Understanding the Potential Impact of Climate Change: The Example of Sea Level Change

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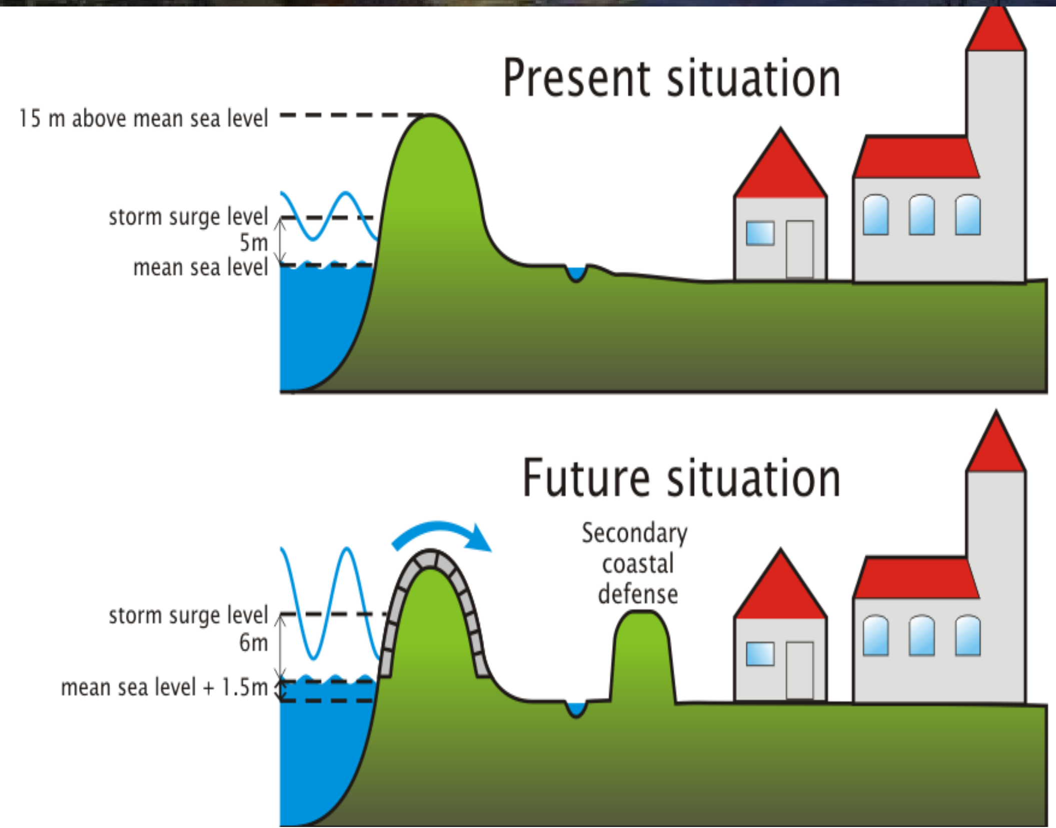
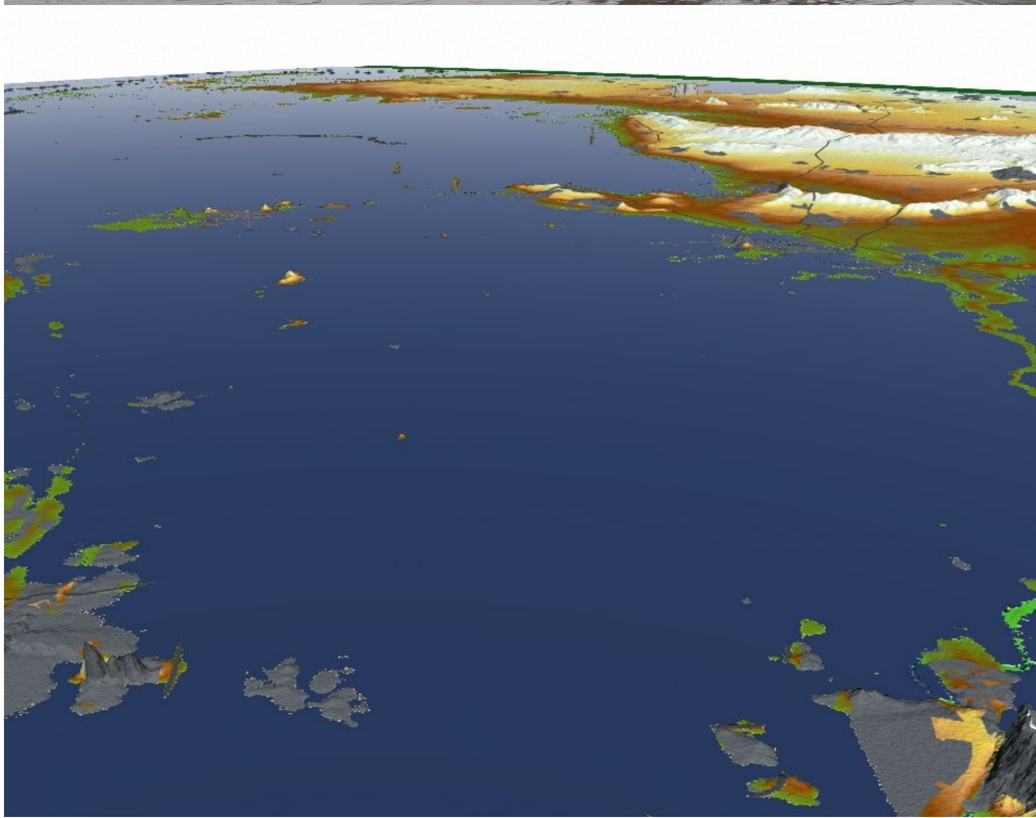
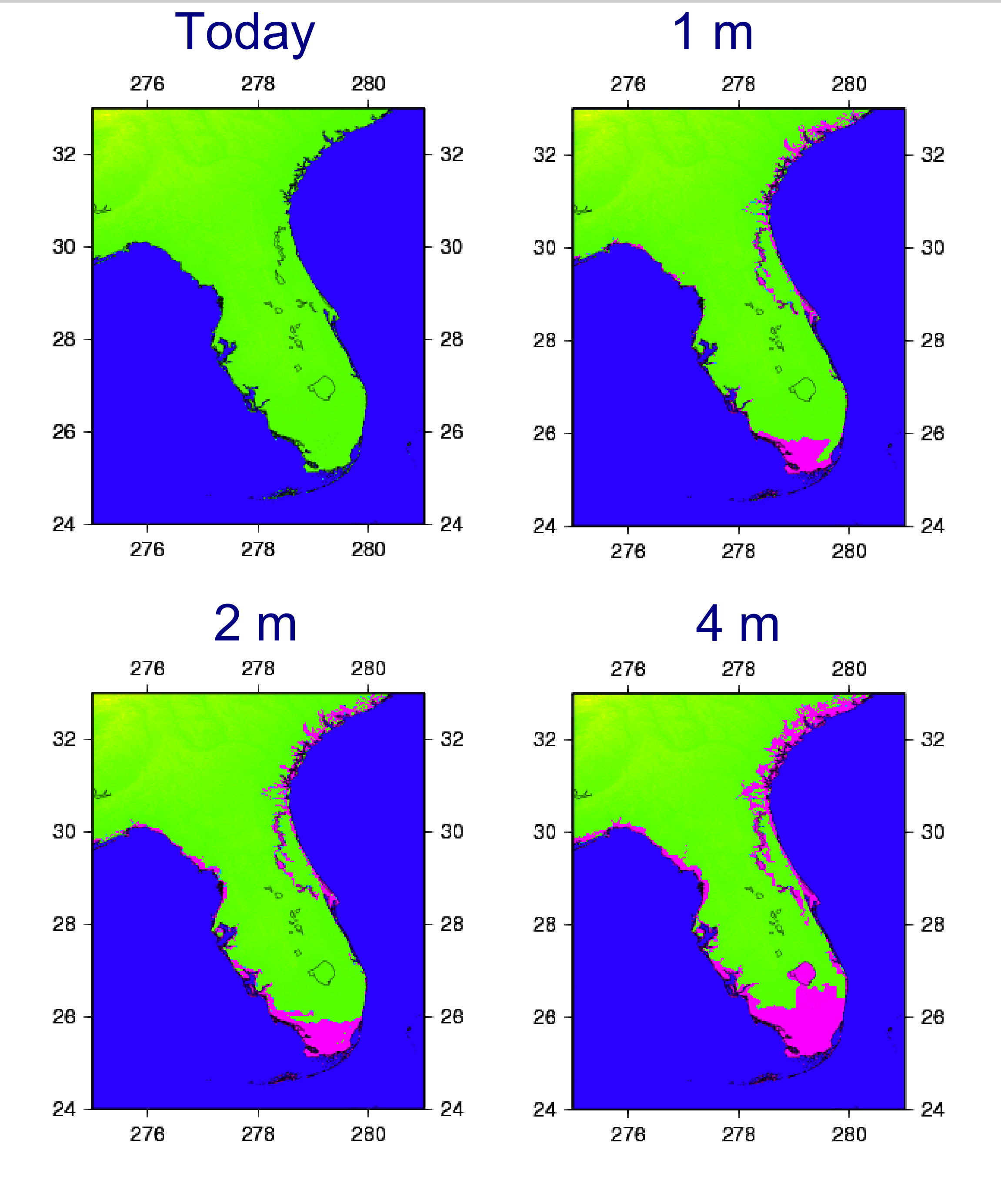
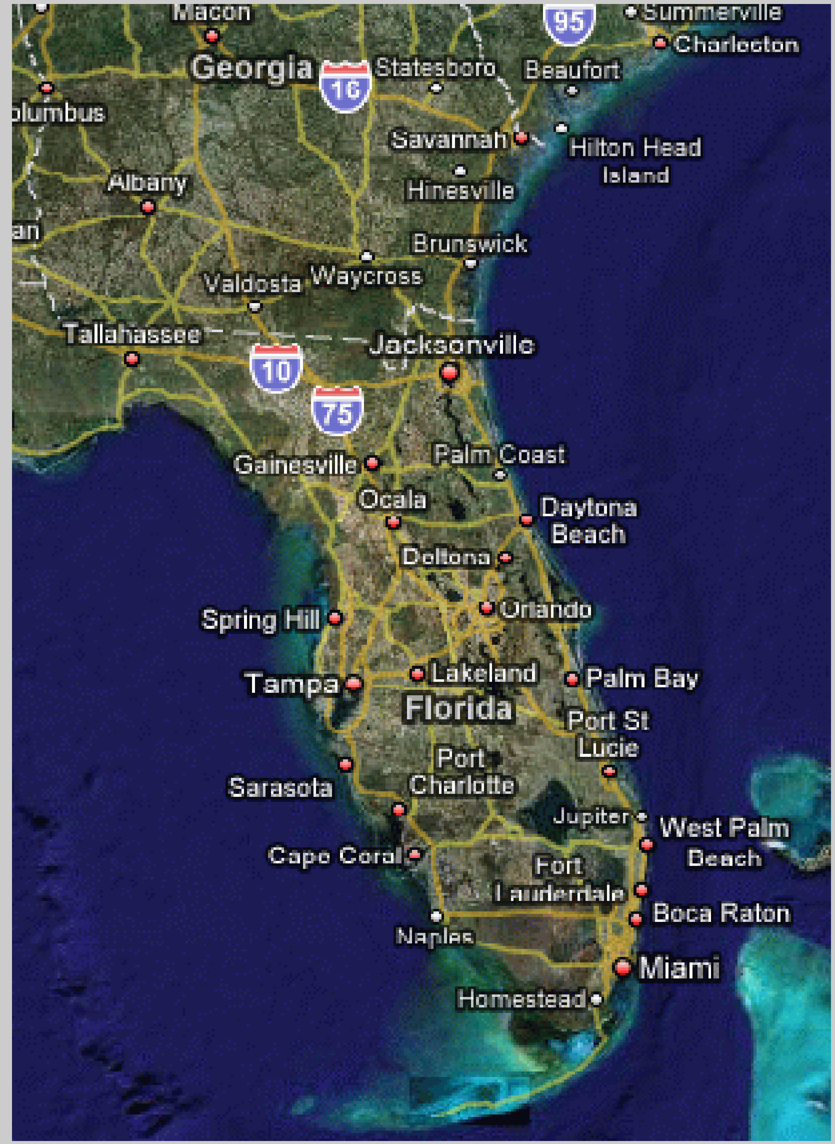
GONDOLE


Present situation
15 m above mean sea level
storm surge level
5m
mean sea level
Future situation
Secondary
coastal
defense
storm surge level
6m
mean sea level + 1.5m

