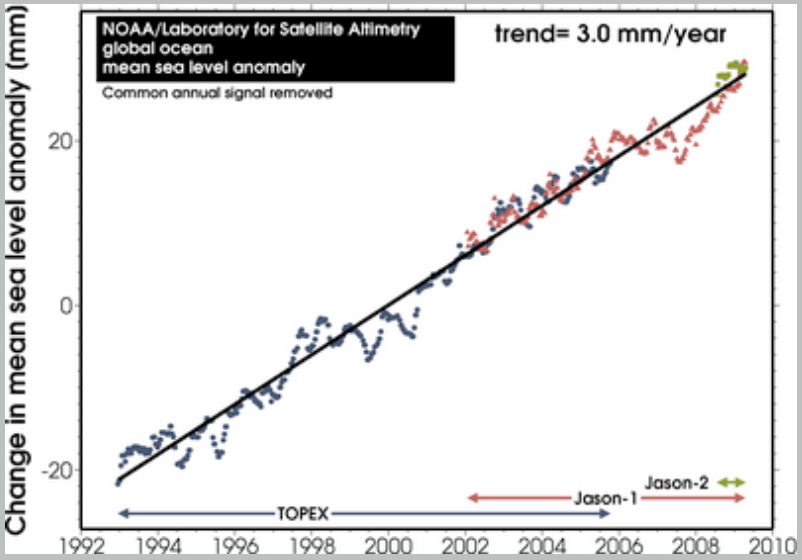
Global Sea Level Change

Seattle June 2009

Carl Wunsch, MIT

Global mean sea level from TOPEX/ Poseidon and Jason-1

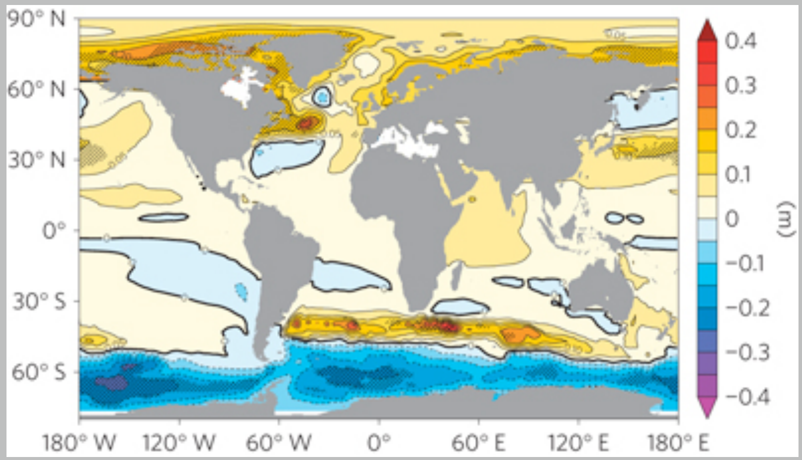


Note the imputed accuracy of 0.1mm/y.

Is this result reliable? (A lot rides on it.)
Can we understand it quantitatively? How much regional variation is there? Can we predict reliably?

And of course, people are claiming to predict it.

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.

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

Satellite altimetry has become the standard estimator for global sea level change

But starts only in 1992

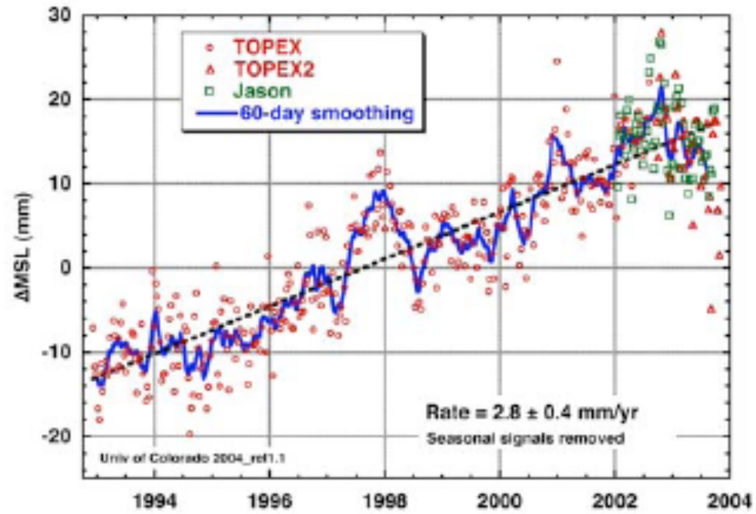


Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the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

Cazenave and Nerem, Revs. Geophys. 2004

This result may be fully accurate and precise, and there is no specific basis for questioning it other than a sense of the complexity of the overall system. One seeks reassurance. And, can one understand it?

Computation of the global mean to an accuracy of less than 1 mm/year, and preferably better than 0.1mm/year, is a very tough goal. *Anyone* can compute a nominal global average. The science question is to understand the real accuracy and precision.

Challenges include:

(1) Modeling
(2) Observation
(3) Theory
for ocean, atmosphere, cryosphere, crust, and mantle

The problems of the altimetric era are different from those of the preceding eras, and the eras of tide gauges differ among themselves and differ from the pre-tide gauge era. Cannot treat as a single problem!

Systematic errors are pernicious.

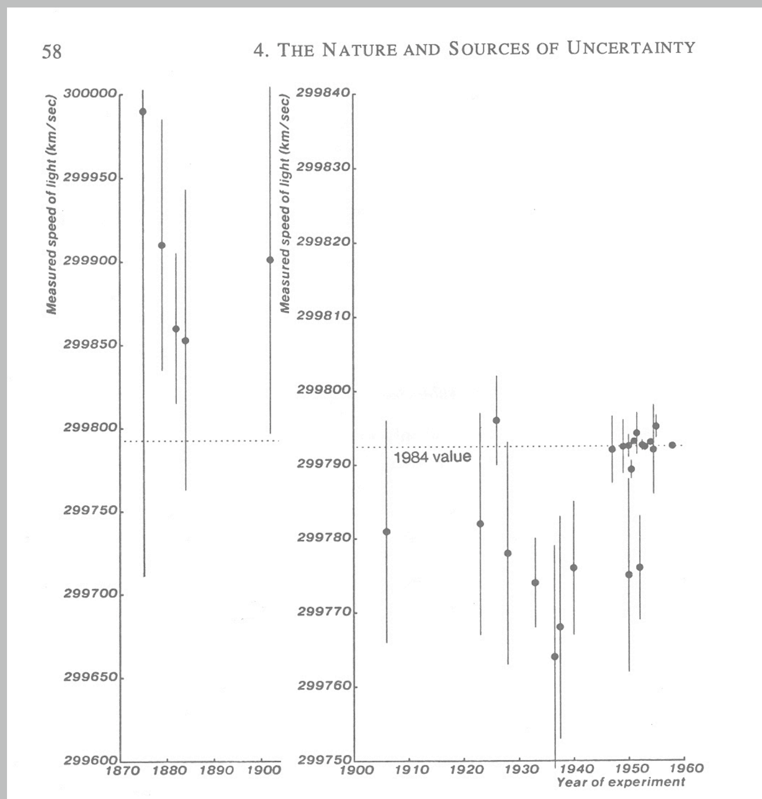


Figure 4.1. Experimental measurements of the speed of light between 1875 and 1960. Vertical bars show reported uncertainty as standard error. Horizontal dashed line represents currently accepted value. Less than 50% of the error bars enclose the accepted value, instead of the expected 70%. From Henrion and Fischoff, 1986.

A nice classroom example: Measurements of the speed of light---under extremely carefully controlled laboratory conditions by obsessive scientists.

Vertical bars are the standard errors.

Did it change with time (some theories support that interpretation)? Or were there systematic errors?

The concept of altimetric sea level change is beautifully simple. Twenty-five years of hard work has gone into making the data sets easy to use. Many people using gridded data have no conception of what has been done to the raw radar returns.

It's easy to forget how complex is the system required to achieve useful accuracies.

Corrections (and warnings) for the Jason data:

orbital altitude, CNES EIGEN-GL04C [m]
altimeter range corrected for instr. effect
ECMWF dry tropospheric correction [m]
JMR wet tropospheric correction [m]
smoothed dual-frequency ionosphere correction
local+global inverse barometer correction
solid earth tide [m]
ocean tide, GOT4.7 [m]

Trends in many of these will produce apparent trends in sea level. Each must be corrected at a very high level of accuracy. (The original global estimate (1995) was later halved when a single-line coding error was found.) And it is easy to forget that the data are not really global (high latitudes, shallow water missing), nor are they homogeneous with season. Gridding methods introduce various unquantified biases. Altimetric systems are *not* linear.

How many of these are known to have trends of less than 0.1mm/y?

off-nadir angle squared from waveforms (Ku)
reference frame offset [m]

Spatial/temporal amplitudes vary from nearly a meter to millimeters.

