GLOBAL SEA LEVEL RISE

Carl Wunsch, MIT
EPA October 2008

Who cares? How does one determine it? Is it understood?
What will happen in the future?

Useful general references:

B. C. Douglas, M. S. Kearney and S. P. Leatherman, Eds.
Sea Level Rise. History and Consequences. Academic Press, 2001.

IPCC (2007) Chapter 10 Sea Level Change *(available onllne).*

Disclaimer (added by EPA)

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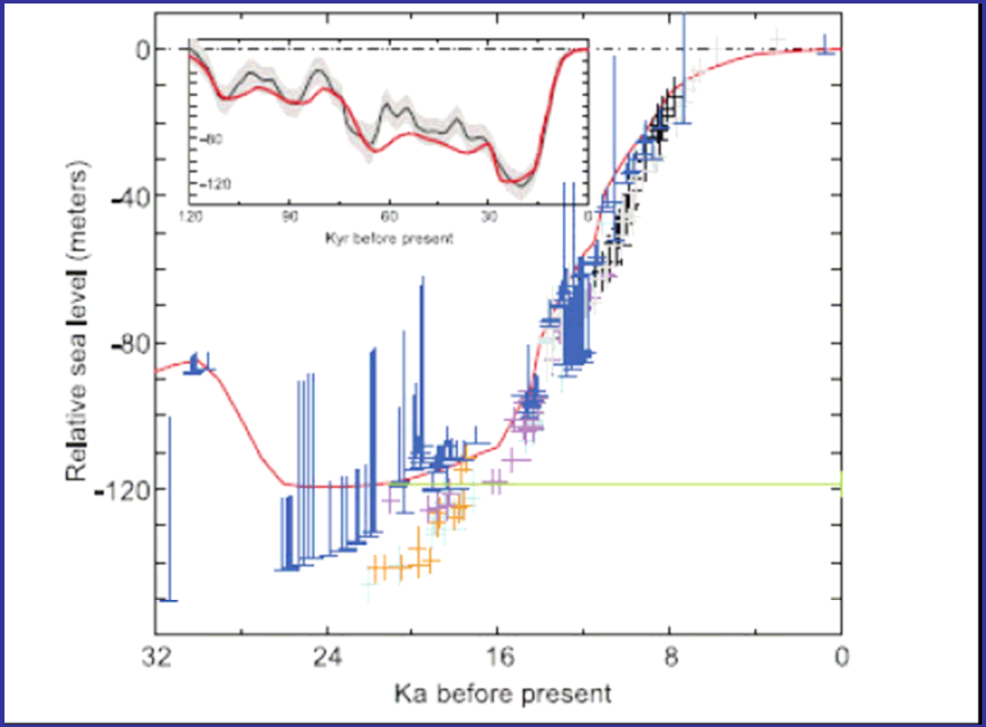
A seemingly simple problem.

In practice, extraordinarily difficult and easy to fall into the trap of thinking one understands it far better than is justified. As a measurement it is extremely difficult; involves processes acting over tens of thousands of years to decades and years and the system is extremely noisy. Prediction is hard. The economic consequences of continued rise are immense.

Among the future changes in climate in a world with growing CO_2 there are three elements about which there would be almost no debate at all:

1. Acidification of the ocean
2. Sea level rise
3. Increased global mean temperatures

Important background: sea level has been rising for about 16,000 years. In the last interglacial it appears to have been a few meters higher than today.



Peltier & Fairbanks, 2006

Sea level is virtually guaranteed to keep rising. The only issue is whether the rate of rise is, or is going to, accelerate.

15,000Y BP

11,500Y BP

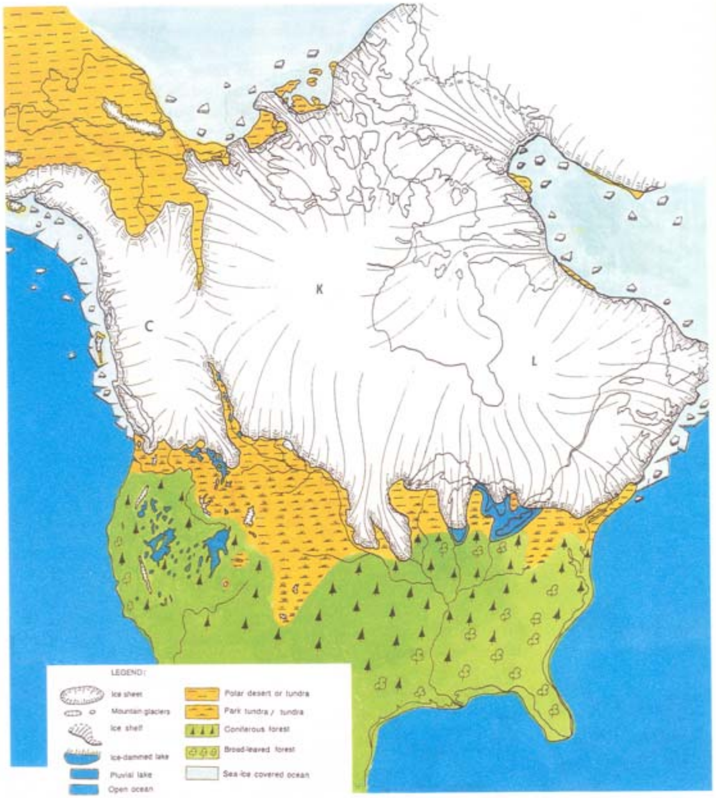


Fig. 2–49. North America, 15 000 years ago. The Cordilleran Ice Sheet (C) was larger and the Laurentide Ice Sheet smaller than 18 000 years ago. The tundra zone had become narrower in the west and midwest, but remained extensive in the east. The maximum ice-sheet model has been used for the Canadian-islands area (see minimum model on Fig. 2–31).

A

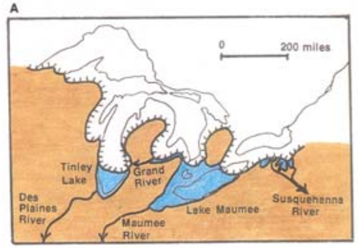


Fig. 2–50. Three selected phases during the deglaciation of the Great Lakes area. Ice-dammed lakes were formed and increased in size within the basins in front of the ice sheet as the ice front retreated. During an early phase (A) the lakes drained southwards towards the Mississippi River, while some smaller lakes drained through the Susquehanna River to the Hudson River. Later (B) the lakes Erie and Iroquois drained through an outlet at Rome, New York, to the Hudson River. During the final glacier retreat (C) the St. Lawrence Lowland was opened by deglaciation and marine water transgressed into the Lake Ontario basin. At that time the St. Lawrence area (S) was isostatically depressed more than 200 m. Since isostatic depression was greater towards the north (Fig. 1–16A), the northerly located outlets of lakes Chippewa and Stanley lay at relatively low levels, and therefore the lakes experienced a marked low-level phase. As the isostatic uplift and tilting of the land gradually progressed, the lakes were allowed to increase to the size of the present-day lakes Michigan and Superior, and the St. Lawrence Lowland emerged from the sea.

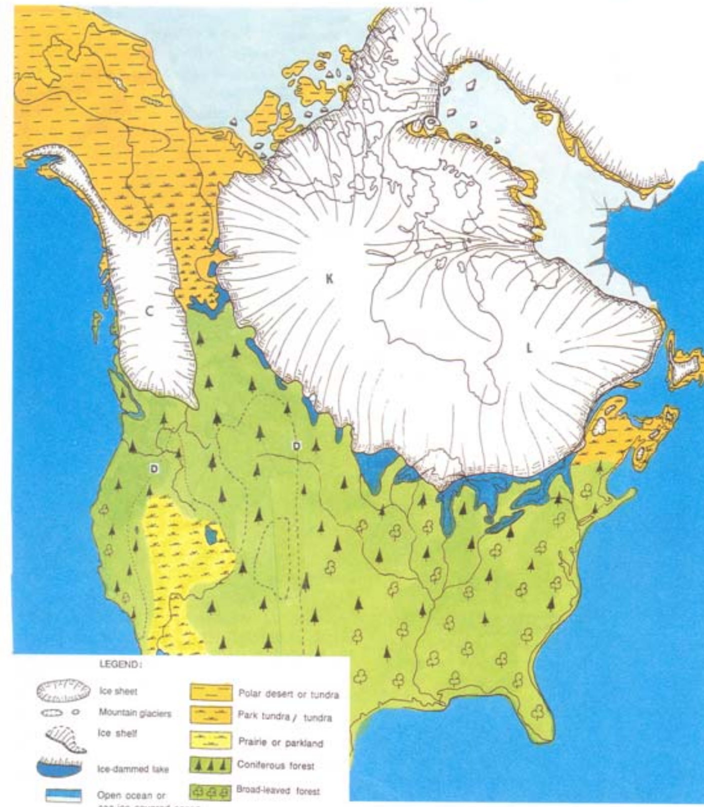


Fig. 2–51. North America, 11 500 years ago. The Laurentide and the Cordilleran ice sheets probably separated about 14 000 years ago. The mixed coniferous/broad-leaf forest zone was wide. Open woodland or parkland is indicated for many of the areas which are covered with mainly deserts today, but information about the exact conditions during the period 12 000–10 000 years ago is sparse. Present-day desert conditions were gradually established and completed about 8000 years ago, and most of the area limited by the dashed line (D) changed to prairies or deserts.

B

C

Melting all the ice now in Greenland would raise sea level by about 7 meters. Melting all the ice in Antarctica would produce about 100m rise.

Andersen and Borns, 1994. The Ice Age World

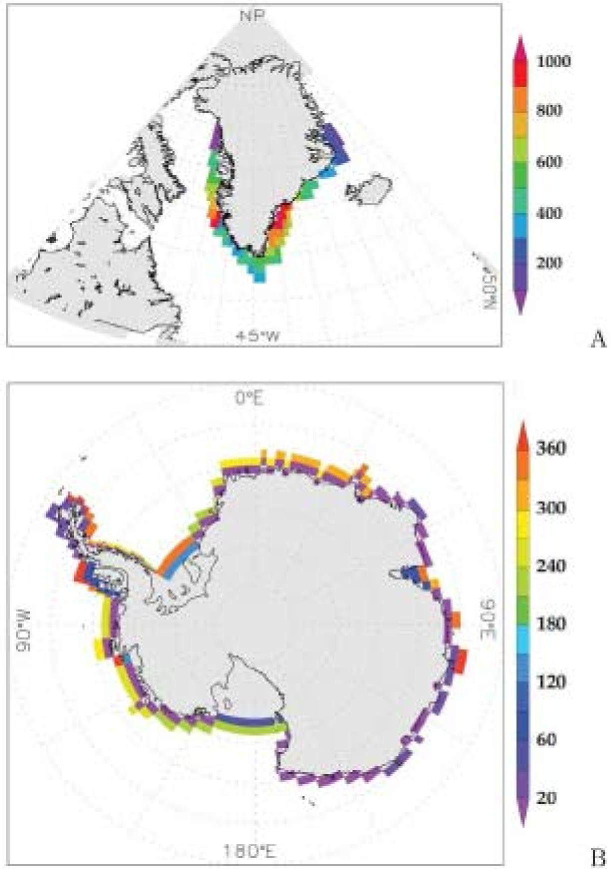


Figure 1. Surface freshwater flux anomalies (in m^3/s) per model grid point associated with loss of polar ice sheets and added to the NECEP/NCAR net freshwater forcing after divisio surface area of each grid cell for (a) the Greenland run and (b) the Antarctic run.

