Sea level change

- Important processes
  - Global vs. local
  - Geologic
  - Modern
- Current rates of rise
  - Observations, calculations, and models
- Lessons from the past
- Projected future changes

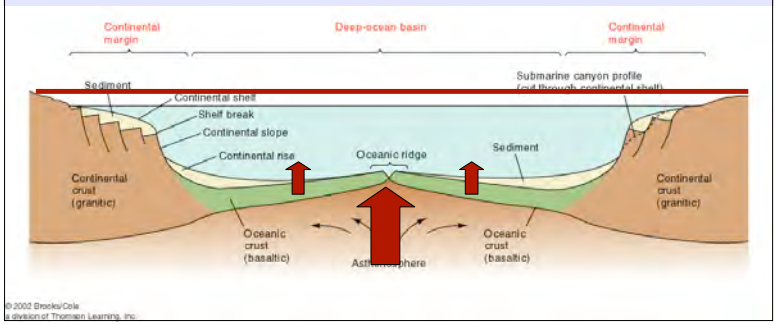
Eustatic sea level change

- Global signal of sea level change
- Causes:
  - Tectonics
  - Ice sheet growth and decay
  - others (smaller): thermal expansion/contraction; addition of juvenile water; sedimentation

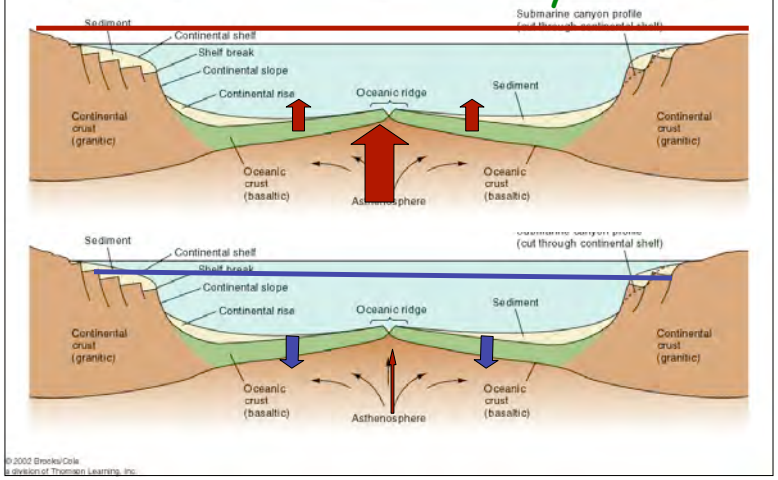
Tectonic control of global sea level

1. Change the size of the ocean basins. A bigger or smaller container.

•Slow changes, over millions of years

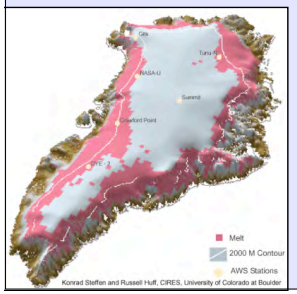


Tectono-eustasy



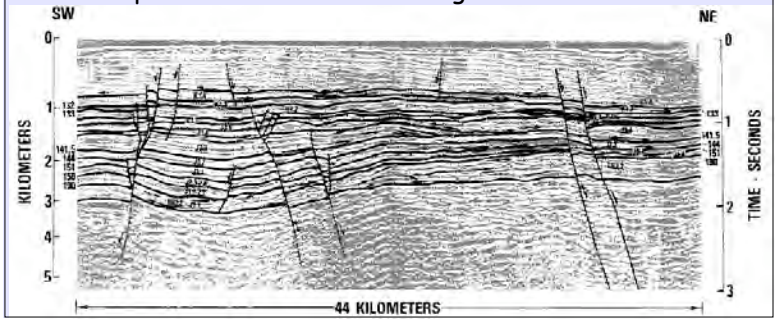
Glacio-eustatic sea level change

- Changes amount of water in ocean basins
- Largest volumes tied up in ice sheets
  - Greenland, Antarctica
- Colder climates have lower sea level (on this large scale)