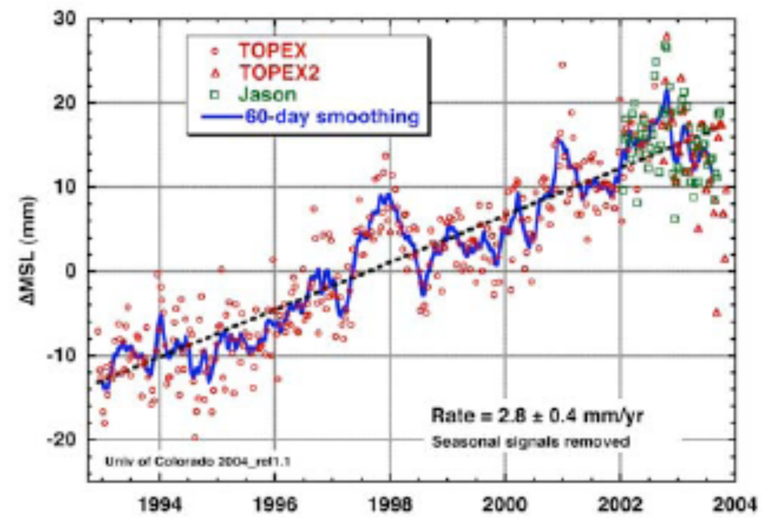
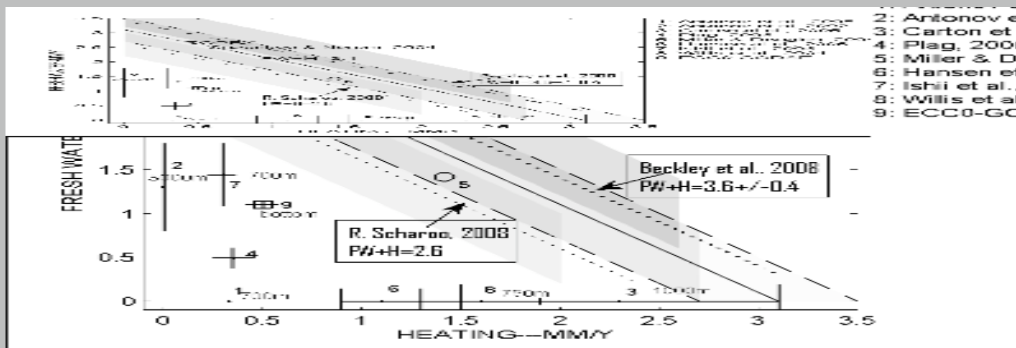


Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the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

Can one confirm and understand this result from in situ observations and/or modeling?

Why is it changing??



TOPEX value includes 0.3mm/y from R. Peltier estimate of ocean volume change (post-glacial rebound---PGR), a 3rd axis for the graph

o from Miller & Douglas is pure tide gauge value.

ECCO-GODAE

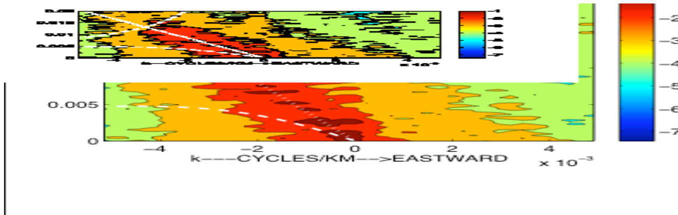
Completely inhomogeneous in time interval, depth of integration, data type, gridding,….

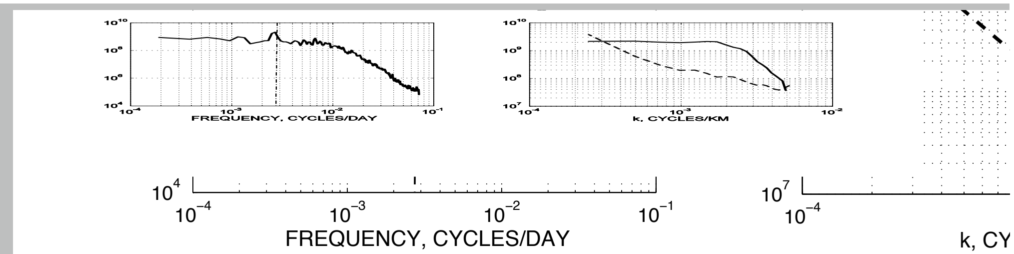
The use of in situ data raises all kinds of interesting issues.

Everyone knows that the space/time sampling of the ocean is extremely inhomogeneous.

If the ocean were spatially *statistically* homogeneous, computation of the uncertainty owing to the sampling inhomogeneity would be easy. But spatial variances of variability vary by more than two orders of magnitude, and the space/time structure also varies greatly.

I am unaware of *any* convincing estimate of the changing error statistics with space and time.

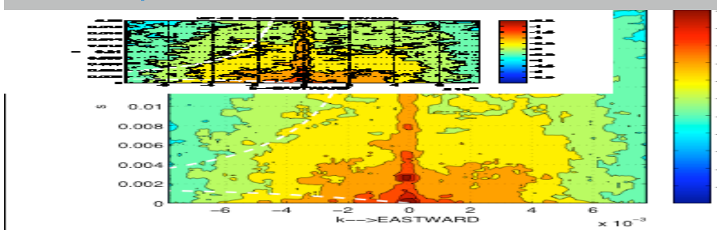


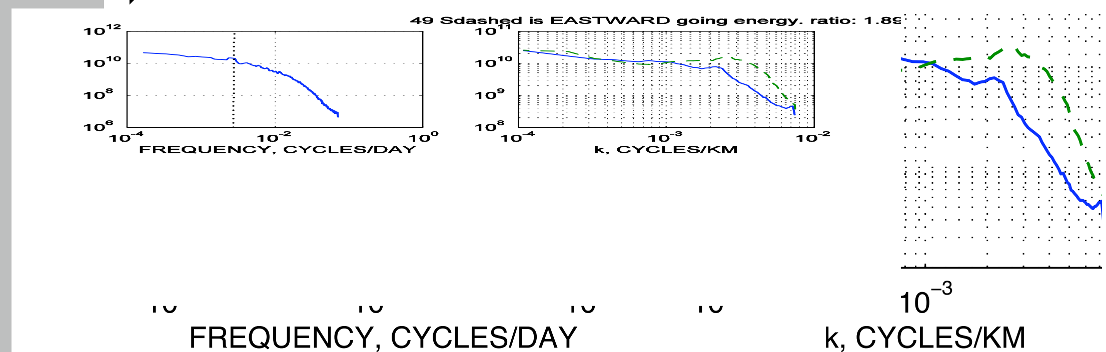


frequnecy

wavenumber

frequency/wavenumber power density
subtropical latitudes





frequnecy

wavenumber

Sampling characteristics of the Southern Ocean are very different from anywhere else. Any realistic error estimate must account for that.

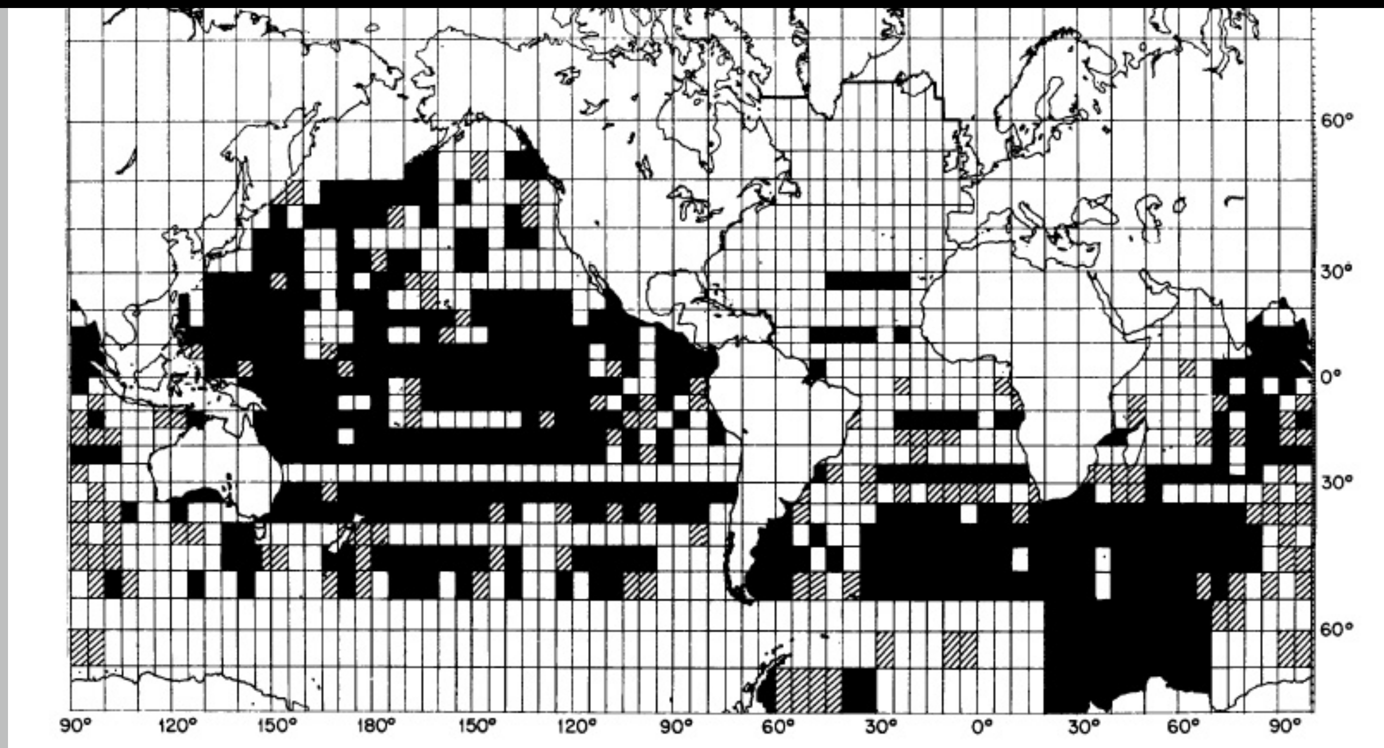
frequency/wavenumber power density
Southern Ocean

Error from not sampling the Southern Ocean cannot be computed from sampling statistics of mid-latitudes

Consider the sampling problem for in situ hydrographic (temperature and salinity) data.

