Where Do We Go From Here?

AMOC June 2010 Miami

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We have a variety of North Atlantic state estimates, from varying data sets, models, durations, methodologies, resolutions, assumptions., and goals.

So what? What is the purpose of all of this?

(1) Curiosity driven research. How does the ocean “work”? (Until recently, this was why we all did oceanography.)

(2)Understanding the possible changes induced in, and induced by, the ocean on the climate and biological systems.
(3) The *possibility* of true prediction of things we care about in the social sense.
(4) Useful prediction, if possible.

One of the major difficulties in formulating a scientific plan for understanding the climate system is the huge variety of possibilities and interests, such as changes in heat content, salinity, meridional enthalpy transports, carbon uptake and transports, sea surface temperature, …. on time scales of years, decades, centuries,…., dynamics versus kinematics.

How do you get a focus? A particular problem for designing observing systems.

A suggestion:

The problem of prediction is an all encompassing one, as it goes to fundamentals of the understanding of the climate system, as well as all the practical issues such as sensitivity to initial conditions, model skill, missing boundary conditions, the design of observing systems, and knowledge of their adequacy.

Consider the regional sea level forecast problem spans essentially all of the problems of the ocean circulation: exchanges of enthalpy with the atmosphere, fresh water inputs, wind-derived circulation changes, abyssal heat and fresh water storage changes, open boundary transport fluctuations,…. and every different time scale from hours to millennia.

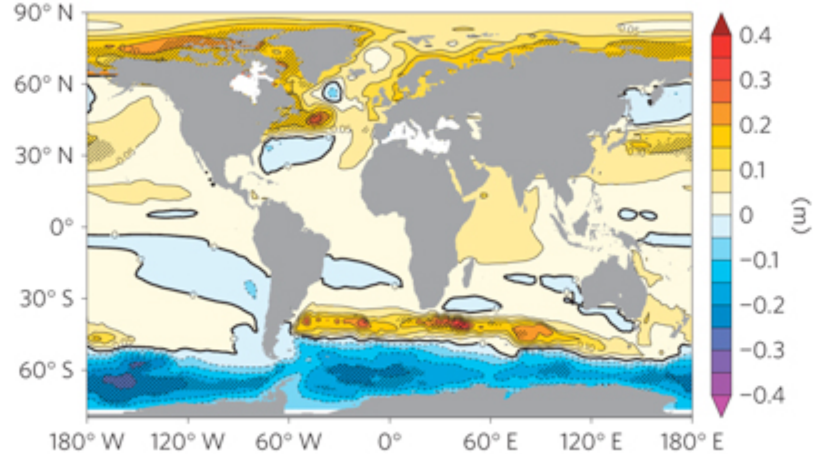
All such phenomena and their changes encompass theory and dynamics.

A much more intuitive impact on non-specialists than meridional heat or volume transports.

I will use this as a possible theme for future state estimation and the supporting observation network. Aim is to be quantitative.

Attempts are already being made to predict regional sea level change

The values show the mean change (2091–2100 relative to 1981–2000) projected by ten AR4 climate models under the A1B scenario. Stippling indicates the regions where the ensemble mean divided by the ensemble standard deviation is greater than two. See Supplementary Fig. S1 for the models used in the calculation of the ensemble mean and their projections.



From a prediction of the ocean circulation to 2100.

Is this science? Or science fiction?

Model projections of rapid sea-level rise on the northeast coast of the United States

Jianjun Yin[1], Michael E. Schlesinger[2] & Ronald J. Stouffer[3]

Nature Geoscience 2009

Northeast US could suffer most from sea rise

Add 8 inches for the region, new study says

By Seth Borenstein

Associated Press / March 16, 2009

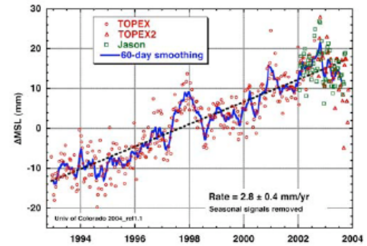
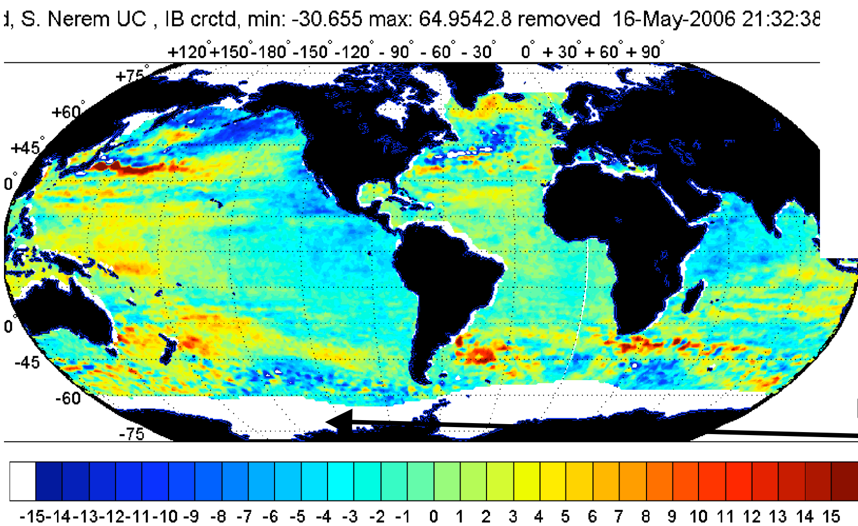


Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the altimeter data, and seasonal variations have been removed.

global mean. alt. alone
Nerem & Cazenave, 2004



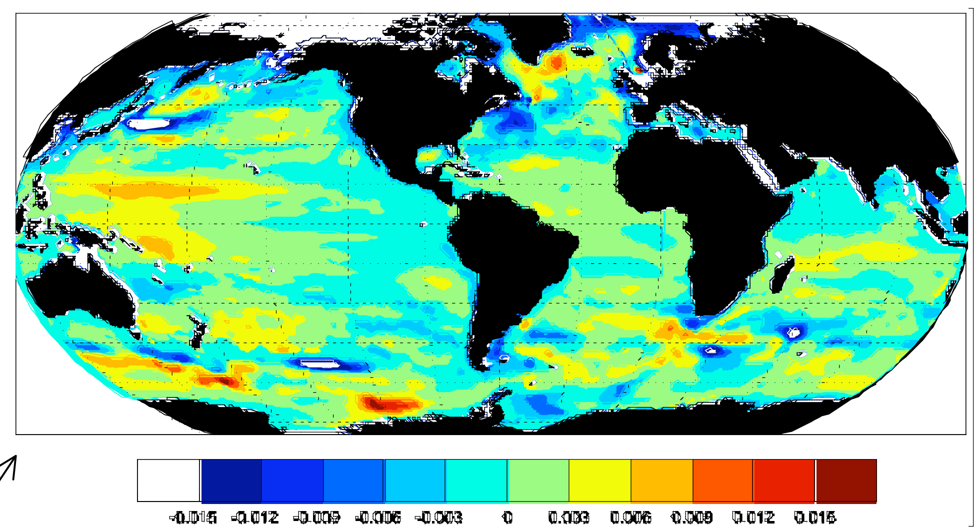
no data

mm/y

What controls regional sea level change?

Directly measured by a satellite. Note how complicated the pattern is. The global mean value is estimated as about 2.8mm/y +/-0.3mm/y

According to Peltier (1991) should add another 0.33mm/y for post-glacial rebound



ECCO-GODAE version 3.73 (more complete sea ice model)