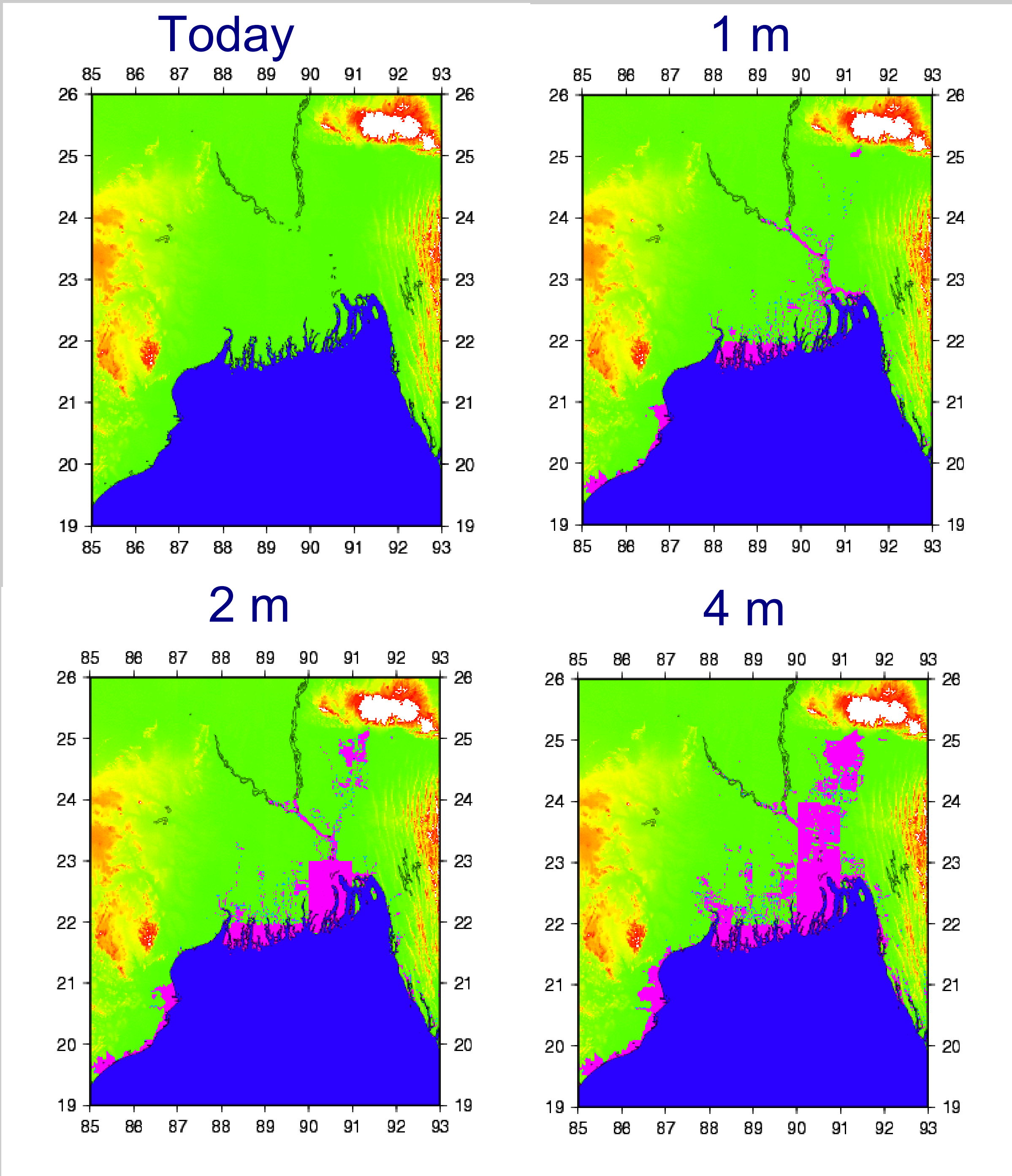


Potential impact: Example Florida



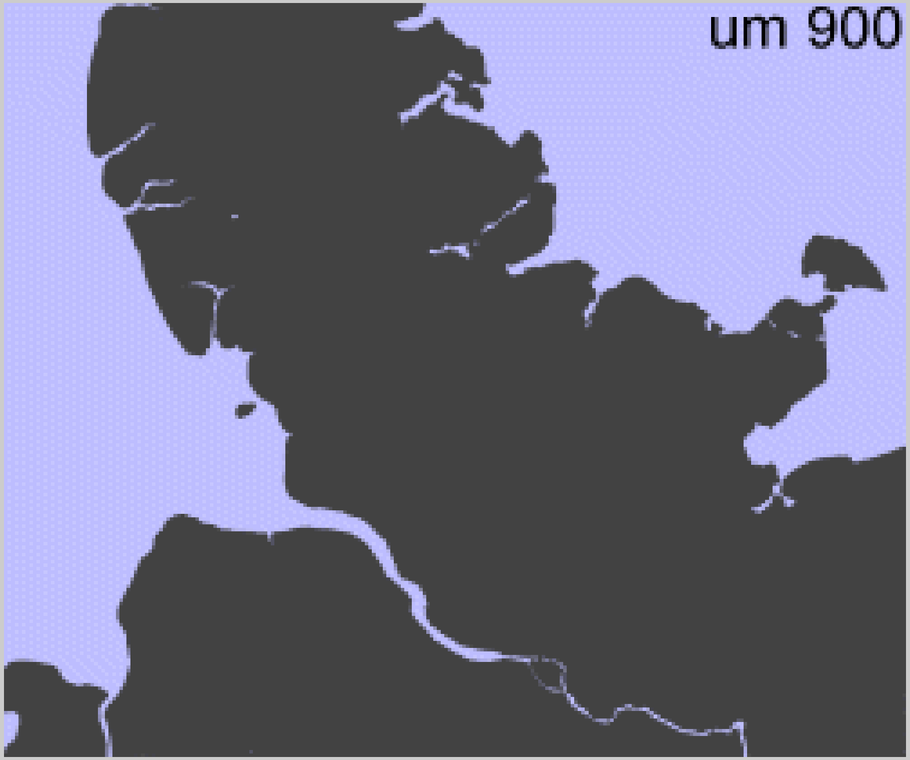


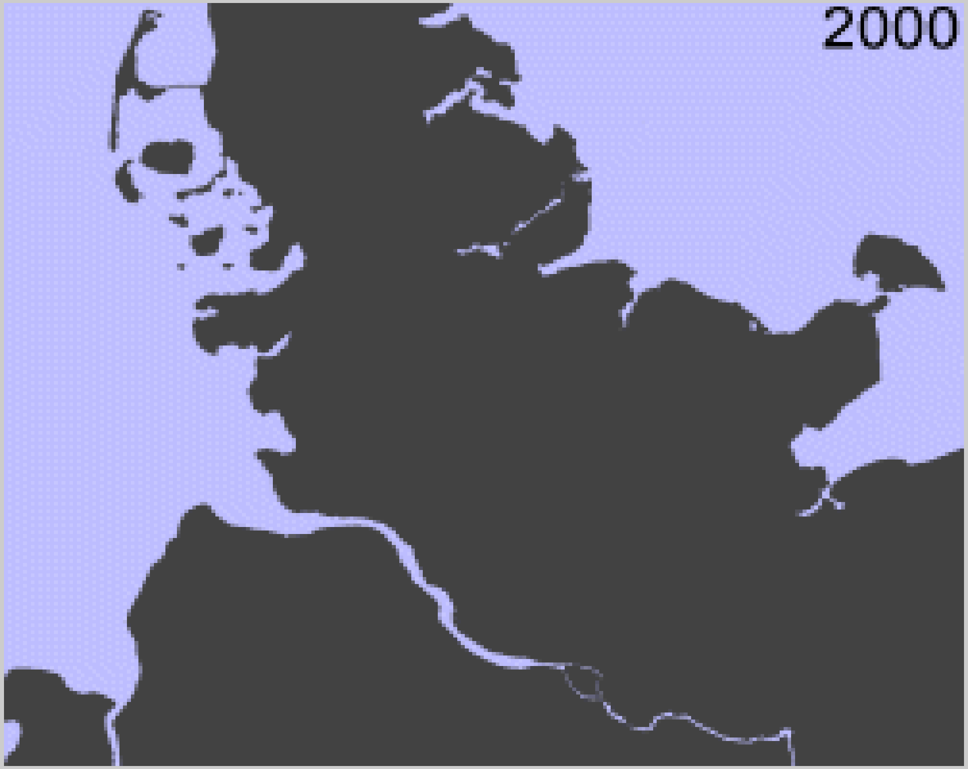
Potential impact: Example Bangladesh



Observed Impacts on Coast Line

Long-term changes
Example: Danish Coast





Observed Impacts on Coast Line

Instantaneous Impacts:
Example:
December 26, 2004 Tsunami
Lampuuk, northwest Sumatra

Observed Impacts on Coast Line

Instantaneous Impacts:
Example:
December 26, 2004 Tsunami
Gleebruk Village


Observed Impacts on Coast Line

Instantaneous Impacts:

Example:

December 26, 2004 Tsunami

Gleebruk Village

Understanding the Potential Impact of Climate Change: Example of Sea Level Change

My focus: Understanding slow sea level changes, their relation to climate change, and their impacts:

- Comments on past sea level changes (IPCC AR4)
- Basic terms
- Local sea level equation (illustrating the complexity)
- Observation-based approximation (simplification)
- Understanding past sea level changes: the example of the Dutch coast
- Plausible Forcing scenarios and range of predictions
- Uncertainties (main contributions)
- How to address the uncertainties in decision making?

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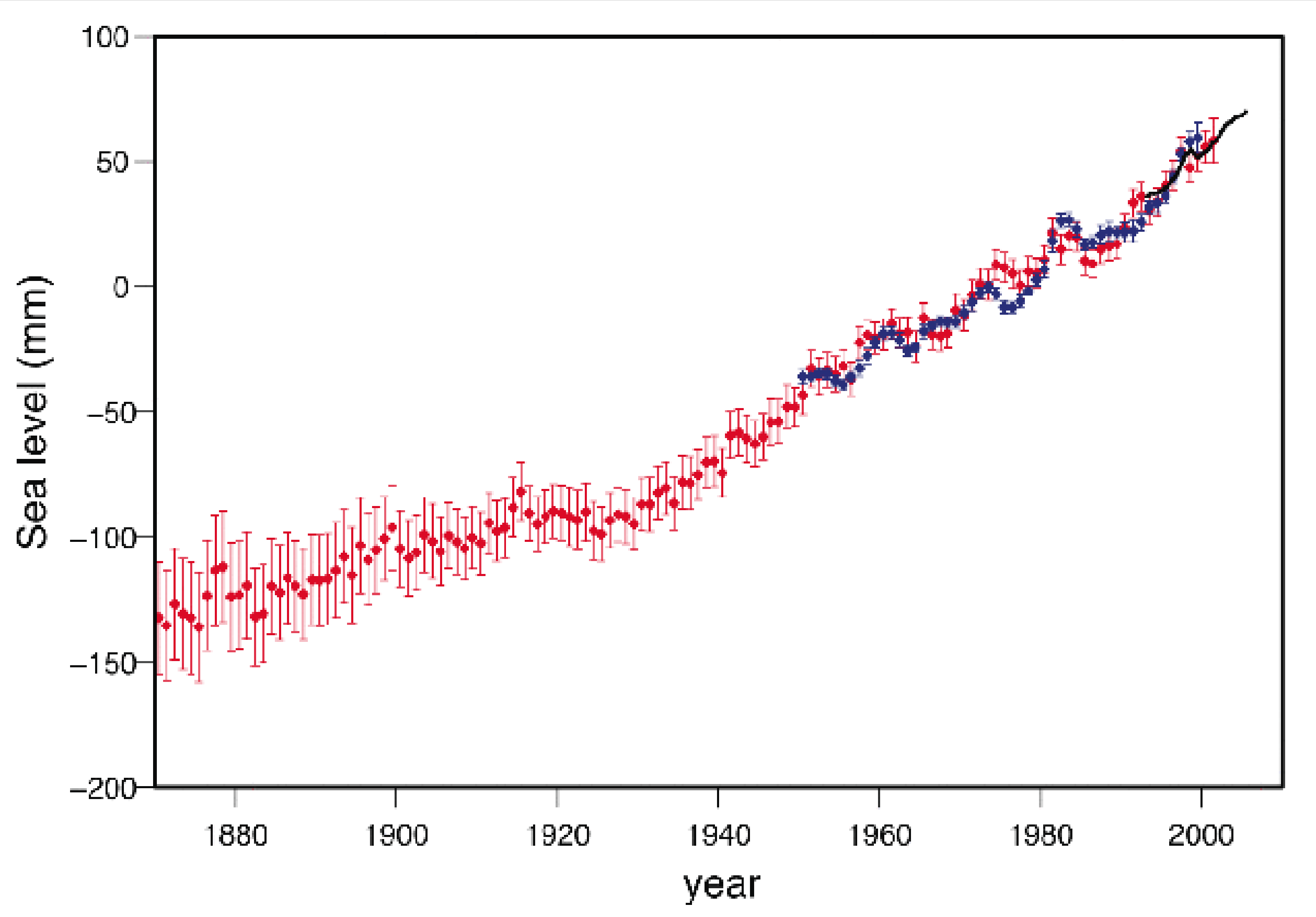
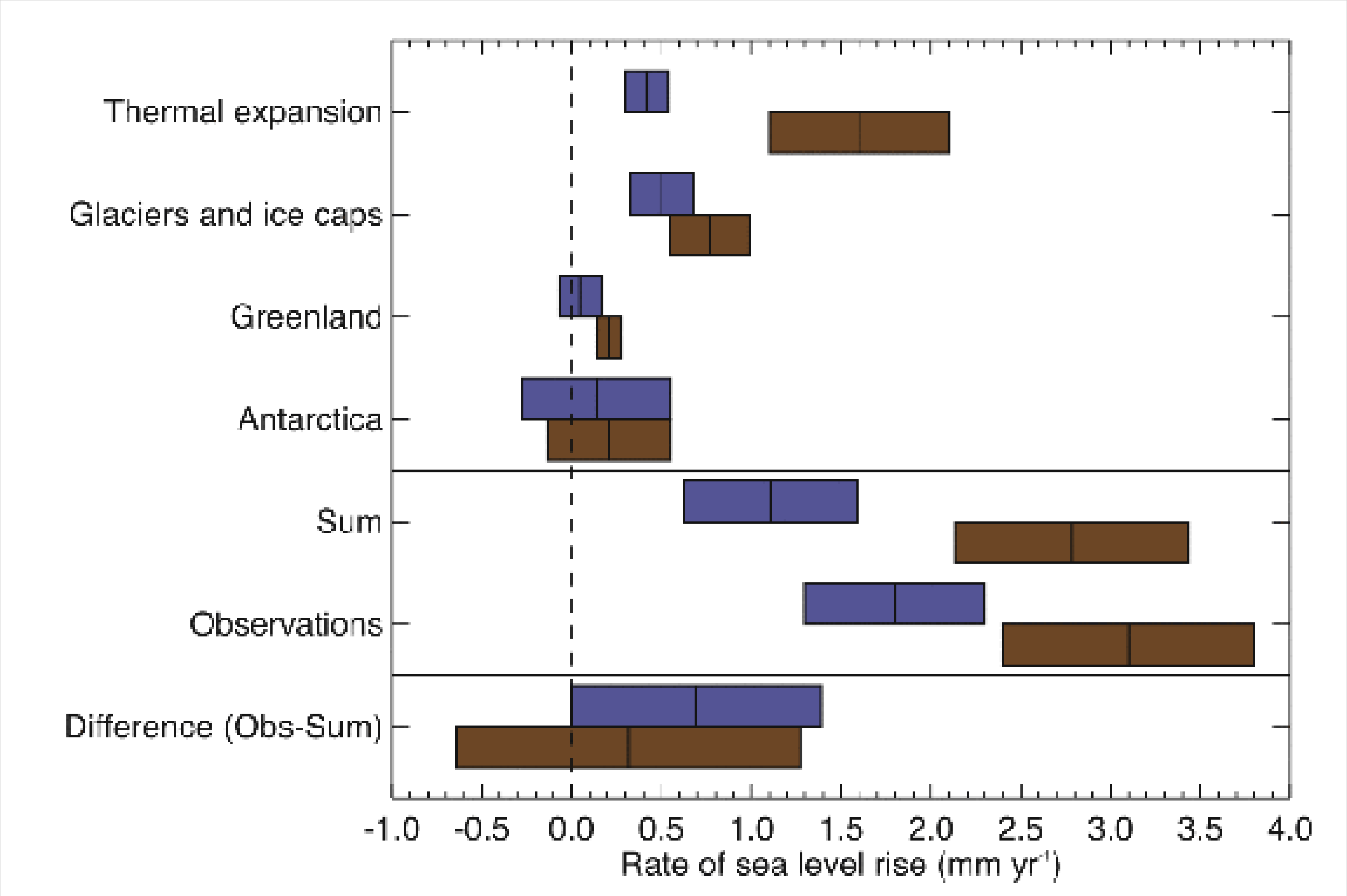
Global Sea Level Rise



Annual averages of the global mean sea level (mm).
Red curve: reconstructed sea level since 1870 (Church and White, 2006);
Blue curve: coastal tide gauge measurements (Holgate and Woodworth, 2004)
Black curve: satellite altimetry (Leuliette et al., 2004).