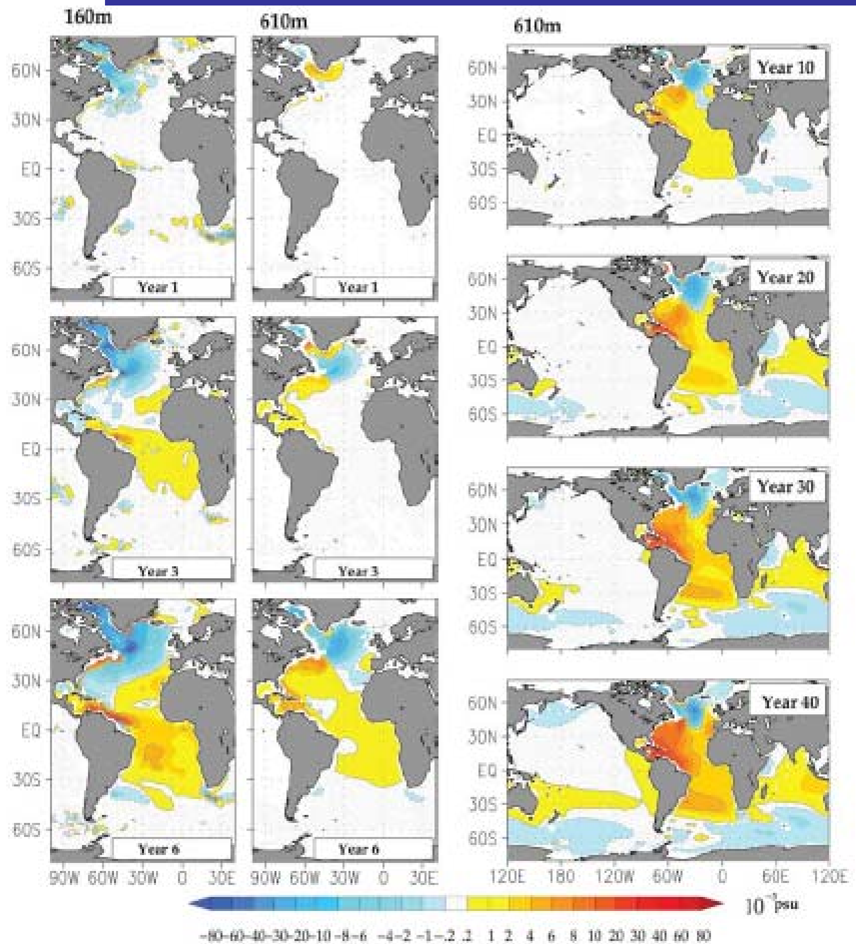


Figure 2. (two left columns) December-mean salt anomalies at 160 m and 610 m depth from the model years 1, 3, and 6 of the Greenland run. (right) December-mean salt anomalies at 610 m depth are shown from the years 10, 20, 30, and 40.

Stammer, JGR, 2008

salt anomaly

It takes decades and longer for the ocean to fully equilibrate with fresh water addition or removal.

Satellite altimeters have become the de facto standard. But the measurements are only useful after 1992. The problem thus divides into the period before and after 1992 and the inferential problems are very different.

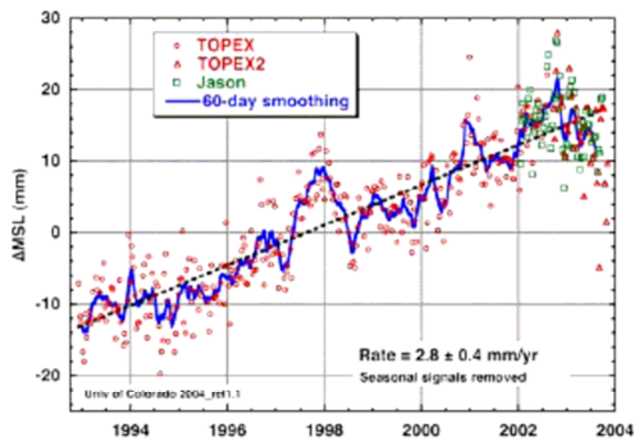
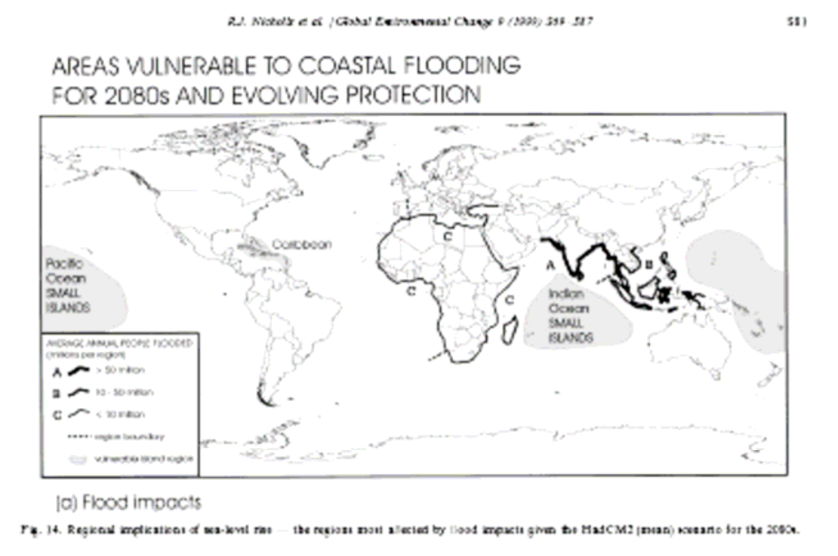
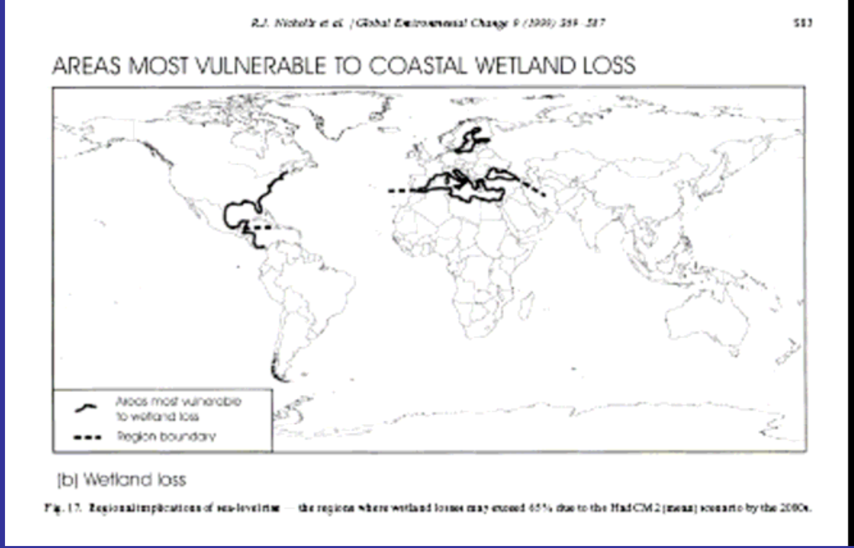
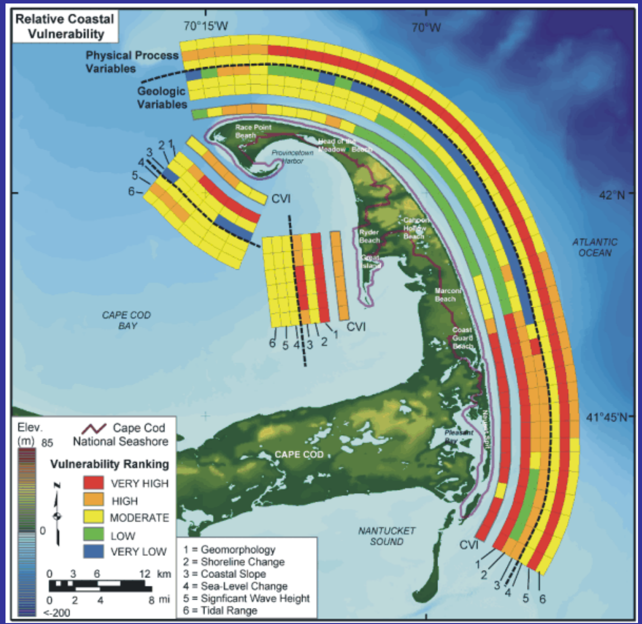


Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the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

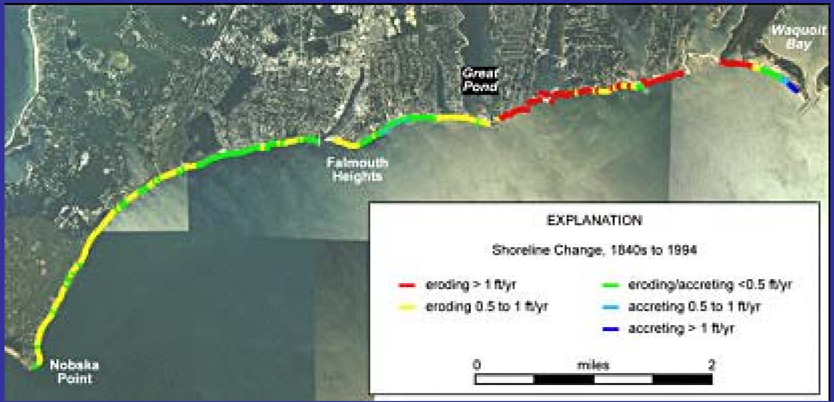
Cazenave and Nerem, Revs. Geophys. 2004







USGS



USGS, WHOI

Katrina-like storm surges,….

