Global Sea Level Changes: Patterns and Causes

Carl Wunsch
October 2006

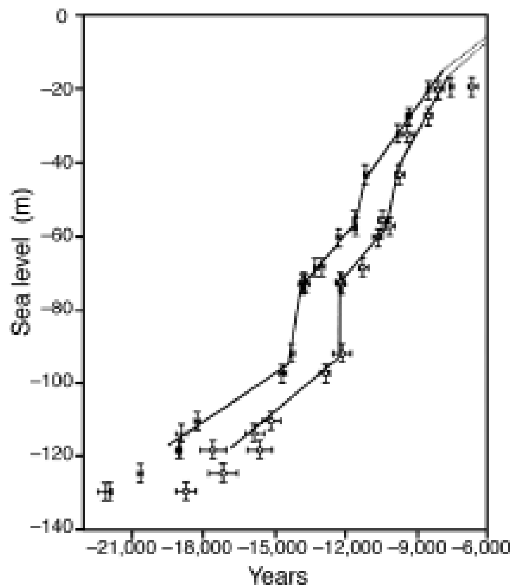


Figure 1. Redrawn from Bard *et al.* (1990), with time reversed to increase from left to right. U
curve is estimated sea level with respect to today using Barbados terraces and U/Th dates. Lo
curve is identical except that ^{14}C dates are used. U/Th dates are believed more accurate, but m
other variables are specified relative to ^{14}C. A 7 meter adjustment for the greater height of the
interglacial was made by Bard *et al.* (1990).

Sea level has been rising globally on average since the glaciers started melting about 20,000 years ago.

From Douglas et al. 2001

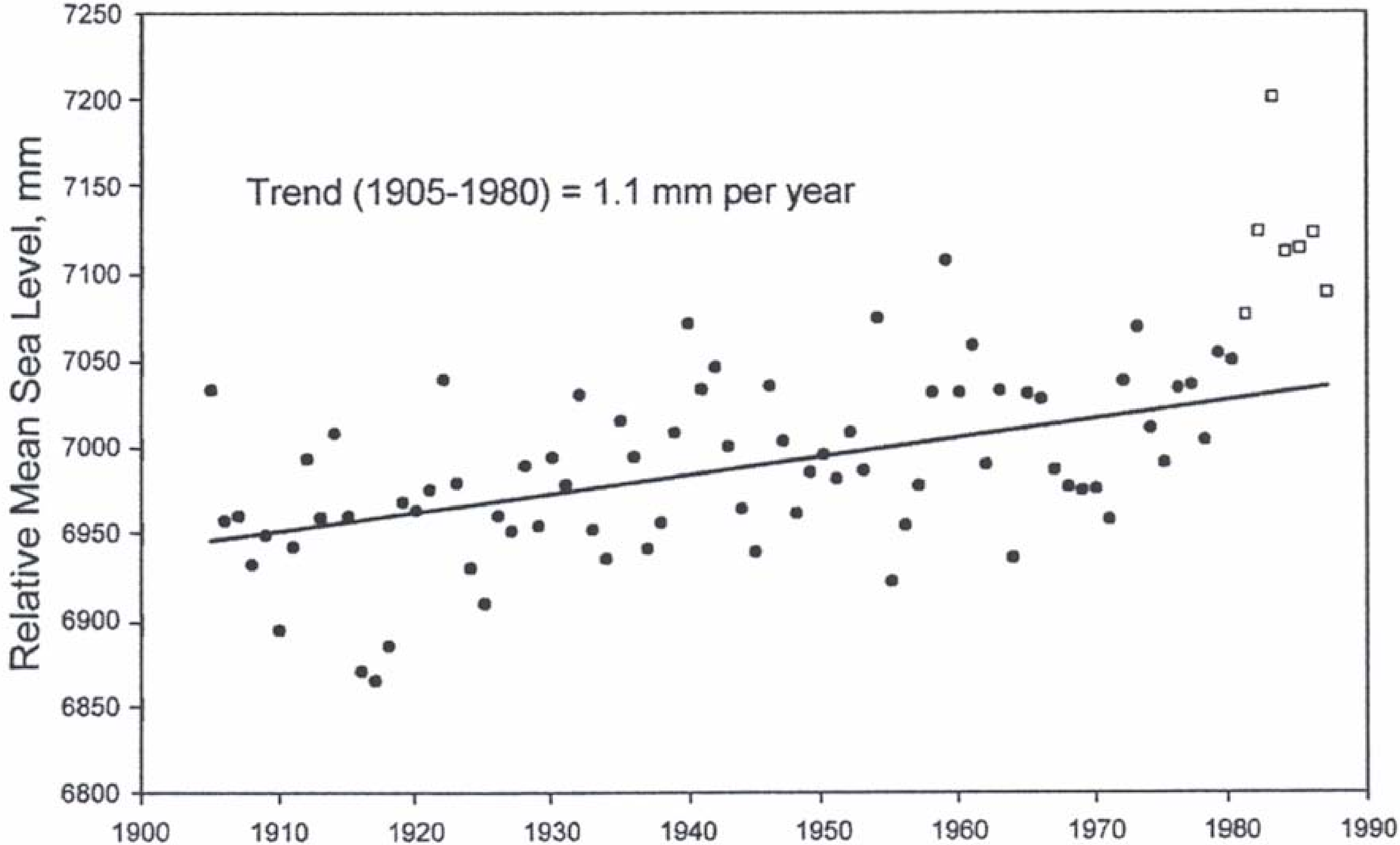
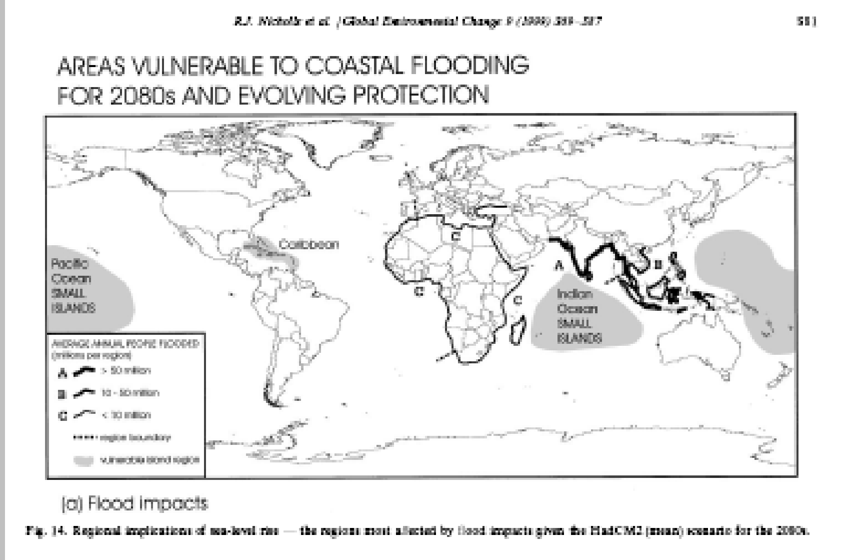
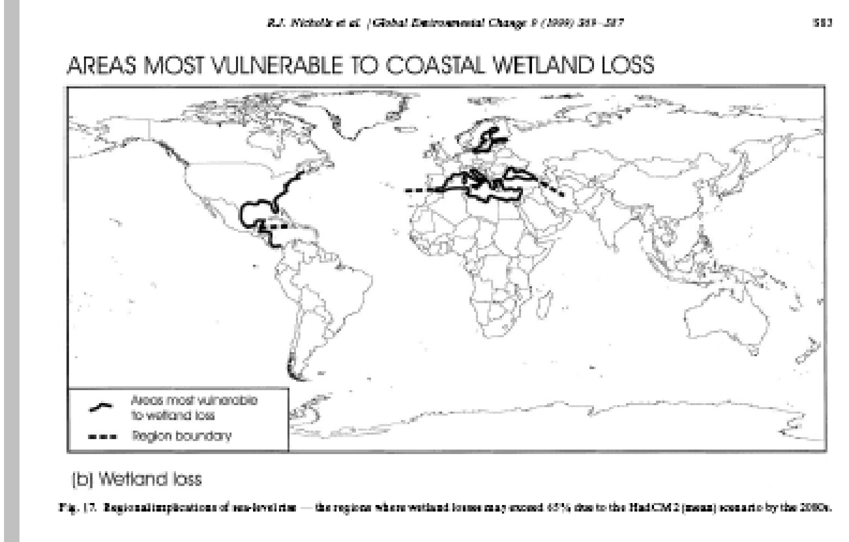
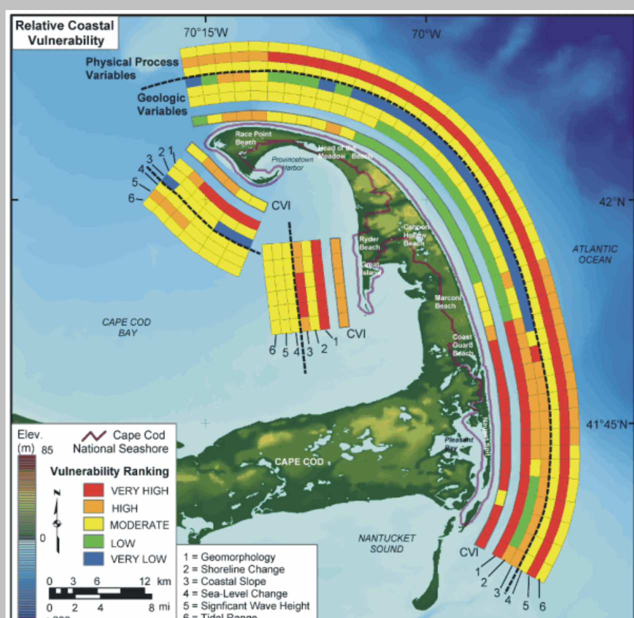


Figure 3.5 Annual mean relative sea level at Buenos Aires.



