Ocean Circulation and Climate:
Observing and Modelling the Global Ocean

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- Brief overview of the ocean circulation, range of scales, complexity
- Observing the global ocean
- Modelling the global ocean

Two problems:

(i) Understanding the role of Southern Ocean eddies in glacial cycles

(ii) Will the Gulf Stream shut down?

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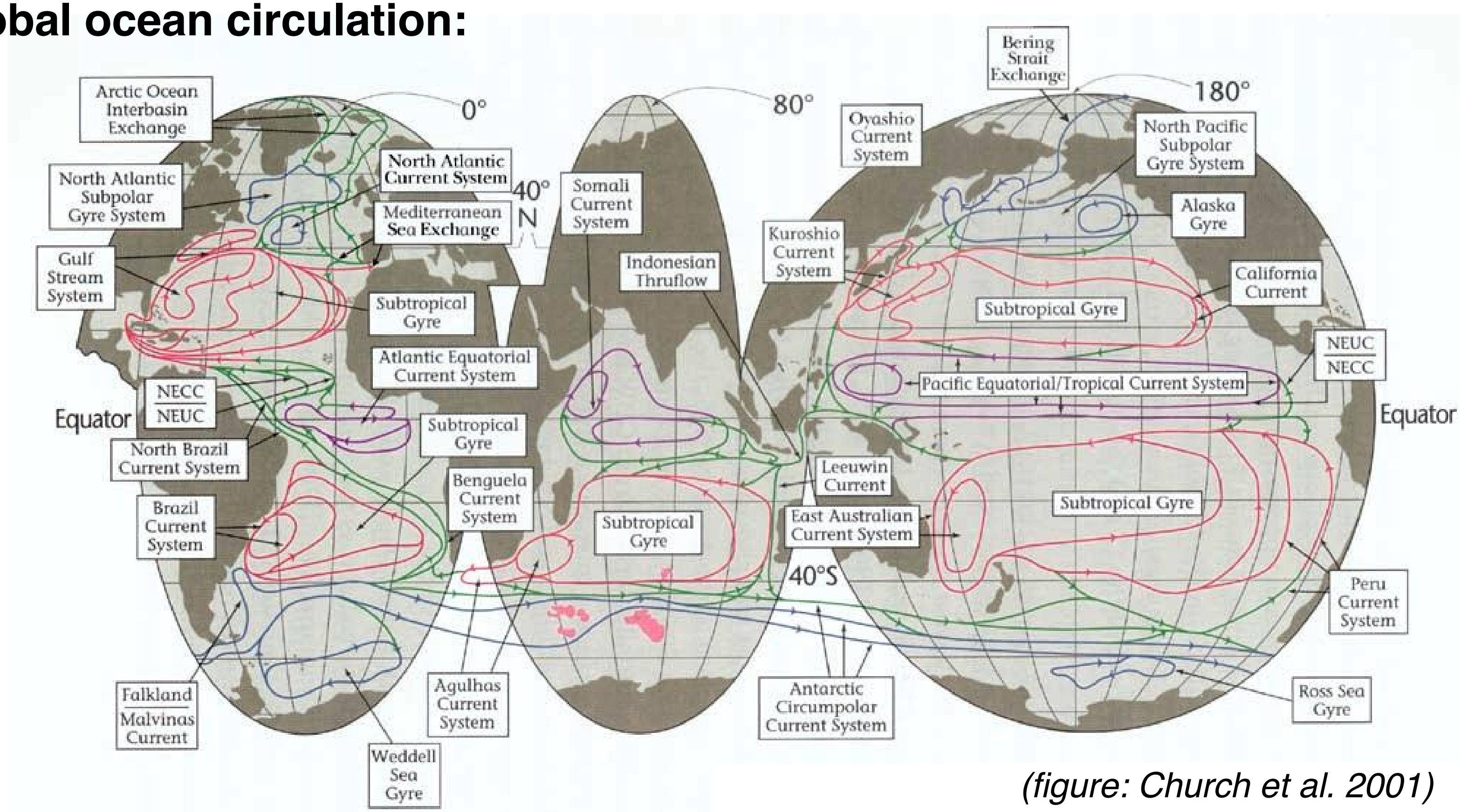
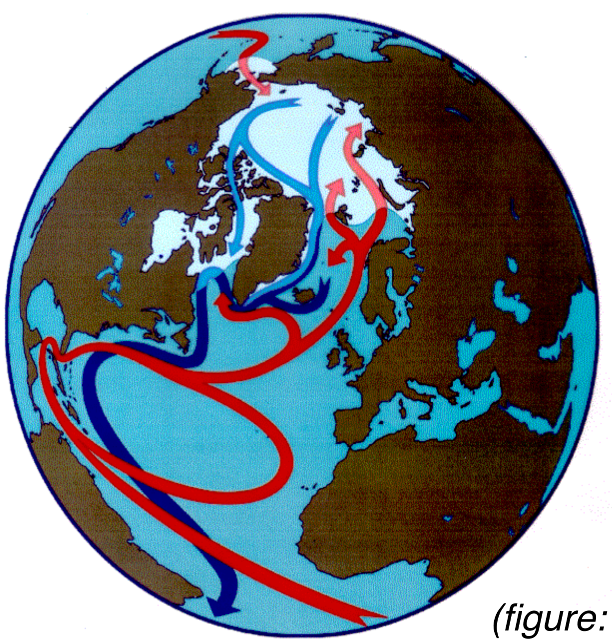
Cartoons of the global ocean circulation:

surface currents



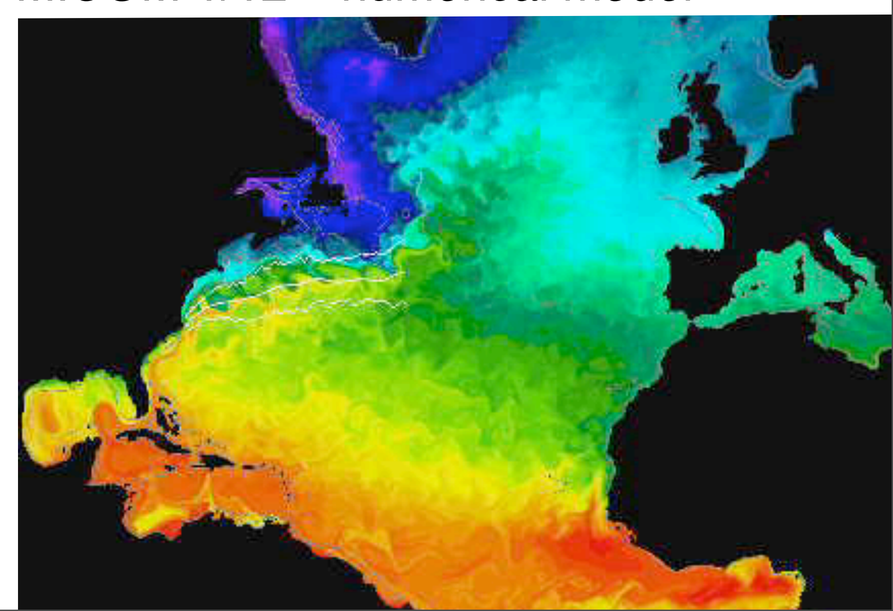
(figure: Church et al. 2001)



Atlantic meridional overturning circulation (AMOC)

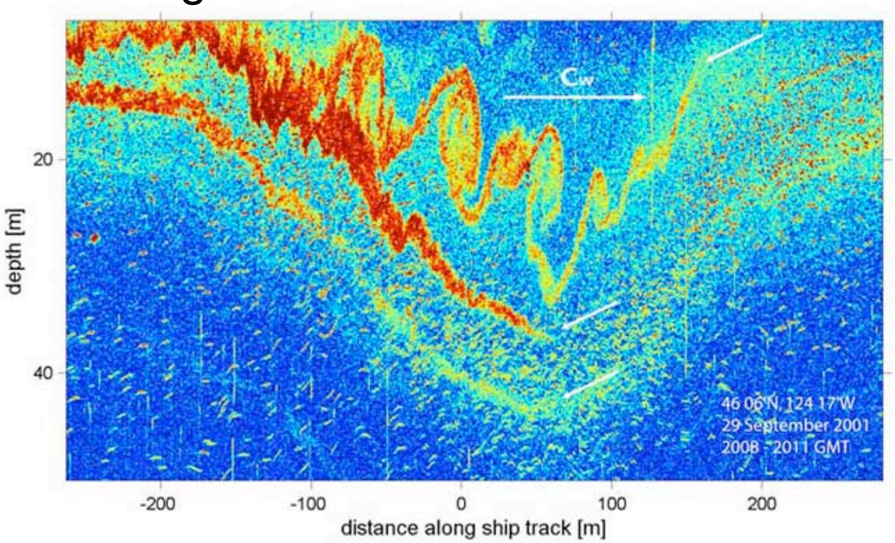
(figure: Holloway)

MICOM 1/12^{0} numerical model



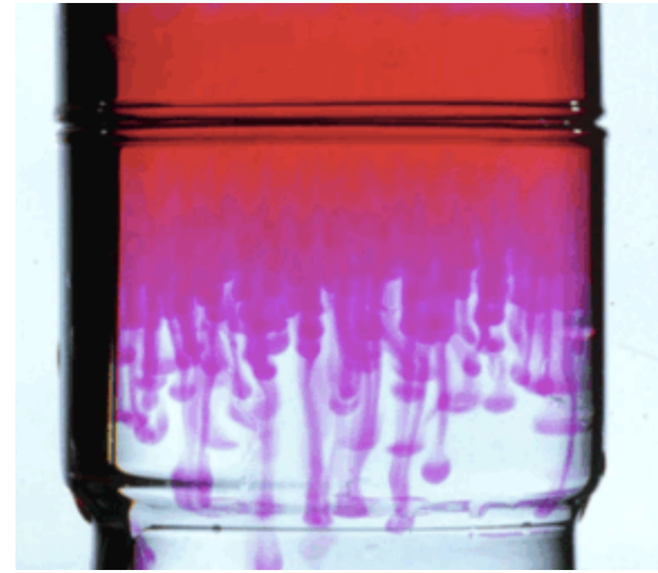
Plus a myriad of smaller-scale processes:

breaking internal waves:



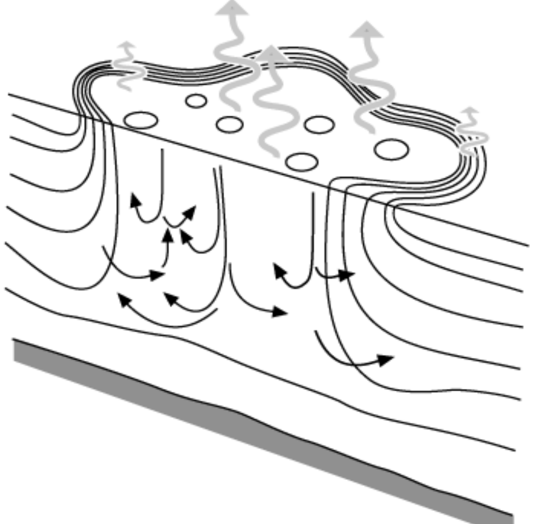
(figure: Oregon State)

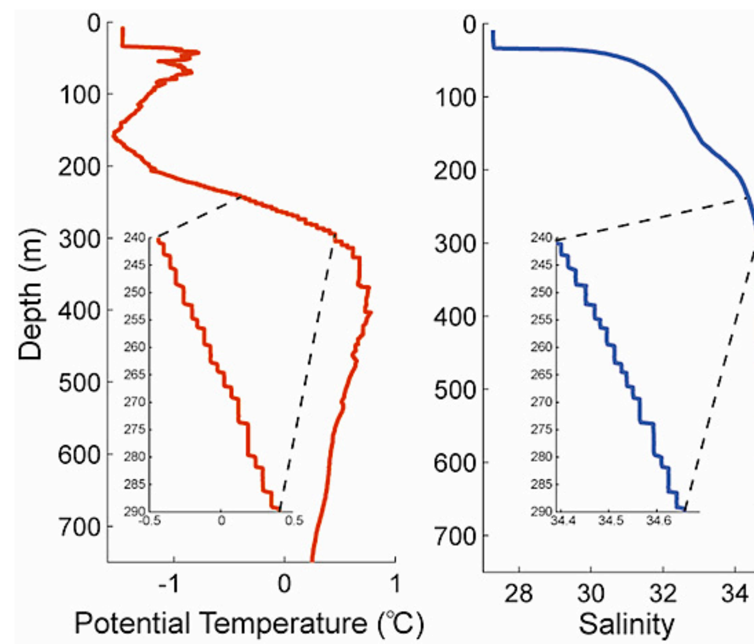
double diffusion:



(figure: Federov)

convective plumes:





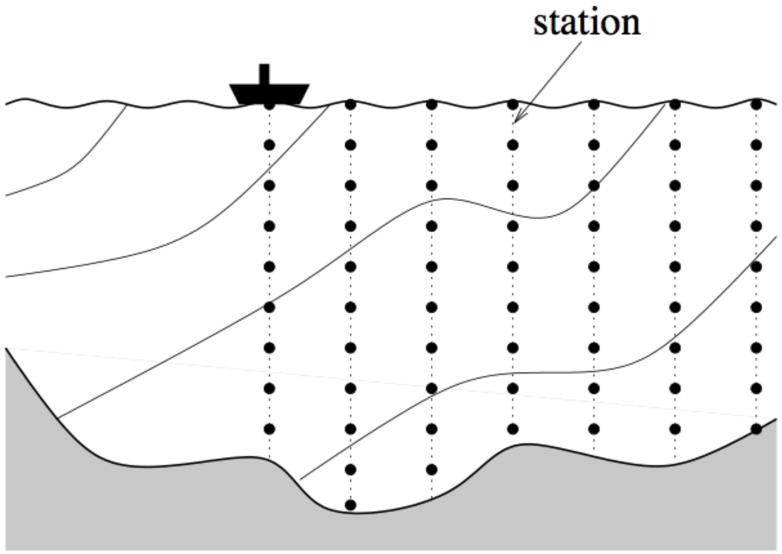
(figure: Timmermans)

The oceans are a **complex** system in the scientific sense (according to most definitions):

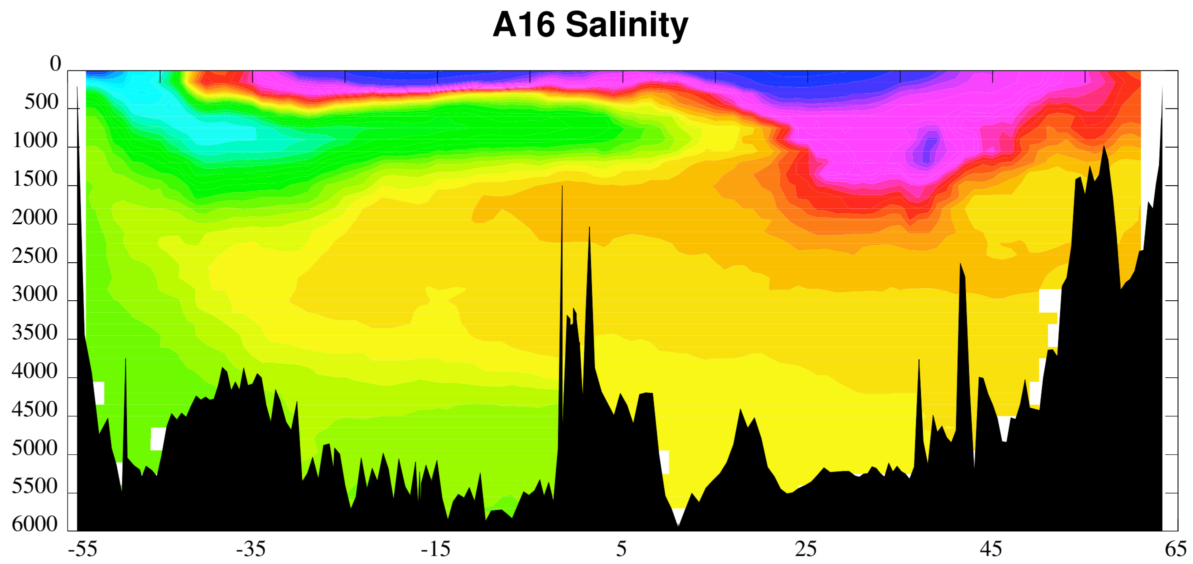
- interactions between many processes at many different scales
- emergent properties
- non-equilibrium
- self-organise into states that show quasi-stability
- feedback to external manipulation

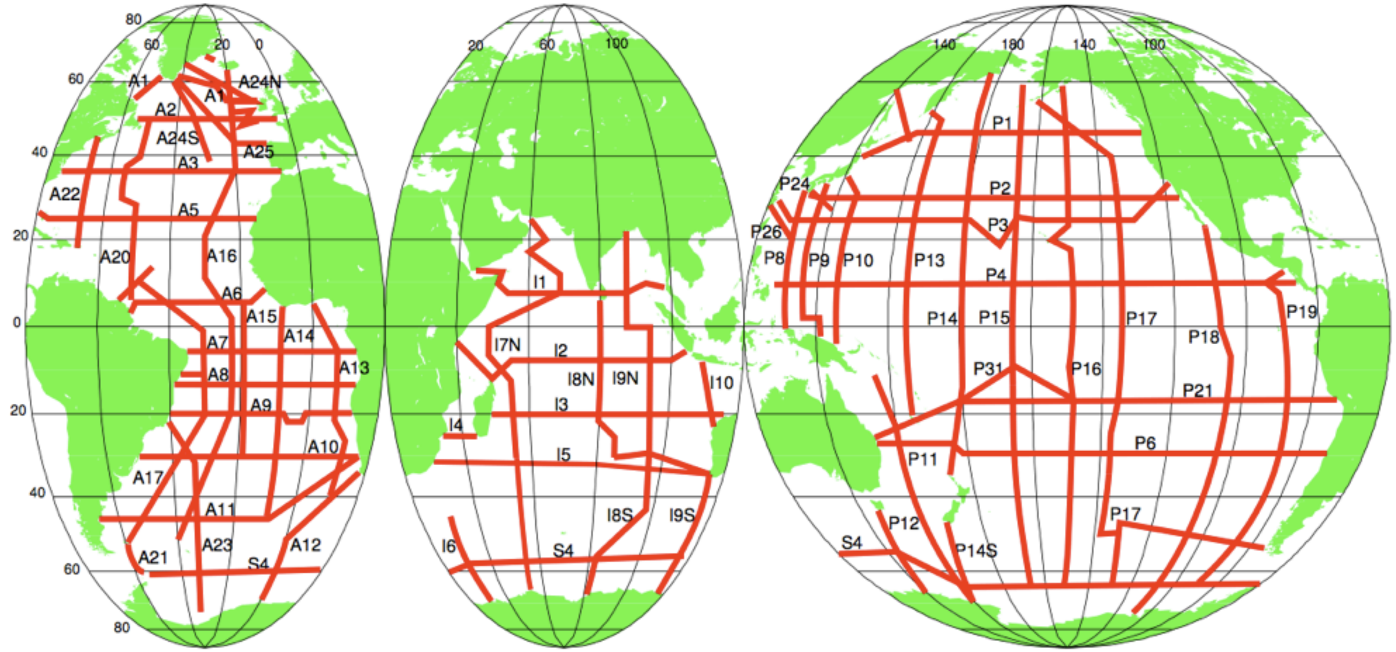
... and also a complex system in the misused sense, i.e., *complicated!*