From Douglas et al., 2001

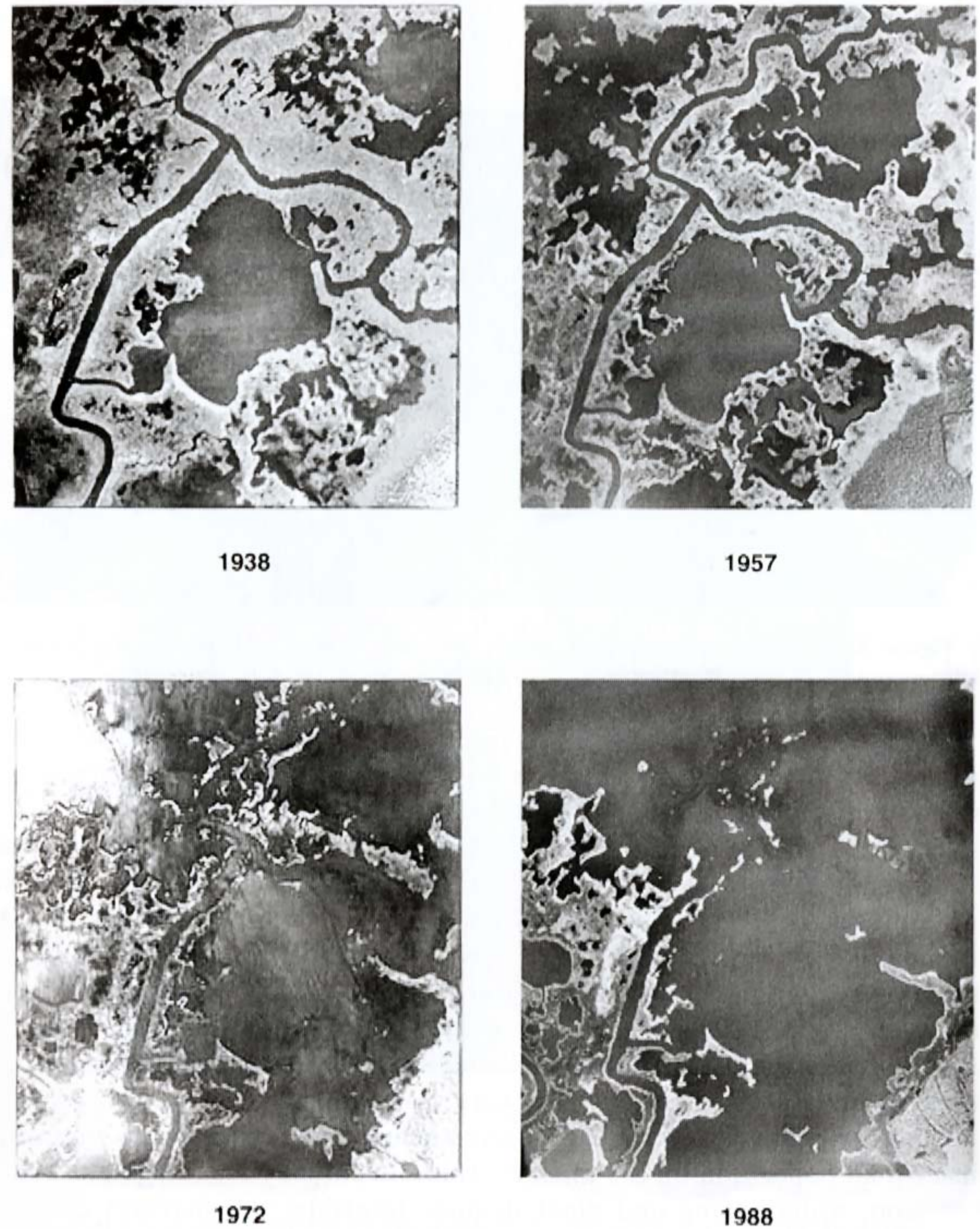
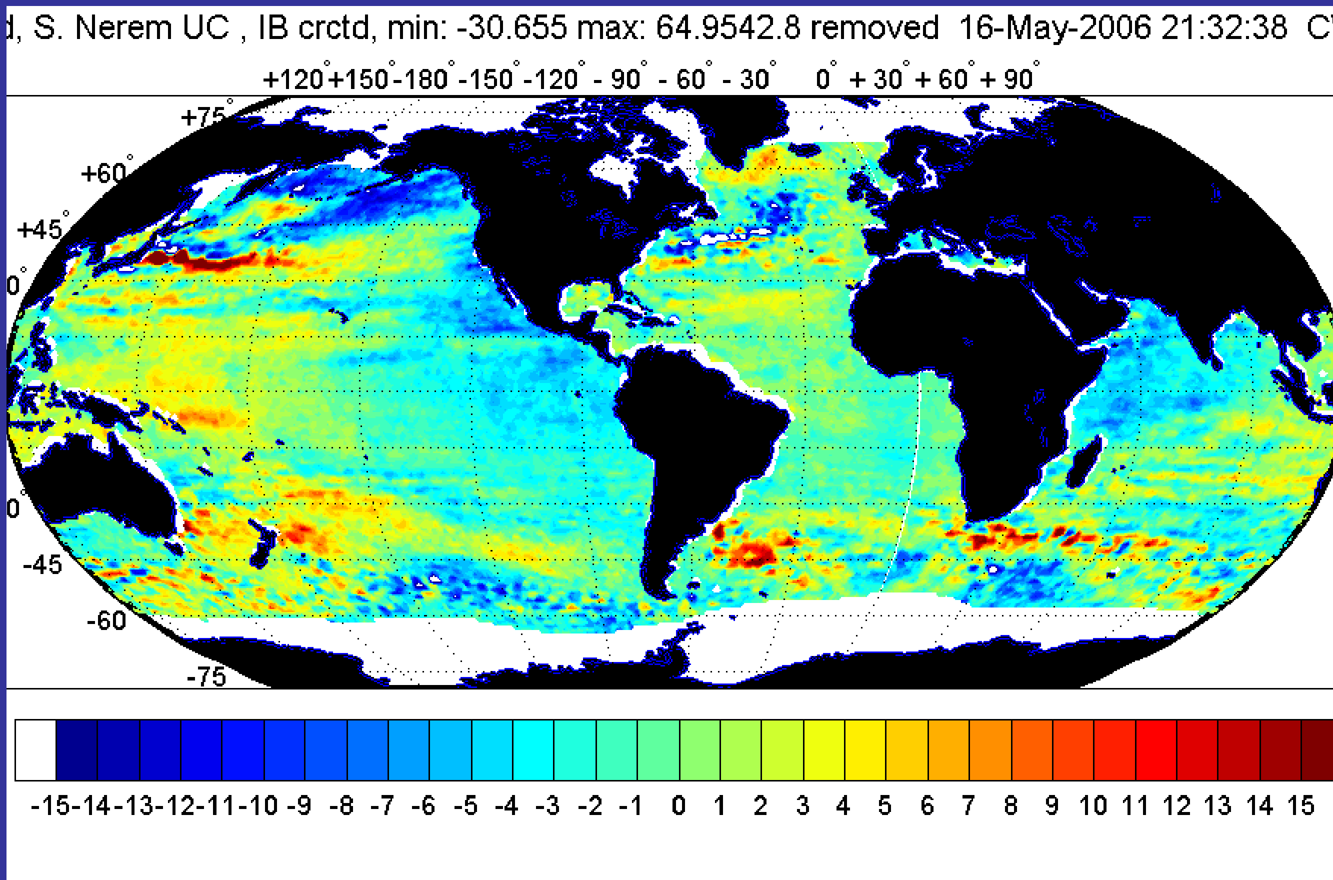


Figure 8.21 Progressive drowning and loss of coastal marshes in Blackwater National Wildlife Refuge near Cambridge, Maryland, in response to a high relative sea level rise.



no data

mm/y

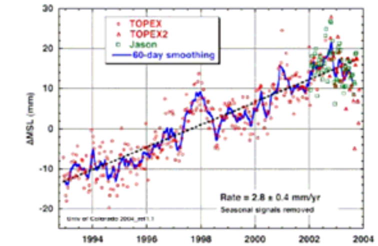


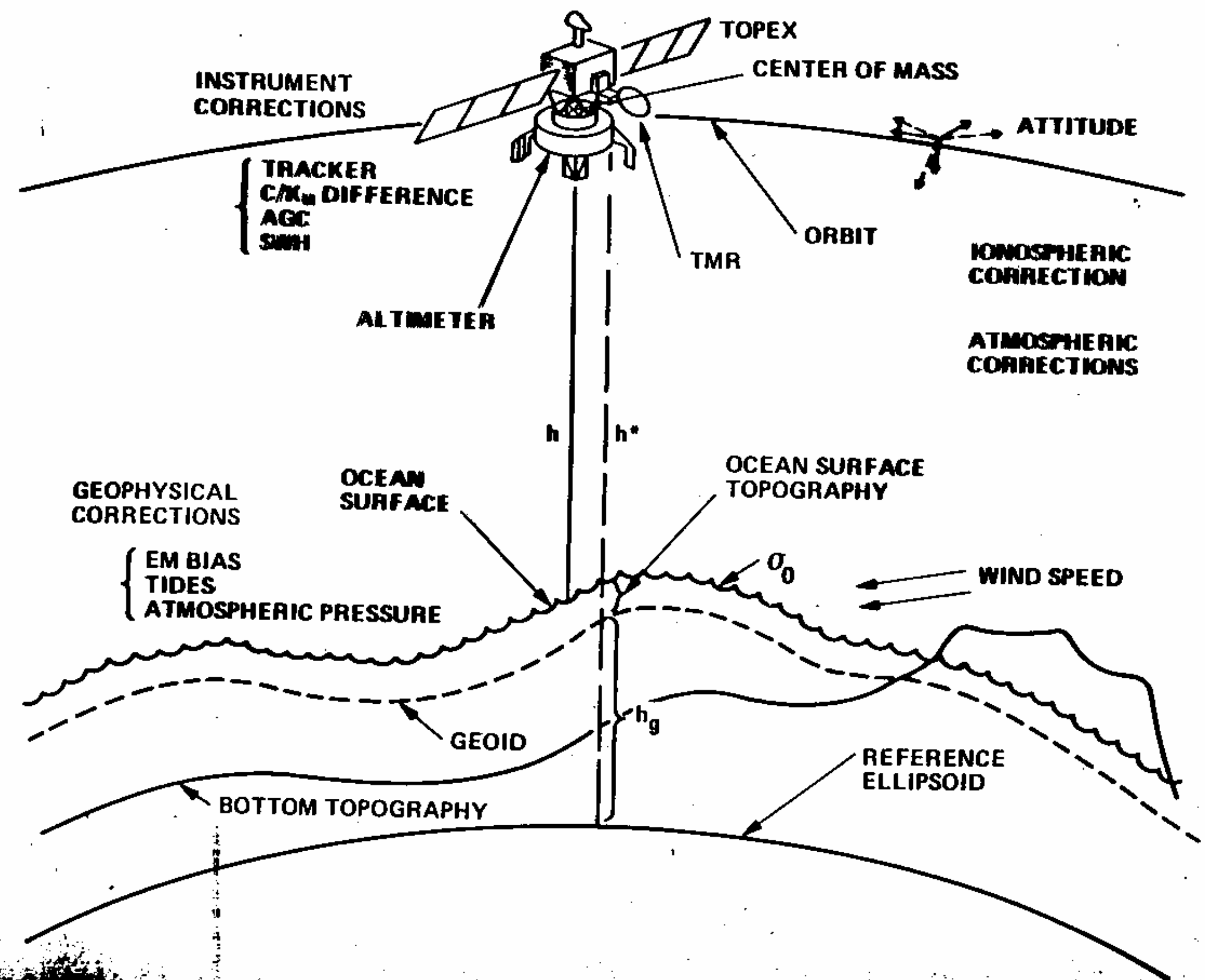
Figure 5. Global mean sea level variations every 10 days from T/P (red circles, red triangles after T/P was moved to new ground track) and Jason (green squares) and after smoothing with a 60-day boxcar filter (blue line) [*Leuliette et al.*, 2004]. No inverted barometer correction was applied to the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

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 (optimistic error bar).

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

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
aliasing of high frequencies
inverted barometer

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 single-line coding error was found.)

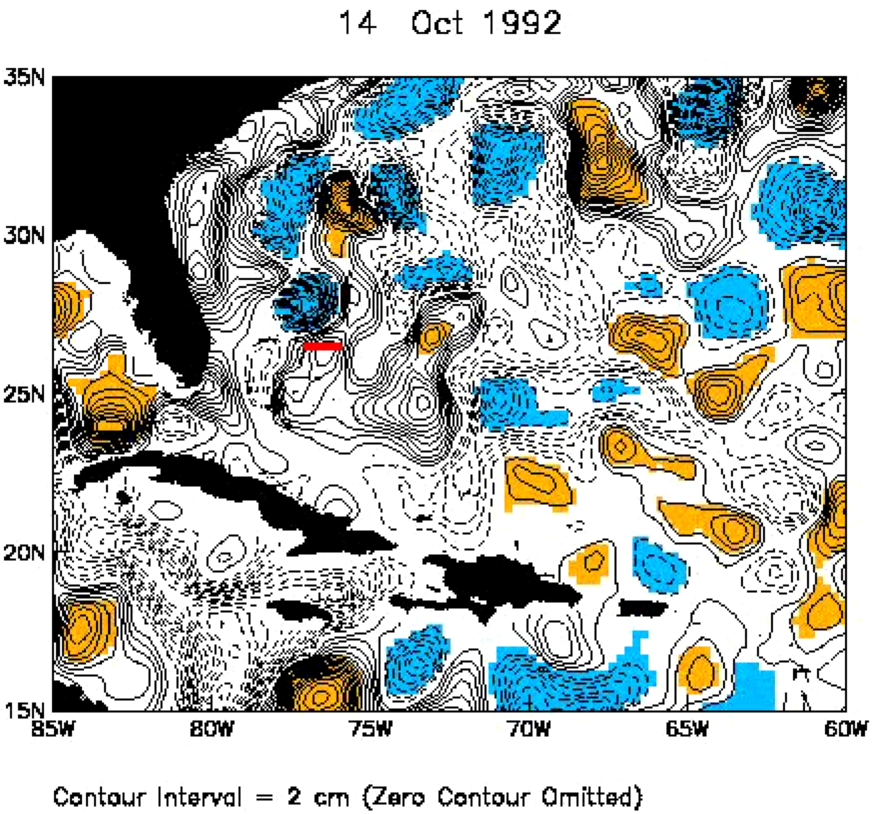
One new worry is the suggestion that the center of mass of the earth may have position trends (e.g., owing to post glacial rebound, ice transfer, etc.)