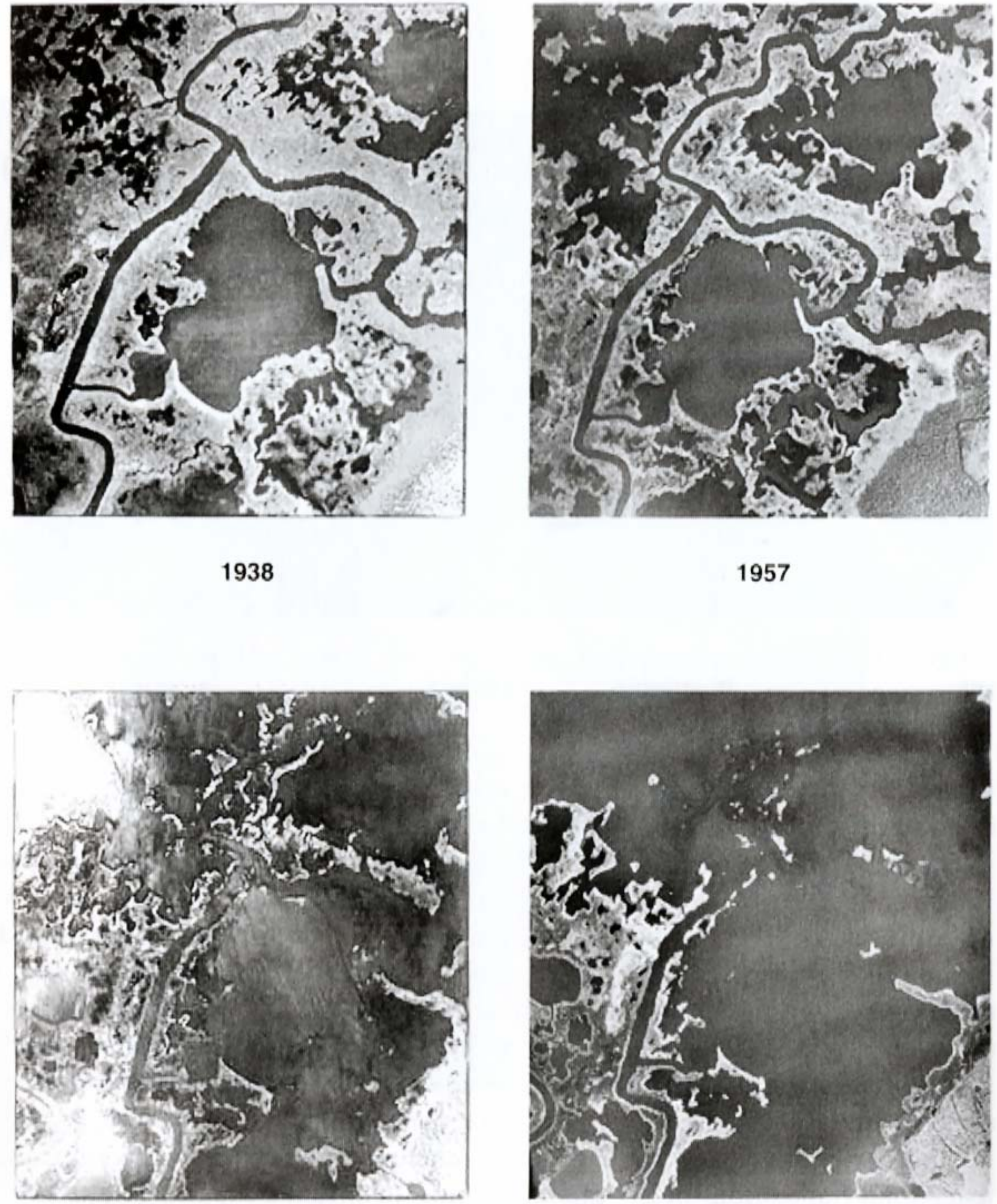




USGS

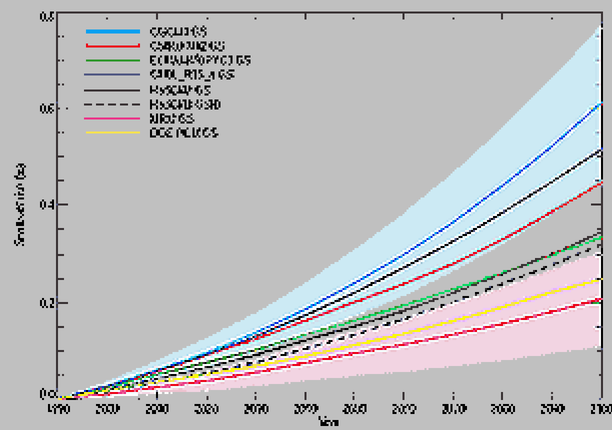
USGS, WHOI

From Douglas et al., 2001



1938 1957 1972 1988

Figure 8.21 Progressive drowning and loss of coastal marshes in Blackwater National Wildlife Refuge near Cambridge, Maryland, in response to a high relative sea level rise.



From Church et al. (2001)

Figure 11.1: Global average sea level changes from thermal expansion simulated in AOGCM experiments with historical concentrations of greenhouse gases in the 20th century, then following the IS92a scenario for the 21st century, including the direct effect of sulphate aerosols.
See Tables 8.1 and 9.1 for further details of models and experiments

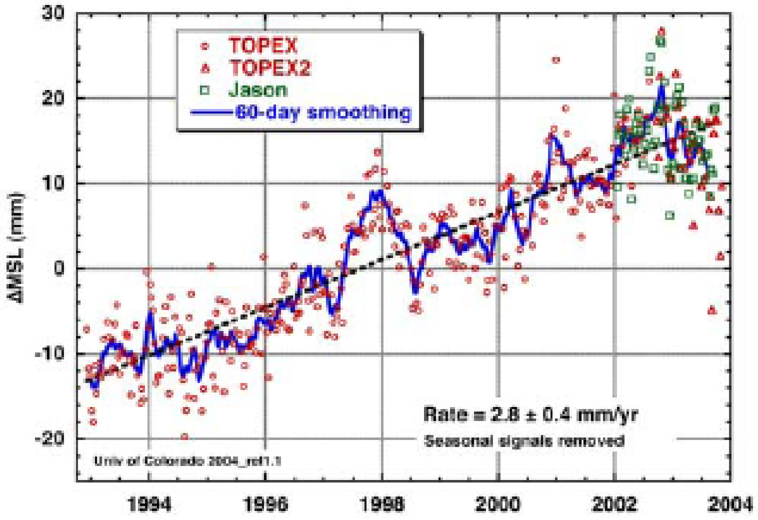


Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the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

Cazenave and Nerem, Revs. Geophys. 2004

If examine the reanalysis results carefully, discover that the NCEP-NCAR meteorological forcing appears to be evaporating about 2 cm/yr of water. This is much larger than anyone has ever suggested possible. Also appears to be heating the ocean by about $2W/m^2$, which is about twice as large as has previously been suggested (as greenhouse warming).

Are the Greenland and Antarctic ice sheets expanding or contracting? Is sea ice melting (doesn’t change sealevel, but does change oceanic salinity)? Can we believe meteorological estimates of the net warming of the ocean? Is it possible to calculate the oceanic freshening and temperature change over decades using measurements, with an accuracy we would care about?

Everything appears to be open to question! The economic and political stakes are immense.

No accurate altimetry prior to 1992 .

There exist a number of published attempts at determining the global average prior to the altimeter measurements based on (1) tide gauge records; (2) temperature and salinity changes.

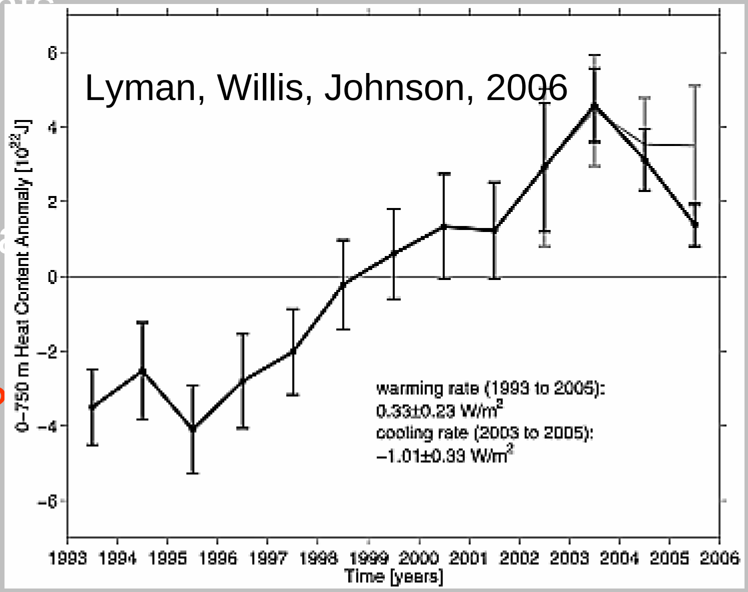
These have been the subject of considerable dispute, as the calculations prove very difficult.

Issues pertain to:

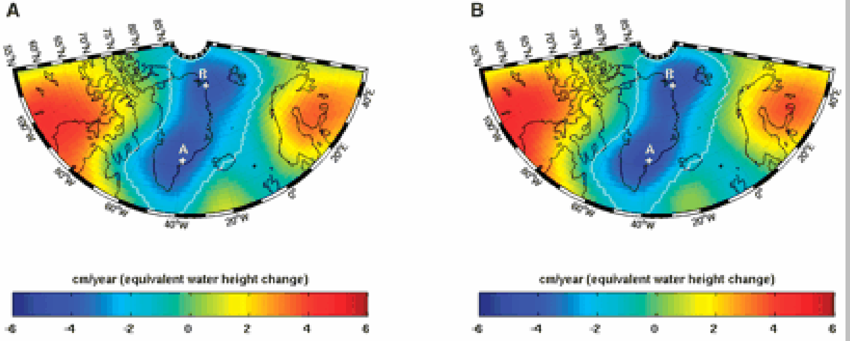
The spatial distribution of the measuremen

The interpretation of density changes

Calibration (or lack of it) in the various mea



Is sea level rising? Is the ocean getting warmer? where, and by how much, and why?



Chen, Wilson, Tapley, Science, 2006

Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet

(note 3 years of data)

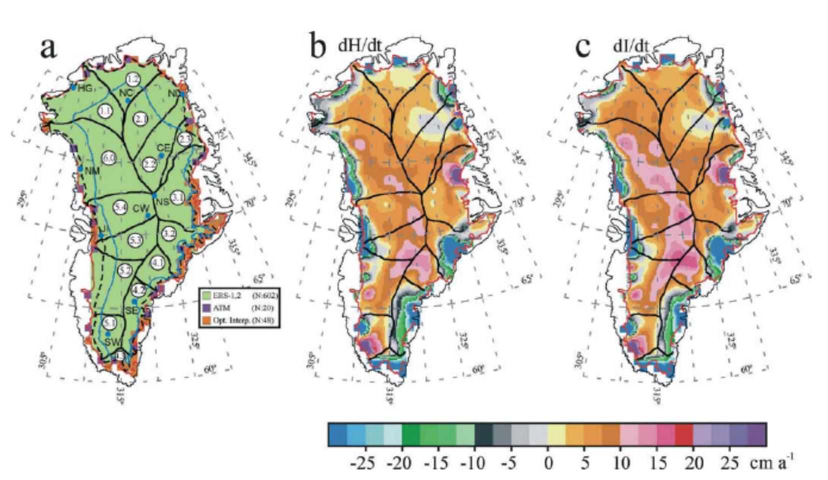


Fig. 1. Greenland. (a) Distribution of surface elevation change data by source, derived from ERS-1 and -2 radar altimetry, ATM (closest-neighbor interpolation from airborne surveys), and obtained by optimal interpolation: ice terminus of coterminous ice sheet (red), equilibrium line (black dashes), 2000 m elevation contour (blue), drainage divides (black), drainage system designation (number in circles), and location of *H*(*t*) series depicted in Figure 3a (labeled blue full circles). (b) Distribution of elevation change (d*H*/d*t*). (c) Distribution of ice-thickness change (d*I*/d*t*).

Zwally et al., J. Glaciology 2005. “The Greenland ice sheet …[has] a small overall mass gain, +11+/-3 Gt/a.”

Are the ice sheets growing or shrinking?