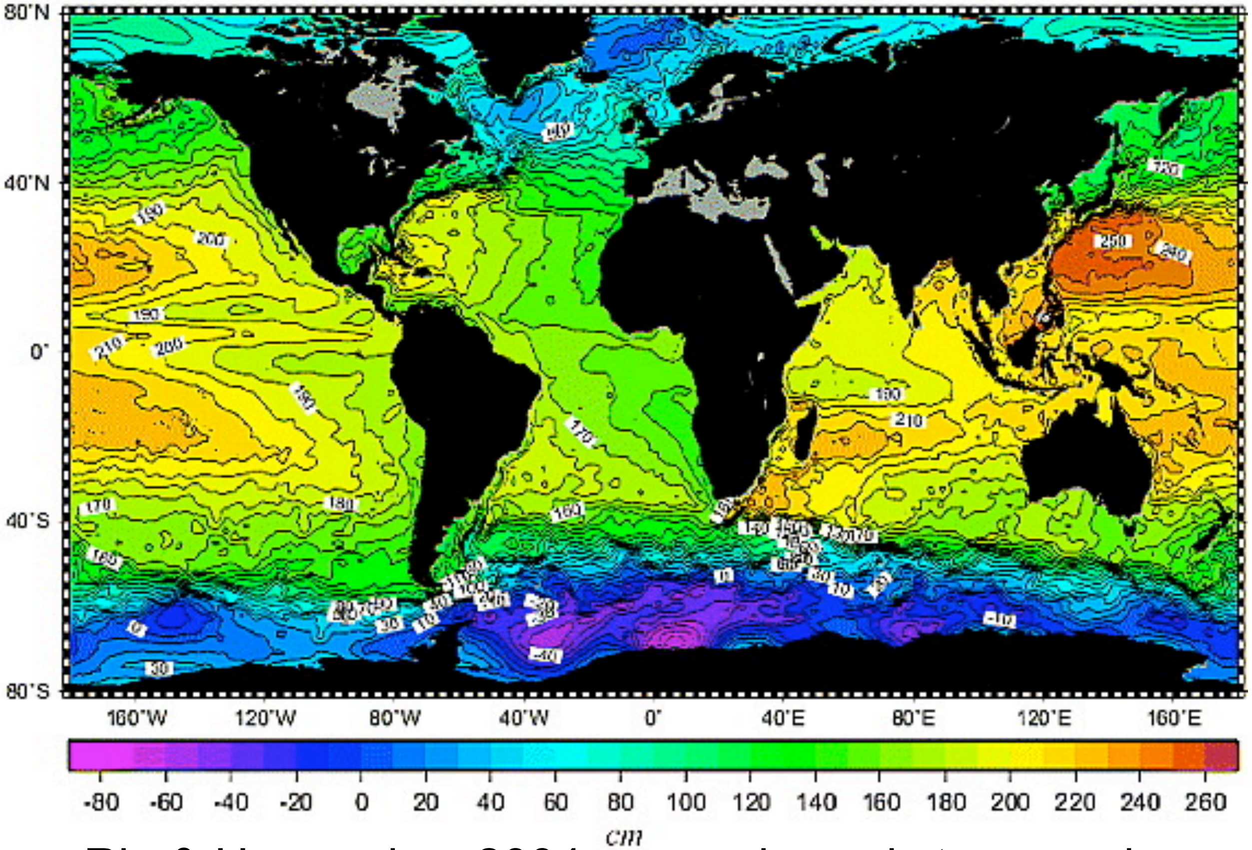
What can change global mean sea level?:

Net temperature change (heat exchange with the atmosphere)
Addition or subtraction of fresh water (exchange with atmosphere, land, ice)
Change in volume of the ocean (post glacial rebound; spreading
rate changes)
Melting or formation of sea ice with non-zero salinity

What can change regional mean sea level?

All global contributions plus:

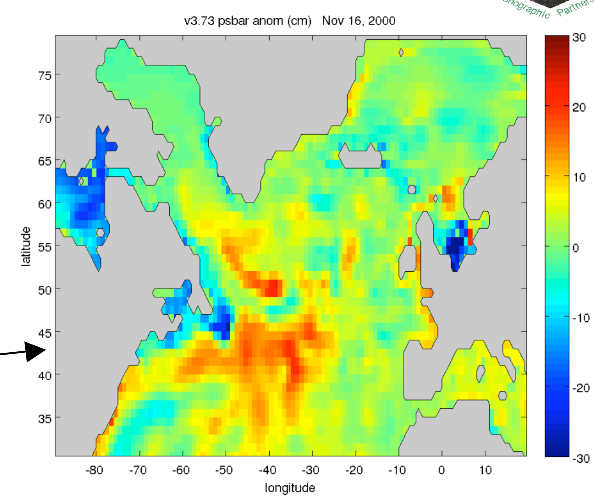
Local temperature shifts from air-sea interaction, advection, and diffusion
Local addition or removal of fresh water
Displacement of ocean circulation features
Tectonic shifts (uplift,…)
Gravity field modification (melting of glacial ice, post-glacial rebound)
Change in ocean load (local atm. pressure)
….



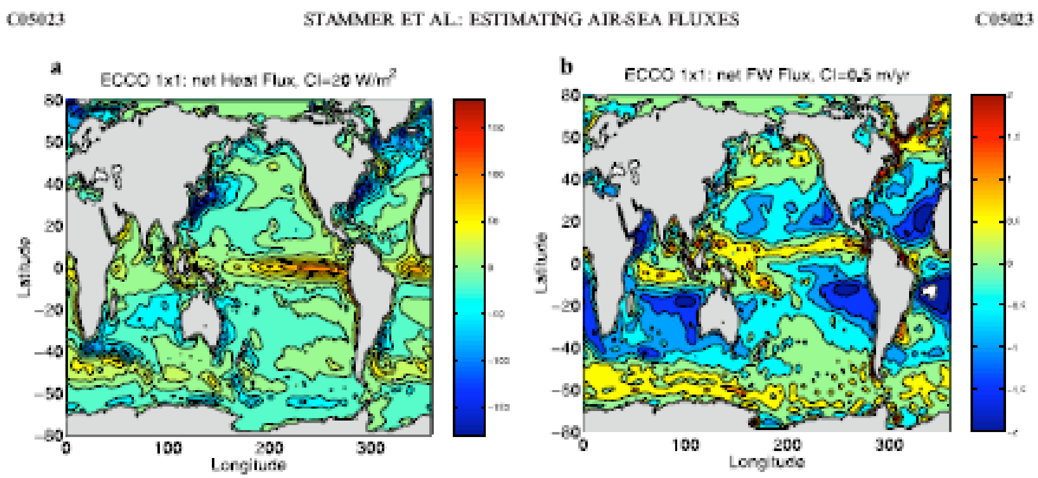
Rio & Hernandez, 2004, mean dynamic topography

One day surface elevation
from ECCO-GODAE v3.73

General circulation dynamic topography is a 2m signature process subject to lateral shifts.



Lots of issues in every element of this problem:



Many problems are meteorological in origin.

Global total P about 1m (Peixoto and Oort, 1992) and approximately equal to the net E-R.

Note large disagreements

Beranger et al., Oc. Dyn., 2006

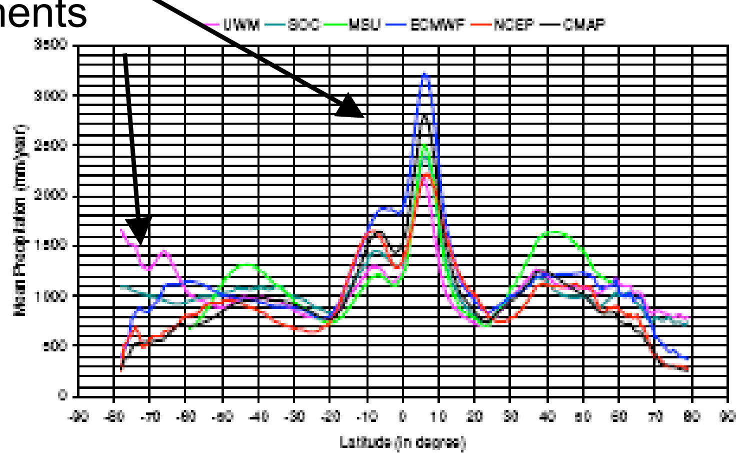
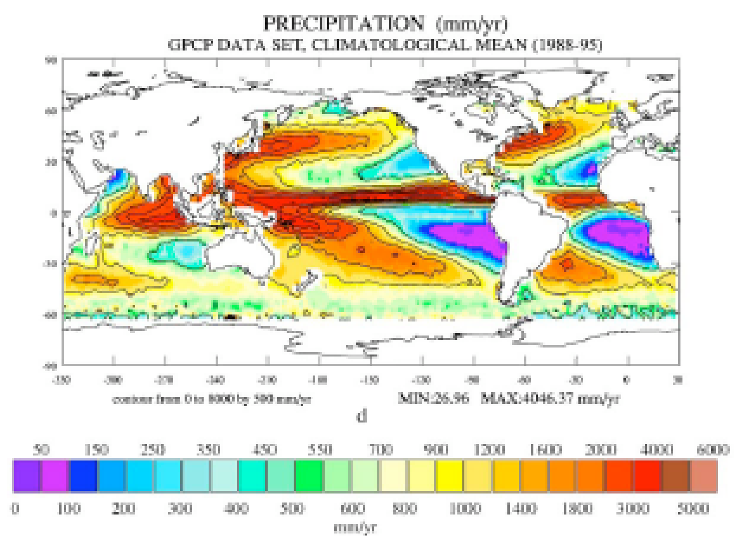
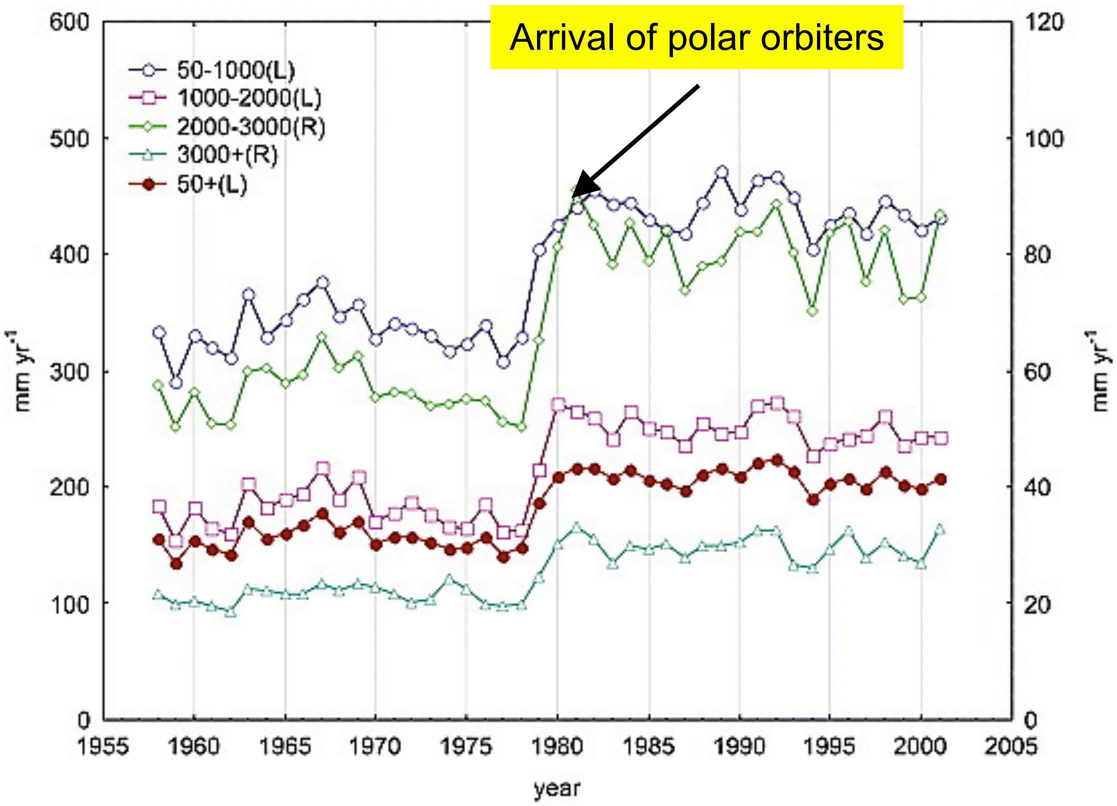