The system is very noisy!

animated altimetry (that is, *sea level*) using an eddy identification code

2cm height change is approximately 14 Sv of transport if barotropic.

From Dudley Chelton, 2008



(An animation)

What can change the apparent “mean” sea level at a point?

- Addition/removal of water from melting land ice
- Addition/removal of water from land (rivers, percolation through the continental margin). Dam/reservoir construction. Changes in land use, evaporation/precipitation over the continents.
- Local vertical movement of the land relative to the global average.
- Change in total ocean volume (postglacial rebound).
- Change in local gravity (removal of glaciers, postglacial rebound, change in earth rotation rate and rotation pole position)
- Warming/cooling of the water column.
- Redistribution of fluid by the ocean circulation.
- Change in instrument calibration.

….?

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 geometric volume of the ocean

Strategies:

•Measure it directly
•Measure the inputs/outputs (freshwater and heating) and calculate the volume changes

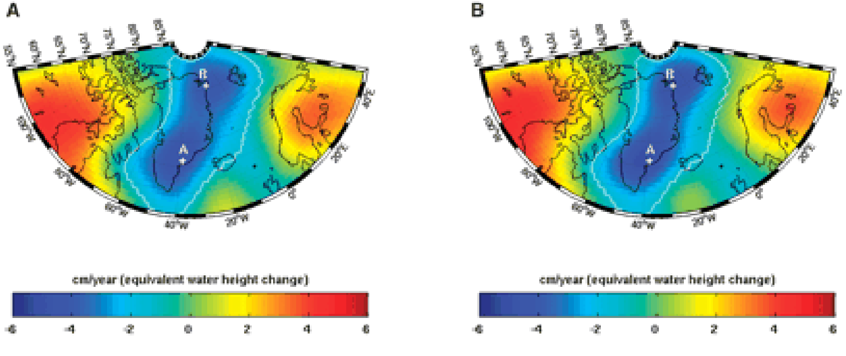
Inputs/Outputs:

One possibility is to determine the net heating and fresh water input from meteorological forcing.

But meteorological analyses prove too inaccurate.

Are the Greenland and Antarctic ice sheets expanding or contracting? Is sea ice melting (doesn't change sea level, but does change oceanic salinity)? 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.



Chen, Wilson, Tapley, Science, 2006
Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet
(note only 3 years of data)

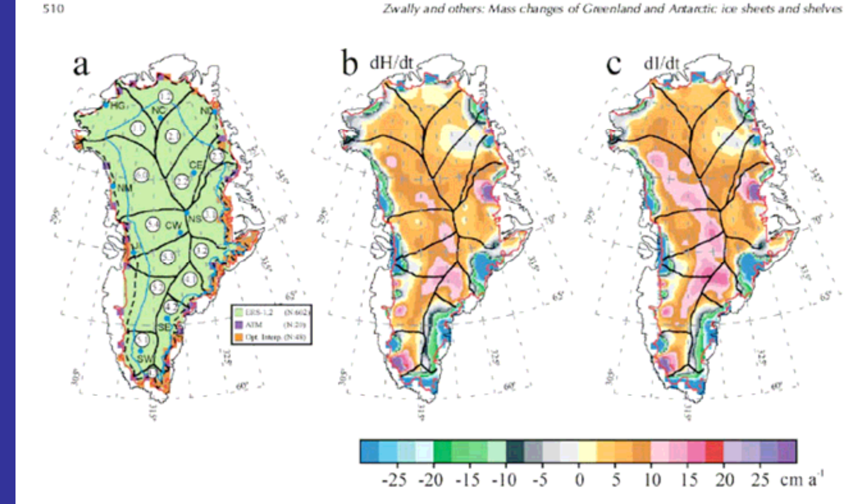


Fig. 1. Greenland. (a) Distribution of surface elevation change data by source, derived from ERS-1 and -2 radar altimetry, ATM (closest-neighbor interpolation from airborne surveys), and obtained by optimal interpolation; ice terminus of coterminous ice sheet (red), equilibrium line (black dashes), 2000 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 (dH/dt). (c) Distribution of ice-thickness change (dI/dt).

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

Rignot and Kanagaratnam, 2006
in IPCC 4, 2007

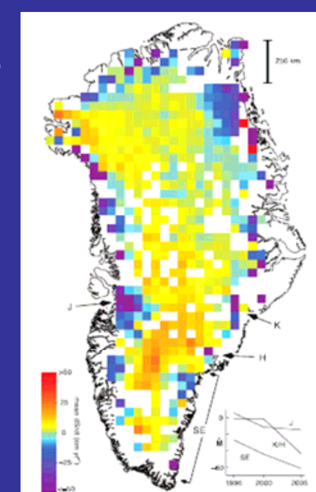


Figure 4.17. *Rates of surface elevation change (dS/dt) derived from laser altimeter measurements at more than 16,000 locations on the Greenland Ice Sheet where ICESat data from 2005 overlay aircraft surveys in 1998/1999 (using methods described by Thomas et al., 2006). Locations of rapidly thinning outlet glaciers at Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H) and along the southeast coast (SE) are shown, together with an inset showing their estimated total mass balance (M, Gt yr⁻¹) between 1996 and 2005 (Rignot and Kanagaratnam, 2006).*

Are the ice sheets growing or shrinking?

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.

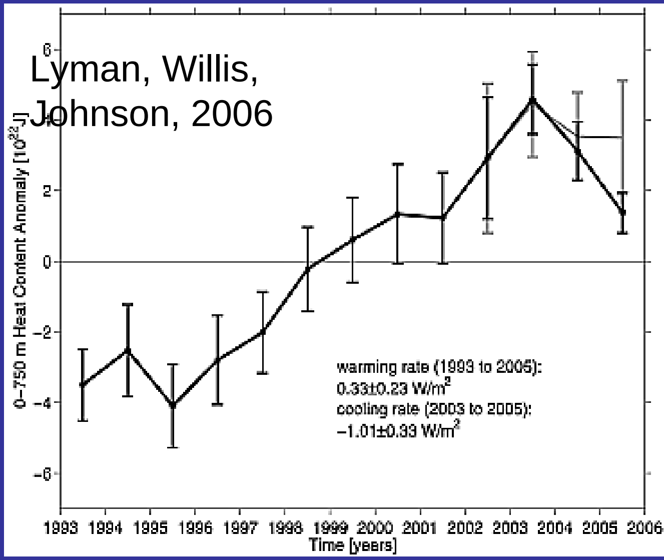
These have been the subject of considerable dispute, as the calculations prove very difficult.

Issues pertain to:

The spatial distribution of the measurements

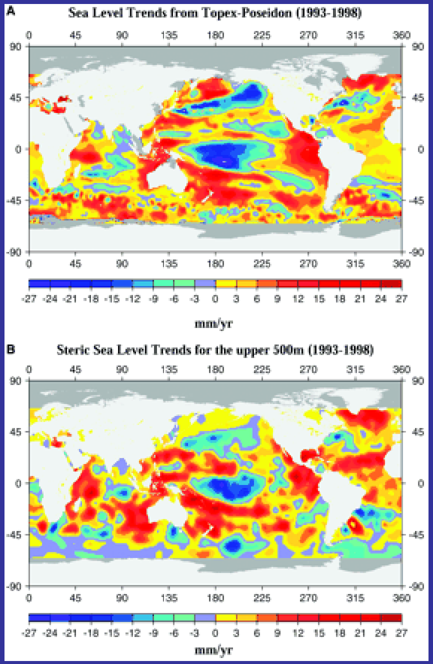
The interpretation of density changes

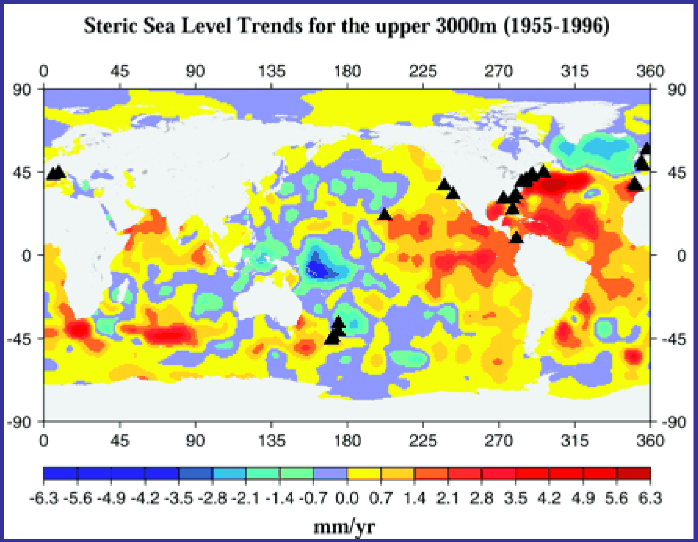
Calibration (or lack of it) in the various measurements



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

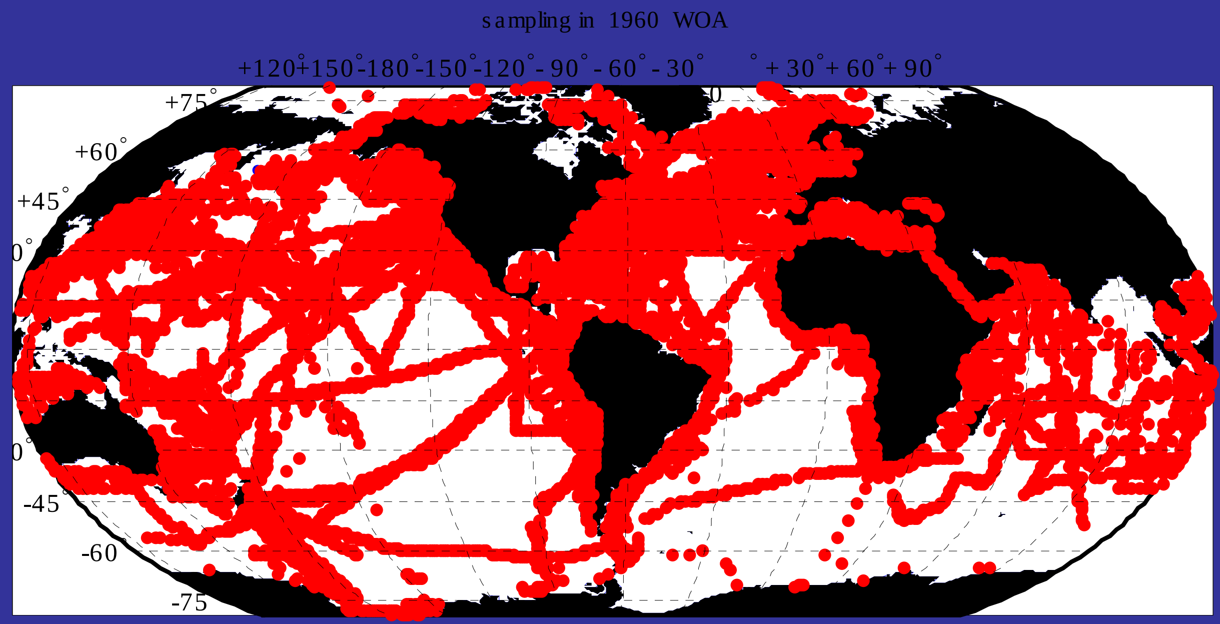
"The 3.2 ± 0.2 millimeter per year global mean sea level rise observed by the Topex/Poseidon satellite over 1993-98 is fully explained by thermal expansion of the oceans. For the period 1955-96, sea level rise derived from tide gauge data agrees well with thermal expansion computed at the same locations. 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."