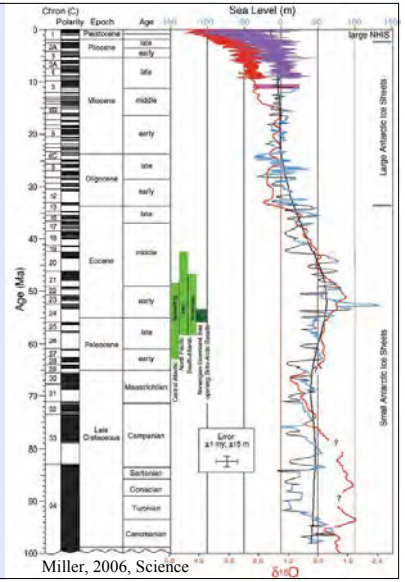
Eustatic sea level over geologic time

- How? Combination of seismic stratigraphy and geologic interpretations
  - Lines indicate layers that indicate drying
- Requires global dataset and impeccable geochronology
- Gives timing, not necessarily magnitude
- Compare with other indices to get at causes



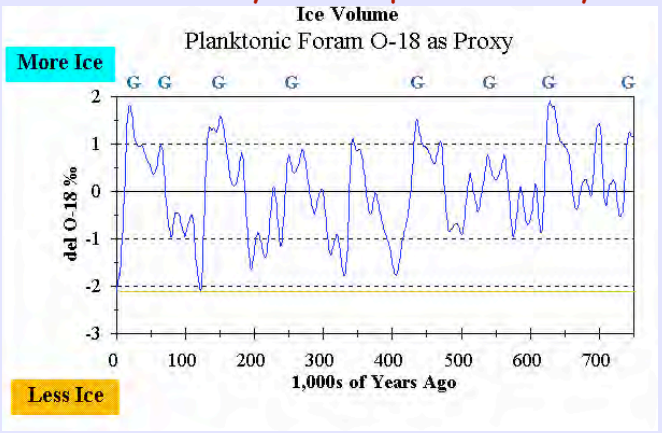
Geologic record of sea level change

- Use geologic data to identify sedimentary sequences that indicate sea level change
- Use technique called "backstripping" to remove local and subsidence-related factors
- Result is history of eustatic sea level change
- Range over 100my: ≤100m more than today



Miller, 2006, Science

Sea level history of the past million years



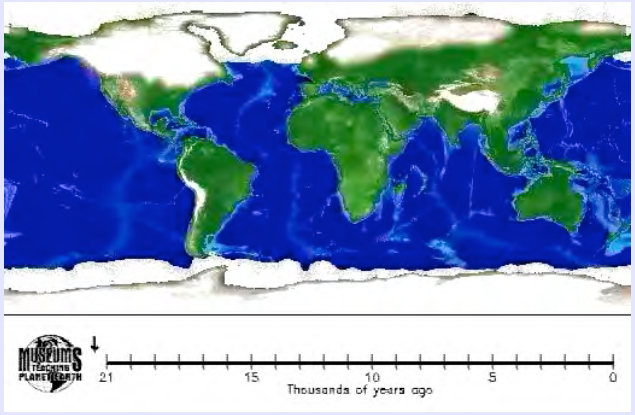
- More ice = lower sea level

Sea level from foraminiferal oxygen isotopes

- Seawater exists in different isotopic forms.
  - $H_2{}^{16}O$ (common), $H_2{}^{18}O$ (rare)
- The rarer heavy form is less easily evaporated, thus precipitation has relatively less ^{18}O than seawater
- When ice sheets form from snow, they too are relatively depleted in the heavy isotope compared to seawater
- Seawater thus has higher ratio of heavy to light isotopes during times when more H_2O is on land as ice
- Foraminiferal shells ($CaCO_3$) pick up the isotopic signal in seawater.
- Forams in deep-sea cores can be analyzed to provide histories of seawater ^{18}O content, hence relative ice volume (and sea level)

Last 20,000 years of ice sheet change

How much did sea level change?



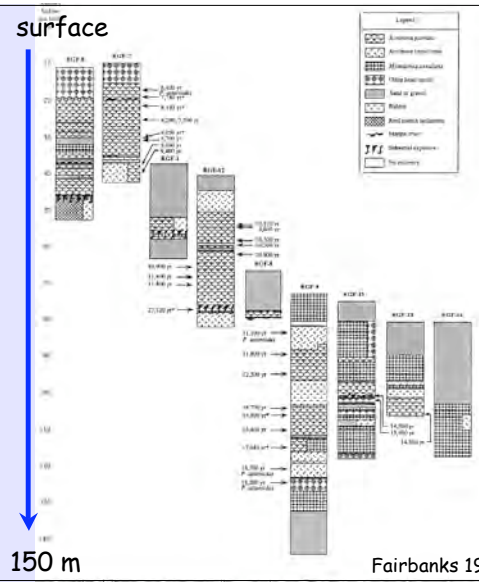
http://earth.rice.edu/mtpe/cryo/cryosphere/topics/ice_age.html