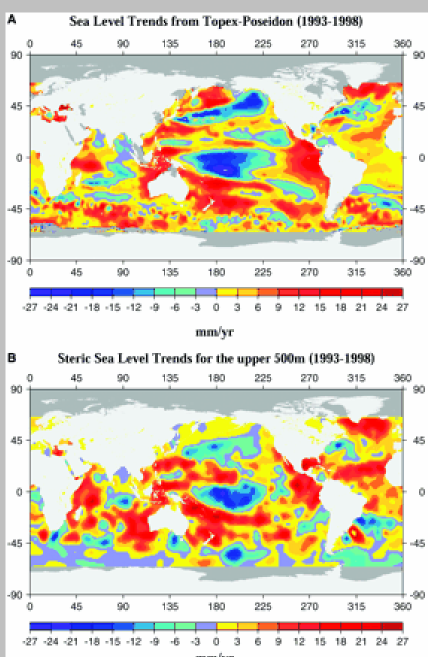
From temperature

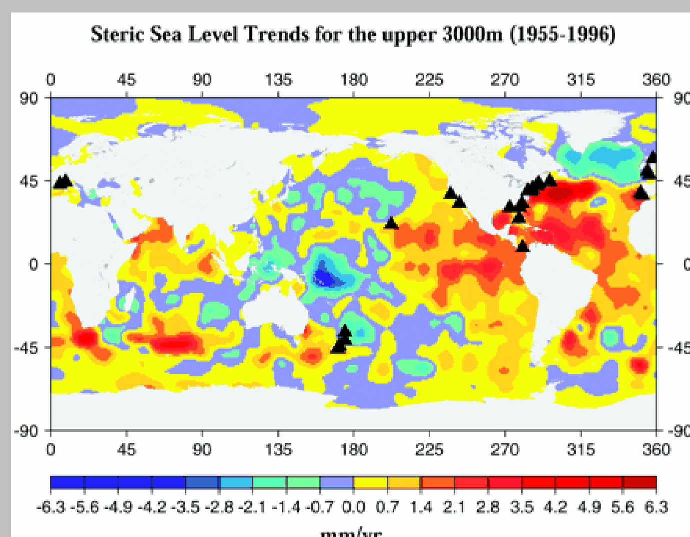
From freshwater (salinity change)

Thermosteric Change [mm/y]	Integr. Depth [m]	Freshwater (______) Change [mm/y]	Total Change [mm/y]	Interval	Comment
Antonov et al. (2005)					
≈0.33	700			1955–2003	hydrography
Antonov et al. (2002)					
	3000	1.3 ± 0.5		1957–1994	hydrography
Willis et al. (2004)					
1.6±0.3	750			1993–2003	XBT & altimetry
Carton et al. (2005)					
2.3±0.8	1000			1958-2001	altimetry & hydrography
Plag (2006)					
		0.49±0.12	1.05 ± 0.75	1950–1998	tide gauges & reworked hydrography*
Ishii et al. (2006)					
0.31 ± 0.071	700	1.44±0.36	1.75±0.36	1995–2003	hydrography+
Miller and Douglas (2004)					
			≈ 2	20th century	tide gauges
Hansen et al. (2005)					
0.85 ± 0.15 W/m^2 = 1.1±0.2				1993–2003	coupled model alone

Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations
Cecile Cabanes, Anny Cazenave, Christian Le Provost (2001)

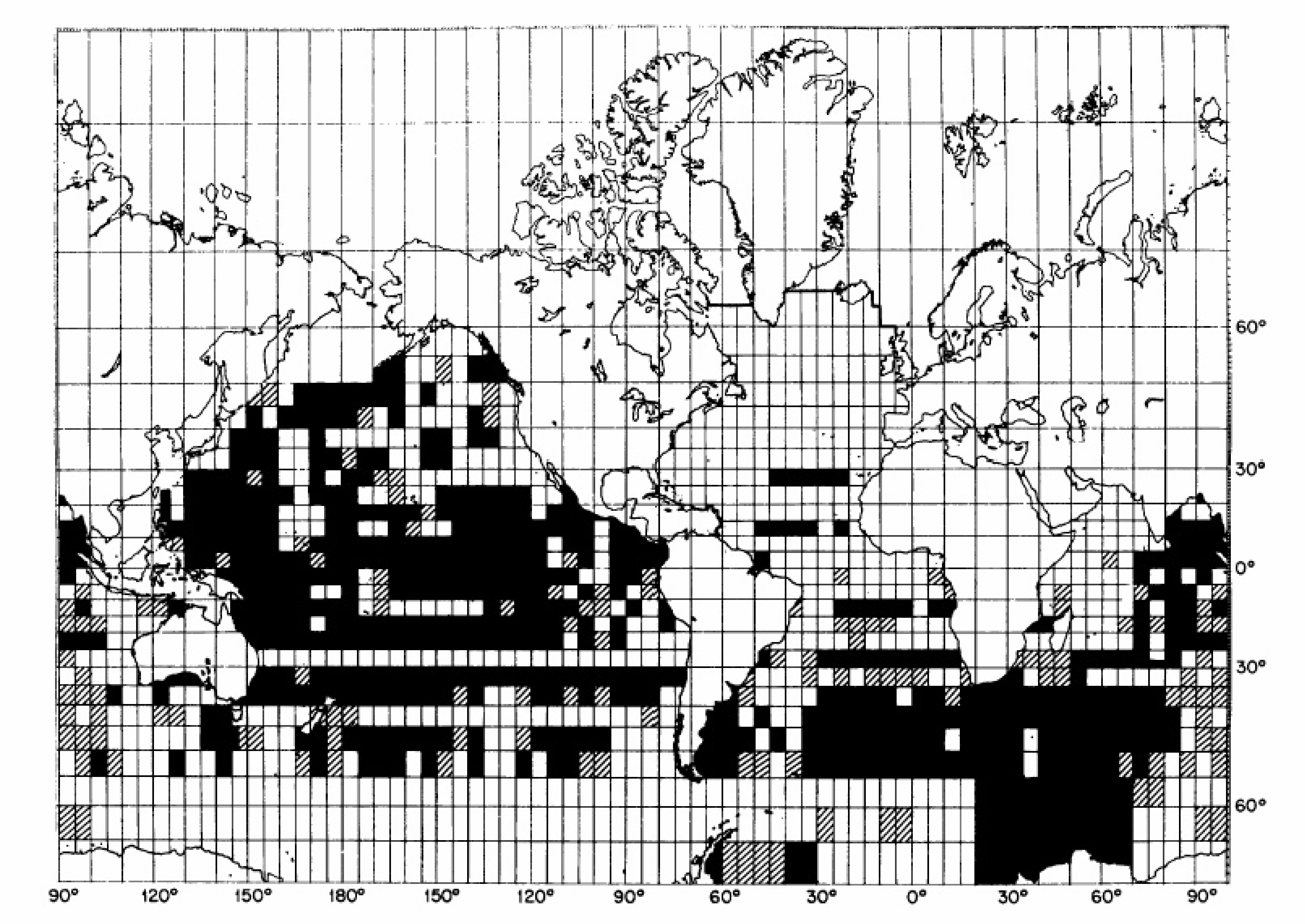
"The 3.2 ± 0.2 millimeter per year global mean sea level rise observed by the Topex/Poseidon satellite over 1993-98 is fully explained by thermal expansion of the oceans. For the period 1955-96, sea level rise derived from tide gauge data agrees well with thermal expansion computed at the same locations. However, we find that subsampling the thermosteric sea level at usual tide gauge positions leads to a thermosteric sea level rise twice as large as the "true" global mean. As a possible consequence, the 20th century sea level rise estimated from tide gauge records may have been overestimated."



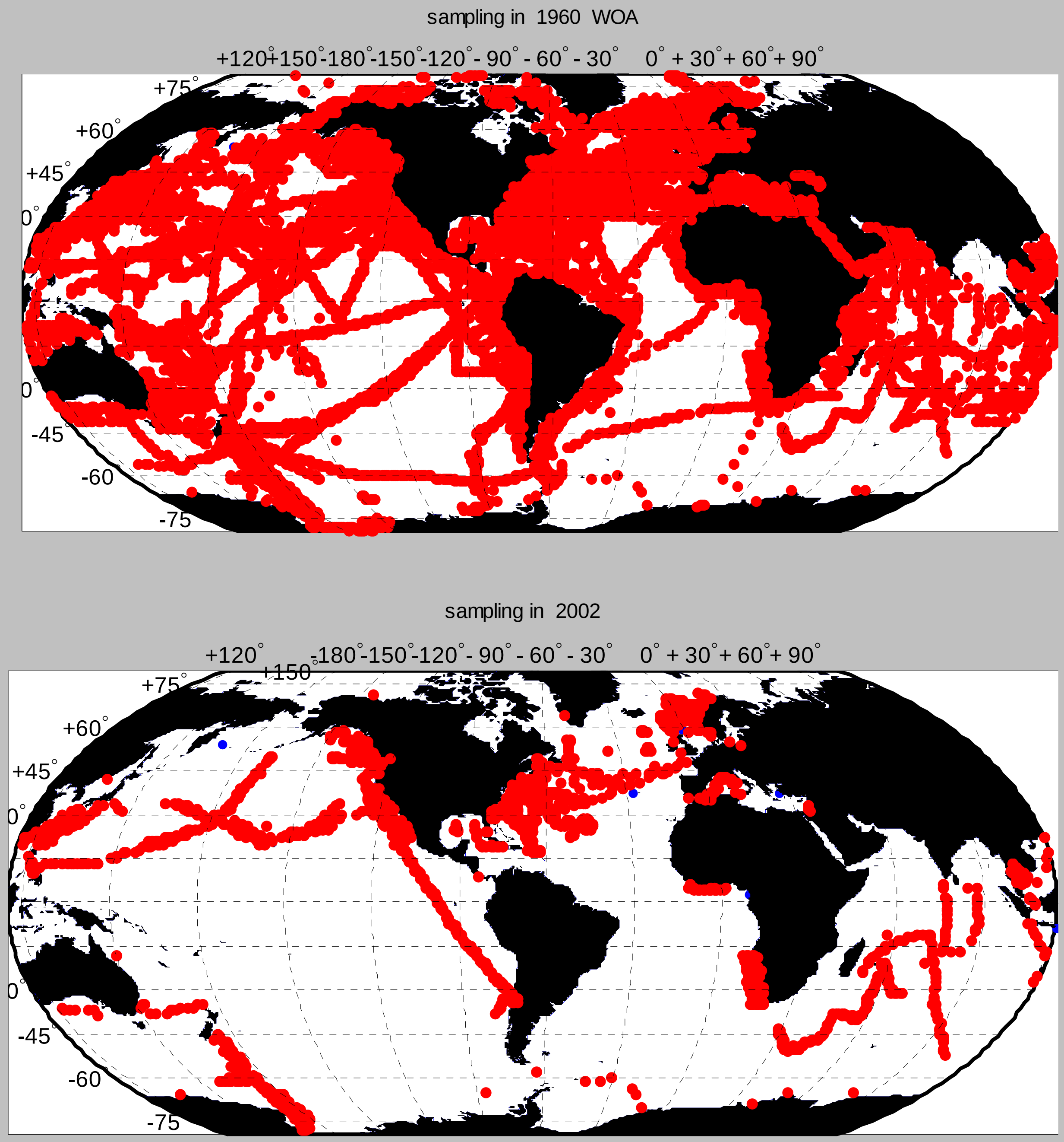


But, Miller and Douglas, Nature, 2004, show the apparent bias is due to smoothing in the Levitus et al., hydrography

