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Reducing Uncertainties in Local Sea Level Projections for Developing Climate Change Mitigation Strategies

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Outline

- Introduction: Basic terms and concepts
- Global Versus Local Sea Level Changes
- Plausible Forcing Scenarios and Range of Predictions
- Main Uncertainties
- How to Address these Uncertainties for Policymakers

Basic Terms and Concepts in Sea Level Studies

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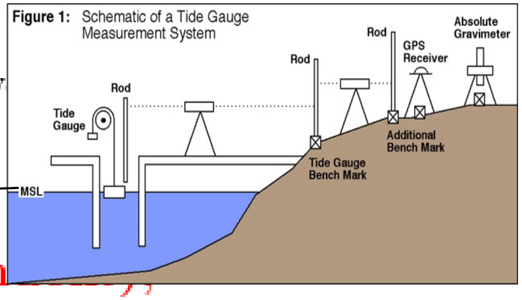
Sea surface

Sea floor

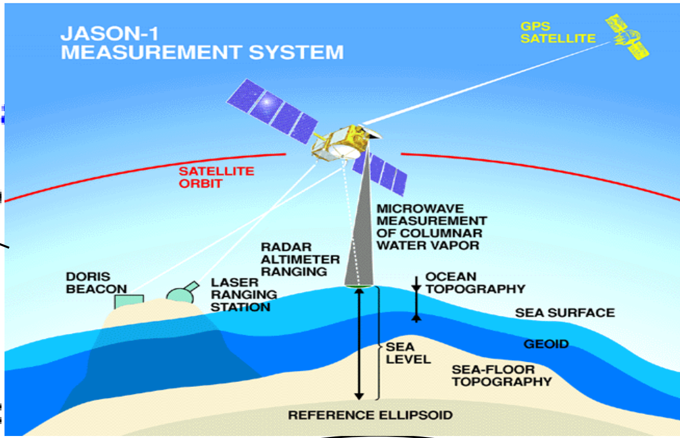
Local Sea Level (LSL):

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

r_0 and r_1: geocentric positions of the sea floor and sea surface, respectiv
ϕ, θ: geographical longitude and latitude, respectively.



– **LSL is an absolute quantity (i.e. reference frame indepen**
– **Sea Surface Height (SSH) is a relative quantity.**



Global Ocean Volume (GOV):

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

Global Ocean M

$$M_O = \int_O \rho$$

Water Cycle Mass Balance:

$$0 = \sum_{i=1}^{n} \frac{dM_i}{dt},$$

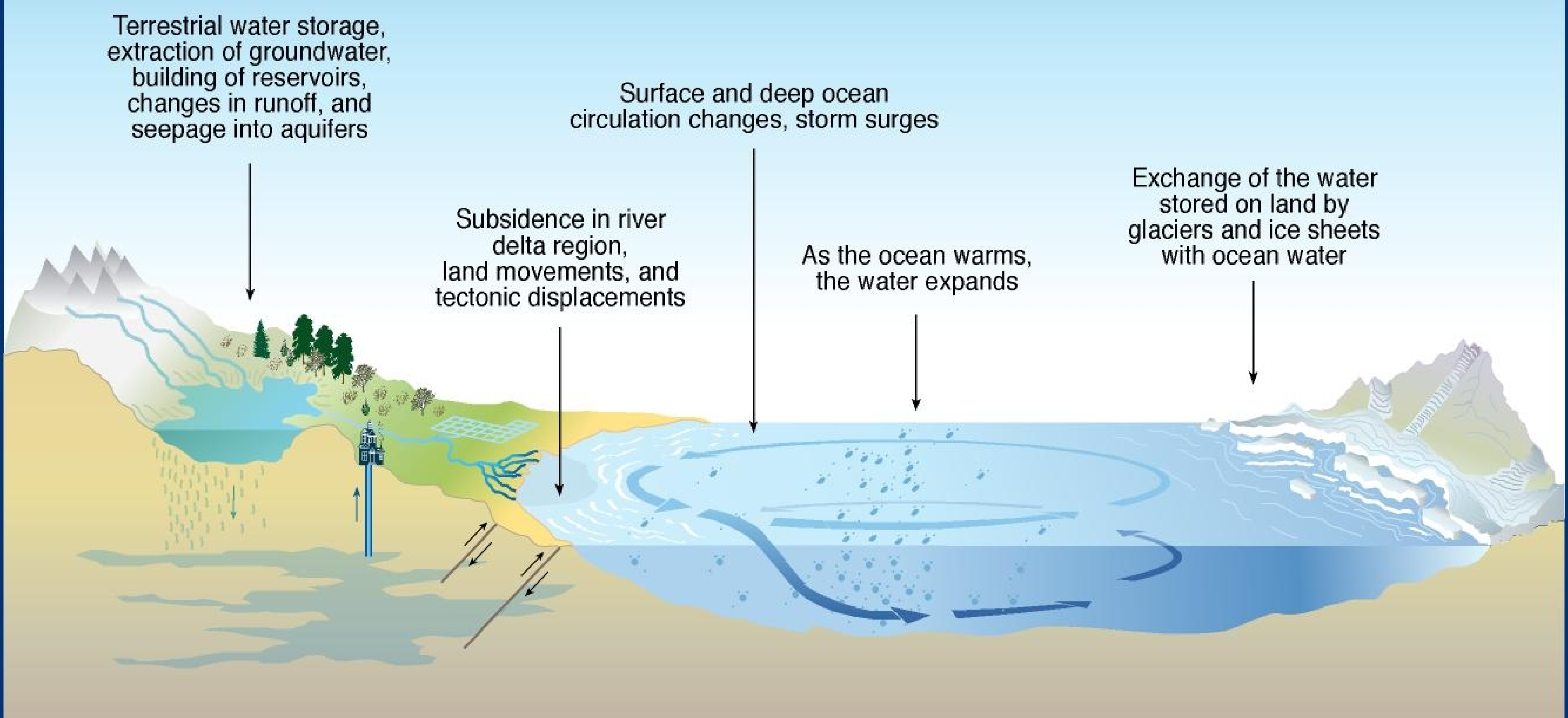
M_i: mass of the water in reservoir i,
n: number of separate reservoirs.

Volume changes:

Volume change = steric change+mass change

Spatially variable due to interaction of gravitational and visco-elastic response of the solid Earth and LSL to loading.

What causes the sea level to change?