Fig. 4 Zonal average of climatological mean (14-year mean from 1980 to 1993) precipitation over the global ocean for the six da which have this period in common





The “reanalyses” are nearly impossible to use for climate change purposes.

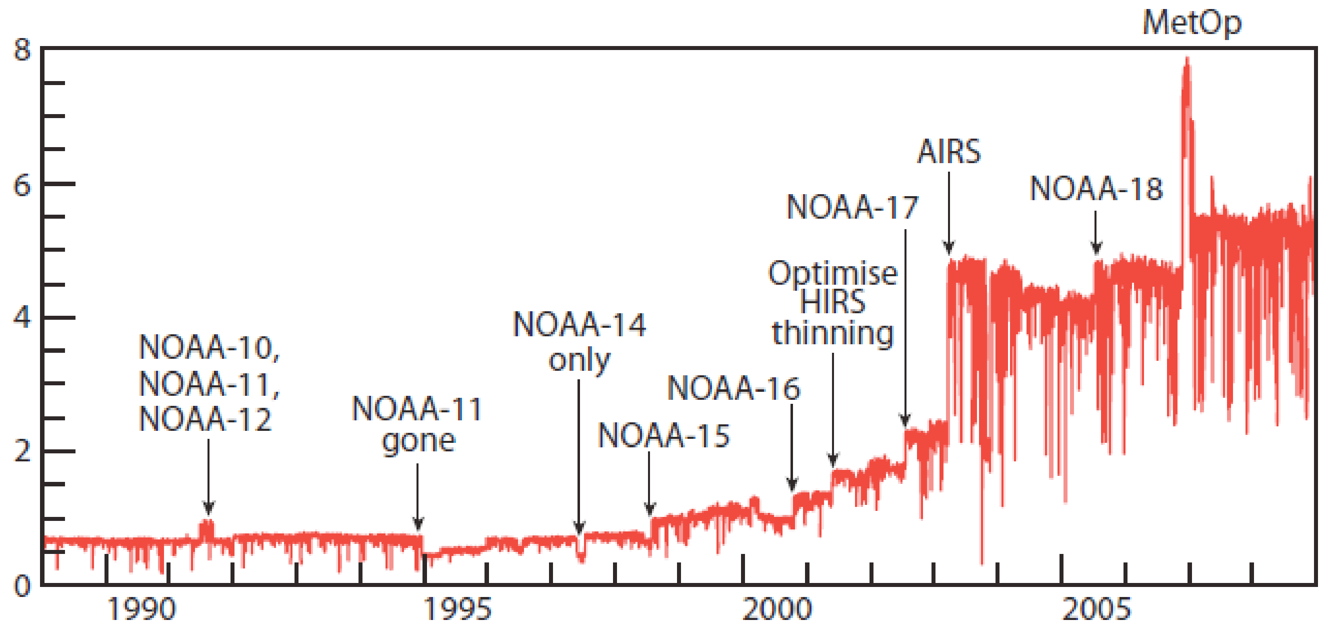
Annual mean area-weighted P-E in Antarctica for various regions and different elevations.

Bromwich et al., 2007, JGR

(from D. Bromwich, 2010)

- A related scenario in the 1990s-2000s?
- Dramatic increase in the amount and quality of satellite observations assimilated into the reanalyses (or available for assimilation).

Number of observations assimilated in ERA-Interim

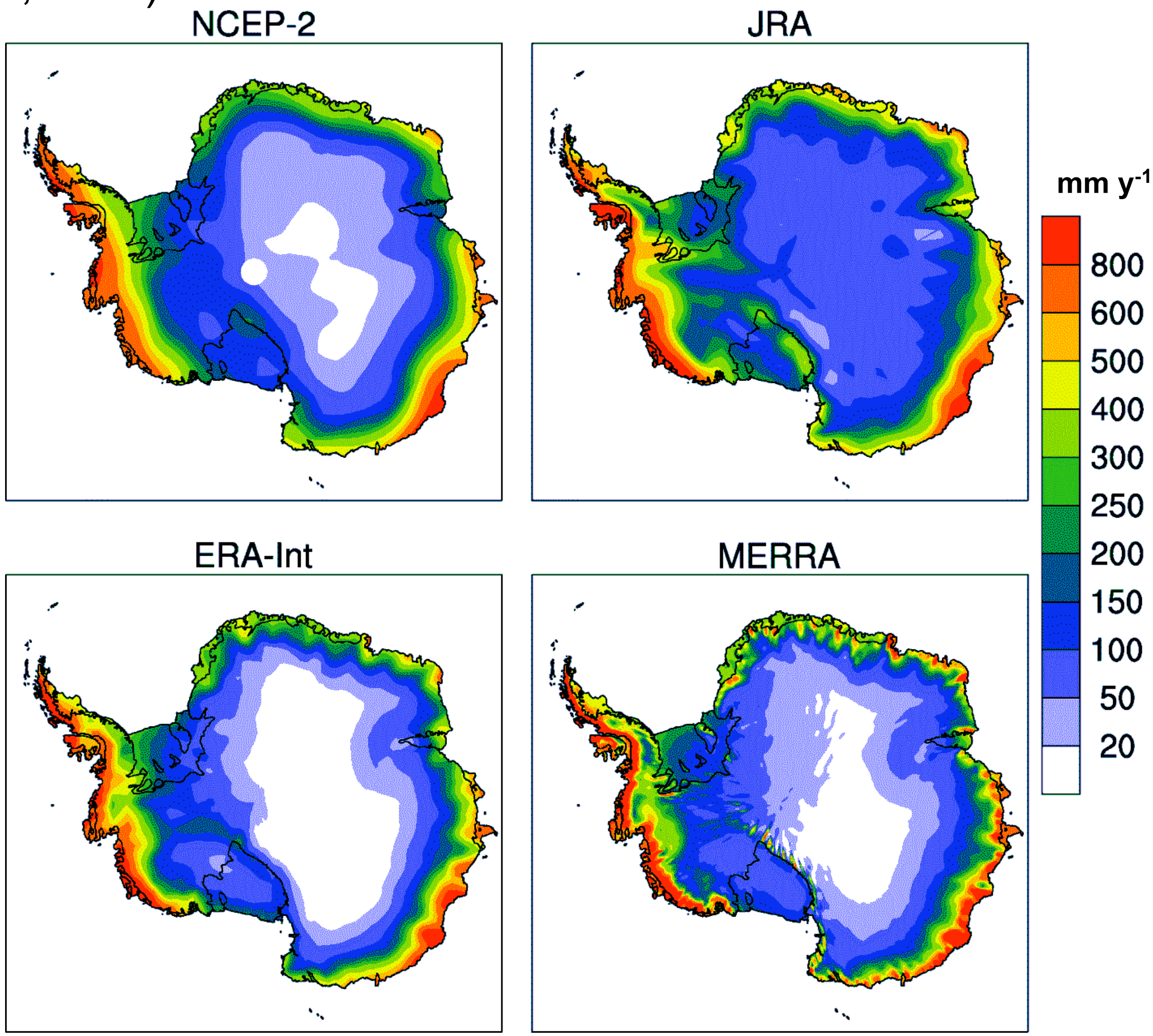


[Dee et al., 2009, *ECMWF Newsletter* (119)]

