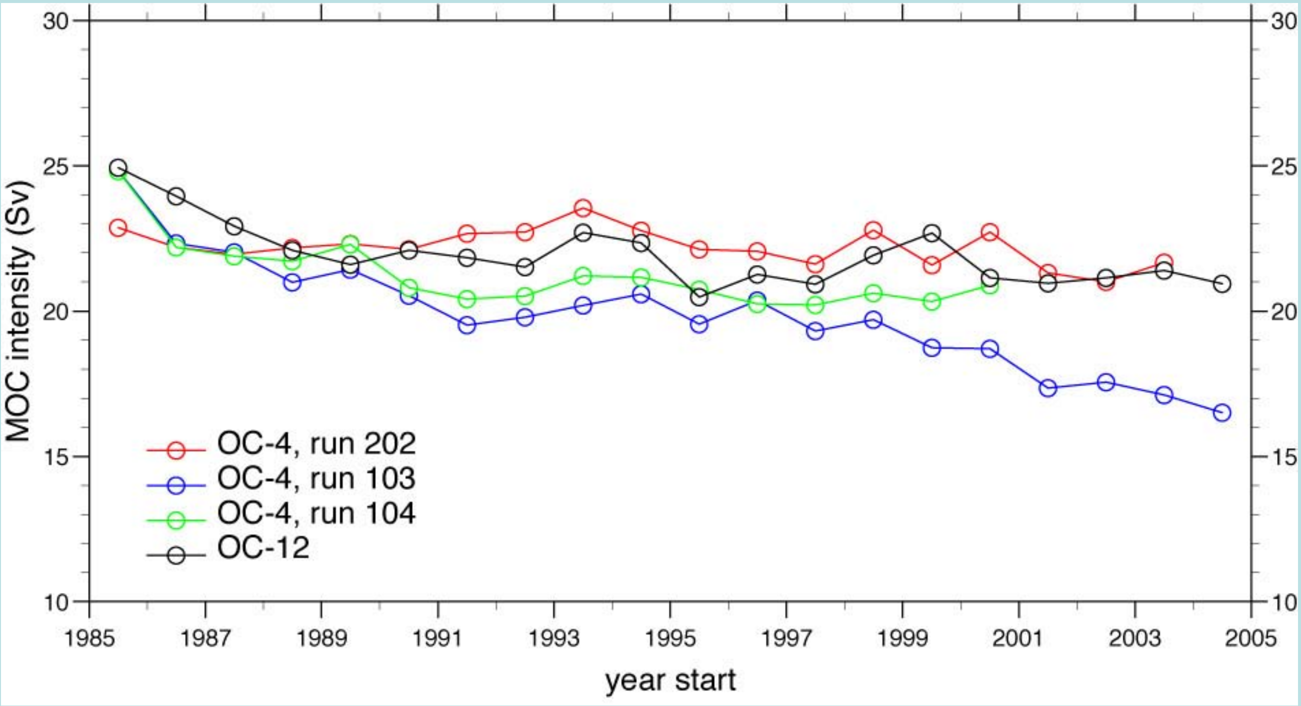
➢ Most of tropical & subtropical heat transport due to MOC