SYR - FIGURE 3-4

Local Sea Level Equation

Low-frequency part of LSL equation:

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

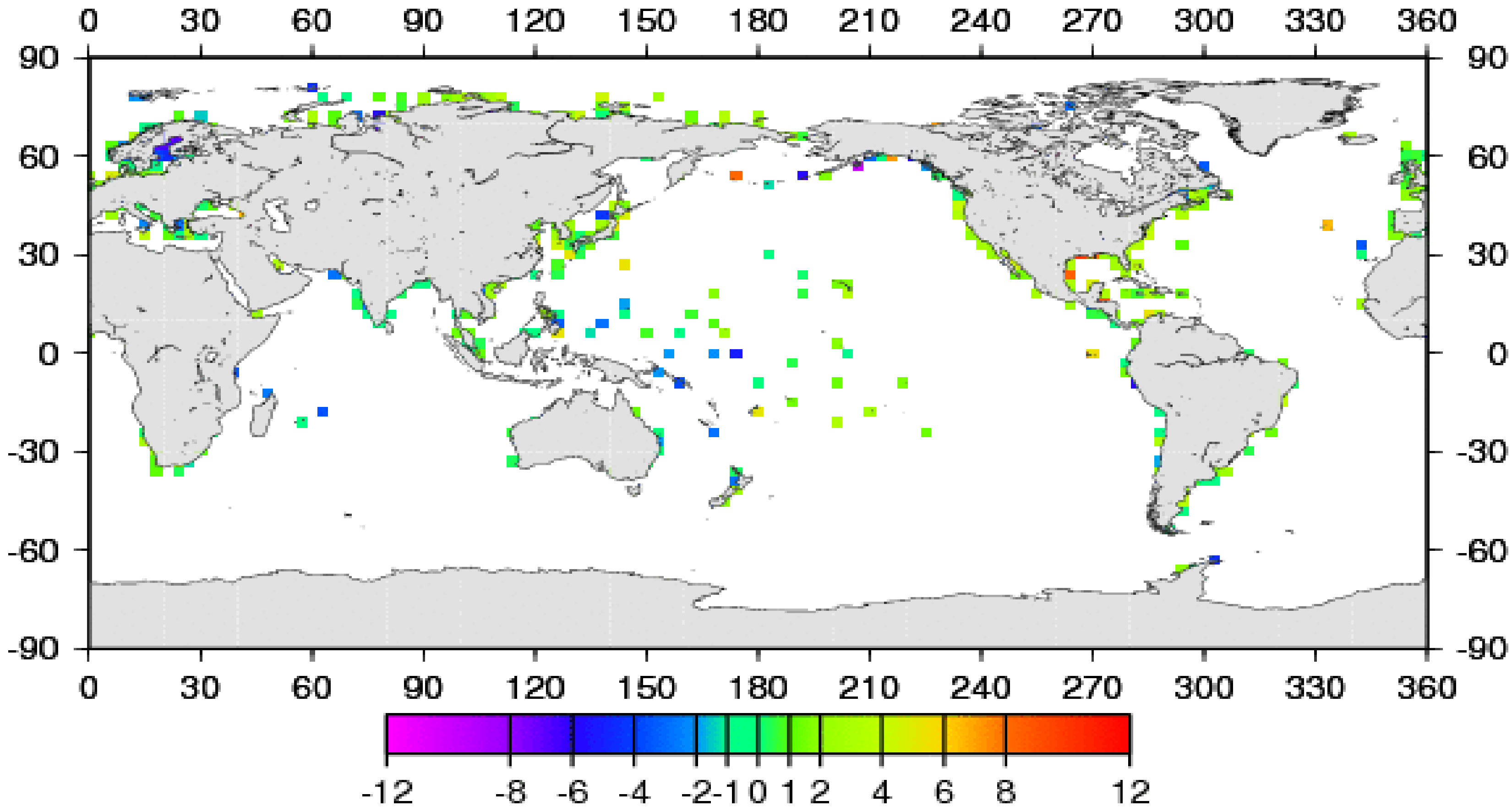
$$\delta h_{\mathrm{M}}(\vec{x},t) = S(\vec{x},t) + C(\vec{x},t) + A(\vec{x},t) + I(\vec{x},t) + G(\vec{x},t) + T(\vec{x},t) + P(\vec{x})(t-t_0) + V_0(\vec{x})(t-t_0) + \delta V(\vec{x},t) + B(\vec{x},t)$$

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.

Important for projection of mean sea level

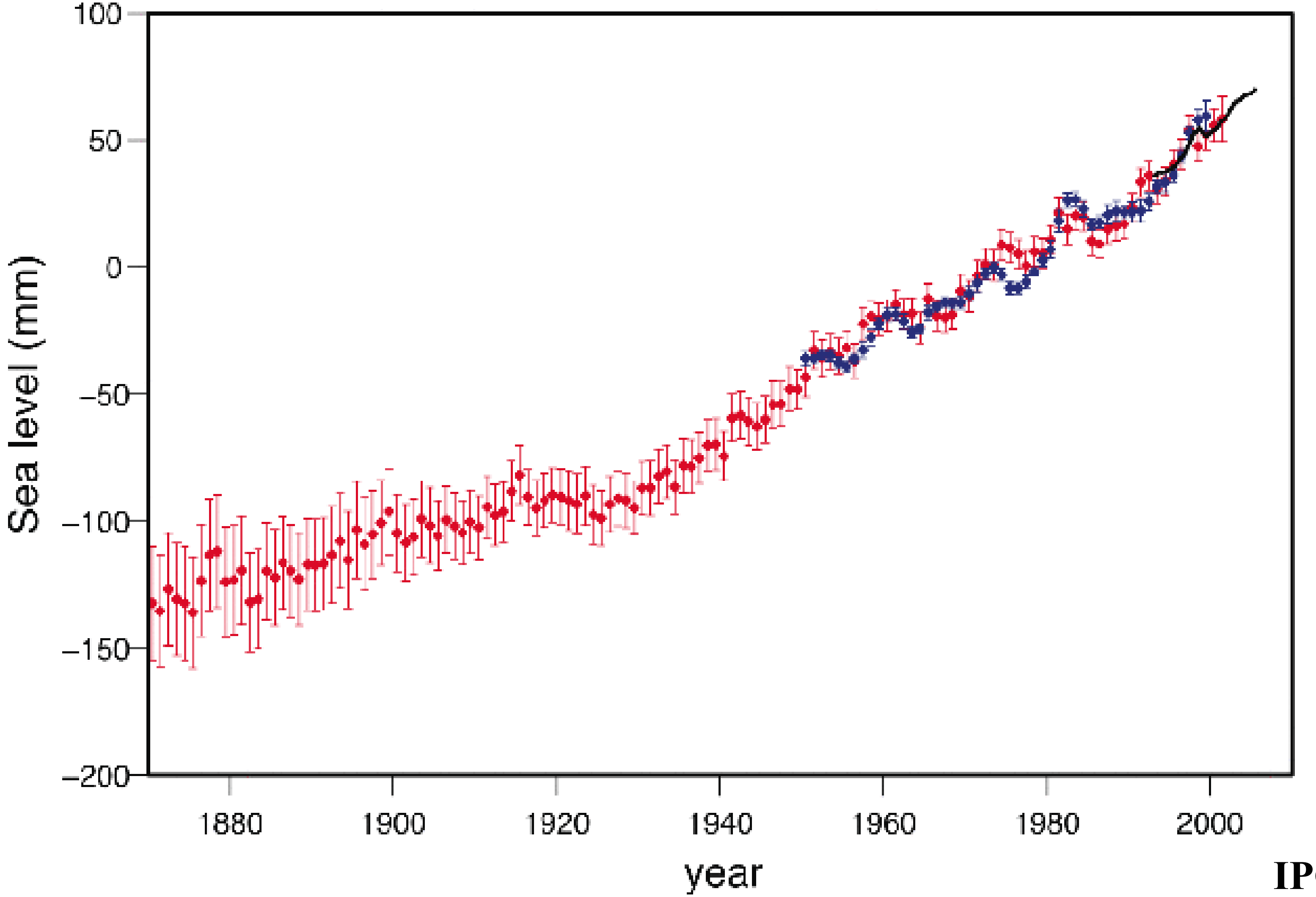
Result of local, regional and global processes!