IPCC, AR4

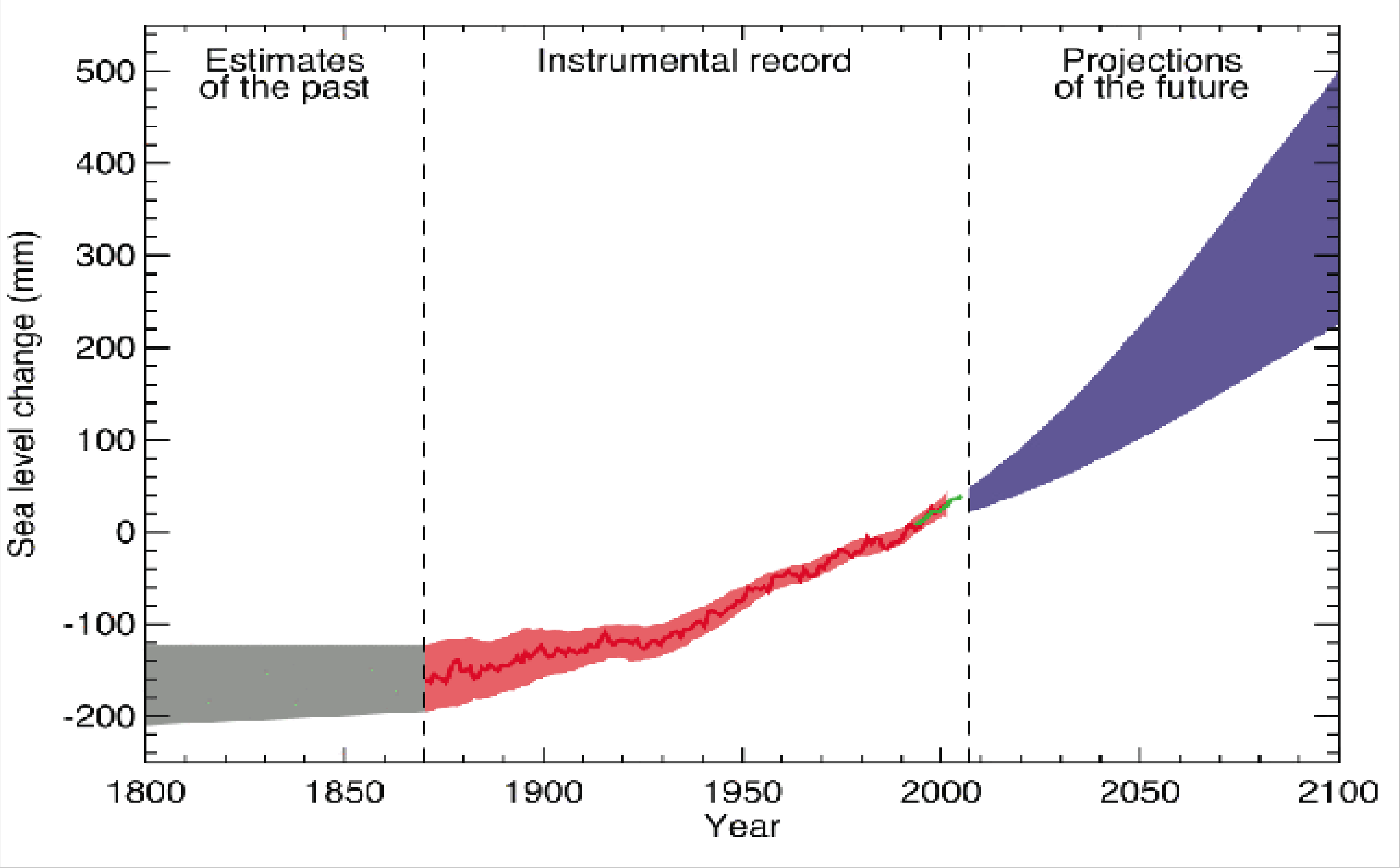
Global Sea Level Rise



Budget of the global mean sea level change
Blue: 1961 to 2003
Brown: 1993 to 2003
Bars represent the 90% error range.

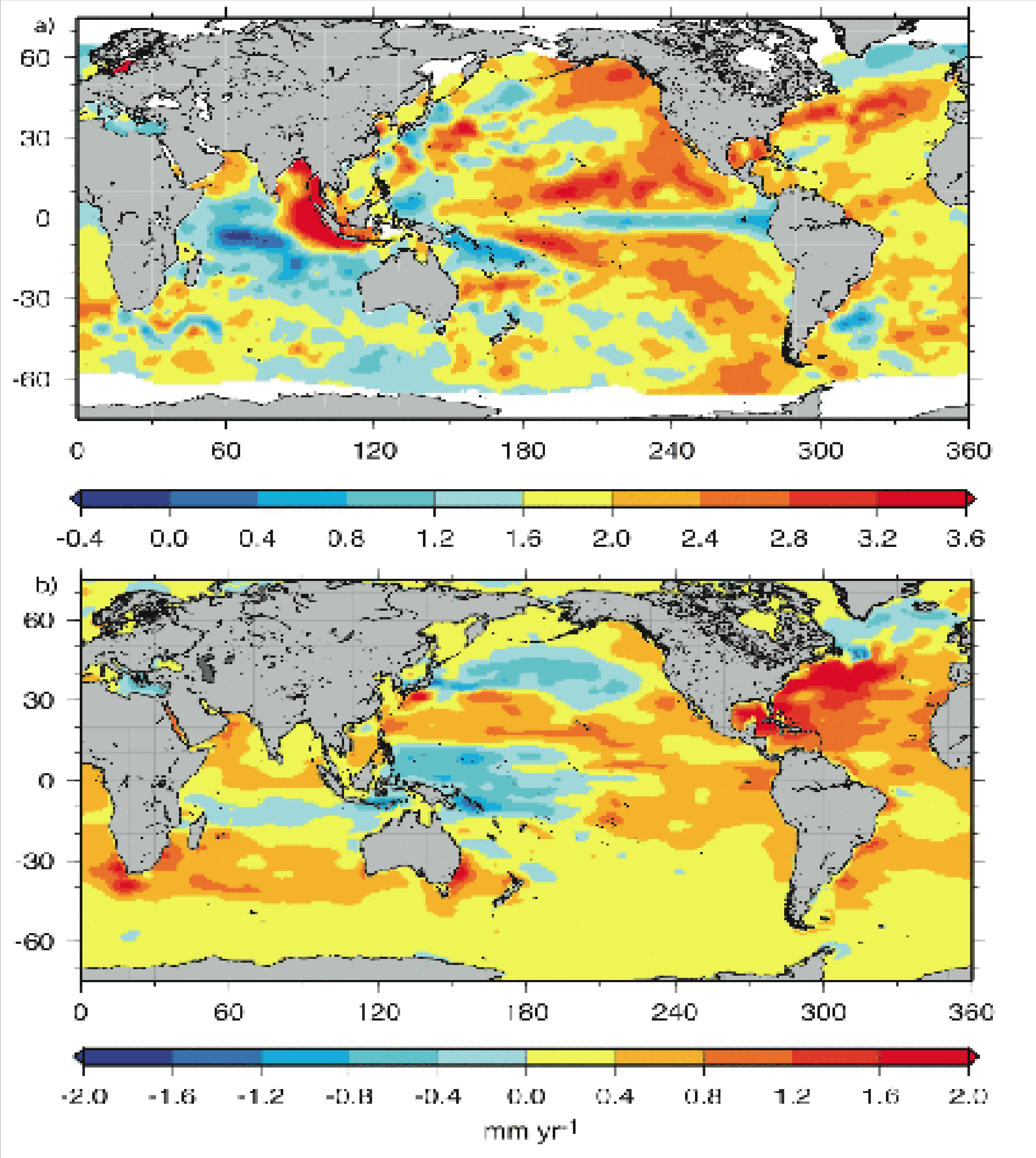
IPCC, AR4

Global Sea Level Rise



IPCC, AR4

Local Sea Level Rise



(a) Geographic distribution of long-term linear trends in mean sea level (mm yr^{-1}) for 1955 to 2003 as reconstructed based on tide gauges and altimetry data (Church et al., 2004).

(b) Geographic distribution of linear trends in thermal expansion (mm yr^{-1}) for 1955 to 2003 (700 m, Ishii et al., 2006).

IPCC, AR4

Basic Terms and Concepts in Sea Level Studies

Sea surface

Sea floor

Local Sea Level (LSL):

$$h(\phi,\theta,t) = \begin{cases} r_1(\phi,\theta,t) - r_0(\phi,\theta,t) & : \text{ ocean} \\ 0 & : \text{ land} \end{cases},$$

r_0 and r_1: geocentric positions of the sea floor and sea surface, respectiv

ϕ, θ: geographical longitude and latitude, respectively.

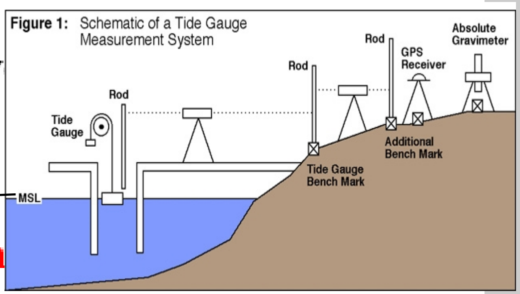
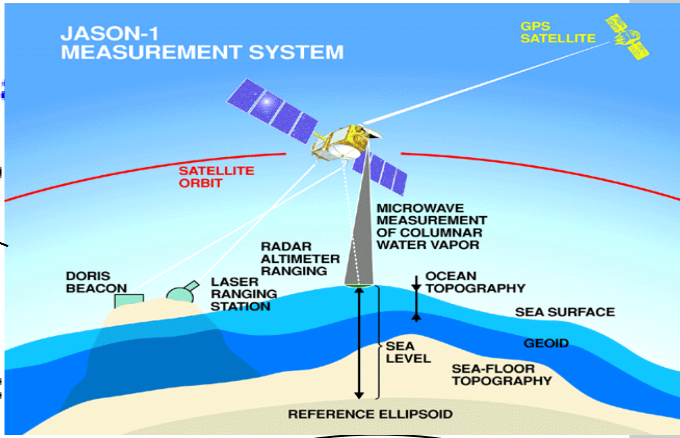


Figure 1: Schematic of a Tide Gauge Measurement System

– LSL is an absolute quantity (i.e. reference frame indepen

– Sea Surface Height (SSH) is a relative quantity.



Global Ocean Volume (GOV):

$$V_O = \int_O \mathrm{d}V = \int_0^{2\pi} \int_0^{\theta} \left(\int_{r_0(\theta,\phi)}^{r_1(\theta,\phi)} r^2 dr \right) \sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

Global Ocean M

$$M_O = \int_O \rho$$

Water Cycle Mass Balance:

$$0 = \sum_{i=1}^{n} \frac{\mathrm{d}M_i}{\mathrm{d}t},$$

M_i: mass of the water in reservoir i,

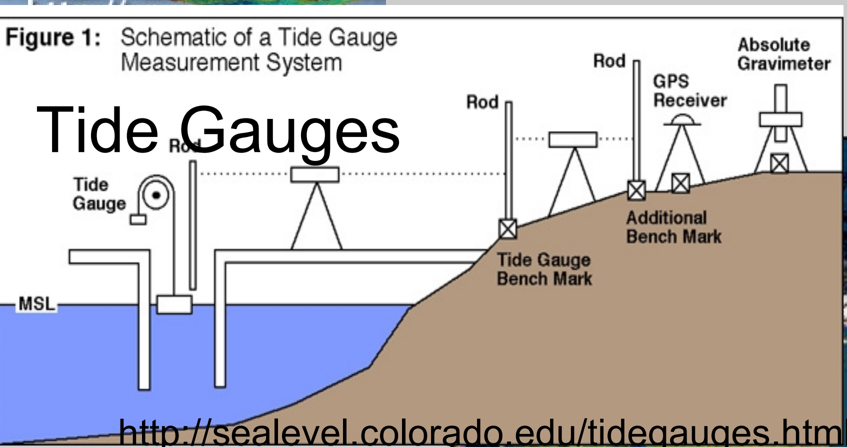
n: number of separate reservoirs.