➢ Most of mid-latitude heat transport due to gyre & eddies

➢ Most emphatically in OC-12

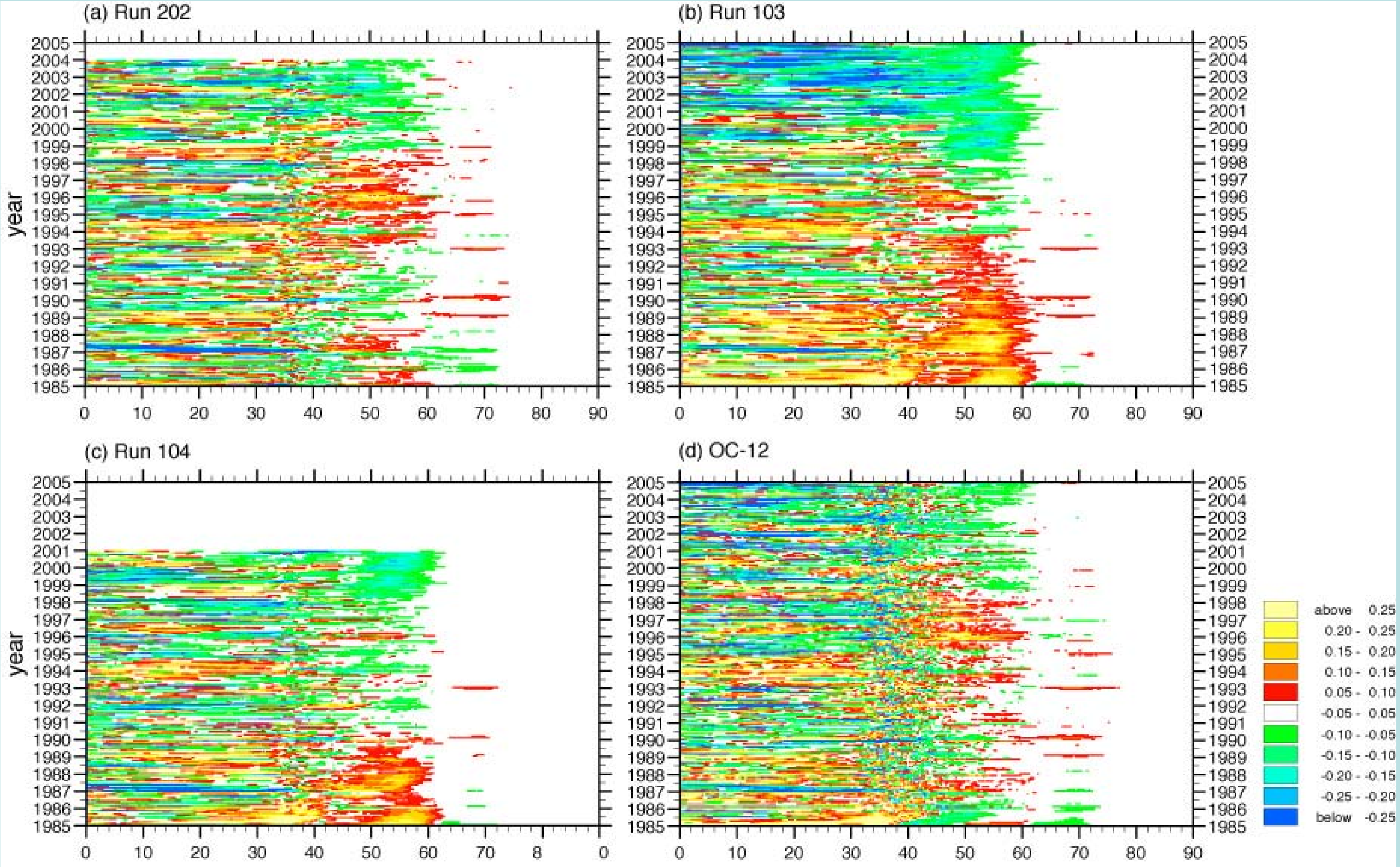


Annual-mean AMOC intensity



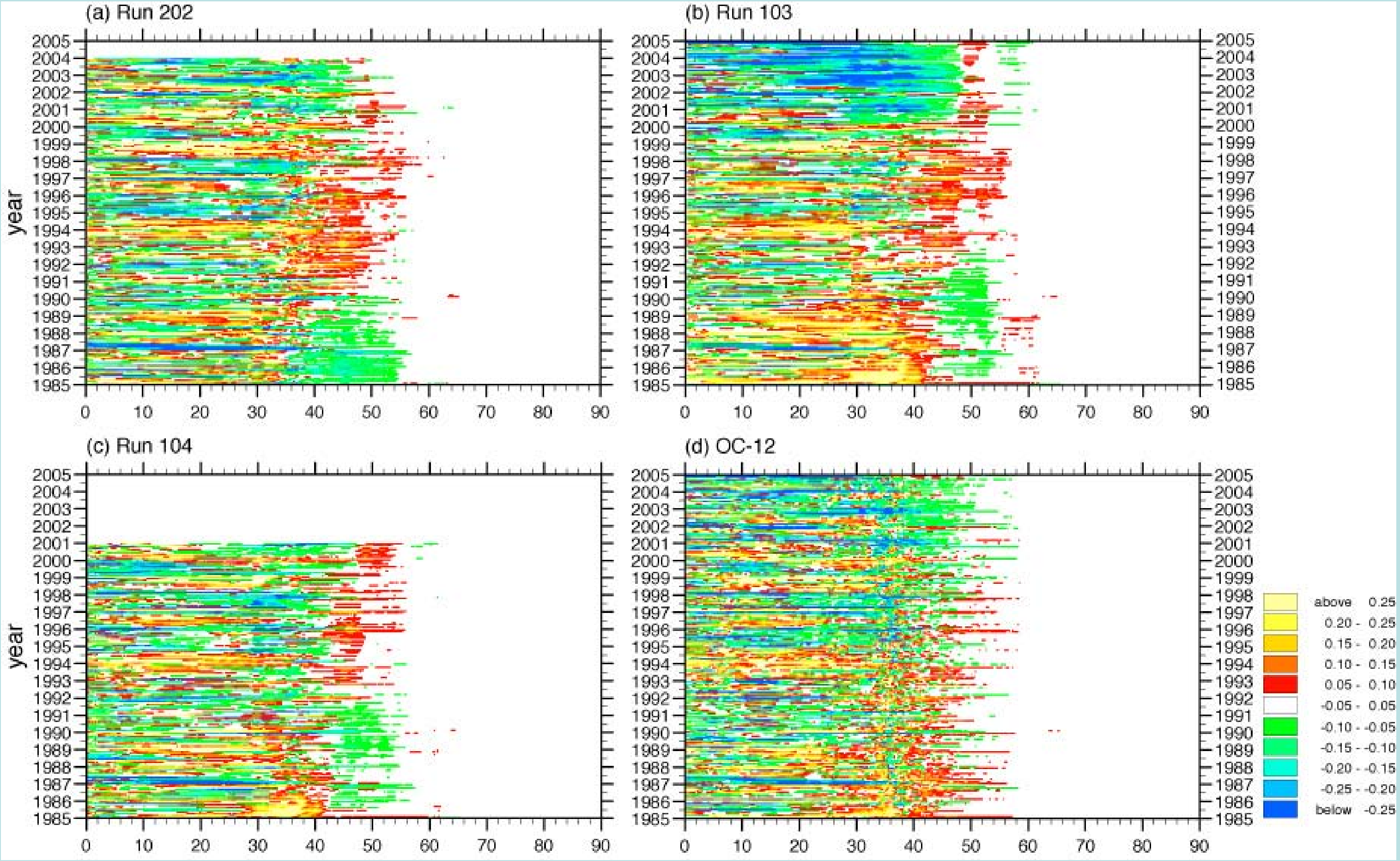
- ➢ OC-4 (runs 202, 104) simulated fairly steady AMOC (Marsh et al. 2005)
- ➢ OC-4 (run 103) in contrast simulate AMOC decline (as Bryden et al. 2005, for 1990s)
- ➢ OC-12 in further contrast simulates fairly steady AMOC
- ➢ Demonstrating the difficulty of simulating AMOC changes!
- ➢ Nevertheless, we can investigate variability of heat transport …