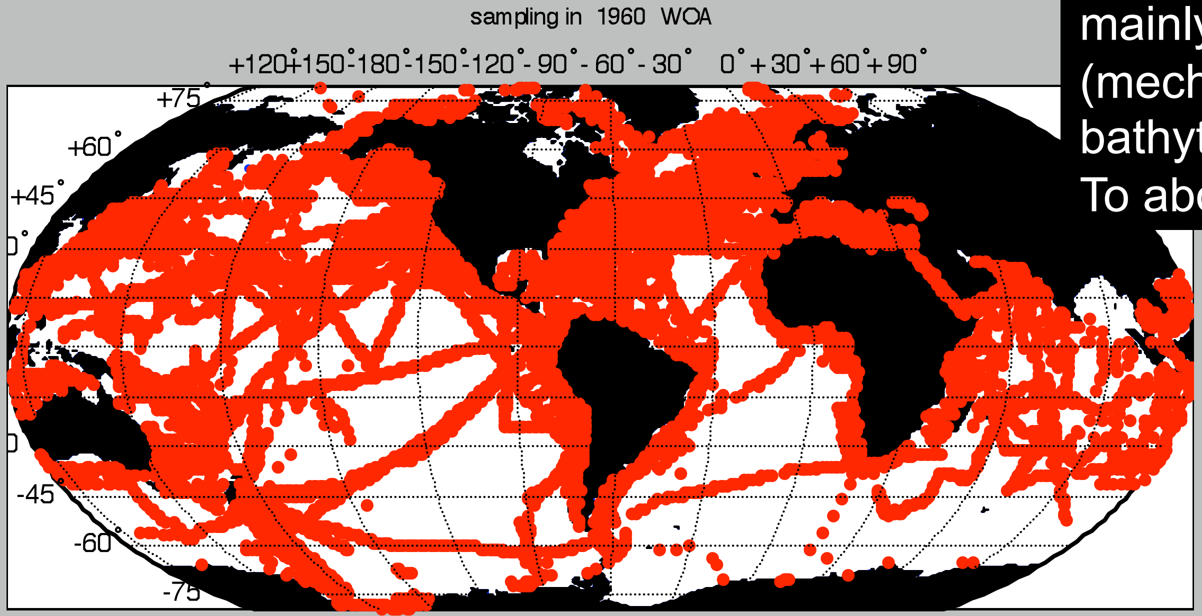
Worthington, 1981, Evol. of Physical Oceanography

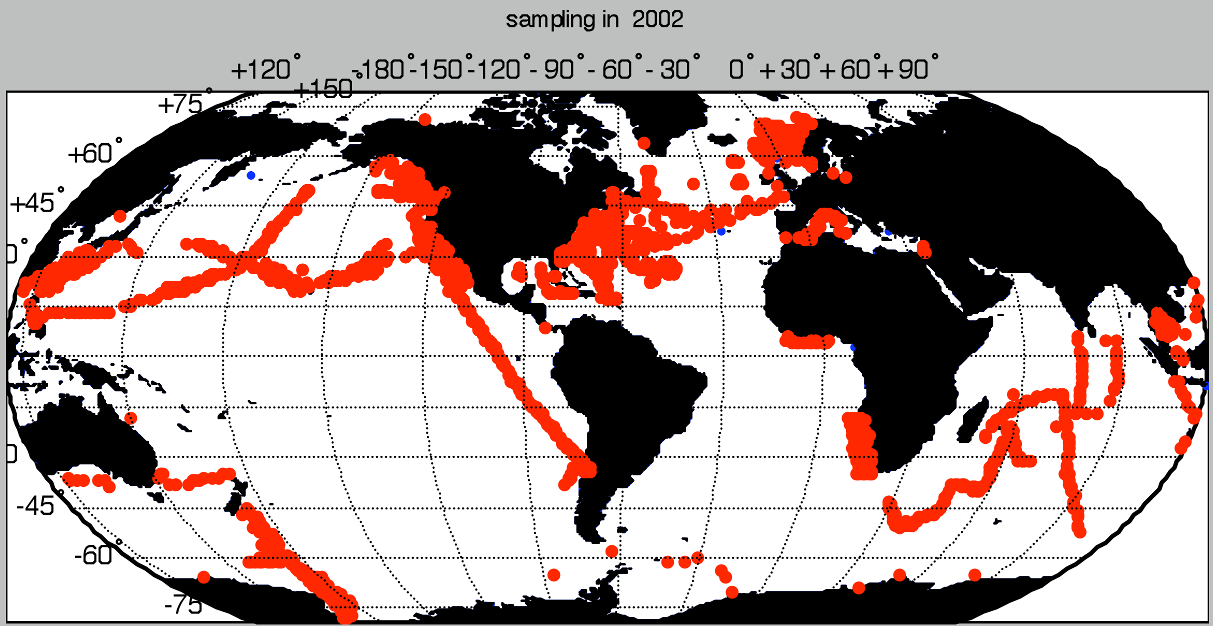
Worthington threw out almost all data, as being inaccurate, except those obtained by a small private club of trusted hydrographers. Contrasts greatly with some recent “data mining” activities. Are the errors in the data Worthington rejected random? Or systematic?

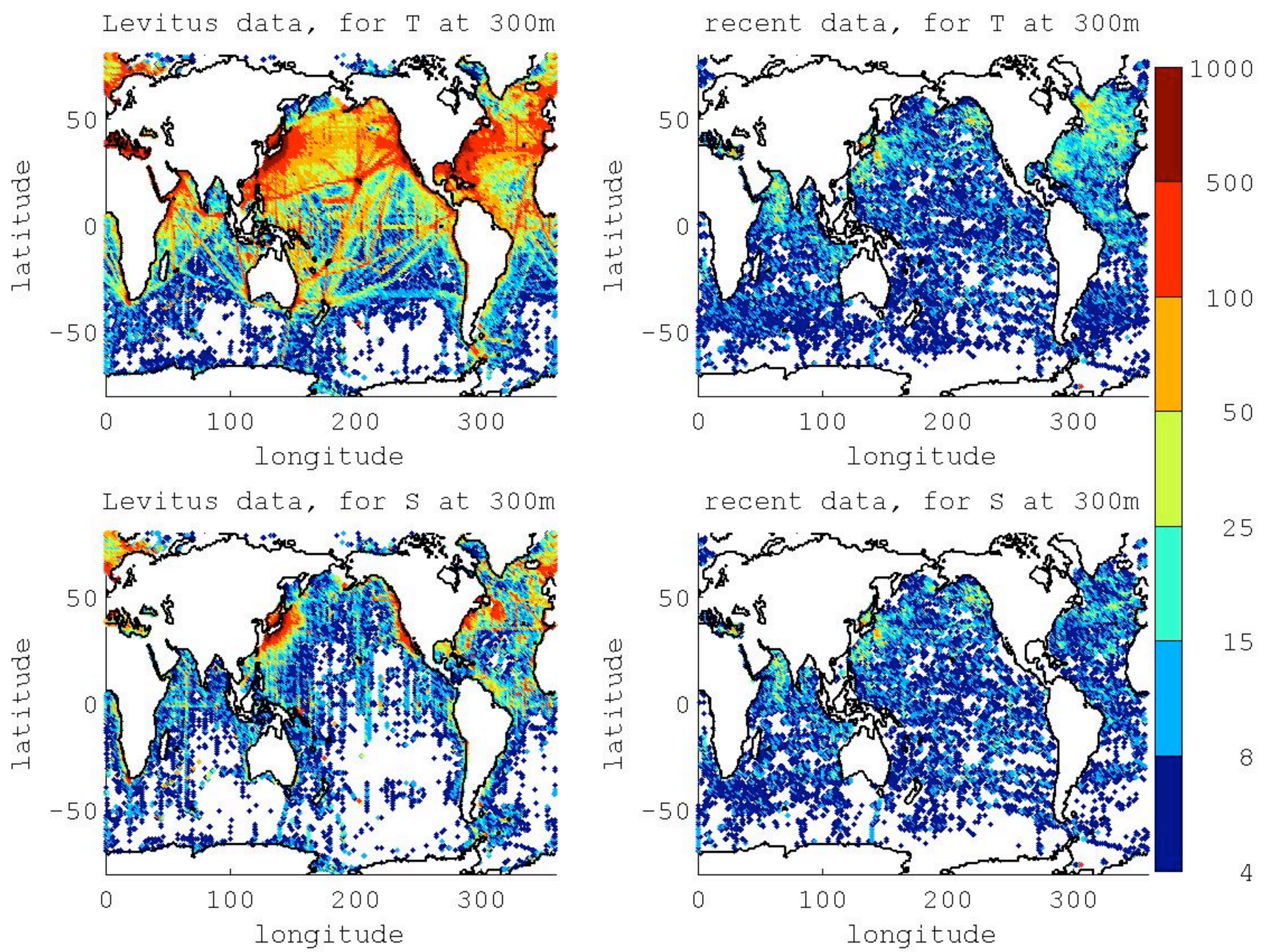


As of 1977, white squares had at least *one* acceptable deep station, Hatched had at least *one* intermediate depth station, and black had *no* acceptable station.

mainly MBTs
(mechanical
bathythermographs)
To about 400 feet (sic)







G. Forget

More than 4 measurements in a 1 degree square in 50 years.
"Recent" means WOCE & later. To 300m (recall that the mean ocean depth is 3800m).