Observing the global ocean: historically, treated oceans as steady



hydrographic section



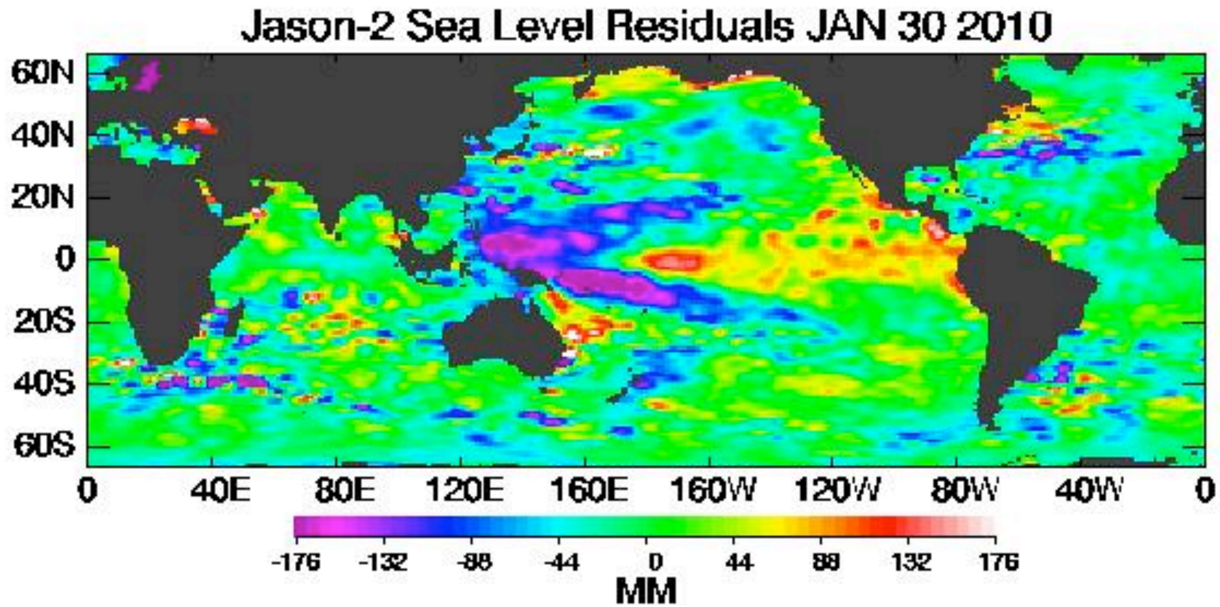


WOCE Hydrographic Programme One-Time Survey
(Penny Holliday, WOCE IPO)

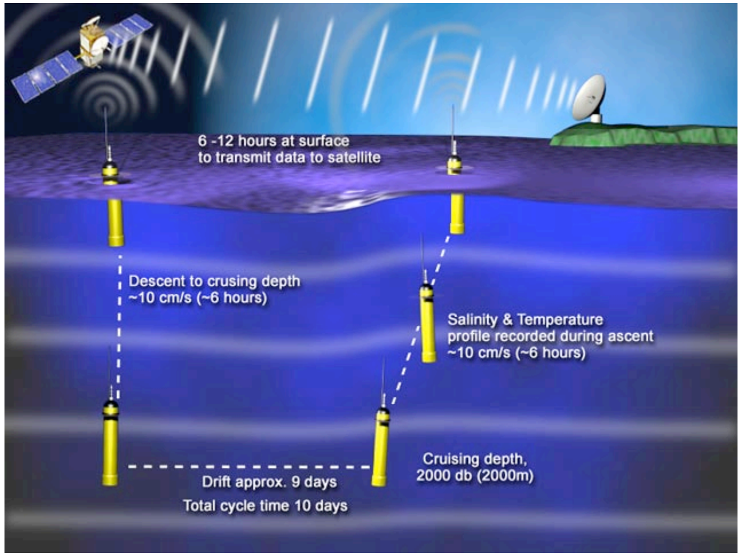
Some key elements of the present-day global observing system:

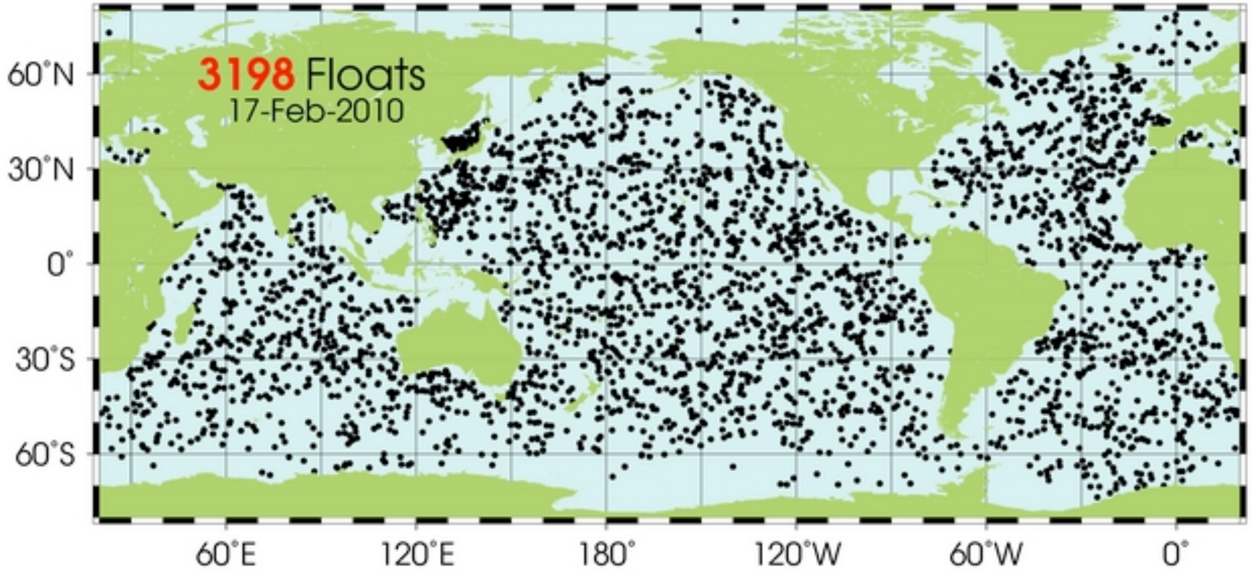
Altimeter - sea surface elevation:

topex-www.jpl.nasa.gov



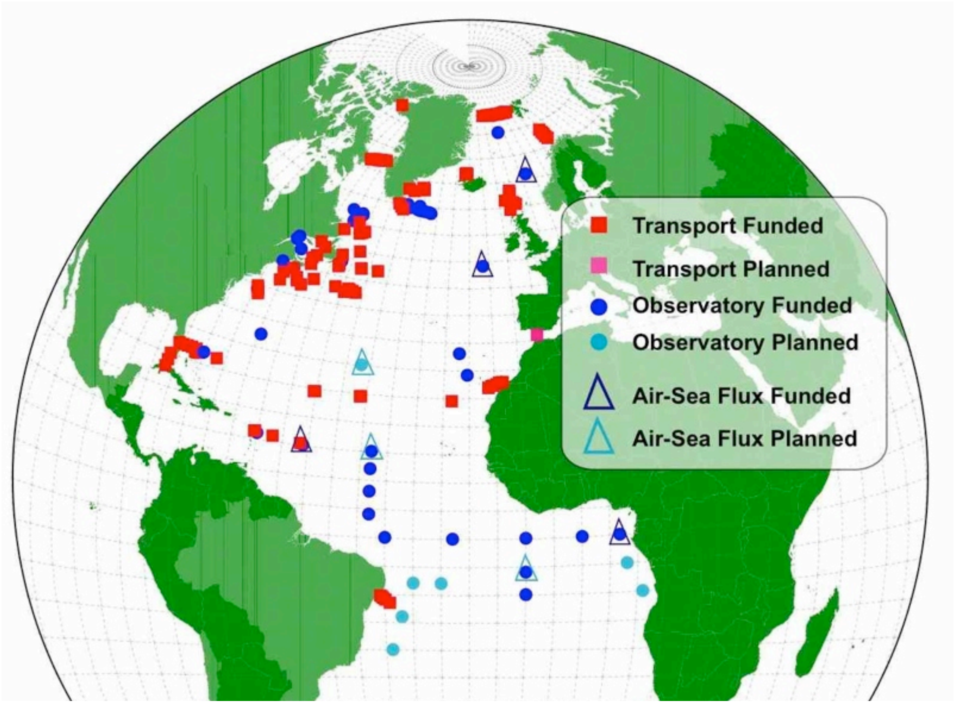
ARGO profiling floats:



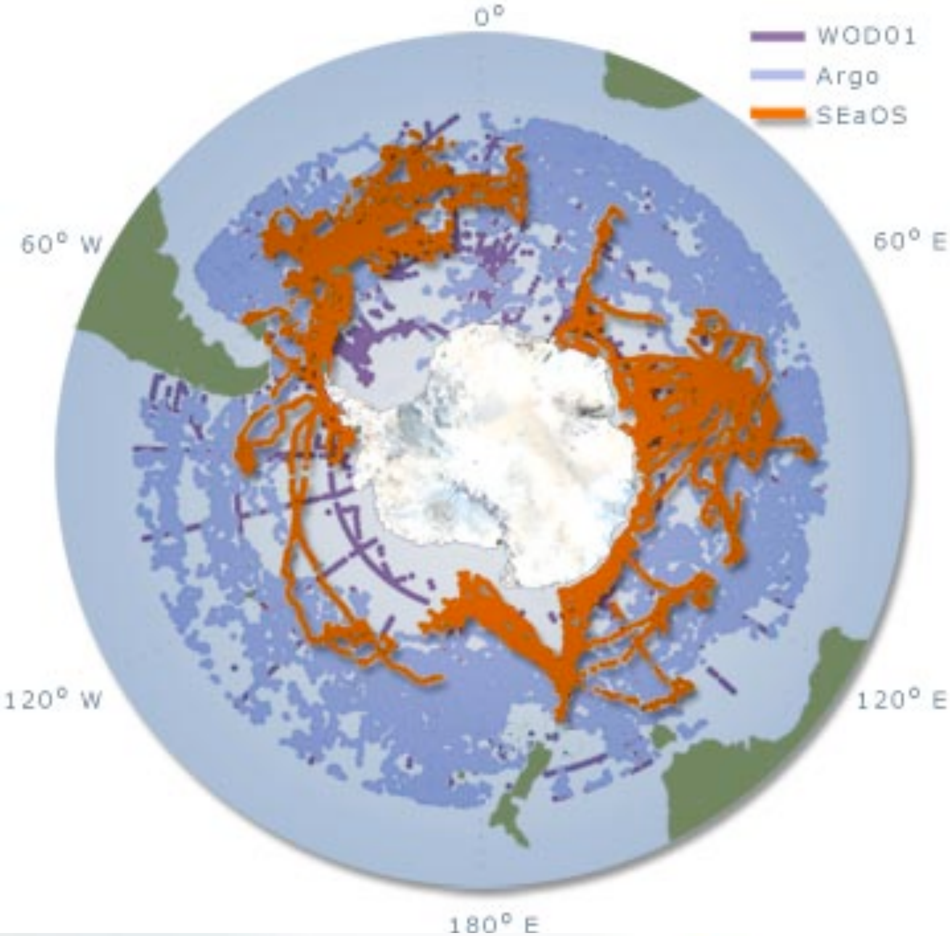


www.argo.ucsd.edu

Mooring time series:



(figure: Boscolo)



+ always room for new ideas:

biology.st-andrews.ac.uk/seos/

+ process experiments to develop improved parameterisations of small-scale processes

Modelling the global ocean

In principle, we know the equations of motion for the ocean ...

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla\mathbf{u} + 2\mathbf{\Omega}\times\mathbf{u} + \frac{1}{\rho}\nabla p + g_a\mathbf{k} = \nu\nabla^2\mathbf{u}$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\mathbf{u}) = 0$$

$$\rho = \rho(\theta, S, p)$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u}.\nabla\theta = \kappa\nabla^2\theta + \mathcal{H}$$

$$\frac{\partial S}{\partial t} + \mathbf{u}.\nabla S = \kappa_S\nabla^2 S + (\mathcal{E} - \mathcal{P})$$

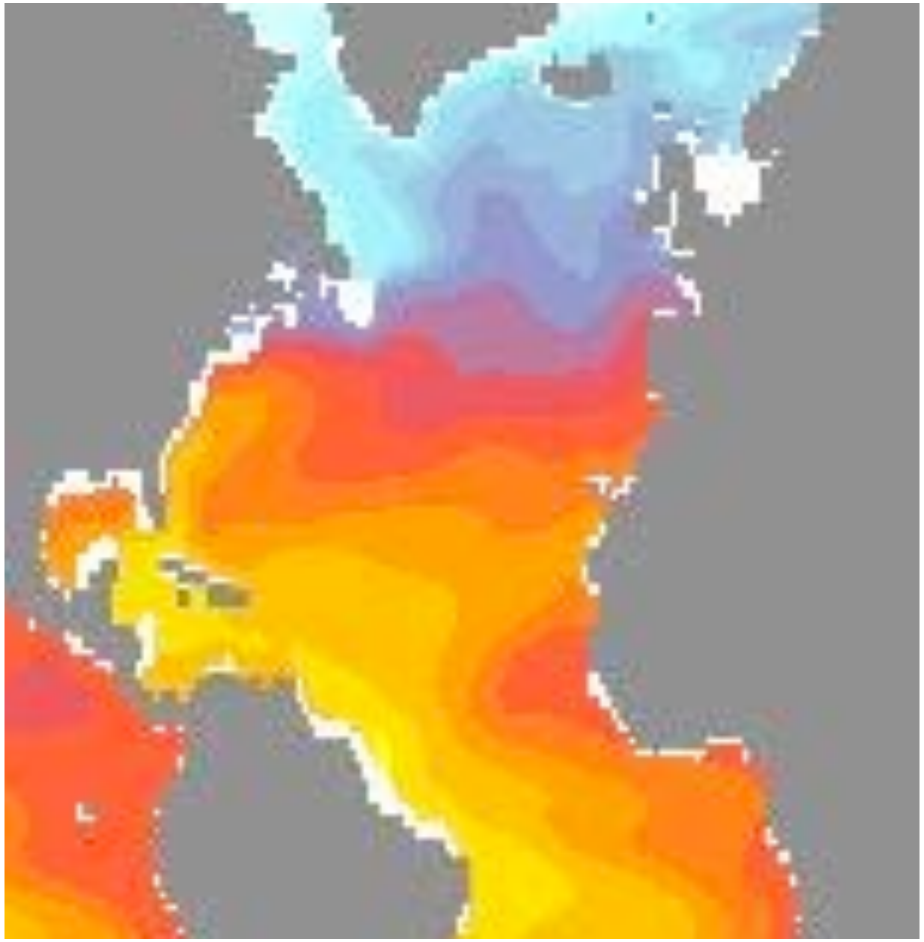
... however, these apply to each fluid parcel.

assuming each 1mm^3 of seawater evolves independently gives 6 x 10^{27} degrees of freedom

- impractical to solve for each fluid parcel, nor would we want to!

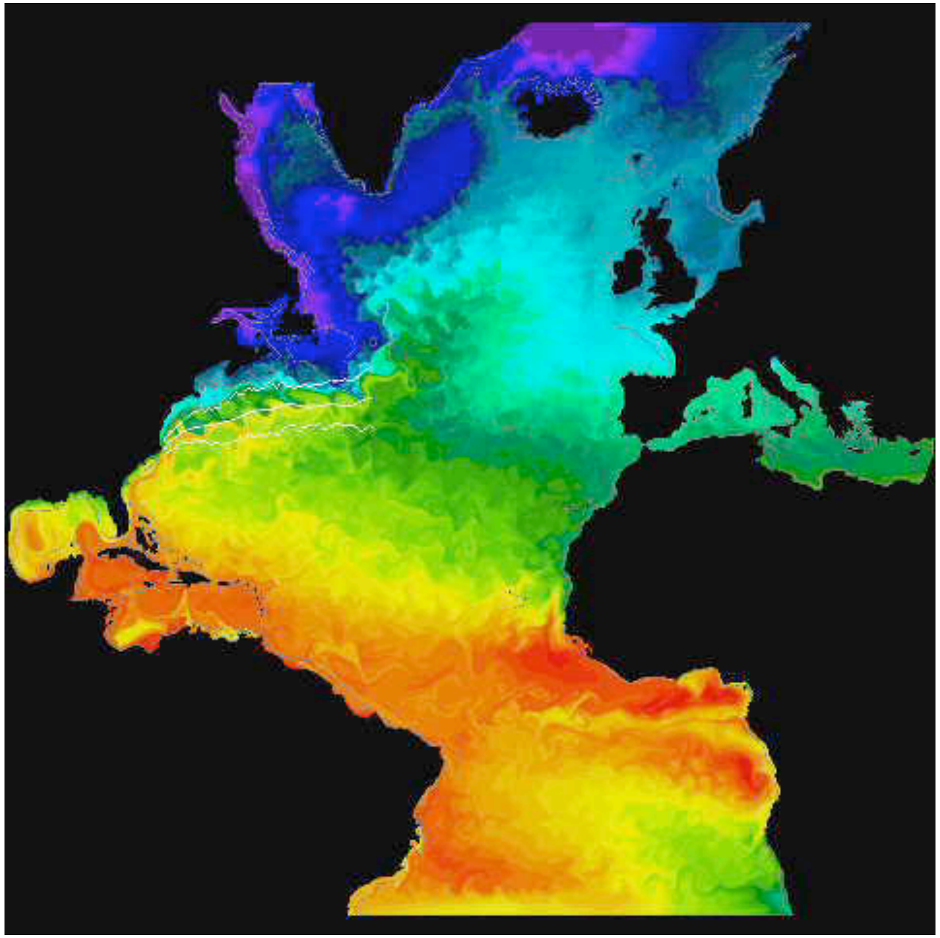
Instead, solve approximation to the equations of motion on a finite grid:

1^0 (climate) resolution



viscous

$1/12^0$ resolution

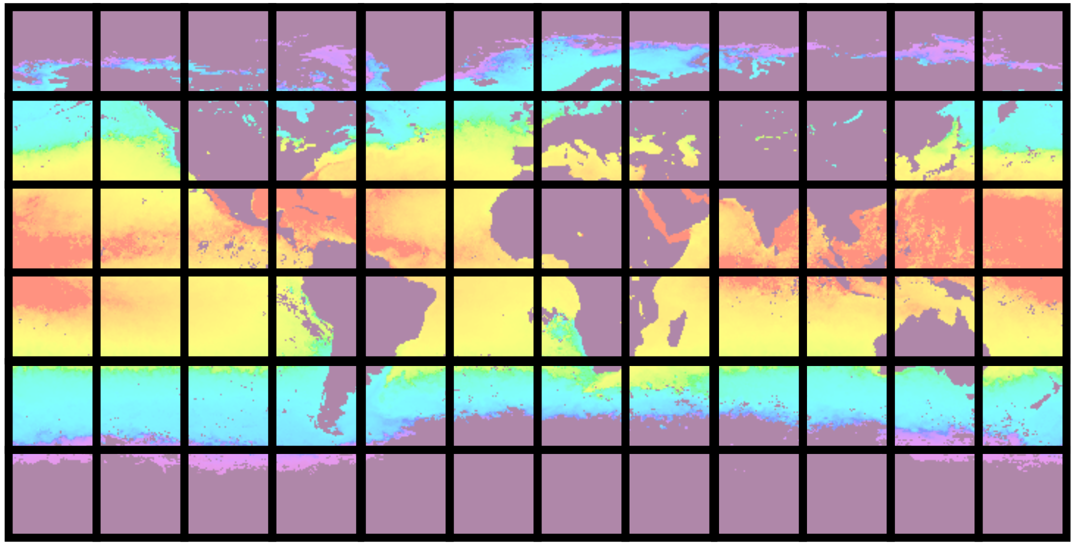


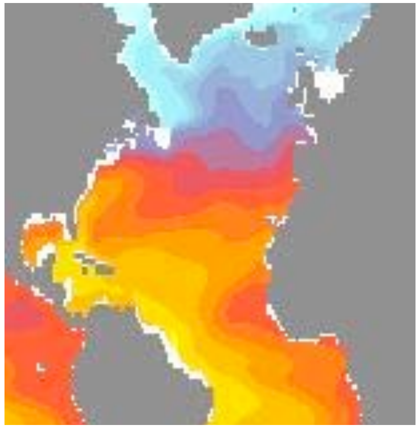
less viscous

- many processes are sub-grid scale and need to be parameterised (i.e., separately modelled)

- smallest scales can affect the largest scales and vice-versa

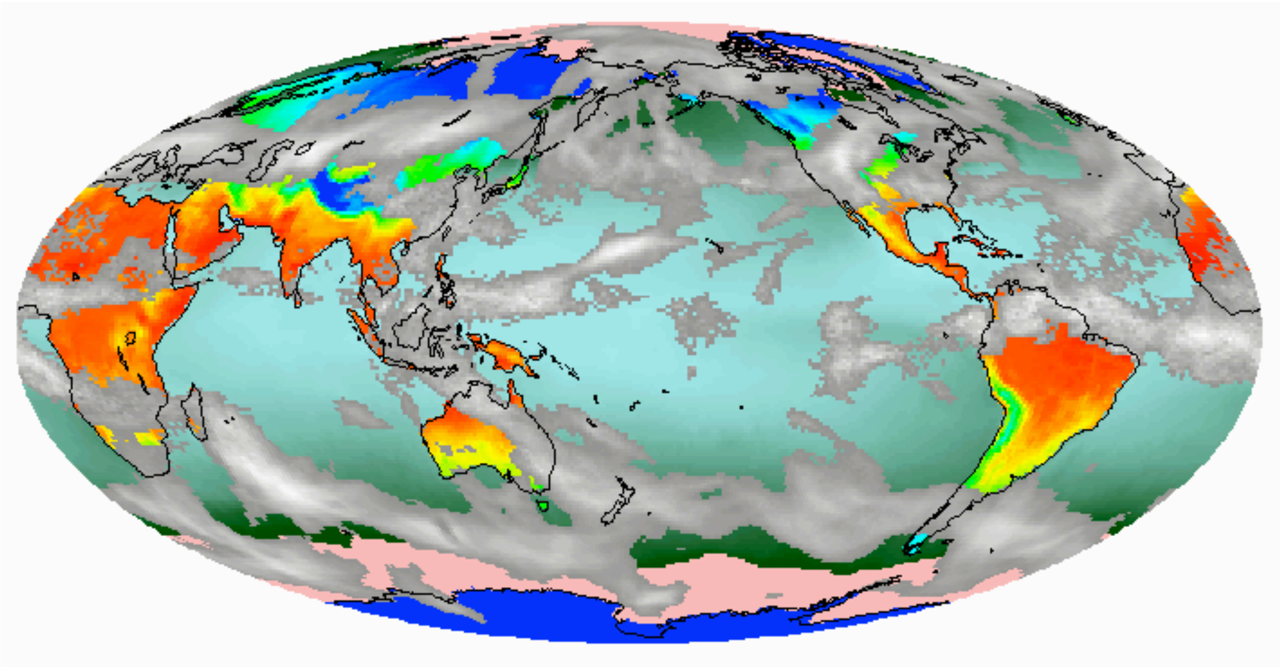
Equivalent resolution for atmospheric weather systems as a 1 degree model for ocean eddies?

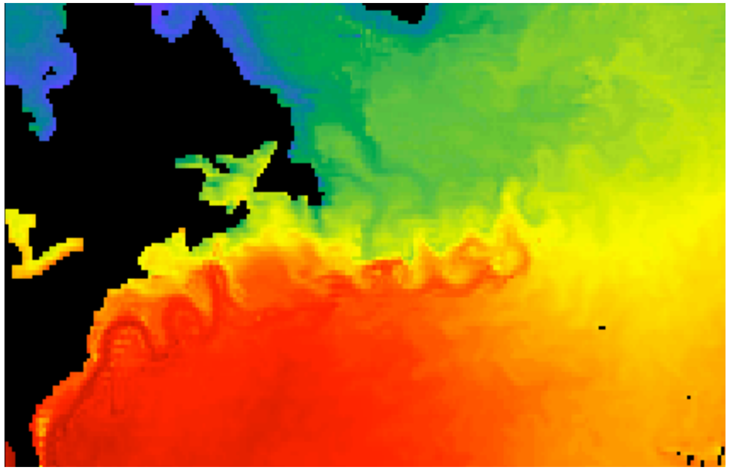




(after Killworth)

Part of the answer is increased resolution, e.g., HiGEM:





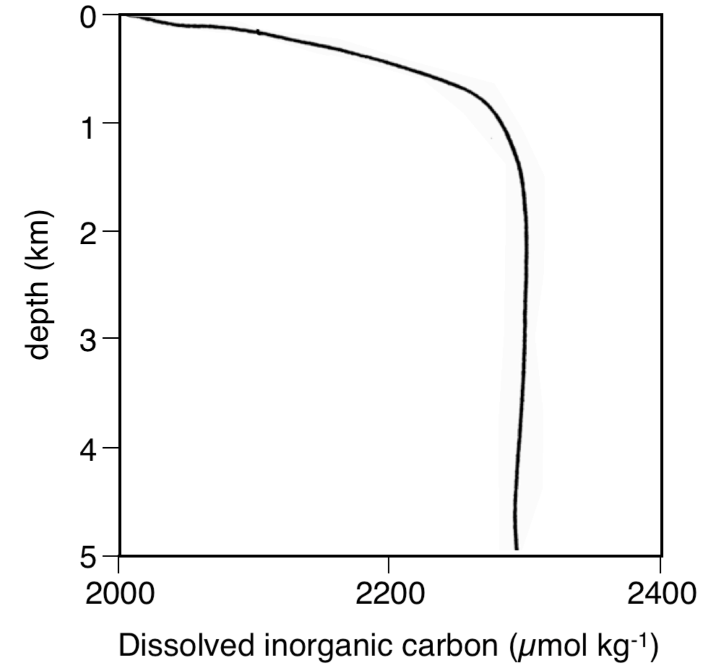
(www.higem.nerc.ac.uk)

but brute force is not sufficient ...

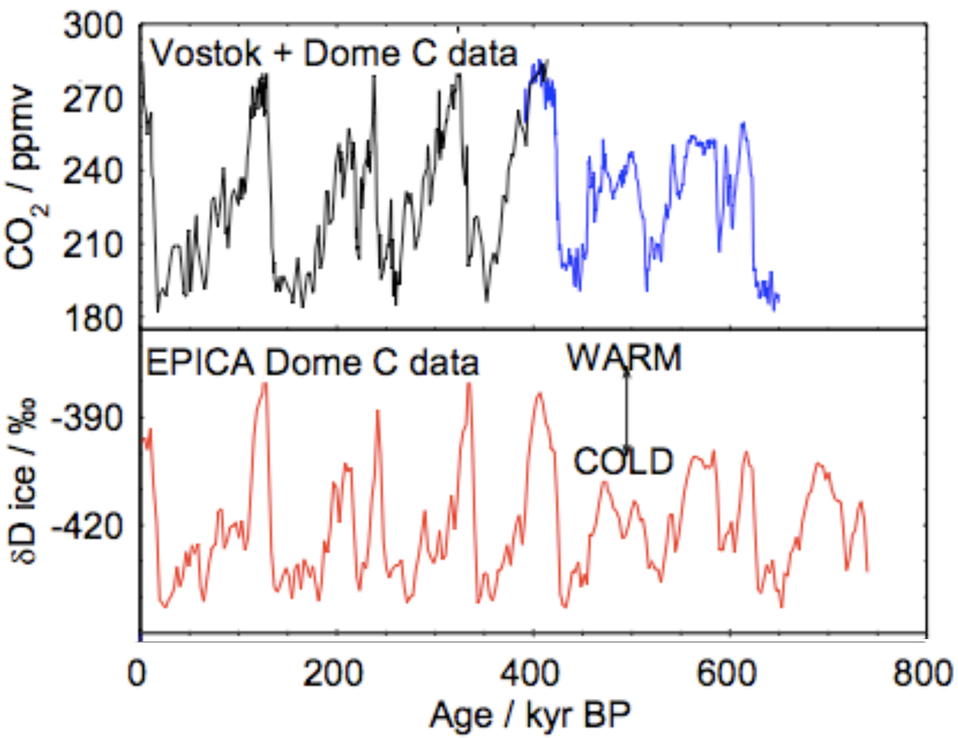
(NB: Bob Bishop - 18 Mar)

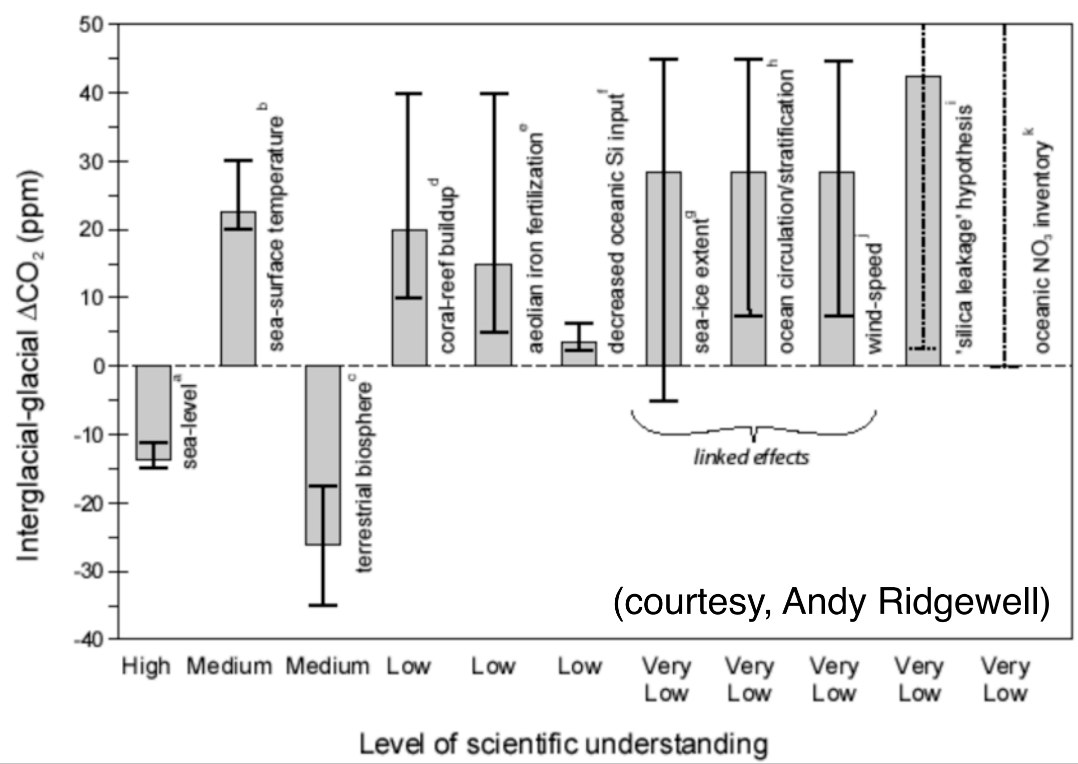
Problem (i) Understanding the role of Southern Ocean eddies in glacial cycles

(with David Munday, Lesley Allison, Helen Johnson)

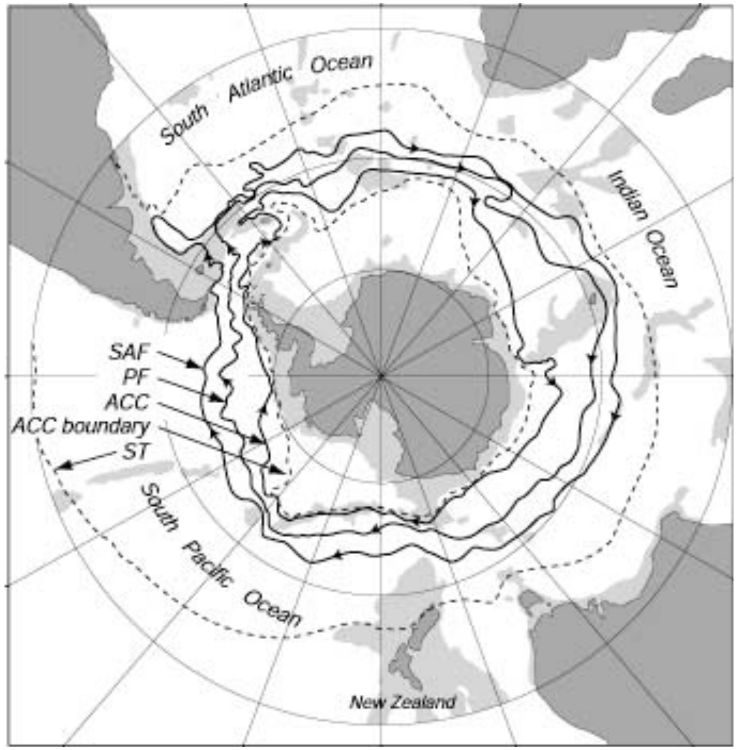


Q: Why is glacial CO_2 much lower than interglacial CO_2?

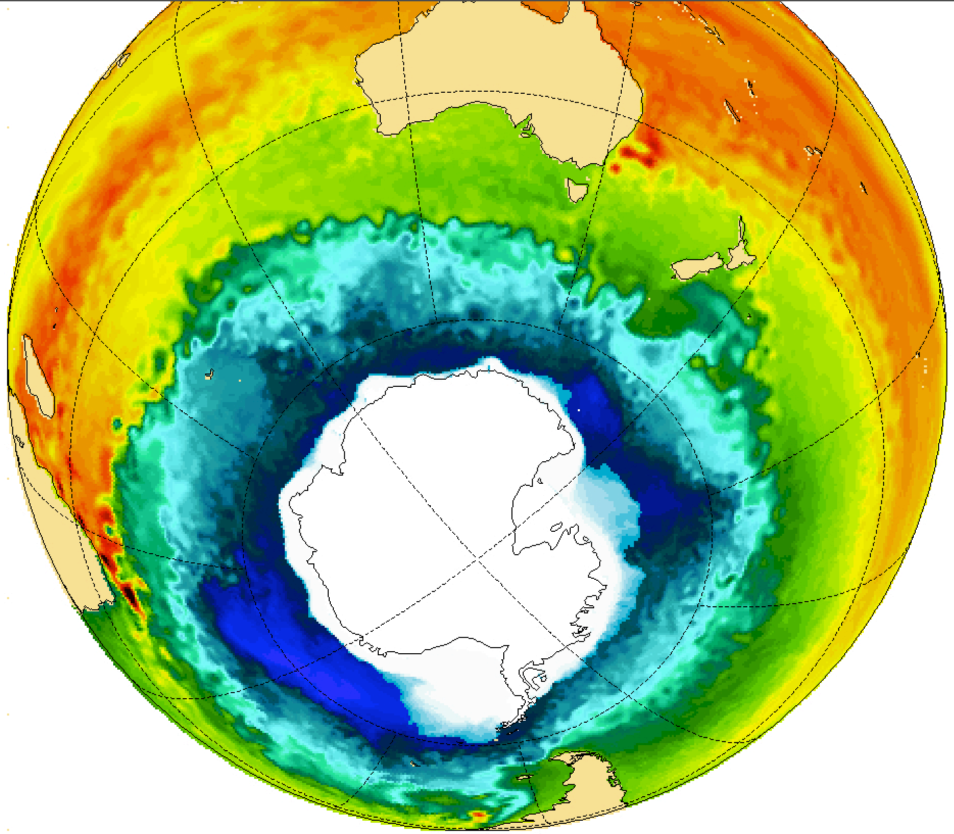




(courtesy, Andy Ridgewell)