Observations: Local Sea Level Trends



Plag, 2006

Global Sea Level Rise



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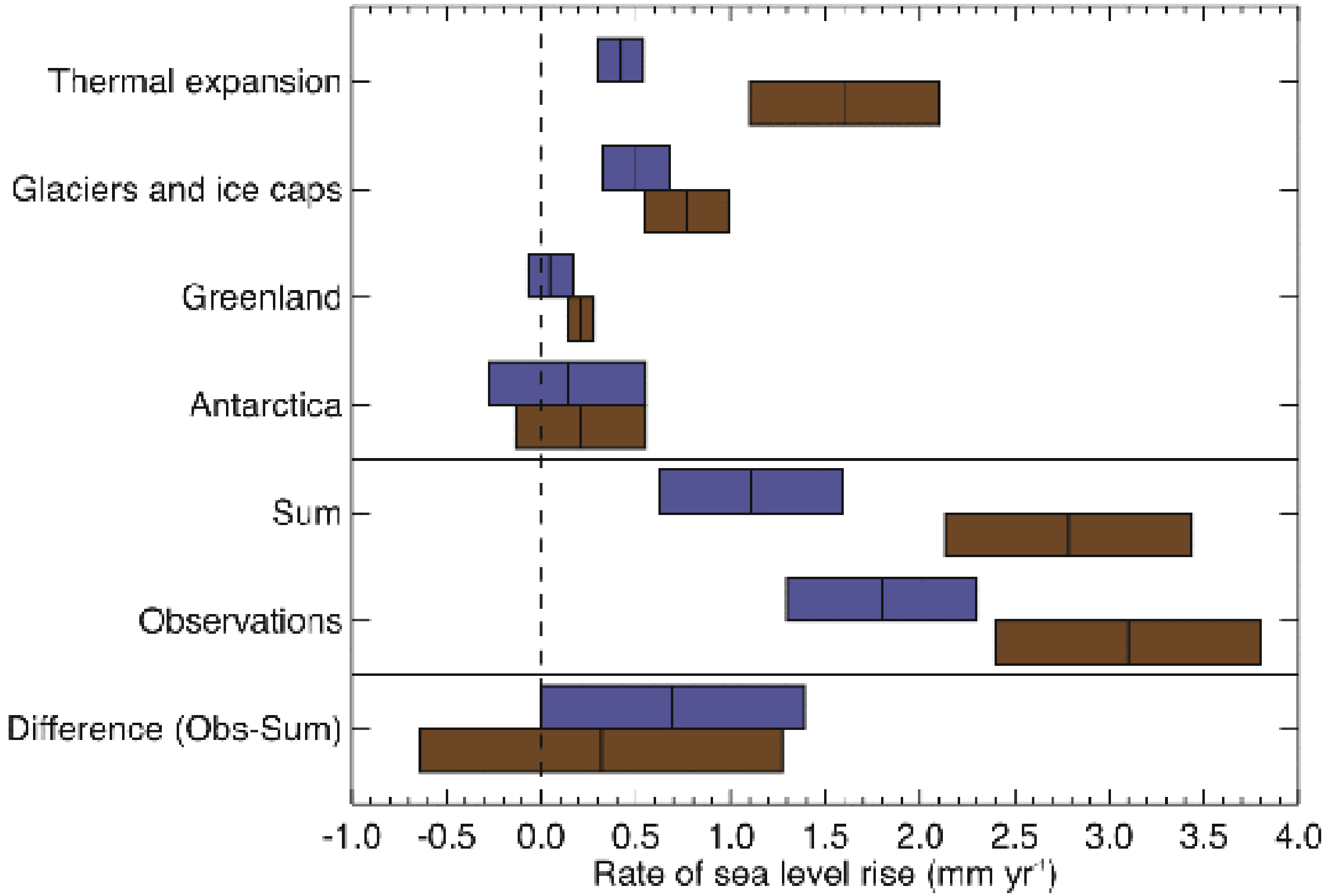
- Annual averages of the global mean sea level (mm).
- Red curve: reconstructed sea level since 1870 (Church and White, 2006);
- Blue curve: coastal tide gauge measurements (Holgate and Woodworth, 2004)
- Black curve: satellite altimetry (Leuliette et al., 2004).