With what accuracy can one compute global averages from such data???

Examples of possible systematic errors in data leading to trends:
(XBT fall rate errors have attracted much attention. But many others.)

Salinity:

the technology changed from water samples run by titration to water samples run on conductivity machines which evolved (to Schleicher/Bradshaw). The definition of salinity changed several times. Samples were often drawn into poorly rinsed bottles; they were often stored for later measurement ashore, weeks or even months later (evaporation was found to be a problem). Seasonal and latitudinal sampling biases.

Temperature:

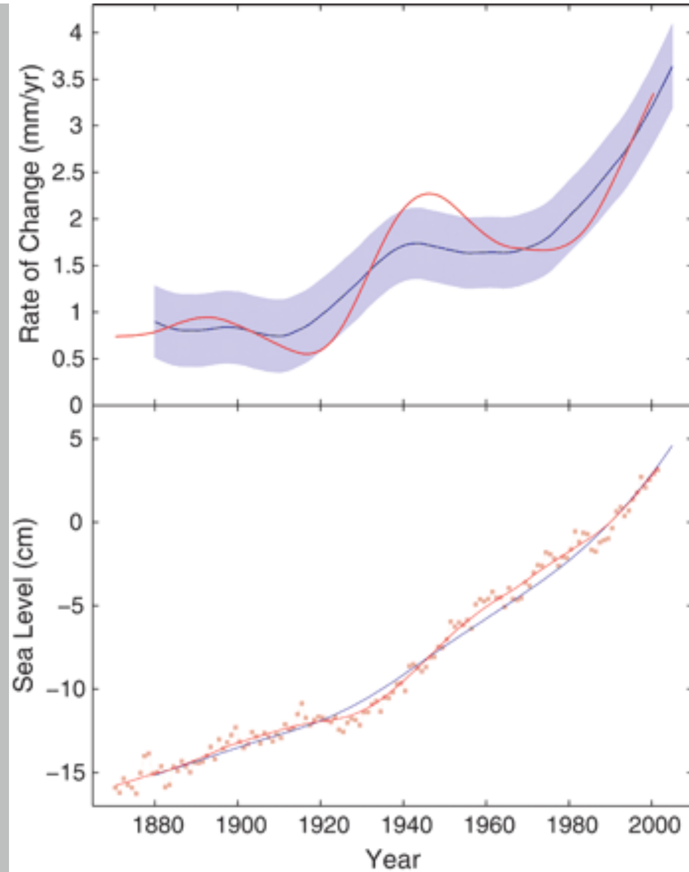
Main issue is probably the depth inference, which shifted from reversing thermometers to pressure gauges. Gouretski and Jahncke (2001) found in their climatology an inordinate number of samples at the nominal bottle depth---suggesting a failure to use unprotected thermometers. Seasonal and latitudinal sampling biases.

Temperature and salinity problems were what led Worthington to his data cull (failure to recover the deep T-S relationships).

Tide Gauges:

Tectonic corrections. Location shifts. Harbor construction.

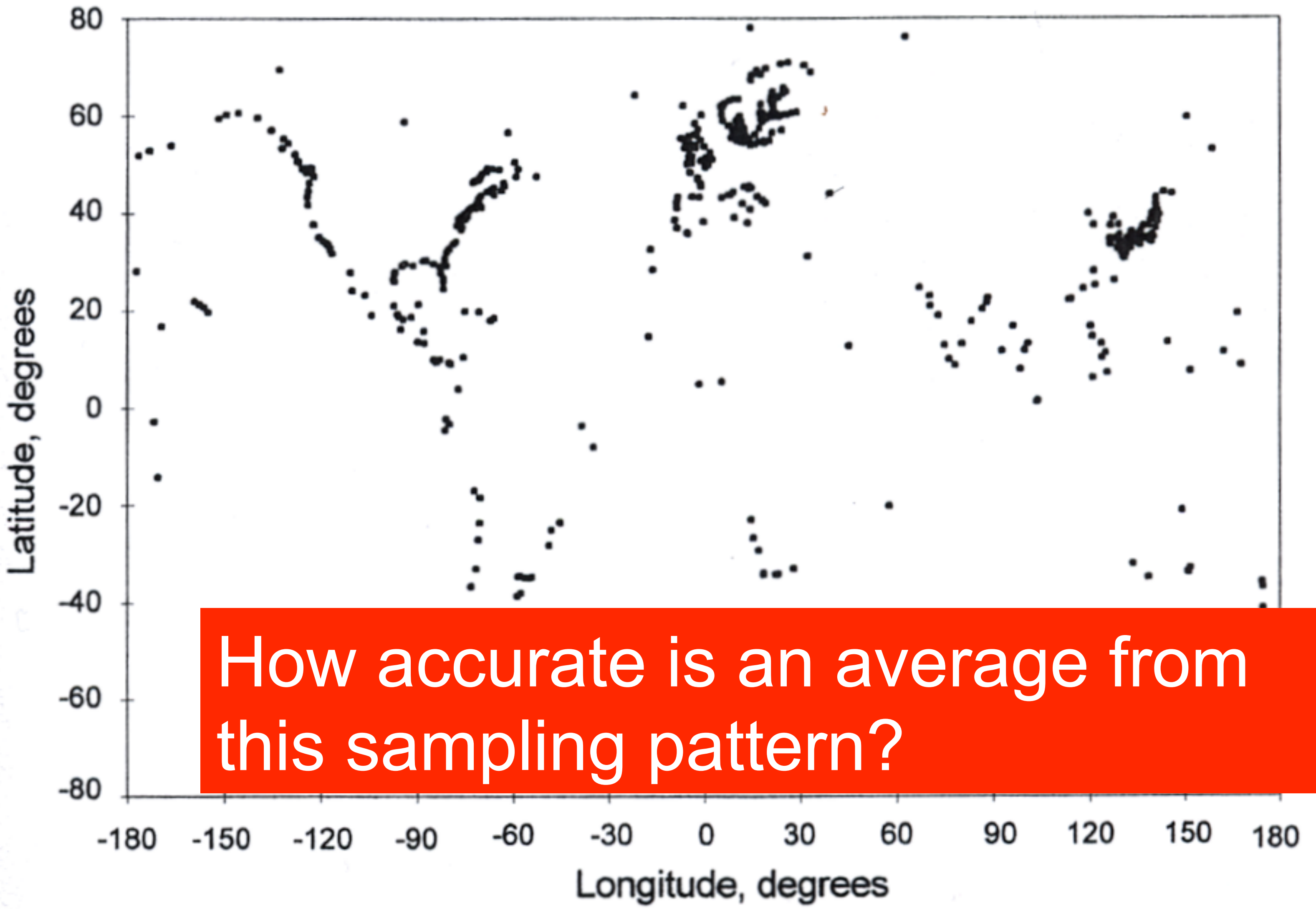
Are these errors random, or systematic? Yes. How large are they?



Comparison of putative global mean sea level and global mean temperature.

Rahmstorf, Science, 2007. Can one reconstruct sea level and global mean temperatures with useful accuracy back to 1875? If so, why are we paying huge sums for new observation systems?

Fig. 3. (**Top**) Rate o computed from glob simple linear predict Fig. 2 legend) and c sea-level data.



How accurate is an average from this sampling pattern?

Figure 3.12 RLR tide gauge locations with records longer than 20 years.

Can one model global sea level change? Again, anyone can write a model.

And modelling might be regarded as irrelevant, if one can directly measure the sea level shift.

But an inability to model implies a lack of understanding, and prevents any credible prediction. Predictions are nonetheless proliferating. So worth examining the modelling problem.

Calculation of the mean sea surface in an ocean model of mean depth of 4000m to an accuracy of 0.1mm/yr requires a volumetric accuracy of 1 part in 10^7/y. Are models that that accurate over decades with time steps of order 1 hour?

