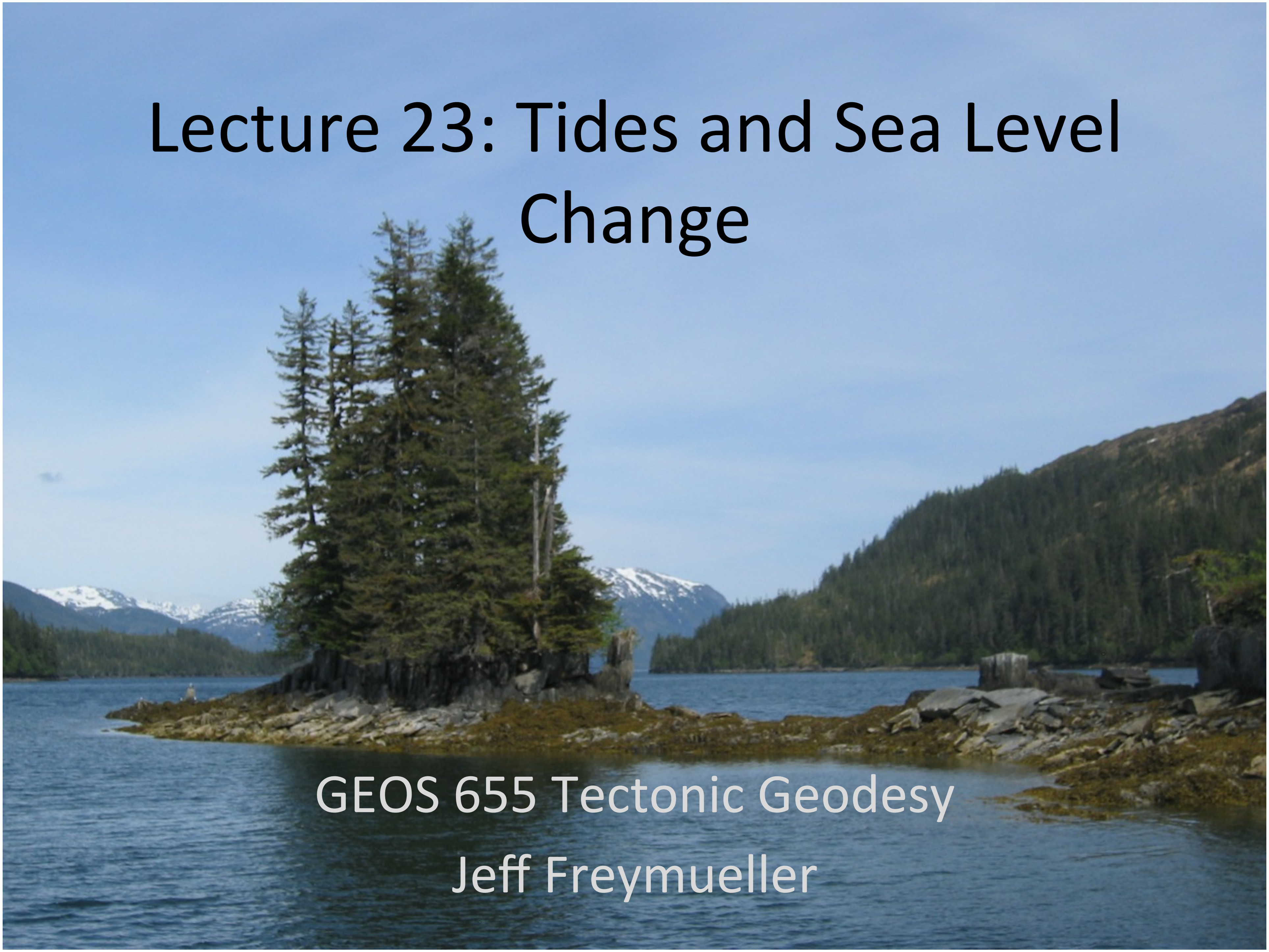
Lecture 23: Tides and Sea Level Change



GEOS 655 Tectonic Geodesy

Jeff Freymueller

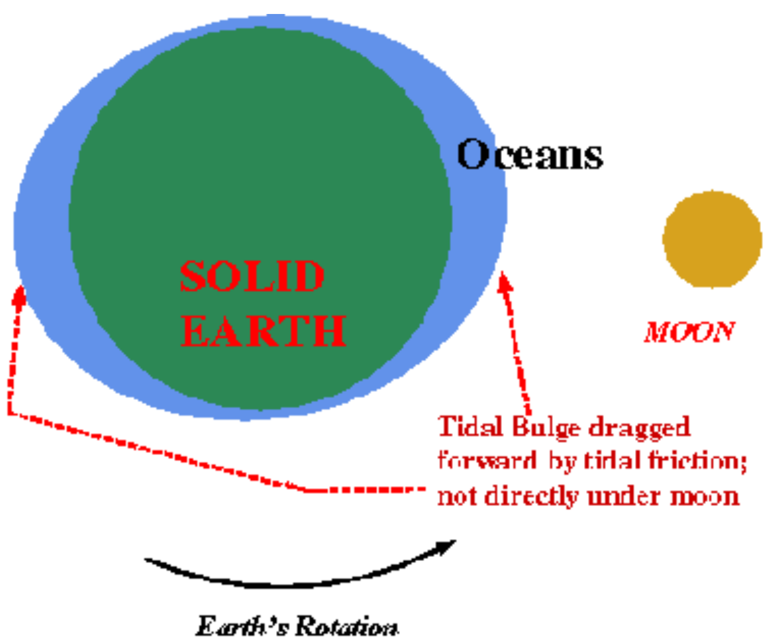
Topics Today

- Tides
- Tide Gauges and Measurement of Tides and sea level variations
  - Tide surveys and tidal benchmark surveys
  - Long-term tidal records
- Sea level history
- The Sea level equation and ocean function

Tides as a Measure of Changing **g**

- Tides are the most obvious change in gravity, caused by the attraction of the moon and sun.
  - Solid earth deforms due to changing tidal gravitational potential (***solid earth tide***)
  - Ocean water flows around due to changing potential (***ocean tides***)
  - Solid earth deforms due to changing load of ocean tides (***ocean tidal loading***)
- Tidal bulge is two-sided because of earth rotation, and because Earth is orbiting about CM of Earth-Moon system
- ***Tidal potential*** (gravitational potential) varies with position of Moon and Sun relative to Earth.
- Tidal variations generally described as a sum of harmonic terms.

Tidal Friction

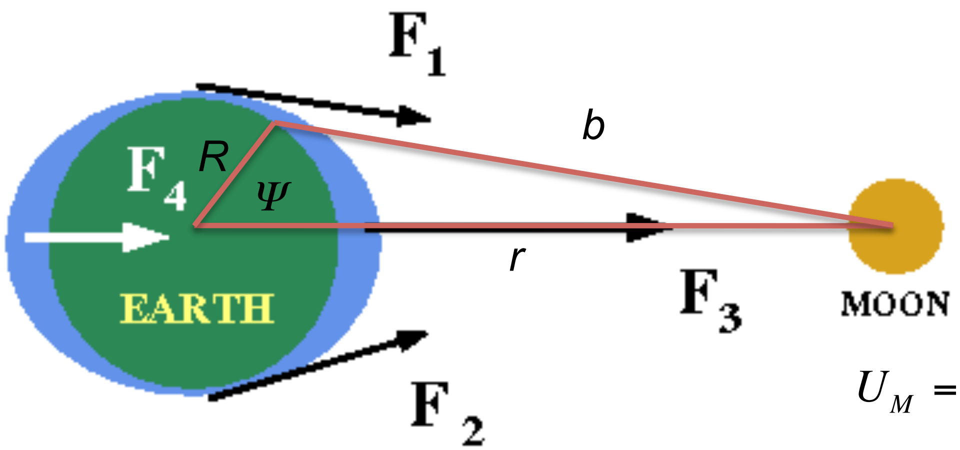


- Earth's tidal bulge gets ahead of Moon position because of rotation of Earth
  - Tidal friction slows Earth rotation and increases orbital radius of Moon
  - Length of day has increased ~10% since Devonian, present rate of change about 0.002 sec/year
    - Geodetic observations of change in length of day reflect mostly exchange of angular momentum between solid earth and hydrosphere.

Tidal Potential

From the Law of Cosines:

$$b^2 = R^2 + r^2 - 2Rr\cos\Psi$$



- We can compute the tidal potential at any point on the Earth's surface from basic physics

$$U_M = -\frac{GM_m}{b}$$

$$U_M = -\frac{GM_m}{r\left[1 + \frac{R^2}{r^2} + 2\frac{R}{r}\cos\Psi\right]^{1/2}}$$

$$U_M = -\frac{GM_m}{r}\left[1 + \frac{R}{r}\cos\Psi + \frac{R^2}{r^2}\left(\frac{3}{2}\cos^2\Psi - \frac{1}{2}\right) + \cdots\right]$$

Tidal Potential Terms

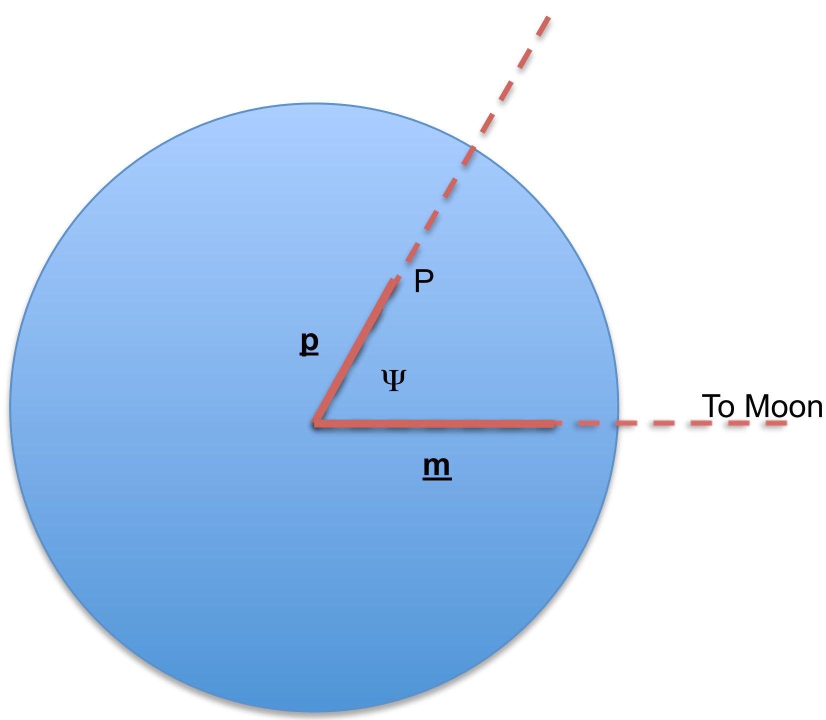
$$U_{M(1)} = -\frac{GM_m}{r}$$

$$U_{M(2)} = -\frac{GM_m R}{r^2}\cos\Psi$$

$$U_{M(3)} = -\frac{GM_m}{r}\left[\frac{R^2}{r^2}\left(\frac{3}{2}\cos^2\Psi - \frac{1}{2}\right) + \cdots\right]$$

- First order approximation: distance to Moon is constant.
- First term is constant
- Second term relates to orbit of Earth around CM of Earth-Moon system
- Third and following terms are ***tidal potential***.
- We'll look at that third term in more detail.

Relation of Ψ to Lat-Long



$$\cos\Psi = \cos\theta\cos\theta_m + \sin\theta\sin\theta_m\cos(\varphi - \varphi_m)$$

- The angle Y is measured in the plane defined by the vectors **p** and **m**,
- Define (θ,ϕ) as as co-latitude + logitude of P
- Define (θ_m,ϕ_m) as co-latitude + longitude of Moon (varies)
- Longitude changes by 2π per day (non-rotating coordinate system)

$$\frac{1}{2}(3\cos^2\Psi - 1) = \; = \left(\frac{3\cos^2\theta - 1}{2}\right)\left(\frac{3\cos^2\theta_m - 1}{2}\right) + \\ + \frac{3}{4}\sin^2\theta\sin^2\theta_m\cos 2(\varphi - \varphi_m) \\ + \frac{3}{4}\sin 2\theta\sin 2\theta_m\cos(\varphi - \varphi_m)$$

Periods of these terms

- **Semi-diurnal** tide $$\frac{3}{4}\sin^2\theta\sin^2\theta_m\cos 2(\varphi-\varphi_m)$$
  - Undergoes a complete cycle every time $2(\phi-\phi_m)$ changes by 2π, roughly twice a day
  - Amplitude varies over course of lunar month
- **Diurnal** tide $$\frac{3}{4}\sin 2\theta\sin 2\theta_m\cos(\varphi-\varphi_m)$$
  - Undergoes a complete cycle every time $(\phi-\phi_m)$ changes by 2π, roughly once a day
  - Amplitude varies over course of lunar month
- **Fortnightly** tide $$\left(\frac{3\cos^2\theta-1}{2}\right)\left(\frac{3\cos^2\theta_m-1}{2}\right)$$
  - Undergoes a complete cycle twice per lunar month
- Plus higher order terms from ellipticity of Moon's orbit.

Solar Tides

- Solar tides come from the same causes as lunar tides.
  - Magnitude ~0.42 of lunar tides due to ratio of masses and ratio of distances cubed.
- Solar tides include semi-diurnal and diurnal, but vary with year rather than lunar month
- Solar tidal components may be out of phase with lunar components

Tidal Components are Named

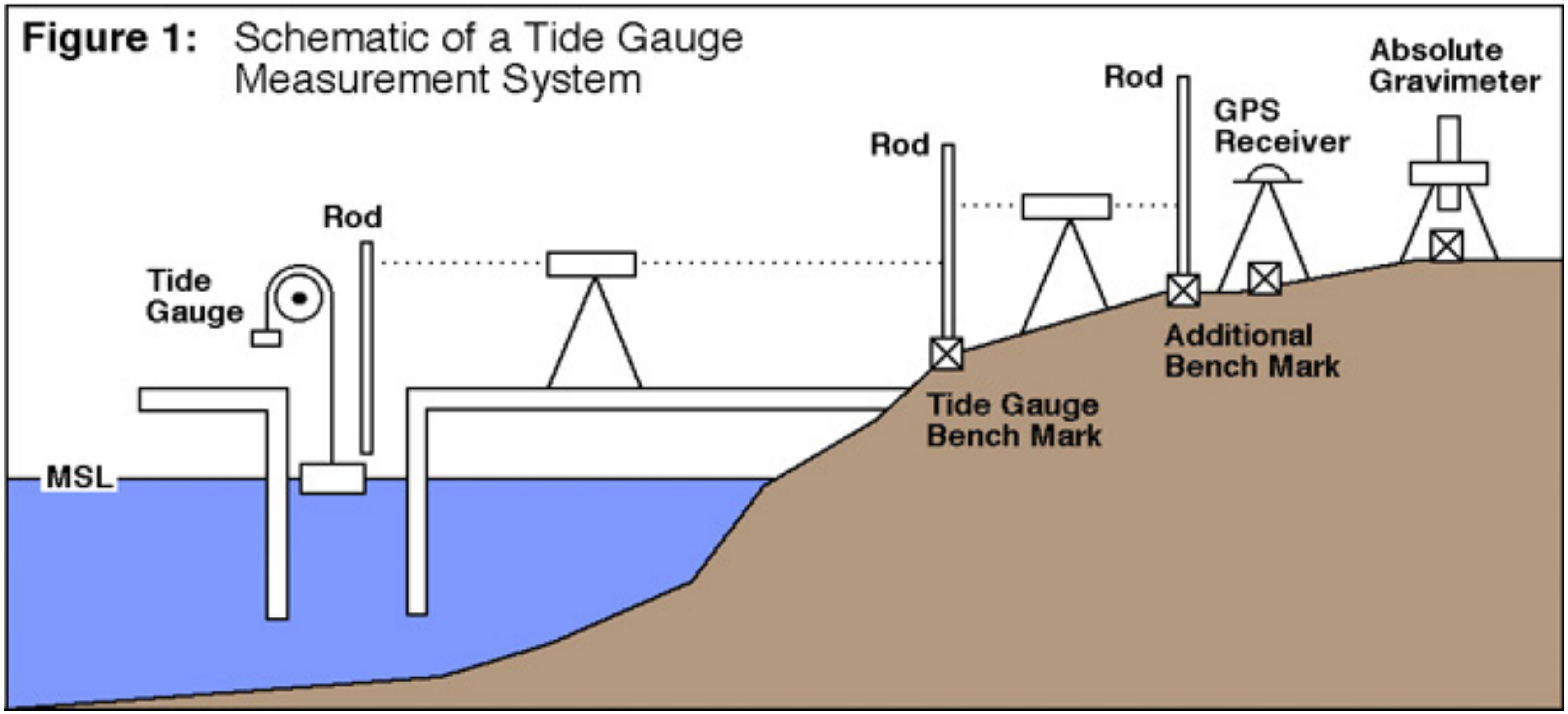
- Only major tidal components listed here
- Lunar tides
  - Semi-diurnal M2
  - Diurnal K1, O1
  - Elliptical J1, L1, K2, L2
- Solar Tides
  - Semi-diurnal S2
  - Diurnal P1
  - Elliptical R2, T2
- See http://en.wikipedia.org/wiki/Theory_of_tides

The M2 tide is very large in Alaska due to a resonance in the Gulf of Alaska

Predicting Tides

- The periods of the tidal harmonic components are known.
- Tides can be predicted forward in time by fitting amplitudes and phases for each harmonic component based on some data.
- Non-tidal components include:
  - Storms and storm surges
  - Variations in currents/salinity
  - El Niño/La Niña
  - Pacific Decadal Oscillation and other basin-scale variations
  - Some of the non-tidal components repeat seasonally

Example Tide Gauge Site



Oldest continuous tide gauge site: Amsterdam, since 1700

Classical Float Gauge (from about 1832)

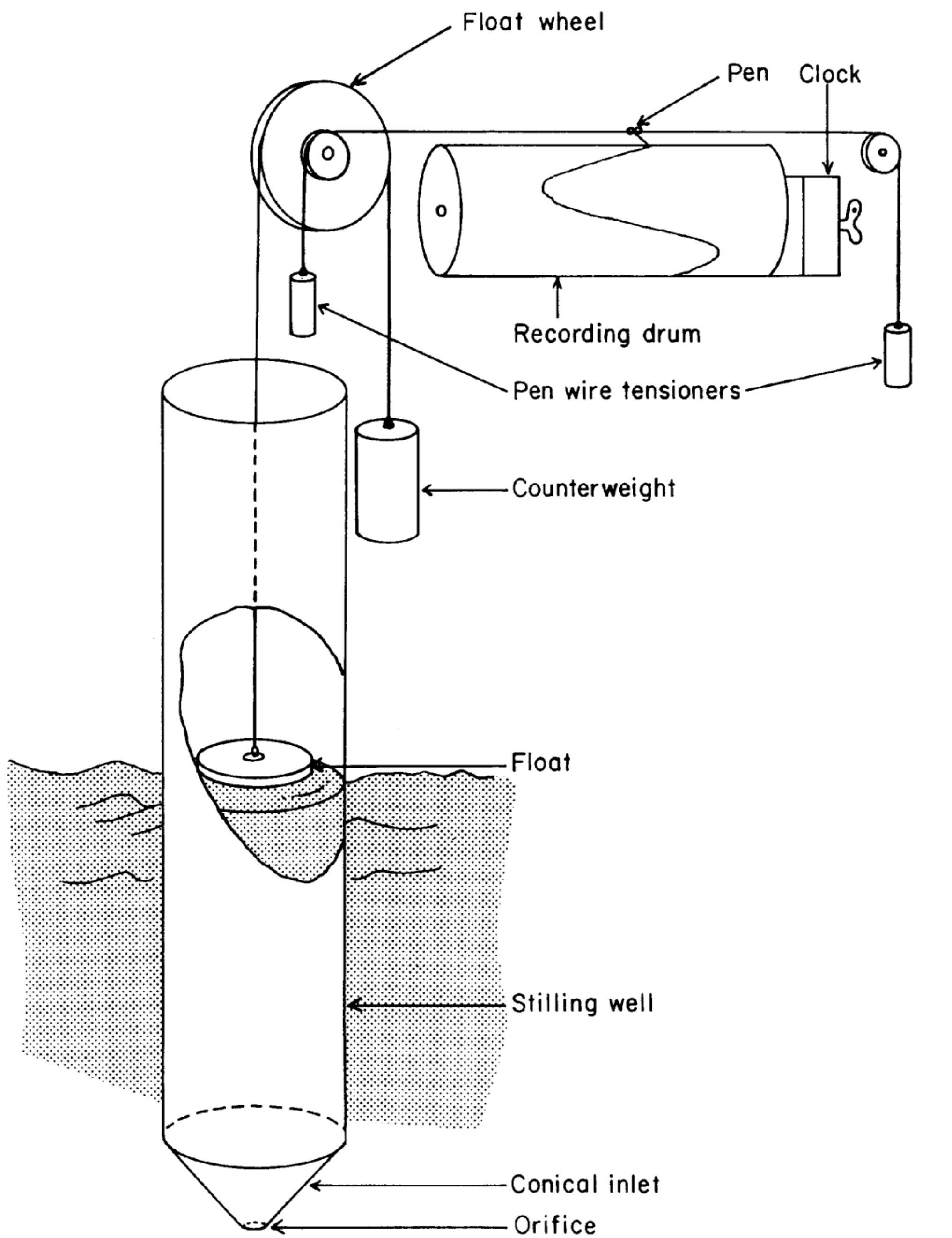
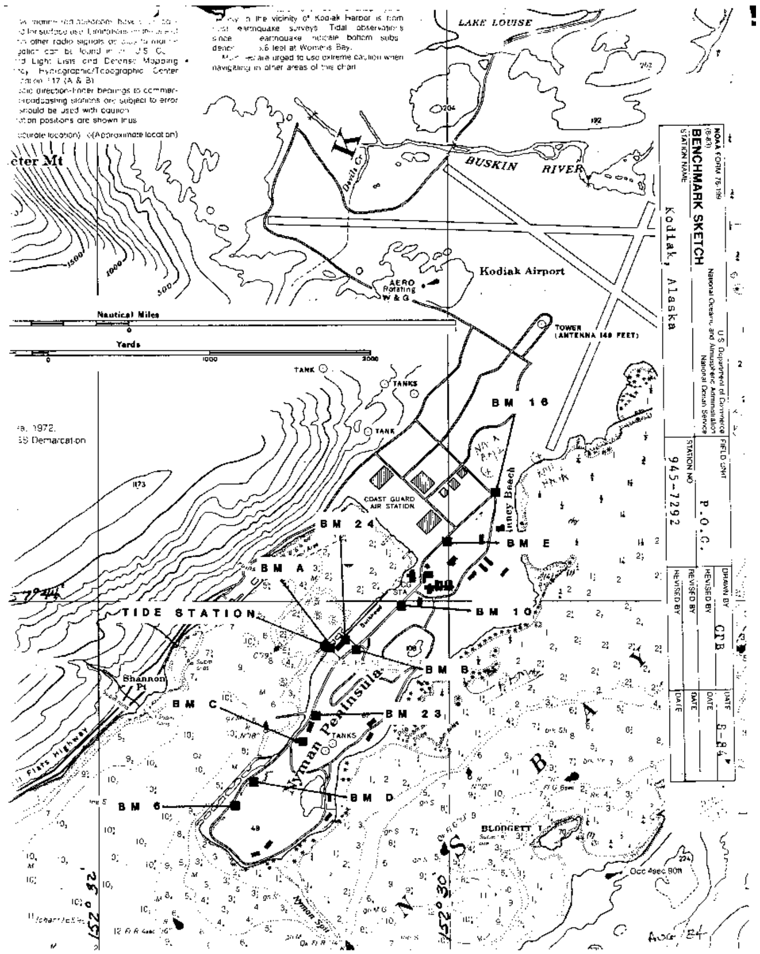