Glacial sea level

- This coral (*Acropora palmata*) always grows in shallow water (<5m)
- Cores taken through Barbados reef have *A. palmata* at many different depths

Barbados reef drilling

- Cores penetrate different reef facies
- *A. palmata* identified and dated
- Gives measure of location of sea surface at that date

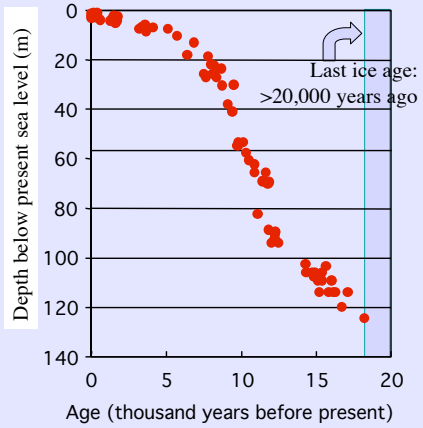


Fairbanks 1989

Glacial sea level change

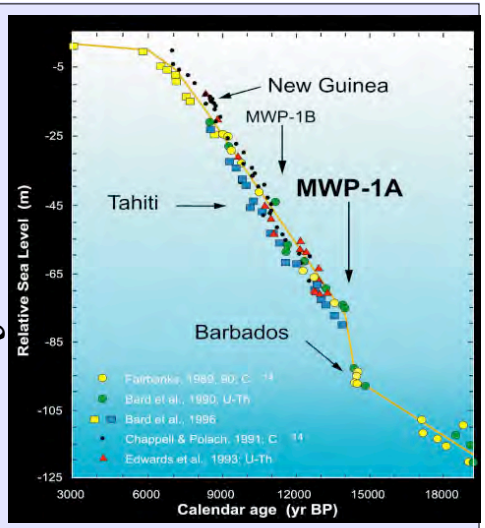
- Plot age and depth of *A. palmata* samples = where the ocean surface was and when

- *Conclusion: sea level was ~125m lower during last ice age*
- *Can also infer rates of sea level rise…. More on this soon.*



Sea level - more sites

- Tahiti - assigned reading
- New Guinea, Barbados, Vanuatu for comparison
- Why need many sites?
- Is sea level rise steady?
- What is evidence from Tahiti for MWP 1-A?

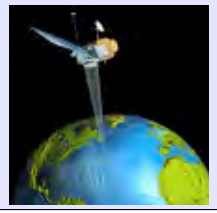


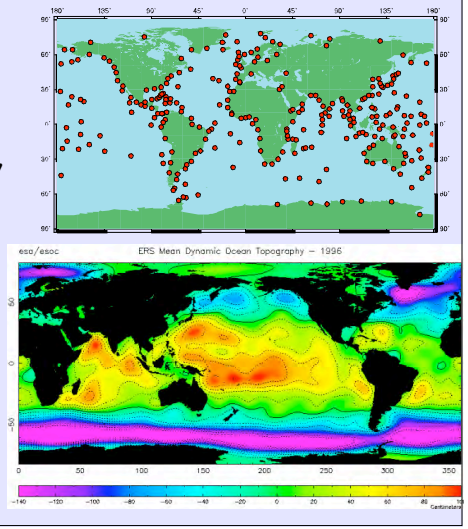
Global sea level changes

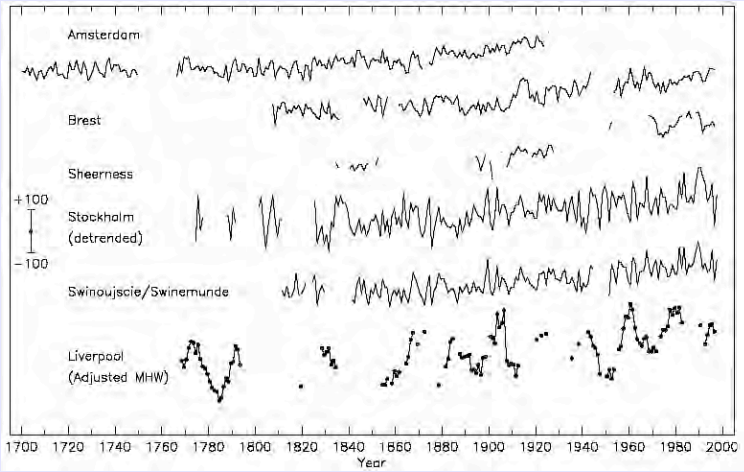
- Geologic time (100my): up to 100m higher
- Ice ages: 125m range lower
- Very small increases (0.1-0.2mm/yr) or stable in Holocene (post-ice age)
- Mid-19th century: global rise begins
- 20th century: Rise intensifies as world warms
- Prediction: ≤ 1m in this century
  - Conservative: no ice sheet melting assumed