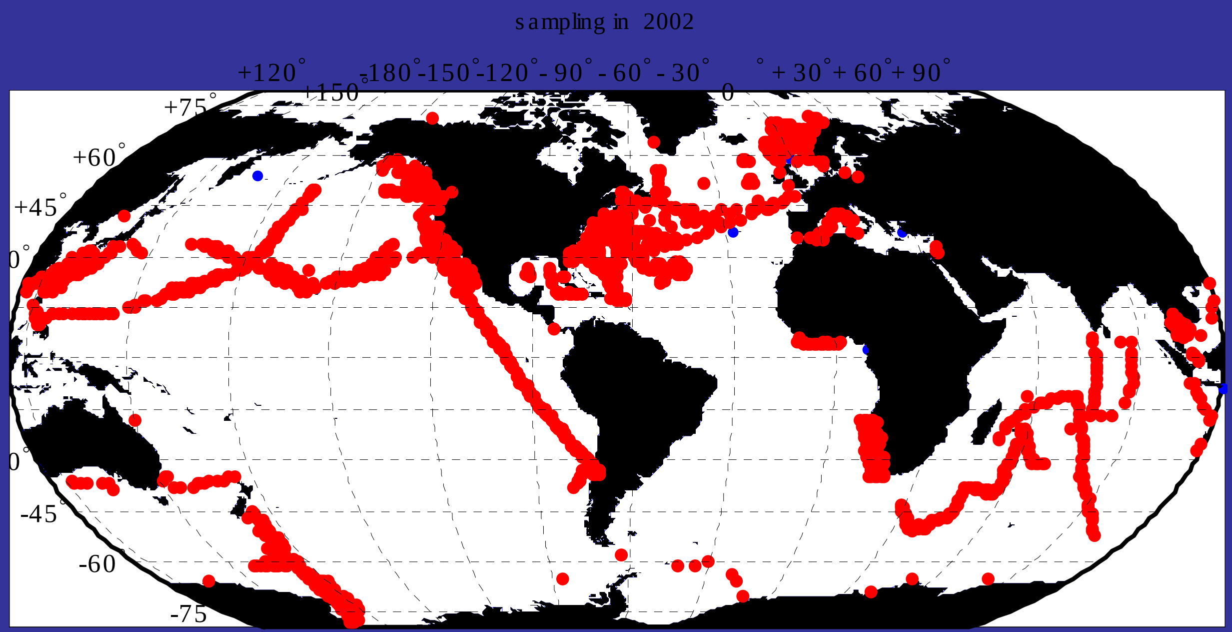


Gauges disproportionately located in regions of excess warming

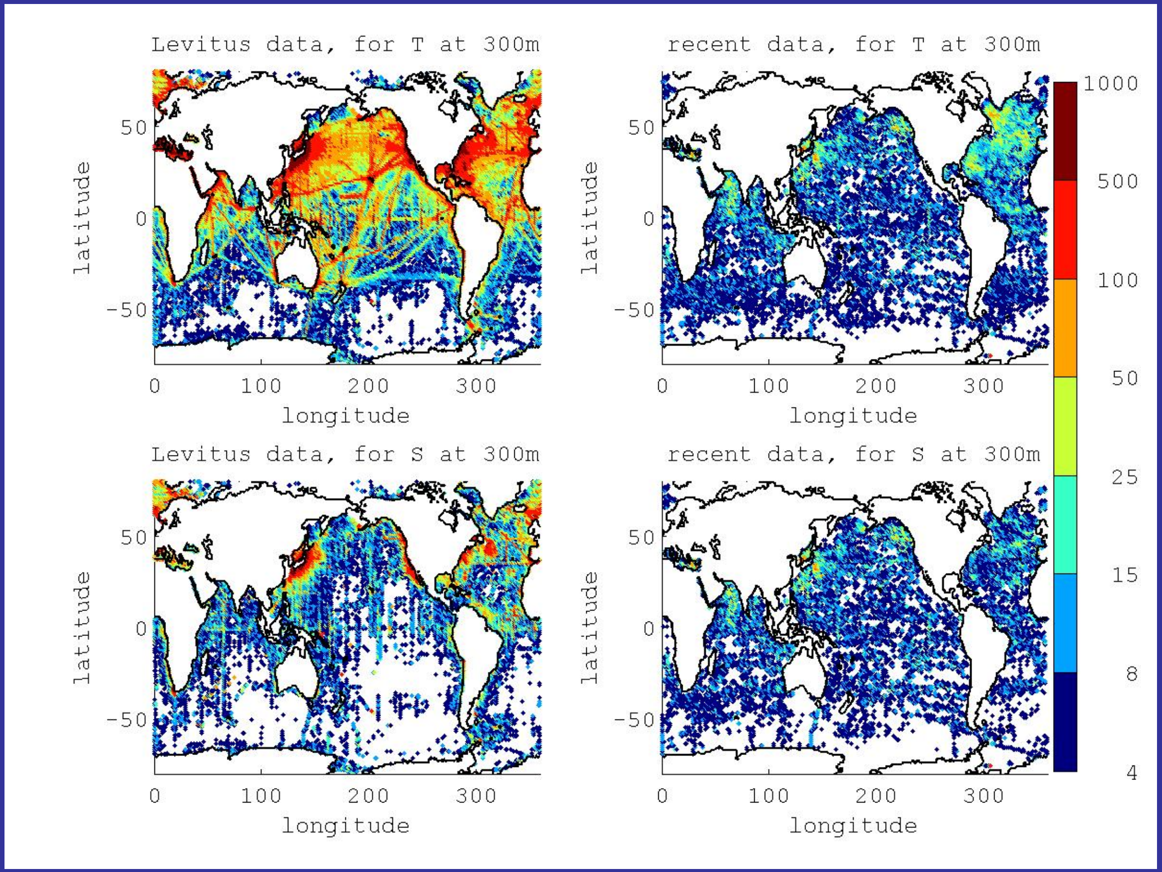
But, Miller and Douglas, Nature, 2004, show the apparent bias is due to smoothing in the Levitus et al., hydrography


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

mainly MBTs

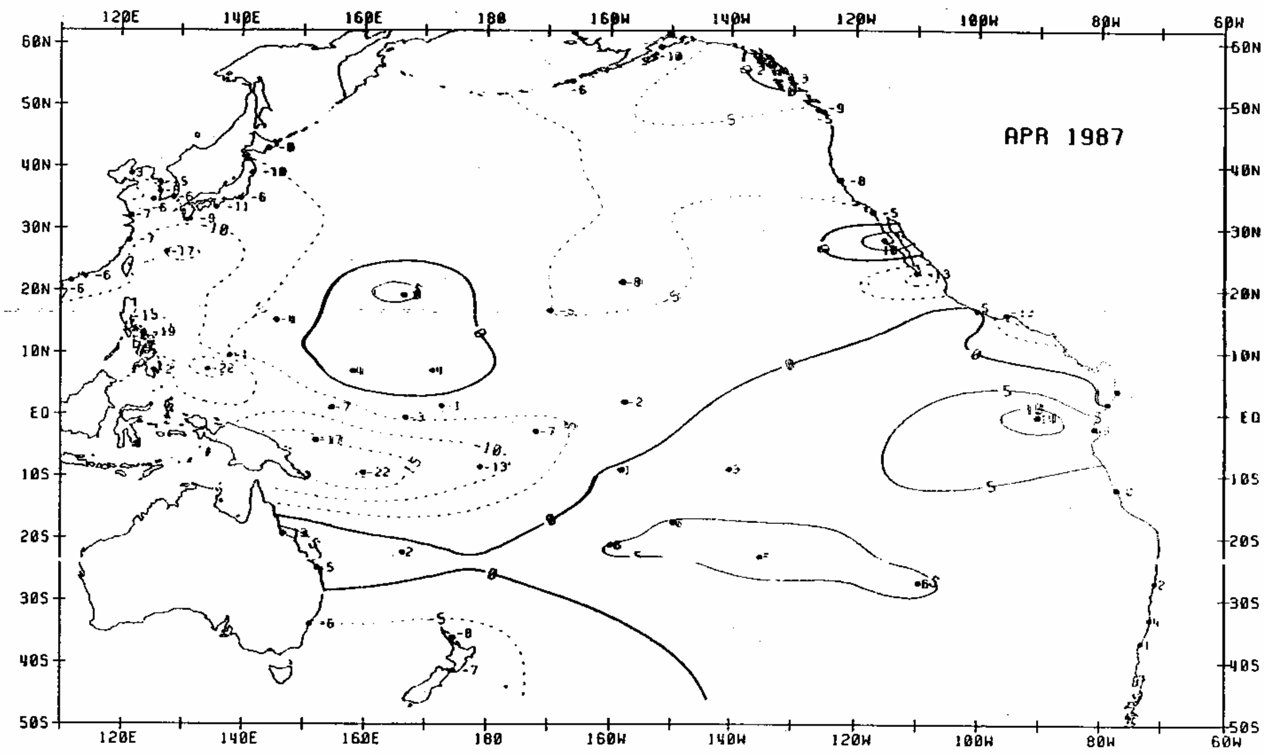

sampling in 2002
+120° +150° -180° -150° -120° - 90° - 60° - 30° 0 + 30° + 60° + 90°
+75°
+60°
+45°
-45°
-60°
-75°

G. Forget



More than 4 measurements in a 1 degree square in 50 years.
"Recent" means about 1990 & later.

Can one really compute global averages from these that have the necessary accuracy?



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

From Douglas et al. 2001

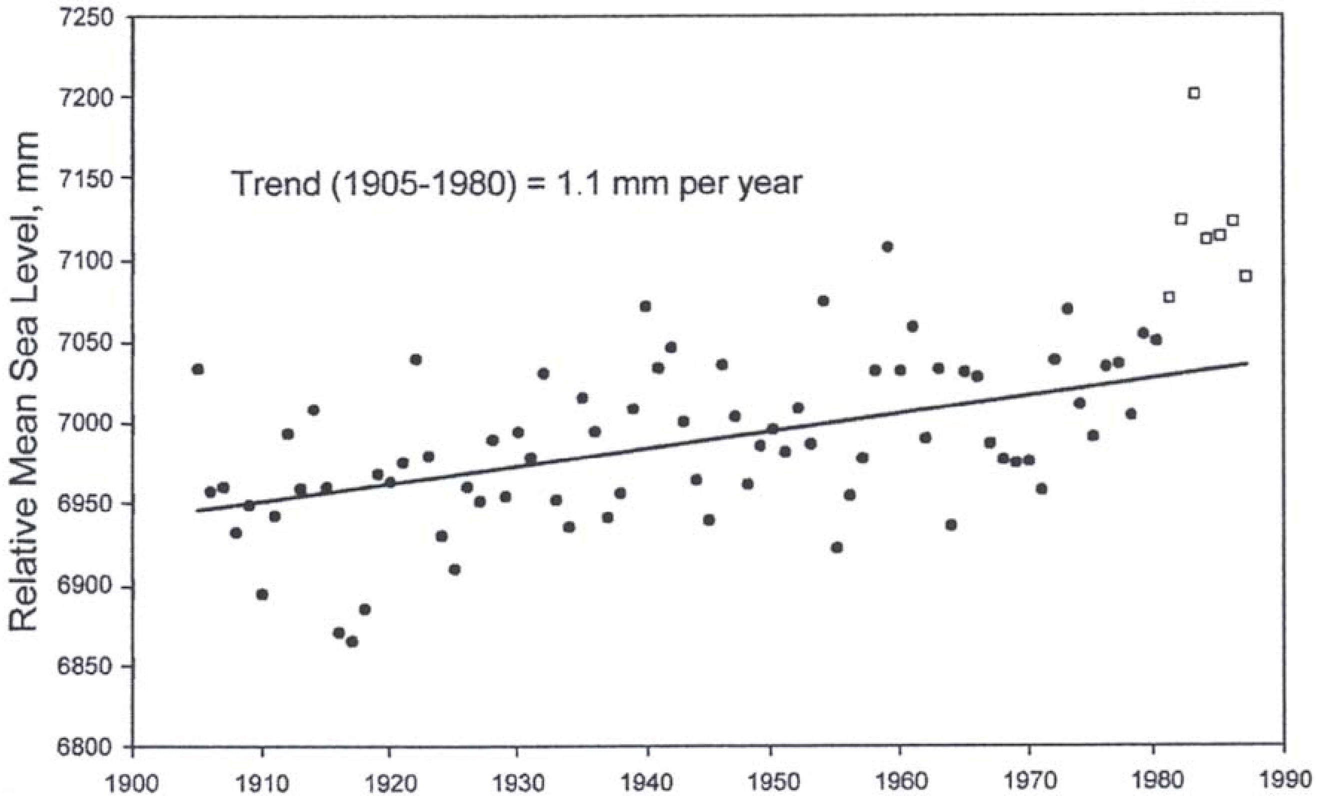


Figure 3.5 Annual mean relative sea level at Buenos Aires.