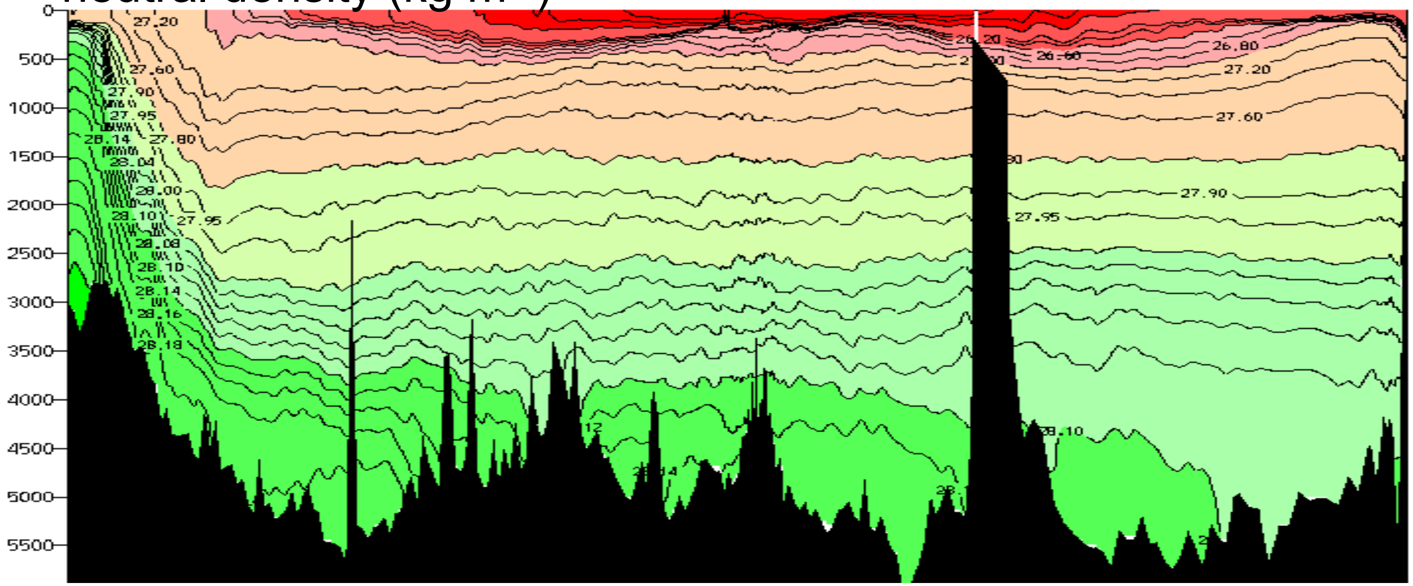


Antarctic Circumpolar Current (ACC)



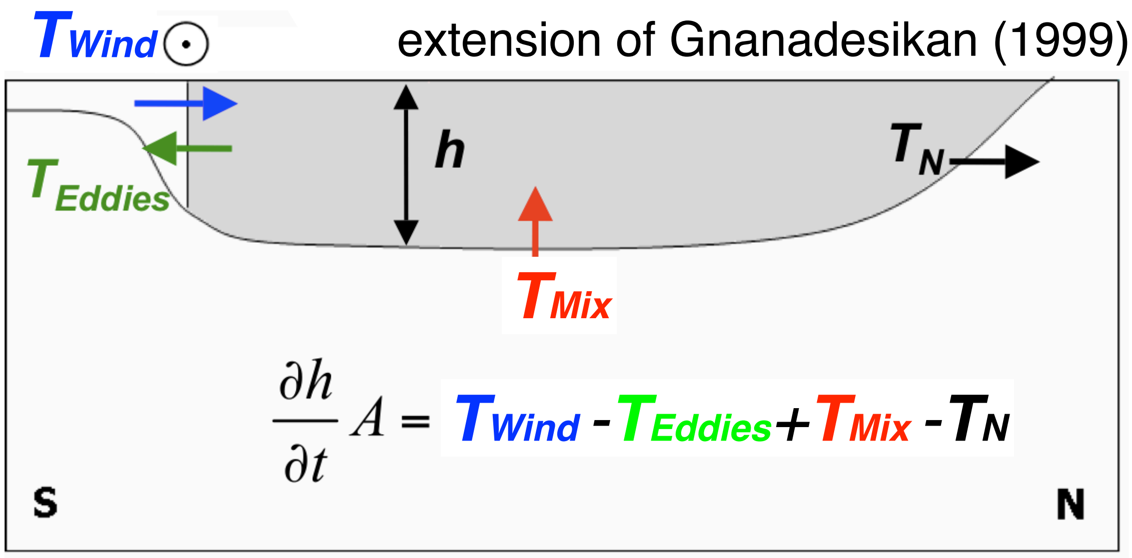
snapshot of sea surface height , DRAKKAR 1/4^o resolution

neutral density (kg m^{-3})



60S EQ 50N

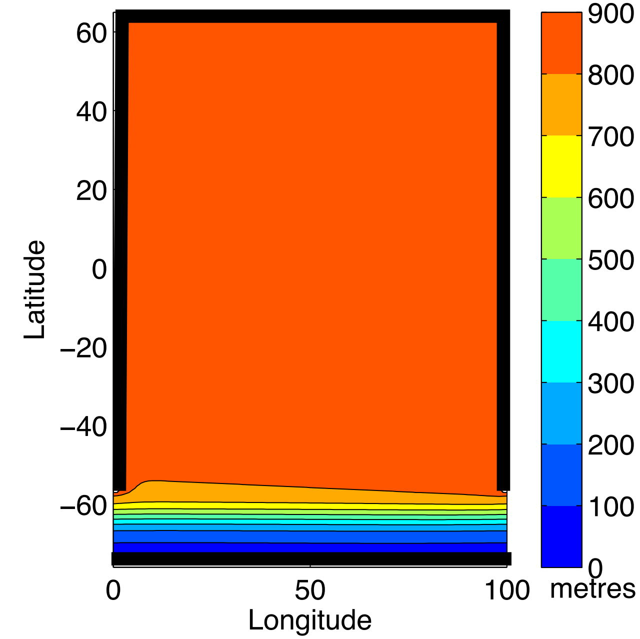
Simple model:

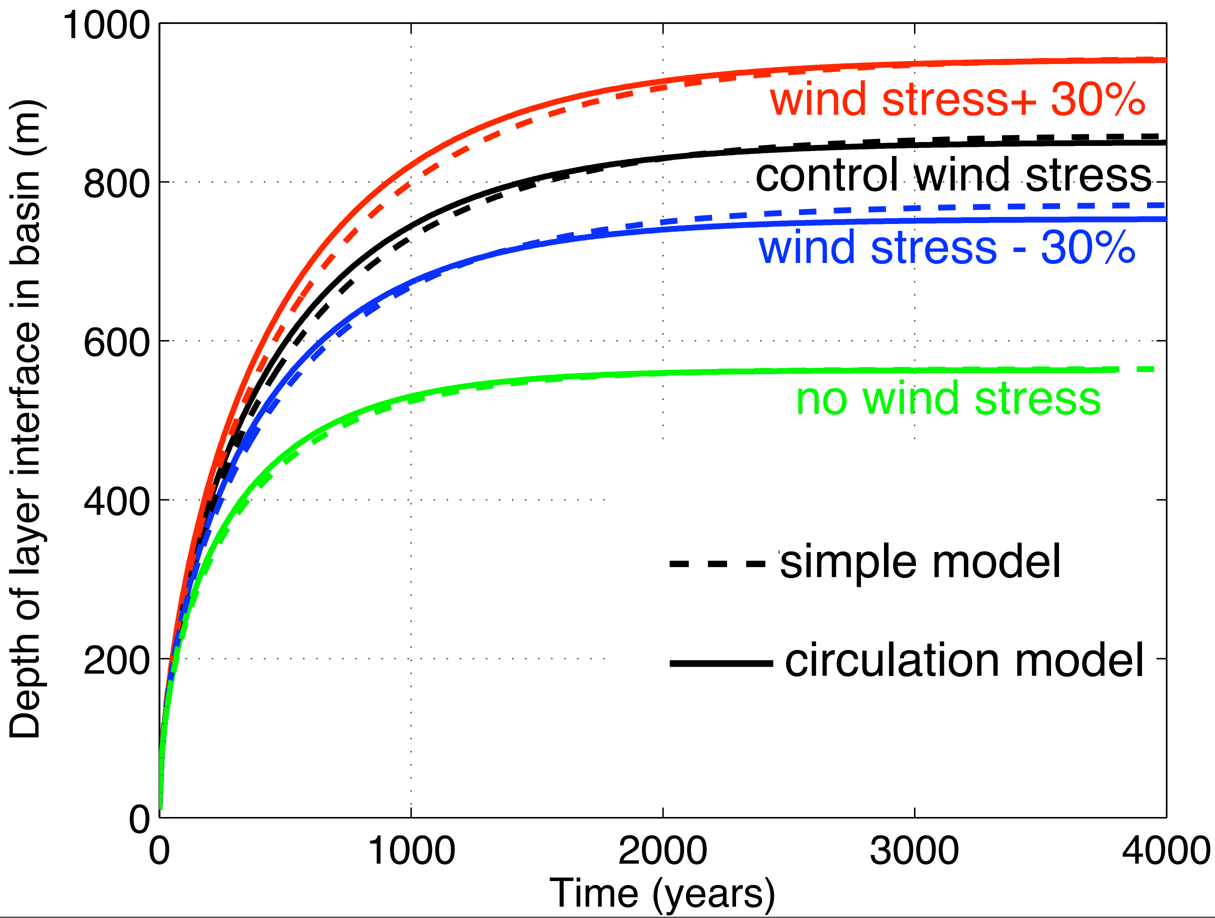


$$\frac{\partial h}{\partial t} A = T_{Wind} - T_{Eddies} + T_{Mix} - T_N$$

2-d circulation model:

(parameterised eddies)

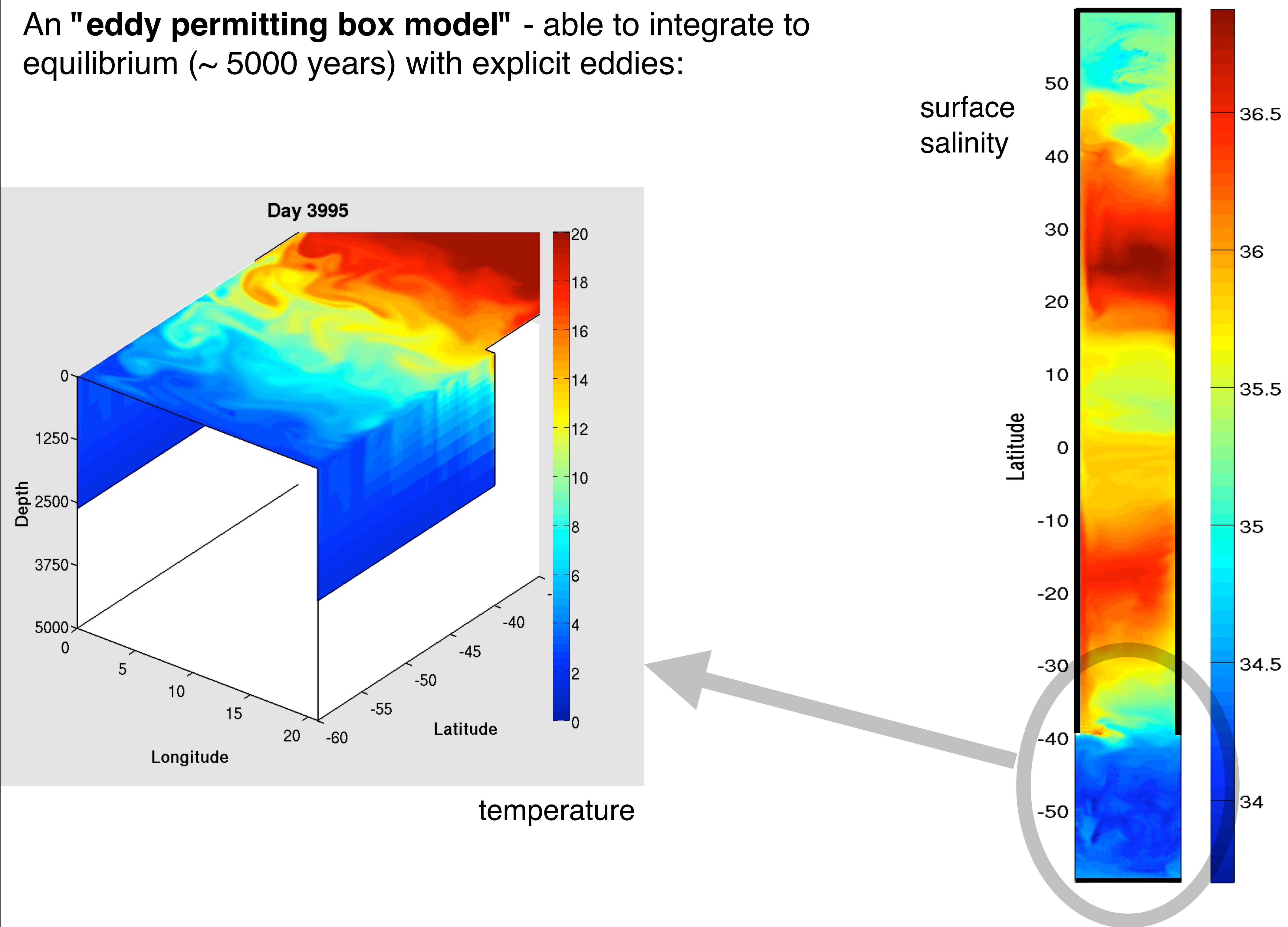




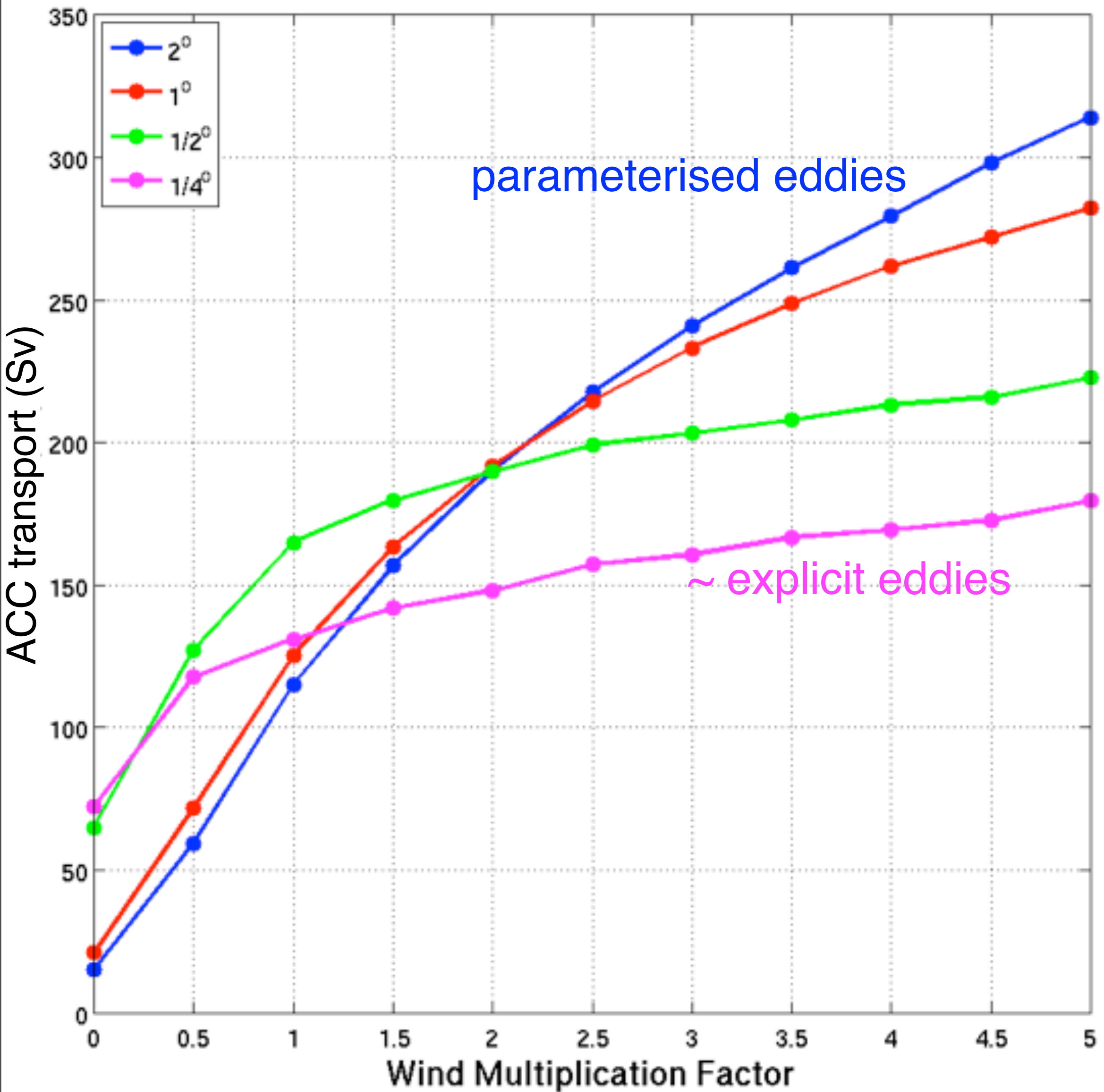
Everything depends on how we parameterise Southern Ocean eddies 😲

(Allison et al., 2010)

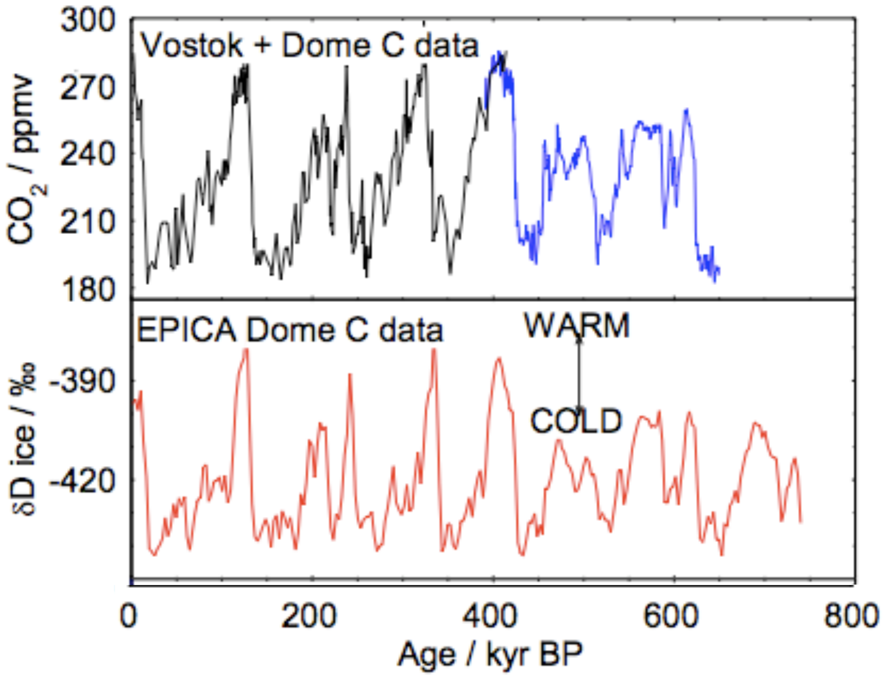
An **"eddy permitting box model"** - able to integrate to equilibrium (~ 5000 years) with explicit eddies:



temperature



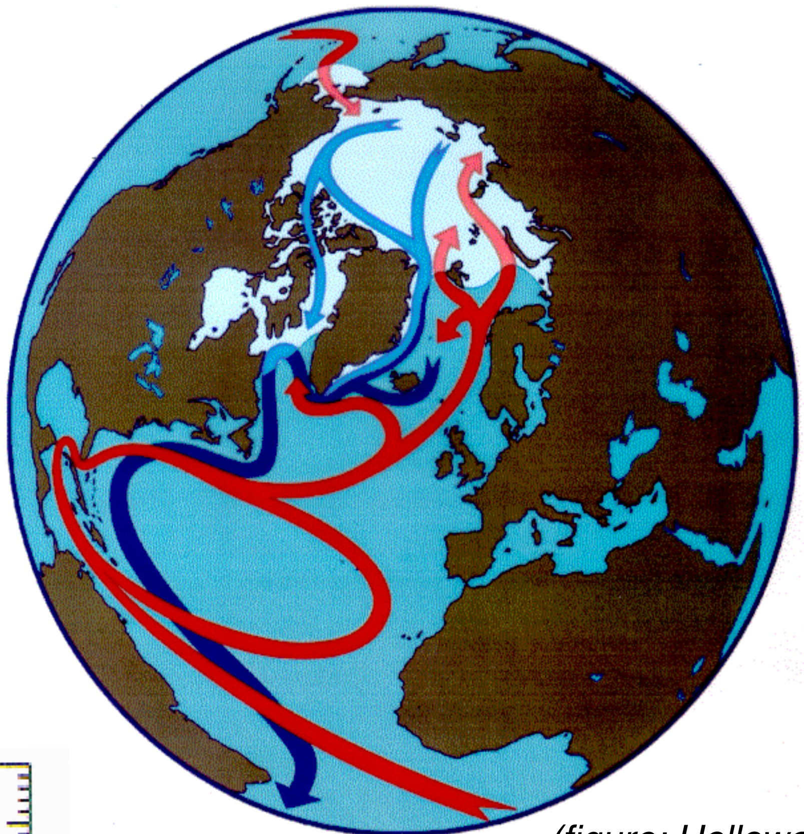
2°
1°
1/2°
1/4°
parameterised eddies
~ explicit eddies
ACC transport (Sv)
Wind Multiplication Factor
0
50
100
150
200
250
300
350
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Vostok + Dome C data
CO_2 / ppmv
300
270
240
210
180
EPICA Dome C data
WARM
COLD
δD ice / ‰
-390
-420
0
200
400
600
800
Age / kyr BP