Sea level measurement

- Tide gauges
  - Local factors = big complications!
- Satellite altimetry
  - Global picture, short records (decade-scale)



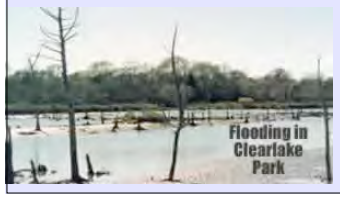


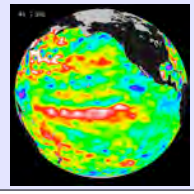


- Long tide gauge records are sparse
- Decadal variability in all records is significant
- Trends vary widely depending on interval over which calculated

Local sea level changes

- Weather/climate: wind, barometric pressure, storm surges
- Land subsidence: compaction from pumping water or oil
- Sedimentation
- Changes in water storage on land: reservoirs, deforestation
- Vertical motion of land: earthquakes, isostatic rebound
- Ocean circulation



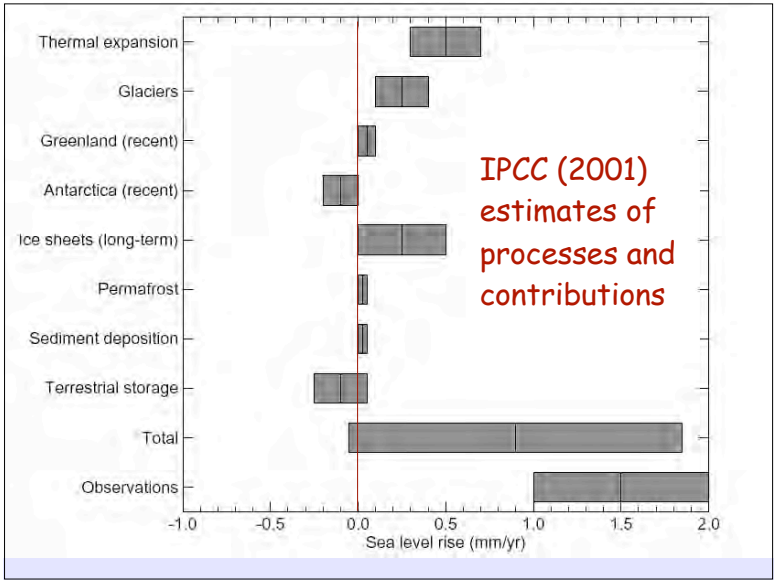


Why care about 21st-century sea level change?

- Small island states and low-lying coastal regions could be inundated
- Potential for increased coastal erosion
- Intensification of storm surges
- Saltwater incursion into freshwater aquifers
- Coastal wetlands threatened - often little chance for migration inland
- All made more problematic by especially rapid population growth in coastal regions

Causes of modern sea level change

- Changes in water storage
  - **-Melting glaciers, ice sheets**
  - -Groundwater extraction
  - -Reservoirs
  - -Deforestation
  - -Permafrost
- Ocean processes
  - **-Thermal expansion**
  - -Circulation
- Local complications



20th Century Rates of Sea Level Rise (IPCC TAR 2001)

- Observe from coastal tidal gauges: 0.6 - 1.8mm/yr
- Calculate from summing relevant hydrological factors: best guess ~ 1mm/yr
- Ocean Model: 0.2-1.0 mm/yr

Are these discrepancies important?

What's right?

Reconcile sea level change estimates?

Problem: tide gauges say up to 2mm/yr; models and calculations say 1mm/yr

- Are tide gauges representative?
- Do we know all of the factors that add into the hydrologic calculations? (esp. large ice sheet behavior)
- Do we have full information on temperature for thermal expansion calculations?
- How well do models simulate future changes?

Satellite data promise to help….