Mean annual precipitation (P)

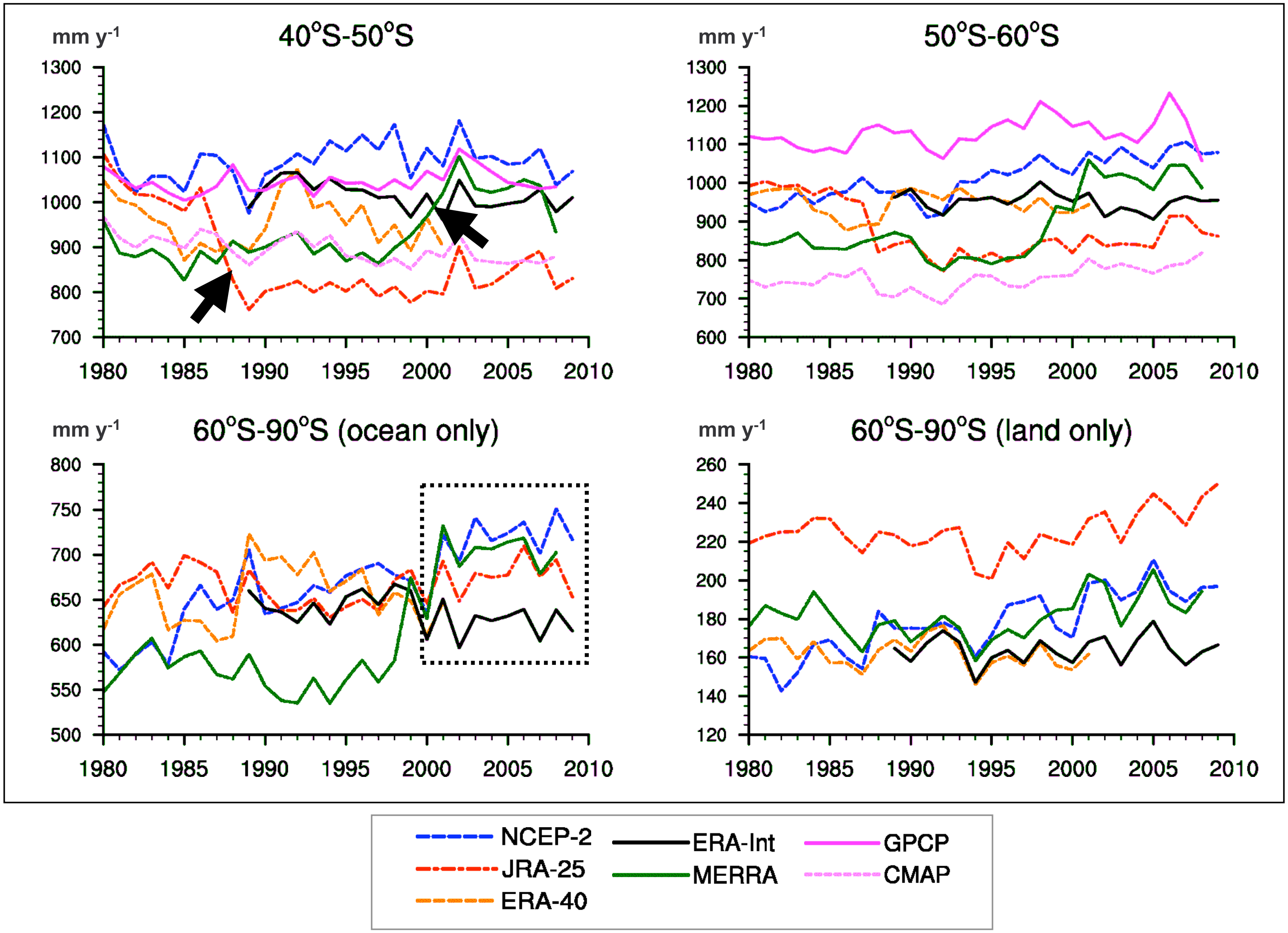
1989-2008

(from D. Bromwich, 2010)

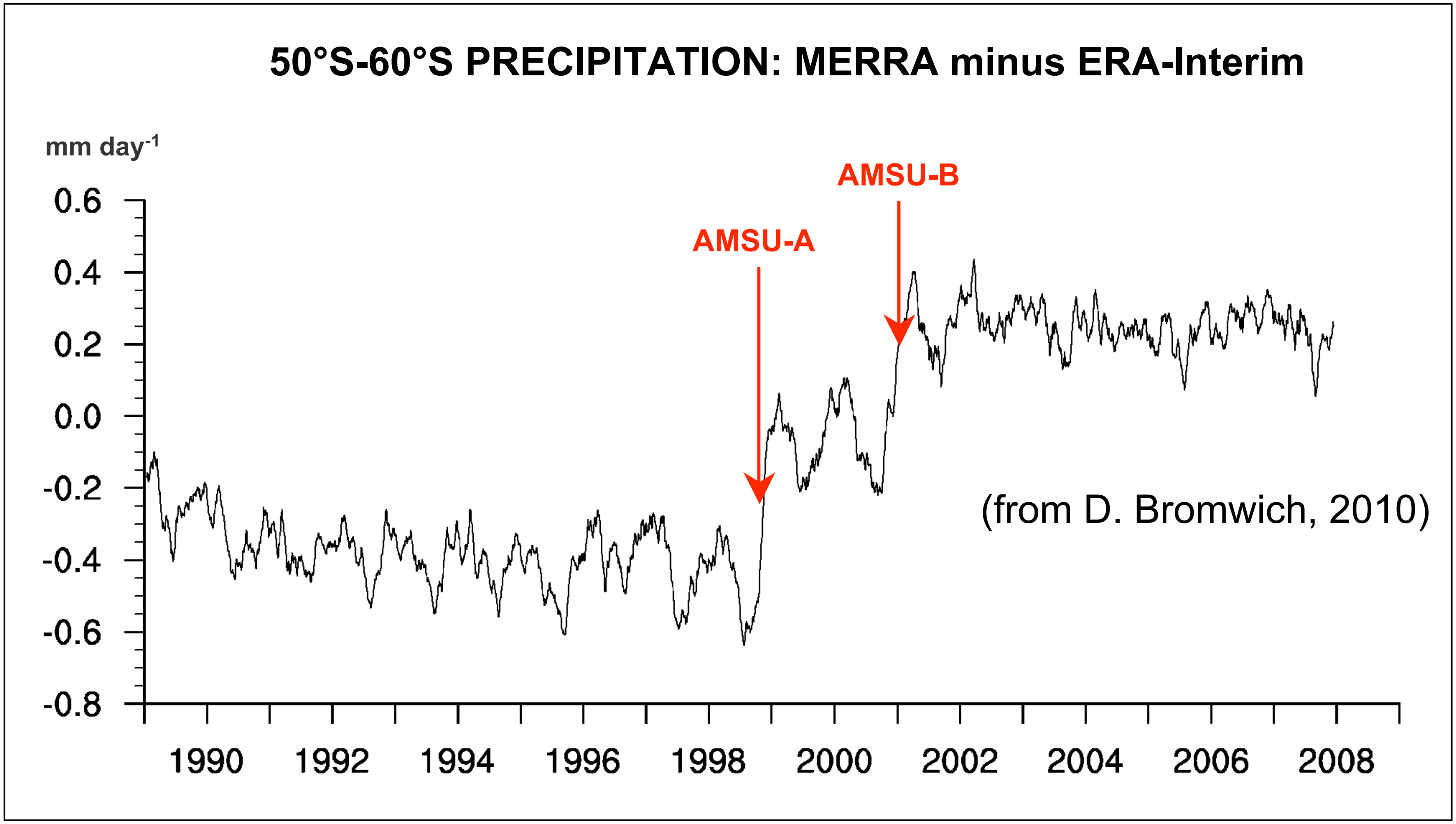


Precipitation by latitude bands

(from D. Bromwich, 2010)