Volume changes:

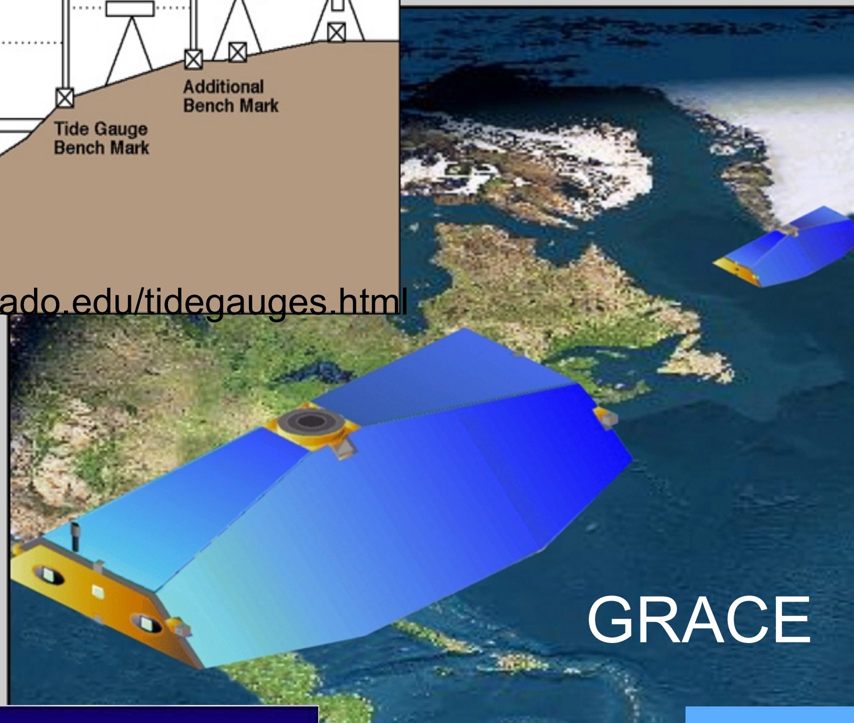
Volume change = steric change+mass change

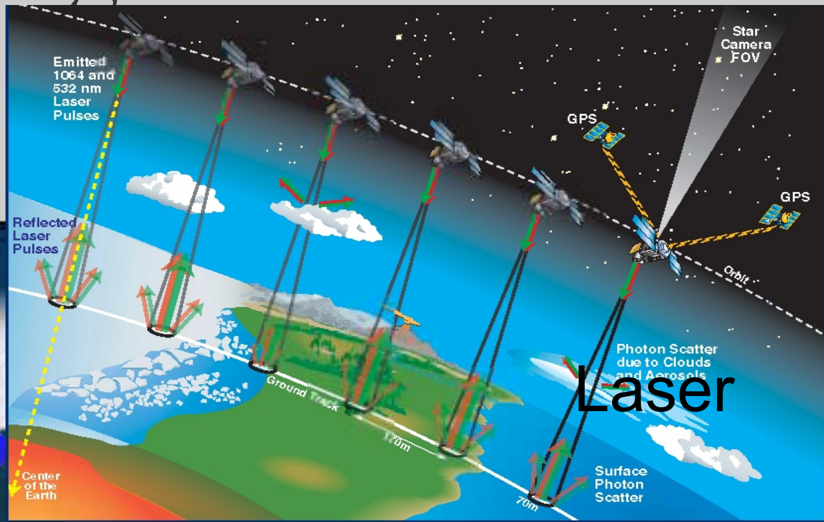
Comments on the relation between mass changes (exchange and redistribution) and LSL

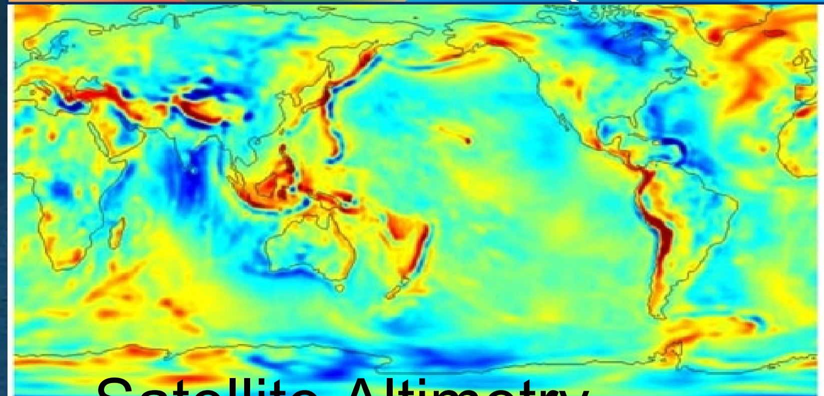
Geodetic Monitoring of Sea Level



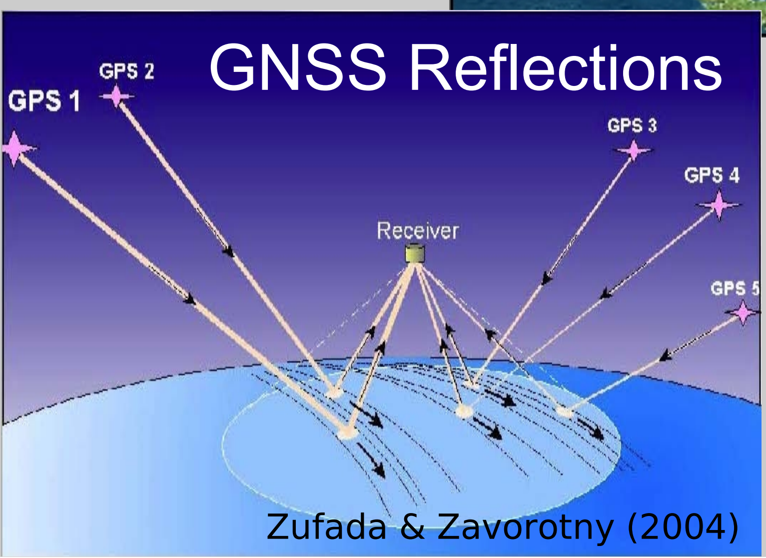
http://sealevel.colorado.edu/tidegauges.html

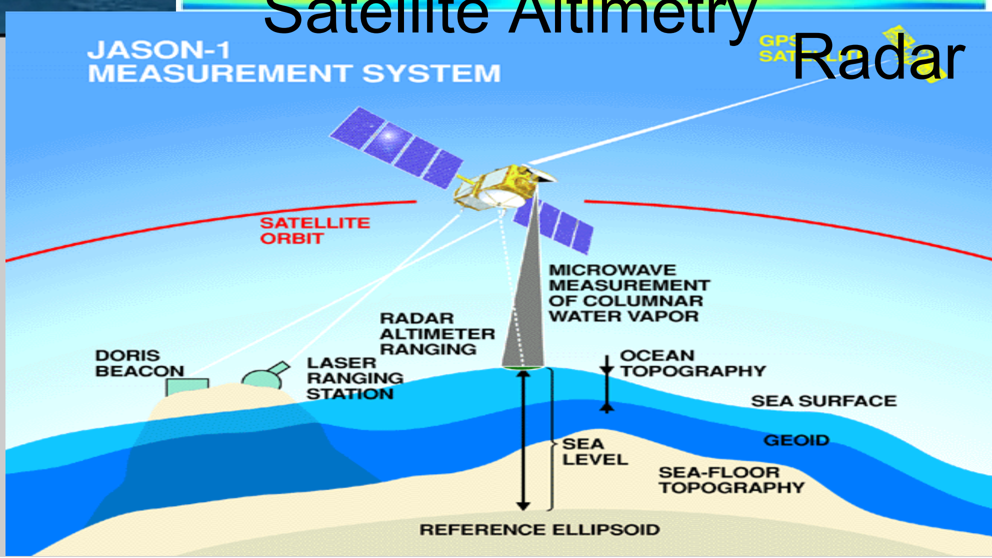




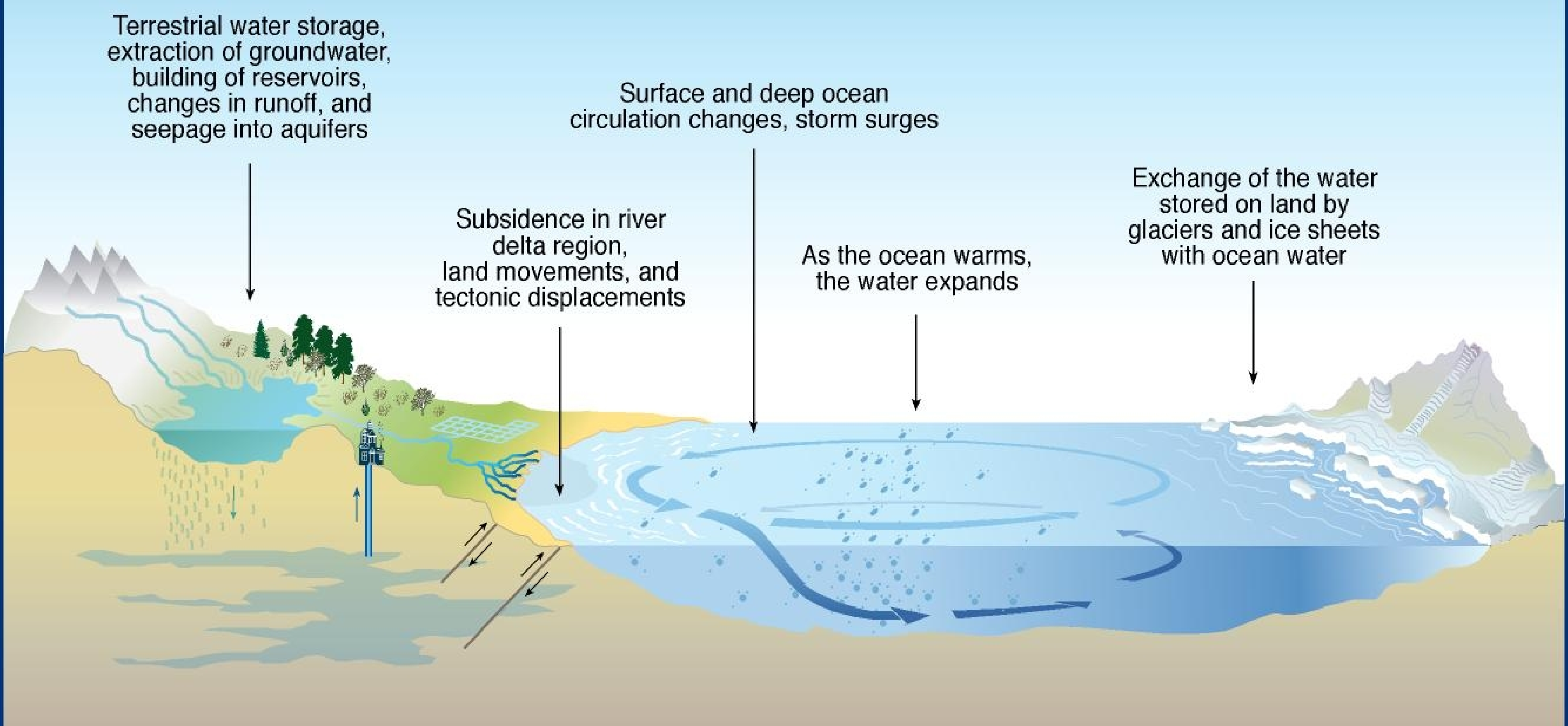


Satellite Altimetry



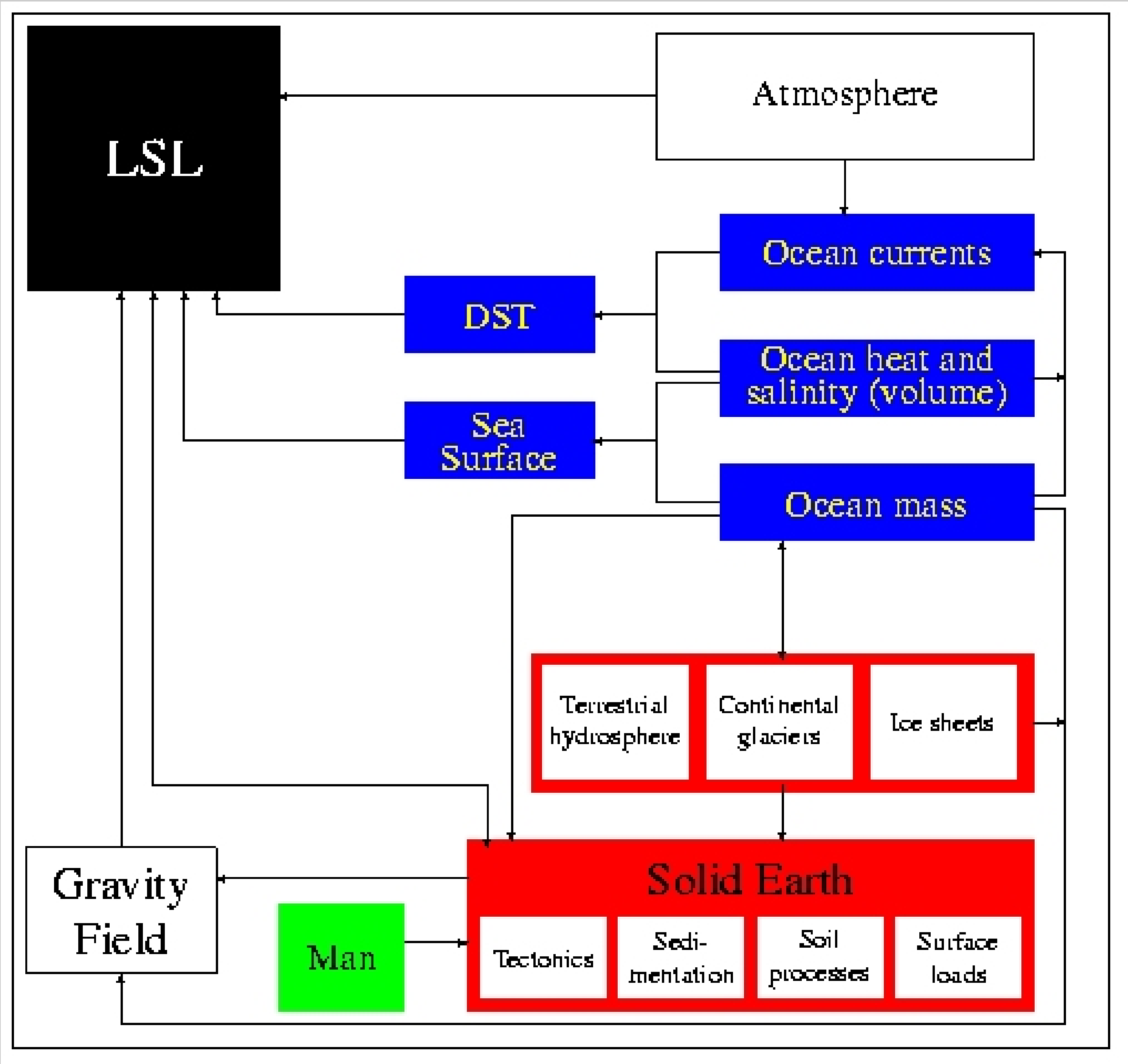


What causes the sea level to change?



SYR - FIGURE 3-4

Local Sea Level (LSL) Equation



Local Sea Level Equation

Local Sea Level (LSL) = high-frequency part + low-frequency part

High-frequency part of LSL equation:

$$h_{\mathrm{hf}}t = w(t) + h_{\mathrm{tidal}}(t) + h_{\mathrm{atmos}}(t) + h_{\mathrm{seiches}}(t) + h_{\mathrm{tsunami}}(t).$$

Important for projection of maximum flood levels

Result of local and regional processes.