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.*

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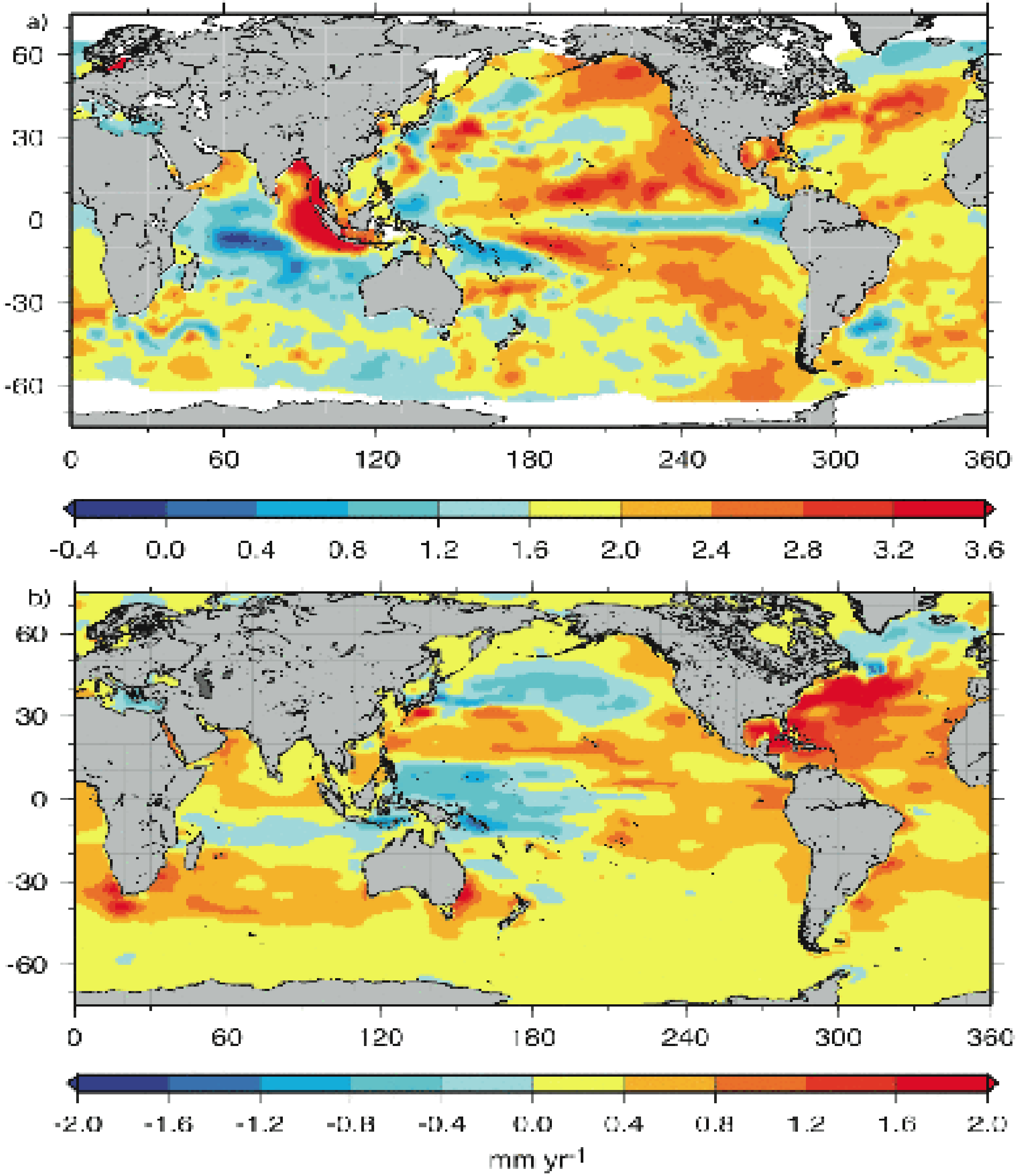
Local Sea Level Rise



(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).

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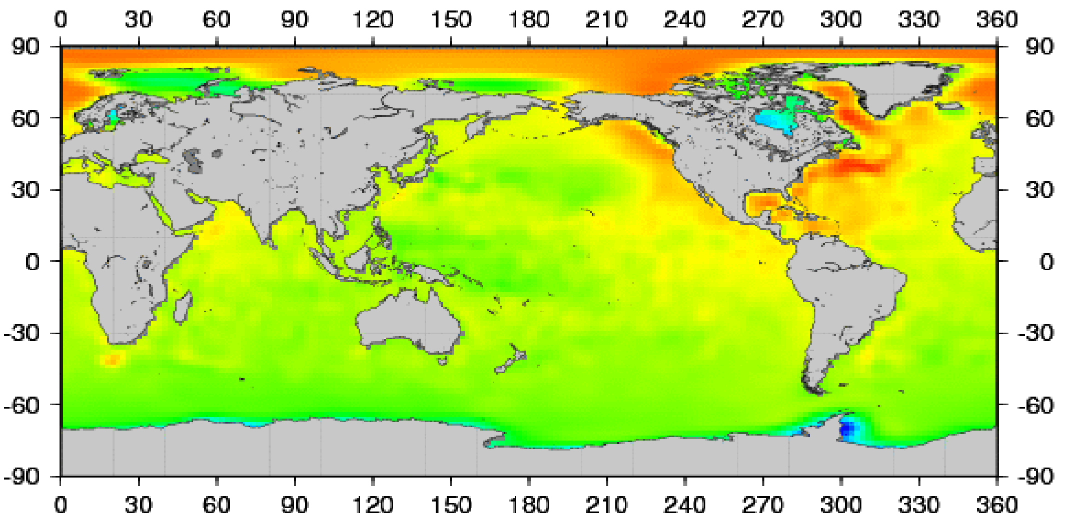
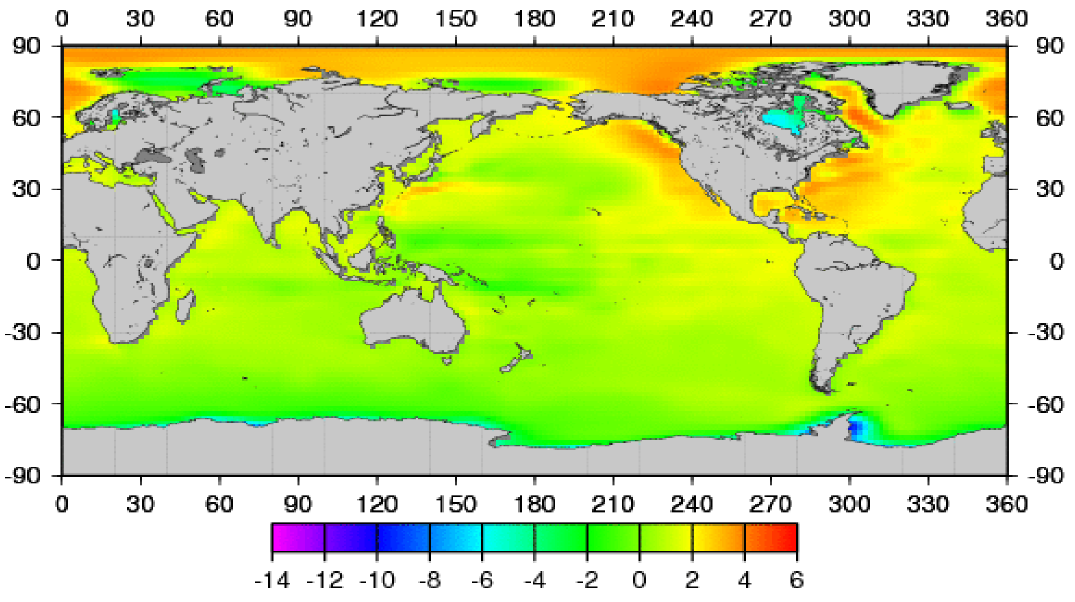
Reconstruction of Local Sea Level Trends



Levitus et al., 2000

Global models are consistent with 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