Spurious trends in MERRA precipitation



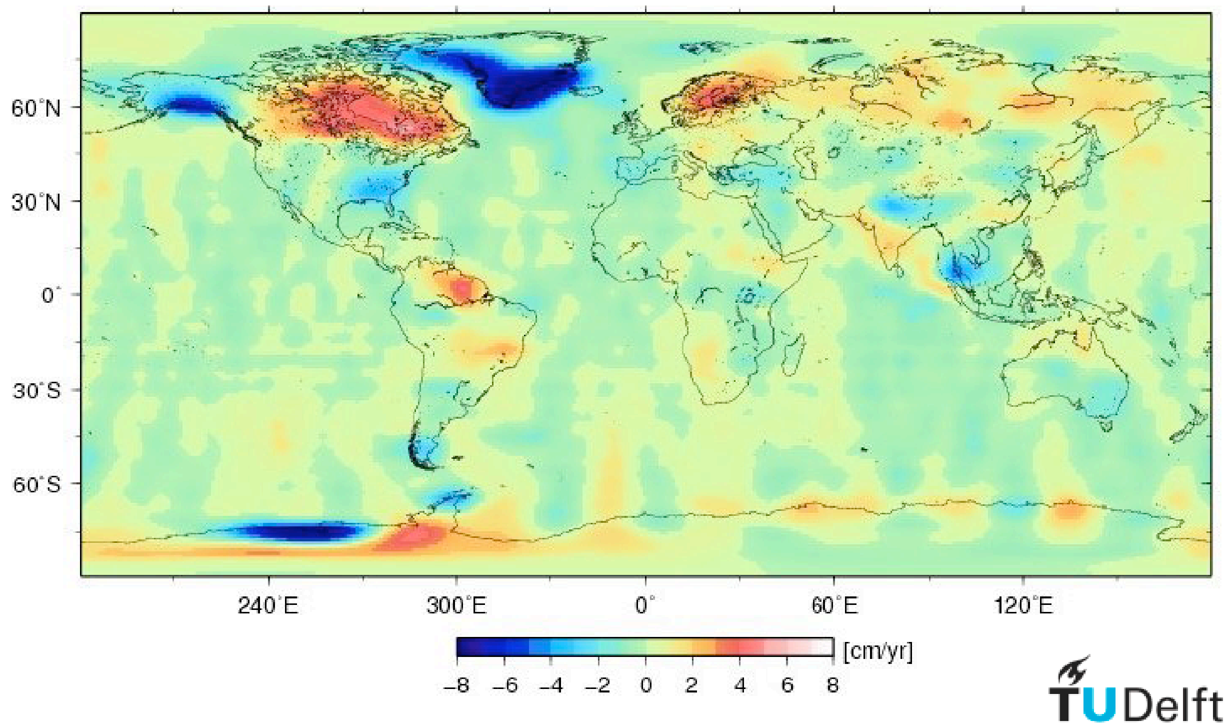
The figure shows the 2-month running average difference between forecast <u>daily</u> precipitation from MERRA and from ERA-Int, spatially averaged over the 50°S-60°S latitude band.

What to believe in the North Atlantic? In the Arctic?

Needs to be quantified.

Other boundary conditions are equally uncertain. Excess ice melt, runoff,…

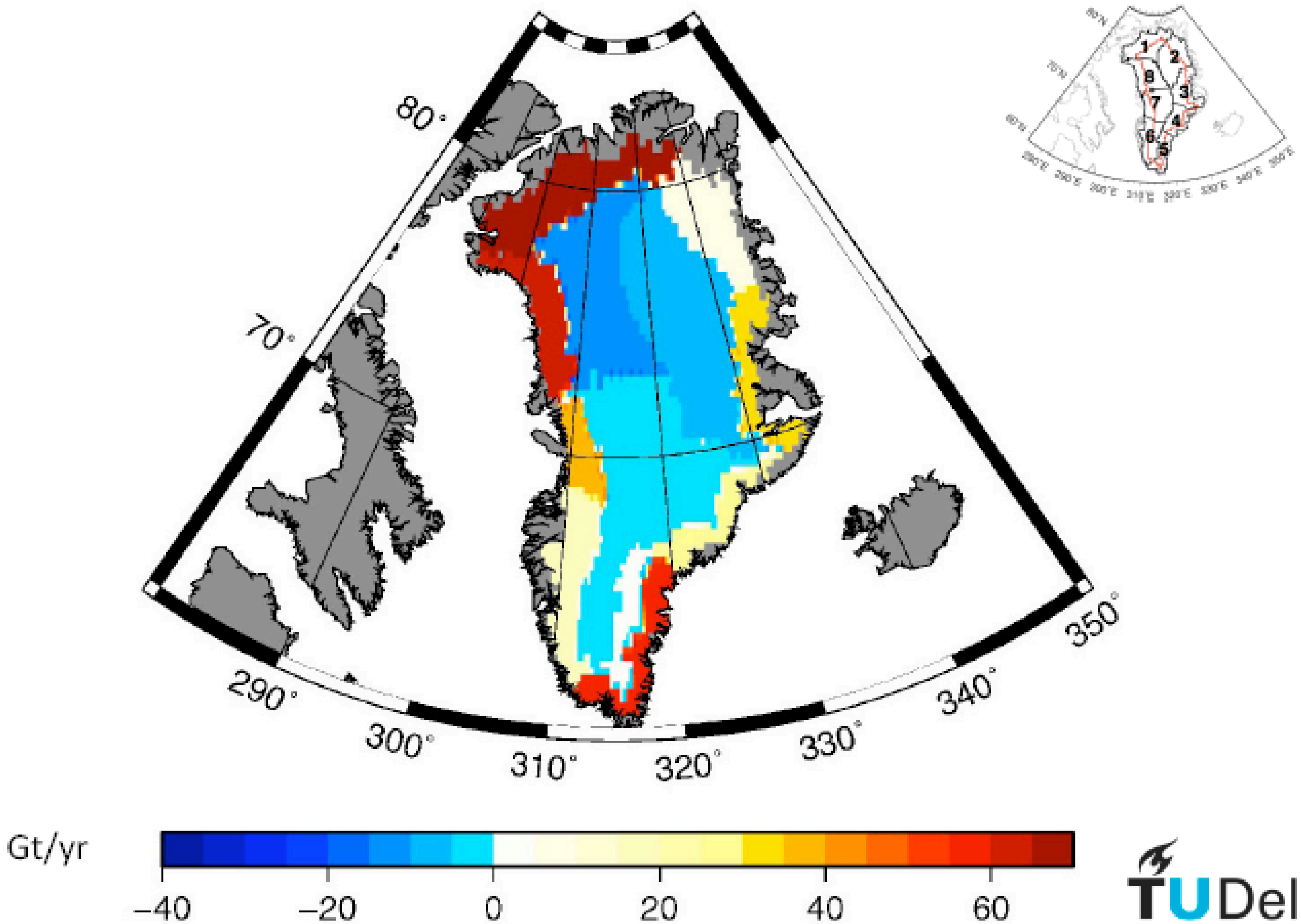
GRACE trend map



An estimate, but not the "truth". Issues of temporal aliasing, atmospheric load, spectral leakage, adjustment for post-glacial rebound, and a very short time-span….