Local Sea Level Equation

Low-frequency part of LSL equation:

Contributing factors for LSL (monthly time scales and longer):

$$\delta h_M(\vec{x},t) = S(\vec{x},t) + C(\vec{x},t) + A(\vec{x},t) + I(\vec{x},t) + G(\vec{x},t) + T(\vec{x},t) + P(\vec{x})(t-t_0) + V_0(\vec{x})(t-t_0) + \delta V(\vec{x},t) + B(\vec{x},t)$$

S: steric changes
C: changes in ocean currents
A: changes in atmospheric circulation
I: changes in the mass of the large ice sheets
G: changes in continental glaciers
T: changes in terrestrial hydrosphere
P: postglacial rebound
V_0: secular vertical land motion
δV: non-linear vertical land motion
B: changes in shape and extent of ocean basins.

Comments on the relation between mass changes (exchange and redistribution) and LSL

Important for projection of mean sea level

Result of local, regional and global processes!

Local Sea Level Equation

Relation between mass changes in the water cycle and LSL:

Sea level equation (Farrell&Clark, 1976)

$$\xi(\vartheta,\lambda,t) = c(t) + O(\vartheta,\lambda,t)\int_{-\infty}^{t}\int_0^{\pi}\int_0^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t')\,\frac{\mathrm{d}}{\mathrm{d}t'}\left\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda',t') + [1-O(\vartheta',\lambda',t')]\,\rho_{\mathrm{L}}\eta(\vartheta',\lambda',t')\right\}\sin\vartheta'\,\mathrm{d}\lambda'\,\mathrm{d}\vartheta'\,\mathrm{d}t'.$$

LSL

Green's Function for LSL

ξ: local sea level change (distance to the deformable solid Earth surface),
G: Green's function for sea level,
O: ocean function,
η: cumulated water/ice load change due to mass added or removed from land,
ρ_{W} and ρ_{L}: densities of the ocean water and the load (water or ice), respectively,
$c(t)$: quantity to ensure mass conservation.

Ocean function

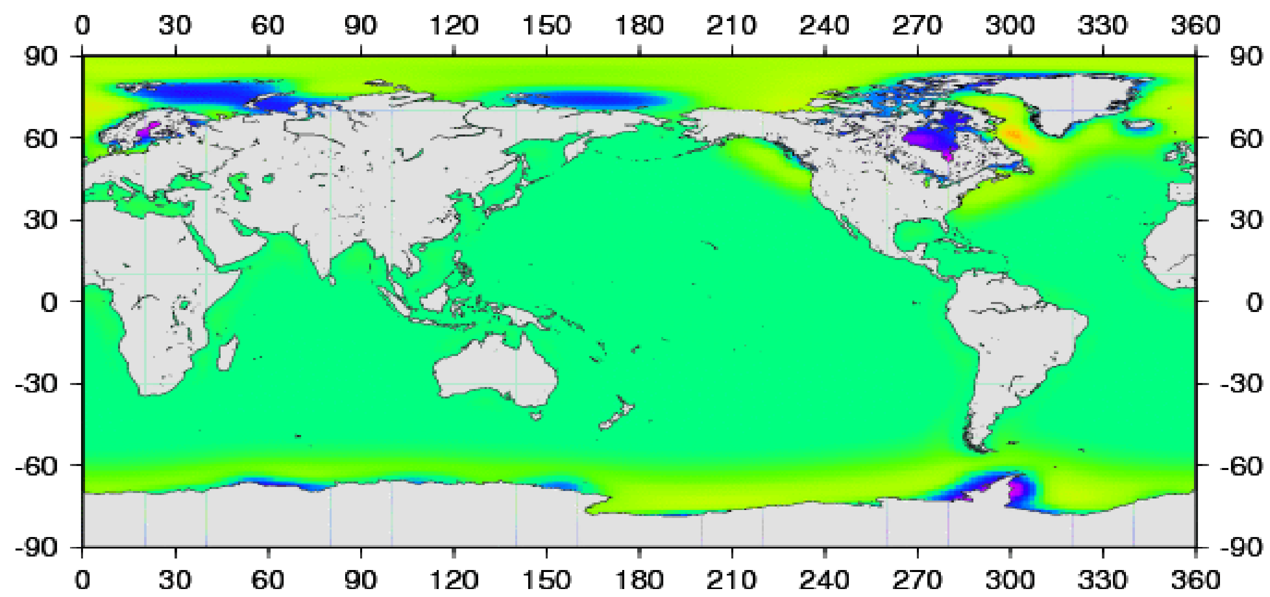
Load on ocean areas

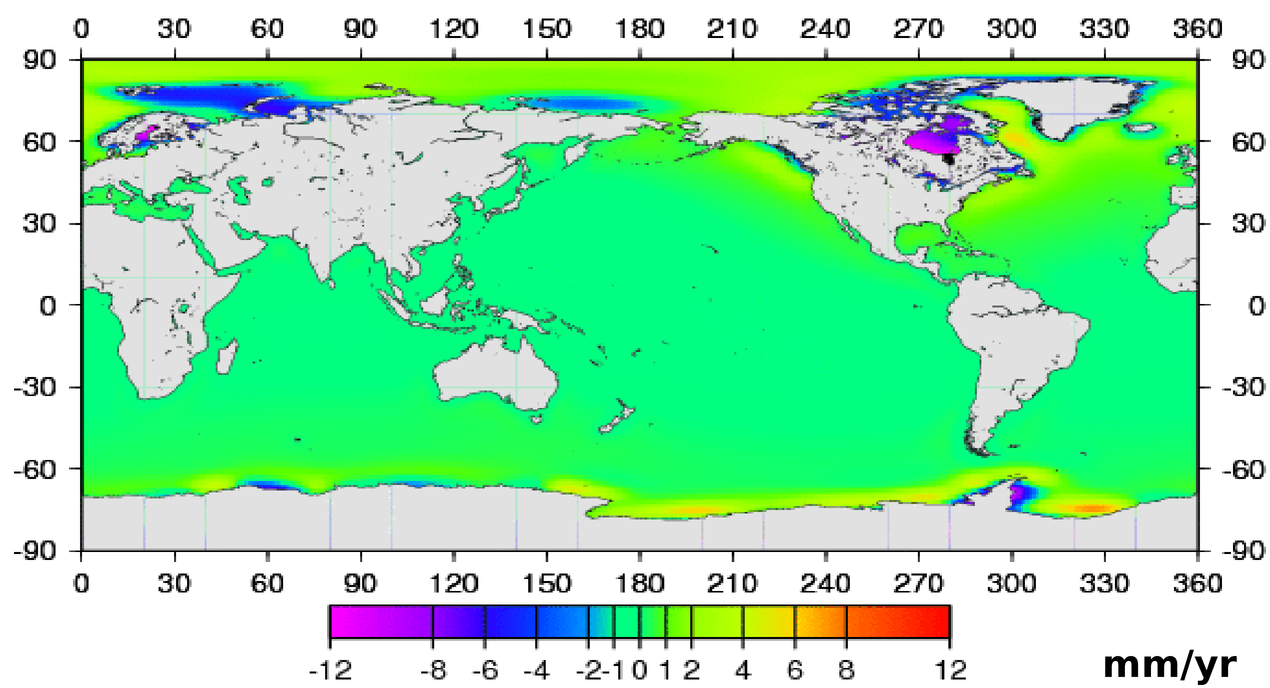
Loads on land areas

All mass movements
- **change the geoid,**
- **displace the ocean bottom vertically**

Forcing: Postglacial Rebound

Postglacial rebound: present-day signal in sea level





N	Author	Model	N_0	d	η_u	η_l
P1	MM	120_1_2	256	120	1.00	2.00
P2	MM	120_1_475	256	120	1.00	4.75
P3	MM	12011.mn	128	120	1.00	1.00
P4	MM	12012.mn	128	120	1.00	2.00
P5	MM	12015.mn	128	120	1.00	5.00
P6	MM	120110.mn	128	120	1.00	10.00
P7	MM	120p32.mn	128	120	0.30	2.00
P8	MM	120p52.mn	128	120	0.50	2.00
P9	MM	7112.mn	128	71	1.00	2.00
P10	MM	9612.mn	128	96	1.00	2.00
P11	P	VM2				
P12	P	VM4				
P13	S	S1				

Forcing: Ice Sheet Fingerprints

Present-day changes in:

* Ice sheets

* Glaciers

* Land water storage

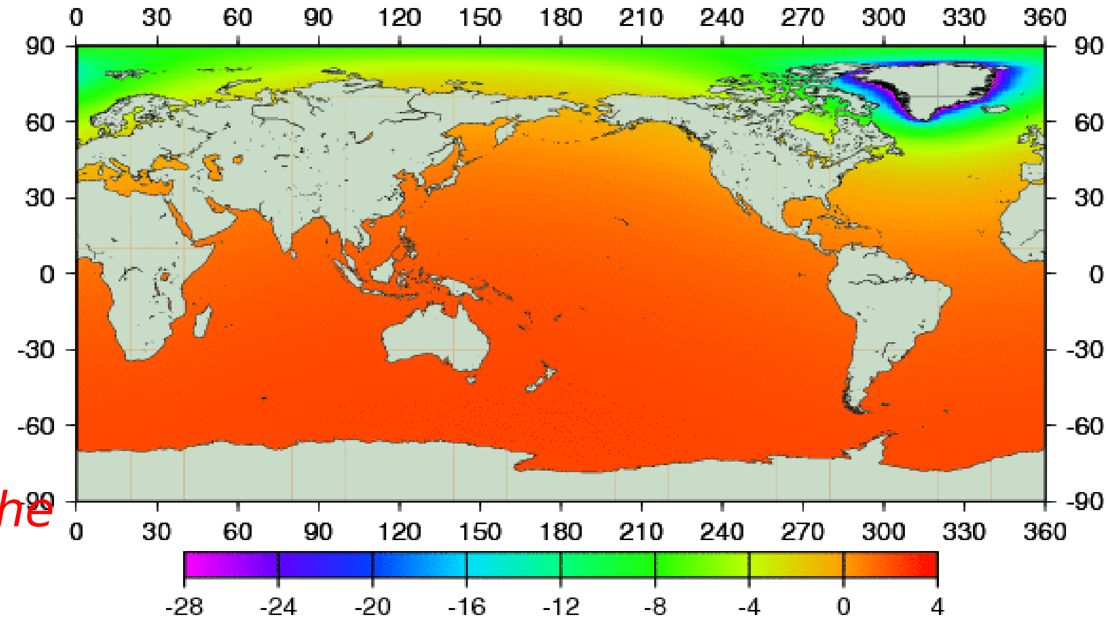
Finger-print functions: *describe the effect of a unit ice mass change in a given area on sea level.*

Solution of the <u>static sea level equation</u> for a unit linear trend over a given ice mass area.

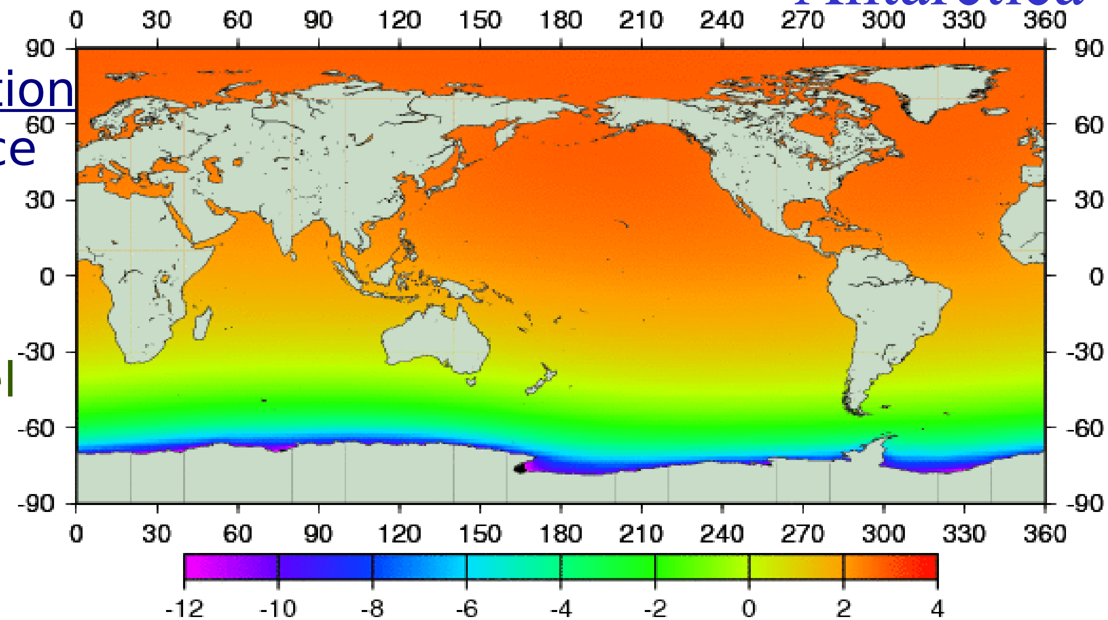
Simplifications:

- spherically symmetric Earth model
- elastic (up to century time scales)