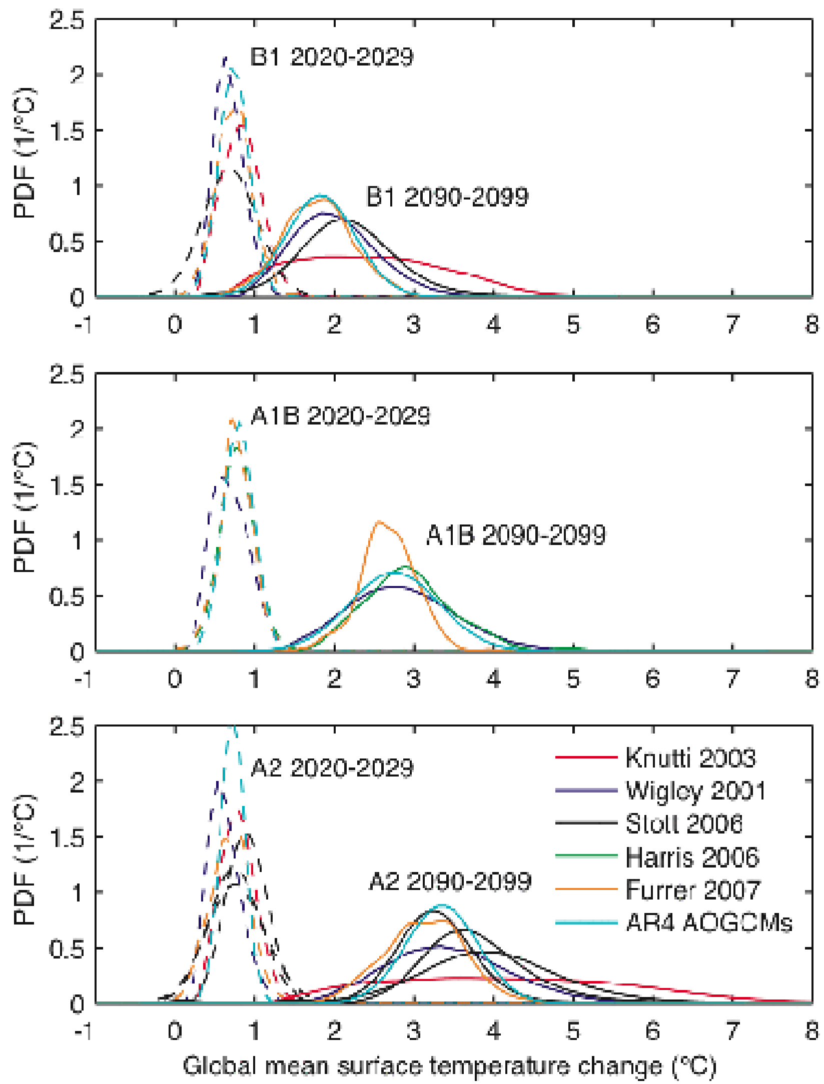
Forcing Scenarios of Future Sea Levels

- **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.

Forcing: Global Temperature

Question: *Can the Probability Density Function for global temperature be translated into a Probability Density Function for local sea level at a coast?*



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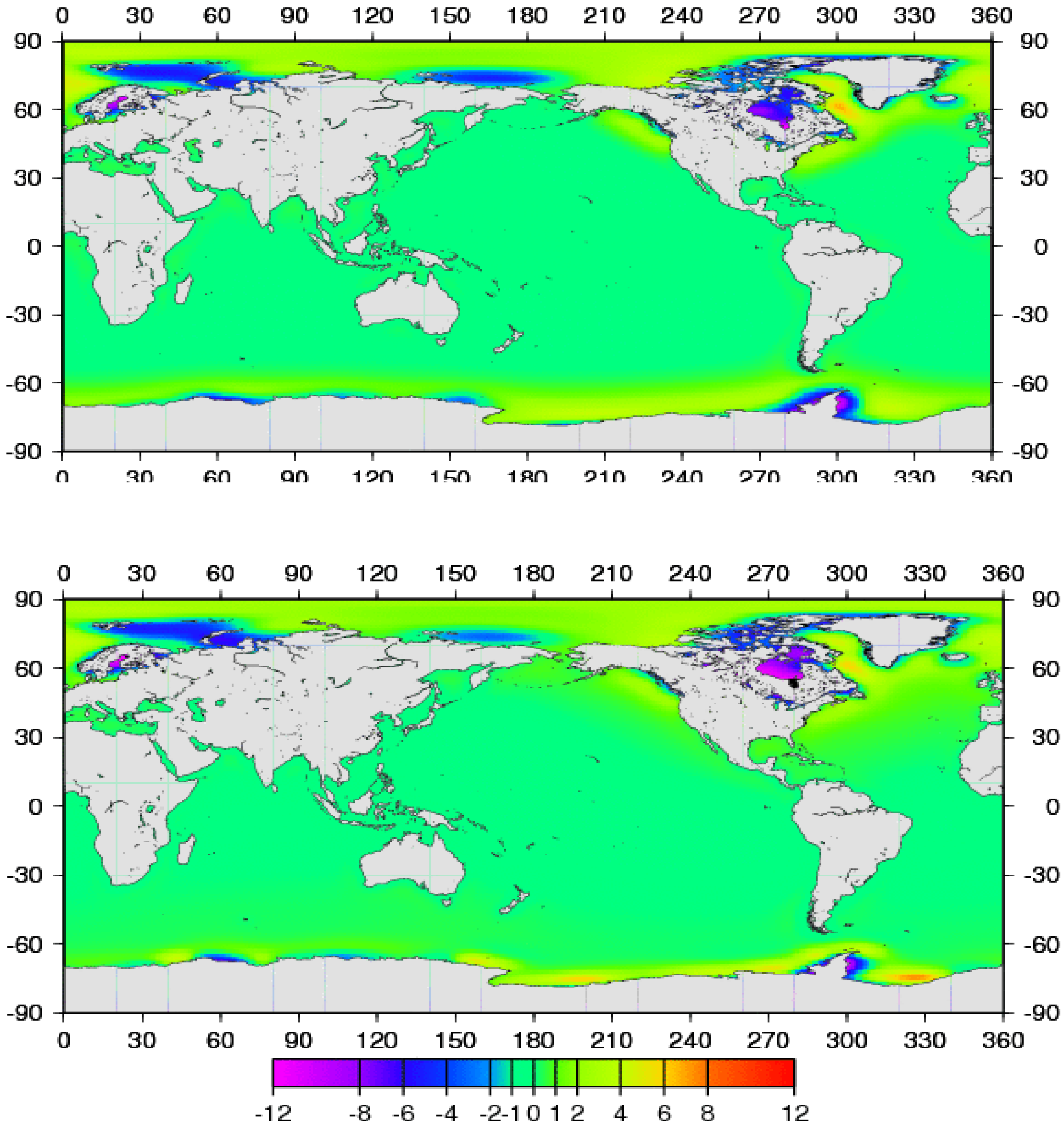
Forcing: Postglacial Rebound

Postglacial rebound: present-day signal in sea level



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Forcing: Ice Sheet Fingerprints

Present-day changes in:

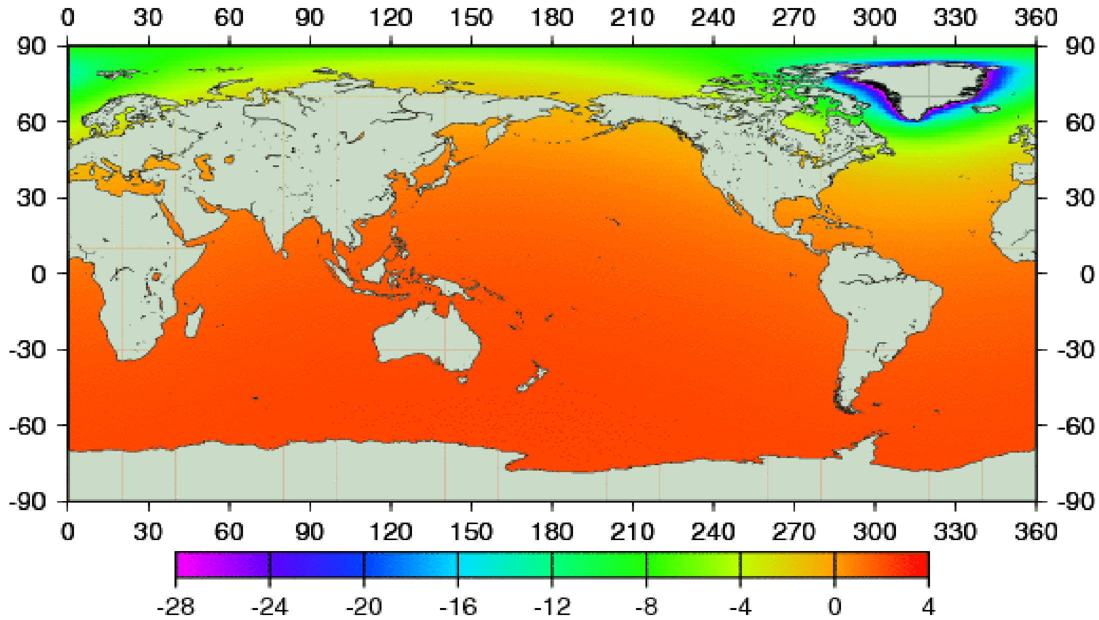
* Ice sheets
* Glaciers
* Land water storage

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

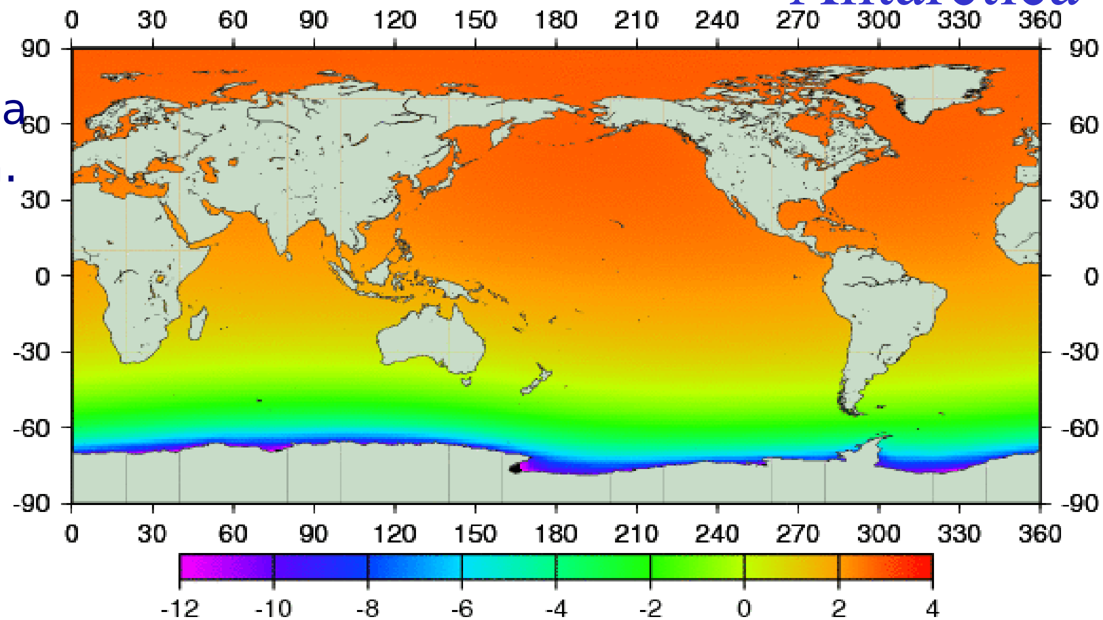
Solution of the static sea level equation for a unit linear trend over a given ice mass area.