Figure 3.1

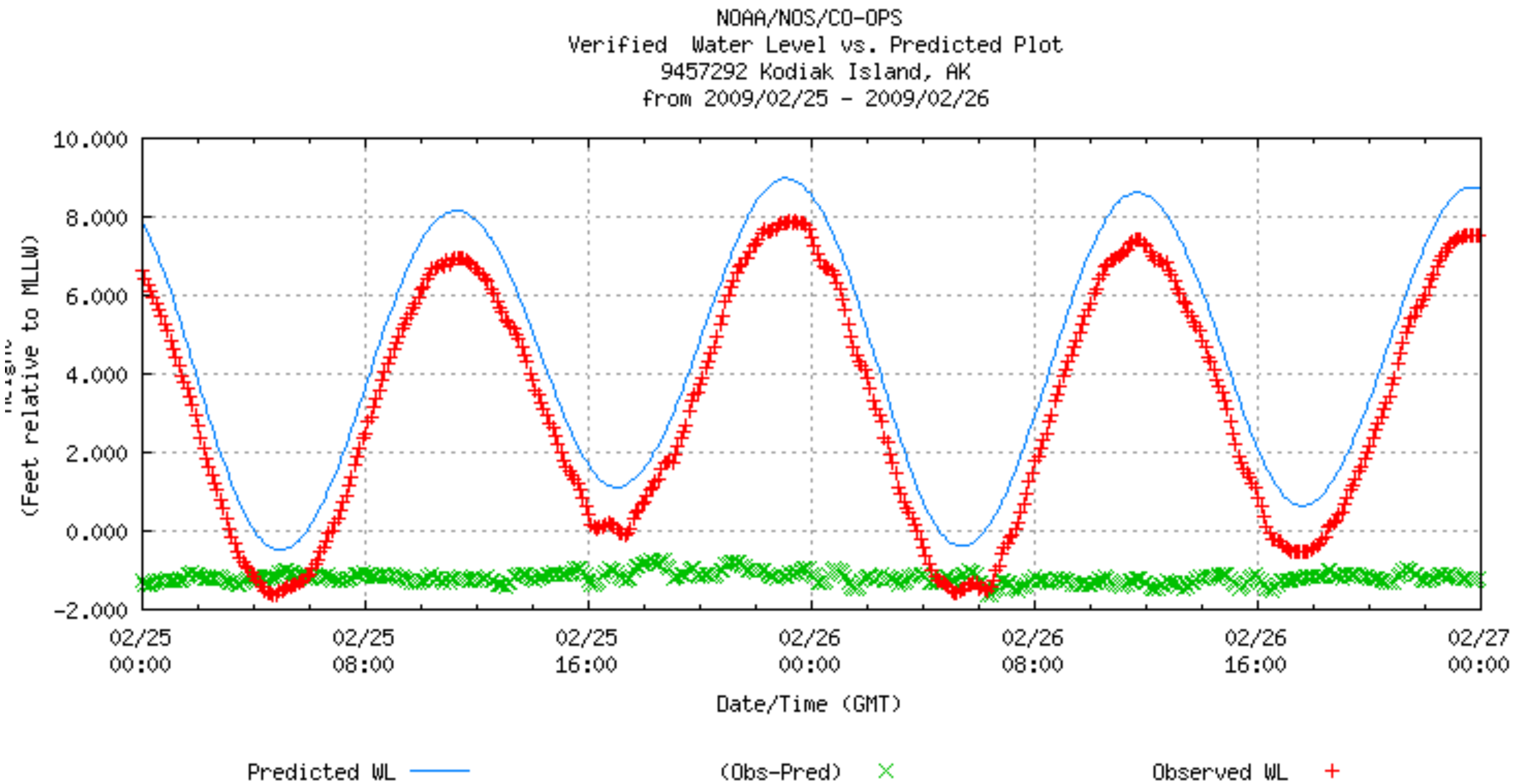
UK Float Gauge at Holyhead

Float gauges
are still important
and can be made
into digital gauges
with the use of
encoders

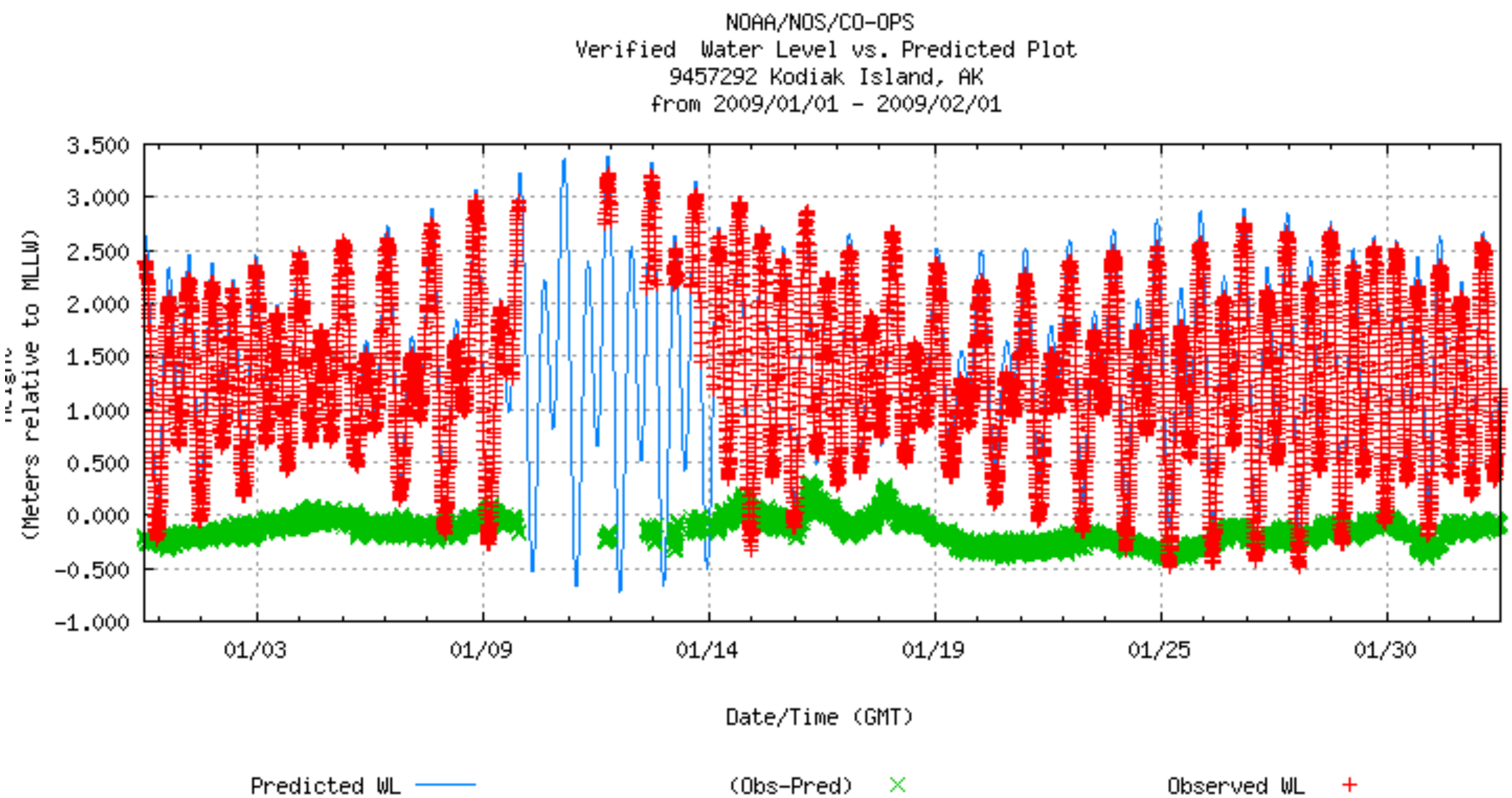
Example: Kodiak Tide Station



Sample Tide Data



A month of Tide Data



Tidal Harmonic Components

- Twenty largest harmonic components at Kodiak Island

Const#	Name	Amplitude	Phase	Speed (= degrees/hour = 360/period)
------	----	---------	-----	-----------
1	M2	3.192	308.1	28.9841042 (= 12.4 hours)
4	K1	1.306	288.6	15.0410686 (= 23.93 hours)
2	S2	1.066	341.4	30.0000000
6	O1	0.850	273.0	13.9430356
3	N2	0.659	284.2	28.4397295
30	P1	0.413	284.4	14.9589314
35	K2	0.295	332.8	30.0821373
22	SA	0.256	262.1	0.0410686 (= 1 year)
26	Q1	0.154	264.8	13.3986609
11	NU2	0.128	284.2	28.5125831
33	L2	0.079	321.0	29.5284789
14	2N2	0.079	258.9	27.8953548
19	J1	0.075	297.9	15.5854433
13	MU2	0.072	277.1	27.9682084
24	MF	0.066	165.2	1.0980331 (= 13.6 days)
27	T2	0.062	329.5	29.9589333
20	MM	0.062	191.7	0.5443747
23	MSF	0.049	51.5	1.0158958
21	SSA	0.049	151.7	0.0821373
18	M1	0.046	293.2	14.4966939

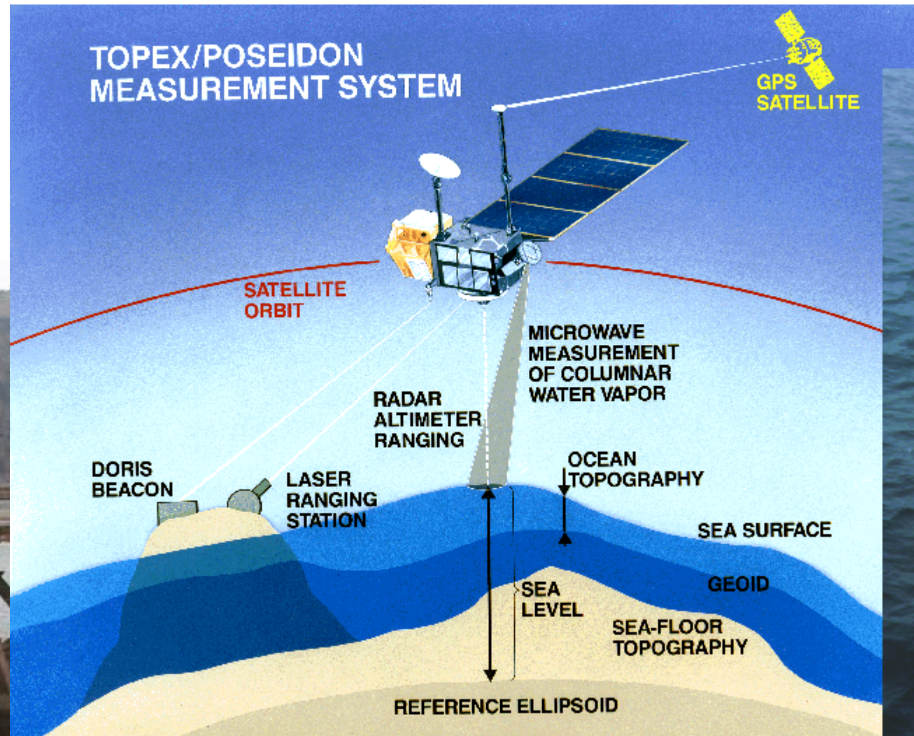
Tidal Benchmark Surveys

- In addition to permanent tide gauges, there are many tidal benchmarks, which have been surveyed relative to tide level.
- Good tidal benchmark surveys include 2-3 months of temporary tide gauge surveys to measure major tidal components.
- Shorter tidal benchmark surveys use nearby permanent tide gauges or even tide tables.

Sea Level Monitoring

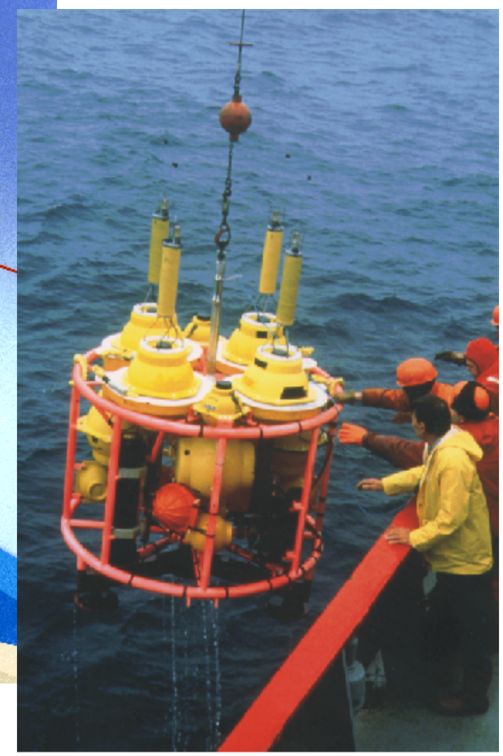
- Each country operates its own tide gauges, data coordinated through international organizations
  - PSMSL = Permanent Service for Mean Sea Level
    - Under ICSU
    - Archives tide gauge data from almost 2000 global stations
  - GLOSS = Global sea Level Observing SyStem
    - Under WMO
    - The main component of GLOSS is the 'Global Core Network' (GCN) of 290 sea level stations around the world for long term climate change and oceanographic sea level monitoring.
    - Also Long-term trends network fed to IPCC, etc.

Measuring Sea Level Changes



Altimeter System

Tide Gauge (float)



Bottom Pressure Gauge

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html

Sea-Level Changes

Maldives Int. Airport

Different Time-Scales

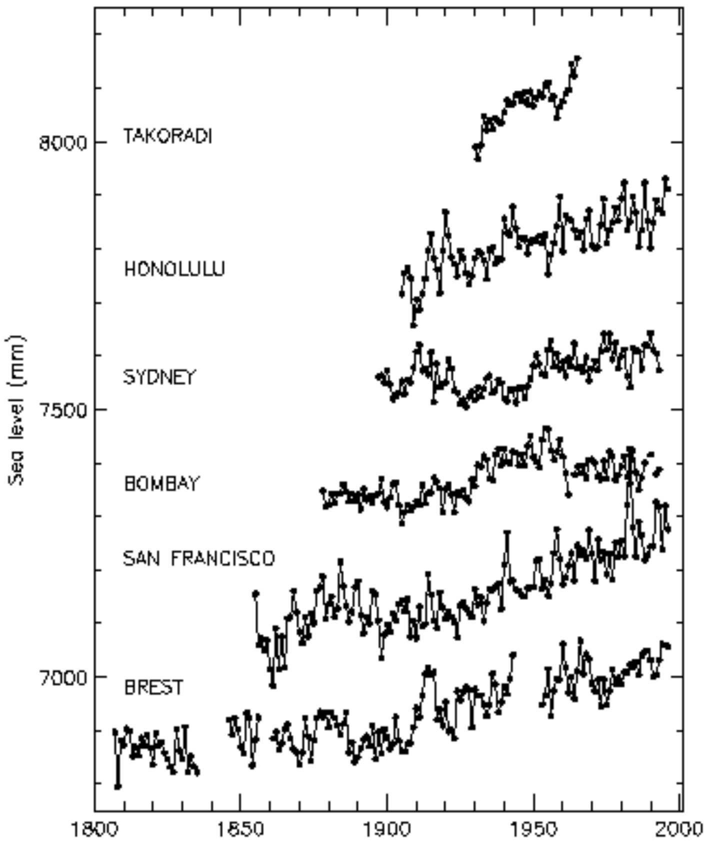
- Momentary changes due to tsunamis
- Daily changes due to tides and surges
- Seasonal changes
- Interannual changes e.g. due to ENSO
- Long term changes due to climate change

Causes of Sea Level Change

- Local processes in river/coastal regimes
- Ocean circulation changes
- Regional and global climate changes
- Geological processes

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html

Long Term Changes in Sea Level

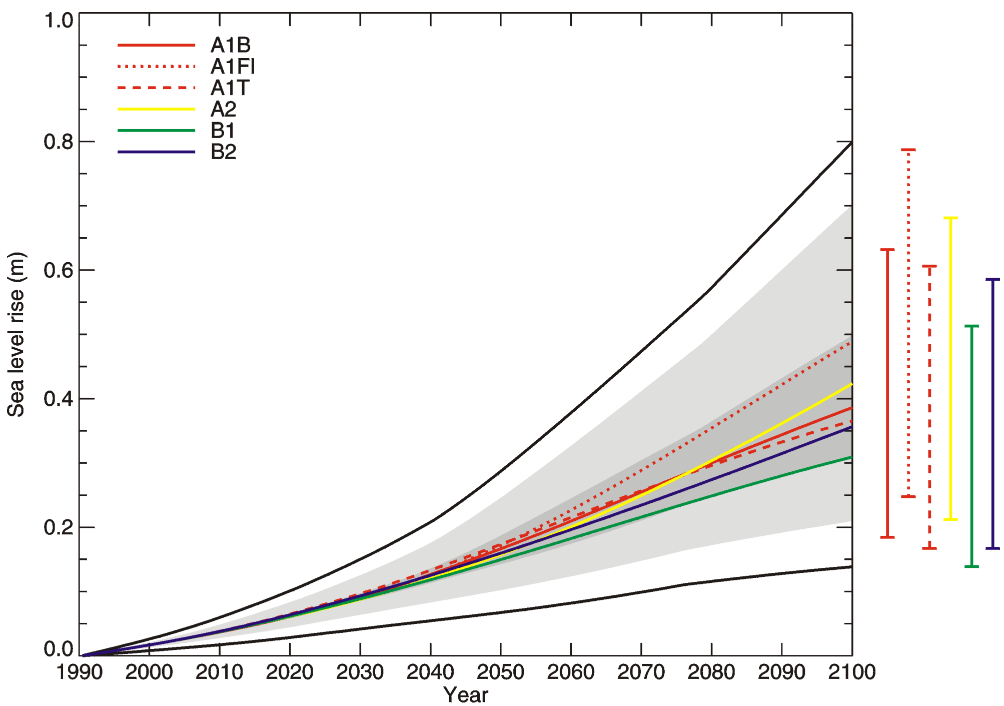


Past 100 years

- Most records show evidence for rising sea levels during the past century
- IPCC concluded that there has been a global rise of approximately 10-20 cm during the past 100 years