From Douglas et. al. 2001.

Note that sea level appears to be falling around Scandinavia. This is a result of post-glacial rebound. So-called tectonic and post-glacial rebound corrections are very important for tide gauges.

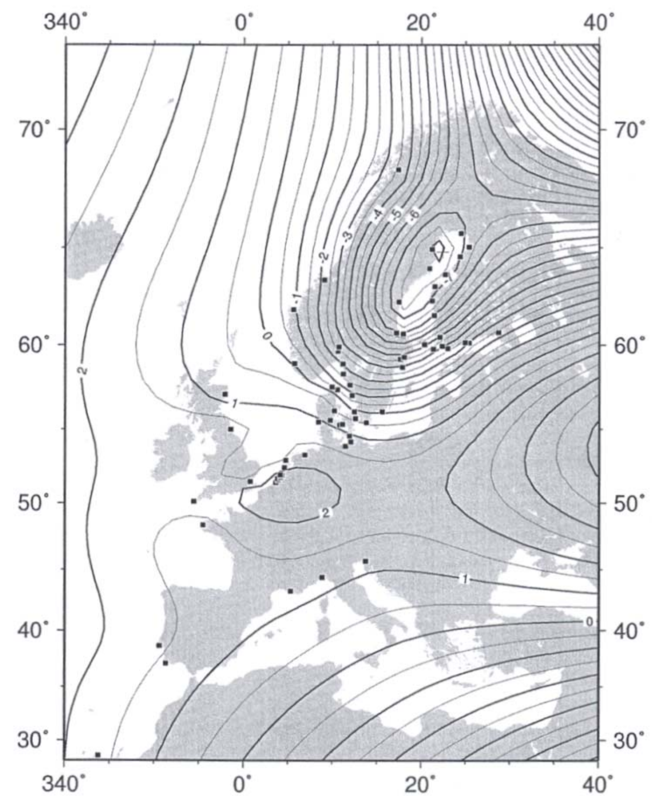
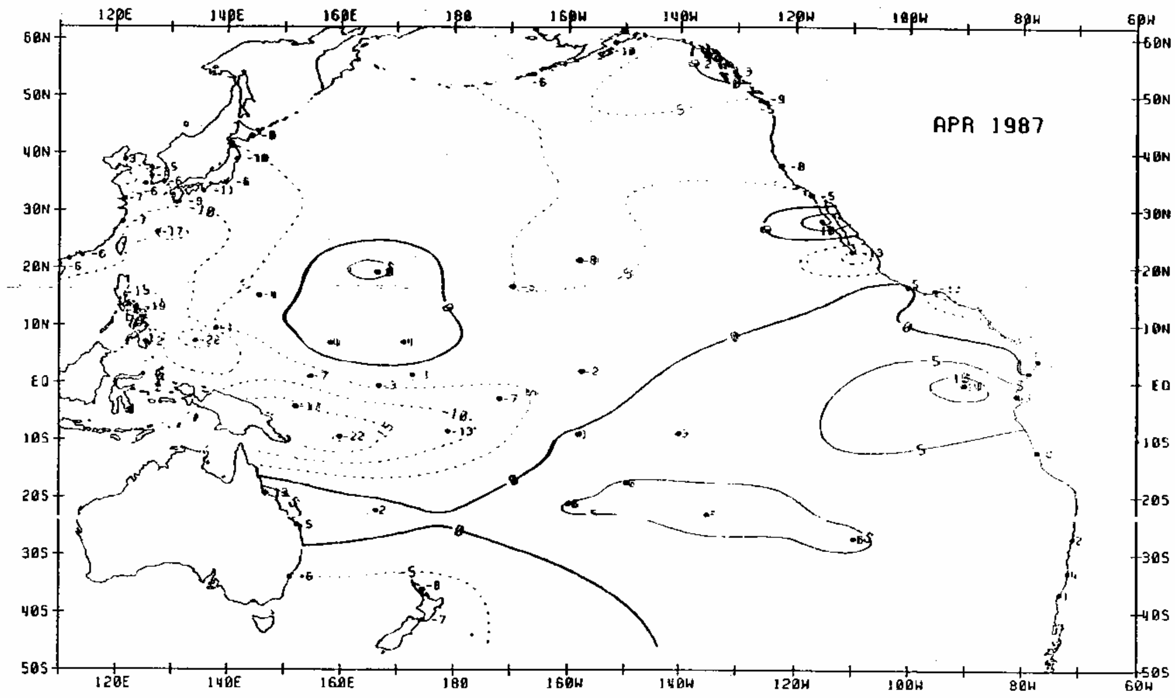


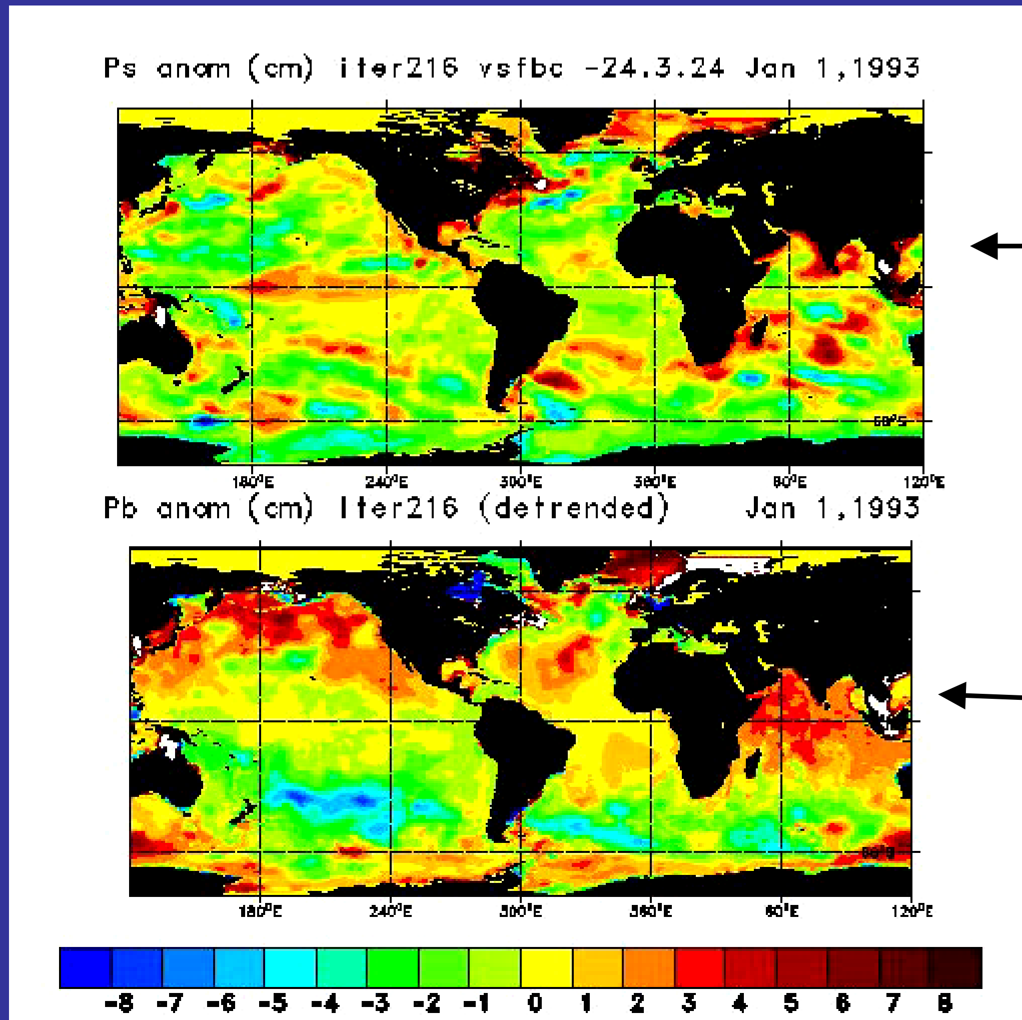
Figure 1.2 Contour plot of 20th-century European sea level trends (mm/yr).



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

Oceanographers have developed numerical models that solve the fluid-dynamical and thermodynamical equations in realistic, rotating spherical, geometries. Can combine them with the observations so that use all the data we have.

(An animation)



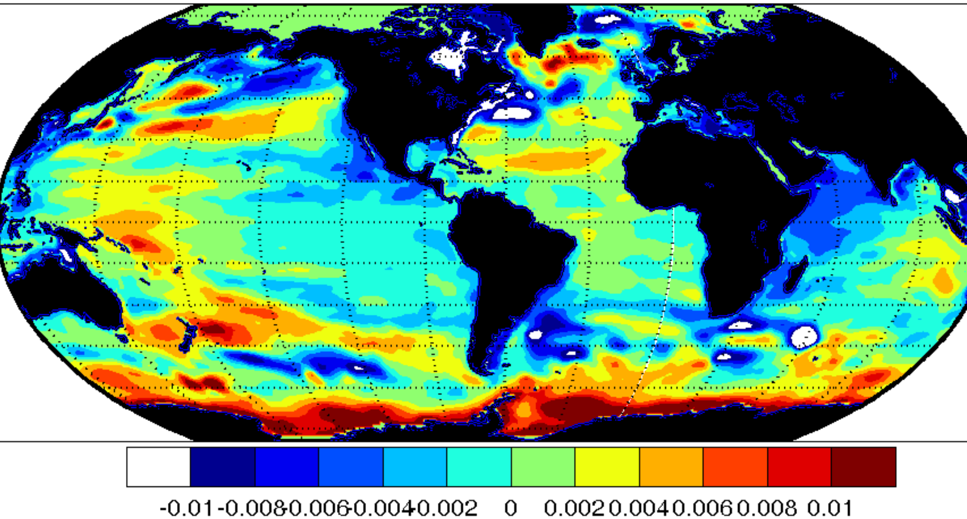
surface elevation
(sea level) anomalies

Deep ocean pressure anom.

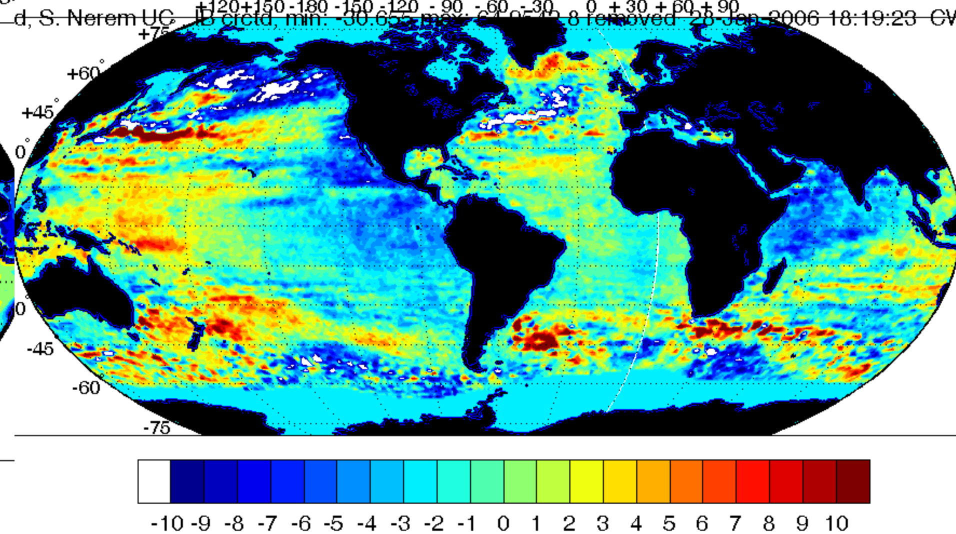
cms

Dynamically, kinematically, and statistically, the Southern Ocean is different from all other ocean regions. It is almost unsampled.