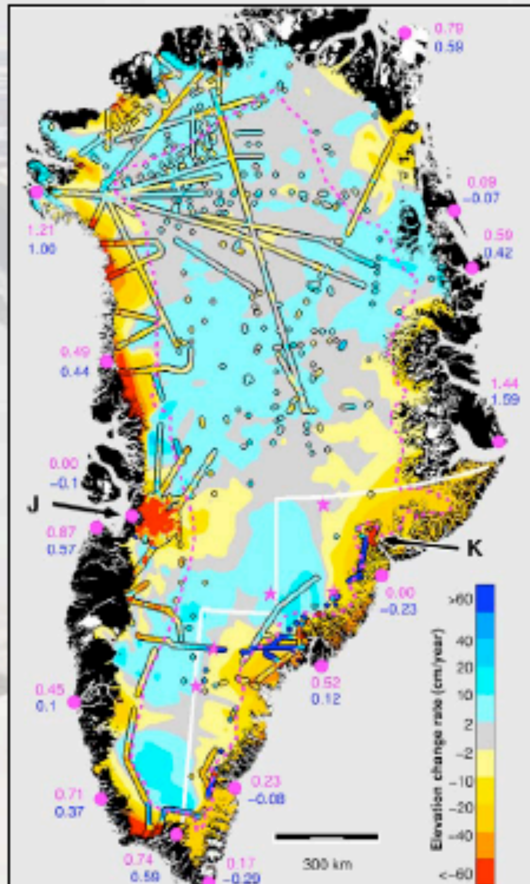
E. Schrama

2006.3 to 2009.3

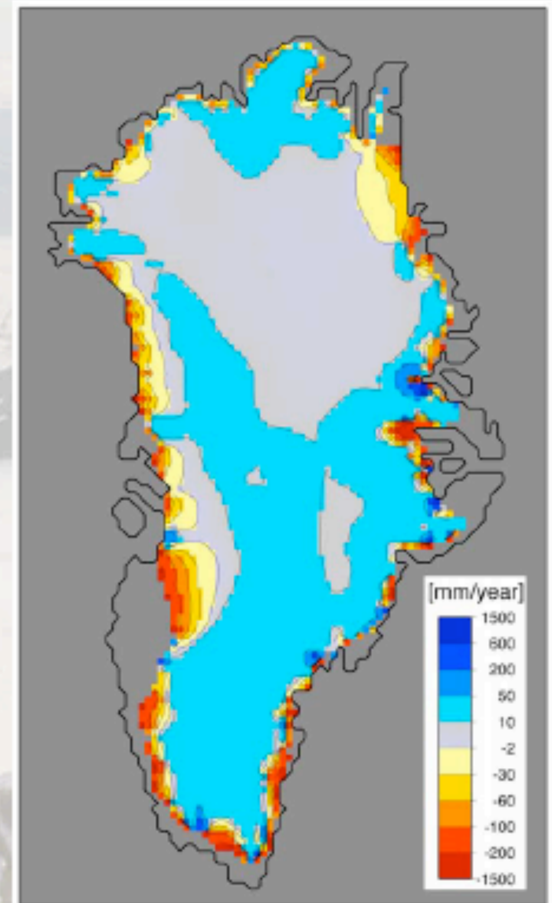


E. Schrama

Patterns of current Greenland ice sheet evolution



Airborne laser altimetry
1993-2003
Krabill et al. (2004), GRL



Modeled long-term evolution
Last 200-year average
Huybrechts et al. (2004), GPC

what is the ocean doing at the margins?
what will it do in the future?

P. Huybrechts

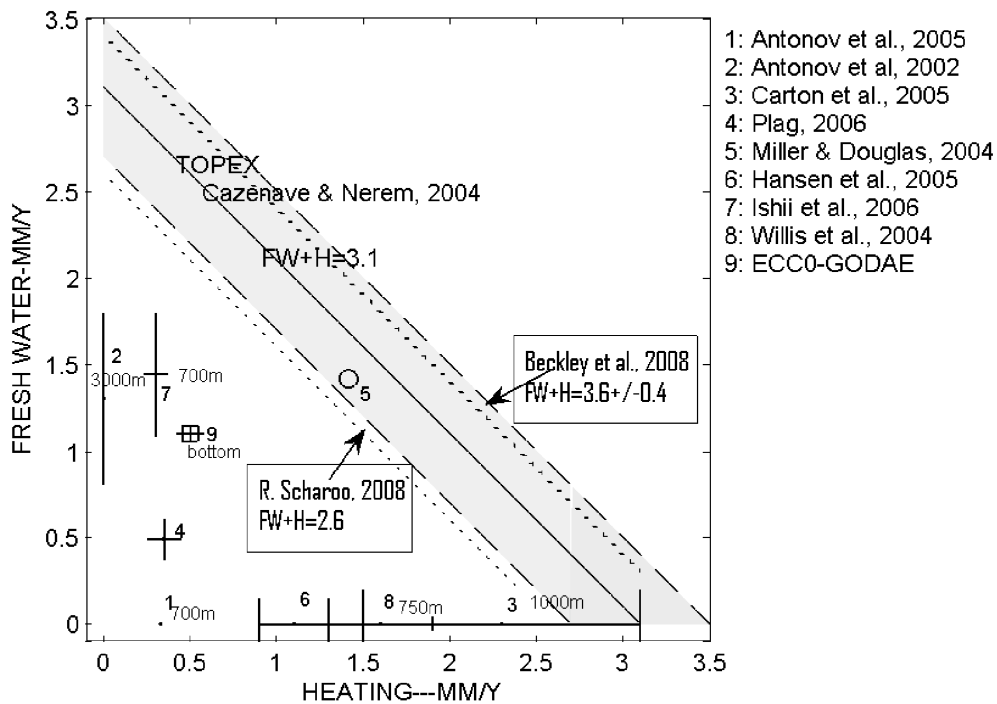
Consider the background hydrological cycle:

Sv (10^6 m^3/s)

1mm/d precip. over Greenland	0.03Sv	0.03	
1mm/d precip. over Antarctica	0.2Sv	0.2	
1mm/y to global ocean (order of mag. of sea level rise)	0.01Sv	0.01	
Global mean ocean precip.	12+/-6Sv	12+/-6	CMAPP website, NOAA, Xie and Arkin, 1997
Global mean runoff to ocean	37,000km^3/y	1.2	Dai et al, 2009, w/o Greenland/Antarctica
Groundwater discharge	2.2-2.4x$10^{12}m^3$/y	0.07	Zektser et al., 2007; see Moore 2010
Global mean evaporation		-13	To balance runoff+precip
Greenland climatological runoff	100-200km^3/y	0.003-0.006	Box et al. 2004.
Antarctica climatological runoff	170mm/y	0.07	Bromwich et al., 2004, Jacobs et al. 1992, 2613km^3/y (error bar?)
Net ice mass loss: Greenland	137to 286 Gt/yr	0.004-0.009	Velicogna, 2009
Net ice mass loss: Antarctica	104 to 246Gt/yr	0.003-0.007	"
1mm/y to global ocean: salinity change	$1.31 \cdot 10^{-5}$/y	negative	
120m sea level rise in 10,000y	1 cm/y globally	0.1	
Deglacial salinity change rate	$1.31 \cdot 10^{-4}$/y	negative	1.1 total S change
Heinrich event 4	2+/1m s.l. change over 250+/-150y	0.025-0-0.3	Roche et al., 2004
120m drawdown of sea level over 100KY		-0.012	

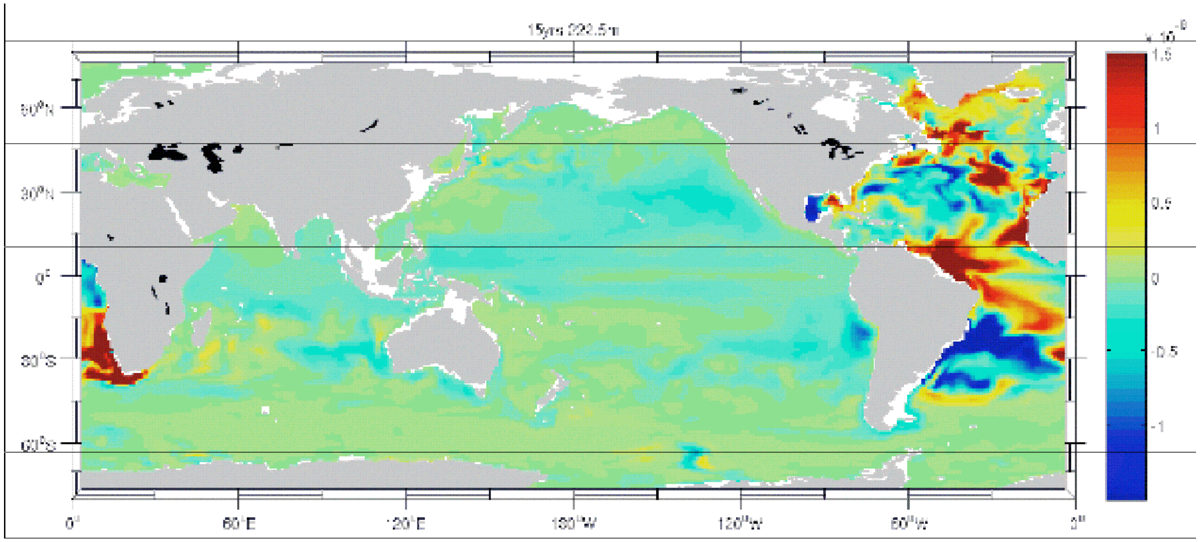
Can one perceive the changes in the N. Atlantic circulation owing to increased fresh water input from the edges?

TOPEX value includes
0.3mm/y from R. Peltier
estimate of ocean volume
change (PGR).
o from Miller & Douglas
is pure tide gauge value.



Everything is positive! --- at least.