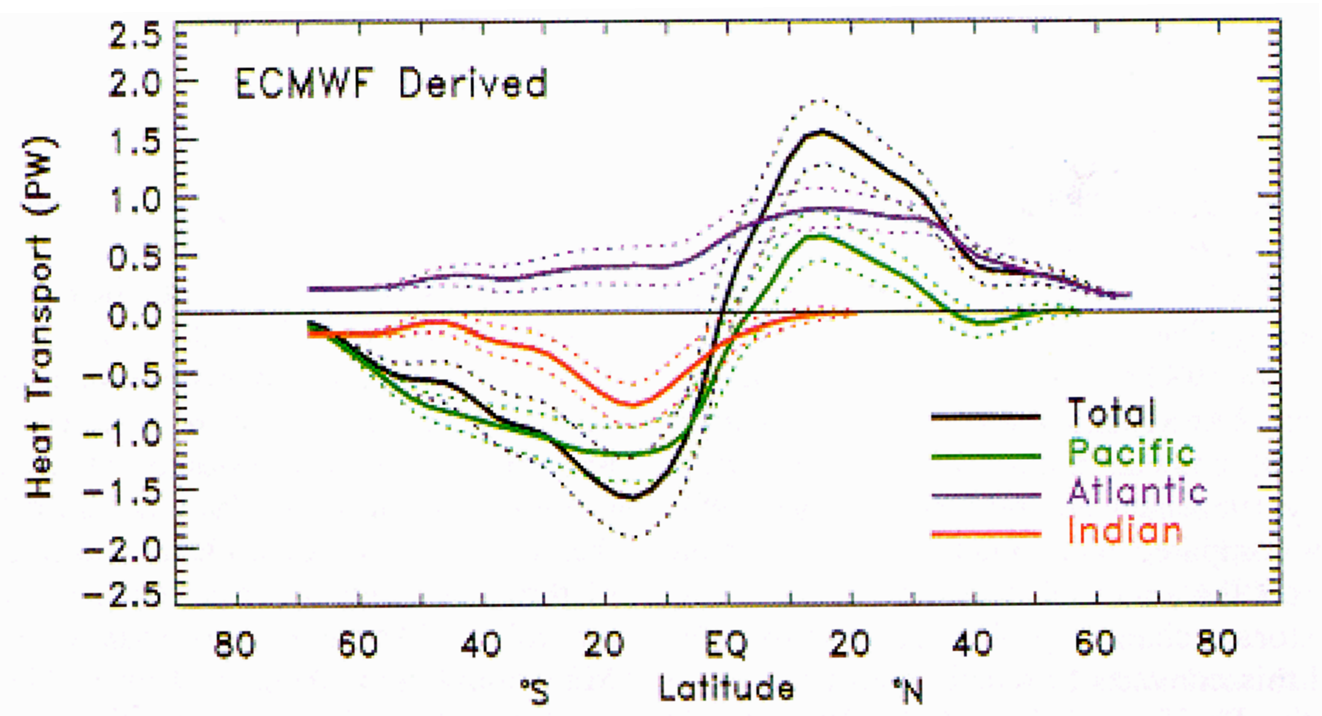
Problem (ii) Is the Gulf Stream going to collapse?

Atlantic Meridional Overturning Circulation (AMOC)
or thermohaline circulation:

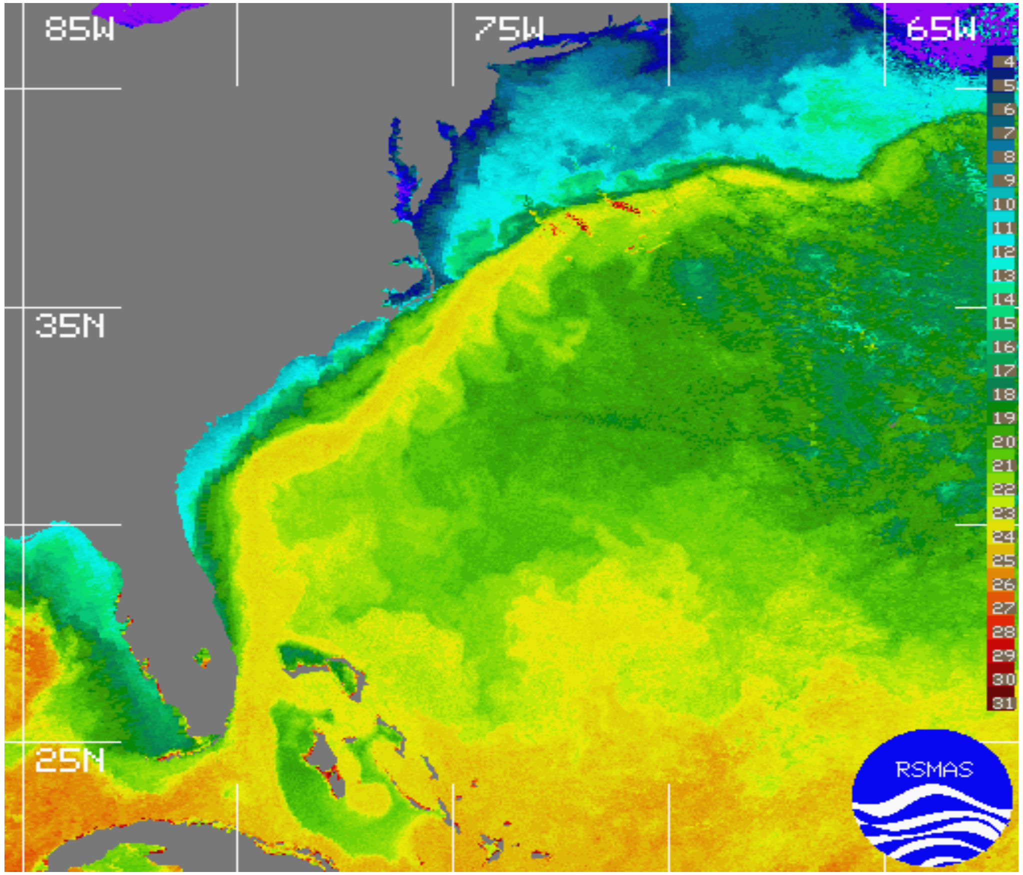


(figure: Holloway)

Northward heat transport (PW) in each basin:

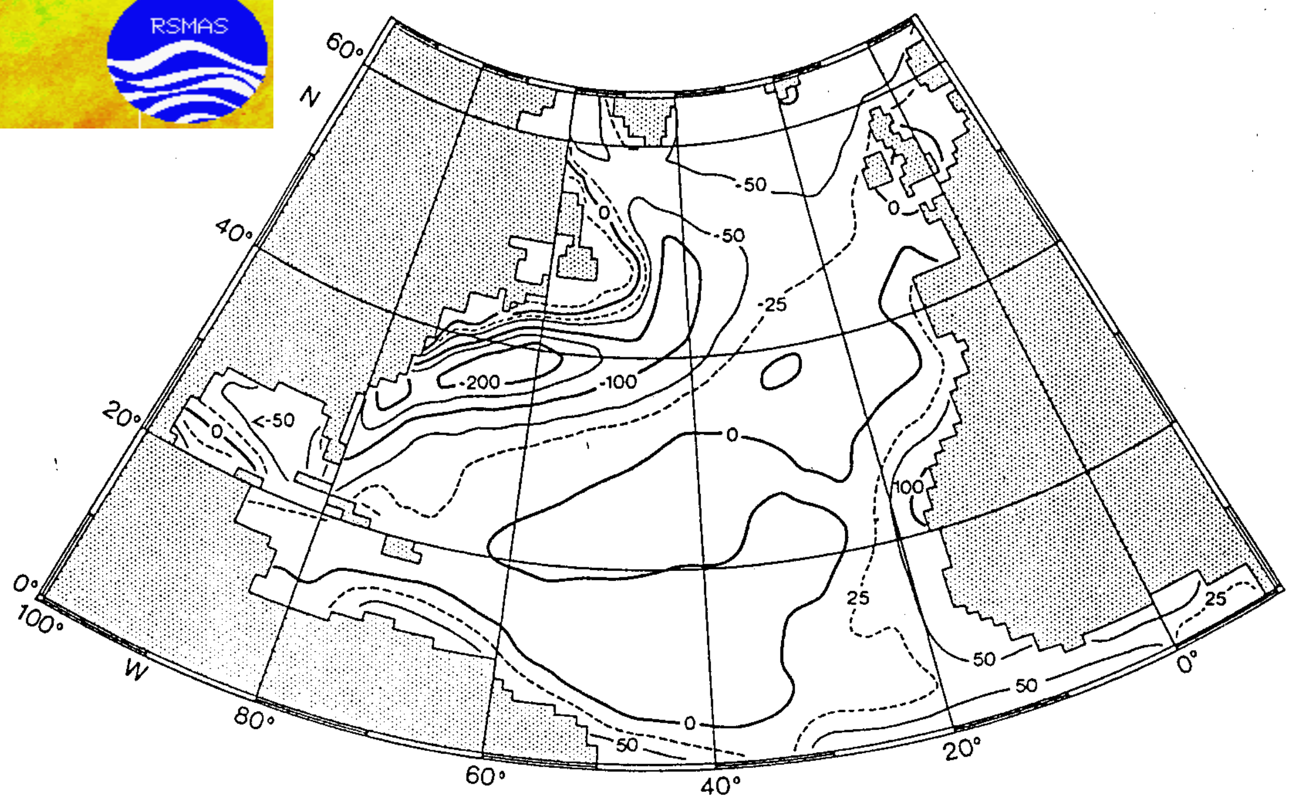


(Trenberth and Caron, 2001)



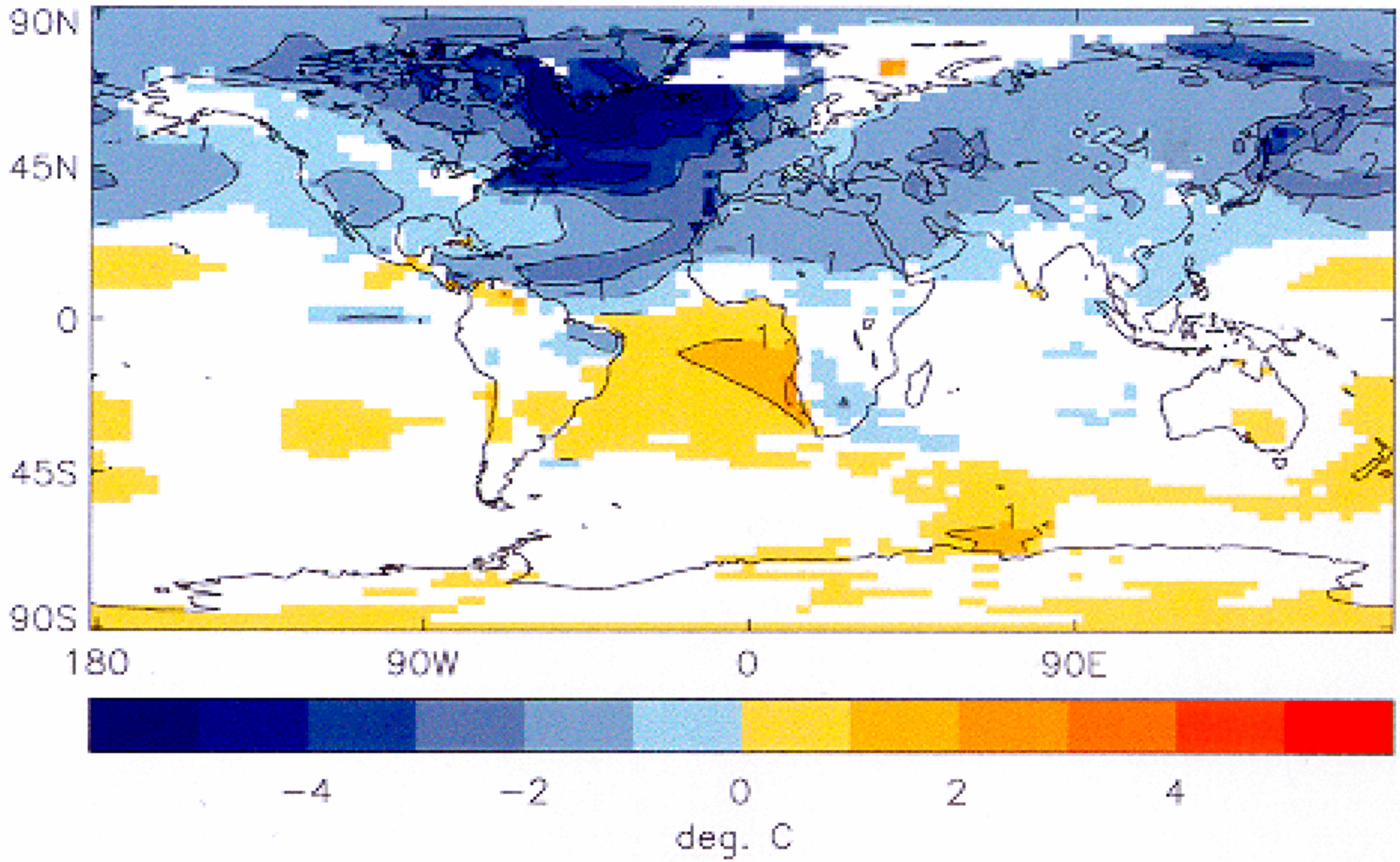
Sea-surface temperature (3 Feb 2003) over the western North Atlantic

(www.rsmas.miami.edu)



Annual-mean air-sea heat flux (Wm^{-2})

(Isemer et al. 1989)



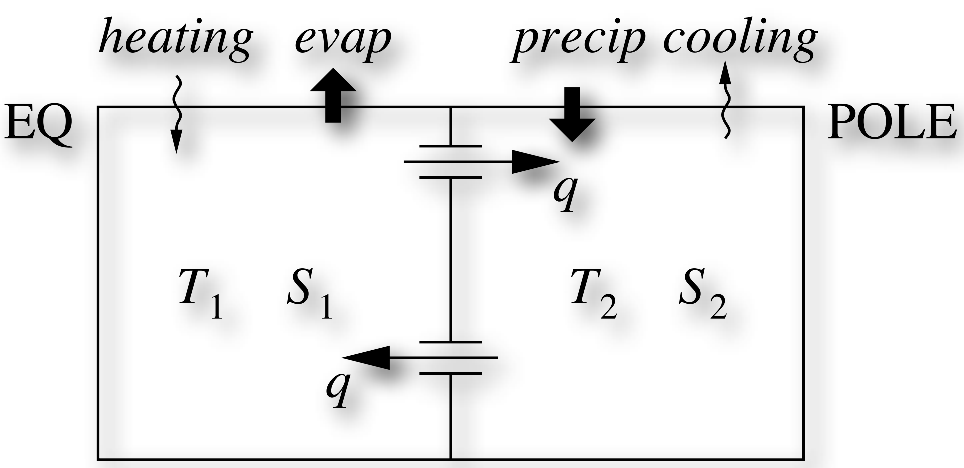
Surface temperature anomalies 20-30 years after the AMOC is removed in the HadCM3 coupled ocean-atmosphere model.

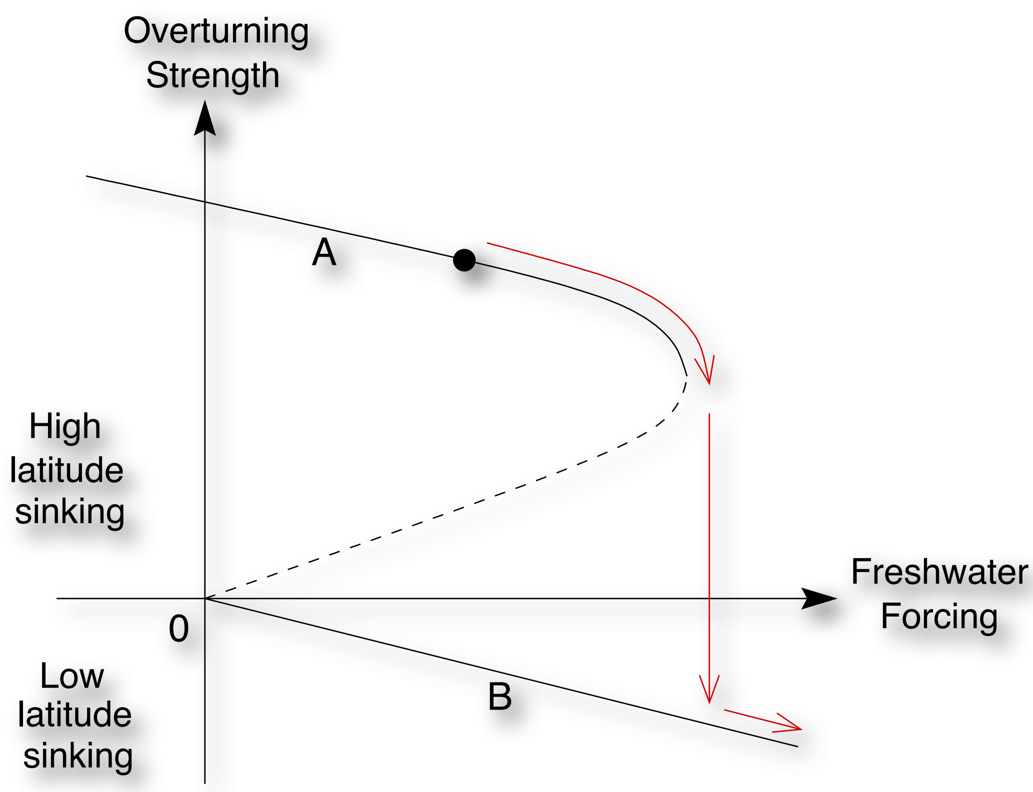
(Vellinga and Wood, 2001)

Abrupt change?