Monthly MHT anomalies



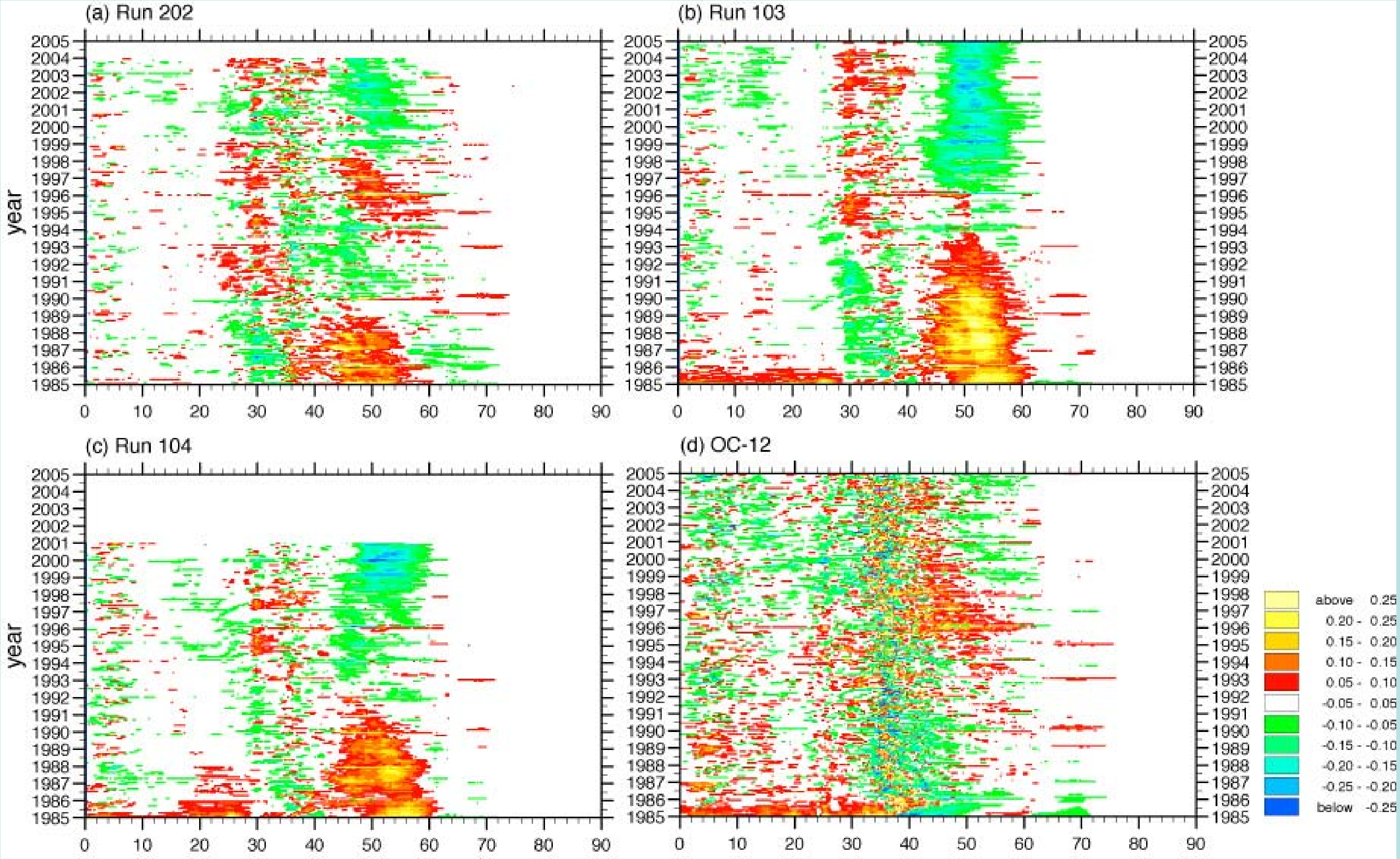
- South of ~40°N: pre-dominantly interannual; wind forced?
- North of ~40°N: pre-dominantly decadal; wind + buoyancy forced?