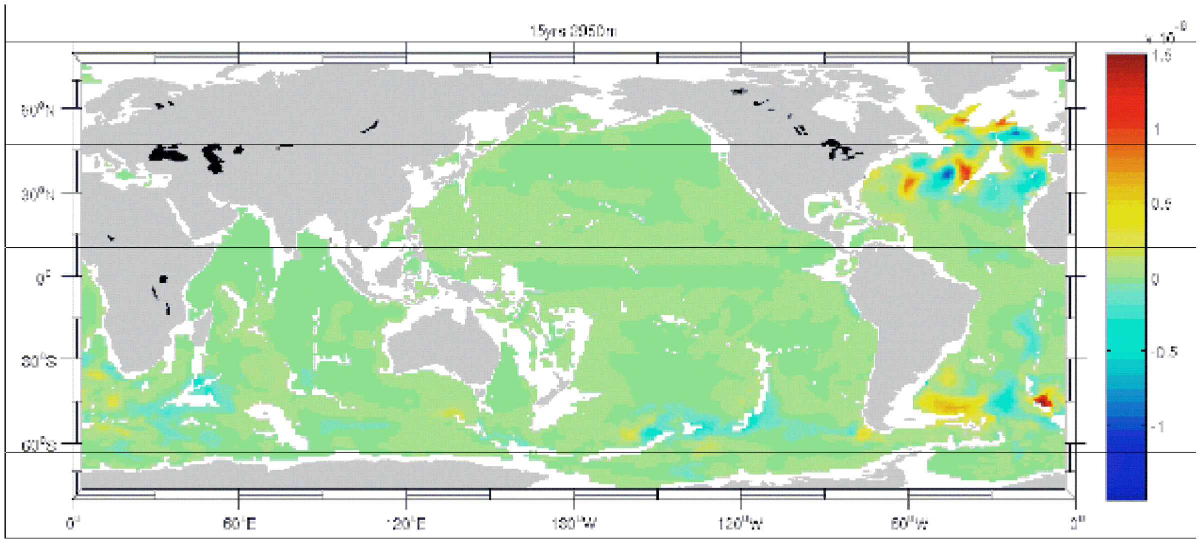
(Global balance is primarily a test of scientific understanding.



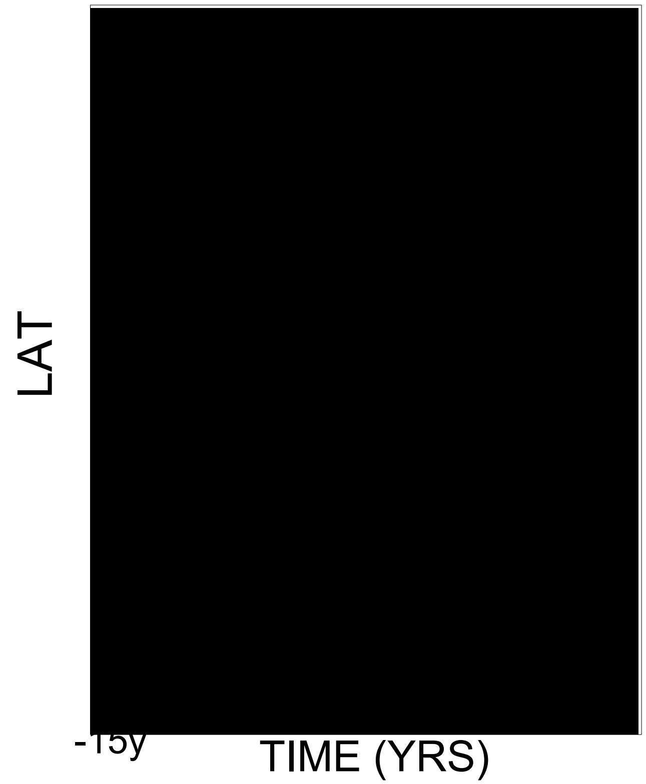
Sea level change sensitivity, western N. Atlantic (US east coast) from (normalized) temperature changes 15 years previously (P. Heimbach from ECCO v3.73)

Normalization is by the expected errors in the measurements.

Clearly, forecasting and understanding of change involve the ocean and atmospheric states over long times

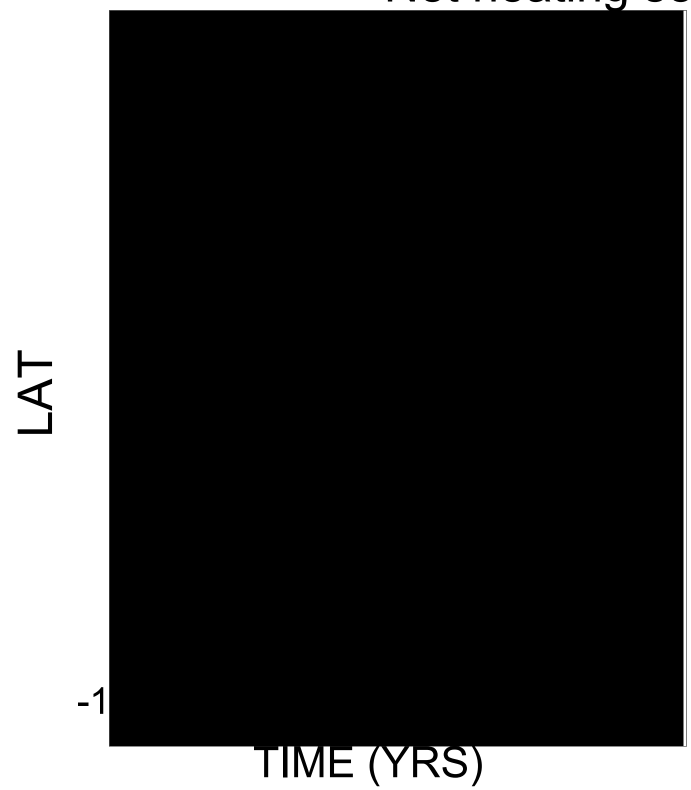


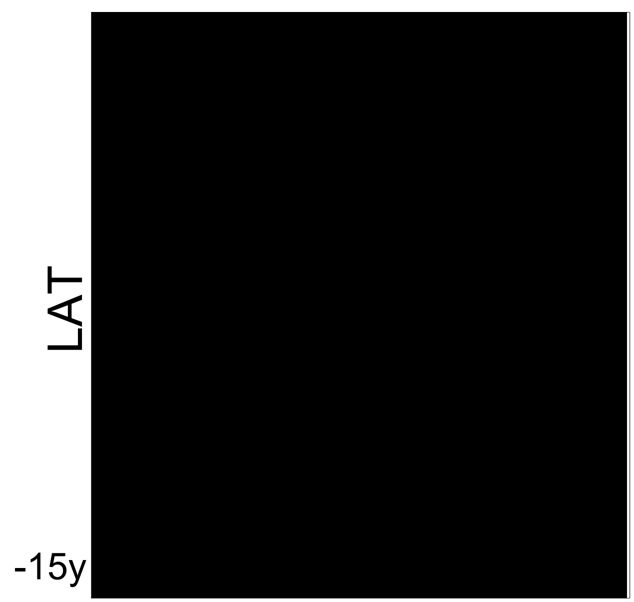
East coast sea level anomaly, t=-15 years, sensitivity to normalized temperature anomaly, 3000m



Sensitivity, east coast sea level, to zonally summed, zonal wind, back to 15 years earlier.

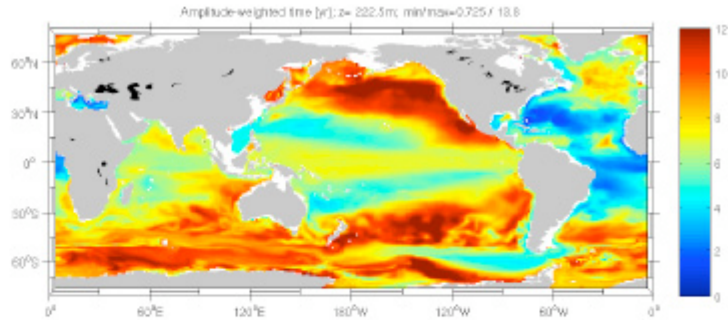
Net heating sensitivity, to-15y



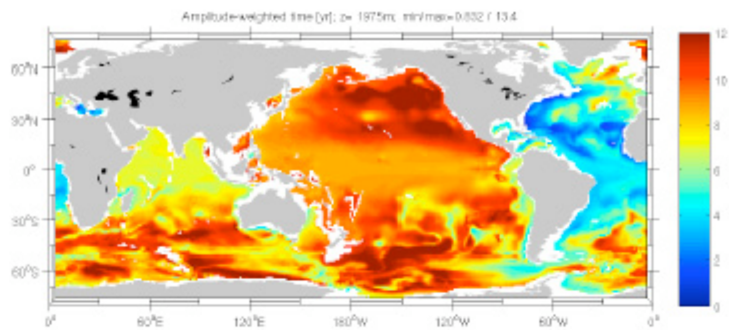


E-P-R

Temperature sensitivity, 26N, N. Atlantic meridional heat flux to disturbances 15 years previous.