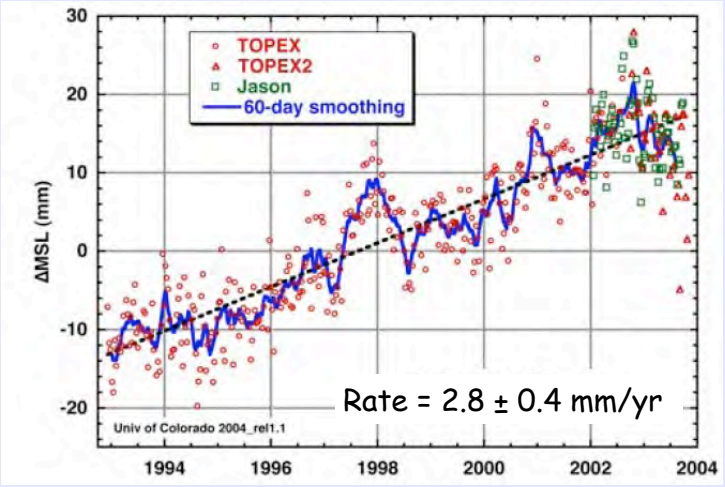
- Short record length to date (since 1993
  - Noisy
  - No historical info

Processes of sea level rise

(Cabanes et al., 2001, Science)

- Satellite data: 1993-98 rise = 3.2 mm/yr
  - TOPEX/Poseidon measures sea surface height
  - Short interval, scatter
- Temperature data from top 500m: thermal expansion should be 3.1 mm/yr
- Important: the actual values of trends over such a short interval must be used with care!
- Thermal expansion is the a primary source of variation.
  - How reasonable is this?

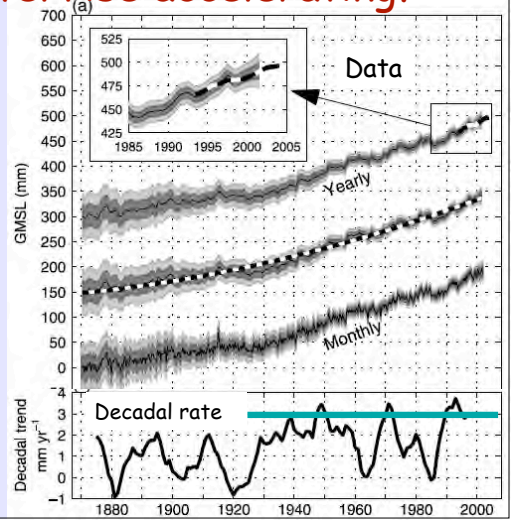
Sea level rise from satellite data



Cazenave and Nerem 2004

Is sea level rise accelerating?

- Update from tide gauge data
- Best fit includes acceleration
- Acceleration begins in early 20th century
- Rates peak above 3mm/yr but vary
- Leads to total rise of ~300mm in 2100
- Will this change?

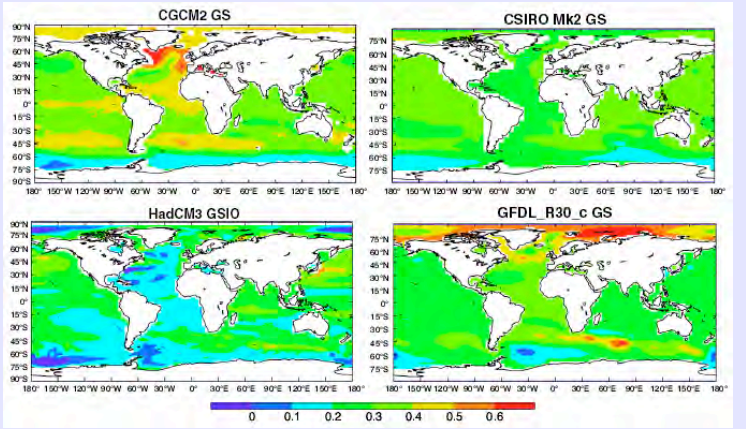


IPCC (2007) estimates of future sea level change

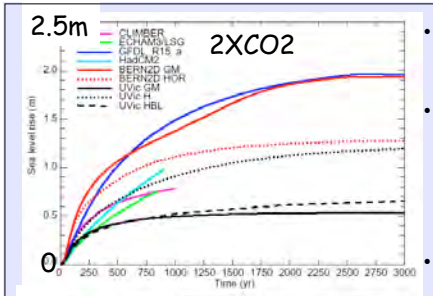
- Use models to include thermal expansion, glacier melting, some terrestrial hydrology
- Prediction: sea level rise of 0.2-0.6m by 2099
  - Very poor understanding of how large ice sheets fit in here!
  - Alternate predictions suggest greater increase
- Sea level will continue to rise after that, due to thermal equilibration with atmosphere
- Ultimate rises will be 0.5-2m for doubled CO2 and 1-4m for quadrupled CO2 - could take 100's of years to achieve (why?)
- Big uncertainties: what will large ice sheets (Greenland, Antarctica) do?