) iter177 surface pres anom yearly trend (m/year) min: -0.0338 max: 0.018818 awm: 1.43

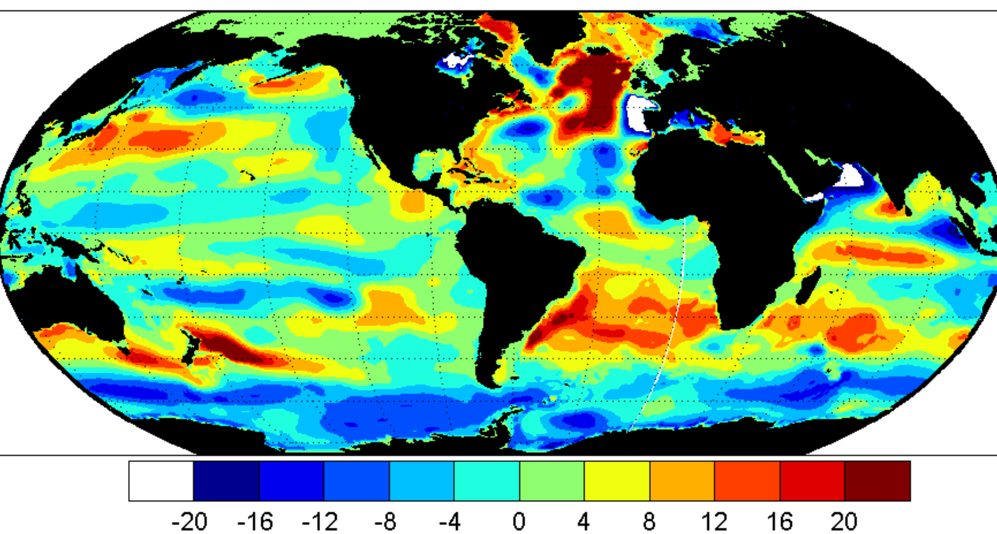


ECCO_surf_anom_177_vm_trend.fig 2006/1/26 - 10:27:24



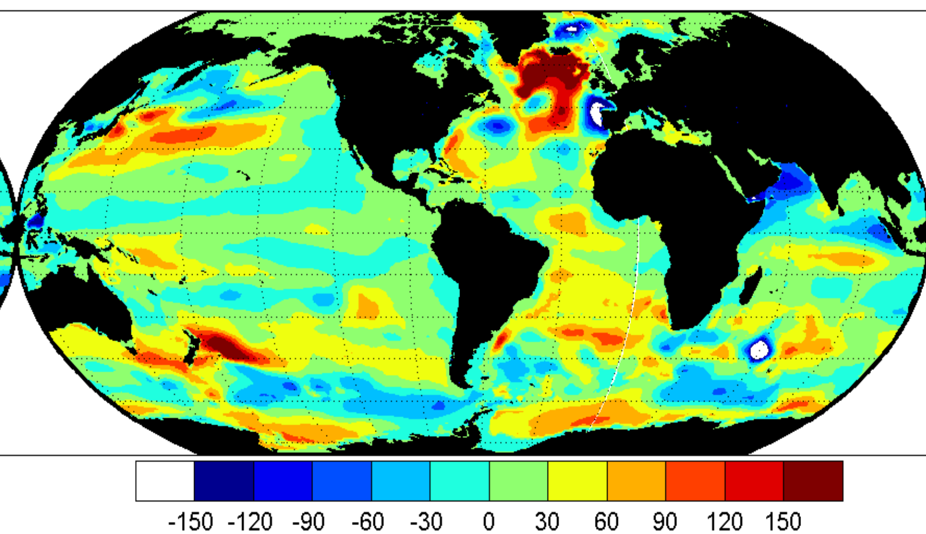
Global mean removed from the sl results

ECCO iter177 Total salinity anom yearly trend min: -56.4988 max: 42.5558 awm: 1.4351

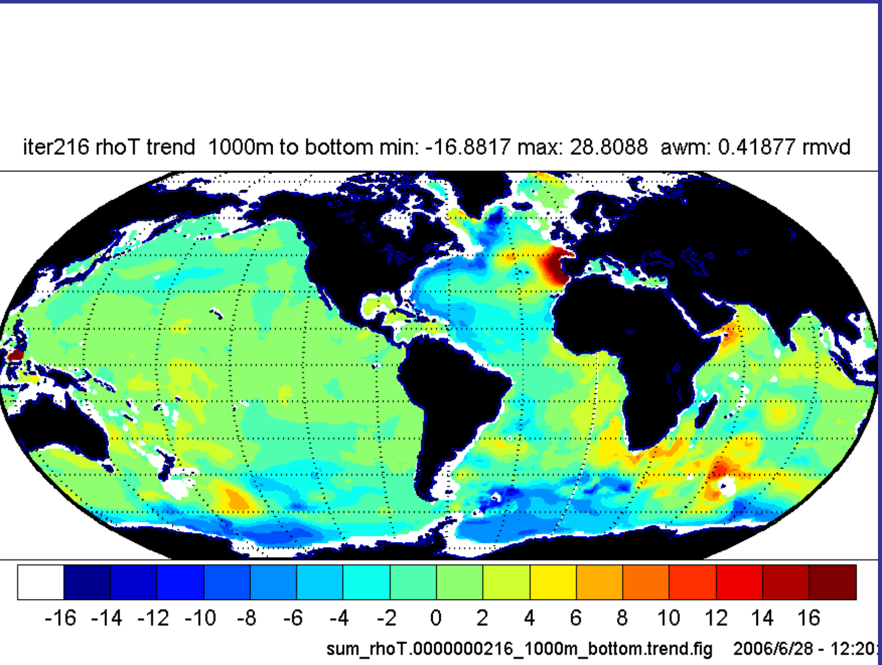


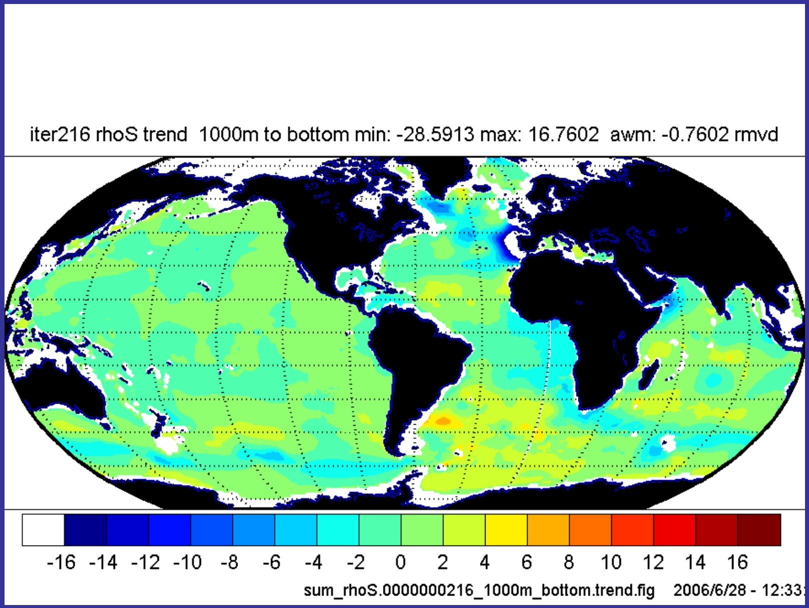
ECCO_sal_anom_177_Tvm_trend.fig 2006/1/25 - 9:53:51

ECCO iter177 Total temp anom yearly trend min: -287.2029 max: 296.9896 awm: 16.5629



ECCO_tmp_anom_177_Tvm_trend.fig 2006/1/25 - 12:30:7

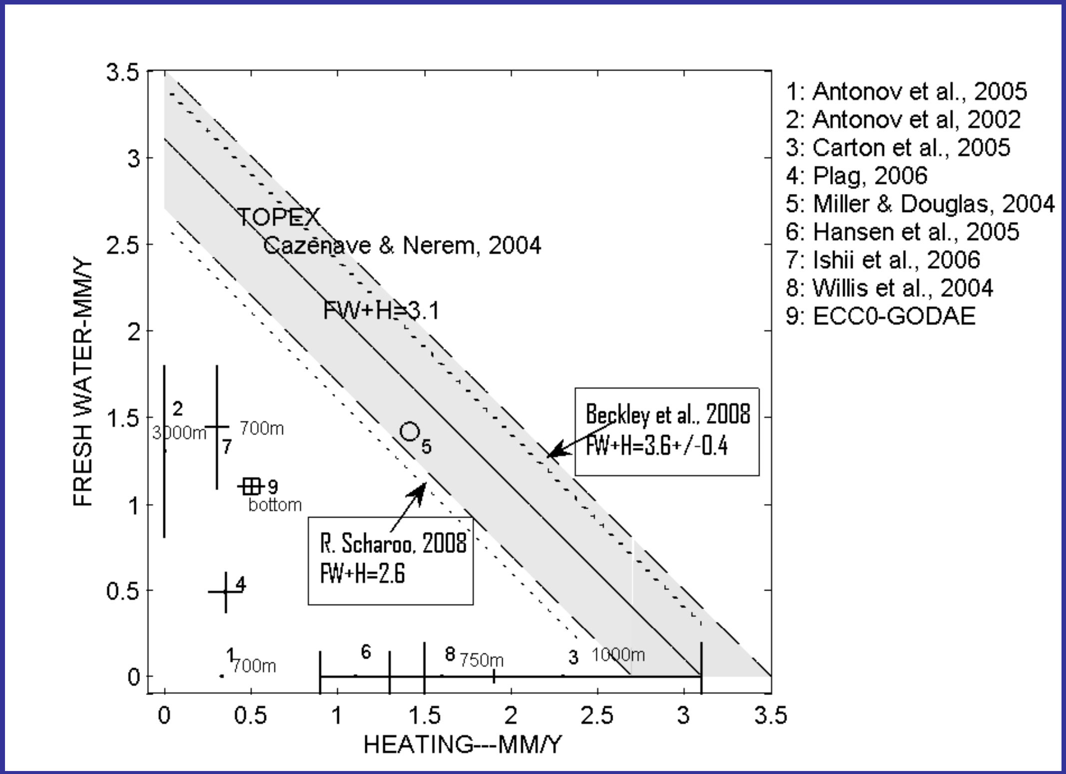




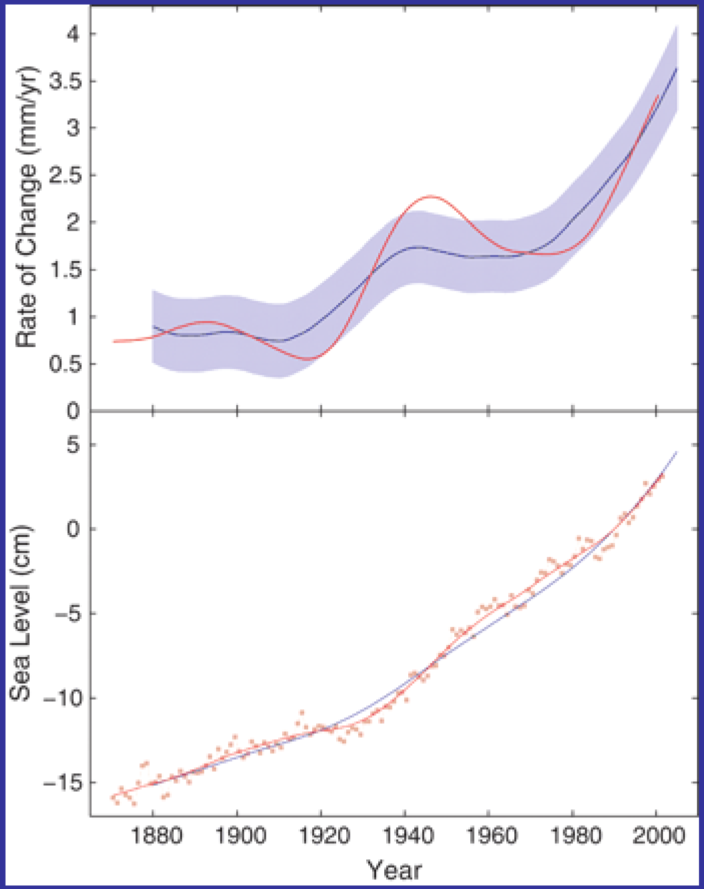
1000m to bottom temperature contribution to density trend mm/y

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

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.