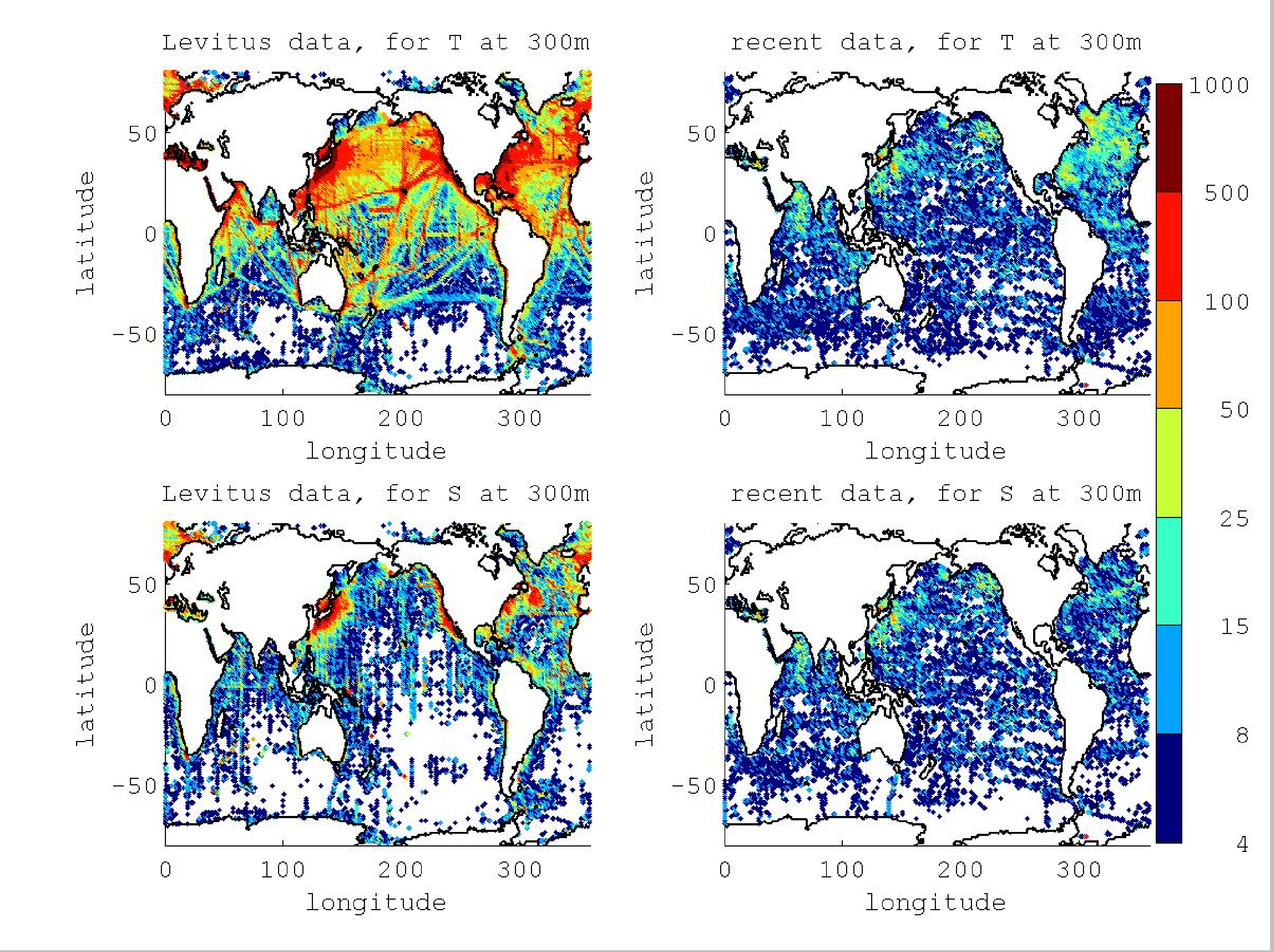
Worthington, 1981, Evol. of Physical Oceanography



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.

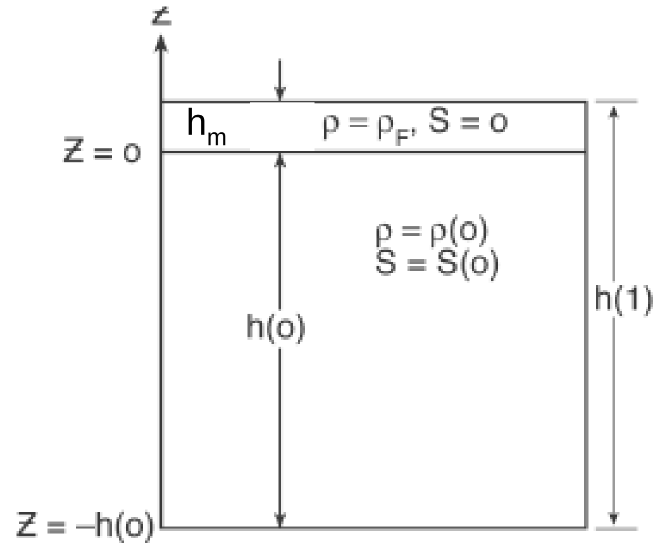

sampling in 1960 WOA
+120° +150° -180° -150° -120° - 90° - 60° - 30° 0° + 30° + 60° + 90°
+75°
+60°
+45°
-45°
-60°
-75
sampling in 2002
+120° +150° -180° -150° -120° - 90° - 60° - 30° 0° + 30° + 60° + 90°
+75°
+60°
+45°
-45°
-60°
-75

mainly MBTs



More than 4 measurements in a 1 degree square. “Recent” means WOCE & later.

Munk (2004) pointed out that there was some misinterpretation of salinity changes as they influence sea level.



Definition sketch of a fluid of initial depth h

The equation of state is approximately linear:

$$\rho = \bar{\rho}(1 - \alpha T + \beta S)$$

Suppose the fluid is well-mixed over a depth $h(0)$ with temperature $T(0)$ and salinity $S(0)$. Then keeping the salinity fixed, and changing the temperature to $T(1) = T(0) + \Delta T$, the fluid mass does not change, and sea level shifts by the "thermosteric" amount, h_T so that

$$\bar{\rho}(1 - \alpha T(0) + \beta S(0))h(0) =$$
$$\bar{\rho}(1 - \alpha T(0) - \alpha \Delta T + \beta S(0))(h(0) + h_T)$$

or,

$$\boxed{h_T \approx \alpha \Delta T h(0),}$$

which is the excess volume of fluid required to compensate for a uniform temperature increase of ΔT. (In a Boussinesq model, $h_T = 0$, and the mass does change.)

If a layer of fresh water of thickness h_m at temperature $T(0)$ is added to the fluid and then well-mixed, the salinity change is,

$$\boxed{\Delta S = -S(0)\frac{h_m}{h(0)}.}$$

The salt content does not change, and the new column depth is $h(0) + h_S$, where h_S is the halosteric change, determinable from

$$\bar{\rho}(1 - \alpha T(0) + \beta S(0))S(0)h(0) =$$
$$\bar{\rho}(1 - \alpha T(0) + \beta S(0) + \beta \Delta S)(S(0) + \Delta S)(h(0) + h_S),$$

or

$$h_S = \beta S(0) h_m$$

or

$$\boxed{h_m = \frac{h_S}{\beta S(0)}}$$

where the "Munk multiplier" $1/\beta S(0) \approx 36$.

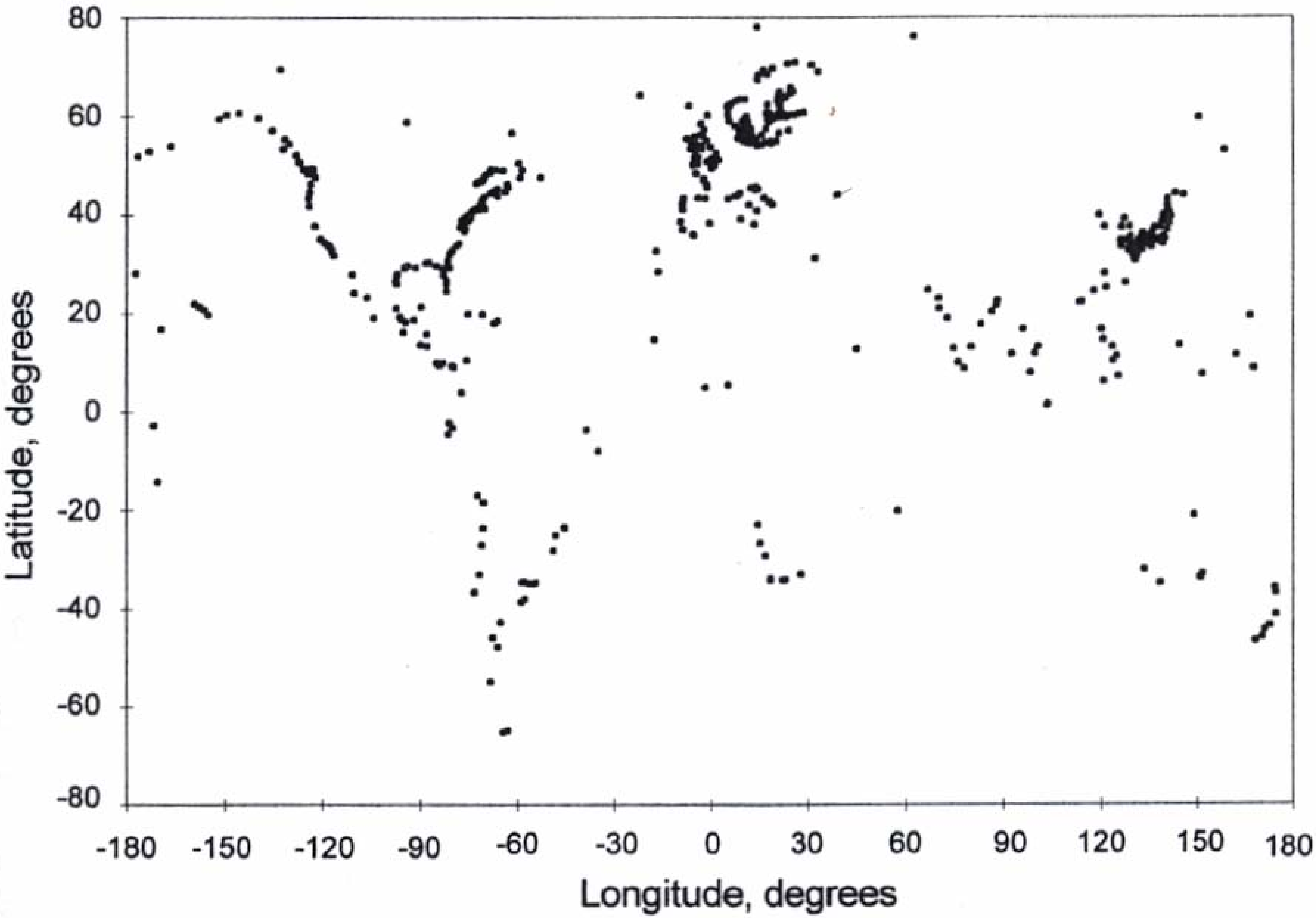
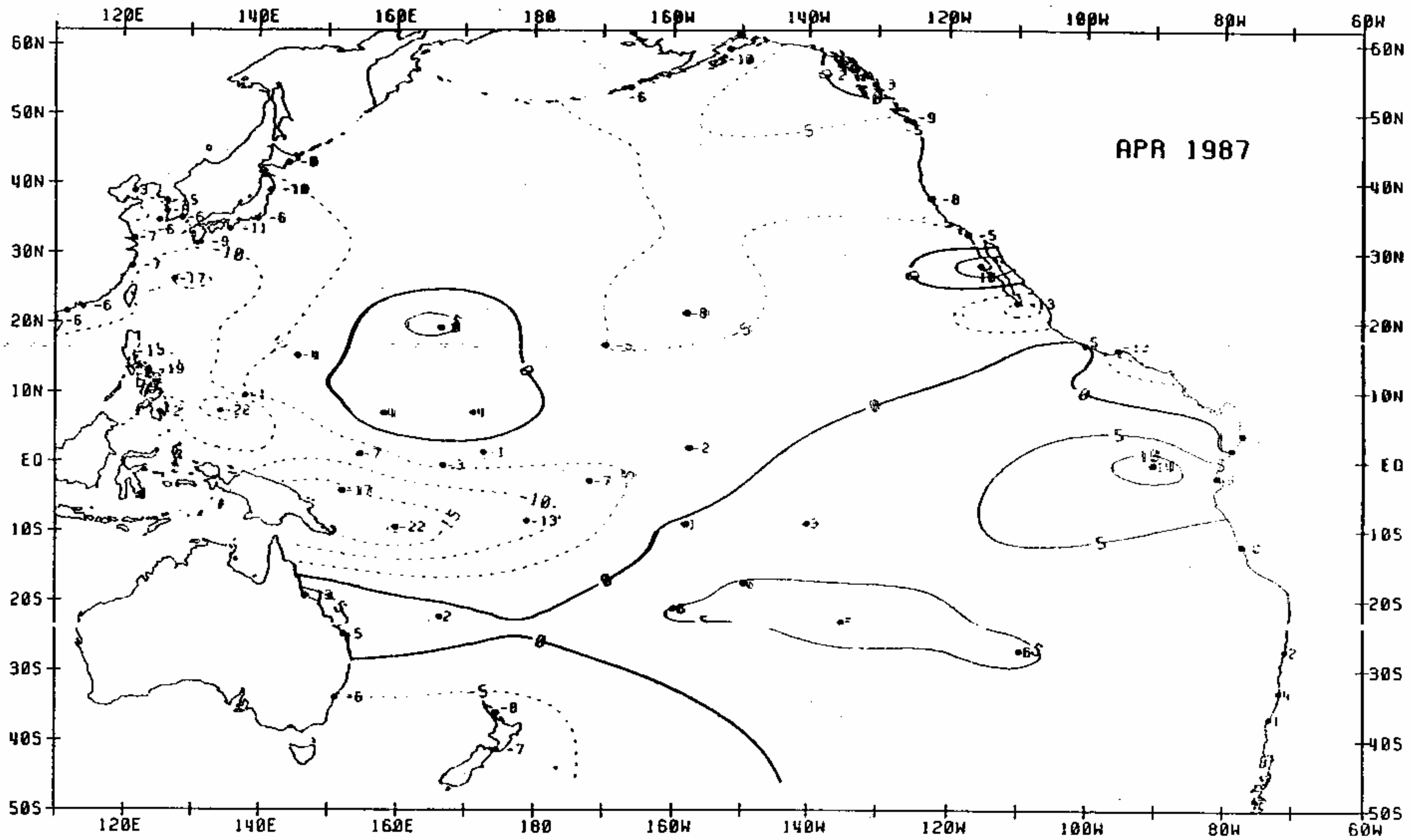