Model uncertainty is large

(note regional differences among models)



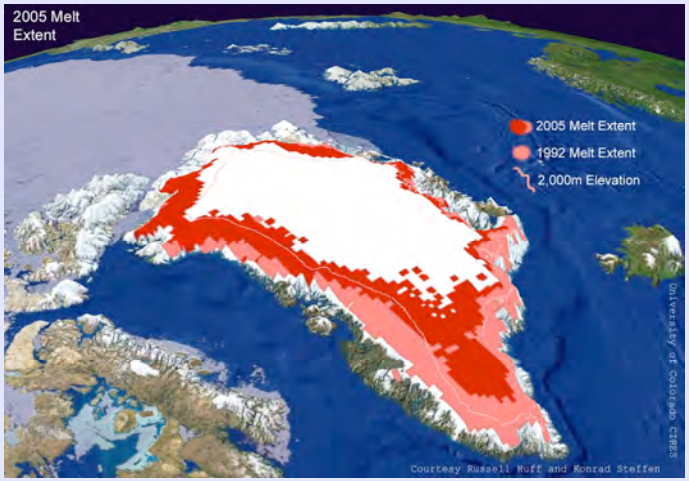
From Church, 2001

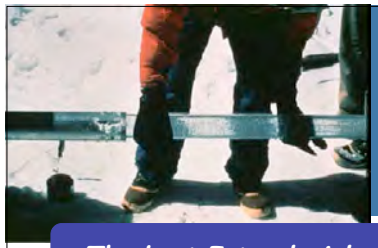


- Models run out to 3000 years
- CO2 increased by 1% per year to doubled (top) and quadrupled (bottom)
- Note that CO2 changes are finished within a couple centuries
- It takes many centuries to reach the full sea level response to warming
- These do not include large ice sheets

From IPCC 2001

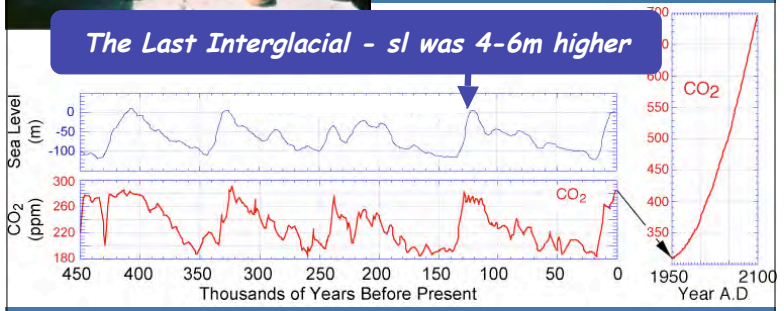
Melt area on Greenland is expanding





The Greenland Ice Sheet hasn't always been like today…

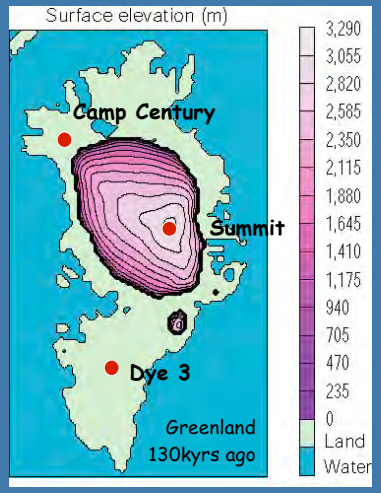
The Last Interglacial - sl was 4-6m higher



The Greenland Ice Sheet (GIS) 130,000 years ago

At the beginning of the last interglacial (130,000 years ago):

- global sea level was 4 to 6 meters higher than today due at least partially,to melting of Greenland Ice Sheet
- How do we know?
  - ice cores, or lack thereof
  - raised shorelines and coral reefs etc.