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

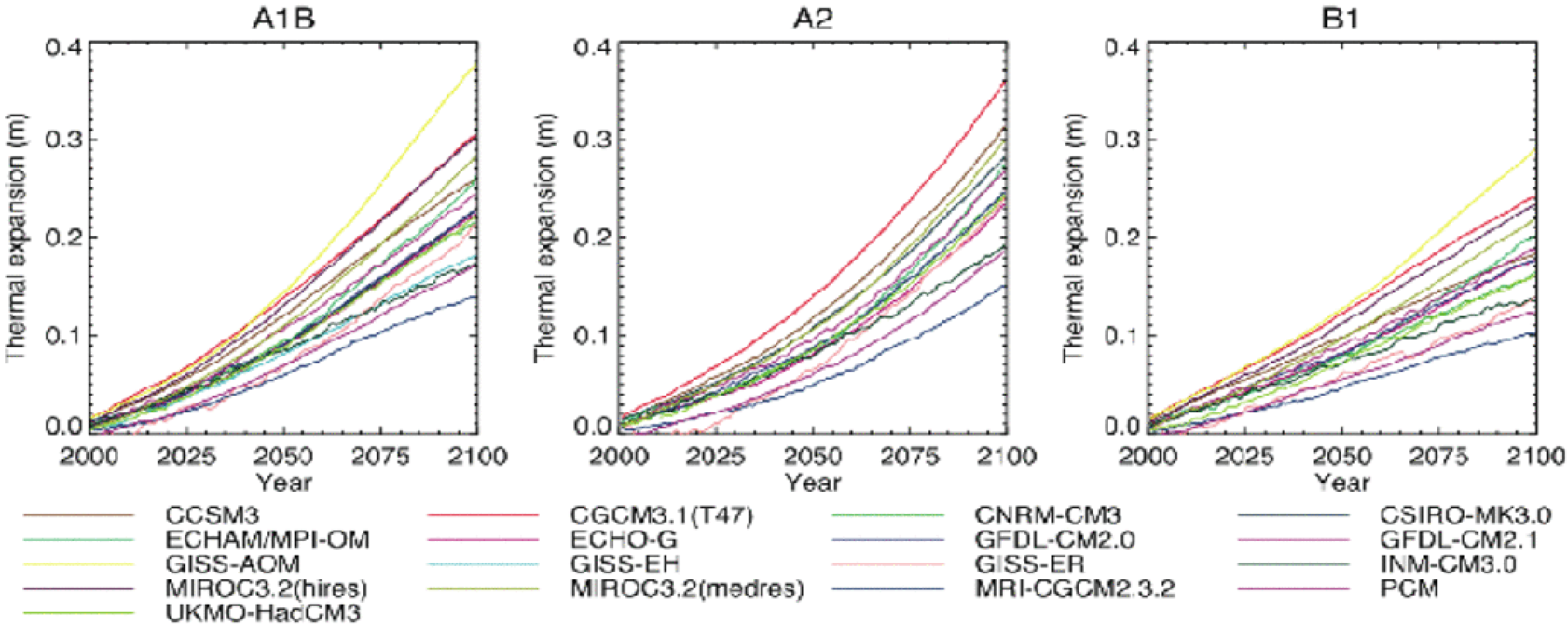
Greenland



Antarctica



Forcing: Global Thermal Expansion



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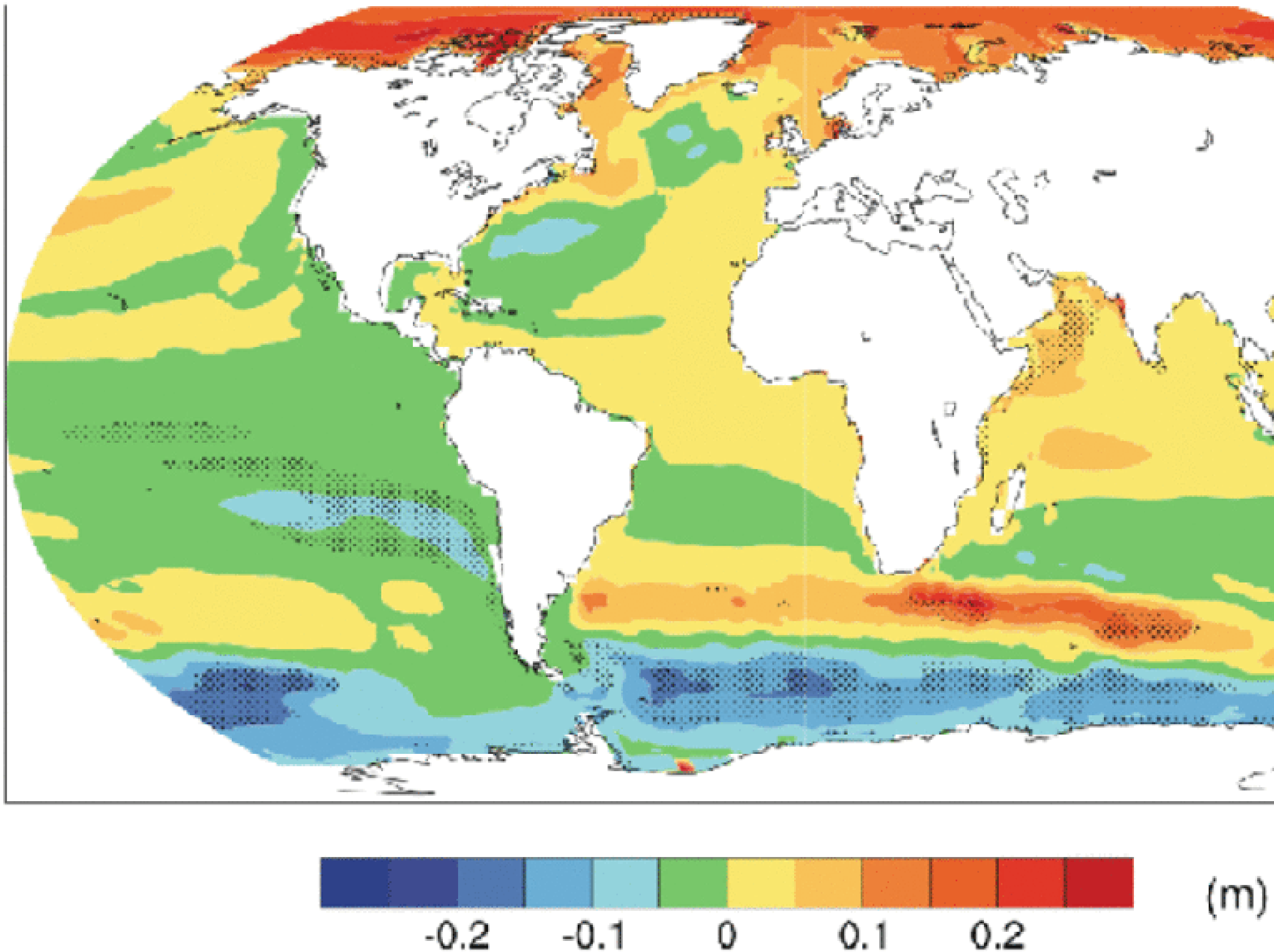
Projections of thermal expansion for various emission scenarios