Figure 3.12 RLR tide gauge locations with records longer than 20 years.



DEVIATION OF SEA LEVEL IN APRIL 1987 FROM THE 1975 TO 1981 MEAN SEA LEVEL IN CENTIMETER.

From Douglas et. al. 2001.

Note that sealevel appears to be falling around Scandinavia.

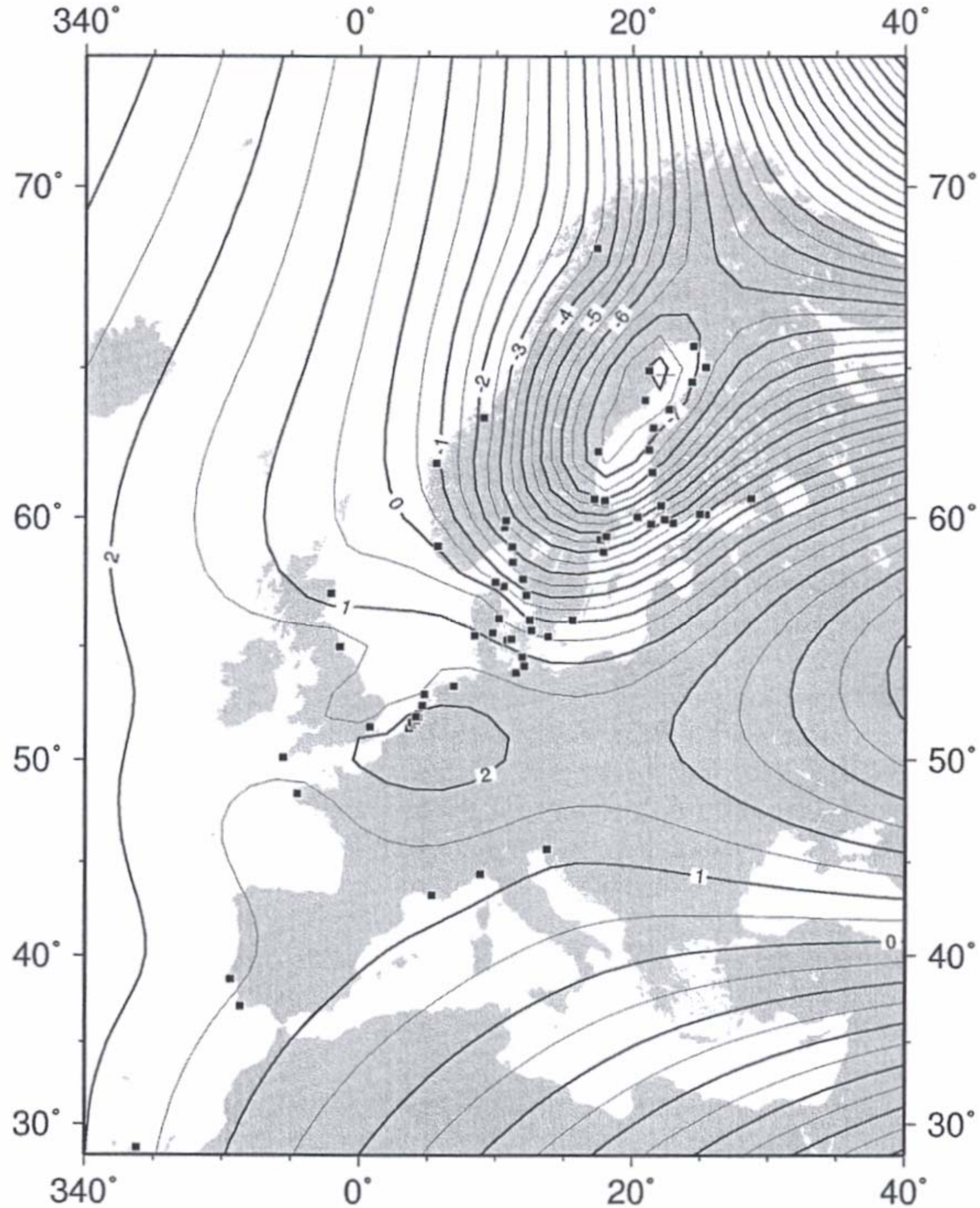


Figure 1.2 Contour plot of 20th-century European sea level trends (mm/yr).

Example of possible systematic errors in data leading to trends:

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 (not in itself an issue). 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. Seasonal and latitudinal sampling biases.

Tide Gauges:

Tectonic corrections. Location shifts. Harbor construction.

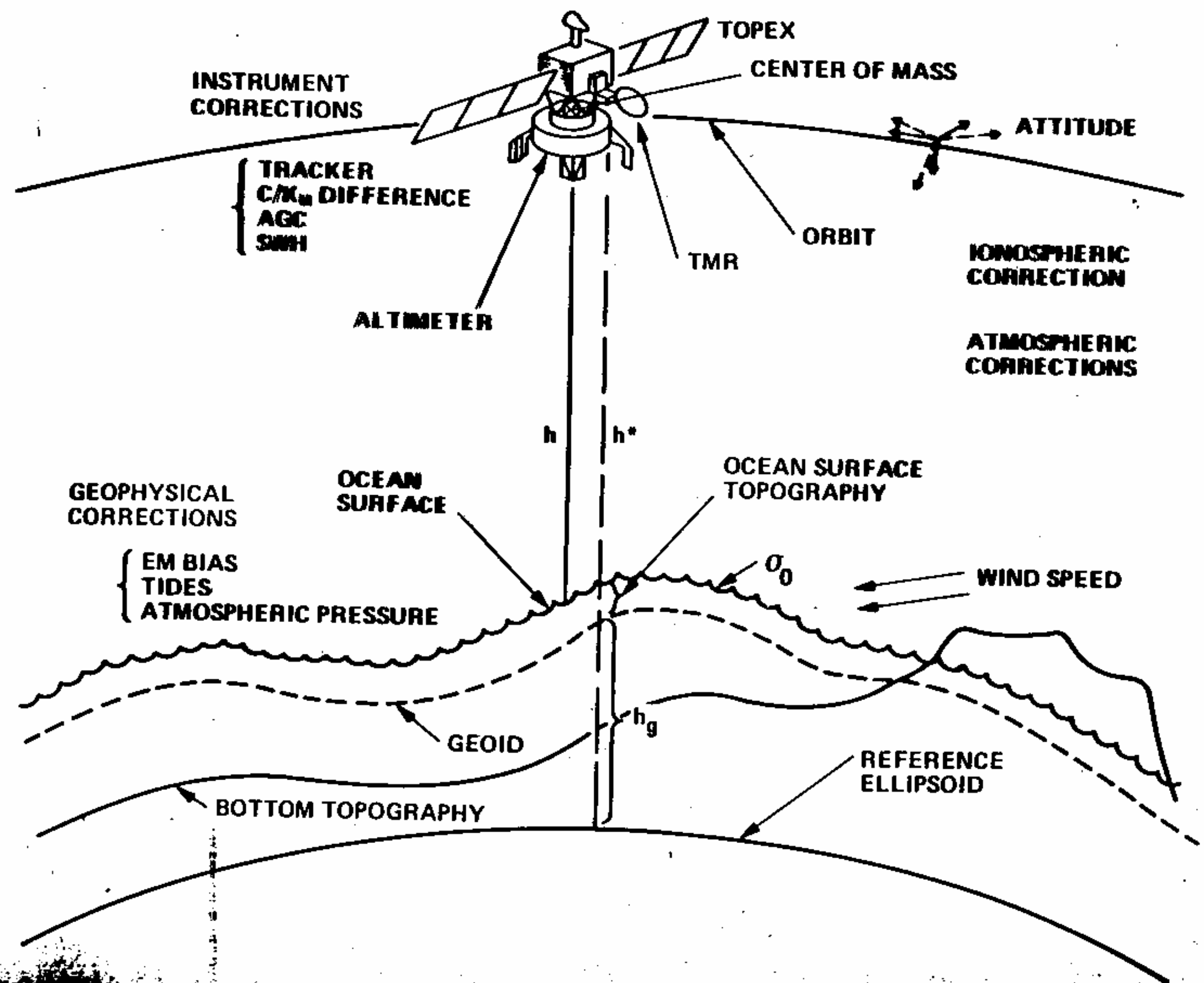
Are these errors random, or systematic? How large are they?

The apparent ability to estimate global sea level rise from altimetry came as a great surprise to the organizers of the TOPEX/POSEIDON mission – as the expected errors were so large compared to the expected signal.

Altimetry is very simple in concept. But in practice, one makes a long succession of corrections.