Monthly MHT anomalies - MOC part



- MOC dominates heat transport variations south of ~40°N
- Hence the RAPID monitoring array at 26°N
- MOC has little influence on the decadal variability further north …

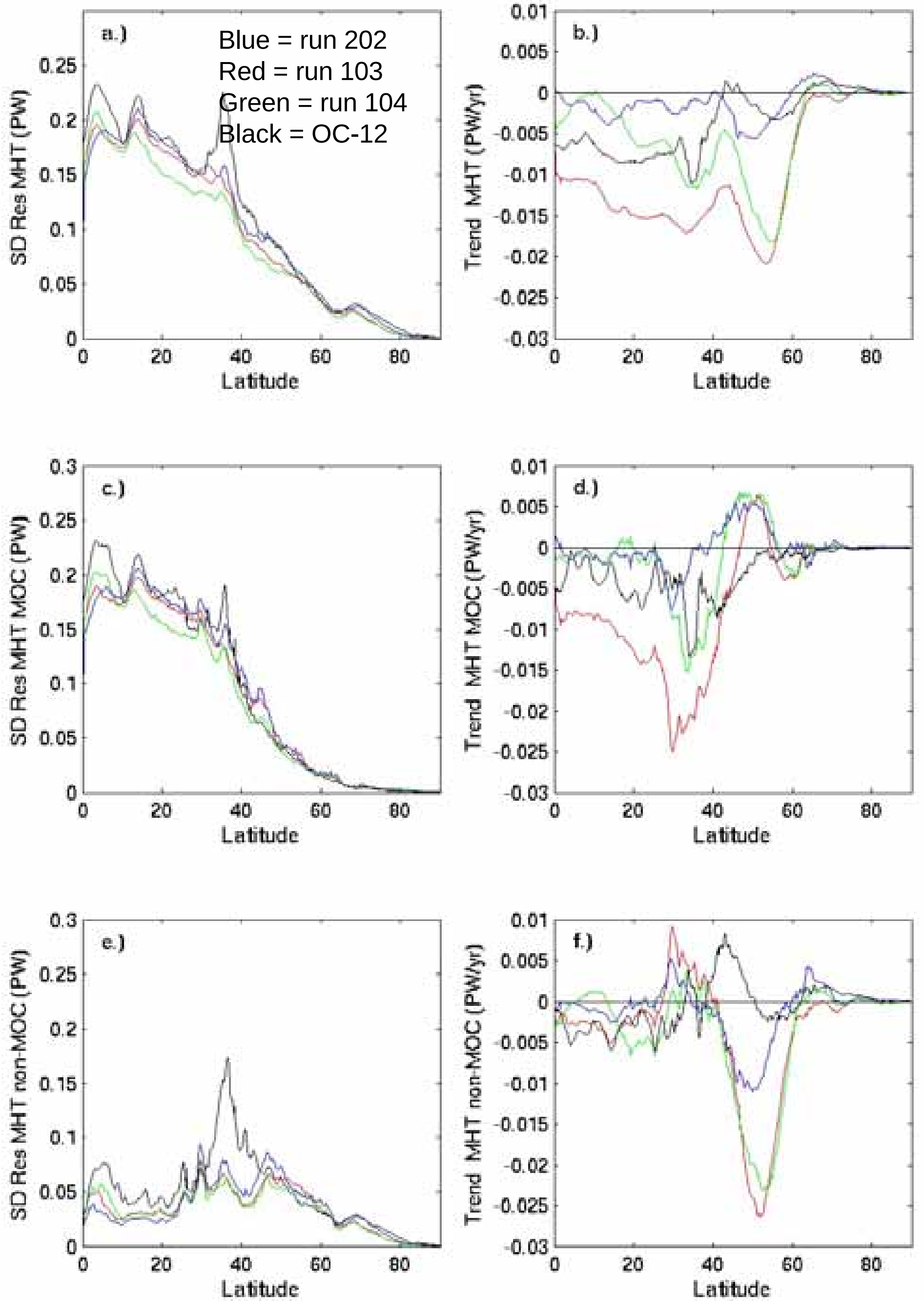
Monthly MHT anomalies - non-MOC part



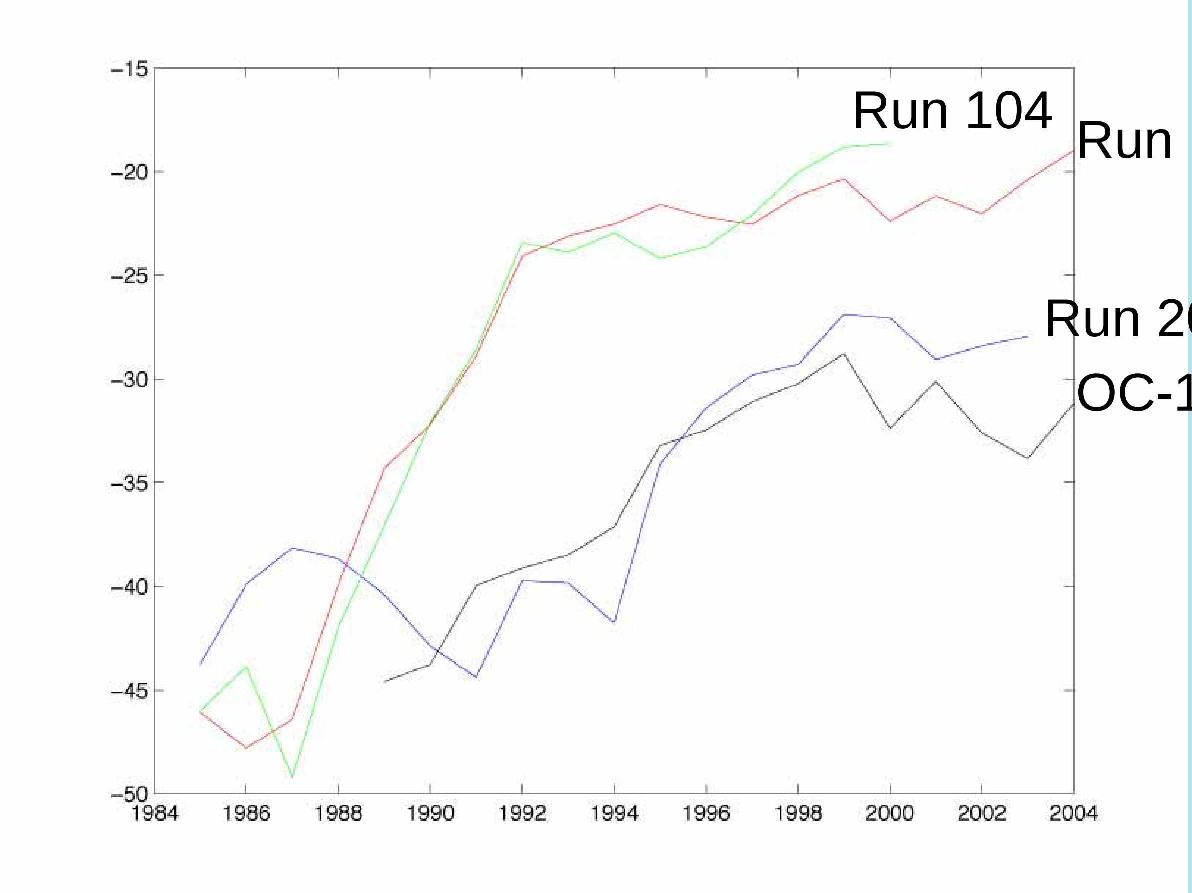
- … which are in fact associated with changes in the subpolar gyre and/or eddy fluxes

MHT: standard deviations & trends

- Confirmation that variability is primarily associated with MOC component in tropics & sub-tropics
- Variability associated with non-MOC component most prominent at inter-gyre boundary (eddies?)
- Most substantial trends associated with MOC component are in run 103
- Substantial trends associated with non-MOC component in run 104, OC-12, in subpolar latitudes …