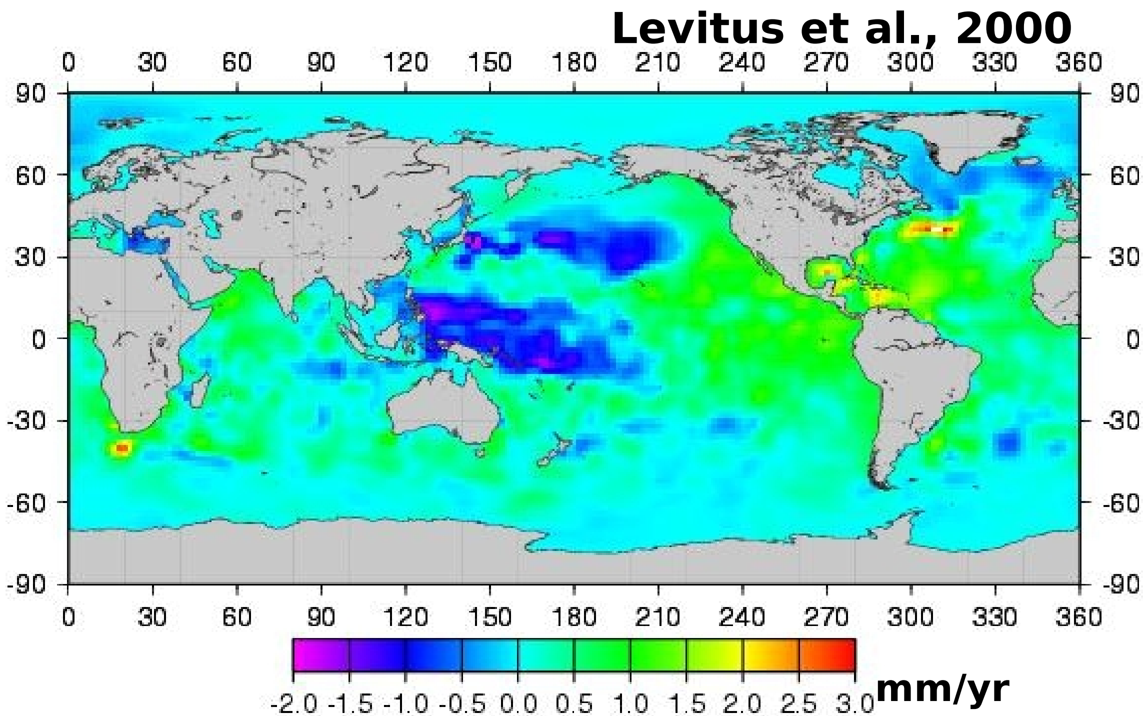
Greenland

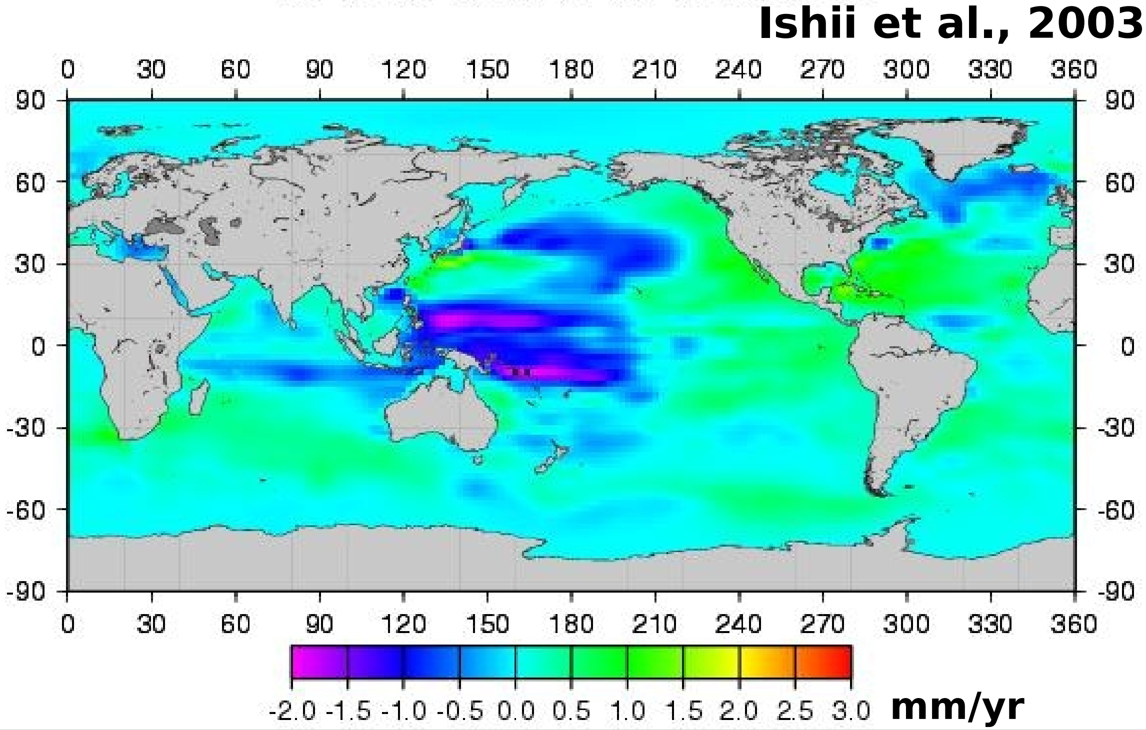


Antarctica



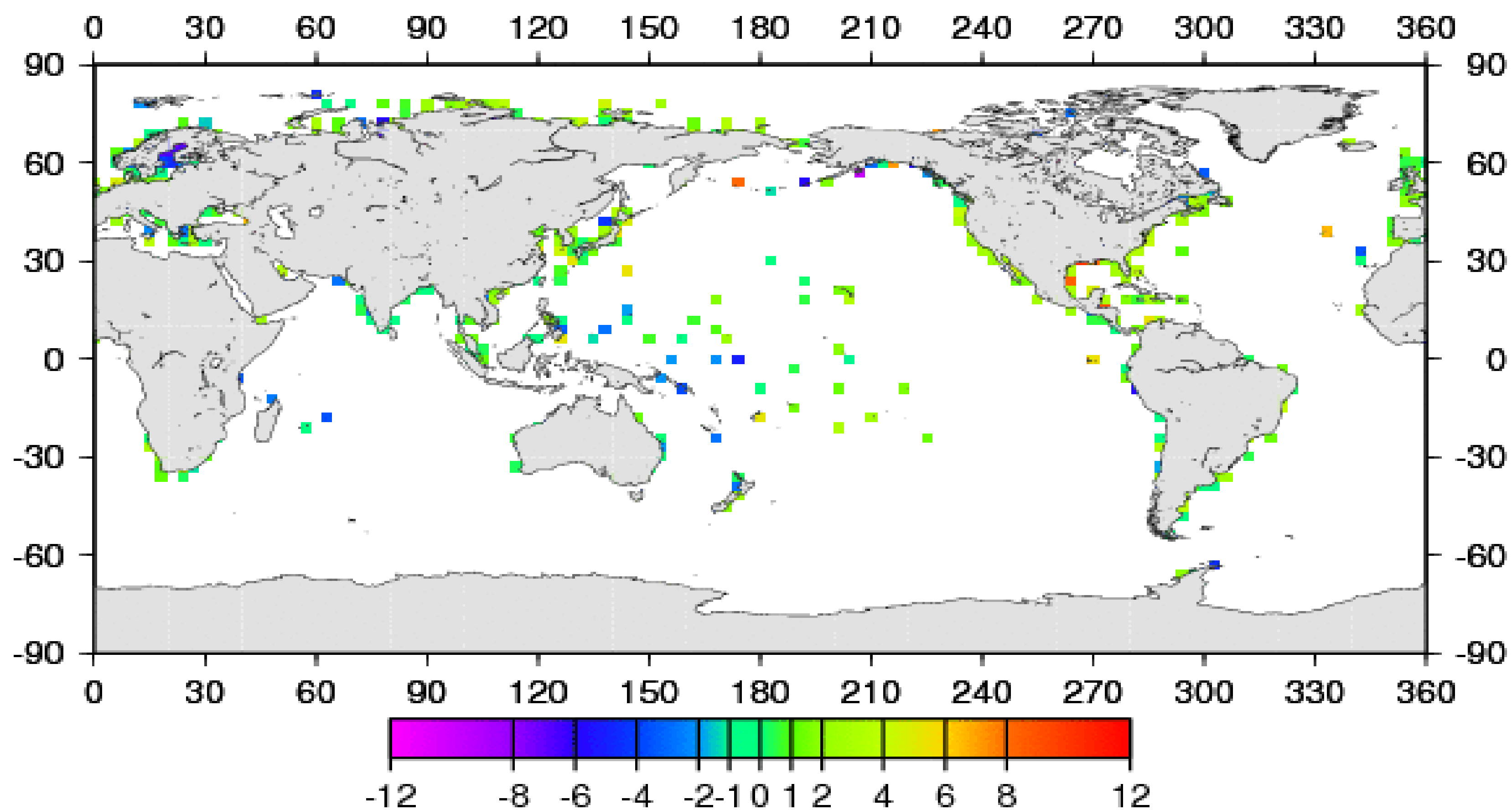
Forcing: Thermo-Steric Changes





Symbol	Oceanographic data	Depth	Temporal
I500	Ishii et al. (2003)	500 m	1 month
L500	Levitus et al. (2000)	3000 m	1 year
L3000	Levitus et al. (2000)	500 m	1 year
L700	Levitus et al. (2000)	700 m	1 year

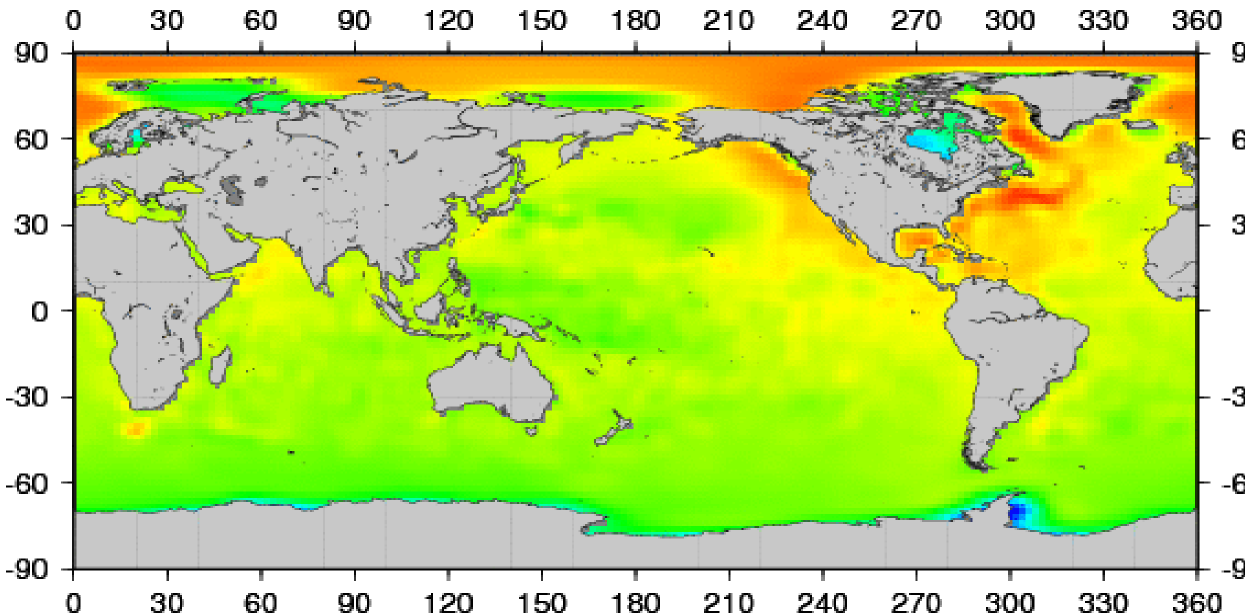
Observations: Local Sea Level Trends



Plag, 2006

Reconstruction of Local Sea Level Trends

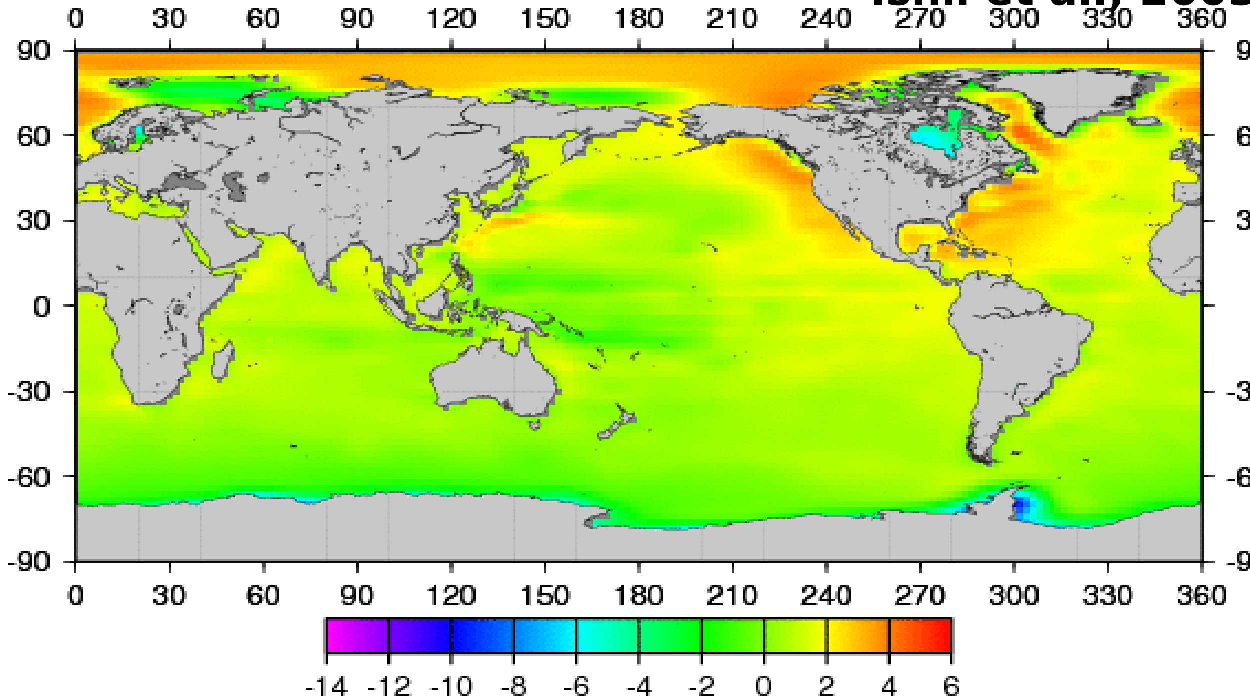
Levitus et al., 2000



Global models consistent with tide tide gauges

Global average:
1.14 mm/yr at tide gauges
0.90 mm/yr global average

Ishii et al., 2003



Global average:
1.10 mm/yr at tide gauges
0.83 mm/yr global average

Plag, 2006

Observation-Based Local Approximation

Alternative LSL equation for observed quantities:

$$\text{Observed LSL trend} = \text{mass contribution} + \text{steric/currents contribution} - \text{land motion} + \text{atmospheric contribution}$$

Understanding past sea level changes on the basis of observations:

$$h_{\text{observed}} = h_{\text{geoid/mass}} + h_{\text{steric/currents}} - h_{\text{land}} + h_{\text{atmospheric}} + e$$

$$h_{\text{tidegauge}} = h_{\text{models}} + h_{\text{oceanography}} - h_{\text{GPS}} + h_{\text{regression/models}} + e$$