JPL

MEASUREMENT EFFECTS SCHEMATIC

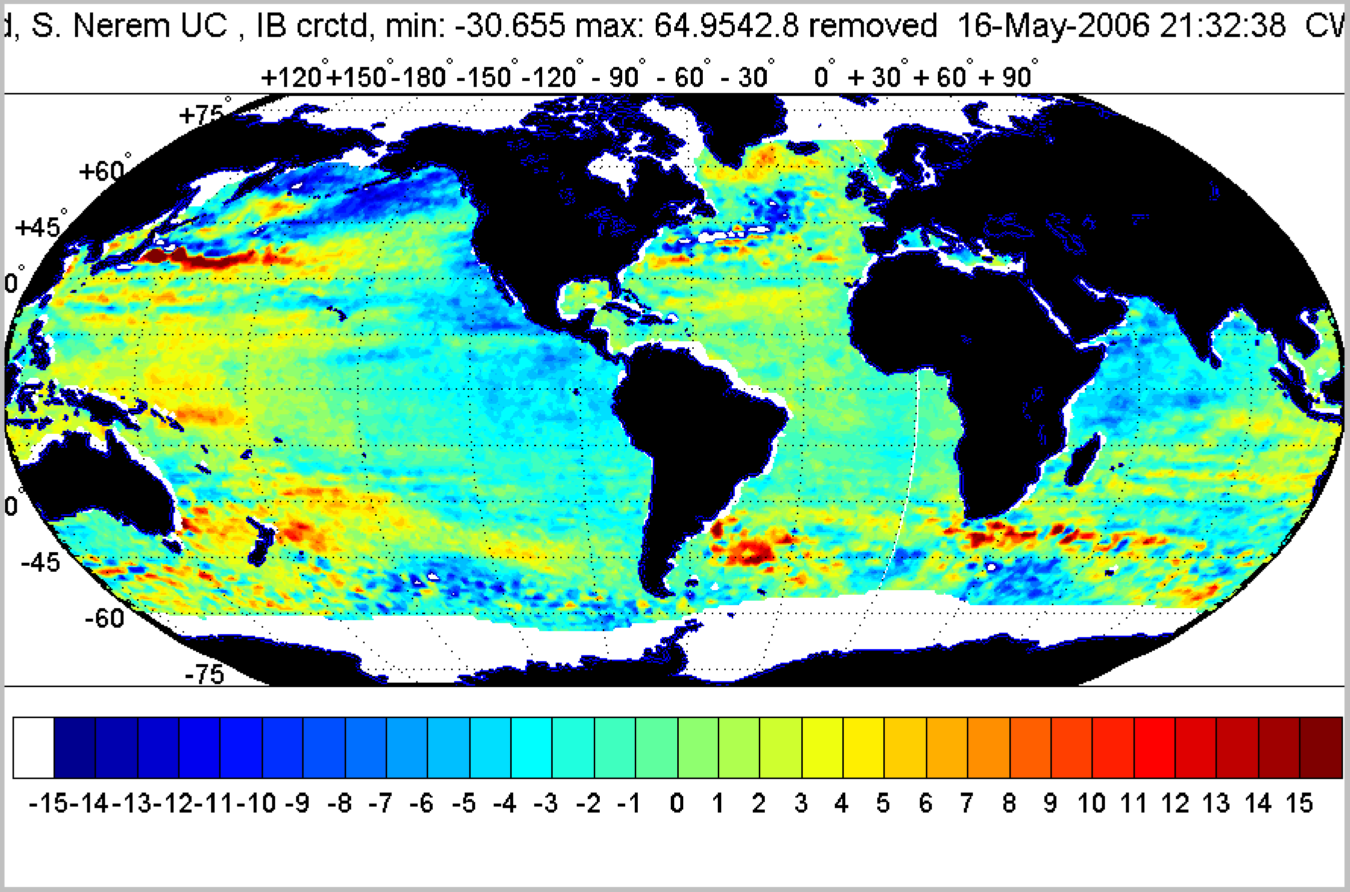


Corrections applied include:

atmospheric water vapor
ionospheric electron content
atmospheric pressure loading
wave height biases of several types
orbits
tides
rotation wobble

Trends in any 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 coding error was found.)

One new worry is the suggestion that the center of mass of the earth may have position trends (e.g., owing to post glacial rebound, ice transfer, etc.)



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

Seek to use the ECCO-GODAE synthesis (MIT/AER) to estimate global patterns of sea level rise, and parititition it amongst heating/ cooling, evaporation/precipitation/runoff, and general circulation shifts as a function of depth.

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

There exist serious modelling questions in this context:

Boussinesq approximation---conserves volume, not mass; conserves salinity, not salt.
Surface boundary condtions for salt---at least 3 in use, including virtual salt flux (Huang, 1993).
Approximations in the equation of state.
Errors in the meteorological forcing including large-scale imbalances.
Incomplete sea ice models.
.
.
Not the present focus and here will ignore for the most part.

Meteorological Variables	**Number**
NCEP/NCAR (6-hrly. windstress, buoyancy flux, short/long radiation)	2.1×10^9
Oceanographic Variables	
Altimetry (TOPEX, Jason, GFO, ERS-1/2, ENVISAT)	3.3×10^7
XBT	1.9×10^7
Argo profile temperature and salinity	2.1×10^7
CTD temperature and salinity	2×10^6
Hydrographic climatologies	1.6×10^7
Sea surface temperature	5.3×10^6
TMI temperatures	1.5×10^6
GRACE geoid	57,600
Bottom topography	57,600
QSCAT winds	1.0×10^7
Approximate Number Oceanographic Observations	1.1×10^8
Approximate Number Total Weighted Values	2.11×10^9

We are solving the
least-squares problem of minimizing model/data misfit, while keeping the model rigorously correct.

$$
\begin{aligned}
J' &= [\mathbf{x}(0) - \mathbf{x}_0]^T \mathbf{P}(0)^{-1} [\mathbf{x}(0) - \tilde{\mathbf{x}}_0] \\
&+ \sum_{t=1}^{t_f} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)]^T \mathbf{R}(t)^{-1} [\mathbf{E}(t)\mathbf{x}(t) - \mathbf{y}(t)] \\
&+ \sum_{t=0}^{t_f-1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t)
\end{aligned}
$$

initial condition controls

model/data misfit

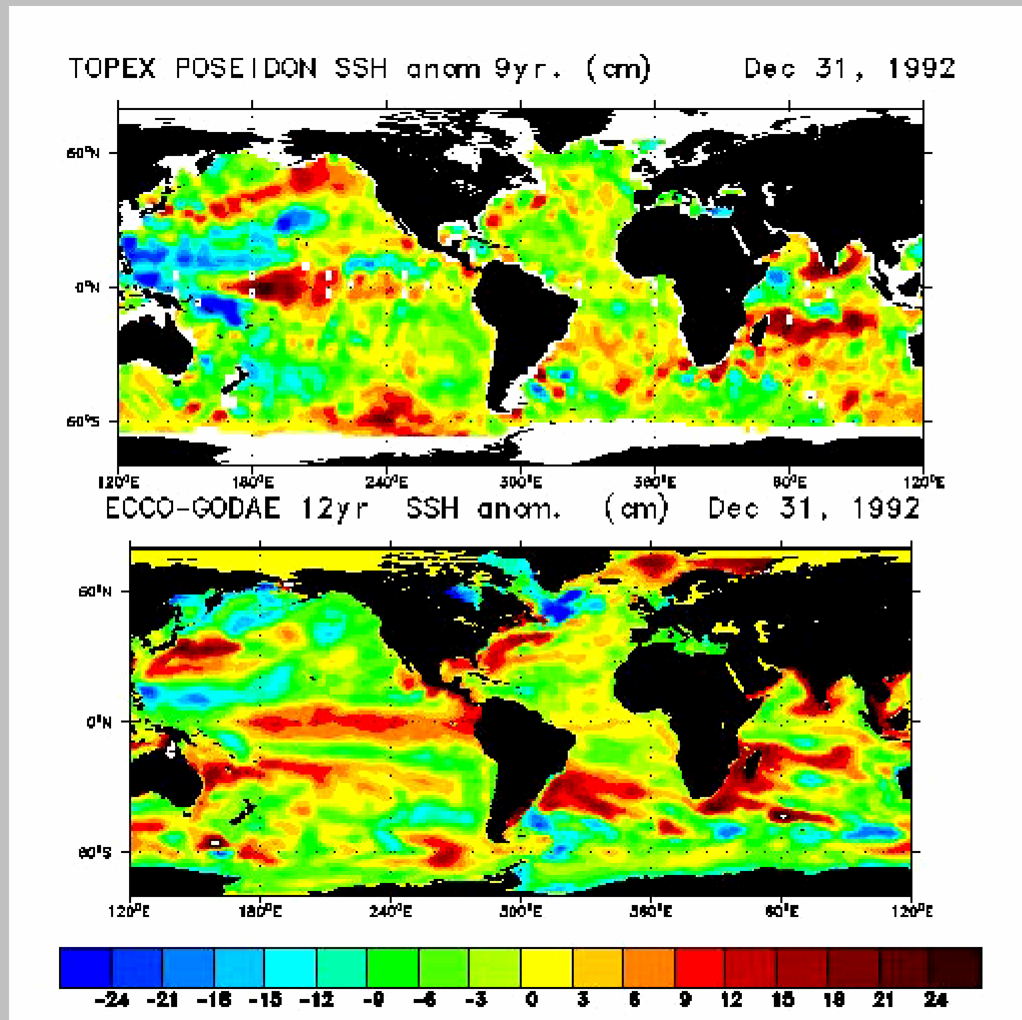
control parameters

‘

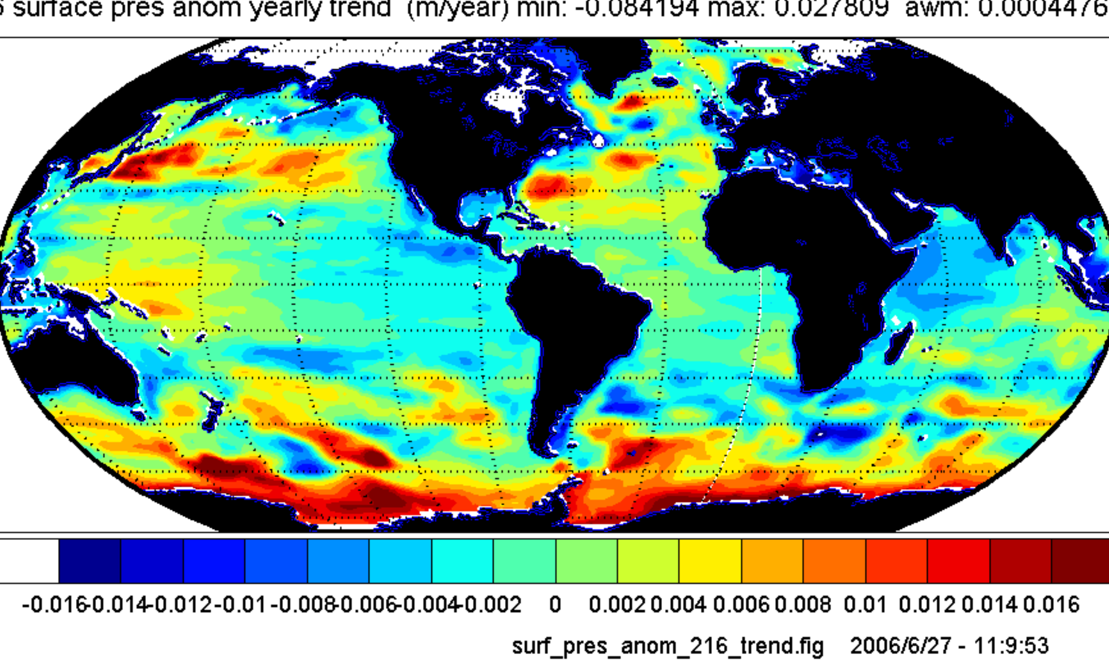
Here the control parameters are primarily adjustments made to the surface meteorological forcing (wind stress, buoyancy exchange) and the initial conditions.