Can the AMOC possess more than one stable mode of operation under identical surface boundary conditions?

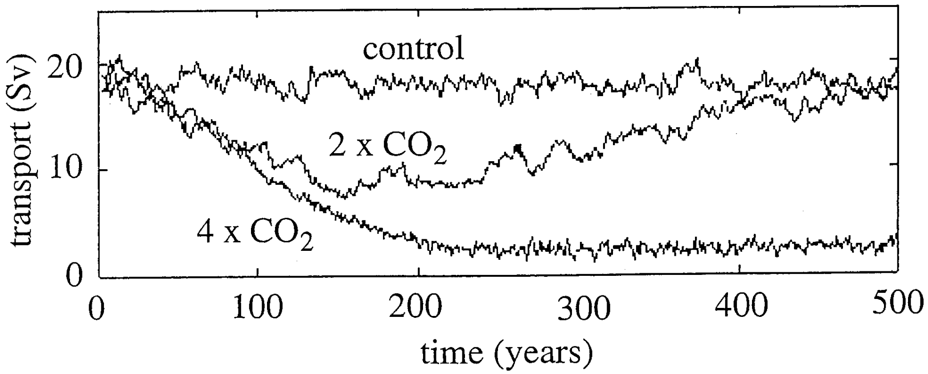
- box models (Stommel, 1961)



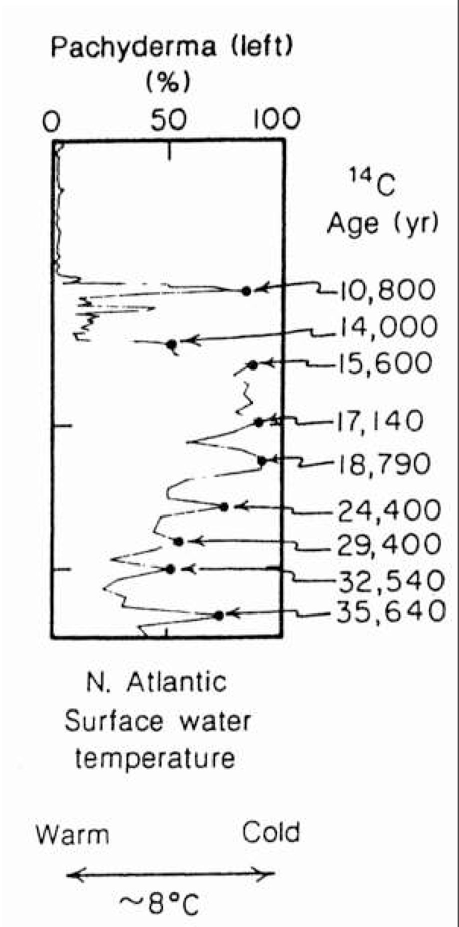


- idealised ocean circulation models (e.g., Marotzke and Willebrand, 1991)

- (coarse-resolution) global ocean-atmosphere models
  e.g., Manabe and Stouffer (1994):

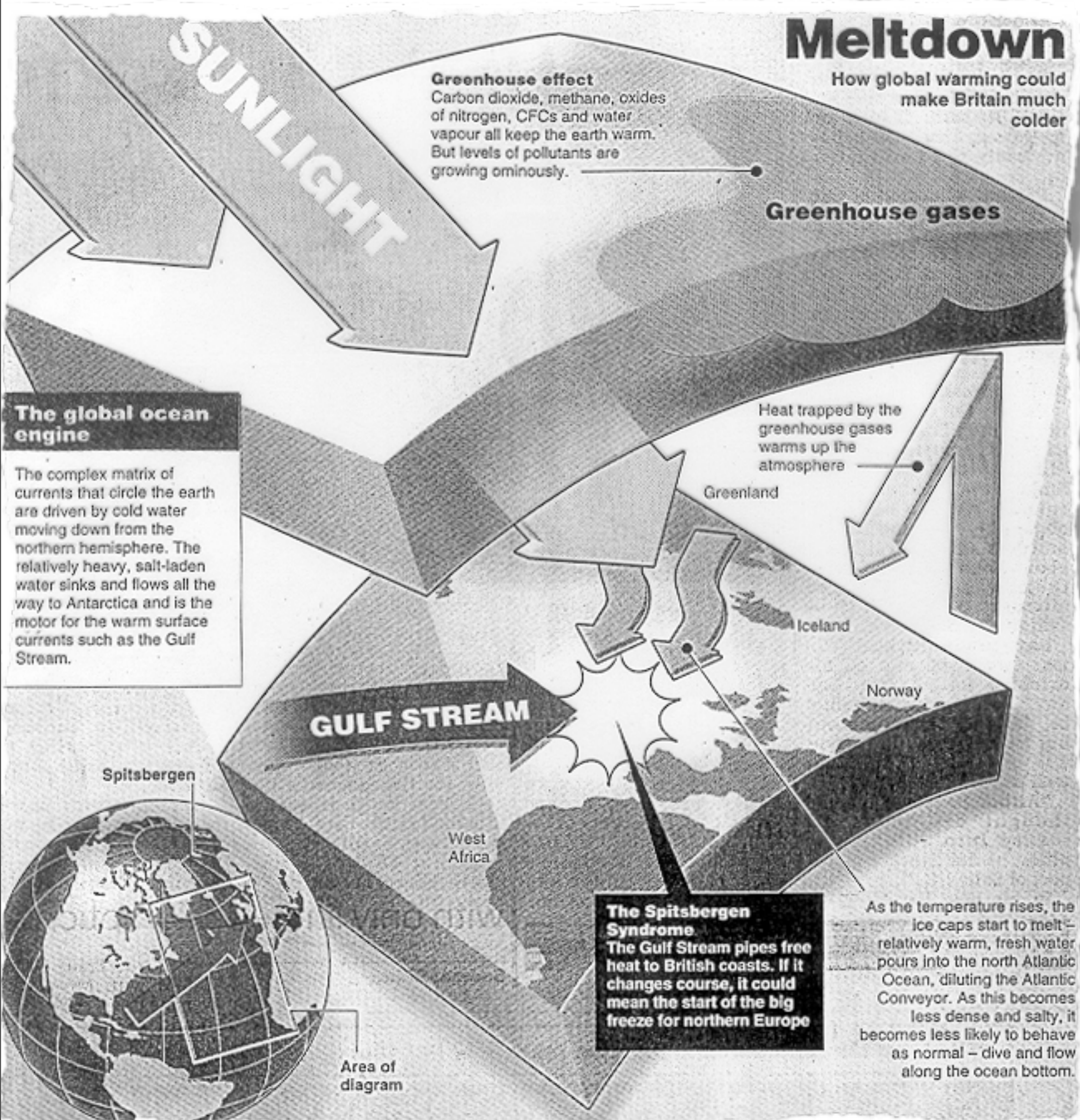


- abrupt changes also seen in paleo-records - link to AMOC?
  e.g., Broecker (1987):



- however, **no** state of the art coupled ocean-atmosphere model
  has yet shown multiple equilbrium states

What is going to happen to the AMOC over the next century?



Summer in SpitsBritain

EARLIER this year, the Department of the Environment painted a picture of the effects of global warming on Britain, *writes Tim Radford*.

The experts spoke of a climate appropriate to the Loire Valley, starting in the south of England and gradually making its way north over the decades.

But from the start, climate scientists have had reservations. Britain's place in the sun depends entirely on an oceanic accident: the curl of the Gulf Stream transporting tropical heat from the Bermuda triangle to the Bristol Channel.

With global warming and the Gulf Stream, there would be a landscape of sunflower fields and vineyards.

With global warming but without the Gulf Stream, the picture would be very different.

Now the scientists of Columbia University have at least taken a guess. In a Spitsbergen summer, temperatures sometimes soar to 15C and ships have even been known to land visitors there.

In winter, temperatures fall to -13C or lower — occasionally a lot lower.

There would be consolations in a SpitsBritain: rainfall in the northern islands would be relatively light at an average of about an inch a month. Tiresome trees would not obscure the view: only little polar willows and stunted dwarf birch would grow amid the mosses and lichens.

Birdwatchers would see snow buntings, ptarmigan, sandpipers and eider ducks.

Instead of red deer and badgers, there would be musk-ox and polar bears. There would be no crops, but hardly any weeding either.

(from *The***Guardian**)

Gulf Stream safe if wind blows and Earth turns

Sir — Your News story "Gulf Stream probed for early warnings of system failure" (*Nature* **427,** 769; 2004) discusses what the climate in the south of England would be like "without the Gulf Stream". Sadly, this phrase has been seen far too often, usually in newspapers concerned with the unlikely possibility of a new ice age in Britain triggered by the loss of the Gulf Stream.

European readers should be reassured that the Gulf Stream's existence is a consequence of the large-scale wind system over the North Atlantic Ocean, and of the nature of fluid motion on a rotating planet. The only way to produce an ocean circulation without a Gulf Stream is either to turn off the wind system, or to stop the Earth's rotation, or both.

Real questions exist about conceivable changes in the ocean circulation and its climate consequences. However, such discussions are not helped by hyperbole and alarmism. The occurrence of a climate state without the Gulf Stream any time soon — within tens of millions of years — has a probability of little more than zero.

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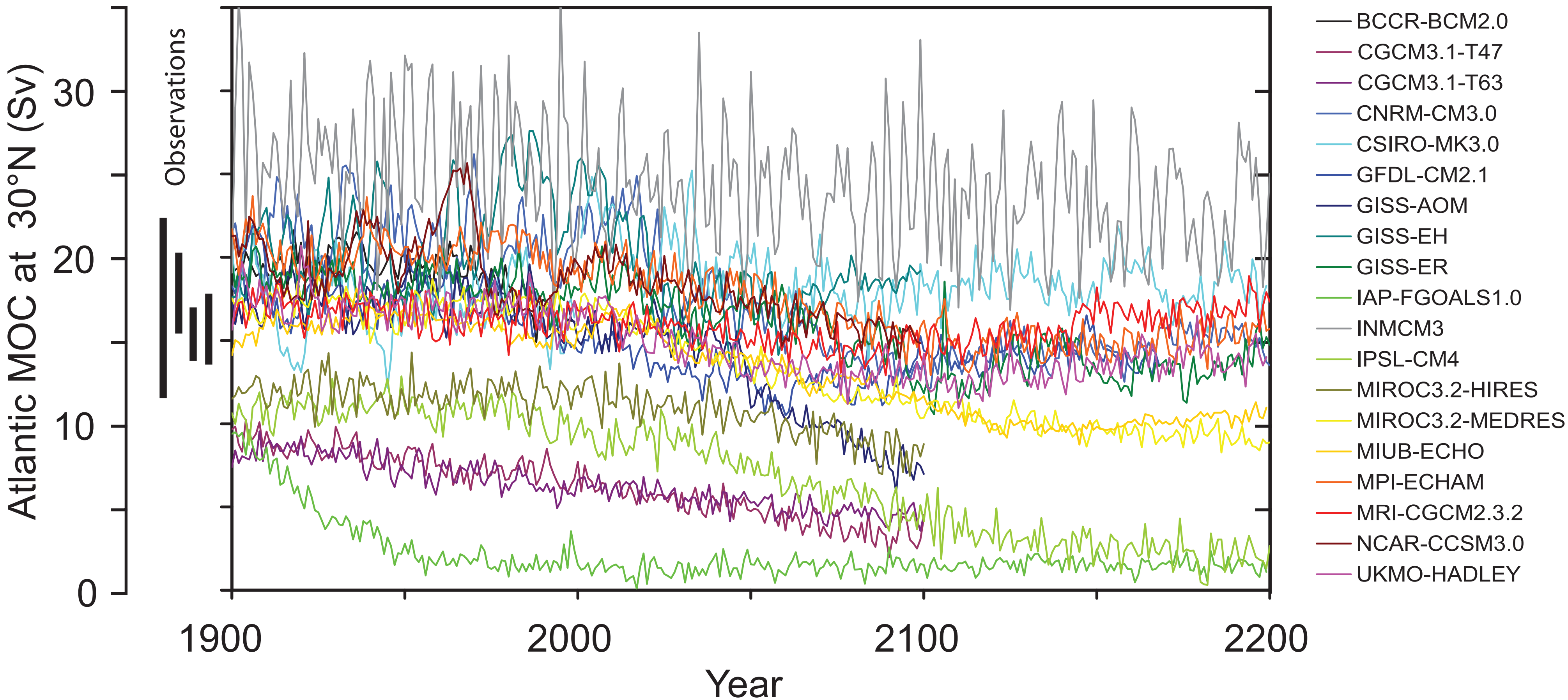
Carl Wunsch (MIT)
George Eastman Visiting Professor, 2011-2012


WHERE WILL YOU BE?
THE DAY AFTER TOMORROW
FROM THE DIRECTOR OF INDEPENDENCE DAY
WWW.THEDAYAFTERTOMORROW.CO.UK
IN CINEMAS WORLDWIDE MAY 28, 2004

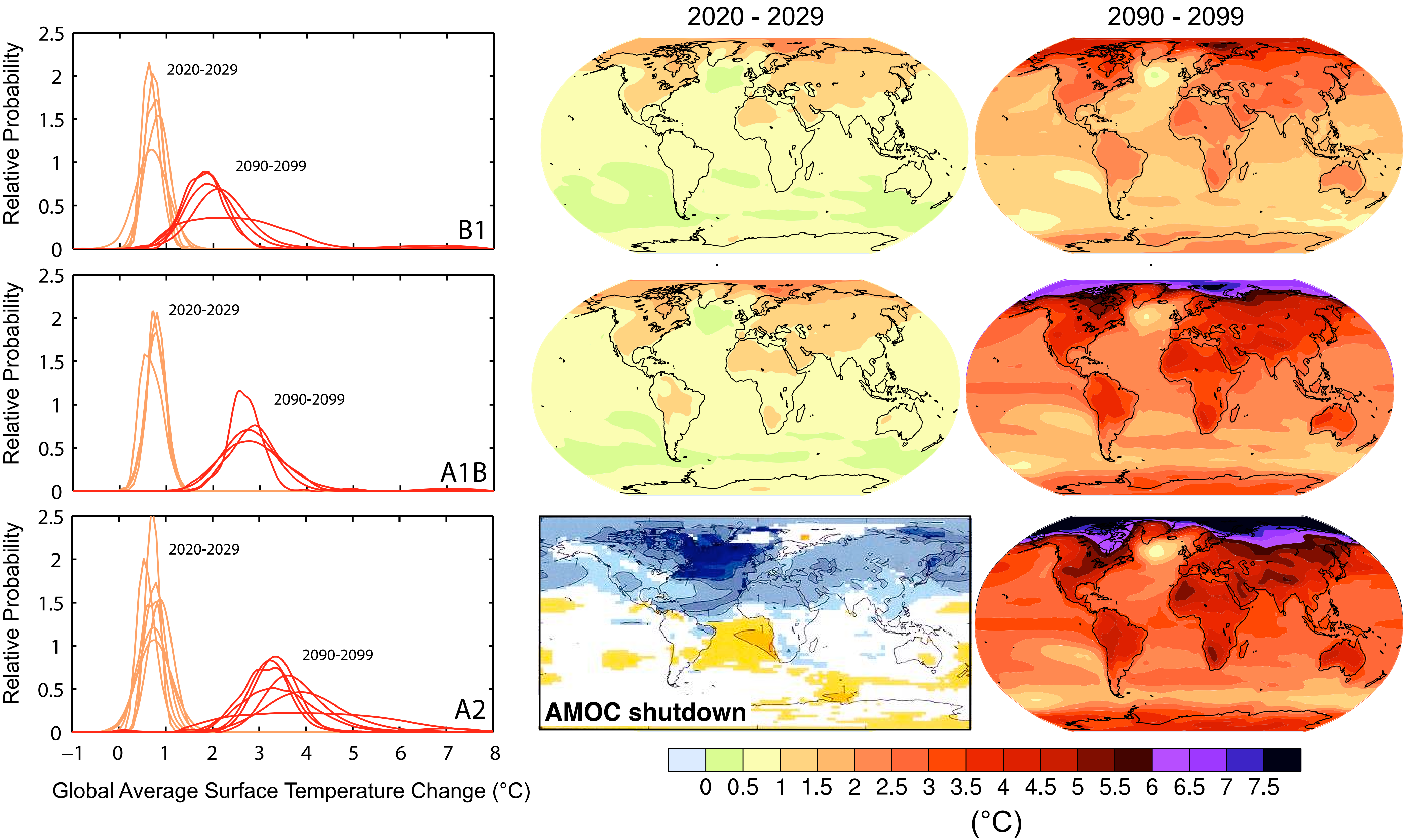
IPCC model projections:



(IPCC, 2007)

Based on current model simulations, it is *very likely* that the meridional overturning circulation (MOC) of the Atlantic Ocean will slow down during the 21st century. The multi-model average reduction by 2100 is 25% (range from zero to about 50%) for SRES emission scenario A1B. Temperatures in the Atlantic region are projected to increase despite such changes due to the much larger warming associated with projected increases of greenhouse gases. It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence.