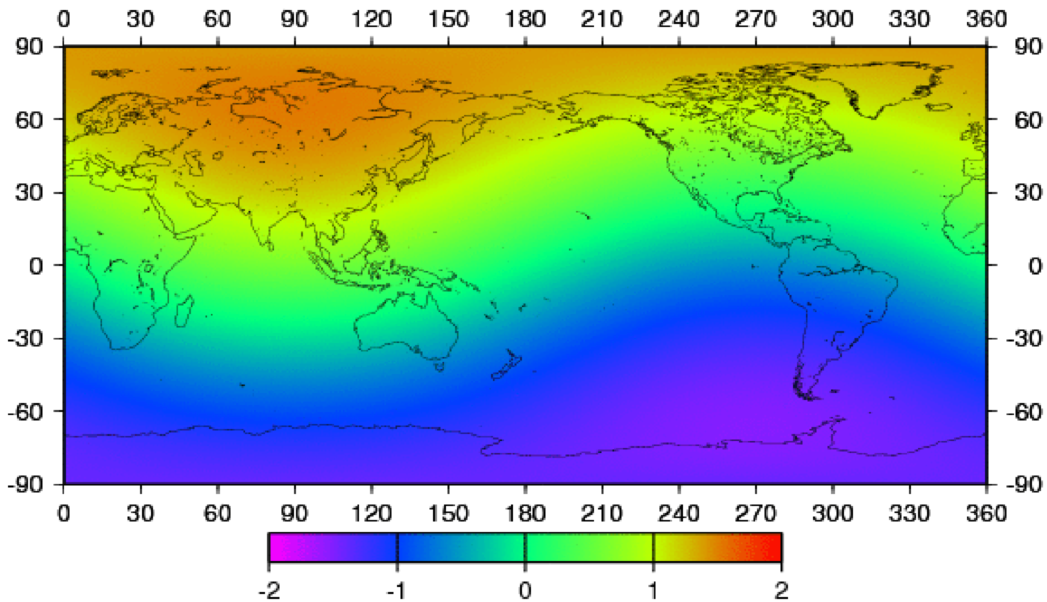
h_{GPS}: **has to be given with respect to the Center of Mass of the Earth System!**

Note: Importance of link between geodetic Reference Frame Origin (RFO) and Center of Mass of the Earth System (CM)

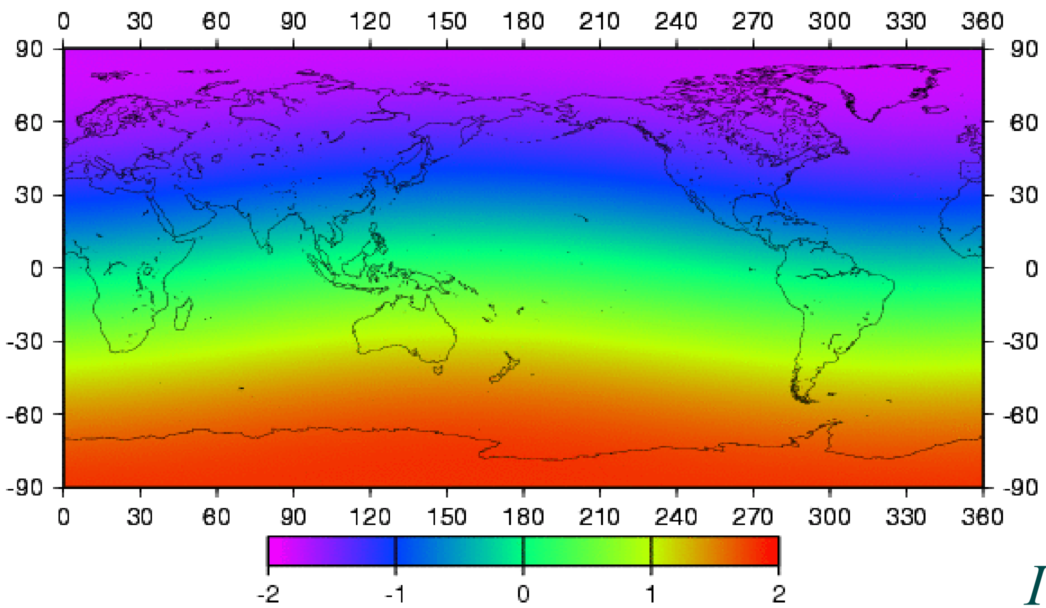
Observation-Based Approximation

Uncertainty in relationship between RFO and CM: ~ 2 mm/yr

Apparent vertical motion due to relative motion of origin ITRF2000 minus ITRF2005



ITRF97 minus ITRF2000



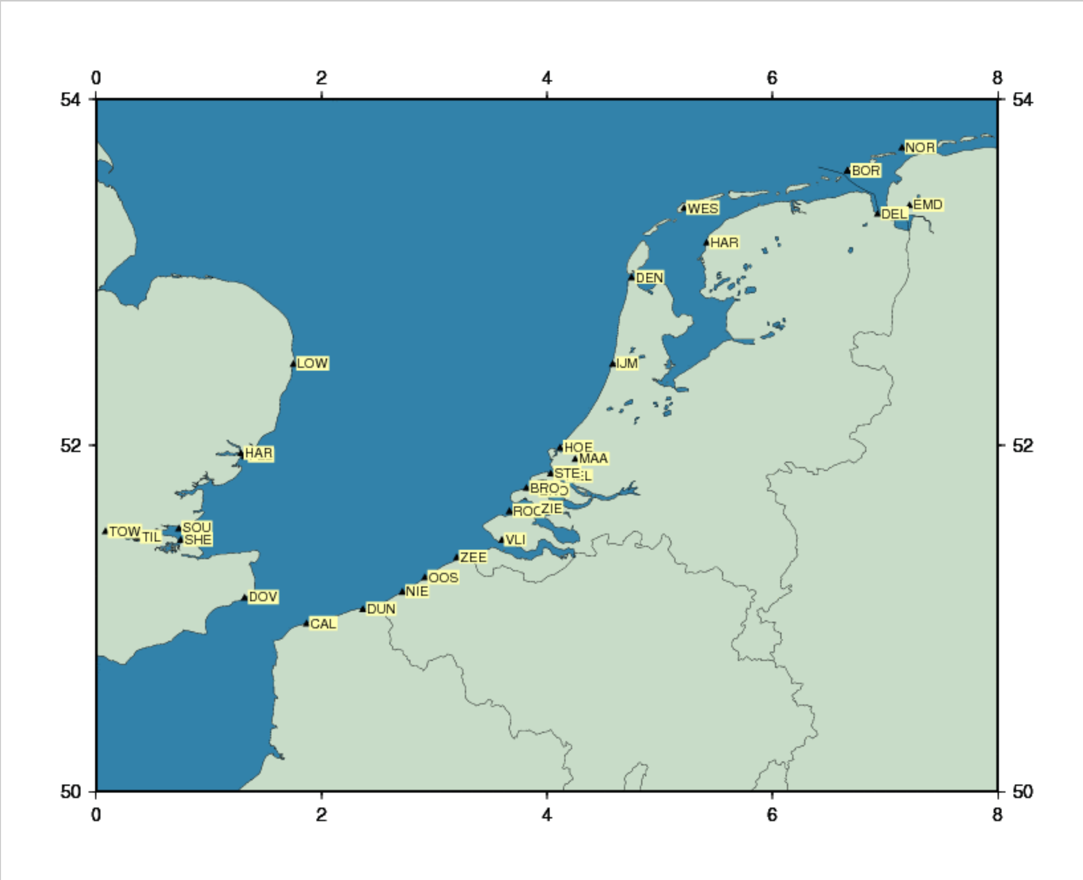
ITRF2000 minus ITRF2005

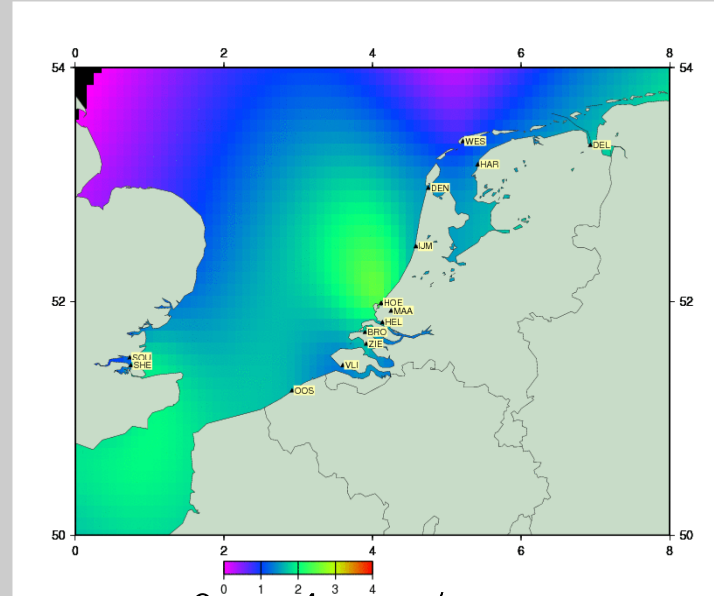
mm/yr

Effect on global sea level: 0.4 mm/yr
(Plag, 2005)

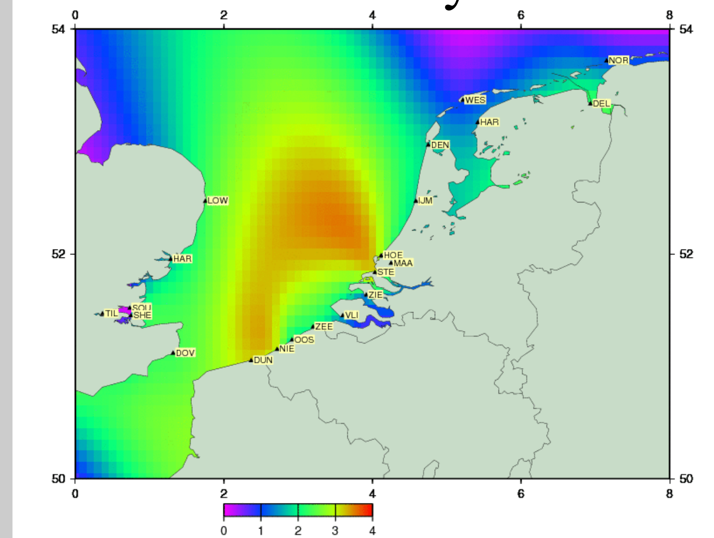
Effect on LSL +- 2 mm/yr

Example Dutch Coast: Spatial Pattern of Past LSL Trends





0 to 4 mm/yr



0 to 4 mm/yr

Observed LSL Trends
Upper: All data
Lower: Data for 1950 - 2008

Example Dutch Coast: Past LSL Trends, Summary

Observed Trends:

* Considerable spatial variability (order ±2 mm/yr)
* Considerable temporal variability from 5 to more decades (order ±1 mm/yr)

Forcing:

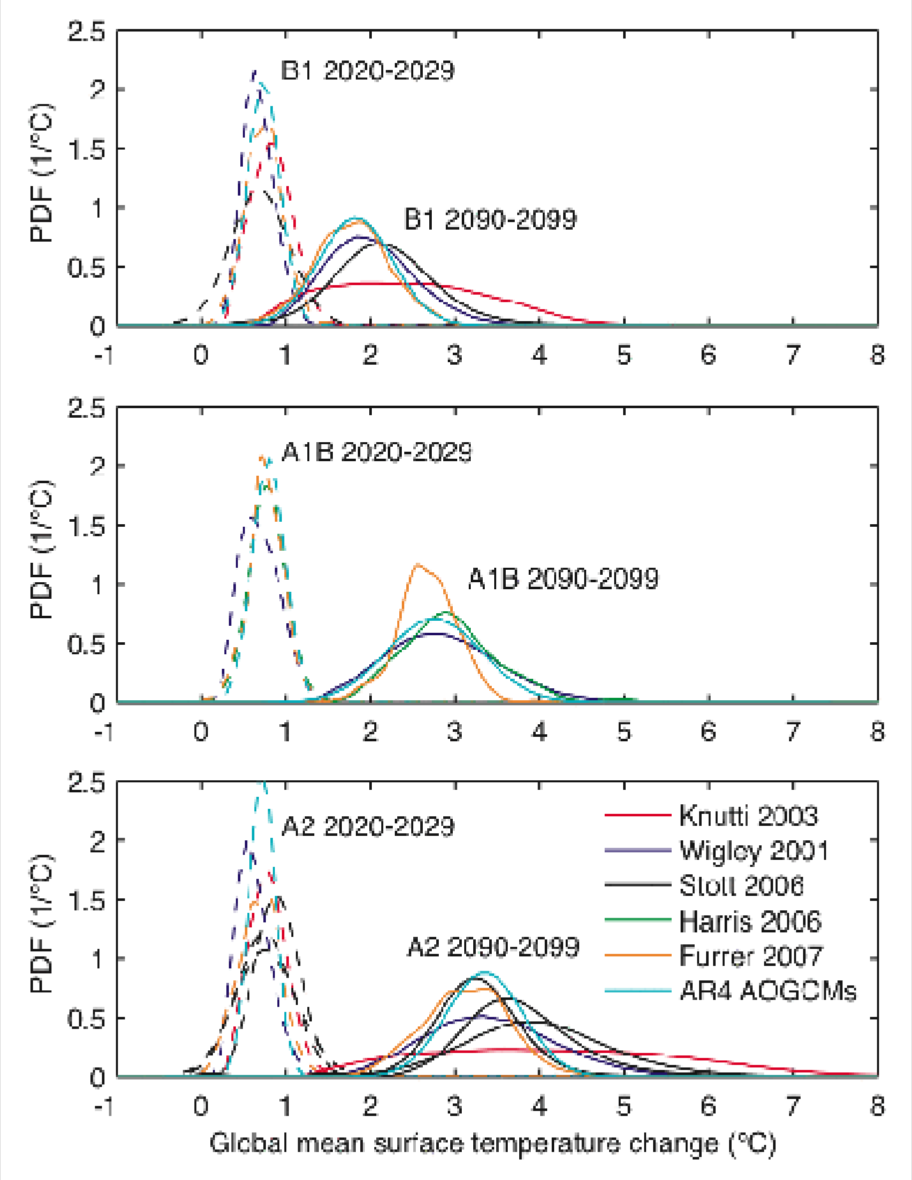
* Atmospheric forcing: order 1 mm/yr over 50 years
* Postglacial rebound: order 1-2 mm/yr with large uncertainties
* thermo-steric: very small, order 0.2 mm/yr
* ice sheets: small, order 0.7 mm/yr (*Plag, 2006, -0.3 and + 1.0 mm/yr*)
* balance for individual tide gauges between -4 and +2.5 mm/yr, mean 0.2 mm/yr.

Main uncertainties:

* Postglacial rebound
* Ice sheets
* Vertical land motion

Example Dutch Coast: Future LSL Changes

Delta Commission, advising the Dutch parliament:
Main Question: Can the Probability Density Function for global temperature be translated into a Probability Density Function for local sea level at the Dutch Coast?