K. Cuffey and S. Marshall, Nature 404, 2000

Changes in Greenland ice sheet simulated by climate-ice sheet model

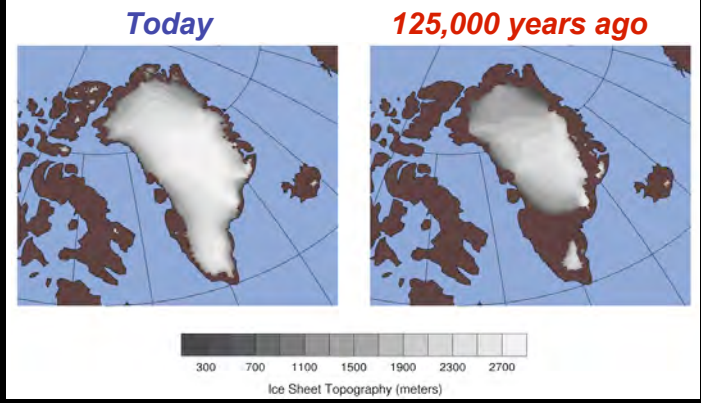
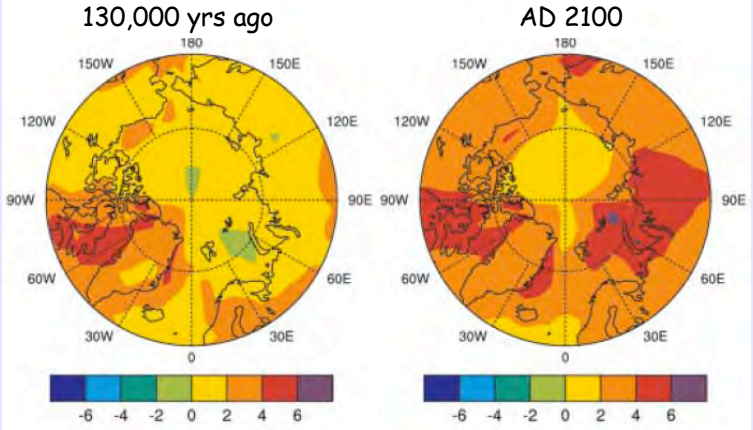


Image from Bette Otto-Bliesner, National Center for Atmospheric Research

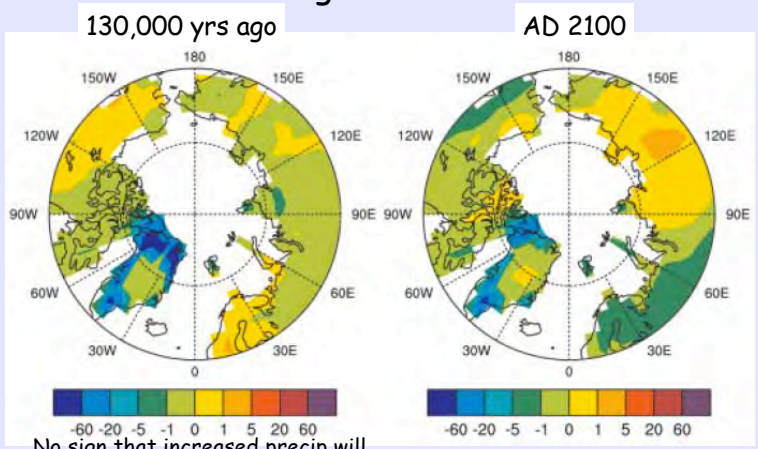
Change in summer temperature: Last Interglacial vs AD 2100



(model results, but consistent with data)

Overpeck et al. 2006, *Science*

Change in annual; snow accumulation: Last Interglacial vs AD 2100



No sign that increased precip will compensate for warming

Overpeck et al. 2006, *Science*

BUT, sea level rise during the Last Interglacial Period appears to have been more… it was likely up to 6m

A reduced Greenland Ice Sheet could only have contributed up to 3-4m

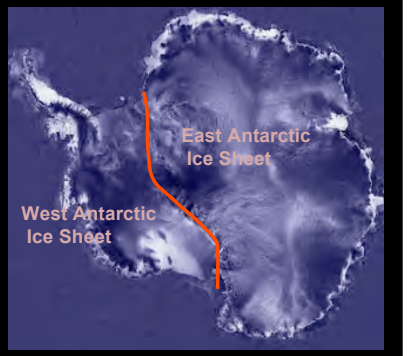
Where did the rest of the water come from?

Today

Most likely Antarctica…

West Antarctic ice sheet is grounded partly below sea level, not pinned to continent

May be more sensitive to warming climate than previously assumed



http://svs.gsfc.nasa.gov

Status check - key points…

- By 2100 to 2130, the Arctic will be warm enough to melt the Greenland Ice Sheet

So, how fast will it melt?

Rates of sea level rise from different methods and intervals

	1993-2004	1955-1998	1900-1999
Tide gauges			0.6 to 1.8 mm/yr
Thermal expansion	3.1 mm/yr	0.5 mm/yr	
Thermal expansion at tide gauge sites		1.4 mm/yr	
Satellite	2.8 mm/yr		
Summing contributions			-0.8 - 2.2 mm/yr

How fast can sea level rise?