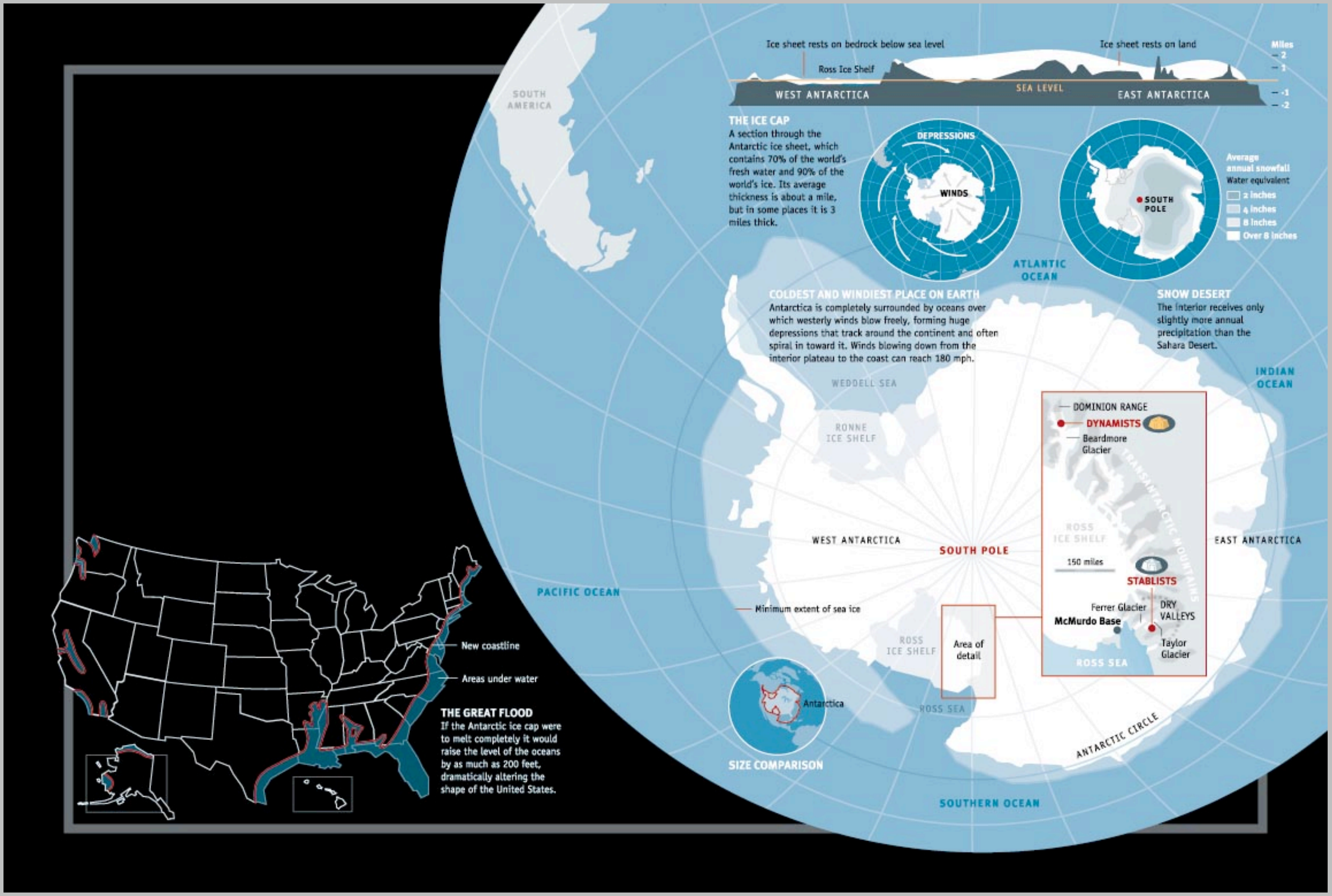
What can change global mean sea level?:

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?

Global contributions plus:

Temperature shifts
Addition or removal of fresh water
Displacement of ocean circulation features
Tectonic uplift
Gravity field modification (melting of glacial ice)
Change in ocean load, including local atm. pressure, and water self-attraction
....



SOUTH AMERICA
Ice sheet rests on bedrock below sea level
Ross Ice Shelf
Ice sheet rests on land
Miles
WEST ANTARCTICA
SEA LEVEL
EAST ANTARCTICA
THE ICE CAP
A section through the Antarctic ice sheet, which contains 70% of the world's fresh water and 90% of the world's ice. Its average thickness is about a mile, but in some places it is 3 miles thick.
DEPRESSIONS
WINDS
SOUTH POLE
Average annual snowfall
Water equivalent
2 inches
4 inches
8 inches
Over 8 inches
ATLANTIC OCEAN
COLDEST AND WINDIEST PLACE ON EARTH
Antarctica is completely surrounded by oceans over which westerly winds blow freely, forming huge depressions that track around the continent and often spiral in toward it. Winds blowing down from the interior plateau to the coast can reach 180 mph.
SNOW DESERT
The interior receives only slightly more annual precipitation than the Sahara Desert.
INDIAN OCEAN
WEDDELL SEA
RONNE ICE SHELF
DOMINION RANGE
DYNAMISTS
Beardmore Glacier
TRANSANTARCTIC MOUNTAINS
ROSS ICE SHELF
WEST ANTARCTICA
SOUTH POLE
EAST ANTARCTICA
150 miles
STABLISTS
PACIFIC OCEAN
Minimum extent of sea ice
Ferrer Glacier
DRY VALLEYS
McMurdo Base
Taylor Glacier
ROSS ICE SHELF
Area of detail
ROSS SEA
New coastline
Areas under water
Antarctica
ROSS SEA
SIZE COMPARISON
ANTARCTIC CIRCLE
THE GREAT FLOOD
If the Antarctic ice cap were to melt completely it would raise the level of the oceans by as much as 200 feet, dramatically altering the shape of the United States.
SOUTHERN OCEAN

NSF

Air-sea flux imbalances in atmospheric analyses & reanalyses are a major problem.

NCEP-NCAR reanalysis evaporates about 6 cm/yr from the ocean. Warms the ocean by over 2W/m^2.

The reanalyses are based upon weather forecast models in which global water and heat budgets are essentially irrelevant. Some strange consequencies, including implied heat transport by the continents.
River runoff surprisingly poorly known.
How should model forcing be handled in the presence of these imbalances?

Seek to use the ECCO-GODAE synthesis (MIT/AER) to estimate global patterns of sea level rise, and partition it amongst heating/cooling, evaporation/precipitation/runoff, and general circulation shifts as a function of depth. Uses a state of the art ocean general circulation model (GCM) so that known physics is used to help the inference.

As much data as can gather and understand in the interval 1992-2004 and a reasonably complete GCM.

From work in collaboration with Rui Ponte (AER), Patrick Heimbach (MIT) in press, J. Climate, and the ECCO-GODAE MIT/AER group more generally.

.

.

.

There exist serious *modelling* questions in a context where submillimeter/year accuracy is needed:
For most models:

Boussinesq approximation---conserves volume,
Conservation is usually of salinity, not salt.
Surface boundary condtions for salt---at least 3 in use, including
virtual salt flux (Huang, 1993) as well as incomplete treatment of surface layer dynamics (2 or 3 different forms). Numerical treatment of the moving free surface is sometimes a gross approximation.

Approximations in the equation of state.

Errors in the meteorological forcing including large-scale imbalances.

Incomplete sea ice models, volume/mass inconsistencies when ice is formed.

Models generally lack self-attraction and pressure load corrections
….

And these models must be run for decades. Many of these errors will necessarily be cumulative.

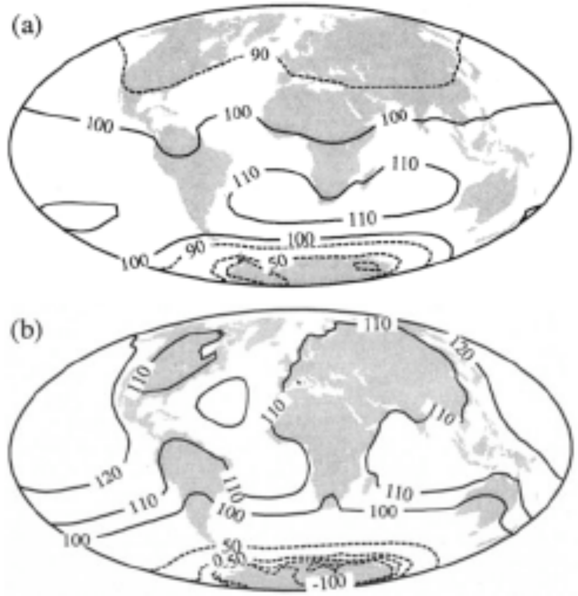


Figure 2. Calculations in which mass depletion in Antarctica is included as the sole continental source of sea level rise. Shown are (a) absolute and (b) relative sea level change. The minimum contour around Antarctica in (a) is $S_A = 0$. Vertical displacement is the difference between (a) and (b).