Projections of Surface Temperatures



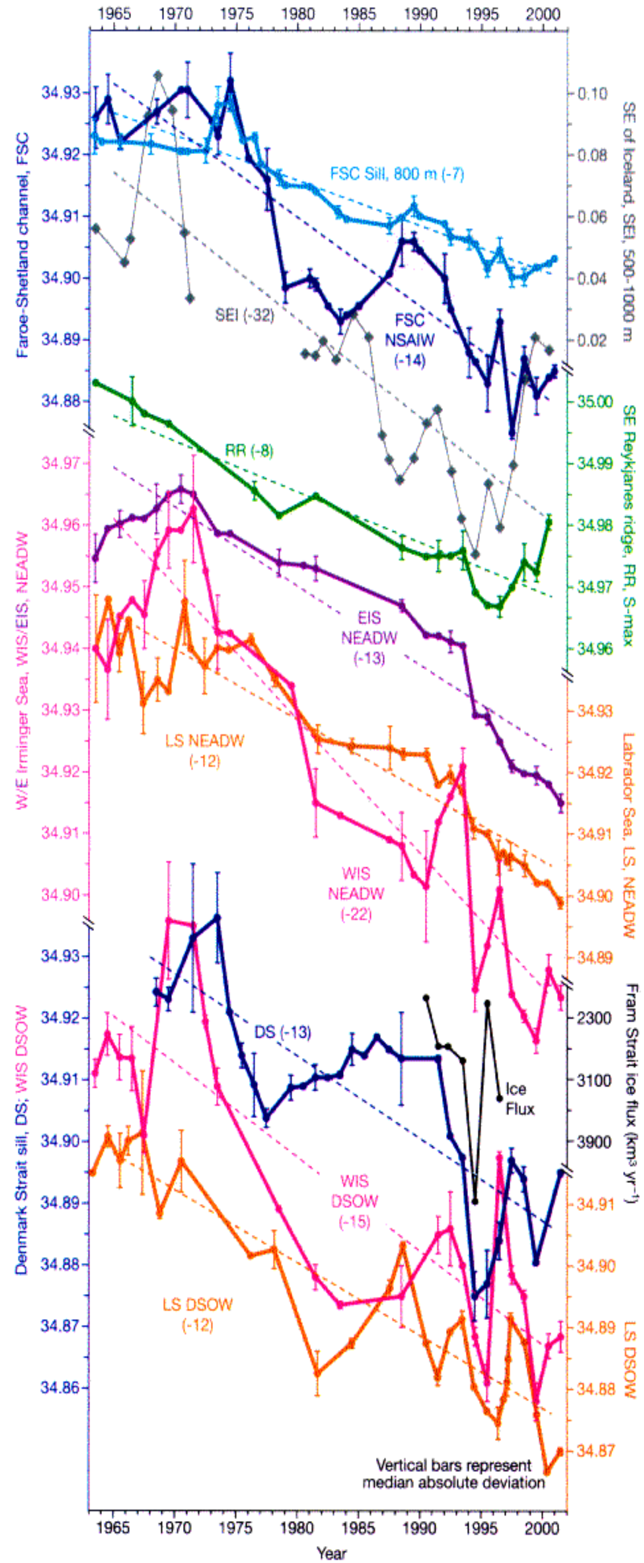
(IPCC, 2007)

Observations?

There is evidence of a wide-spread freshening of the high-latitude North Atlantic over the past 40 years

(Dickson et al. 2002)

(although recent reversal)



Nature, Dec 2005:

Slowing of the Atlantic meridional overturning circulation at 25° N

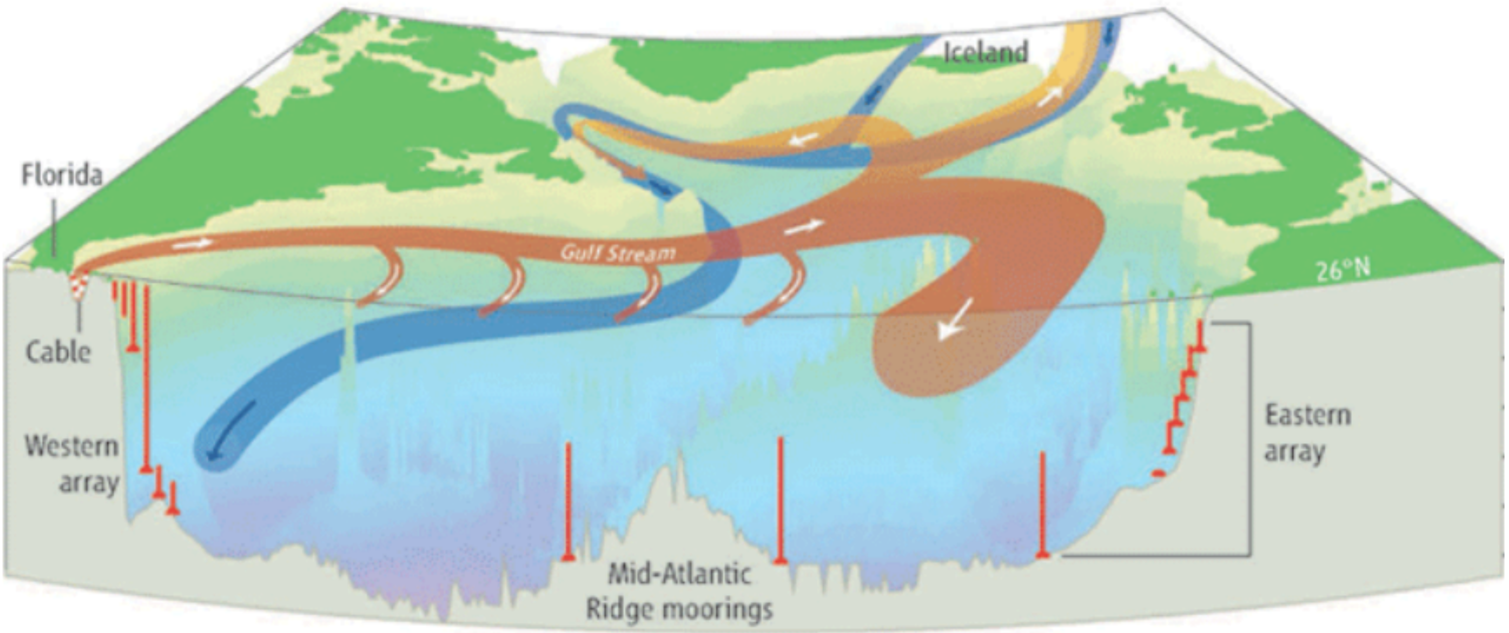
Harry L. Bryden[1], Hannah R. Longworth[1] & Stuart A. Cunningham[1]

Table 1 | Meridional transport in depth classes across 25° N

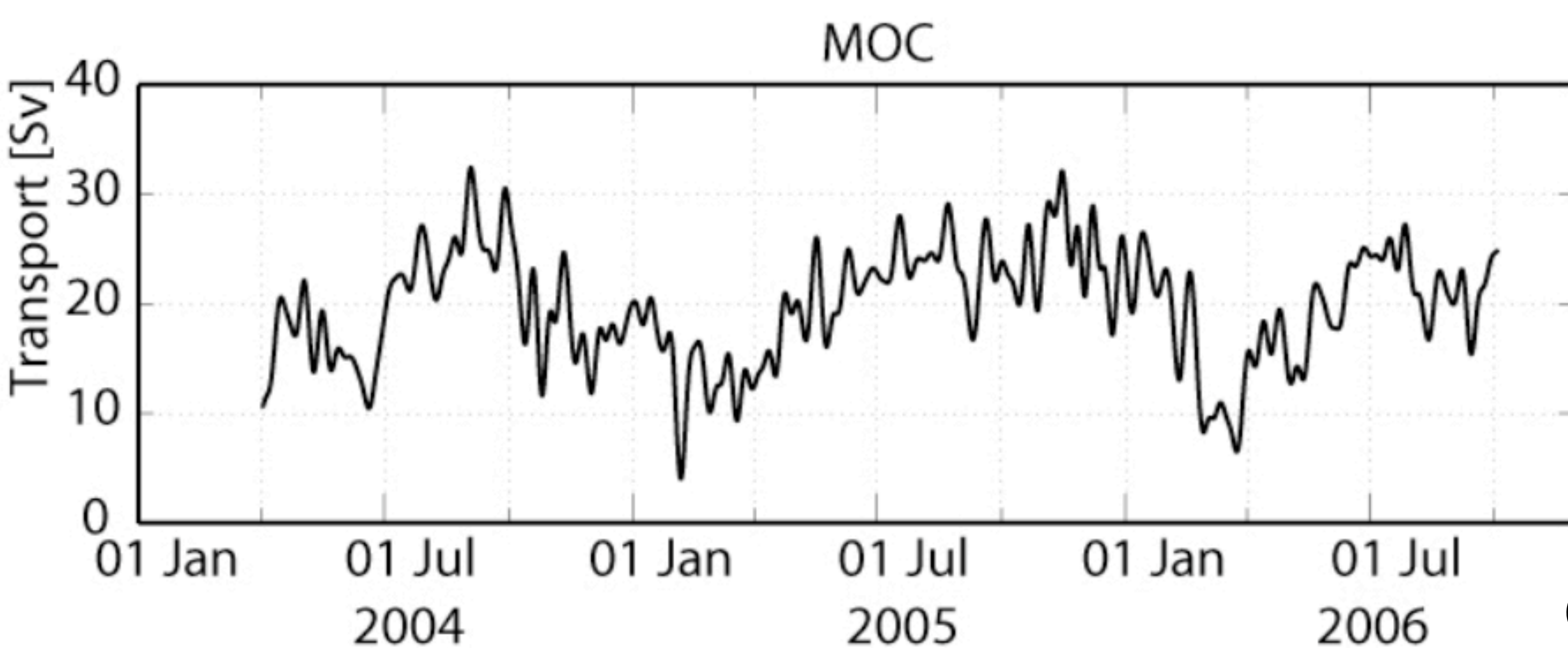
	1957	1981	1992	1998	2004
Shallower than 1,000 m depth					
Gulf Stream and Ekman	+35.6	+35.6	+35.6	+37.6	+37.6
Mid-ocean geostrophic	−12.7	−16.9	−16.2	−21.5	−22.8
Total shallower than 1,000 m	+22.9	+18.7	+19.4	+16.1	+14.8
1,000–3,000 m	−10.5	−9.0	−10.2	−12.2	−10.4
3,000–5,000 m	−14.8	−11.8	−10.4	−6.1	−6.9
Deeper than 5,000 m	+2.4	+2.1	+1.2	+2.2	+2.5

Values of meridional transport are given in Sverdrups. Positive transports are northward.

RAPID AMOC monitoring array at 26N:

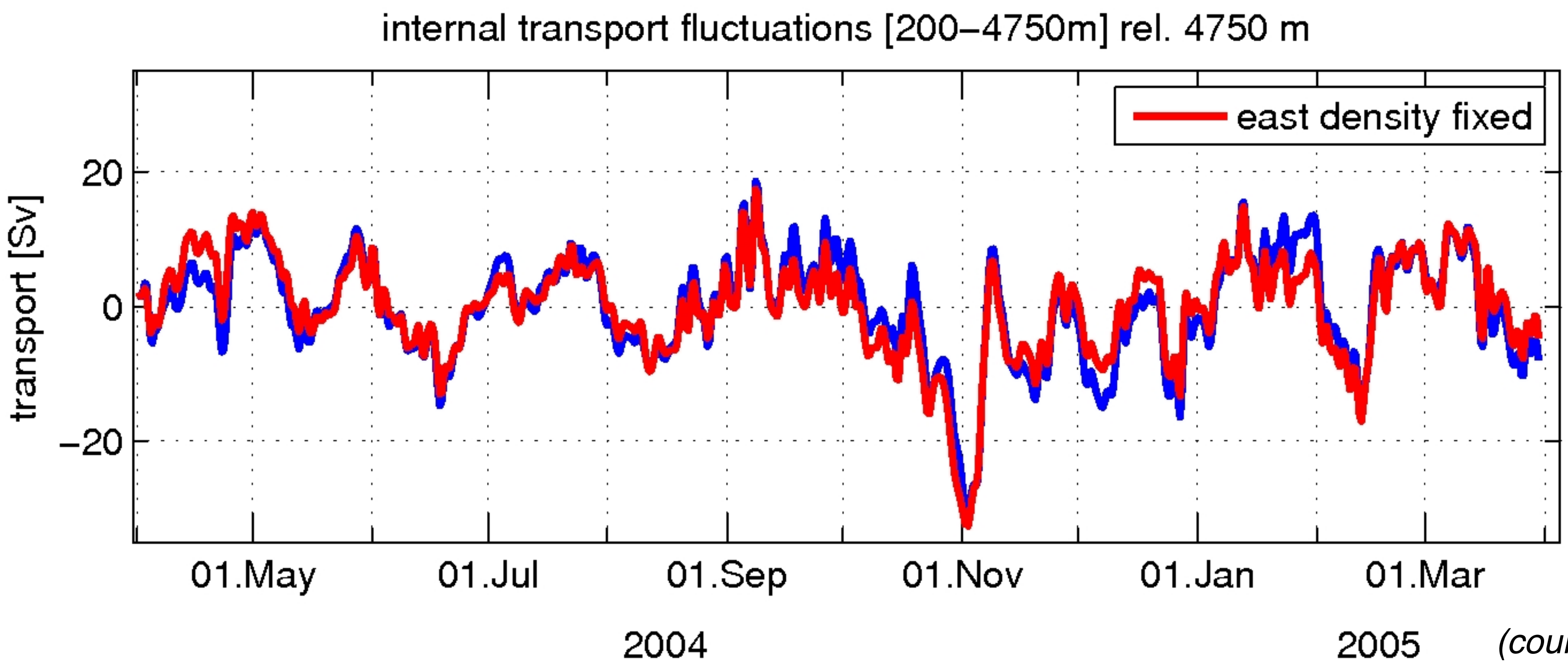


(figure: Church 2007)



(Kansow et al. 2008)

26.5N: AMOC component from E-W density gradient



(courtesy: Kansow)

Sea change: why global warming could leave Britain feeling the cold

- No new ice age yet, but Gulf Stream is weakening
- Atlantic current came to halt for 10 days in 2004

James Randerson, science correspondent
Friday October 27, 2006
The Guardian

Science, Nov 2006:

GLOBAL CLIMATE CHANGE

False Alarm: Atlantic Conveyor Belt Hasn't Slowed Down After All

Fitful flow. Instruments arrayed across the North Atlantic have found surprisingly variable currents that mask any slowing of the Atlantic conveyor.

before the ch
would be notic
above the noise.
The full rea
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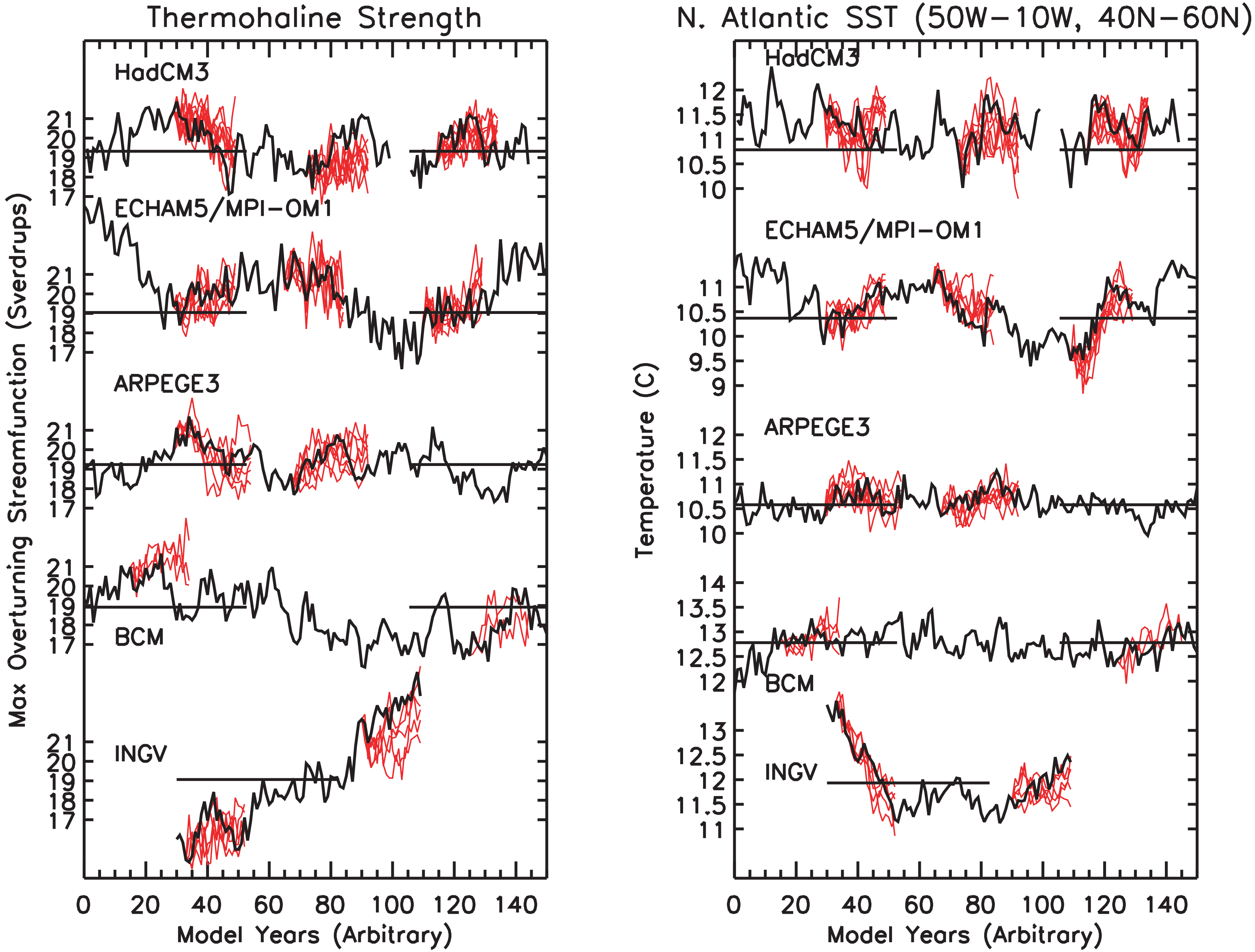
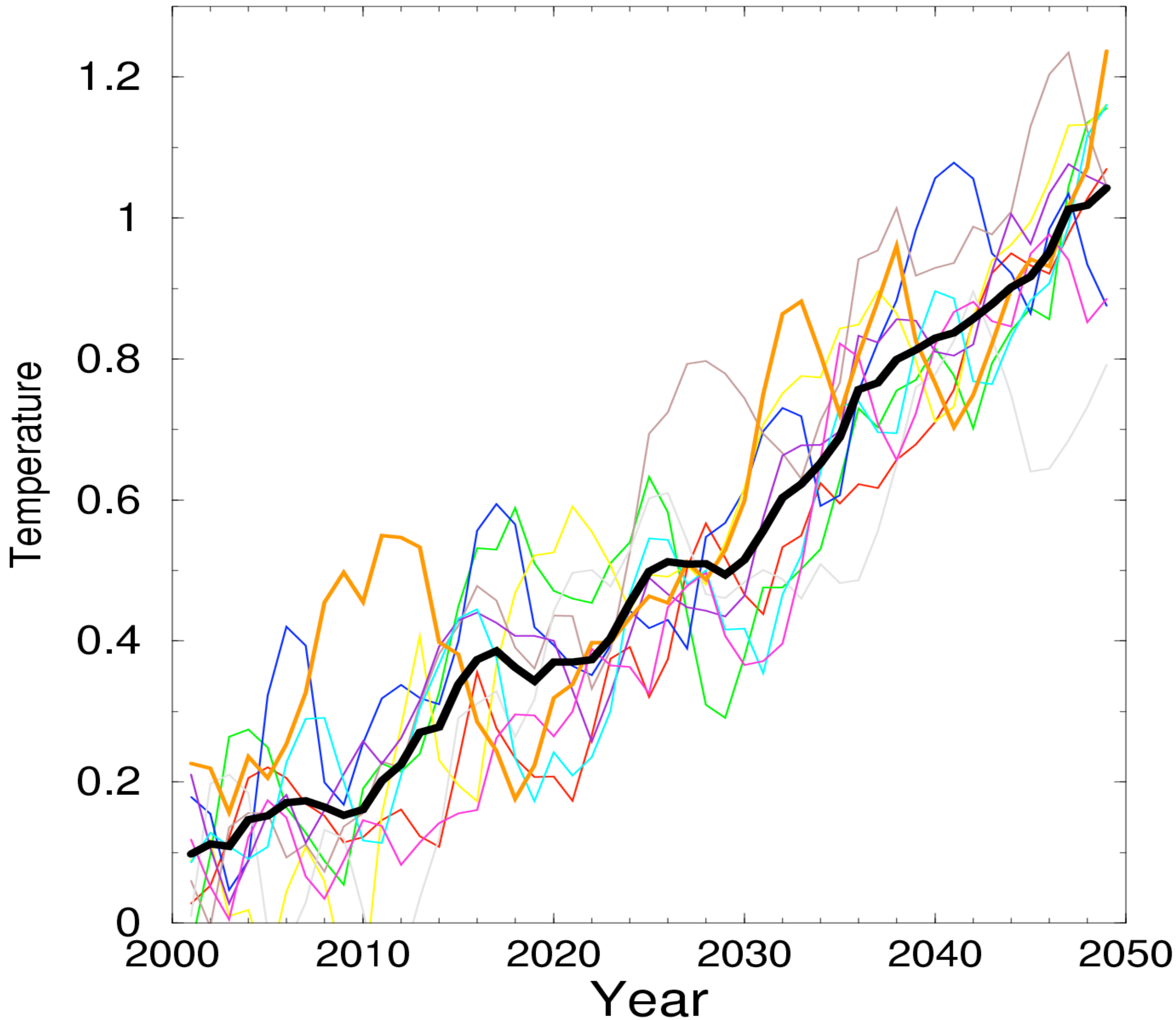
with the first co
ous monitoring o
ocean's north-s
flows. In March

Not interested only in abrupt change - potential predictability?