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html

Long Term Changes in Sea Level



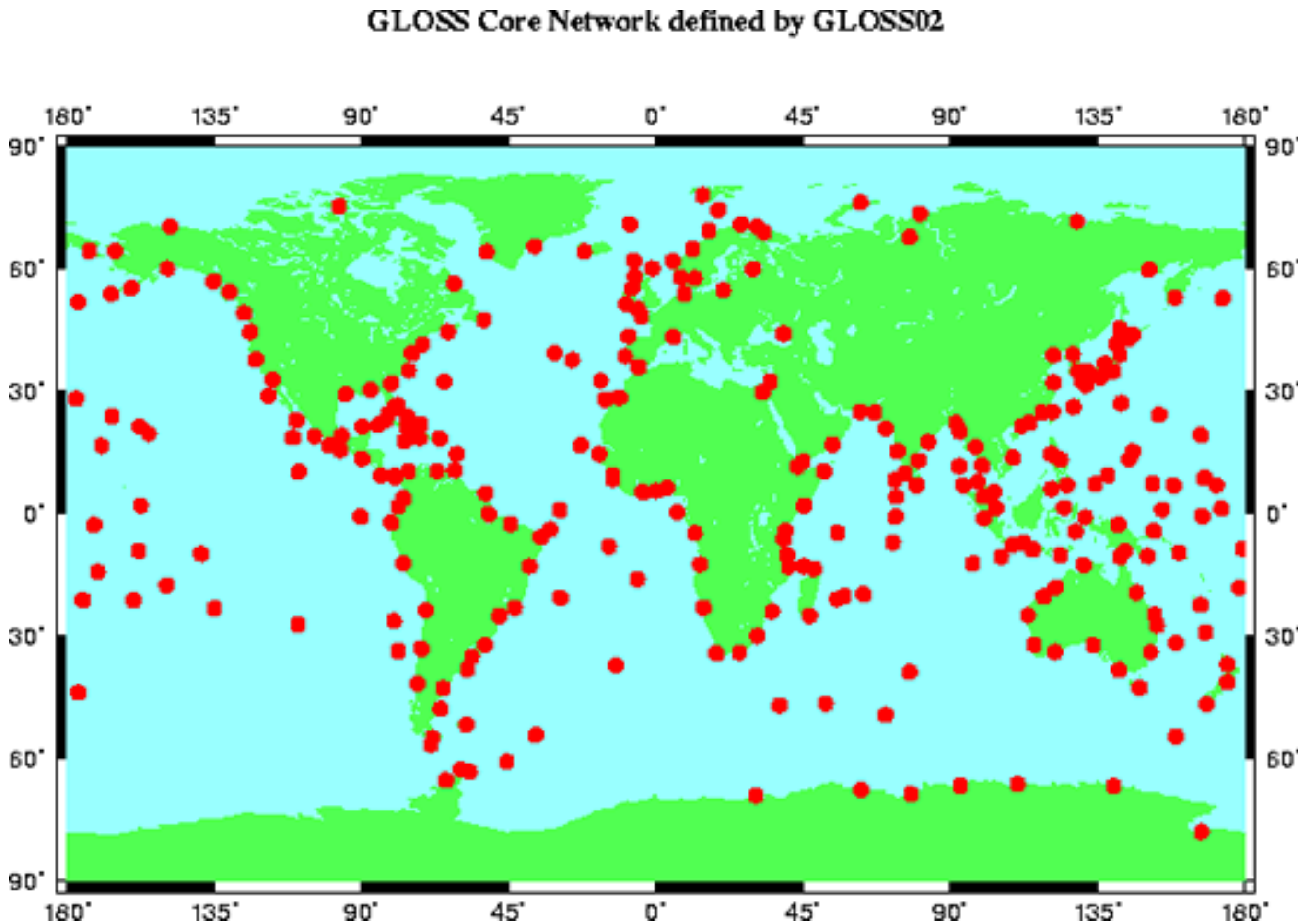
Projected sea level rise, IPCC 2001

Next 100 years

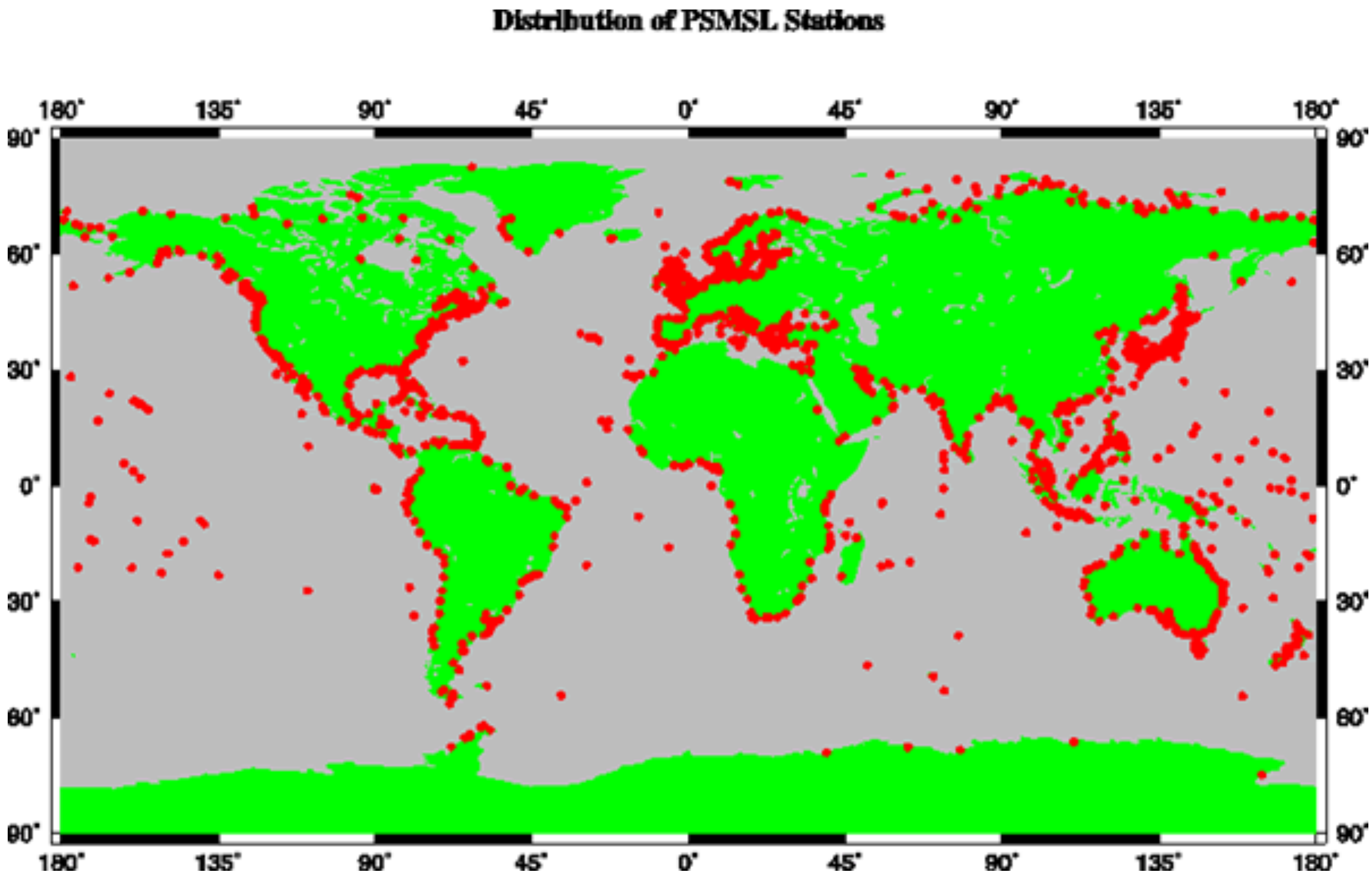
- a rise between 9 and 88 cm
- a central value of 48 cm
- a rate of approx. 2.2 - 4.4 times that of the past 100 years