(a) 222 m depth



(b) 1975 m depth

Figure 5: Maps of mean times weighted by the amplitude of the normalized response fields, eqn. 5, for two different depth levels. Color scale refers to years (from 0 to 12). A small value in a certain region indicates fast dominant time scales of dynamical link between the region considered and 26N in the Atlantic. fig:mean-time-maps

Heimbach et al., submitted, 2010

Information flow in the dual model: anti (dual) Kelvin, Rossby waves etc.

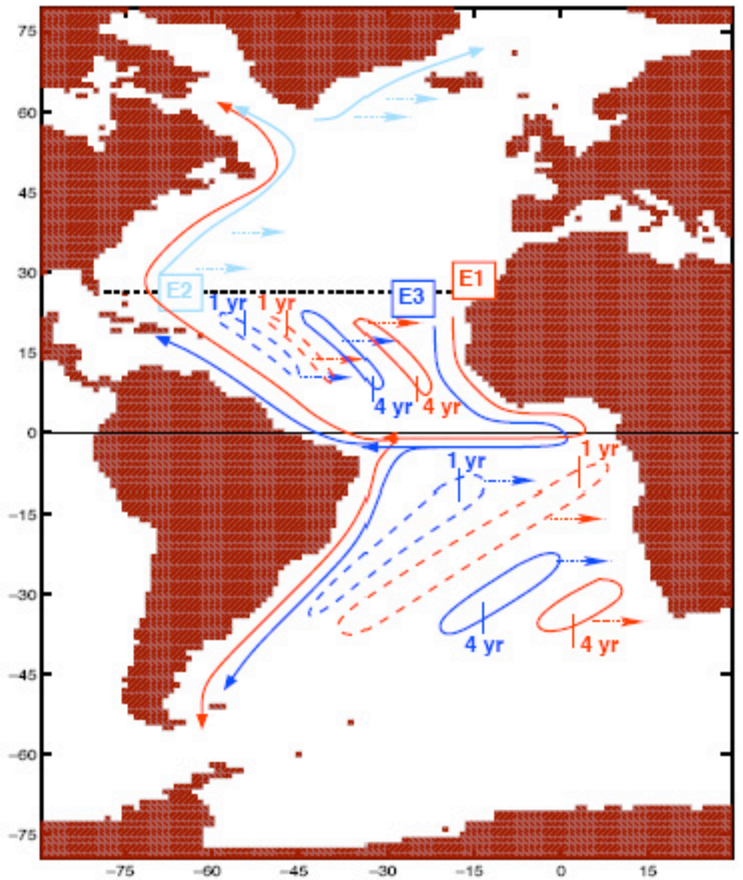


Figure 3: A schematic of anti-Kelvin waves (lines) and anti-Rossby waves (contours and dotted arrows) propagating sensitivities from the 26N line backward in time. Color coding refers to different events discussed in the text ([E1]: red, [E2]: light blue, [E3]: dark blue. `fig:map-schematic`

Heimbach et al., submitted, 2010

Observations:

Need meteorological forcing back several decades---a demand for useful reanalyses (balanced in energy, water, etc.) with physical budgets

Climatological fresh water inputs including runoff, ice melt, subsurface percolation

Increments of ice melt

The ocean state, globally, as far back as is practicable.

Predictions of:

Meteorological forcing, including winds, E-P, total heat transfer.

The ocean state.

Modelling

Resolution issues---numerical convergence
Surface boundary layer issues (manifold)
Mass conservation (Boussinesq approximation)
Geothermal contribution…

mixed layer depth

1deg.

1/9deg

1/54 deg.

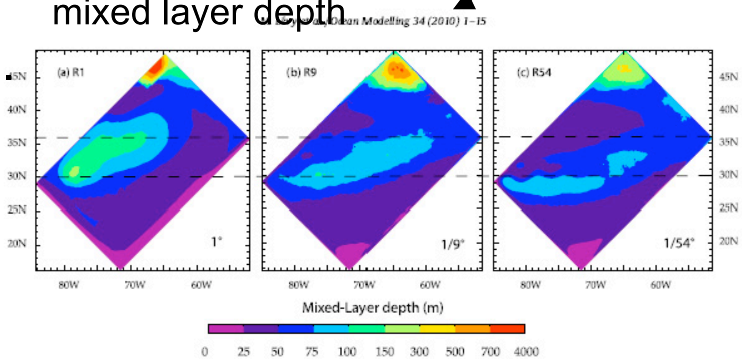


Fig. 9. Ten-year-mean mixed-layer depth (MLD) in experiments R1, R9 and R54. The MLD is computed as the interface of the surface layer whose density does not exceed the surface density by more than 0.01.

Lévy et al., Ocean Mod., 2010

mean density along 72W

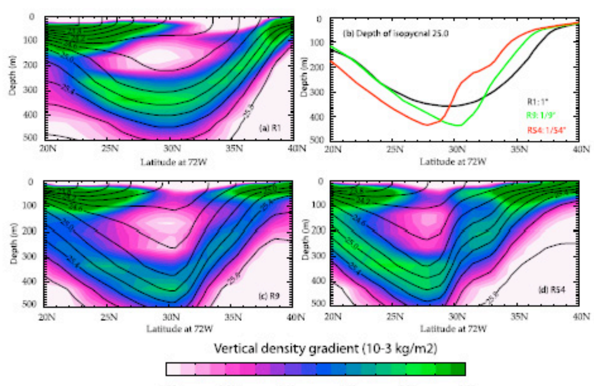


Fig. 11. Ten-year-mean density (black contours) along a section at 72°W in experiments R1, R9 and R54. The colors show the intensity of the vertical density gradient. To facilitate the comparison, the depth of the 25.0 isopycnal is reported in panel (d) for the three experiments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

meridional heat transport

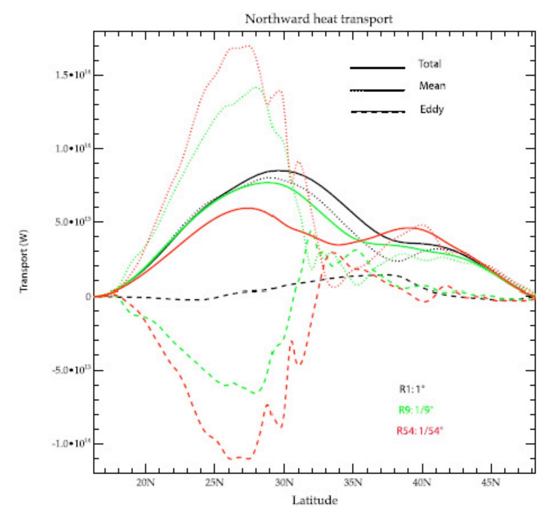


Fig. 12. One-year-mean northward heat transport (in W) in experiments R1 (black), R9 (green) and R54 (red). The plain line shows the "total" heat transport, computed from the integration of 1 year-mean meridional heat fluxes. The dotted line shows the "mean" heat transport, computed from the 1 year-mean flow and 1 year-mean temperature distribution. The dashed line shows the "eddy" contribution, computed as the difference between the "total" and "mean" contributions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

At what skill level are predictions useful? What skill level can be achieved with inevitable uncertainty growth backward into the past? What is that skill as a function of prediction lead time?

An understanding of a predicted regional change over e.g., 1 to 10 decades, requires quantitative measurements and budgets (temporal and spatial) for the regional:

Freshwater input/output: precip., evaporation, land ice, melting/forming sea ice, subsurface percolation,
Heat exchange with the atmosphere
Wind-shifts

Advective inputs of volume/mass from the south and from the Arctic (the open boundaries)

Dynamical, quantitative understanding of the volumetric changes and their time-scales and relative contributions.

Quantitative predictability of these different elements.

A Strawman Proposal

Agree on a goal: US east coast sea level trend to be predicted to 15 years with an accuracy equivalent to 0.3mm/y. (Almost all physical processes show up in sea level and/or are affected by sea level.) Altimeter sets of a nominal accuracy goal.

Design an observing system that would be capable of that accuracy.

Develop the models capable of that accuracy.

Formulate a requirement on meteorological reanalyses capable of that accuracy.

Construct a coupled atmosphere-ocean-sea ice-land ice model formally capable of prediction from a known initial state.

Many people will not find this a compelling goal---but it does provide a framework incorporating almost all imaginable ones related to the ocean circulation. A 15-year time scale is humanly accessible.
It involves several other communities. Is that a bad thing?

Something for everyone:

Model development
Theory
Observations
Real practical potential

A prize (?):

$10,000 to be given to a forecast---made 12 years in advance---of sea level change along the US east coast (north of Cape Hatteras to Cape Cod ?), reproducing the observed trend to within 0.3mm/y. In the event of more than one successful candidate, tie breaking will be determined by the skill in (1) heat content change north of 30N, (2) sea ice cover in January, (3) September sea ice cover….

(Details, and determination of a winner, to be worked out in practice by an appointed committee.)

Thank you.