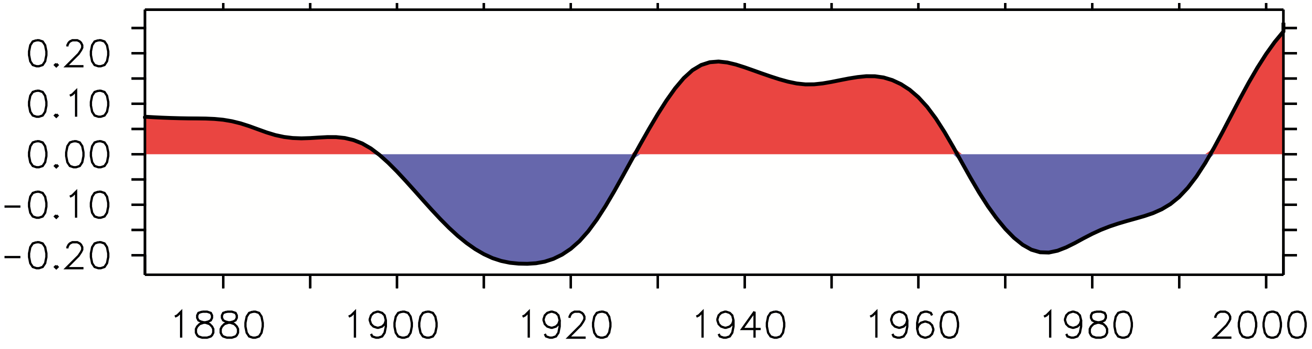
(Collins et al., 2003)

Atlantic sea surface temperature, GFDL climate model ensemble under IPCC A1B forcing:

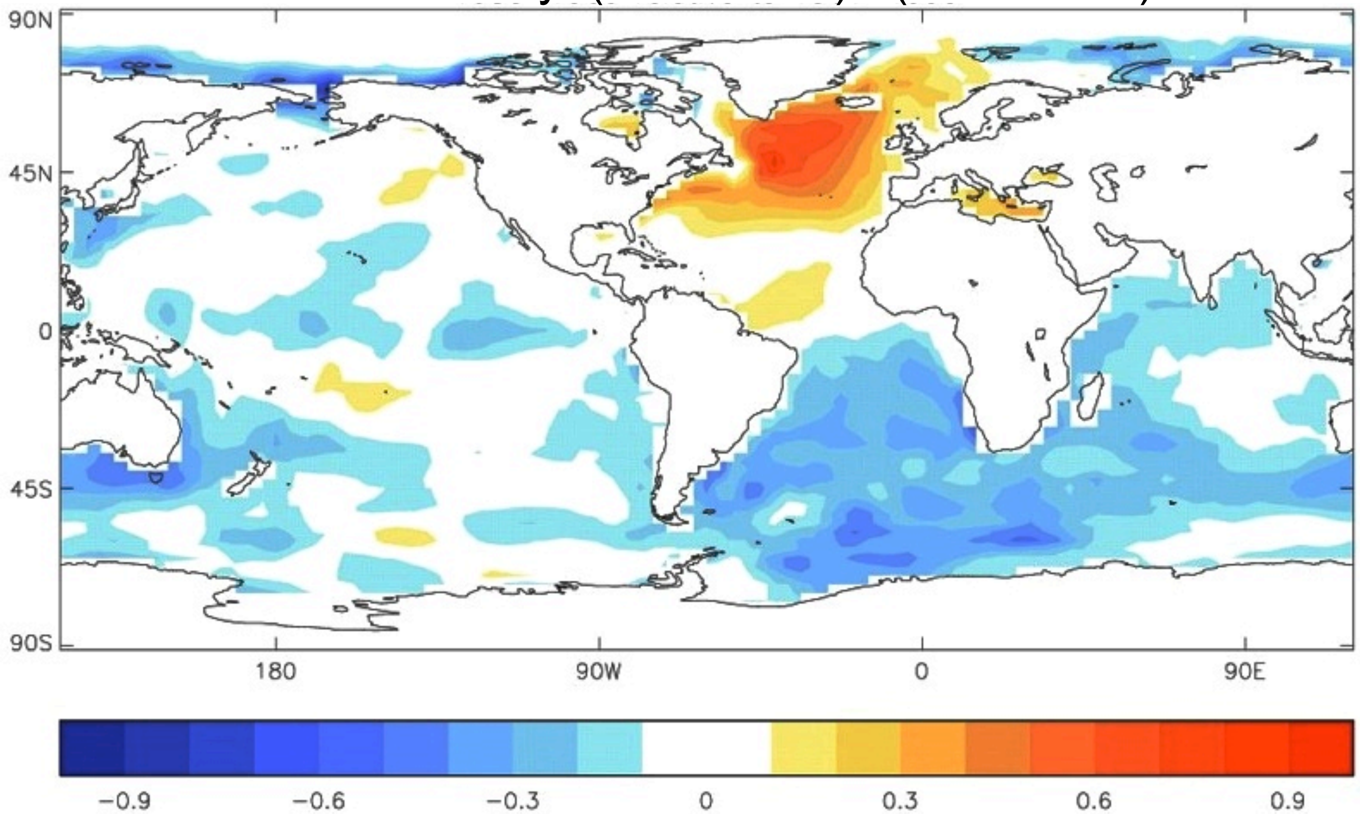


(courtesy: Isaac Held)

Atlantic Multidecadal ~~Oscillation~~ (AMO)



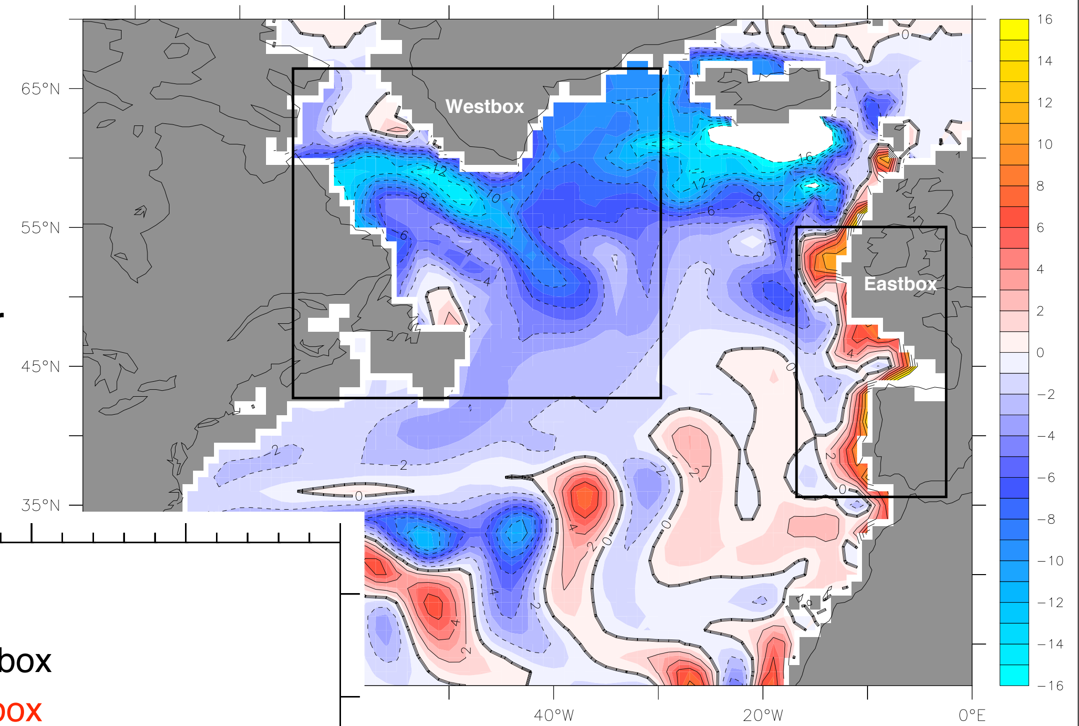
SST anomaly: (1930-1960) - (1960-1990)

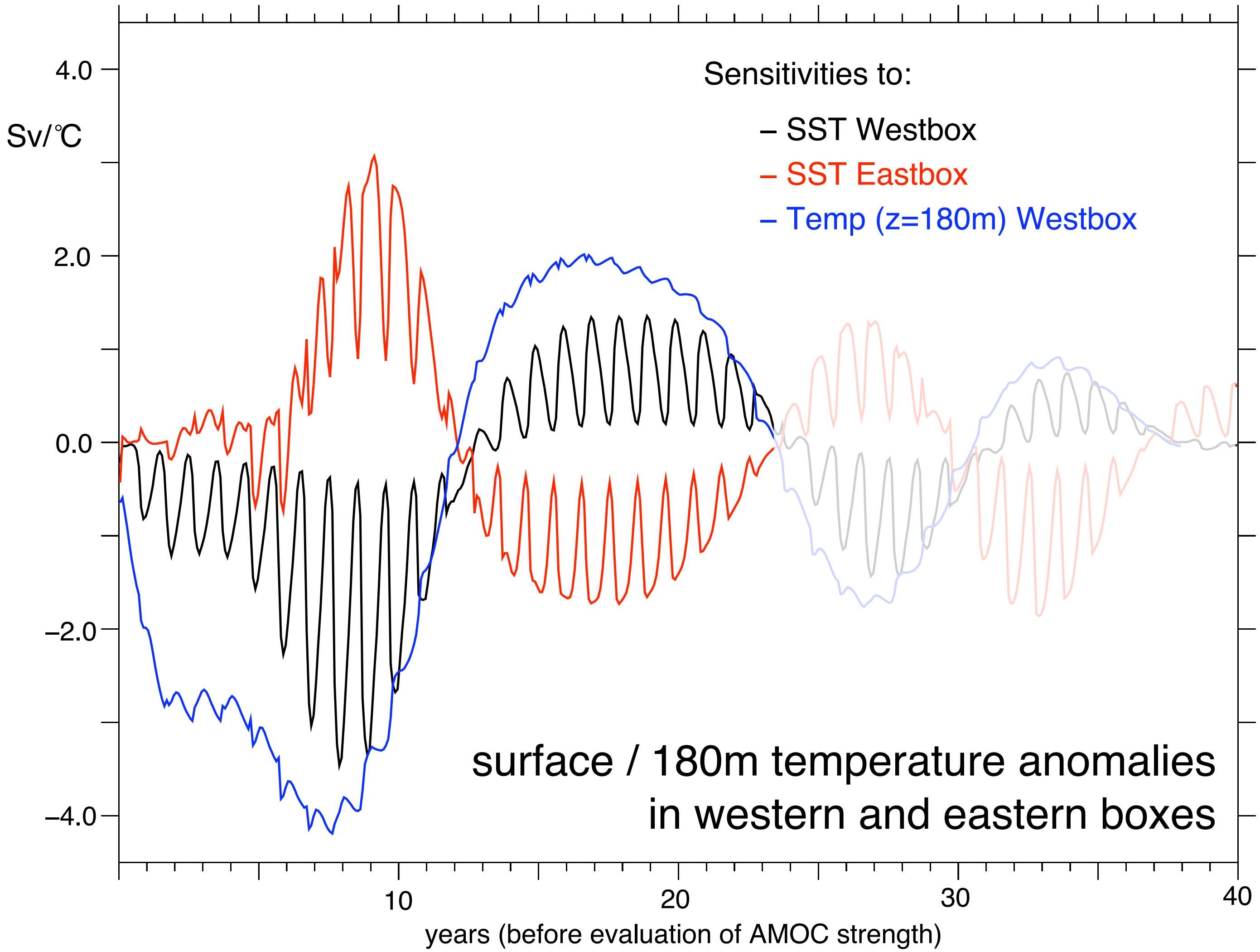


link to AMOC?

Adjoint model - sensitivity of AMOC at 27N to:
(Czeschel et al., 2010)

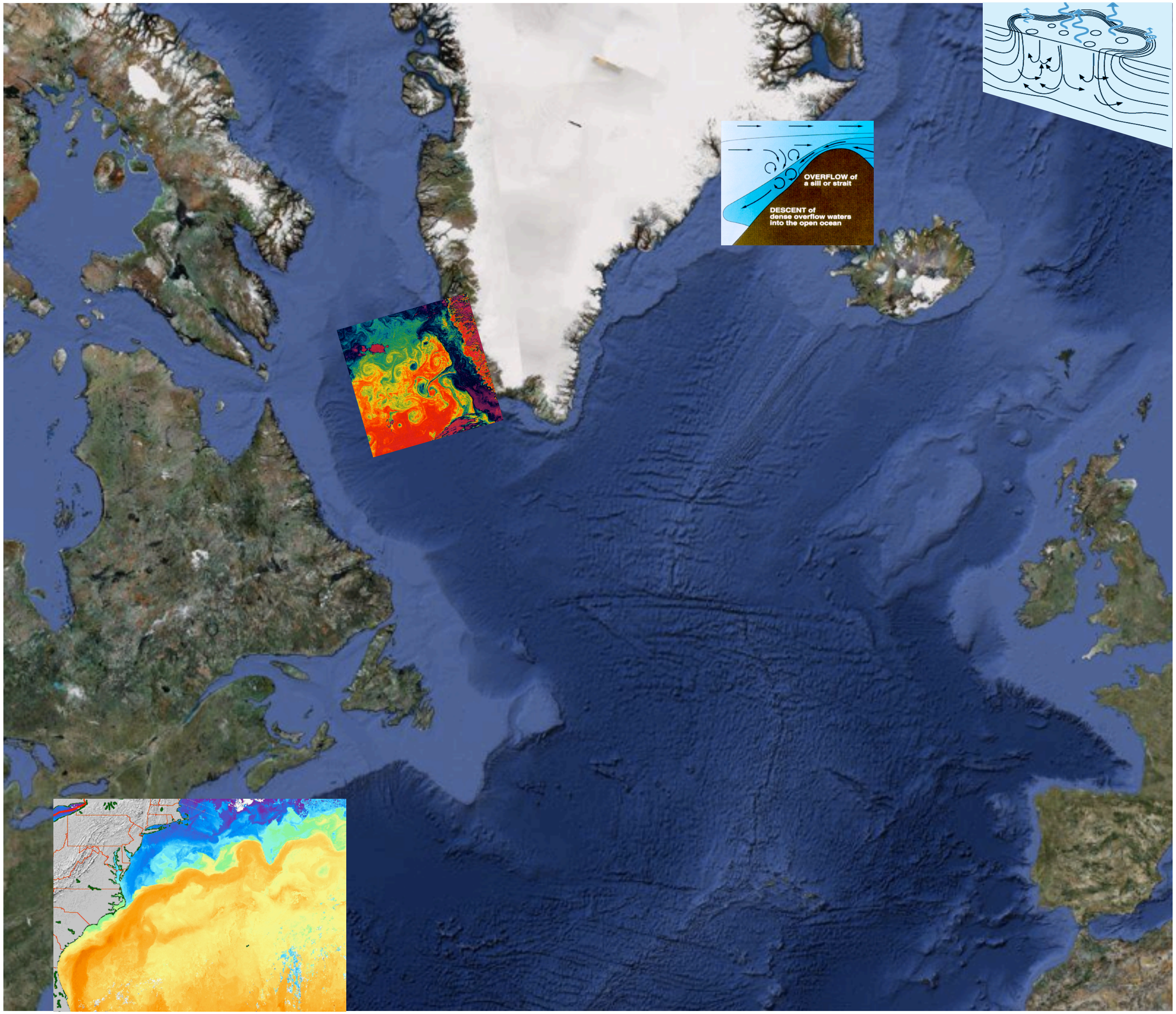
temperature anomalies at 180m,
8.25 years earlier





Laure Zanna (JM Fellow)
using adjoint model to
pick out anomalies that
grow most rapidly
⇒ limits to predictability

Cautionary note: most of the critical processes for the AMOC (convection, overflows, boundary waves, boundary currents, eddies, ...) are either sub-grid scale or poorly resolved by the current generation of ocean models



Concluding remarks

- Ocean circulation spans a bewildering array of spatial and temporal scales.
- The smallest scales can affect the largest scales and vice-versa.
- The ocean is grossly undersampled in both space and time, but the modern observing system gives global coverage for the first time (at least of the upper ocean).
- Making progress requires a careful combination of observations, simple models to test and develop physical understanding, and global numerical models.
- While dramatic scenarios such as "collapse of the Gulf Stream" make good headlines, we need to be careful not to over-dramatise: this can damage the field in the long term and trivialise important (if somewhat less dramatic) issues.