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html

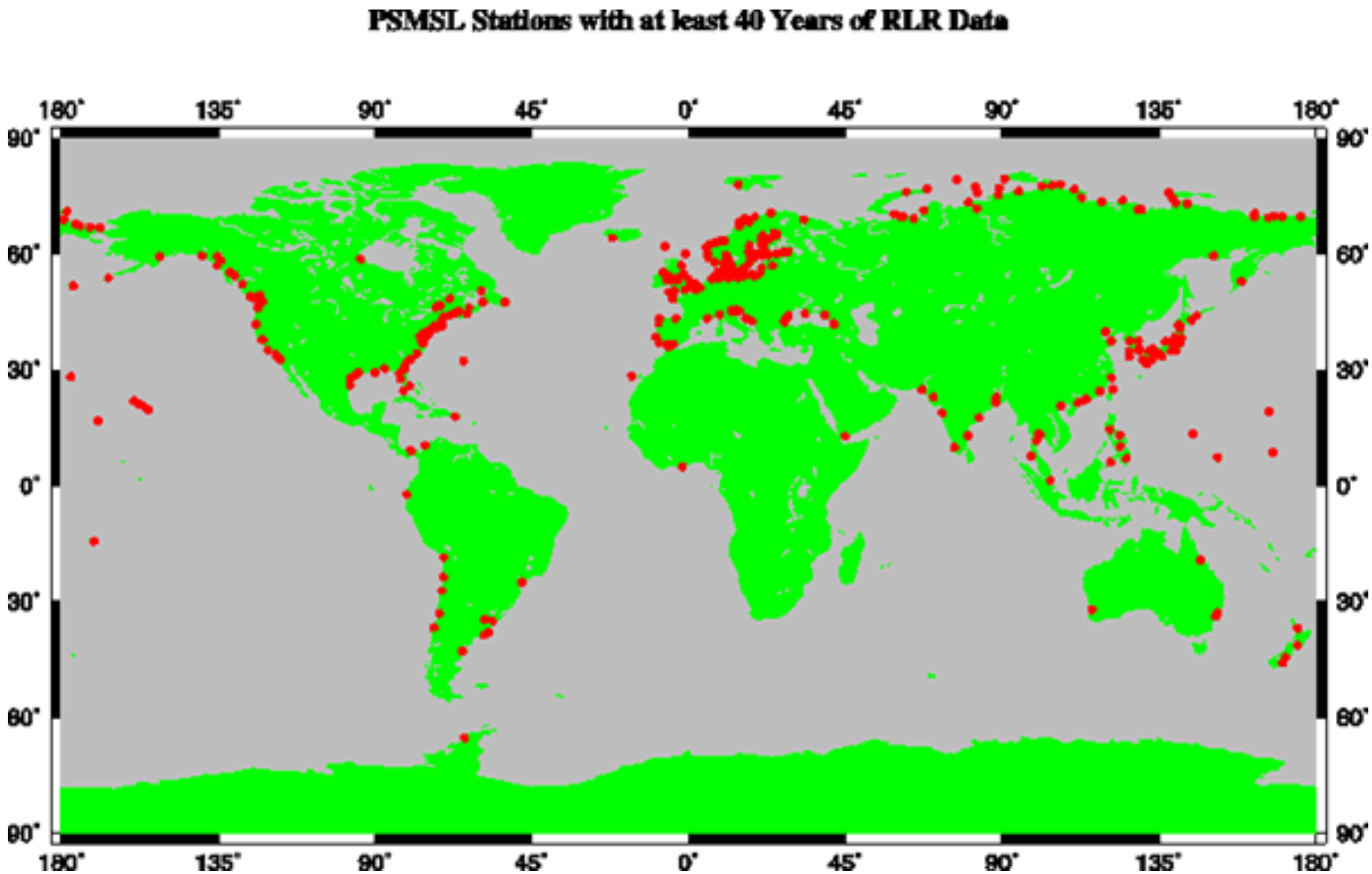
Present GLOSS Core Network



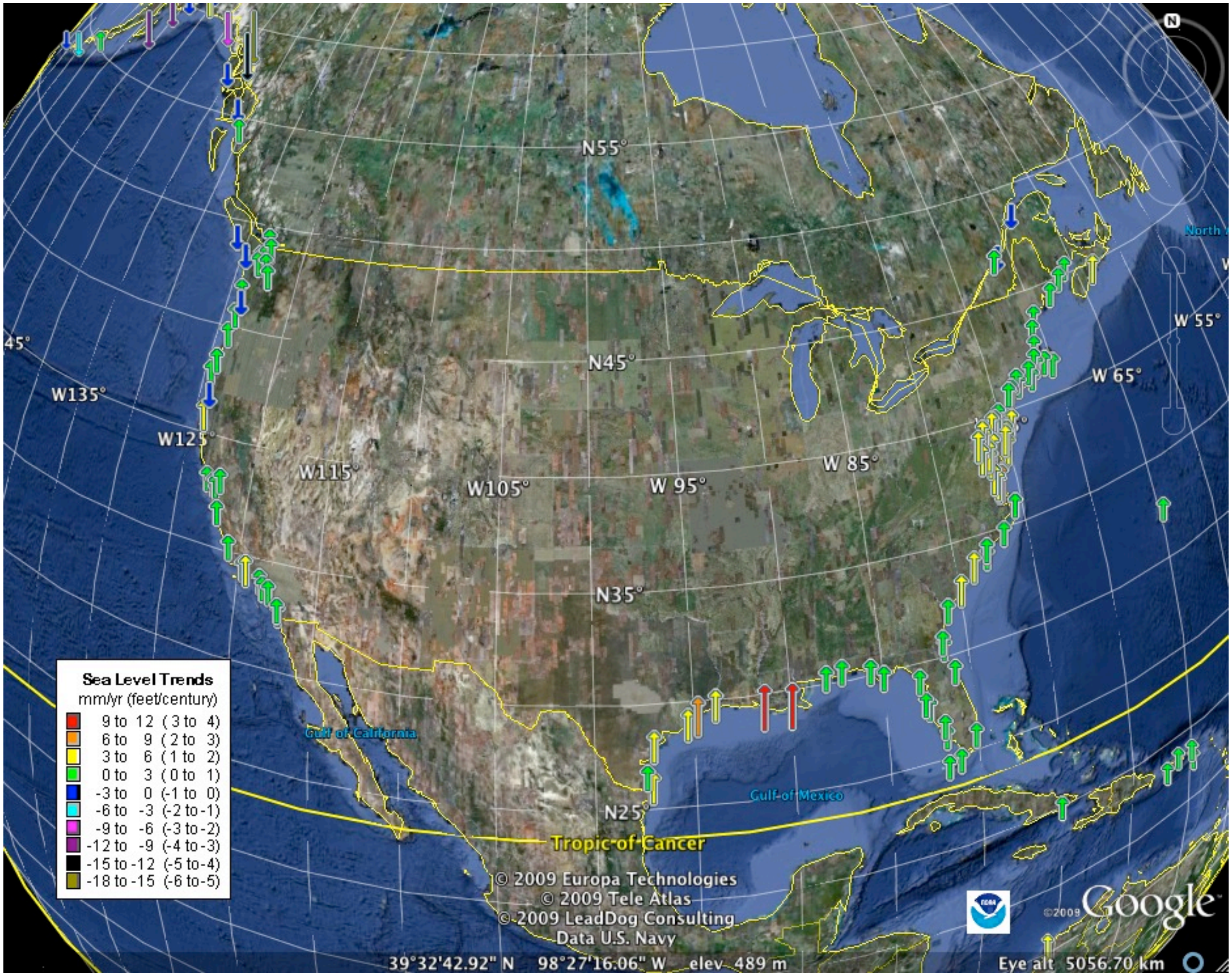
All PSMSL Tide Stations



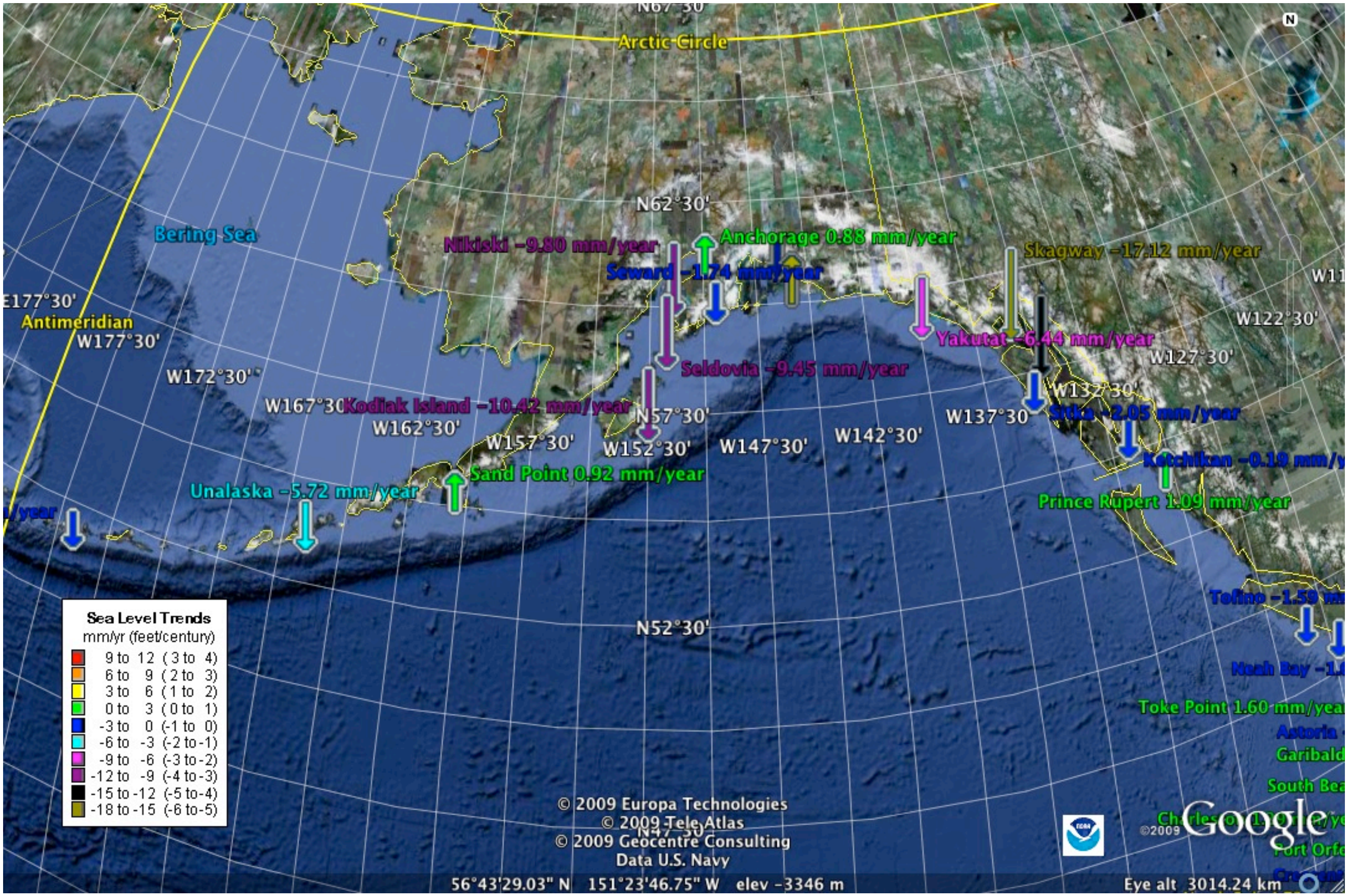
PSMSL with >40 years records



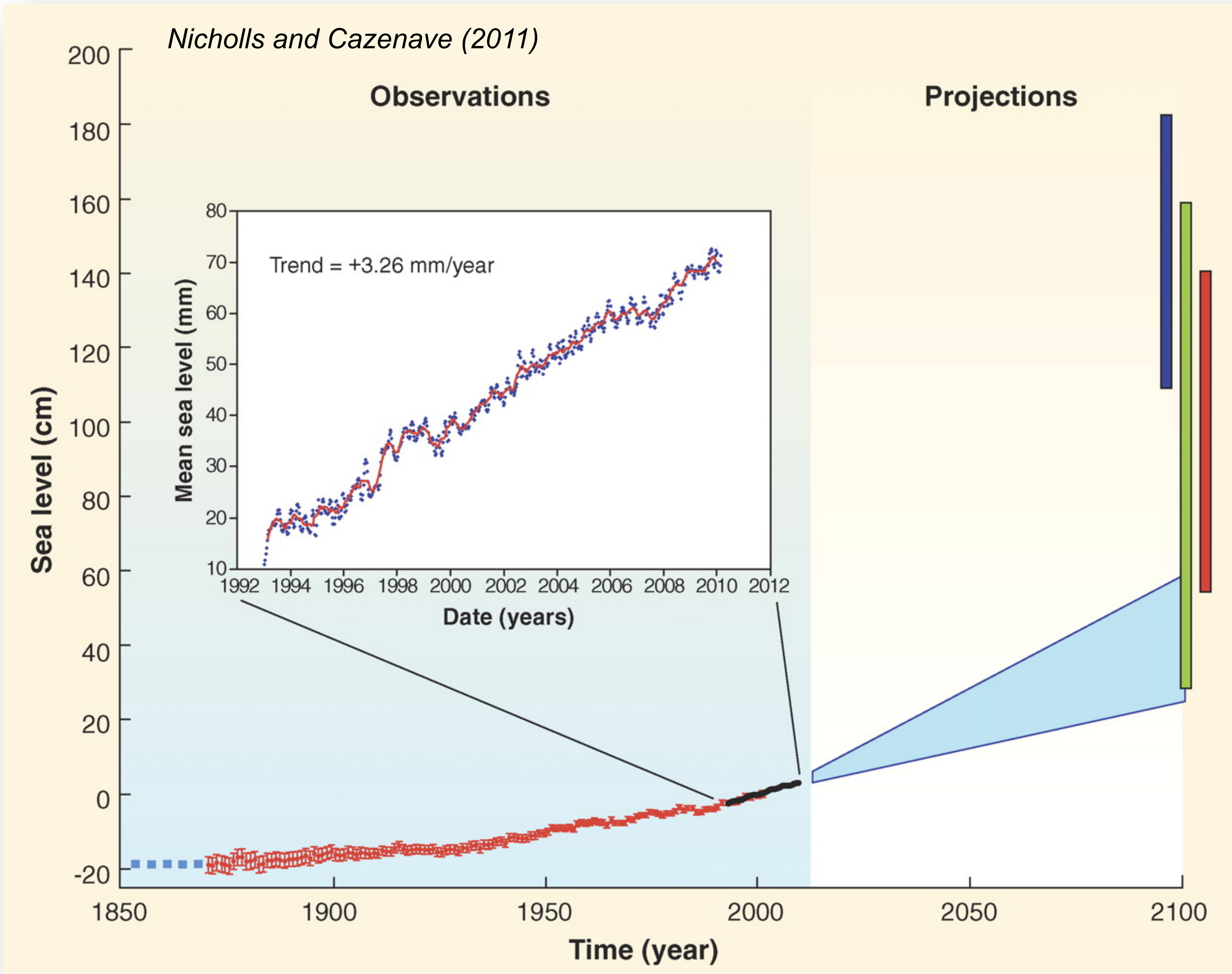
Lower 48 Sea Level Trends



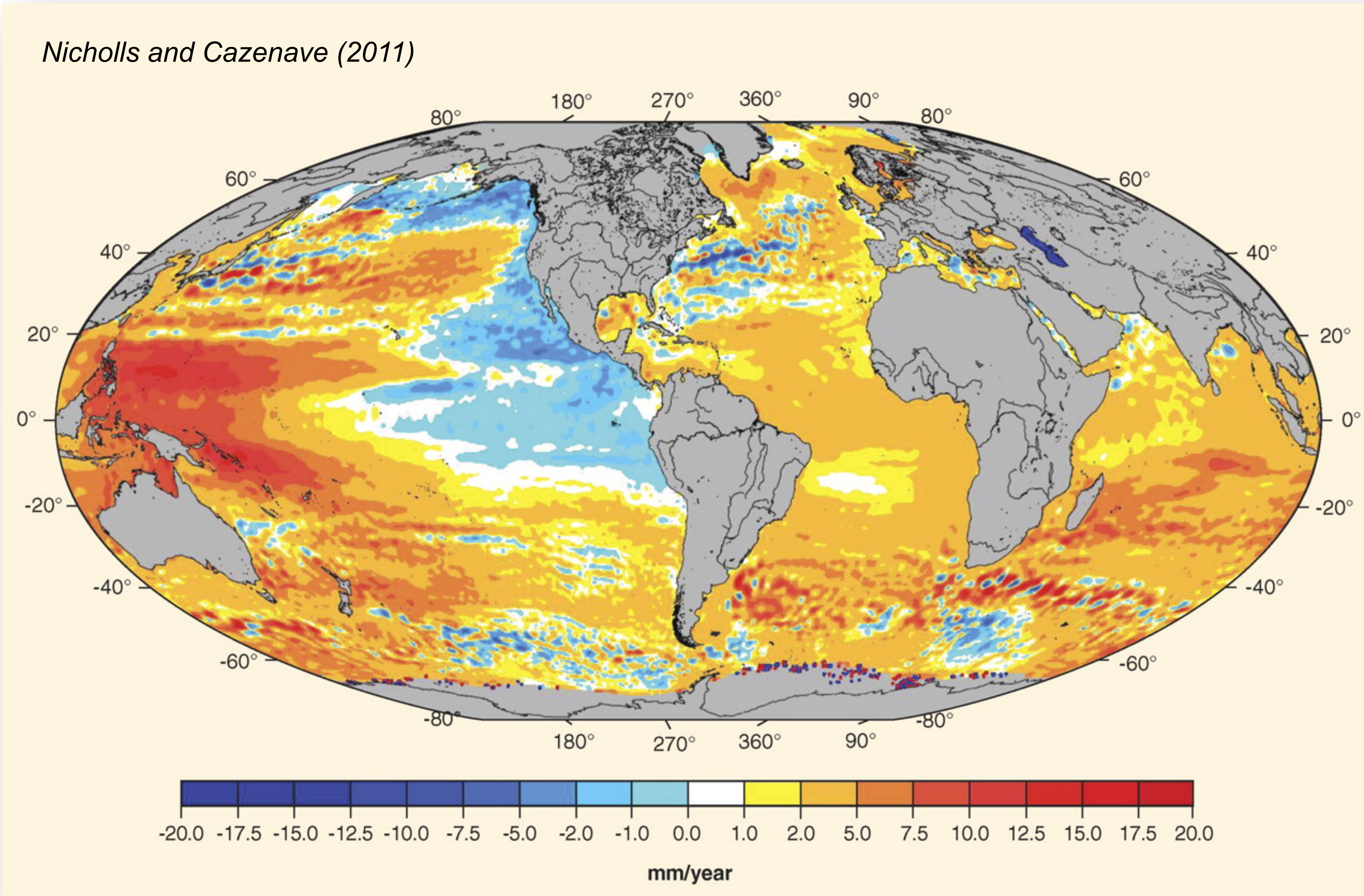
Alaska Sea Level Trends



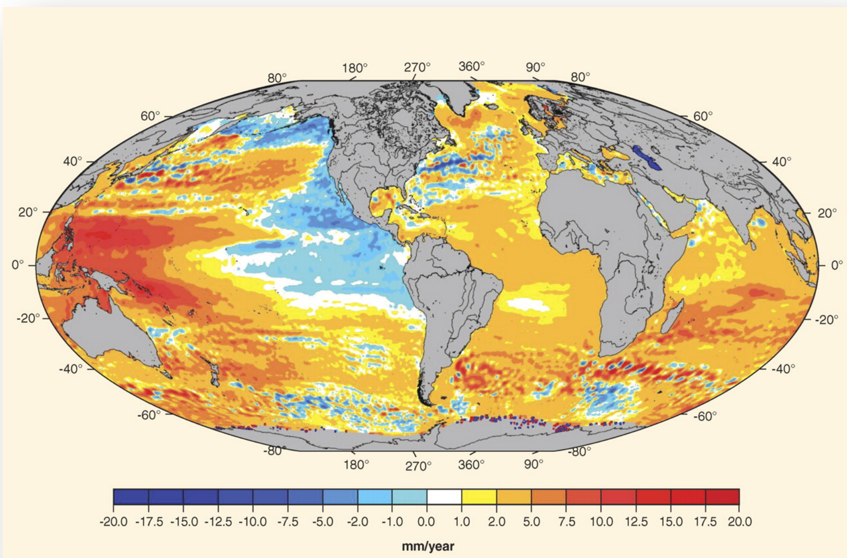
Global Mean Sea Level



Regional Sea Level Trends
1992-2009

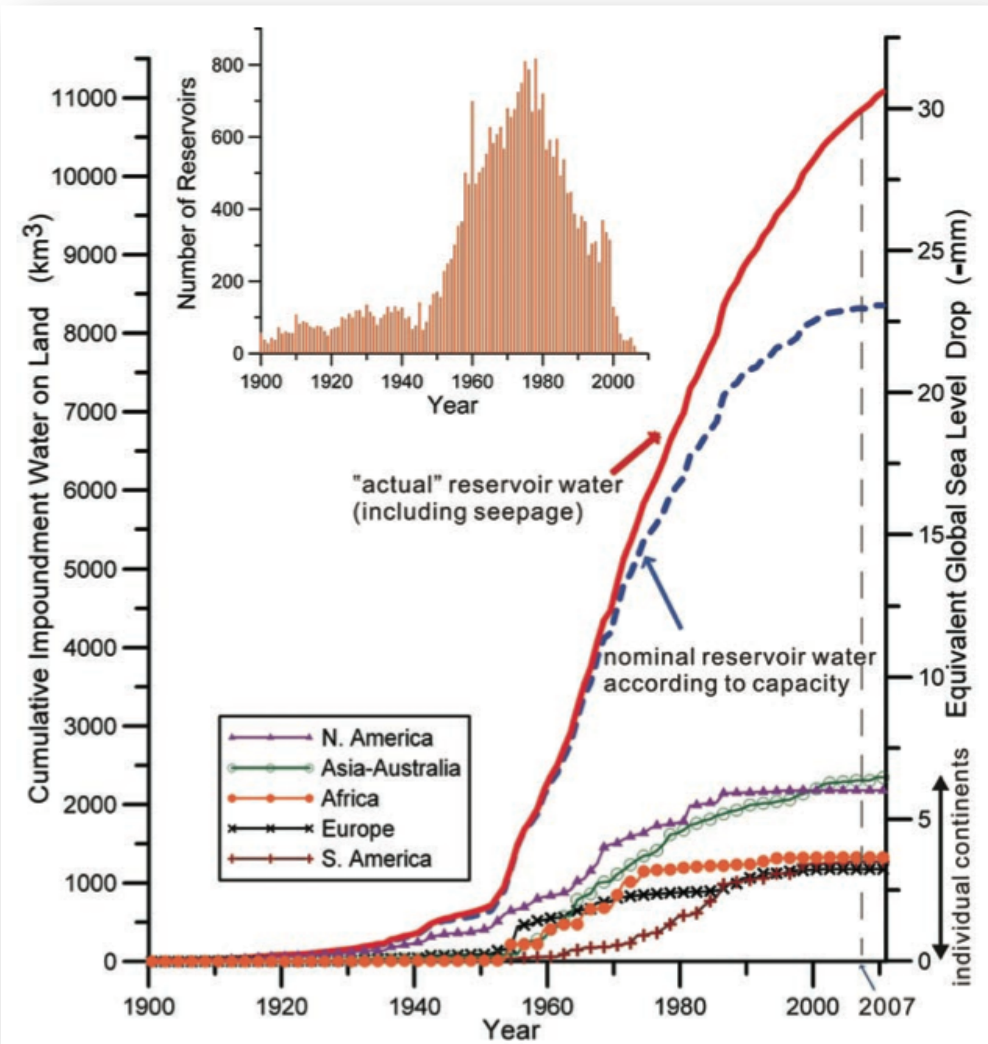


Absolute Sea Level Variation



- Most of the variation in this figure is oceanographic – redistribution of water
  - Thermal expansion of surface waters
  - El Niño/La Niña
  - Other oscillatory shifts in currents
- Some long-term trends are buried in this figure

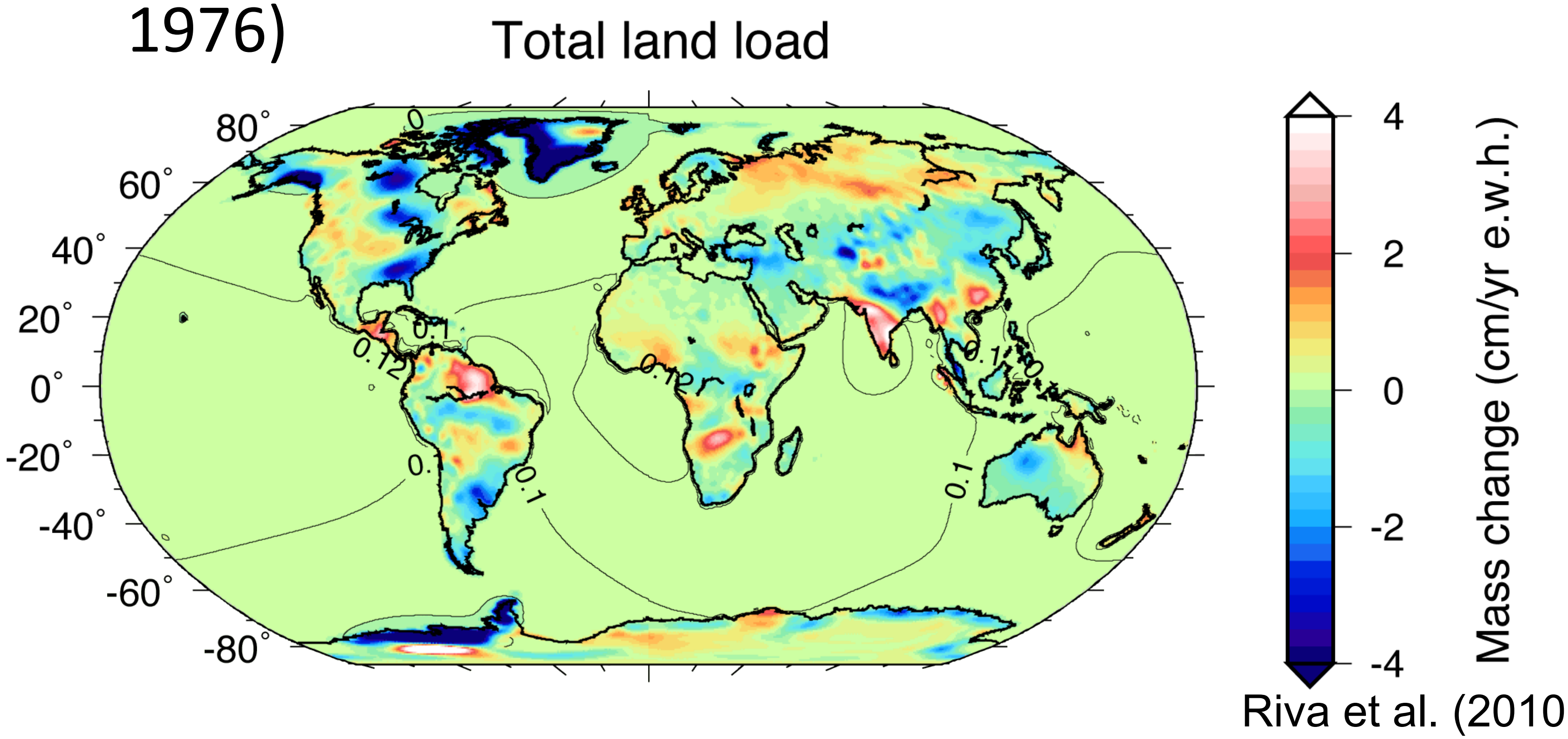
Addition of water to Oceans



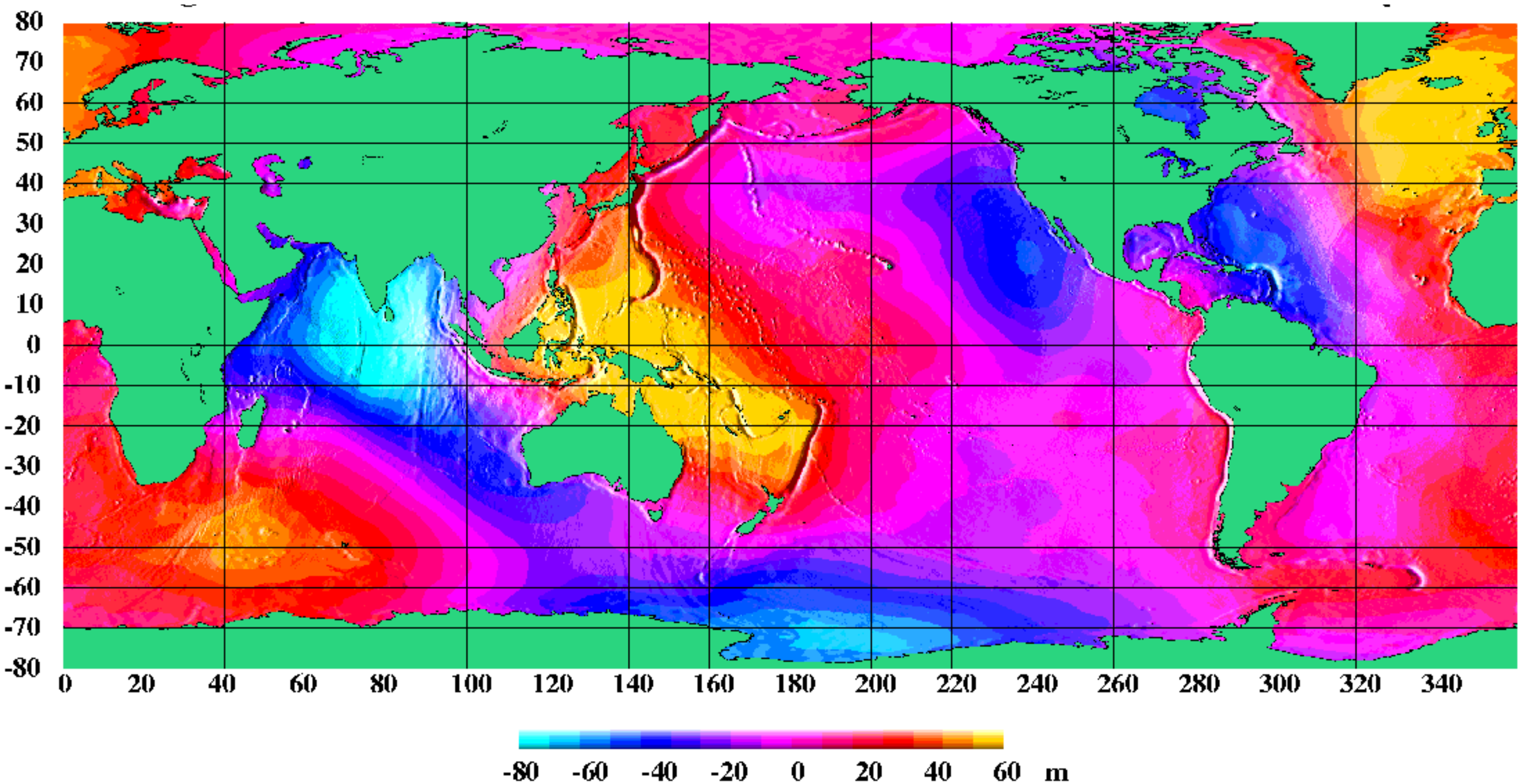
- Melting glaciers are the main contributor of water to the oceans
- Continental water storage (groundwater, reservoirs) has been largest source of uncertainty
- Addition of water to reservoirs has reduced rate of sea level rise (Chao et al., 2008)

Global Scale Variations

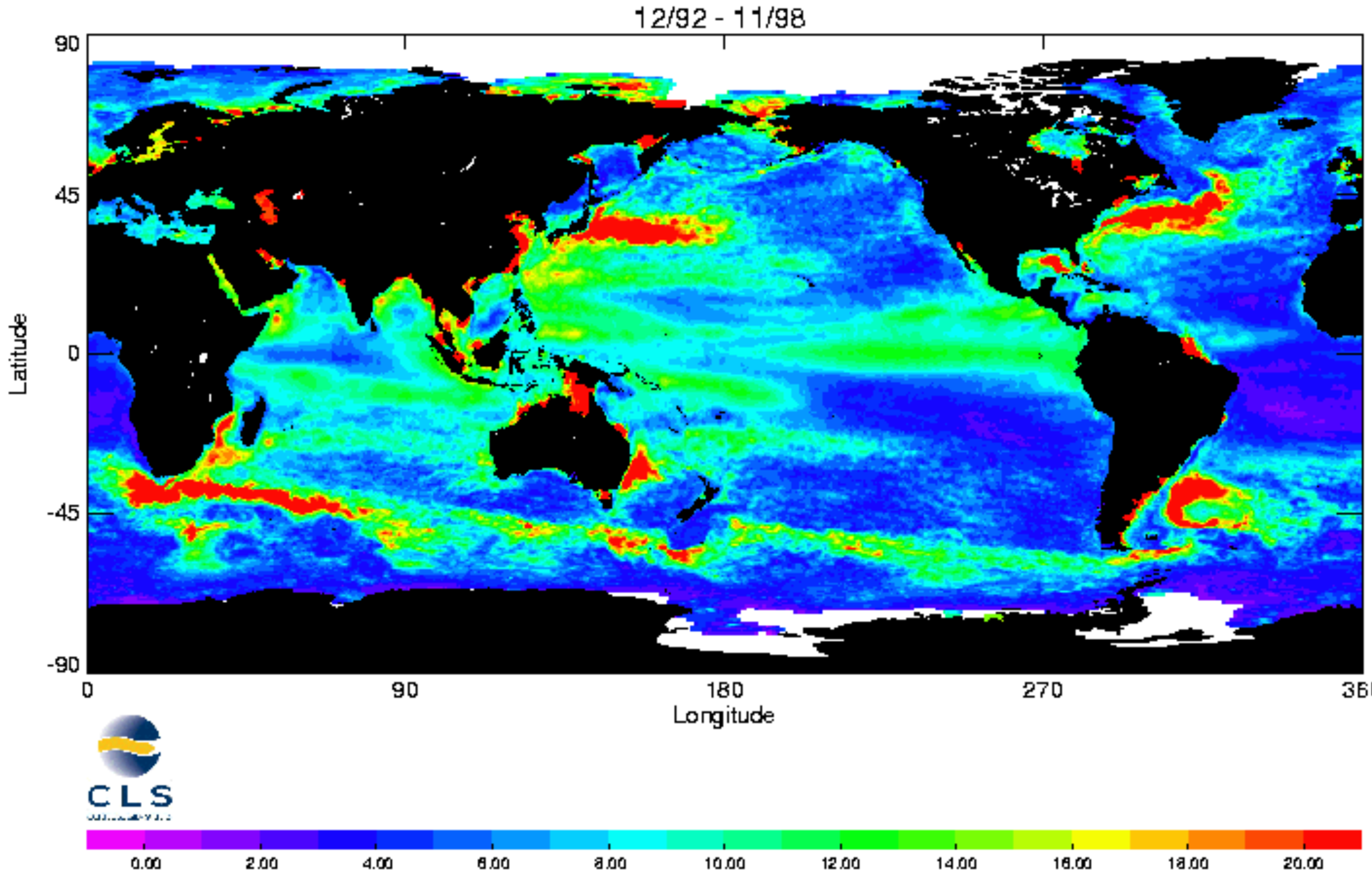
- Measure all mass redistribution using data from the NASA GRACE satellite mission
  - Solve "sea level equation" (Farrell and Clark, 1976)