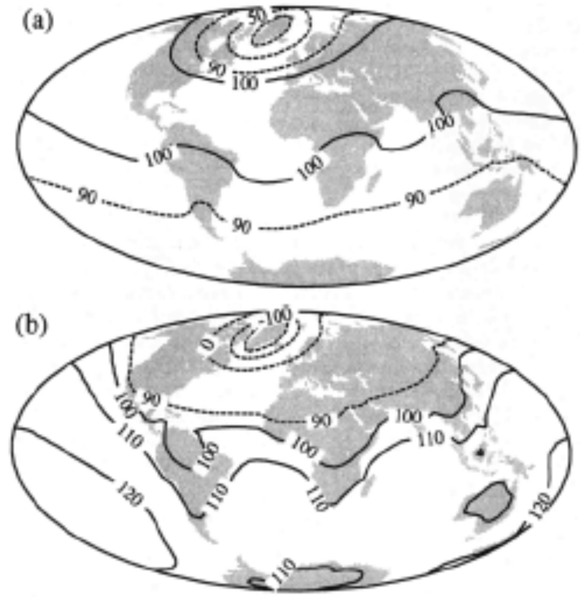
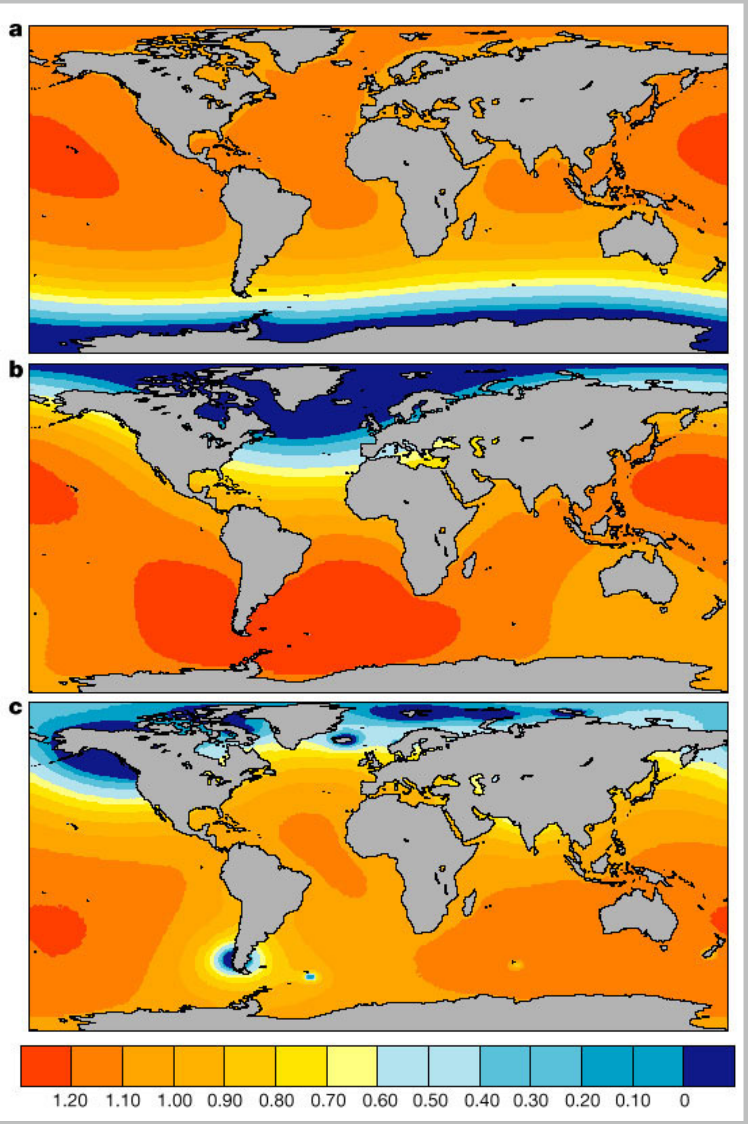


Figure 3. Similar to Fig. 2, using Greenland ice as the continental source of sea level rise. The minimum contours in Greenland are (a) $S_A = -100$ and (b) $S_R = -300$.

Conrad and Hager, GRL, 1997

There are many more complications not yet accounted for, e.g.:



Fractional variation of sea level from melting ice, assumed uniform over restricted areas. 0 means no change.

Antarctica

How well do we know long term ice volume changes? Is a 5 year record meaningful? Can one predict with skill? if so, what is it? How is that known?

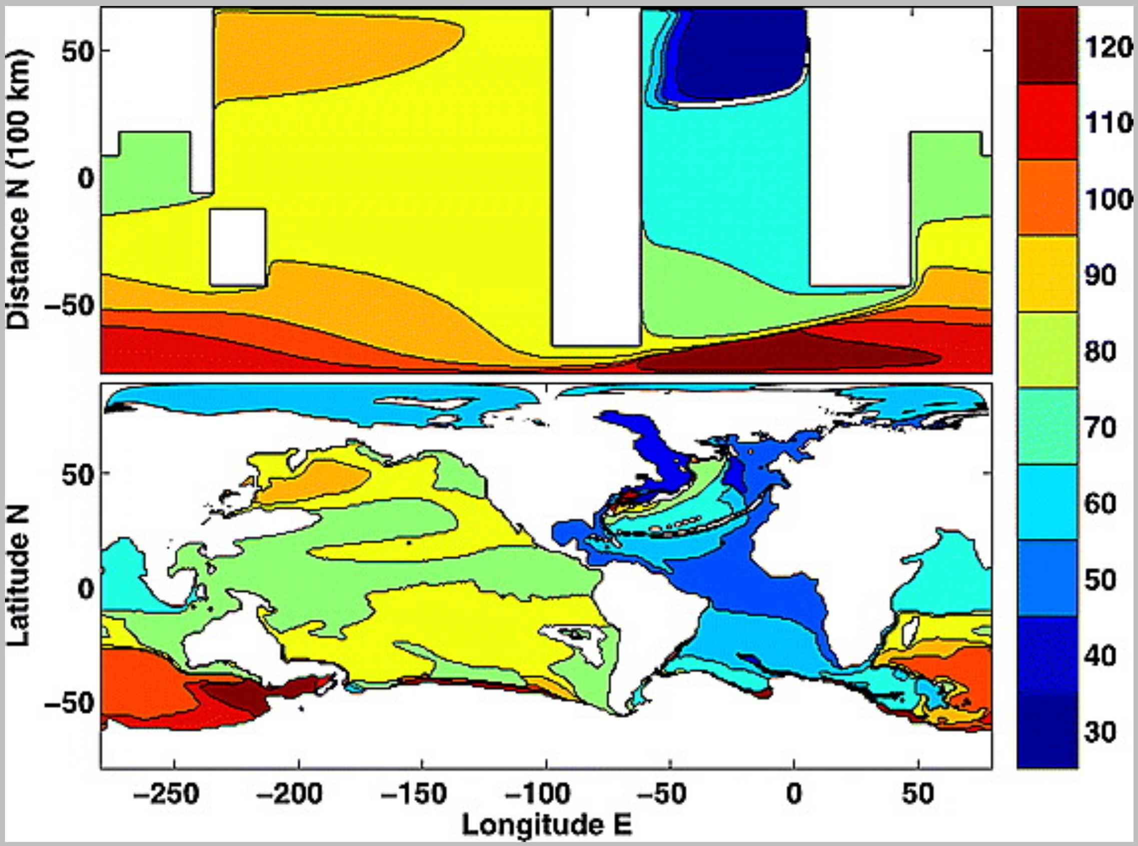
Greenland

Mountain glaciers

Mitrovica et al., Nature, 2001

Regional estimates in global models reflect imposed global constraints---e.g., global volume conservation implies regional compensations occur.

Oceanic baroclinic memories, and hence spatial distribution of sea level change signals, extend to thousands of years.



Cessi et al., 2004.
Time in years for a North Atlantic disturbance to penetrate the world ocean (sea level). Many decades are required for its evolution and many more required to fully observe it. What can one say after 15 years?