It’s a problem of *constrained least-squares* and is using the model to *interpolate* the data --- a much easier task than forecasting.

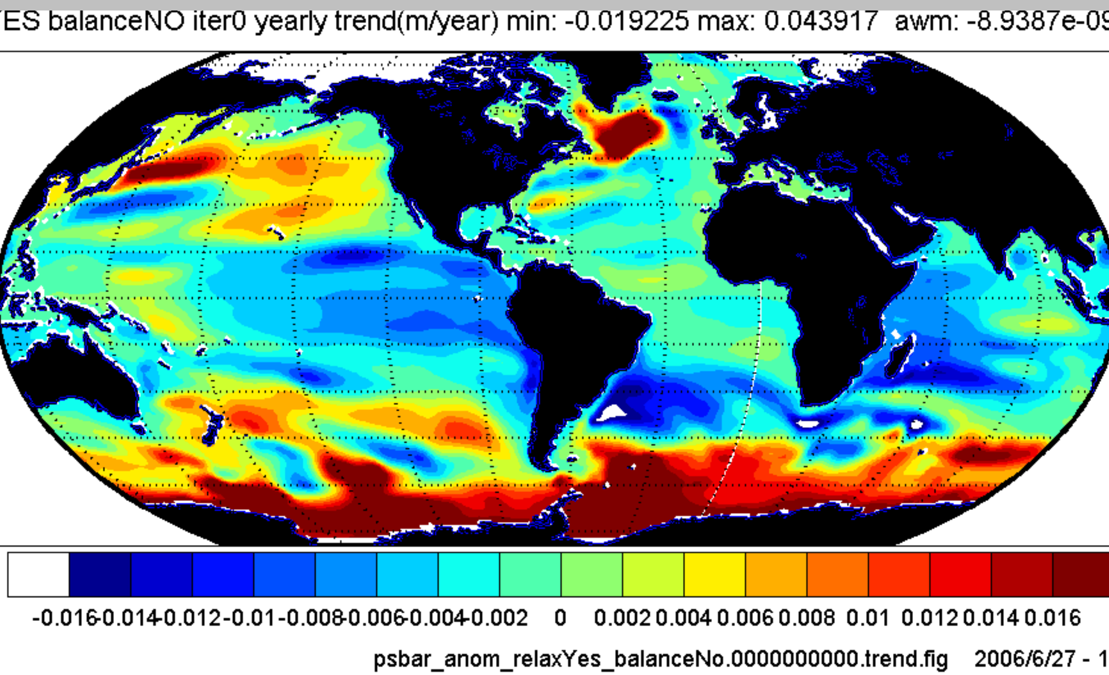
But, results are obtained from an unconstrained, forward, calculation using the adjusted parameters. That is no non-physical processes are present.


TOPEX POSEIDON SSH anom 9yr. (cm) Dec 31, 1992
60°N
0°N
60°S
120°E 180°E 240°E 300°E 360°E 60°E 120°E
ECCO-GODAE 12yr SSH anom. (cm) Dec 31, 1992
60°N
0°N
60°S
120°E 180°E 240°E 300°E 360°E 60°E 120°E
-24 -21 -18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18 21 24

cms

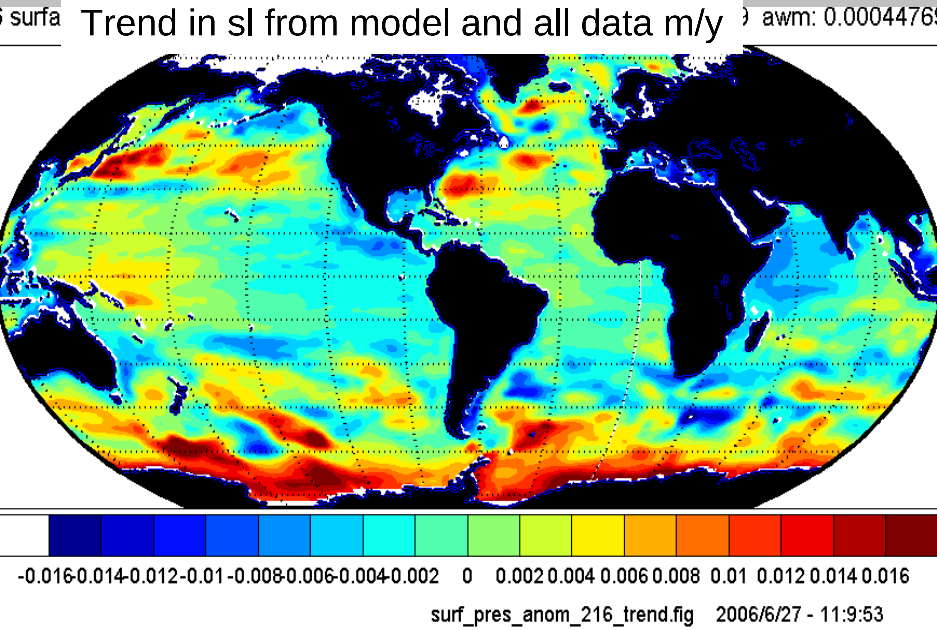


ECCO-GODAE estimate
v2.216 sea level trend in mm/y

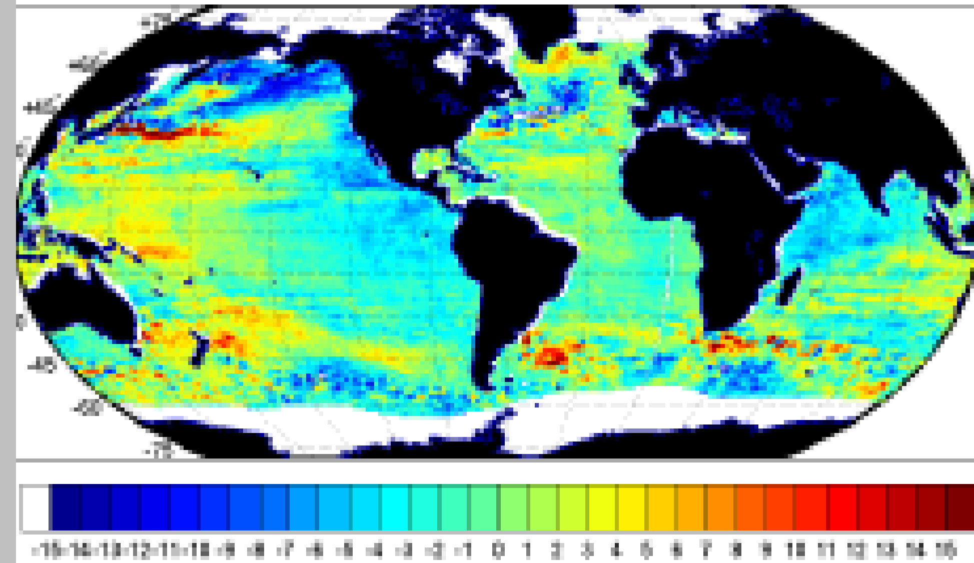


sea level trend in mm/y from
unconstrained model

Trend in sl from model and all data m/y

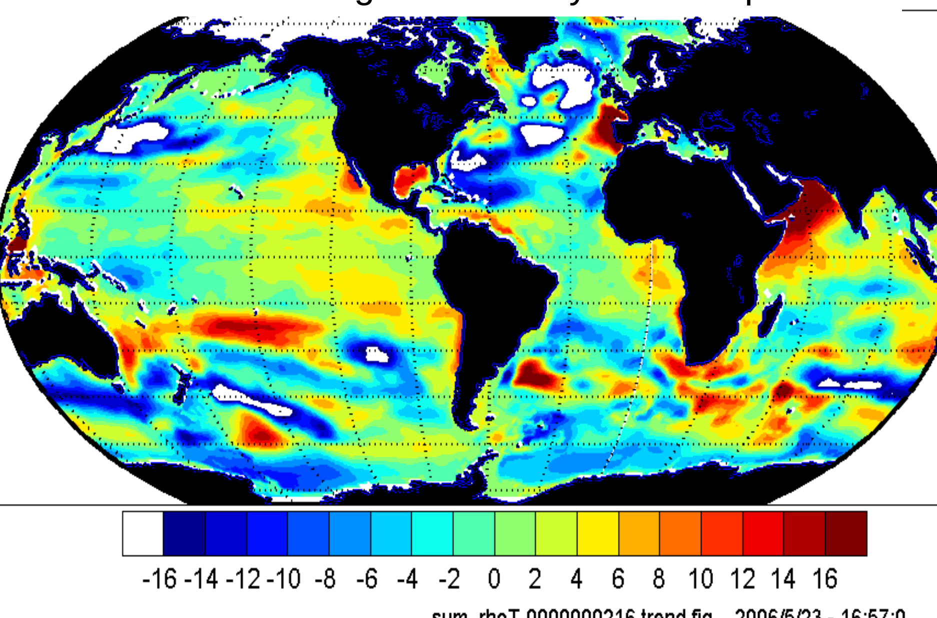


Trend in sl from altimetry data mm/y

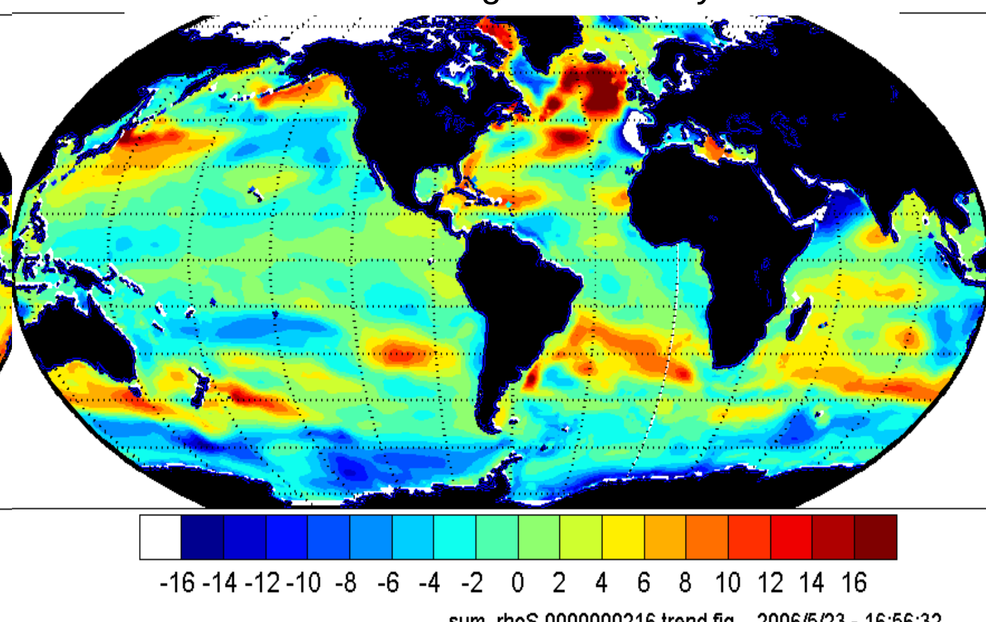


Global mean removed from the sl results

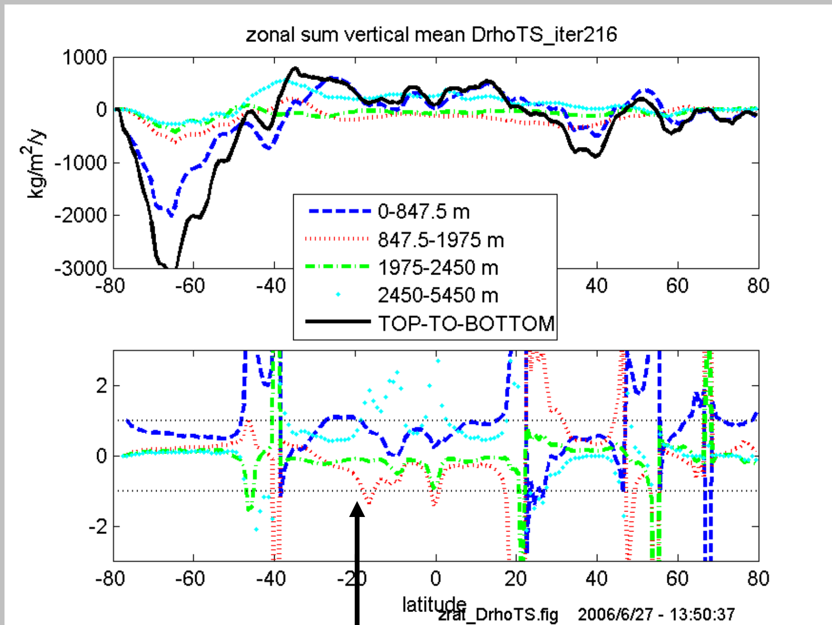
Trend in column integrated density from temperature