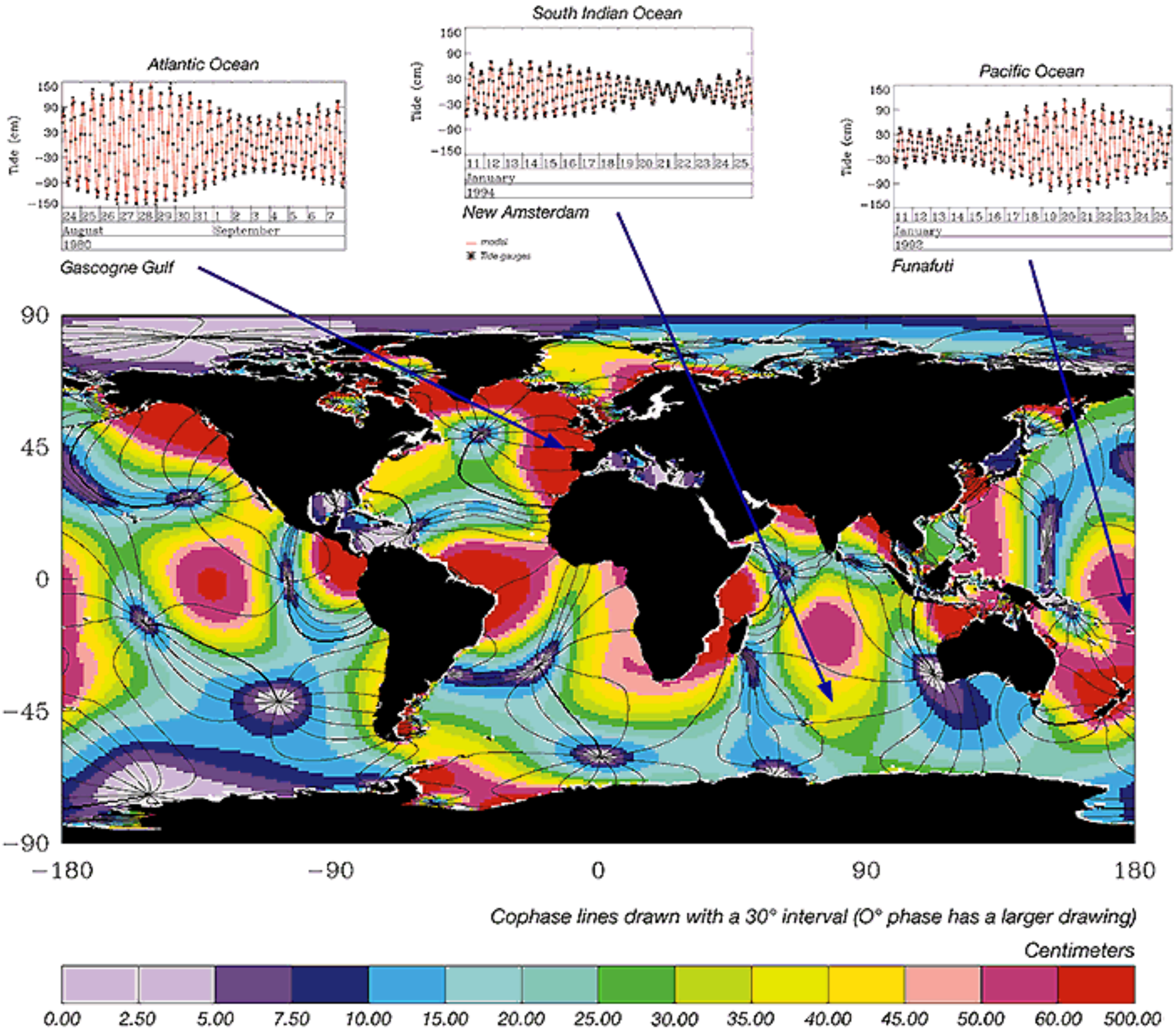
Mean Sea Surface from multi-mission altimetry



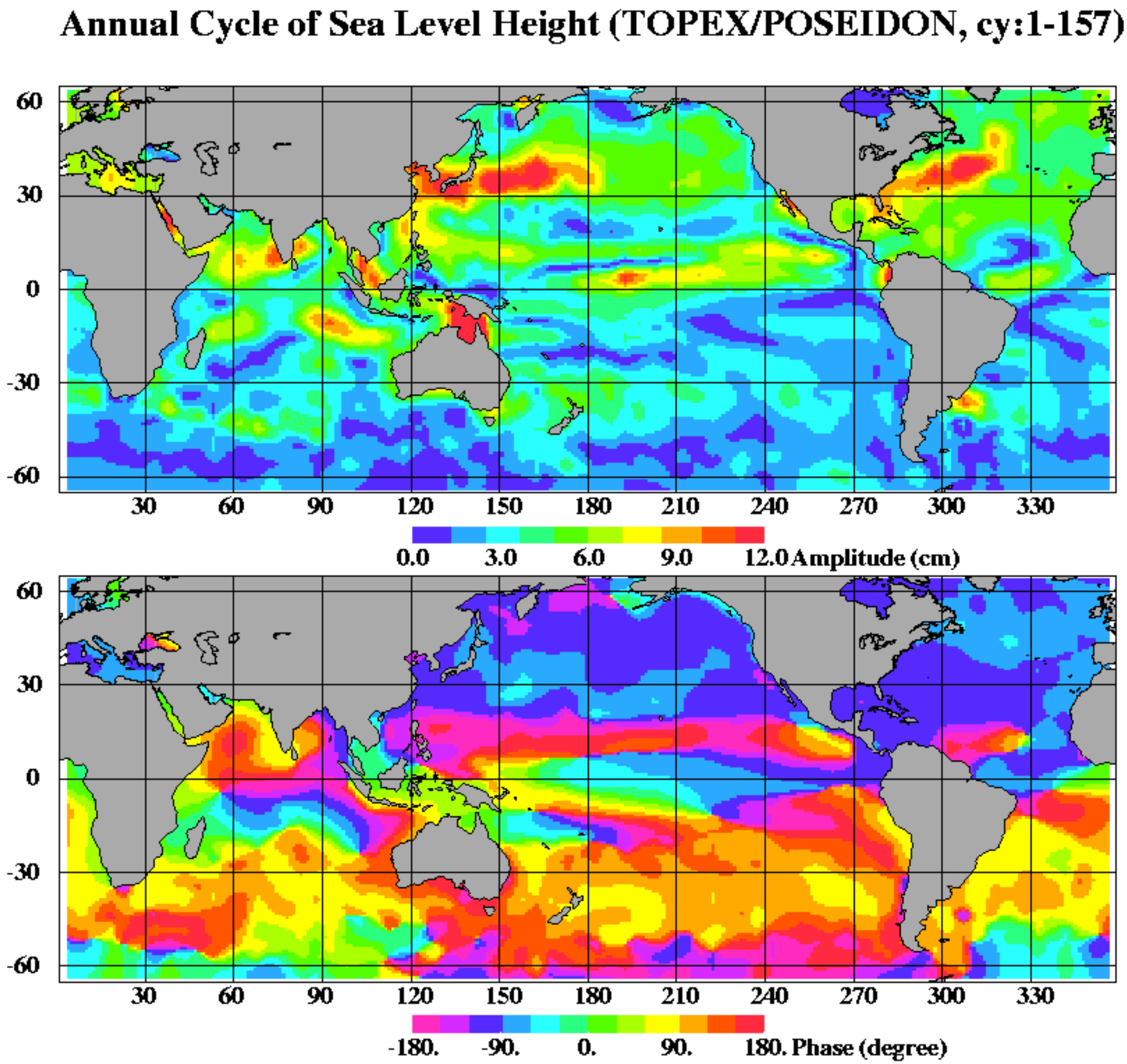
Sea level variability



The up and down of the ocean tides



Source : IMG/LEGI, Grenoble 1995



Annual Cycle of Sea Level Height (TOPEX/POSEIDON, cy:1-157)
60
30
0
-30
-60
30 60 90 120 150 180 210 240 270 300 330
0.0 3.0 6.0 9.0 12.0 Amplitude (cm)
60
30
0
-30
-60
30 60 90 120 150 180 210 240 270 300 330
-180. -90. 0. 90. 180. Phase (degree)

Long Term Sea Level Changes

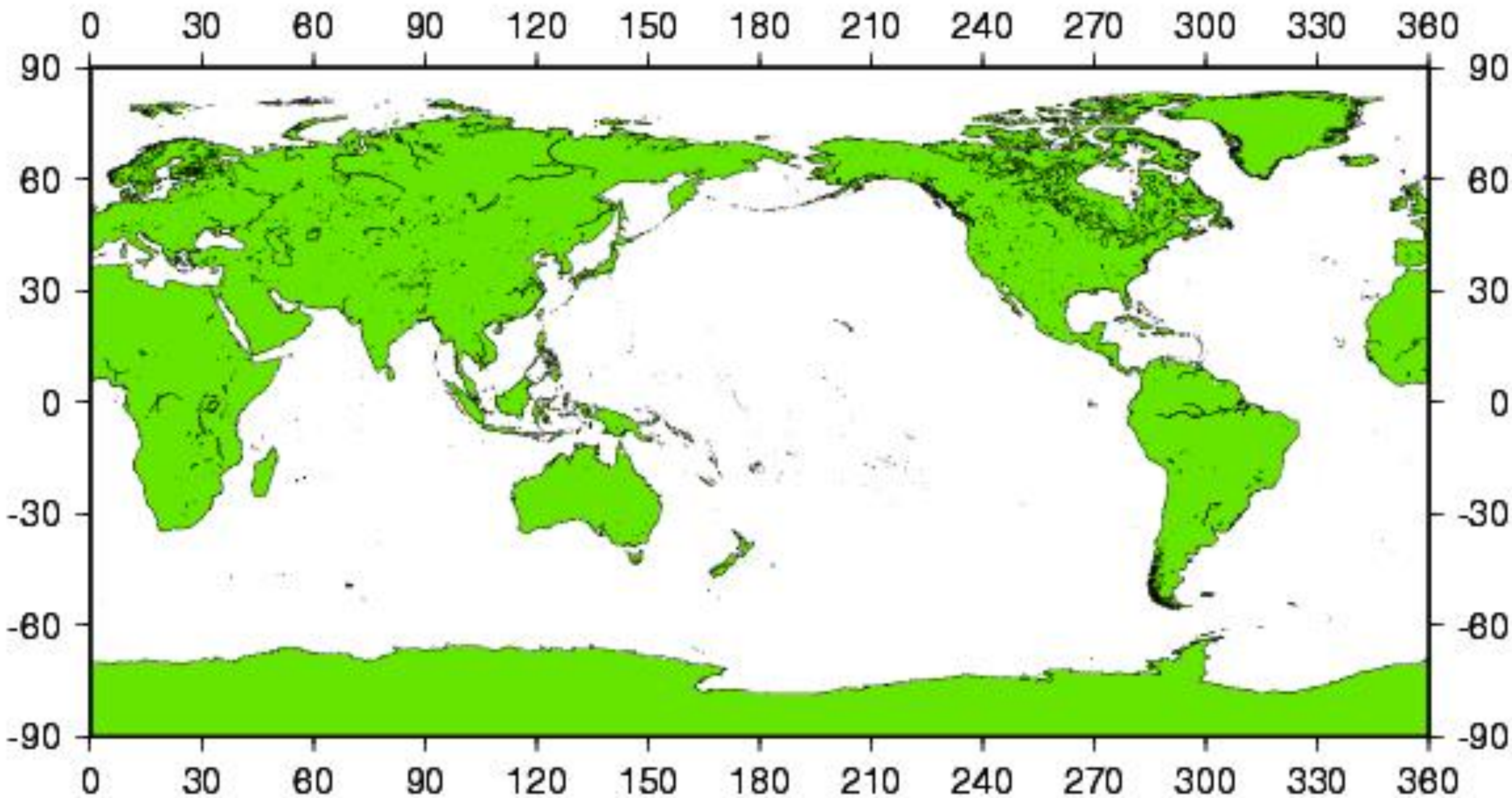
- We know from geologists that sea level has changed over many 1000s of years largely as a result of the exchanges of water between the ocean and ice caps
- So we should not be too surprised if sea level is still changing

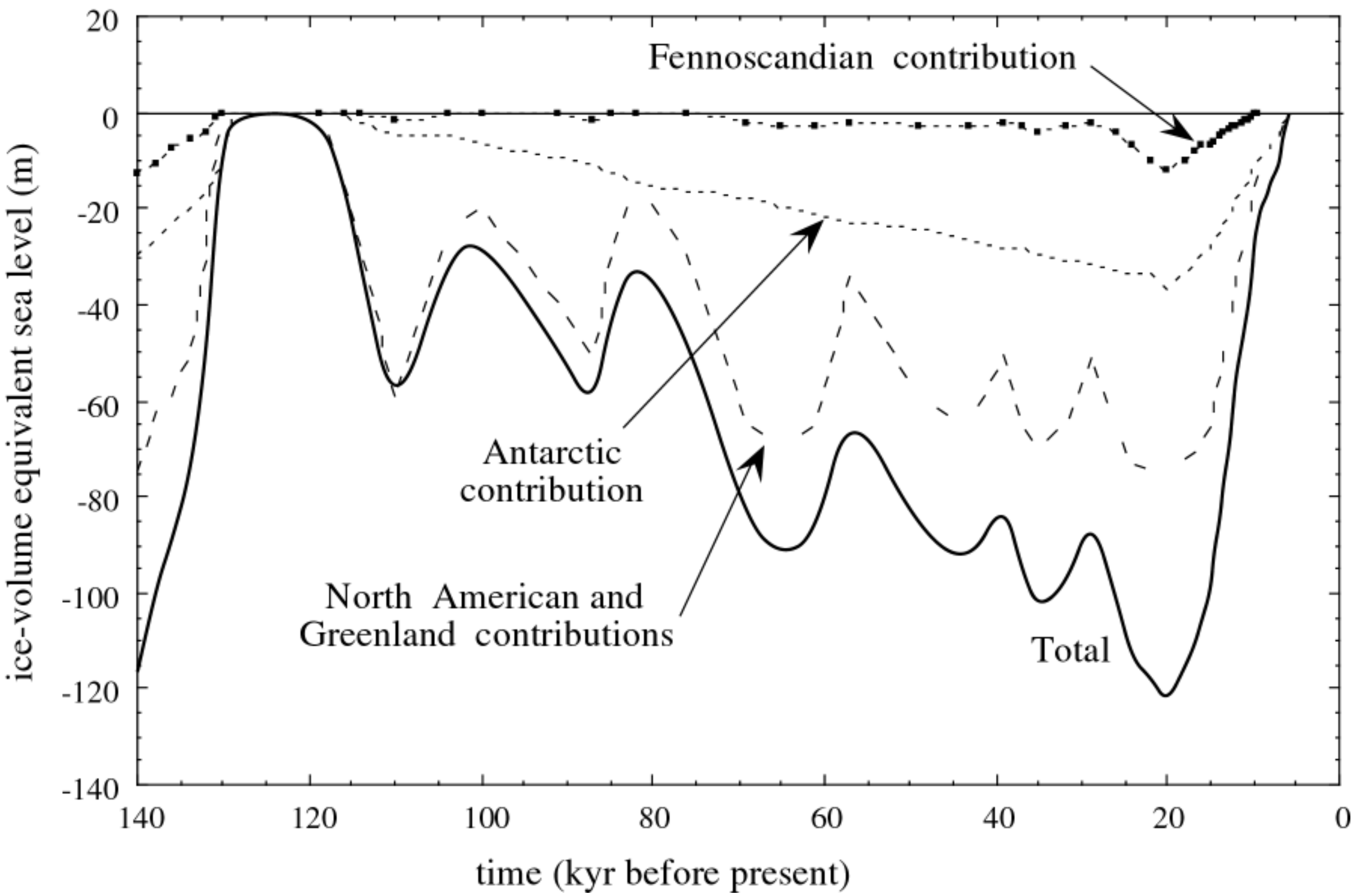
How is water redistributed?

- If water is added to the oceans (from melting glaciers, for example), how is it distributed?
- Small changes
  - Added to present ocean areas, not land. Distribution of ocean described by ***ocean function***.
- Large Changes
  - For the melting of large amounts of ice (Greenland or Antarctica), you have to account for the changes in bathymetry of oceans due to GIA, and also the changes in ocean area as sea level rises onto coastal plains.

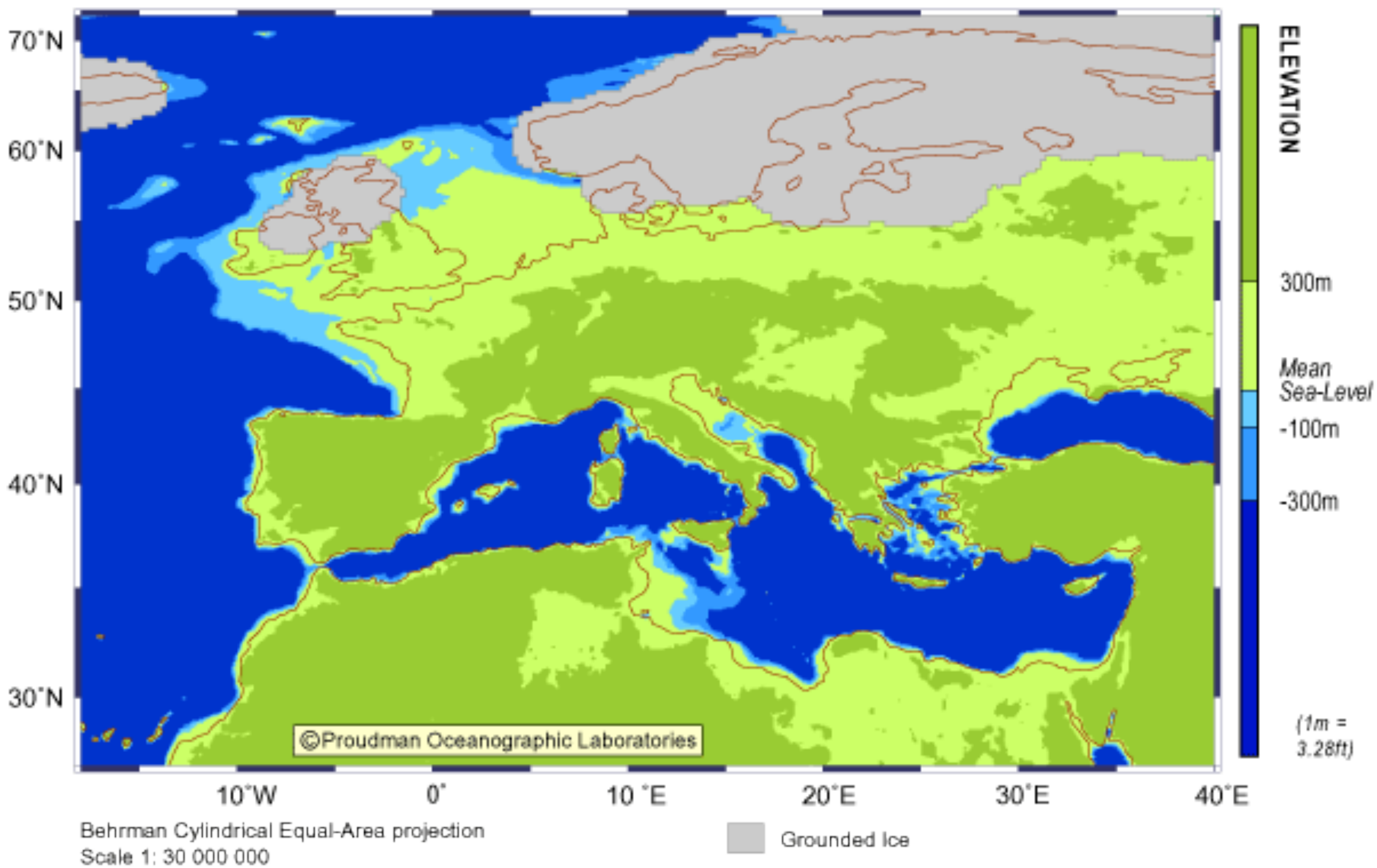
Ocean Function

white = 1; green = 0

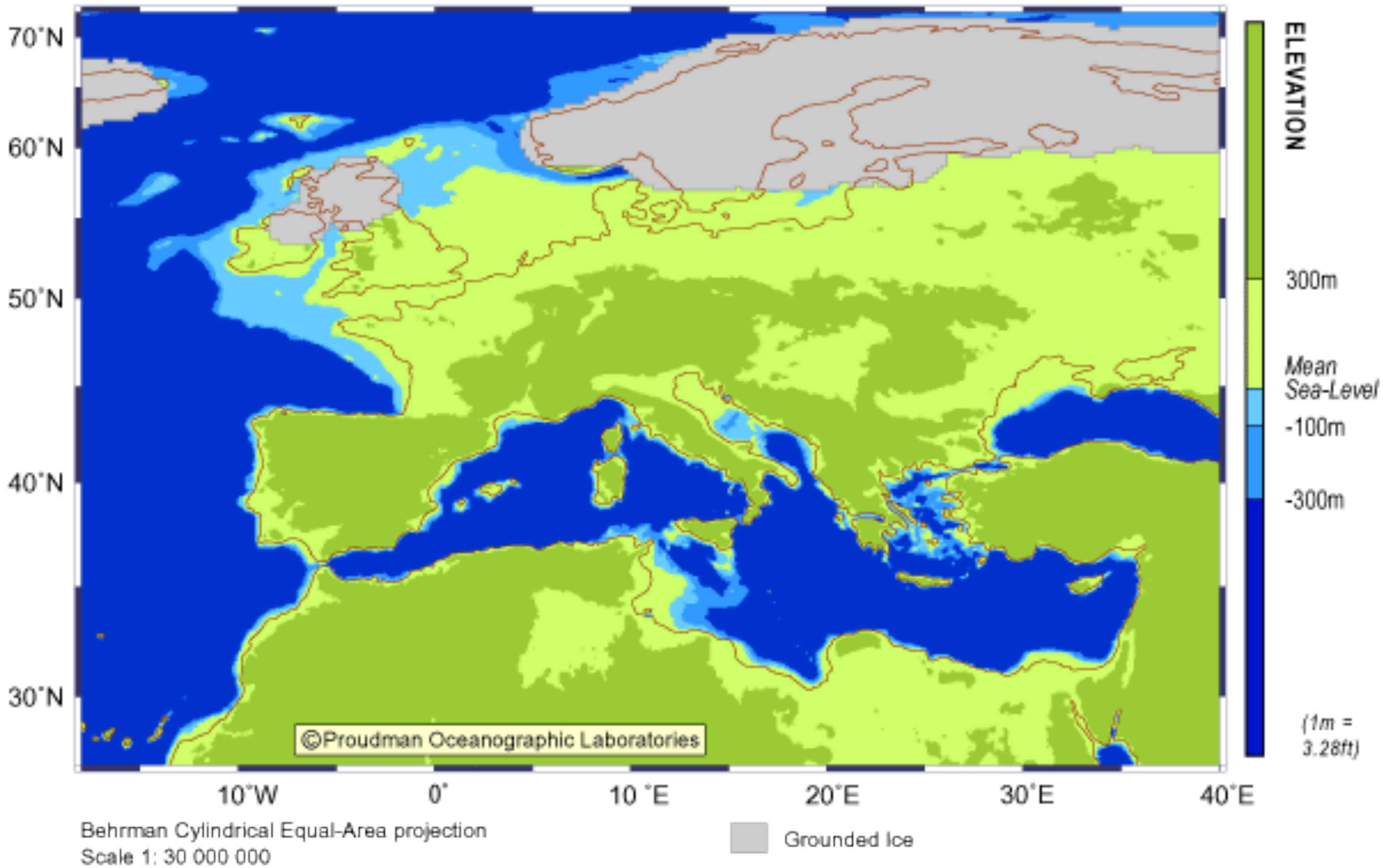




20
0
-20
-40
-60
-80
-100
-120
-140
ice-volume equivalent sea level (m)
140
120
100
80
60
40
20
0
time (kyr before present)
Fennoscandian contribution
Antarctic contribution
North American and Greenland contributions
Total