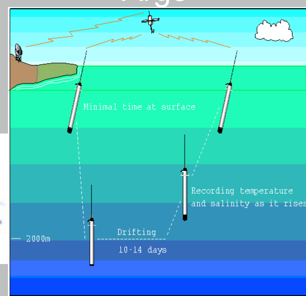
Varied Data

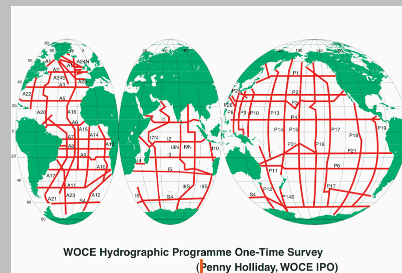
WOCE

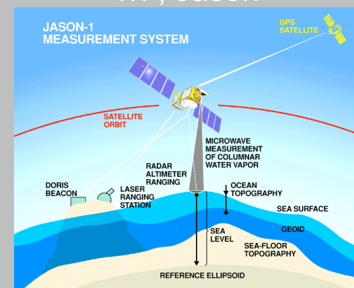
Argo

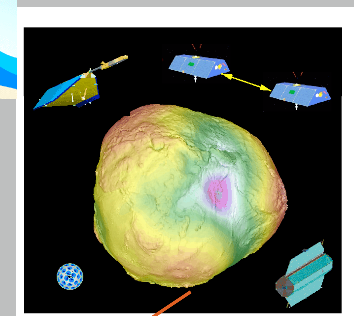
T/P, Jason

GRACE



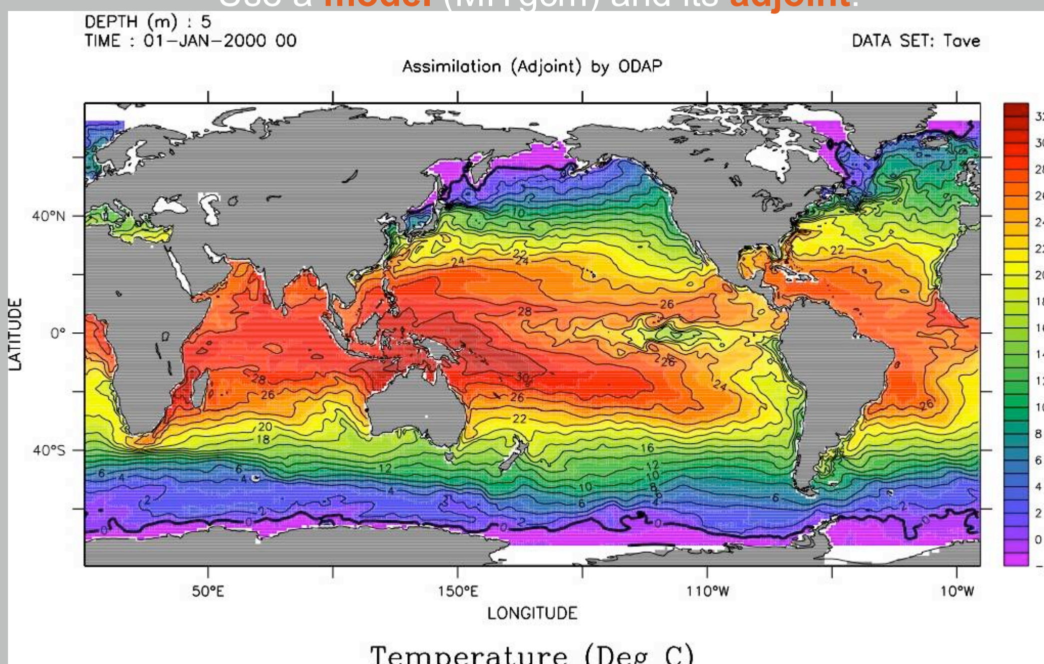






How to synthesize? Estimation/optimal control problem:
Use a **model** (MITgcm) and its **adjoint**:

Many disparate data types.



Navier-Stokes equations of a stratified, rotating, spherical shell of complex lateral boundary and bottom topography (equations of a non-linear vector field theory).

$$\frac{du}{dt} - \frac{uv\tan\phi}{a} + \frac{uw}{a} - 2\Omega\sin\phi v = \frac{1}{a\cos\phi}\frac{\partial p}{\rho\partial\lambda} + F_u$$

$$\frac{dv}{dt} + \frac{u^2\tan\phi}{a} + \frac{vw}{a} + 2\Omega\sin\phi u = \frac{1}{a}\frac{\partial p}{\rho\partial\phi} + F_v$$

$$\frac{dw}{dt} - \frac{u^2+v^2}{a} = -\frac{\partial p}{\rho\partial z} - g$$

$$\frac{1}{a\cos\phi}\left(\frac{\partial u}{\partial\lambda} + \frac{\partial(v\cos\phi)}{\partial\phi}\right) + \frac{\partial w}{\partial z} = 0$$

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial\rho}{\partial\lambda} + \frac{v}{a}\frac{\partial\rho}{\partial\phi} + \frac{w\partial\rho}{\partial z} = 0,$$

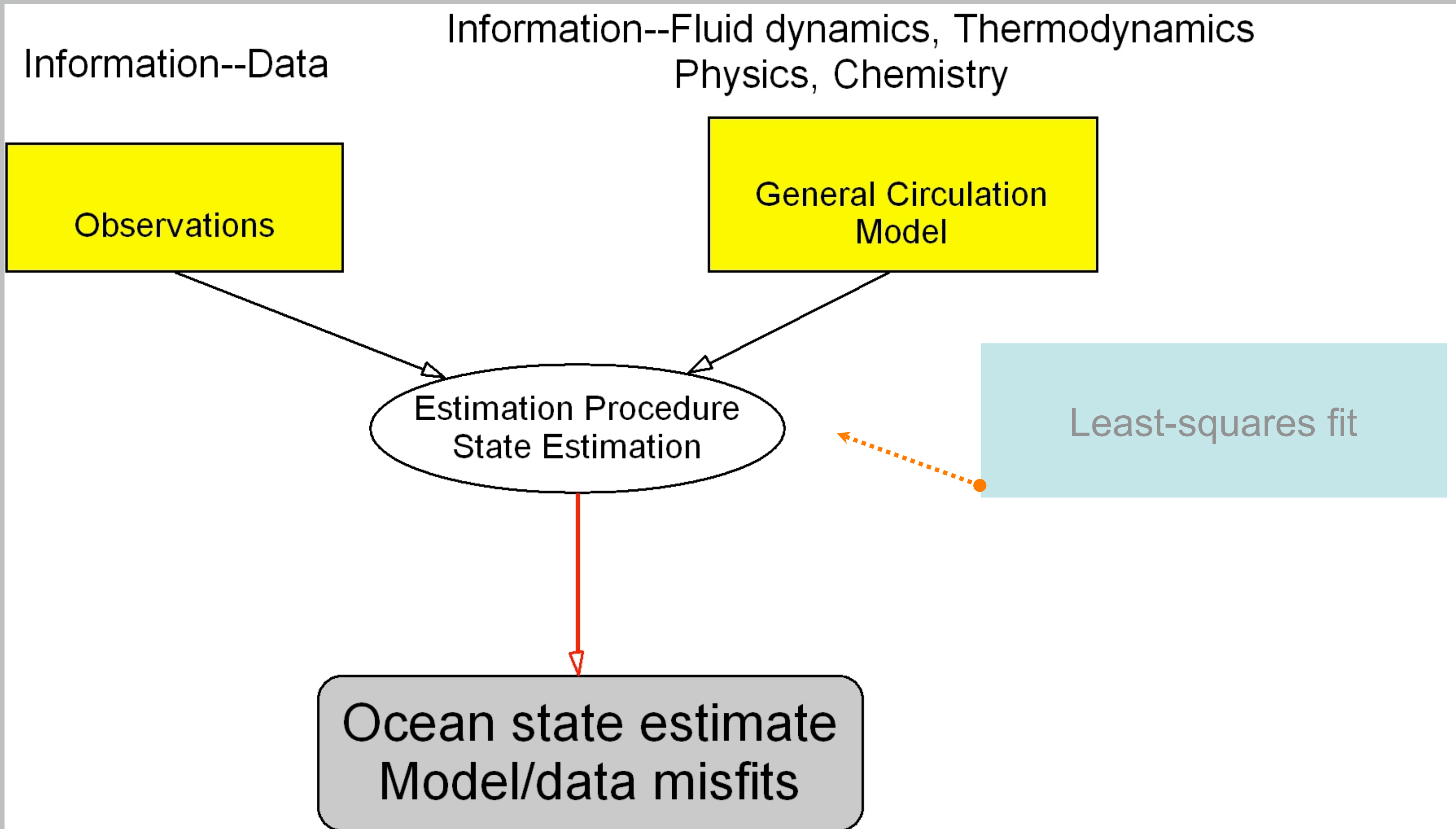
where

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}.$$

These are already somewhat simplified. u,v,w are the 3 components of velocity. ρ is density, φ is latitude, z-vertical, etc.

Use as represented in the so-called MITgcm (J. Marshall & colleagues).

ECCO-GODAE


Information--Data
Information--Fluid dynamics, Thermodynamics
Physics, Chemistry
Observations
General Circulation Model
Estimation Procedure
State Estimation
Least-squares fit
Ocean state estimate
Model/data misfits

ECCO-GODAE estimates are from ordinary least-squares solutions obtained by "adjoining" the model to a model-data misfit function using an ancient mathematical trick: Lagrange multipliers:

$$
\begin{aligned}
J = {} & [\mathbf{x}(0) - \mathbf{x}_0]^T \mathbf{P}(0)^{-1} [\mathbf{x}(0) - \tilde{\mathbf{x}}_0] \\
& + \sum_{t=1}^{t_f} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]^T \mathbf{R}(t)^{-1} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)] \\
& + \sum_{t=0}^{t_f-1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t) \\
& - 2 \sum_{t=1}^{t_f} \mu(t)^T [\mathbf{x}(t) - \mathbf{L}[\mathbf{x}(t-1), \mathbf{B}\mathbf{q}(t-1), \Gamma\mathbf{u}(t-1)]] .
\end{aligned}
$$

misfit to Initial conditions

misfit to the observations

adjustable parameters (controls)