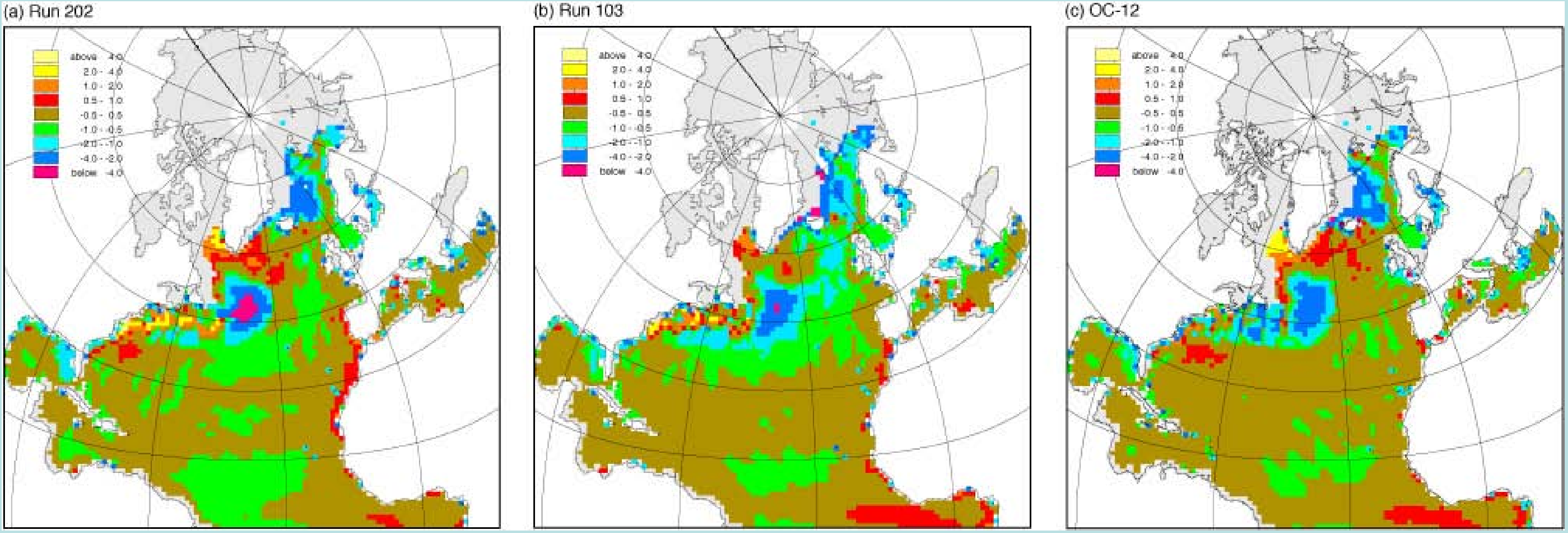
So what happens to the Subpolar Gyre? Annual mean strength (Sv)



- subpolar gyre spins down in all hindcasts, most dramatically in Runs 103, 104 (halving in strength), less so in Run 202, OC-12 (50% weakening)
- As observed in 1990s? (Häkkinen & Rhines 2004)

But we must bear in mind OCCAM SST errors:

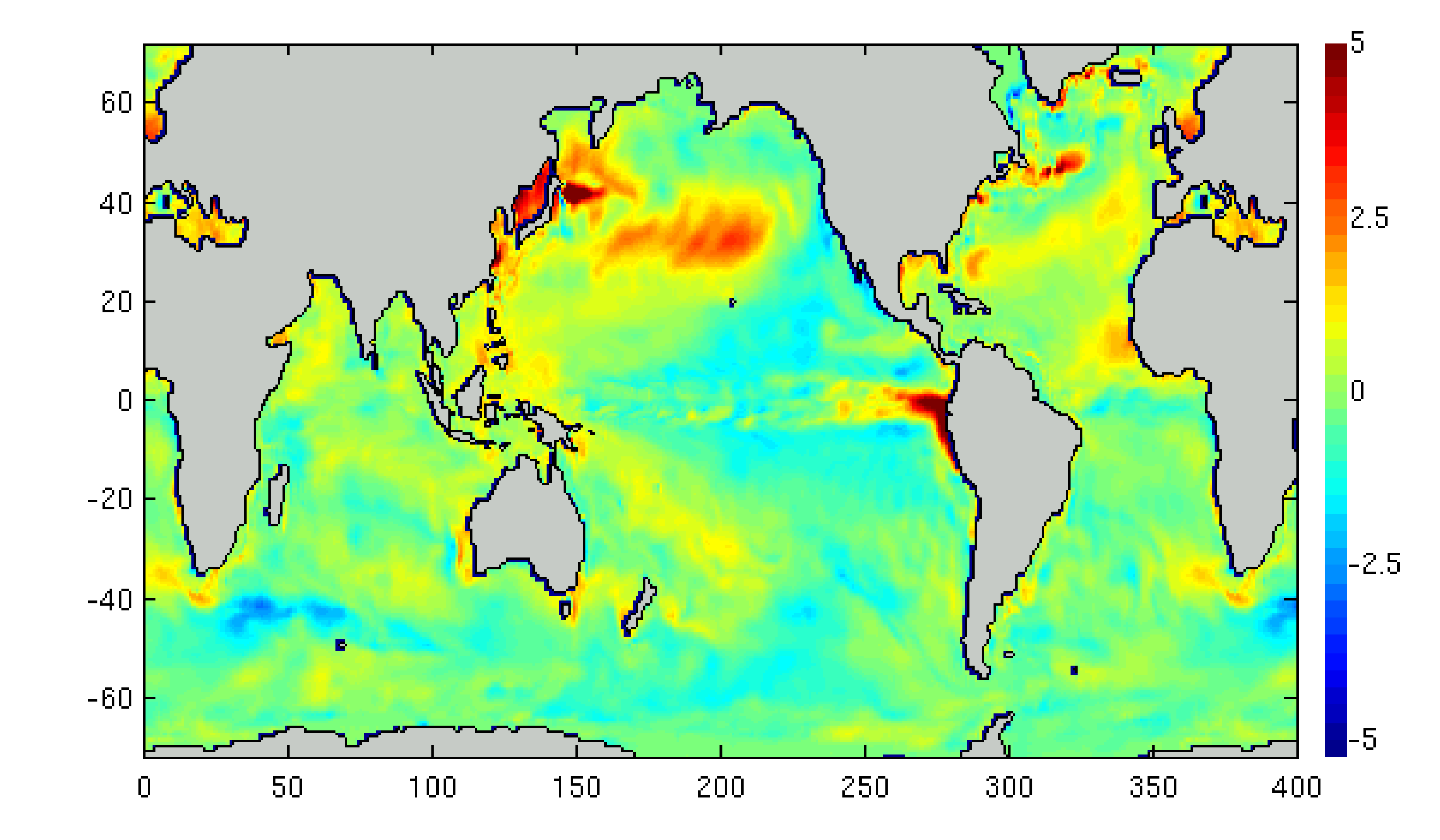
Got bigger → Then got smaller →



- Errors are Model SST minus NOC SST (ship-based measurements)
- Seemingly smallest in the highest resolution experiment
- So perhaps we have most faith in this simulation?
- But can we do better, e.g., state estimation, new models? …