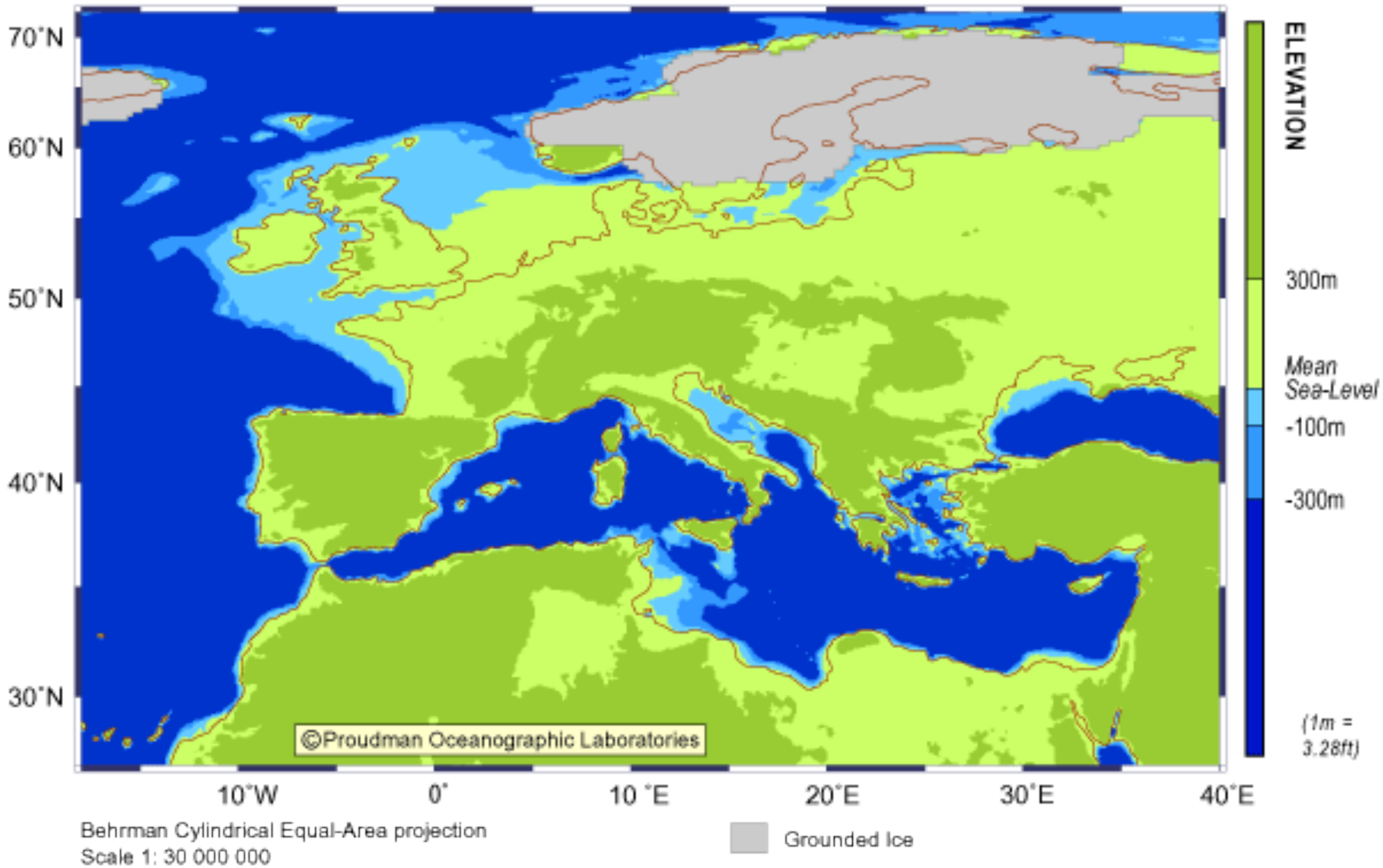

70°N
60°N
50°N
40°N
30°N
10°W
0°
10 °E
20°E
30°E
40°E
ELEVATION
300m
Mean Sea-Level
-100m
-300m
(1m = 3.28ft)
©Proudman Oceanographic Laboratories
Behrman Cylindrical Equal-Area projection
Scale 1: 30 000 000
Grounded Ice

20K BP

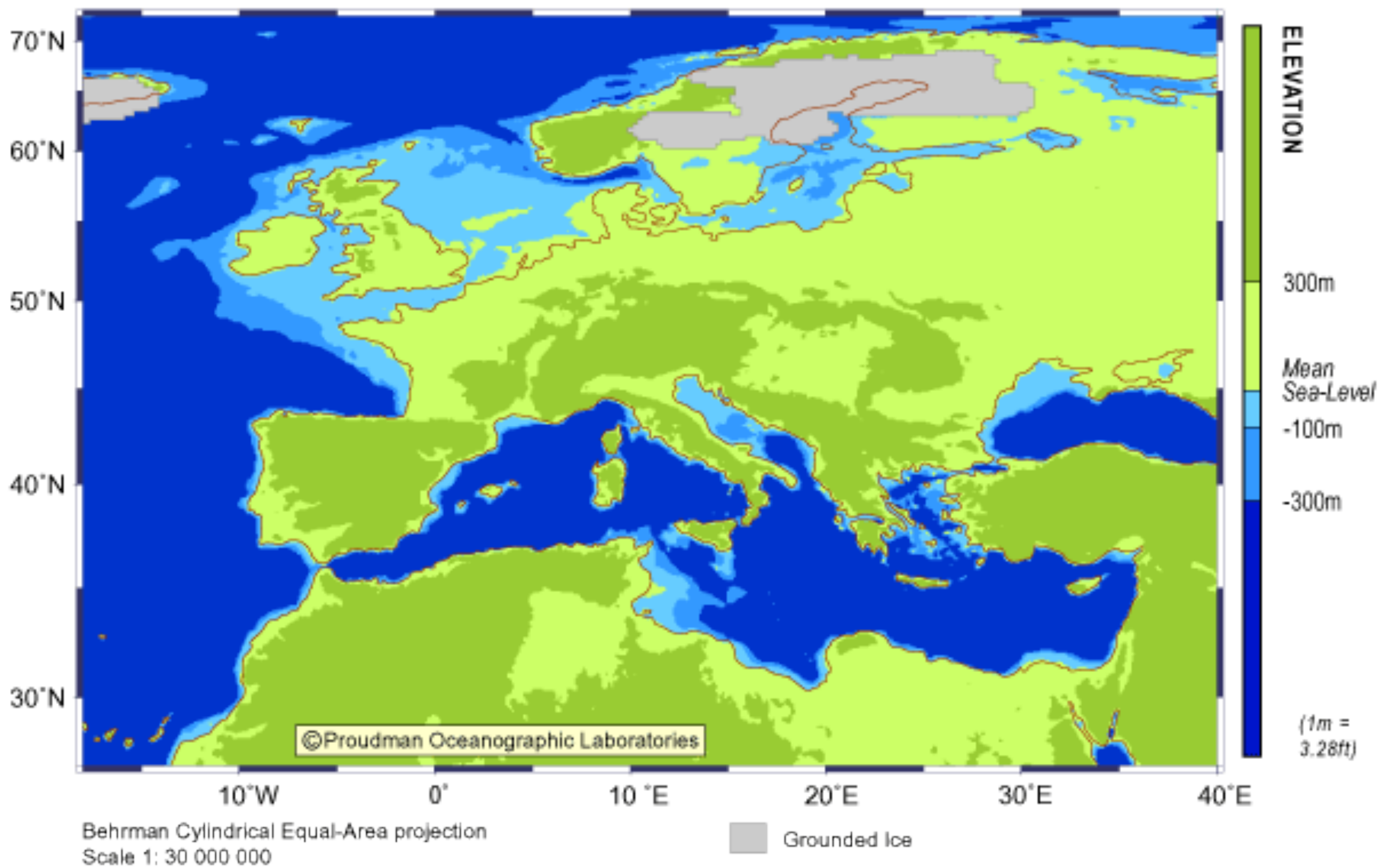


70°N
60°N
50°N
40°N
30°N
10°W
0°
10 °E
20°E
30°E
40°E
ELEVATION
300m
Mean
Sea-Level
-100m
-300m
(1m =
3.28ft)
©Proudman Oceanographic Laboratories
Behrman Cylindrical Equal-Area projection
Scale 1: 30 000 000
Grounded Ice

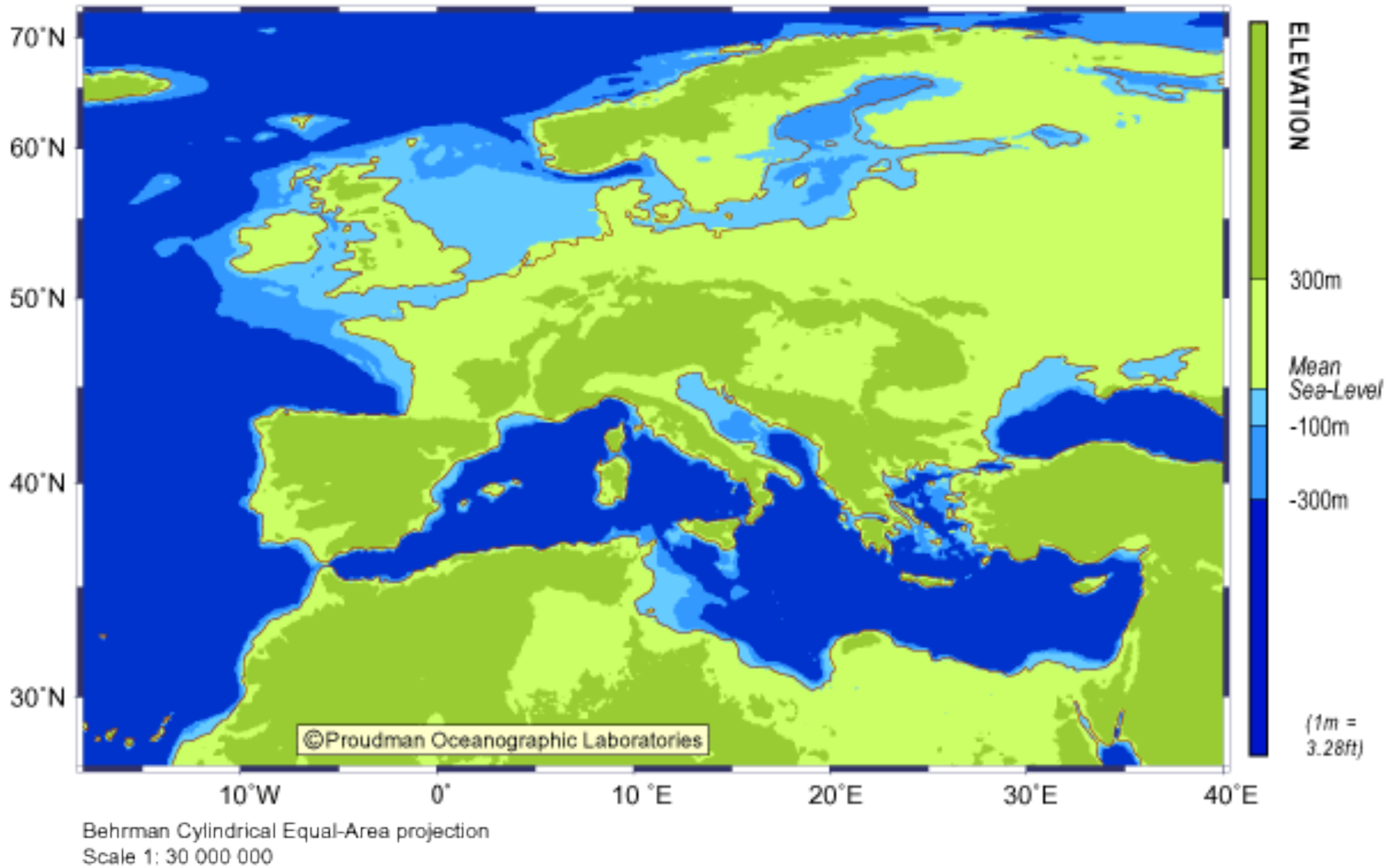
15K BP


70°N
60°N
50°N
40°N
30°N
10°W
0°
10 °E
20°E
30°E
40°E
ELEVATION
300m
Mean Sea-Level
-100m
-300m
(1m = 3.28ft)
©Proudman Oceanographic Laboratories
Behrman Cylindrical Equal-Area projection
Scale 1: 30 000 000
Grounded Ice

12K BP


70°N
60°N
50°N
40°N
30°N
10°W
0°
10 °E
20°E
30°E
40°E
ELEVATION
300m
Mean Sea-Level
-100m
-300m
(1m = 3.28ft)
©Proudman Oceanographic Laboratories
Behrman Cylindrical Equal-Area projection
Scale 1: 30 000 000
Grounded Ice

9K BP


70°N
60°N
50°N
40°N
30°N
10°W
0°
10 °E
20°E
30°E
40°E
ELEVATION
300m
Mean Sea-Level
-100m
-300m
(1m = 3.28ft)
©Proudman Oceanographic Laboratories
Behrman Cylindrical Equal-Area projection
Scale 1: 30 000 000

7K BP

Two Main Problems with the Present 'Global' Sea Level Data Set

- Coverage is not uniform around the globe.
- 'Sea Level' measurements are relative to land level. Land level may be changing, too.

SOLUTION (to #2) ➔ Measure Land Levels using new geodetic techniques such as GPS and Absolute Gravity

Two Main Geodetic Tools for Measuring Land Level Changes

GPS

Absolute Gravity

Questions and Answers

Q. Has global sea level risen during the 20^{th} century ?

A. Yes. By 10-20 cm.

There are many references, see the IPCC Fourth Assessment Report for a review

20th Century Sea Level Rise Estimates

	Region, VLM	Rate ± s.e. (mm/yr)
Gornitz and Lebedeff (1987)	Global, Geological	1.2 ± 0.3
Peltier and Tushingham (1989, 1991)	Global, ICE-3G/M1	2.4 ± 0.9[c]
Trupin and Wahr (1990)	Global, ICE-3G/M1	1.7 ± 0.13
Nakiboglu and Lambeck (1991)	Global decomposition	1.2 ± 0.4
Shennan and Woodworth (1992)	NW Europe, Geological	1.0 ± 0.15
Gornitz (1995)[d]	NA E Coast, Geological	1.5 ± 0.7[c]
Mitrovica and Davis (1995), Davis and Mitrovica (1996)	Far field, PGR Model	1.4 ± 0.4[c]
Davis and Mitrovica (1996)	NA E Coast, PGR Model	1.5 ± 0.3[c]
Peltier (1996)	NA E Coast, ICE-4G/M2	1.9 ± 0.6[c]
Peltier and Jiang (1997)	NA E Coast, Geological	2.0 ± 0.6[c]
Peltier and Jiang (1997)	Global, ICE-4G/M2	1.8 ± 0.6[c]
Douglas (1997)[d]	Global ICE-3G/M1	1.8 ± 0.1
Lambeck et al. (1998)	Fennoscandia, PGR Model	1.1 ± 0.2
Woodworth et al. (1999)	UK & N Sea, Geological	1.0 ± 0.2

N.B. All these analyses use the same PSMSL data set

Questions and Answers

Q. Do we understand why it has risen?

A. **Yes.** (Or at least 'more or less')

Why has sea level risen?

Main driver has been the

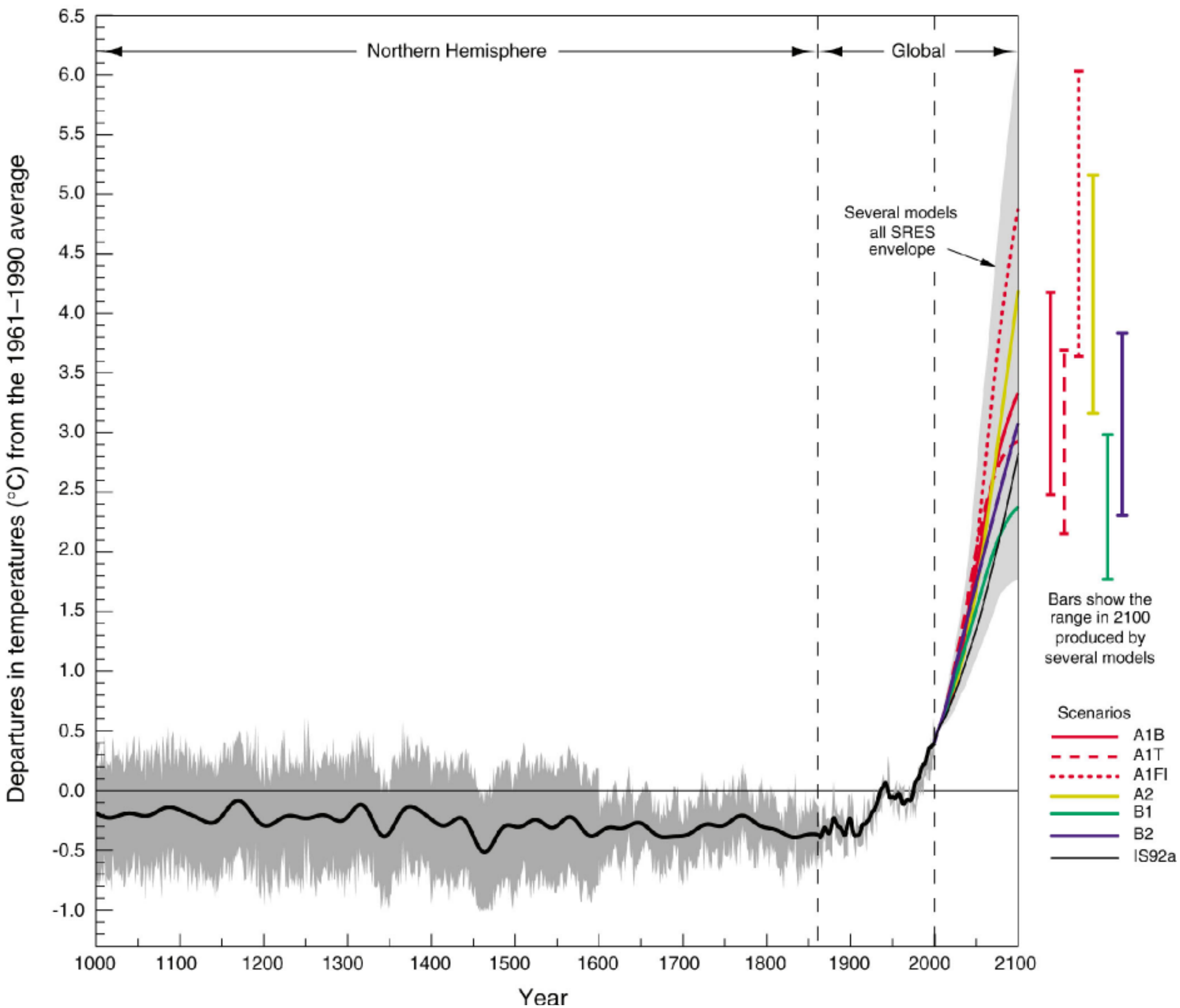
0.6 ºC global temperature change during the past century

but there have been many contributors to the sea level change.

See IPCC 4AR for a review.

Variations of the Earth's surface temperature: 1000 to 2100.