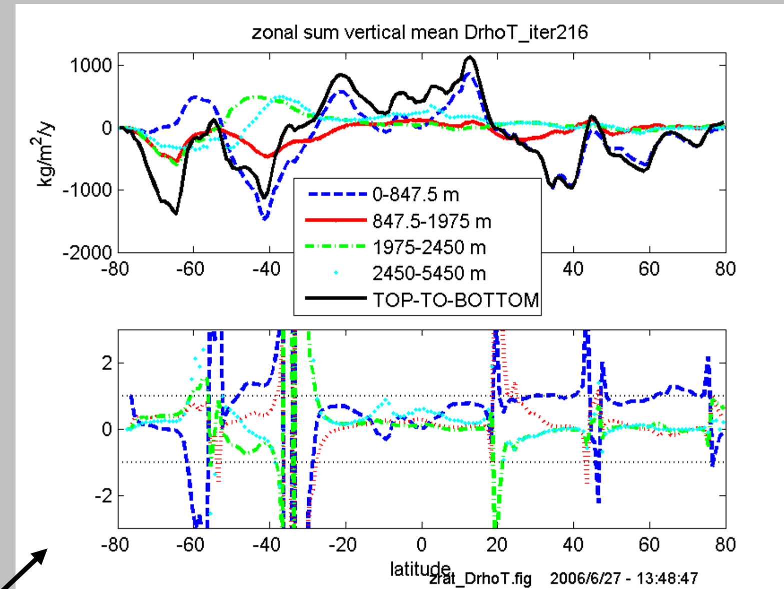
Trend in column integrated density frrom salt



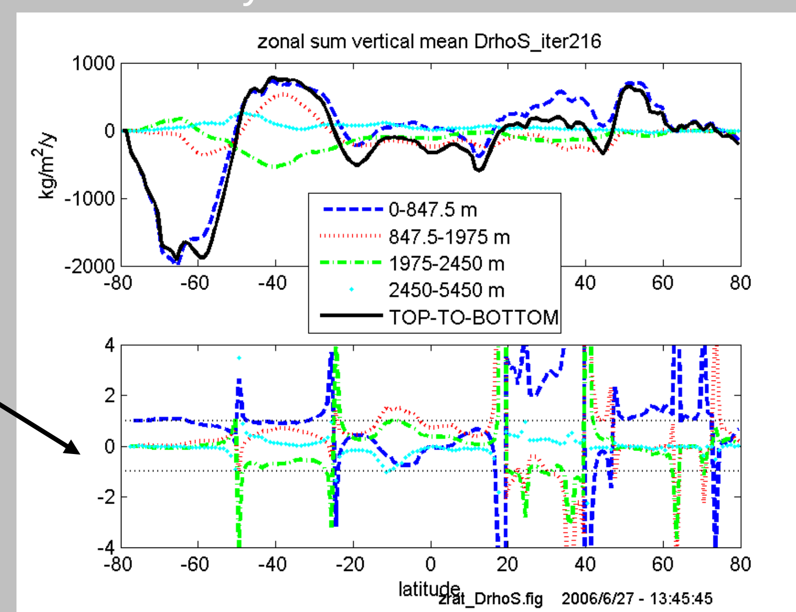
Vertical integrals of net density change



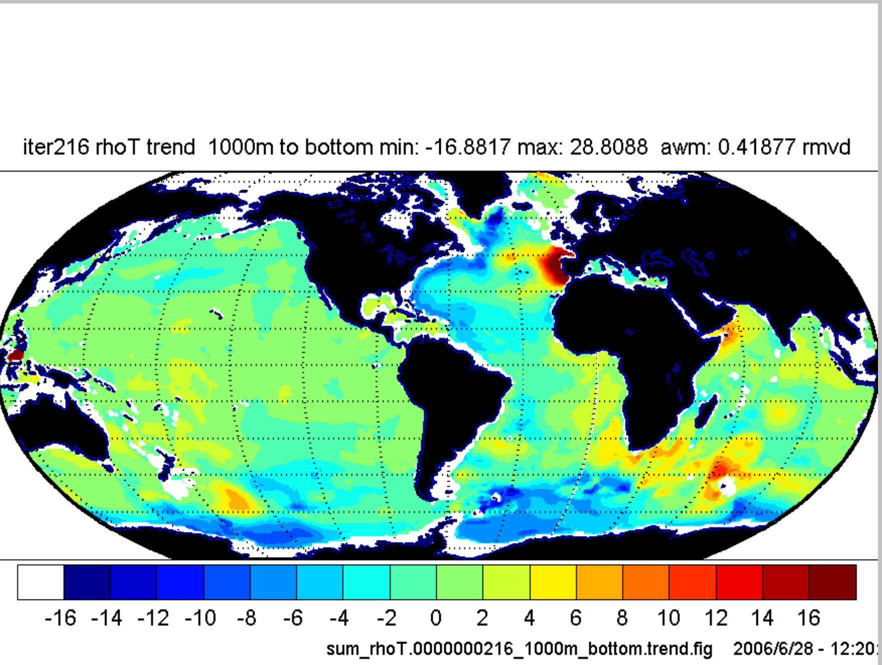
Vertical integrals of net density change from temperature

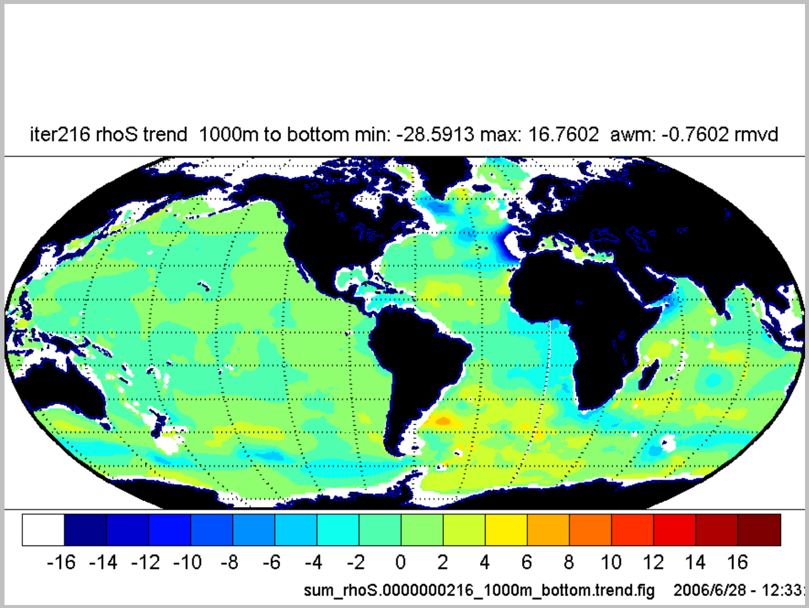


Vertical integrals of net density change from salinity



ratios to the top-to-bottom integral



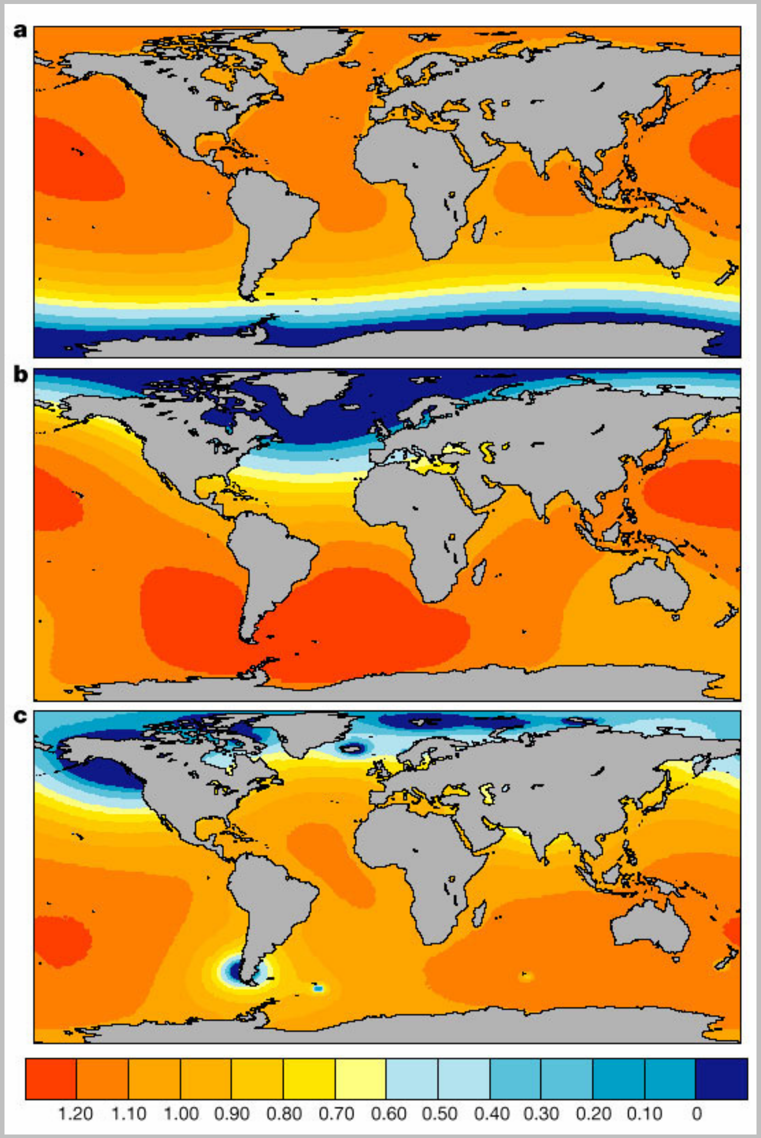


1000m to bottom temperature contribution to density trend mm/y

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

There are many more complications, e.g.:

Fractional variation of sea level from melting ice, assumed uniform over restricted areas.



Antarctica

Greenland

Mountain glaciers

Mitrovica et al., Nature, 2001

A Summary

On decadal time scales, large scale patterns of sea level change are dominated by 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.

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.

Not clear whether net glacial melt is better determined from oceanic or cryospheric measurements.

Thank you.