IPCC AR4

Introduction: Scenarios of Future Sea Levels

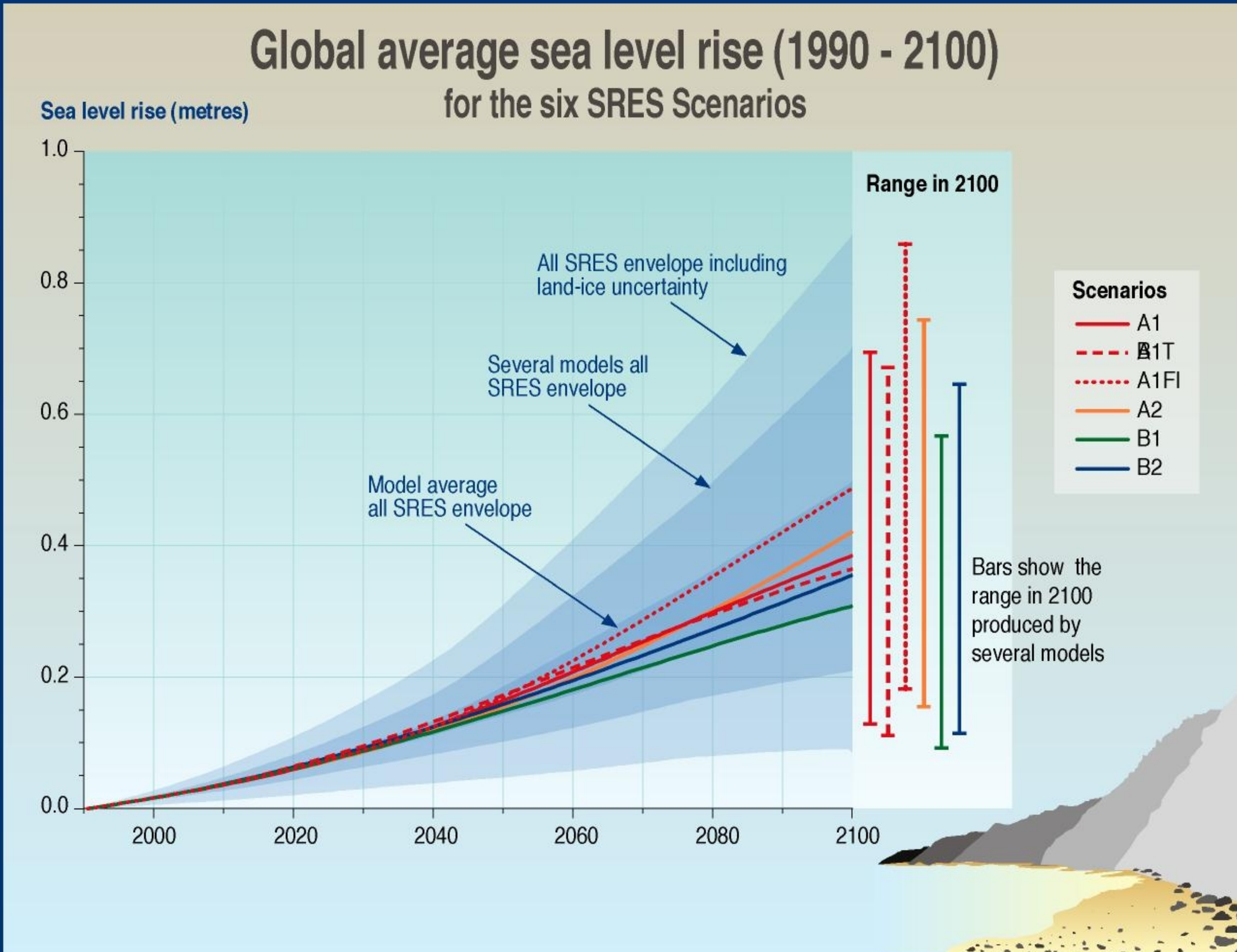
· **Main goal of scenario analysis:** Characterize uncertainties for less predictable aspects of future projections

· **Main approach:** Make different assumption about the forcing

· The case of **climate change**: consider a range of reasonable emission scenarios.

· The case of **Local Sea Level**: consider a range of reasonable ocean warming and ice sheet scenarios combined with model output for ocean and atmospheric circulation, vertical land motion, and LSL fingerprints

LSL is impact parameter for coastal zone.



WG1 TS FIGURE 24

Introduction: Examples of Scenarios

Conservative scenario (Hulme et al., 2002; Nicholls, 2005):

$$
\begin{aligned}
h_{\text{future mean}} &= \text{IPCC projection} + 50\% \text{ regional/local amplification} \\
&= 1.5 * h_{\text{IPCC}}(t = 2100)
\end{aligned}
$$

Examples:

London: 1 m in mean sea level plus 2 m in surges

Germany and Netherlands: 1 m in mean

Denmark: 0.5 m in mean

Local approach:
Model the factors contributing to the LSL equation.

$$h_{\text{future maximum}} = h_{\text{lf}}(t = t_{\text{P}}) + \max(h_{\text{hf}}(t = t_{\text{P}}))$$

For h_{lf}:

Factor	A	B	C	D	...
Steric	local to regional				
Ocean currents	local to regional				
Atmosphere	Order of a few cm over a century				
Greenland	Depends on ice scenario and location				
Antarctica	Depends on ice scenario and location				
Glaciers	Depends on ice scenario and location				
Terr. Hydro.	Depends on load scenario and location				
Land	Depends on reference frame and loction				
Sum	?	?	?	?	?

Forcing Scenarios and Projections of Future LSLs

PDFs

Process	Variable	Mean	90% boundaries	
Atmospheric forcing	mean LSL	0 mm	±50 mm	Oscillatory nature, times scales of 50-100 years
		50 mm	±50 mm	Mean shift in wind and air pressure
Steric, currents	LSL trend	2 mm/yr	±2 mm/yr	
PGR	LSL trend	0.5 mm/yr	±0.6 mm/yr	Spatially variable
Greenland	LSL trend	0.5 mm/yr	±0.1 mm/yr	Global, non-linear response possible
		-1.25 mm/yr	±0.25 mm/yr	At Dutch coasts
Antarctica	LSL trend	0.17 mm/yr	±0.08 mm/yr	Global, non-linear response possible
		0.44 mm/yr	±0.21 mm/yr	At Dutch coasts
Glaciers and ice caps	LSL trend	1.1 mm/yr	±0.24 mm/yr	Acceleration likely
Sea ice	LSL trend	?	?	Freshing effect, may be included in steric
Land water storage	LSL trend	0 mm/yr	±0.4 mm/yr	Estimates are very uncertain
Vertical land motion	LSL trend	−1 to 3 mm/yr	±1 mm/yr	Spatially variable

Forcing Scenarios and Projections of Future LSLs

Forcing Scenarios

Forcing Scenarios:

S1: No accelerated melting, vertical land uplift of 1 mm/yr;

S2: No accelerated melting, subsidence of 3 mm/yr;

S3: As S1 but with increased melting of Greenland;

S4: As S1 but with increased melting of Antarctica;

S5: As S1 but with increased melting of glaciers and ice caps;

S6: As S1 but with increased melting of Antarctica, glaciers and ice caps;

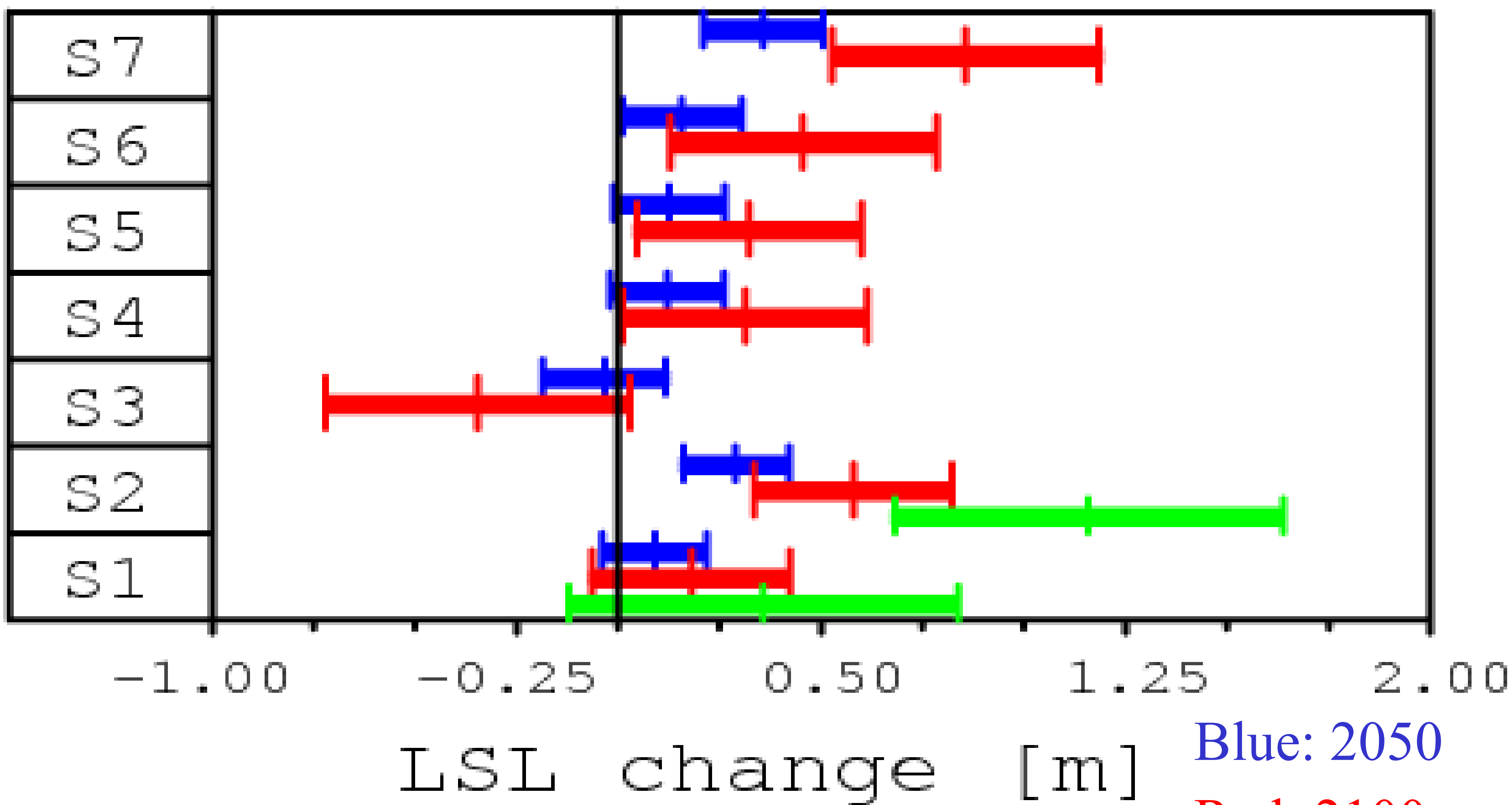
S7: As S2 but with increased melting of Antarctica, glaciers and ice caps.

Forcing Scenarios and Projections of Future LSLs

N	Factor	2050	2100	2200
1	Steric and ocean currents	100 ± 100	200 ± 200	400 ± 400
2	Atmosphere	0.0 ± 50	0 ± 50	0 ± 50
3	Greenland	-63 ± 13	-126 ± 26	-252 ± 52
4		-185 ± 80	-651 ± 282	
5	Antarctica	22 ± 11	44 ± 22	88 ± 22
6		53 ± 57	177 ± 177	
7	Glaciers and ice caps	55 ± 12	111 ± 27	222 ± 54
8		92 ± 45	255 ± 136	
9	Terrestrial hydrosphere	0 ± 20	0 ± 40	0 ± 80
10	PGR	25 ± 30	50 ± 60	100 ± 120
11	Vertical land motion	-50 ± 50	-100 ± 100	-200 ± 200
12		150 ± 50	300 ± 100	600 ± 200
S1	1+2+3+5+7+9+10+11	89 ± 129	179 ± 243	358 ± 479
S2	1+2+3+5+7+9+10+12	290 ± 129	579 ± 243	1158 ± 479
S3	1+2+4+5+7+9+10+11	-33 ± 151	-346 ± 373	
S4	1+2+3+6+7+9+10+11	120 ± 141	312 ± 301	
S5	1+2+3+5+8+9+10+11	126 ± 137	323 ± 277	
S6	1+2+3+6+8+9+10+11	157 ± 147	456 ± 329	
S7	1+2+3+6+8+9+10+12	358 ± 147	856 ± 329	

LSL Projections

Forcing Scenarios and Projections of Future LSLs



Blue: 2050

Red: 2100

Green: 2200

Uncertainties

Manning and Petit (2003, IPCC Theme paper): Five types of uncertainties:

- **Incomplete or imperfect observations (aleatoric uncertainties):** vertical land motion, reference frame, oceanographic observations;
- **Incomplete conceptual framework (epistemic uncertainties):** with respect to climate system: Yes; with respect to mass-sea level relation: No;
- **Inaccurate description of known processes:** one-dimensional models, incomplete mass redistribution, gravitationally inconsistent models;
- **Chaos:** With respect to climate system: Yes; for mass-sea level: No;
- **Lack of predictability:** ice sheet behavior, ocean warming, circulation.

Uncertainties

* Incomplete conceptual framework (epistemic uncertainties):
  with respect to mass-sea level relation: No;

But we have large inter-model difference in ice sheet fingerprints!
Very Surprising!

Elastic Theory well established and applied to:
** Earth tides*
** Ocean tidal loading*
** Atmospheric, hydrological loading*
** Earth rotation*

* Inaccurate description of known processes:
  one-dimensional models, incomplete mass redistribution,
  gravitationally inconsistent models, programming errors;

Uncertainties

"Uncertainties affecting available scientific results need to be explained clearly and in ways that avoid confusion and assist policymakers and non-specialists when considering decisions and risk management" (Manning and Petit, 2003).

Main uncertainties in understanding past/current LSL changes:

· Steric effect not well known due to lack of data;

· Vertical land motion still uncertain in a geocentric reference frame;

· Mass redistribution/Geoid variations not well constrained;

Consequences:

· Separation of the different factors contributing to LSL not satisfactory

· Large uncertainties map into future scenarios creating a wide range of possible sea level changes

Uncertainties

"Uncertainties affecting available scientific results need to be explained clearly and in ways that avoid confusion and assist policymakers and non-specialists when considering decisions and risk management" (Manning and Petit, 2003).

Sea-level related risk of coastal inundation:

- Future changes in **ice sheets** are main uncertainty (large spatial variations).
- Currently, the **range of plausible LSL** scenarios for most locations is **very large**.

Precautionary approach:

- Slow retreat from coastal zone areas prone to inundation or
- Building increasingly more expensive protections where needed?

Don't put your jewellery at the window where the thief can easily get it!

The End