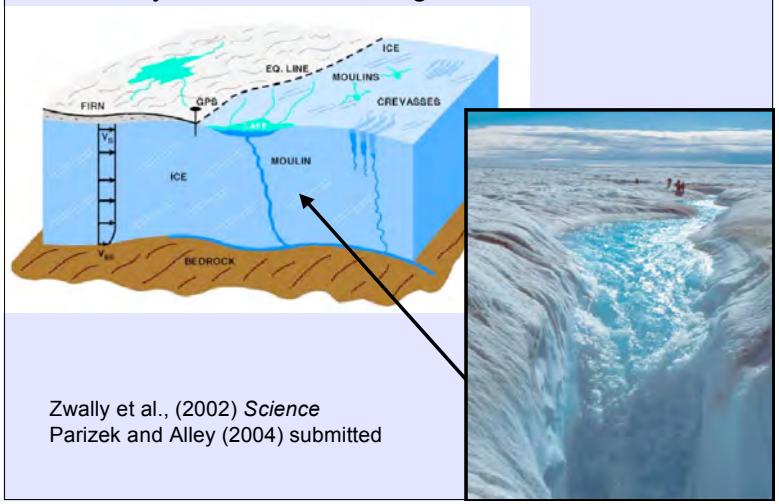
Time Period	Sea level Rise (mm/year)	Source
Next 1000 yrs. (model simulations)	1 to 3.25 (1990's observed = 3.0)	IPCC TAR many **models**
Last Deglaciation Ca. 14,000 yr B.P. (observations)	2.5	Fairbanks, 1990 **coral dating**

What about the last interglacial highstand, ca. 130,000 years ago?

How fast can sea level rise?

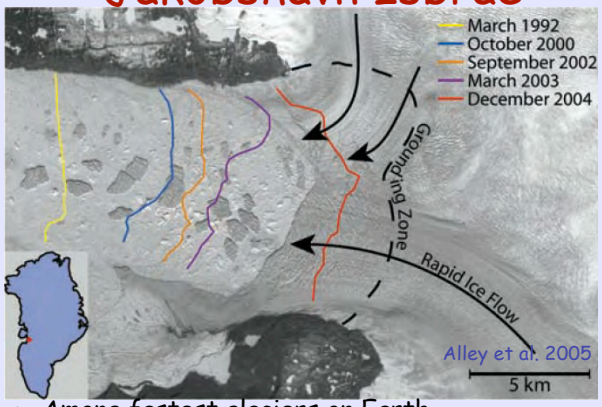
Time Period	Sea level Rise (mm/year)	Source
Next 1000 yrs. (model simulations)	1 to 3.25 (1990's observed = 3.0)	IPCC many **models**
Last Deglaciation Ca. 14,000 yr B.P. (observations)	2.5	Fairbanks, 1990 **coral dating**
Penultimate Deglaciation Ca. 130,000 yr B.P. (observations)	**20 to 50 !?** (2 to 5m/century)	Esat et al., 1999 McCulloch & Esat, 2000 **coral dating**

New mechanisms for increased ice sheet sensitivity to surface warming



Zwally et al., (2002) *Science*
Parizek and Alley (2004) submitted

Jakobshavn Isbrae



- Among fastest glaciers on Earth
- Largest outlet glacier for GIS
- Melting of outlet tongue 1992-2004
- Acceleration to ~13 km/yr!

Status check

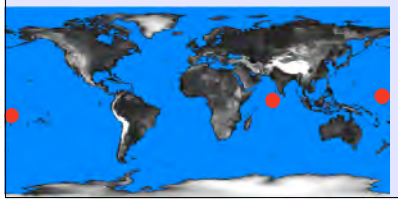
- Current rates of rise are faster than we knew even a few years ago: 3.1 mm/yr vs ~1.
- Recent geologic record (past 130,000 yrs) suggests rapid rates of sea level rise (25-50 mm/yr) occurred on deglaciations
- Conservative predictions for future sea level change (≤1m) do not take into account the potential for rapid ice sheet melting
- Latest ice sheet observations indicate melting is proceeding much faster than expected
- So… what's possible?

Note - slides showing sea level changes on coastlines deleted for space reasons - you can find these images at

http://www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/sea_level_rise.htm

Sovereign nations destroyed by possible future sea level rise

	Rise Required	Population
Indian Ocean		
Maldives	1 meter	291,000
Pacific Ocean		
Marshall Islands	3 meters	51,000
Tuvalu	6 meters	10,000
Kiribati	1 meter (95%)	96,000
Tonga	1 meter (75%)	106,000



"If the greenhouse effect raises sea levels by 1 metre it will virtually do away with Kiribati… if what the scientists say now is going to be true.

In 50 or 60 years, my country will not be there"

President I. Tabai, Kiribati, September 1988