1000 to 1861, N.Hemisphere, proxy data; 1861 to 2000 Global, Instrumental; 2000 to 2100, SRES projections



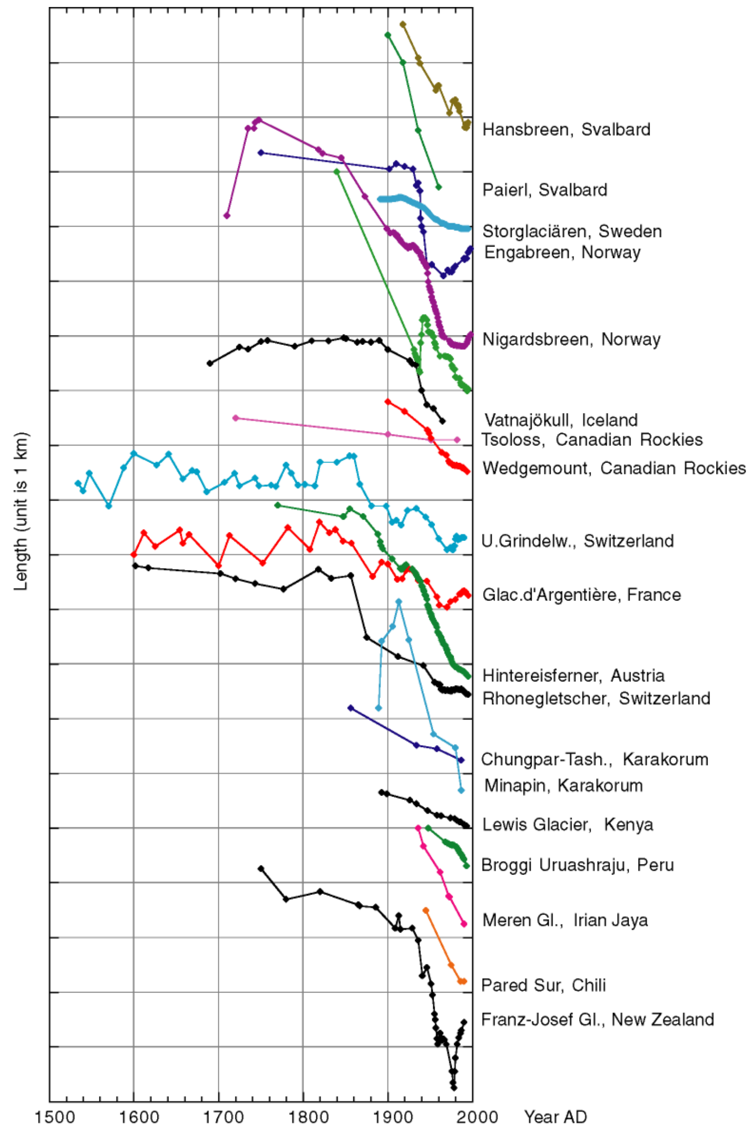
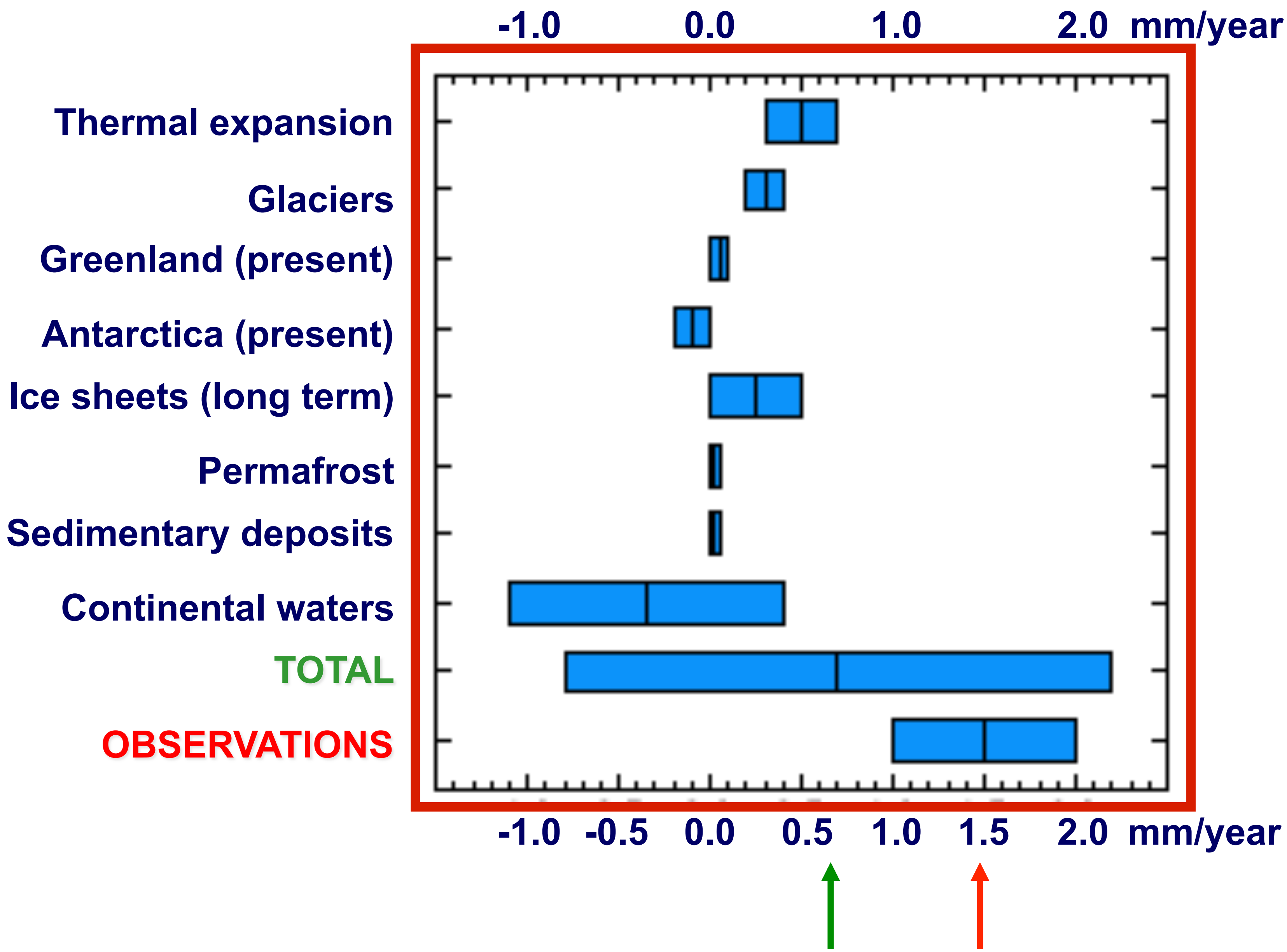


Figure 2.18: A collection of 20 glacier length records from different parts of the world. Curves have been translated along the vertical axis to make them fit in one frame. [Data from the World Glacier Monitoring Service (http://www.geo.unizh.ch/wgms/) with some additions from various unpublished sources].

Melting Low Latitude Glaciers (Alaska etc.)

20th Century Sea Level Rise - IPCC 2001



Progress in Understanding Budget

- IPCC 2001 underestimated several factors
  - Steric (thermal expansion)
  - Contribution from melting glaciers.
- Recent work by Steve Nerem (U. of Colorado) suggests that sea level budget closes fairly well, and consistent with present altimeter rate of >3 mm/yr.
- Chao et al. (2008) estimated water storage in dams and concluded that sea level rate averaged 2.5 mm/yr post-WW2, partially masked by impoundment of water in reservoirs.

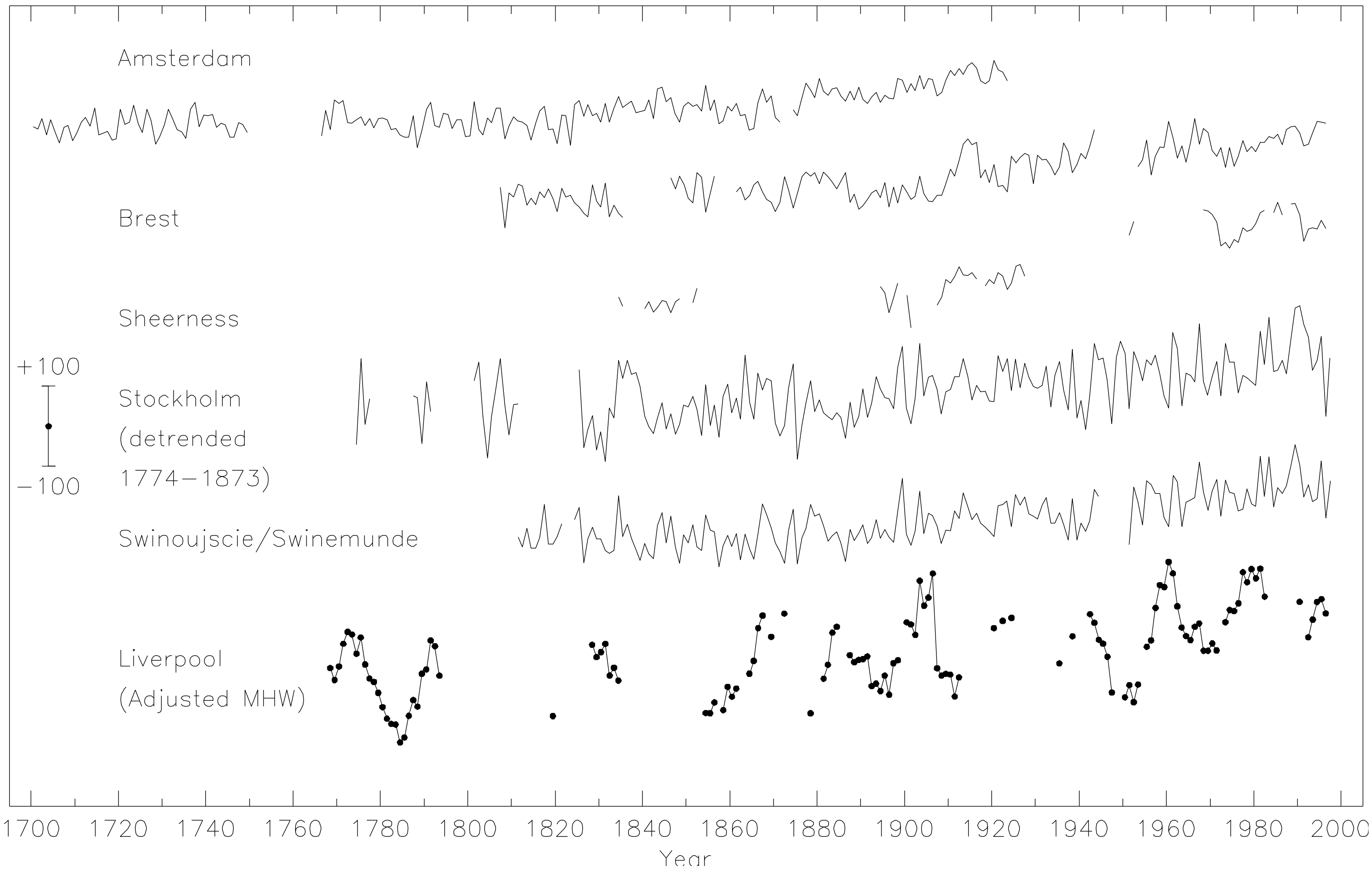
Questions and Answers

Q. Is the rate of rise increasing ?

A.Yes. On basis of study of long records spanning 18th to 20th centuries.

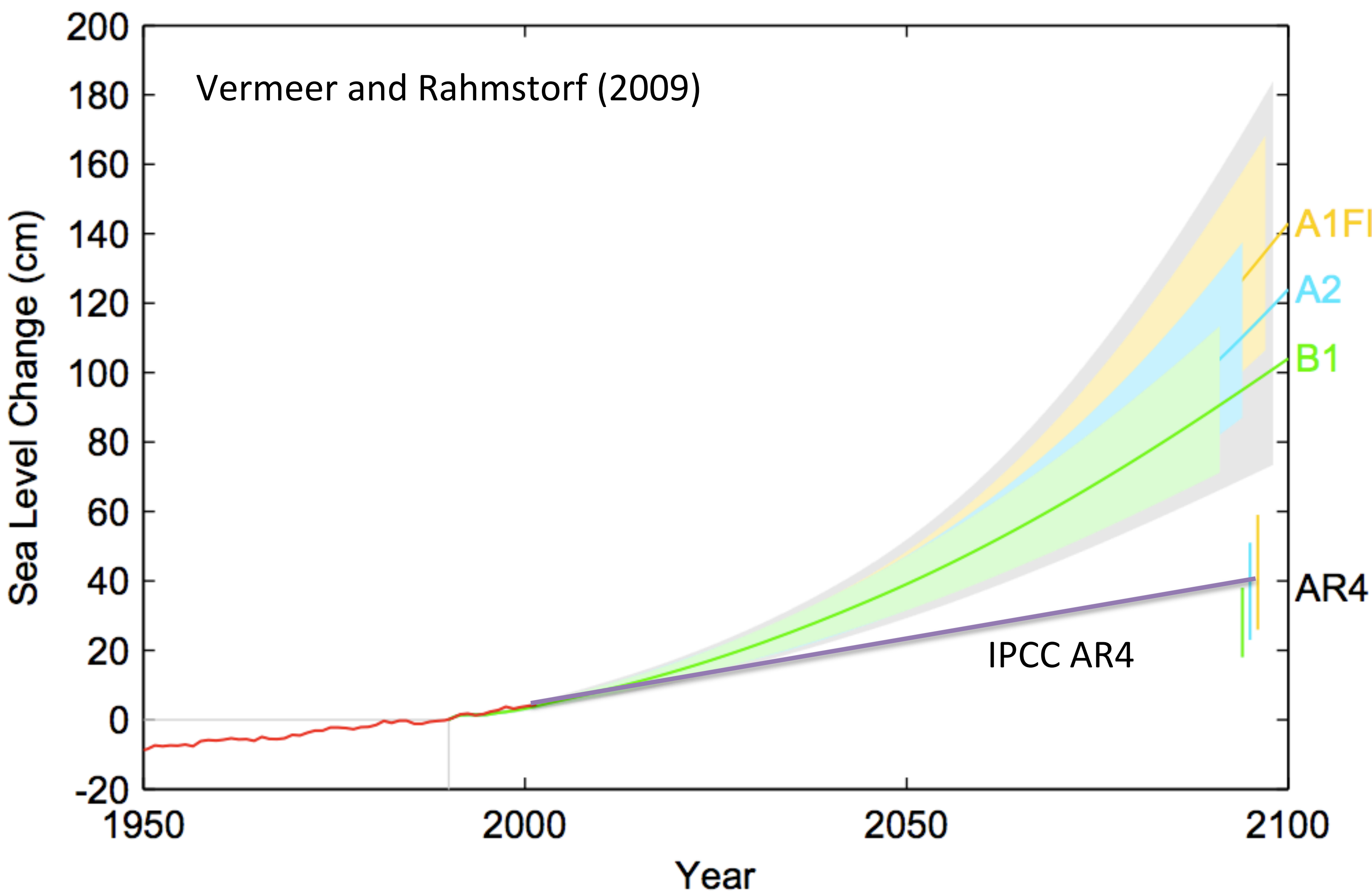
A. **Not clear.** On basis of 20th century tide gauge data alone.

A.Yes. On basis of altimeter and tide gauge from the 1990s.

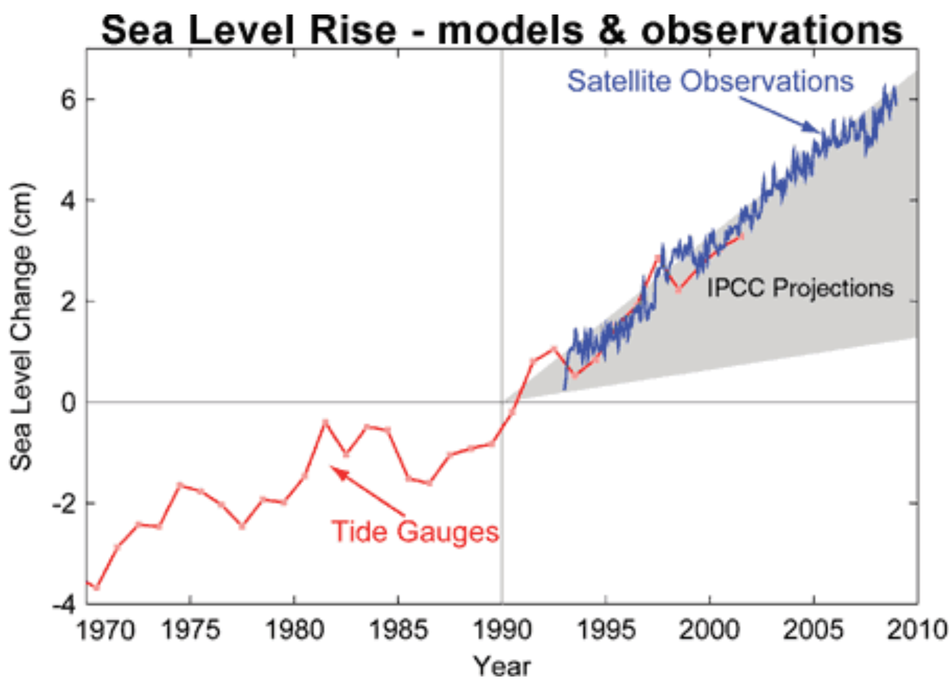


Sea level change contains an acceleration of sea level rise from the 19th to the 20th centuries probably due to climate change

Predicted Global Average Sea Level



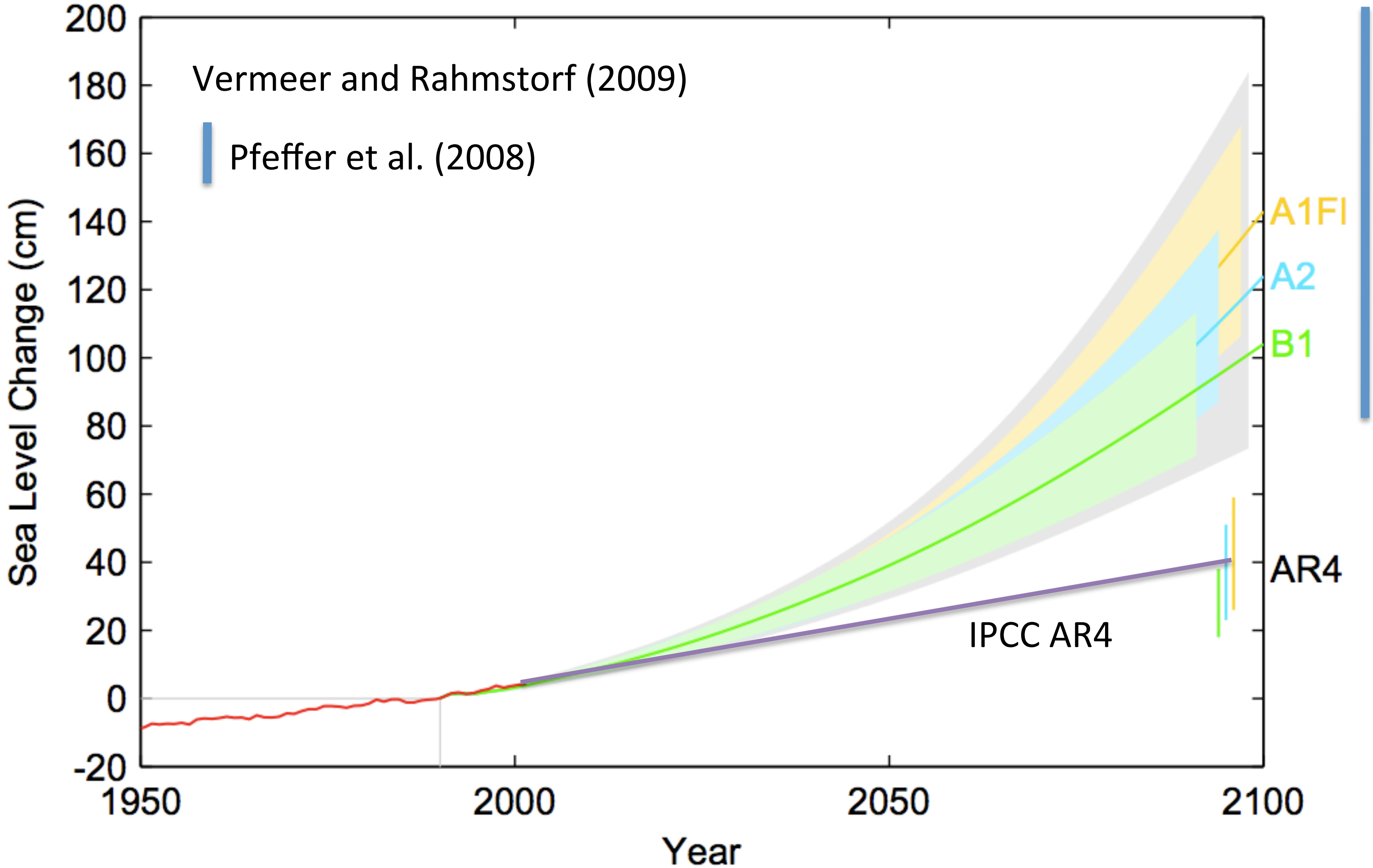
IPCC AR4 Underestimates Rise



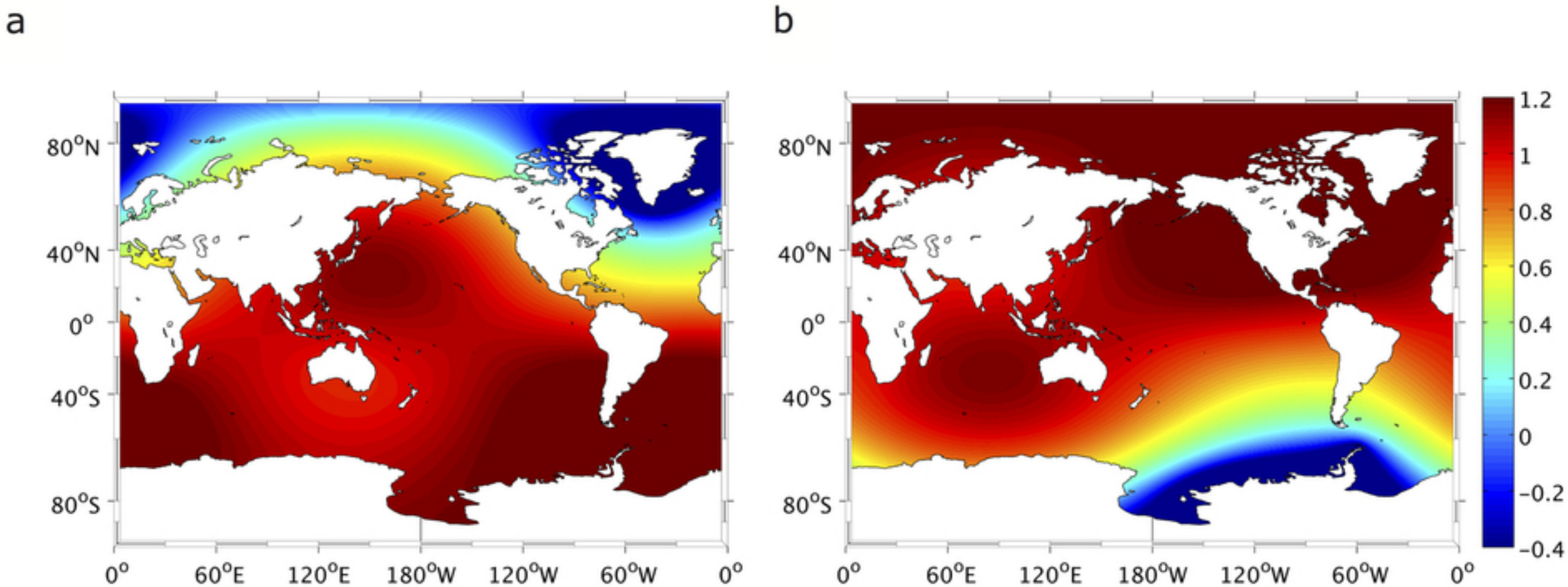
Allison et al. (2009)

- Present observed rate of sea level rise is at the upper envelope of IPCC predictions.
- Why?
  - IPCC AR4 assumed no input to sea level from glacier ice.
  - Because the uncertainty in the future response of glaciers was large
- IPCC AR4 estimates are almost certainly a lower bound on future sea level rise.