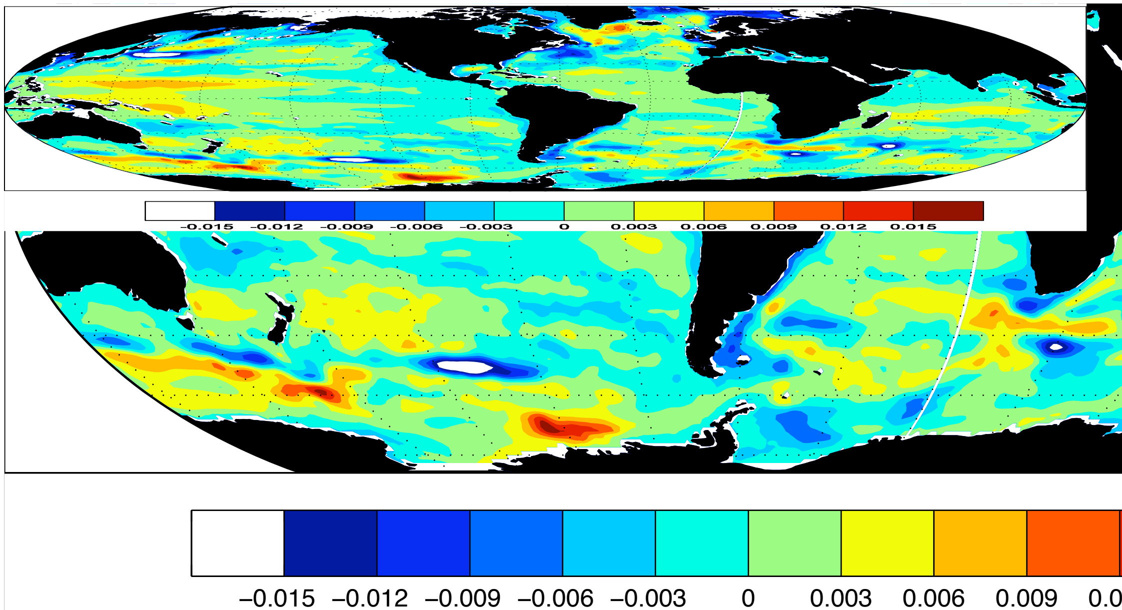
the model

vectors of Lagrange multipliers, AKA, the adjoint or dual solution

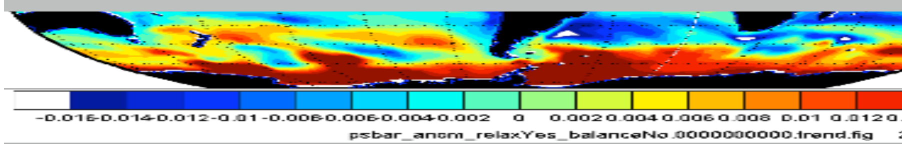
In electrical engineering, called the Pontryagin Minimum Principle, in meteorology 4DVAR, in oceanography the adjoint method, ….

Solved by iteration relying upon knowledge of the partial derivatives of J with respect to x(t), u(t), using automatic/algorithmic differentiation (AD) software tools. Will skip all that here.

Two major difficulties: the size of the problem, and the need to understand errors in everything.



ECCO-GODAE estimate v3.50 sea level trend in m/y (spatial mean removed)

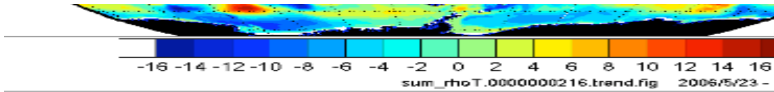


sea level trend in m/y from unoptimized model

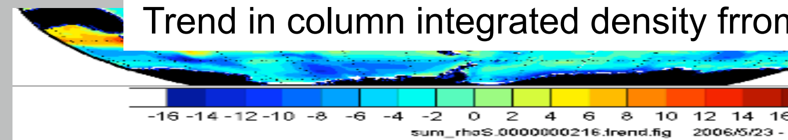
spatial means removed

Red means *increasing* density (decreasing temperature, increasing salinity

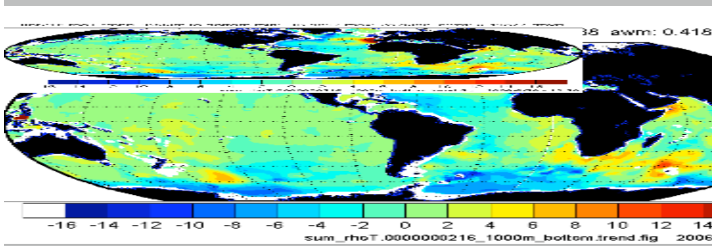
Trend in column integrated density from temperature



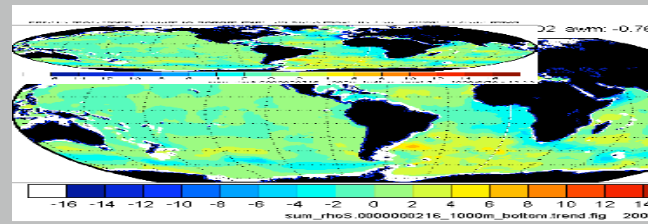
Trend in column integrated density frrom salt



Note compensating temperature and salinity contributions. Much of this is surely lateral and vertical shifting of the mean structures by the time-variable wind field. (Prediction?)



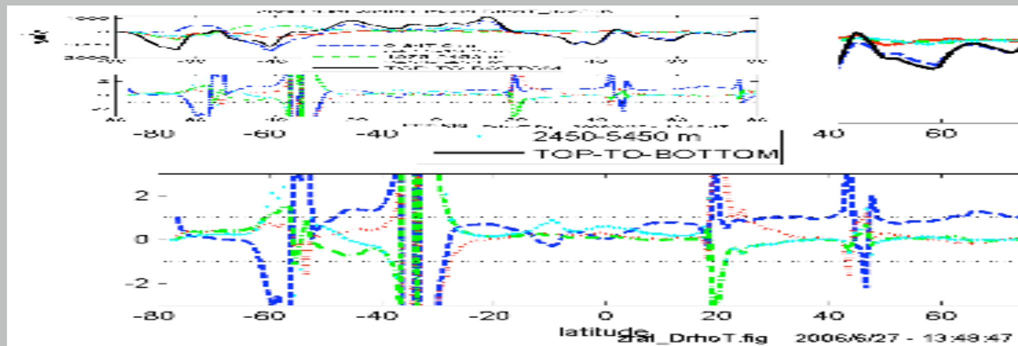
1000m to bottom temperature contribution to density trend mm/y



1000m to bottom salinity contribution to density trend mm/y

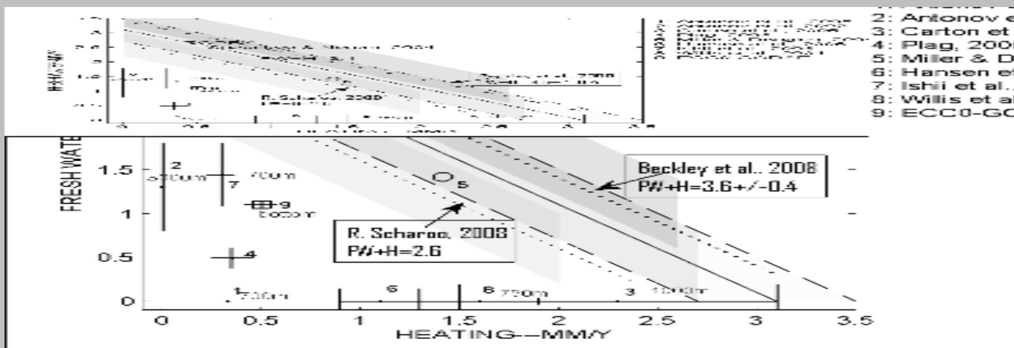
What is the vertical distribution?

Vertical integrals of net density change
& ratio from temperature



ratios to the top-to-bottom integral

Cannot ignore the deep ocean



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.

Some Theoretical Problems:

What happens when fresh water is ejected from land into the ocean---either as liquid runoff, or as ice? Steady-state versus transient?

What is gravity (mass) signature, and how long does it take? What happens to earth rotation parameters, and how long does that take? (Hours to days)

How does sea level adjust and on what time scale? (decades and longer)

What does it do to the ambient ocean circulation? Coastal injection versus icebergs?

A Summary

On decadal time scales, large scale patterns of sea level change have a major contribution from adiabatic shifts in the general circulation, both lateral and vertical.

Global averages remain problematic both in general circulation models, in the data, and in the combination, so that partitioning amongst heating/cooling, addition/removal of freshwater are not robust. (Can a Boussinesq model, with an approximate equation of state, a finite resolution, a virtual salt flux boundary condition and uncertain meteorological forcing compute volume changes to better than one part in 10^8 per year?) Not possible (yet?) to independently confirm the rate seen in the altimetric data. Does not mean it's wrong!

As time goes on, a global average signal may emerge, but one must be wary of systematic errors in both observations and models. True global averages require true global observations and models run over decades. Real challenge is to make these calculations accurate in the future. ←
Not clear whether net glacial melt is better determined from oceanic or cryospheric measurements.

Summary

Understanding global mean and regional sea level change is an intersting, but tractable, grand challenge problem involving models, observation and theory for the ocean, cryosphere, atmosphere, and the solid earth.

Most urgent, and *not* requiring more data, is the need to fully determine realistic accuracies of existing estimates, and which surely vary greatly with time interval and region.

More generally, have to work the problem from several aspects at once, including deficiencies in models, in atmospheric forcing, in ice sheet volumes, sea-ice behavior, hydrological shifts, post-glacial rebound, local load factors,…

What is the skill of the increasing number of forecasts?

The record of ocean observations is woefully short and spatially and temporally biassed. To avoid science fiction, there is sometimes no substitute for more and better data. The highest priority needs to go to assuring that 50 years from now the same issues are not still present.

Slight systematic errors in any of dozens of components of the system can produce erroneous results with societal implications. Some restraint needs to be exercised in proclaiming understanding, and particularly, in prediction.

Thank you.