Latest ECCO State Estimation

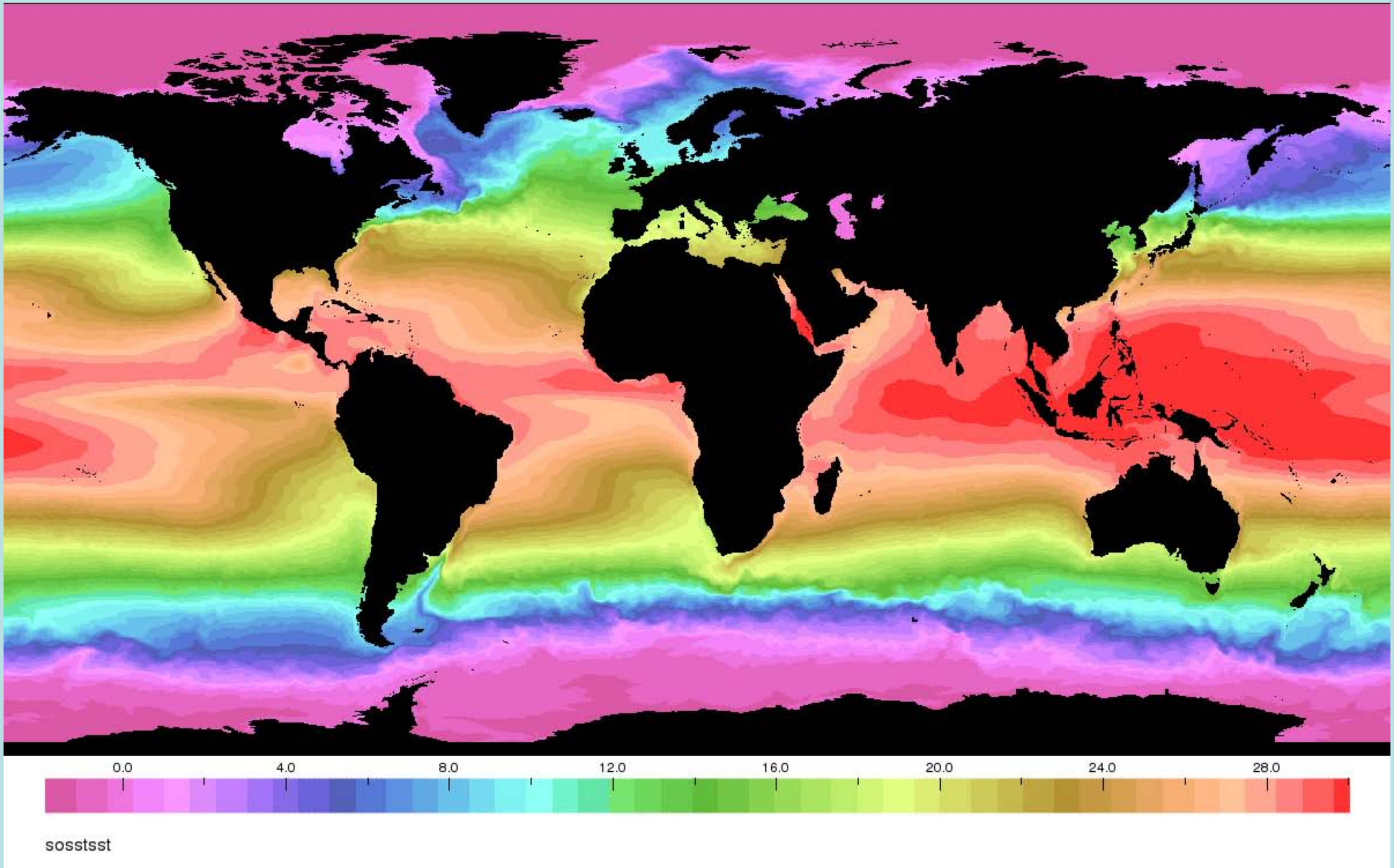
ECCO Near Real-Time Ocean Estimate for April 29, 2008:
Temp. anomaly (°C) relative to average seasonal cycle at surface



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

And OCCAM being superceded by NEMO...

Hindcast now completed for 1958-2001 at 0.25°, e.g., annual-mean SST, 2001:



See http://www.noc.soton.ac.uk/nemo/NEMORUNS/nemorun.php

Summary

- The surface North Atlantic has warmed dramatically since the mid-1980s (+ somewhat more since the 1960s) - seen in observations, well captured in OC-4 hindcast
- Surface warming extends to intermediate depths - almost all of the gain in full-depth ocean heat content (OHC) accounted for in upper 1500 m
- Pattern of SST & OHC anomalies reveals strongest warming in mid-latitudes (some warming in tropics)
- Mid-latitude warming largely controlled by anomalous convergence of ocean heat transport (OHT) in the region: +ve OHT anomaly in northern subtropics, -ve OHT anomaly further north in subpolar gyre
- Further developments of OC-4 demonstrate sensitivity of results to “model details” & surface forcing

Summary (ctd)

- Initial heat budgets with eddy-permitting model hindcast
- Subsequent analysis of eddy-resolving model hindcast - preliminary analysis suggests improved realism (SST)
- Substantial differences (between eddy-permitting & eddy-resolving) in representation of decadal changes in the “non-MOC” component of OHT
- Mechanisms: NAO, AMO, anthropogenic influence ???
- Potential for forecasting? (Smith et al., 2007; Keenlyside et al., 2008)
- Hindcasting: forcing with “best” surface boundary conditions vs. adjoints & assimilation
- Progress continues with NEMO …

Papers

Marsh, R., de Cuevas, B. A., Coward, A. C., Bryden, H. L., and M. Alvarez (2005). Thermohaline circulation at three key sections in the North Atlantic over 1985-2002. *Geophys. Res. Lett.*, **32**, L10604, doi:10.1029/2004GL022281.

Marsh. R., de Cuevas, B. A., Coward, A. C., Nurser, A. J. G., and S. A. Josey (2005). Water mass transformation in the North Atlantic over 1985-2002 simulated in an eddy-permitting model. *Ocean Science*, **1**, 127-144.

Marsh, R., Josey, S. A., de Cuevas, B. A., Redbourn, L. J., and G. D. Quartly (2008). Mechanisms for recent warming of the North Atlantic: Insights gained with an eddy-permitting model. *J. Geophys. Res*., **113**, C04031, doi:10.1029/2007JC004096.

Marsh, R., de Cuevas, B. A., Coward, A. C., Jacquin, J., Hirschi, J. J.-M., and S. A. Josey. Recent changes in the North Atlantic circulation simulated with eddy-permitting and eddy-resolving ocean models, in prep.