Predicted Global Average Sea Level

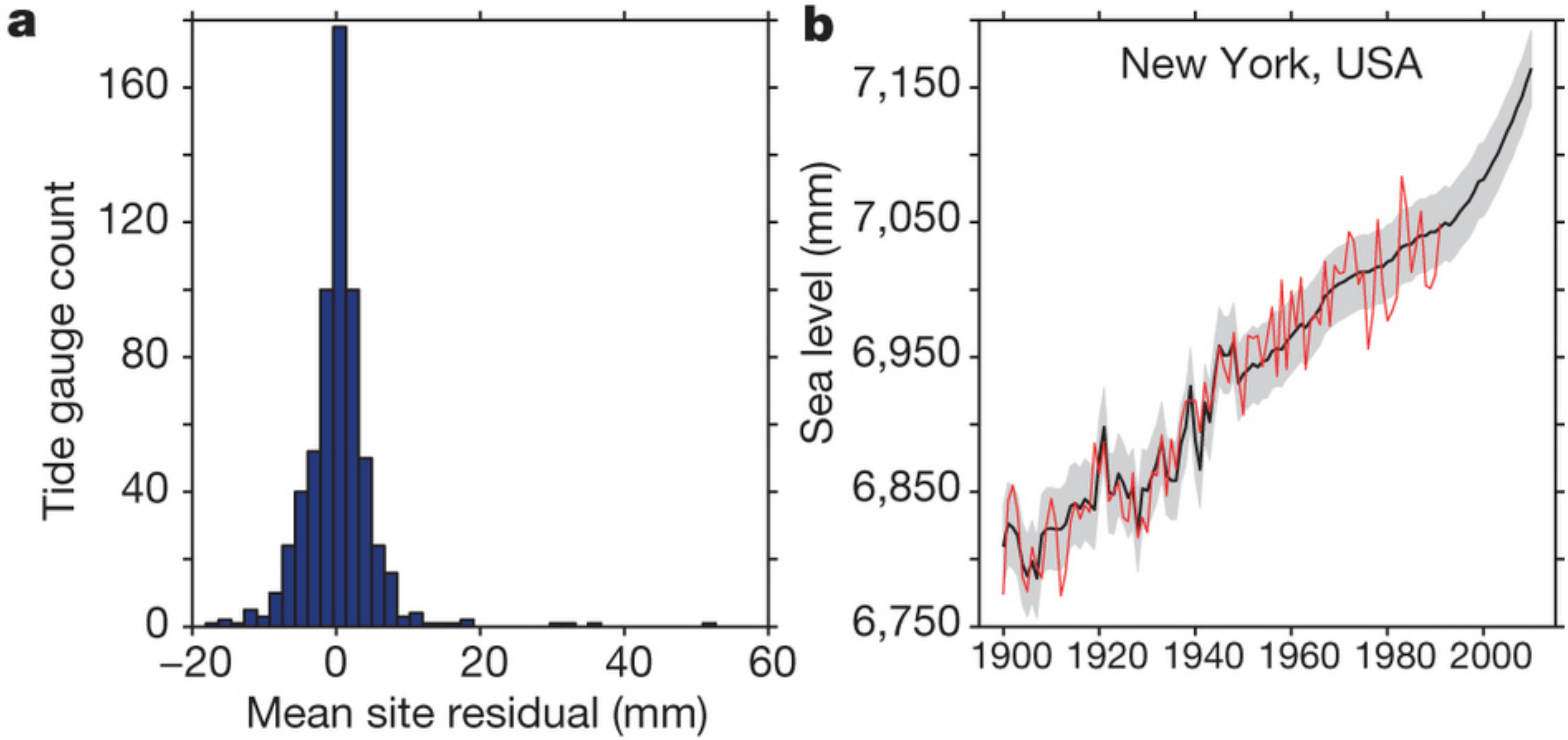


Hay et al. (2015) Reconstruction



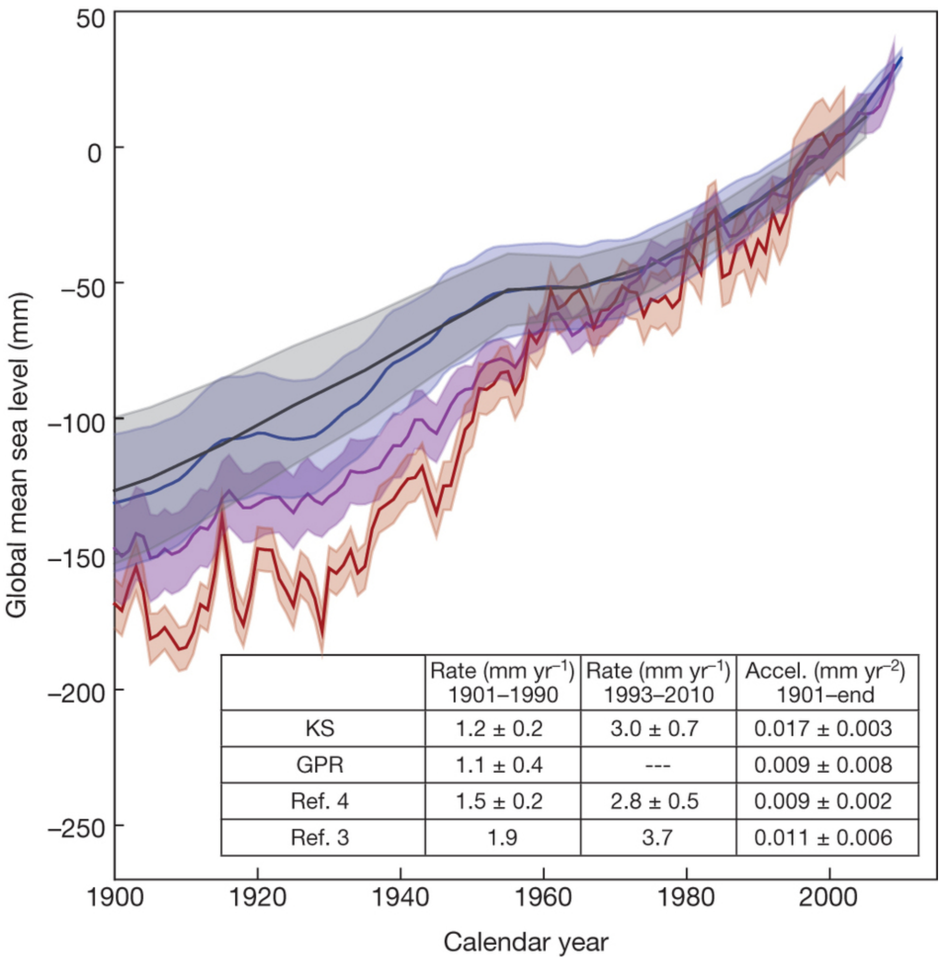
- Reconstruct 20th century sea level change while attributing mass changes
- Inverse problem including gravitationally self-consistent "fingerprints"

Example Data Fits

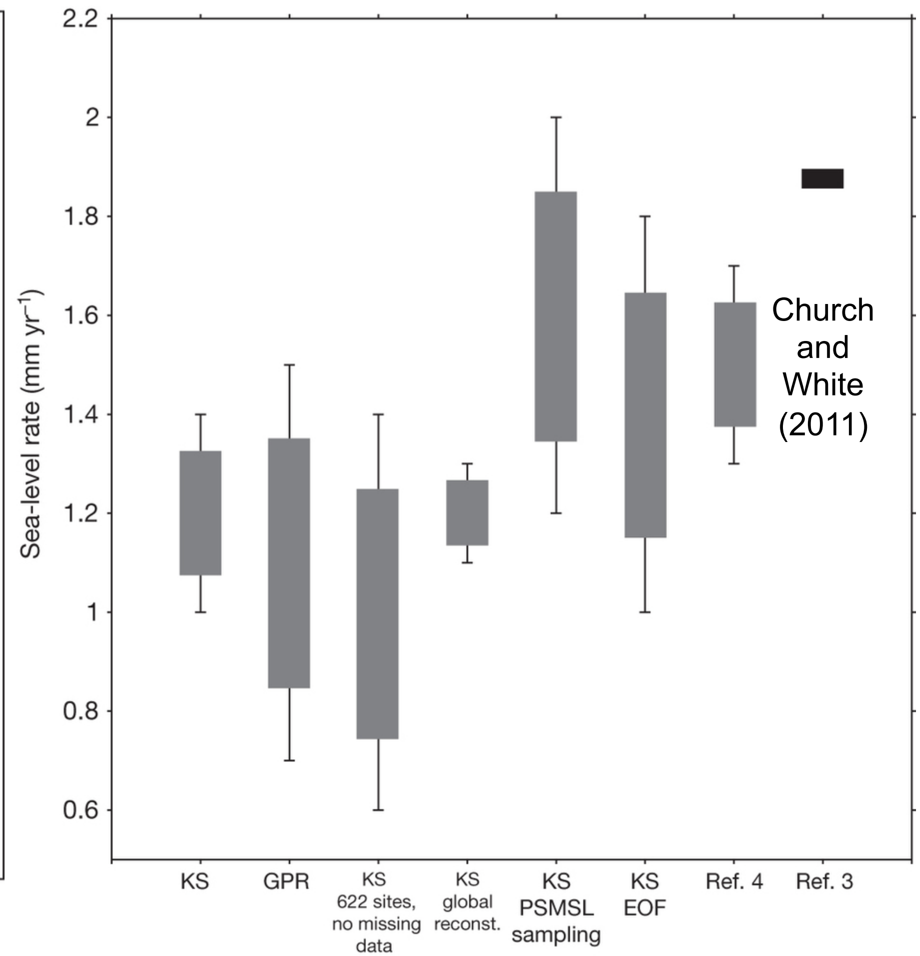


Hay et al. (2015, Nature)

Results



	Rate (mm yr^{-1}) 1901–1990	Rate (mm yr^{-1}) 1993–2010	Accel. (mm yr^{-2}) 1901–end
KS	1.2 ± 0.2	3.0 ± 0.7	0.017 ± 0.003
GPR	1.1 ± 0.4	---	0.009 ± 0.008
Ref. 4	1.5 ± 0.2	2.8 ± 0.5	0.009 ± 0.002
Ref. 3	1.9	3.7	0.011 ± 0.006



Hay et al. (2015, Nature)

Questions and Answers

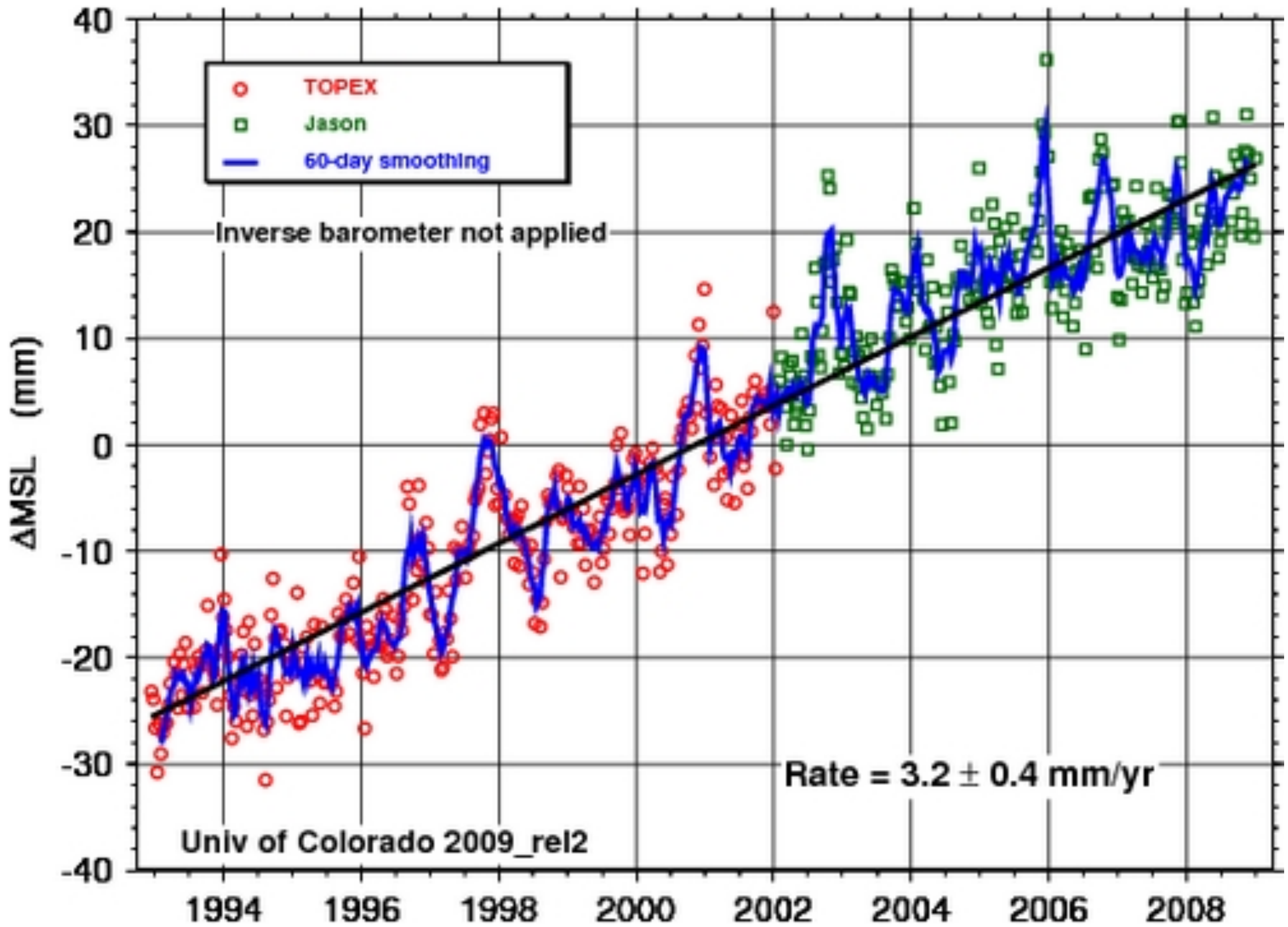
Acceleration in the1990s?

- Look at altimetry
- Look at tide gauge records.
- Look at IPCC-type models.

Answer:

- Yes

Altimeter Sea Level Change



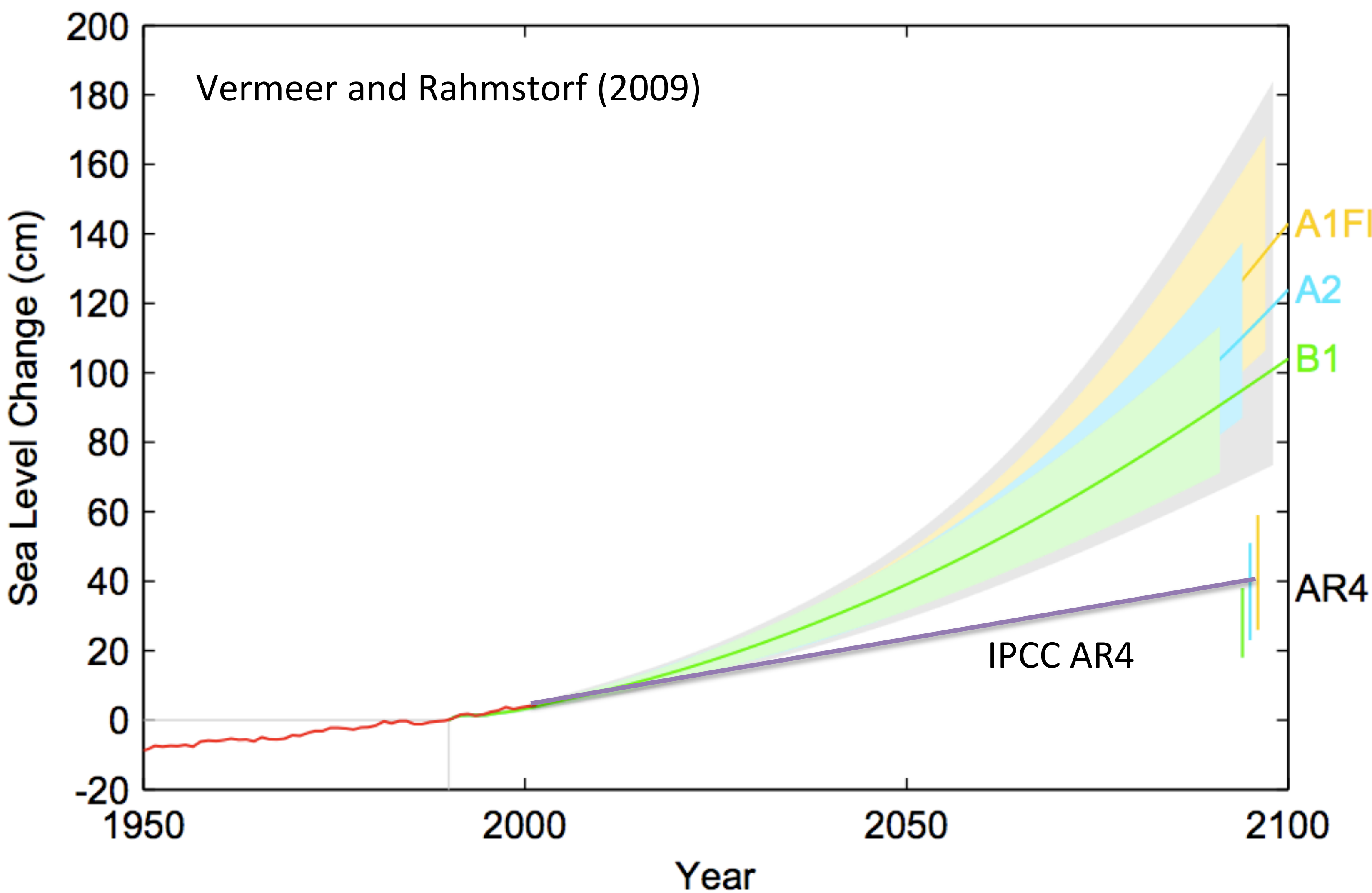
http://sealevel.colorado.edu

Questions and answers

Q. How much might sea level rise in the 21st century?

A. 9-88 cm with central value of 48 cm based on 35 emission scenarios and 7 AOGCMs (IPCC Third Report).

Predicted Global Average Sea Level



Questions and Answers

Q. How important will the 21st century changes be?

A. When MSL (or water depth) changes, and when also there are coupled changes in regional meteorology, there will be changes in storm surges, tides, waves and extreme water levels.

It is important to keep in mind that these rising Sea Levels sooner or later lead to changes in Extreme Levels and often to local flooding. (This is not only a ‘Scientific’ exercise.)

Floods in the Irish Sea 2002

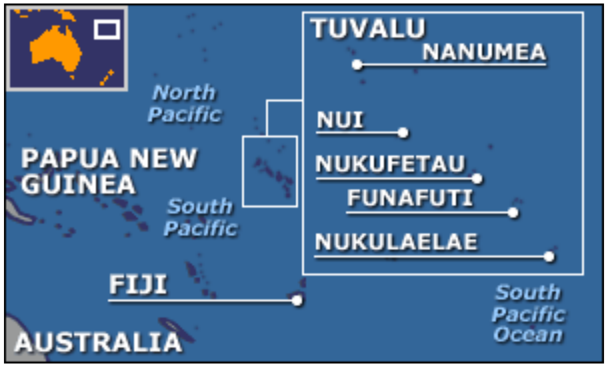
Douglas

Ramsey

"the worst in living memory"

Many £M's damage in few hours

Tuvalu Floods 2002



Typical coral island

Poor infrastructure

Erosion

Plant damage

New Orleans 2005

New Orleans 2005