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

Fig. 3. (**Top**) Rate of sea-level rise obtained from tide gauge observations (red line, smoothed as described in the Fig. 2 legend) and computed from global mean temperature from Eq. 1 (dark blue line). The light blue band indicates the statistical error (one SD) of the simple linear prediction (*15*). (**Bottom**) Sea level relative to 1990 obtained from observations (red line, smoothed as described in the Fig. 2 legend) and computed from global mean temperature from Eq. 2 (blue line). The red squares mark the unsmoothed, annual sea-level data.

Rahmstorf, Science, 2007. Can one reconstruct sea level back to 1875? Can one do it for global mean temperature? Or is this science fiction?

What of the future?

By definition, there are no data. Are dependent upon (1) emission scenarios, (2) extremely complicated models.

Climate models are not simpler than econometric ones. One expects to discover they are not particularly skillful (e.g., as in 2008 financial meltdown). They do not usually show abrupt changes.

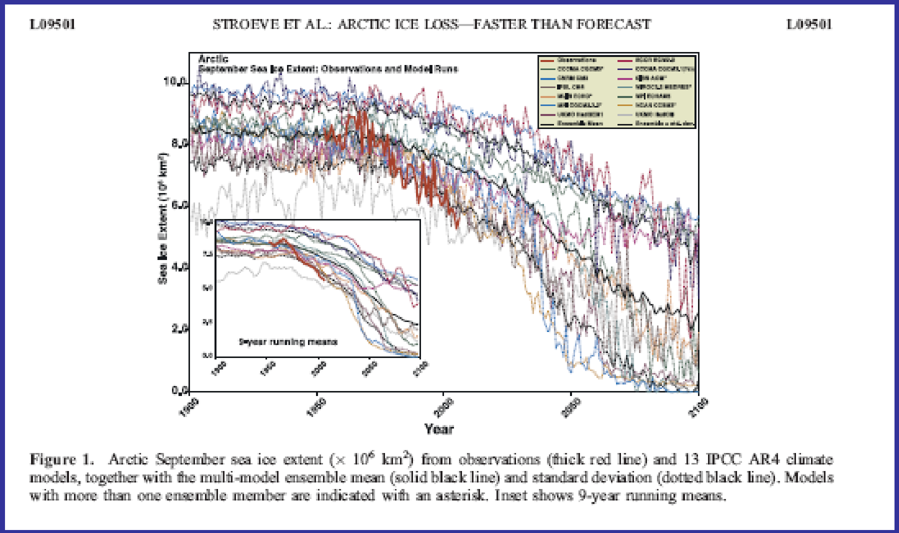
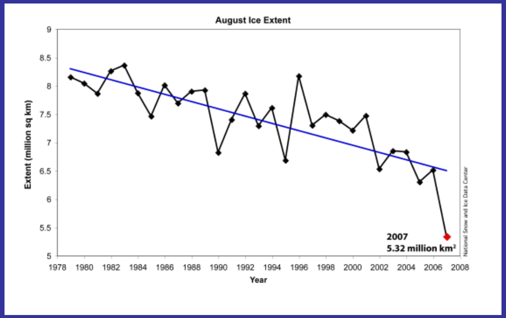

L09501 STROEVE ET AL.: ARCTIC ICE LOSS—FASTER THAN FORECAST L09501

Figure 1. Arctic September sea ice extent (× 10^6 km²) from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). Models with more than one ensemble member are indicated with an asterisk. Inset shows 9-year running means.

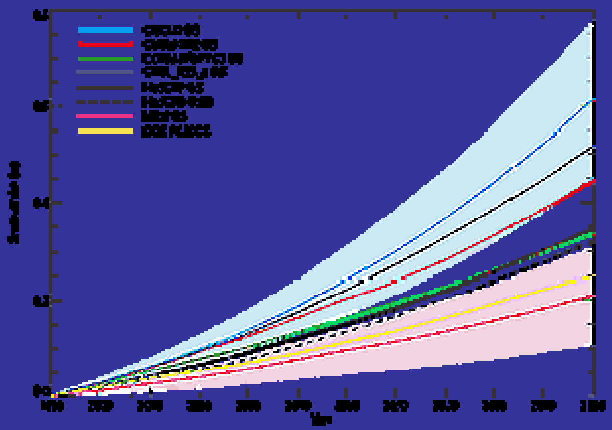


National Snow & Ice Data Center

Climate models are extremely complicated, approaching 1 million lines of code. Probably no one fully understands any one of them. They diverge.

Nonetheless, some things are quite robust---including the global net warming under CO_2 rise, amplification at the poles, melting ice. The threat is real, credible, and will be extremely expensive to deal with.

Surges, ground water contamination, loss of ecosystems, general loss of land areas.



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

update?

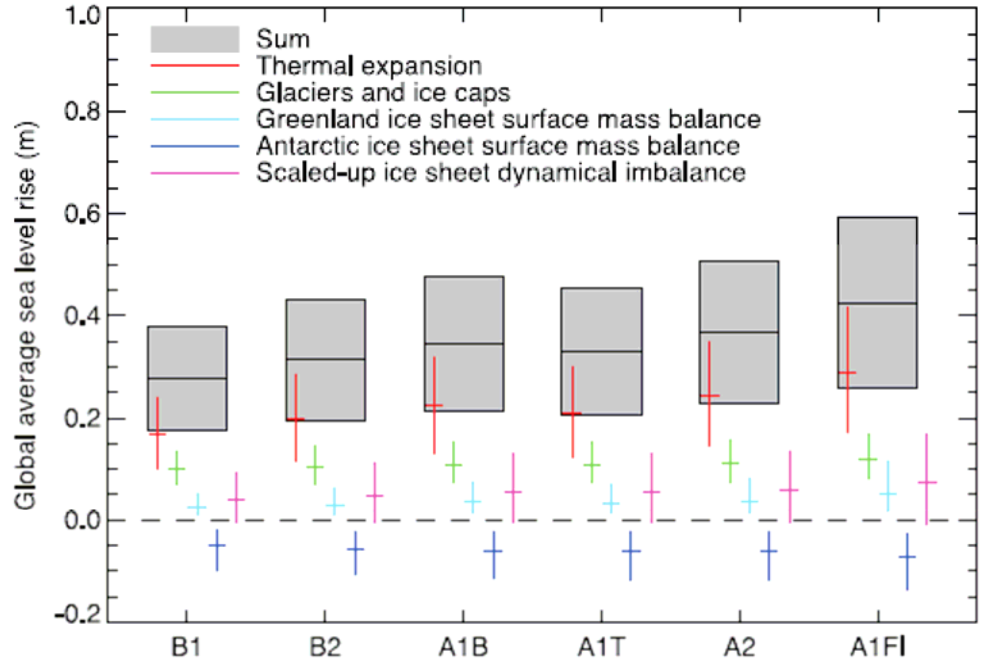
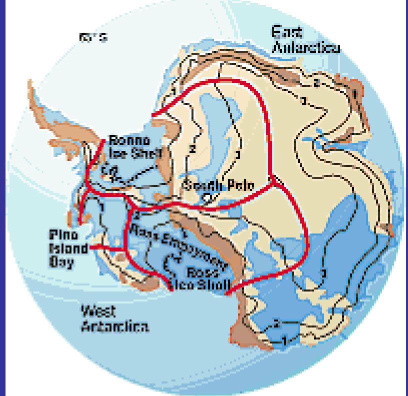
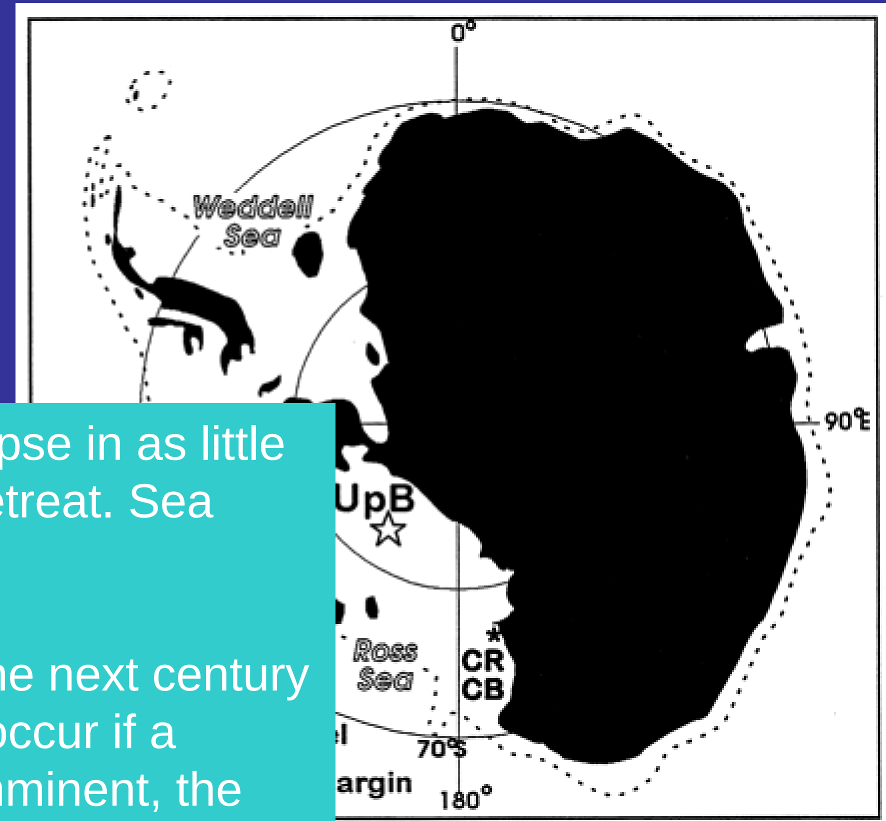


Figure 10.33. *Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m. It must be emphasized that we cannot assess the likelihood of any of these three alternatives, which are presented as illustrative. The state of understanding prevents a best estimate from being made.*

IPCC (2007, Ch. 10. Declined to give scenarios. Surprises are likely. West Antarctic ice sheet?





"[Weertman suggested]…the WAIS would collapse in as little as a century by a catastrophic grounding-line retreat. Sea level would rise half a meter per decade.

…

Thus, I believe that a rapid rise in sea level in the next century or two from a West Antarctic cause could only occur if a natural (not induced) collapse of the WAIS is imminent, the chances of which, based on the concept of a randomly timed collapse on the average of once every 100,000 years, are on the order of 0.1%. "

C. R. Bentley, Science, 1997

ding ice sheet mechanics … to predict the probability of WAIS collapse within the coming centuries, but geologic evidence of past collapse and observations of rapid ongoing changes in the WAIS (1, 24) underscore the need for continued study." R. P. Scherer et al., Science, 1998

Partial Summary:

Global mean sea level is almost surely rising. Historical data are not adequate to compute accurate global averages. No mathematical trick compensates for missing data. Present multidecadal estimates of global averages have an element of fantasy about them. (Among other issues, an unsubstantiated blind faith in models.)

Altimetry represents the only realistic technology for quantitatively determining present and future changes, but much more needs to be understood of errors present in the system.

Modelling present and future global and regional changes lies at the very edge of computational knowledge and capability.

The chief issue is to make sure that some future generation *will* have adequate data.

Thank you!