Forcing: Global Thermal Expansion



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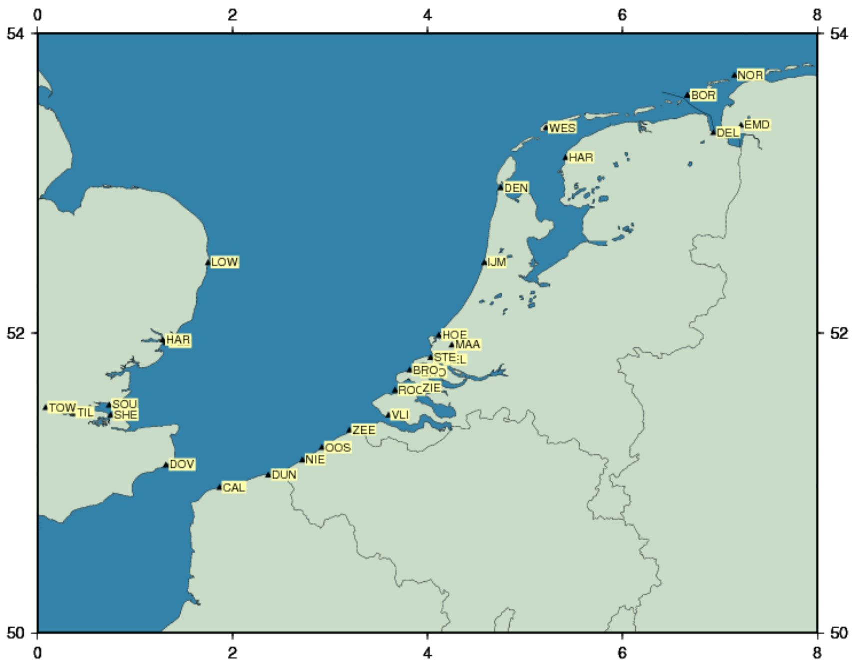
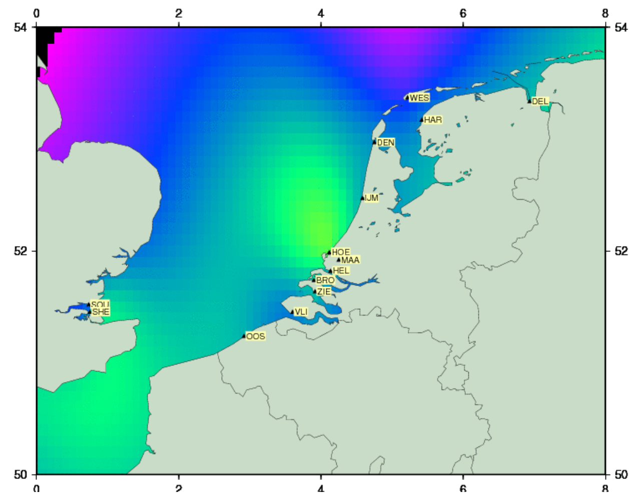
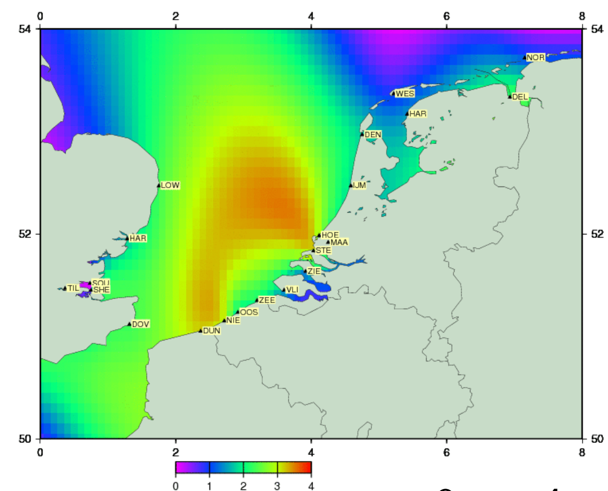
Example Dutch Coast: Spatial Pattern of Past LSL Trends





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

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;

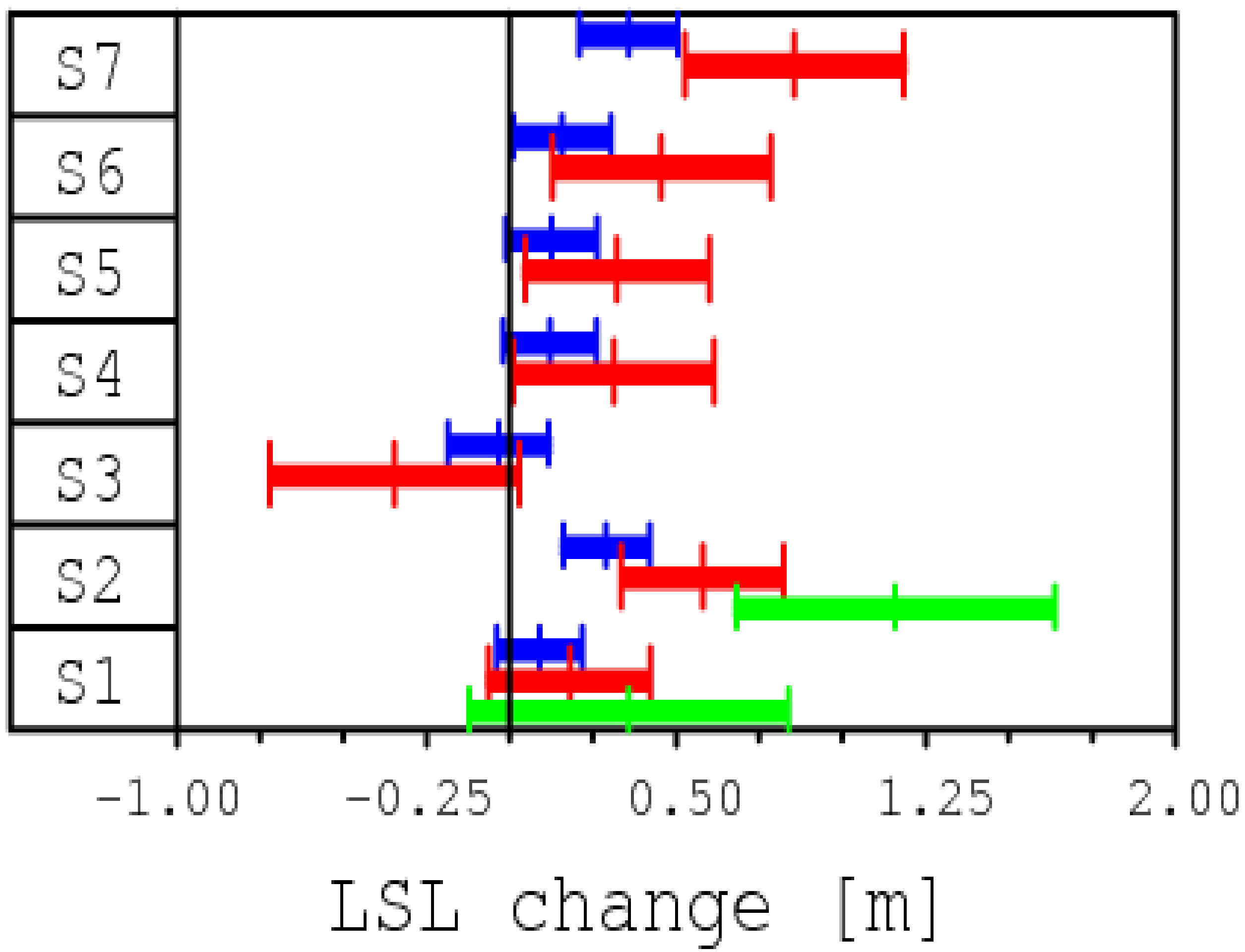
S4: As S1 but with increased melting of Antarctica;

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 Dutch LSLs



Blue: 2050

Red: 2100

Green: 2200

Five types of uncertainties

Manning and Petit (2003, IPCC Theme paper):

- **Incomplete or imperfect observations (aleatoric uncertainties):** vertical land motion, reference frame, oceanographic observations;

- **Incomplete conceptual framework (epistemic uncertainties):** with respect to climate system (including ocean circulation and thermal expansion : 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

"*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).

Past and Current LSL Changes:

Main uncertainties:

- 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).

Future Sea-level Changes:

Main Uncertainties:
- Spatial variability in thermal expansion.
- Dynamic response of **ice sheets** to climate forcing (large spatial variations).

Consequence:
- **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?

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Summary and Conclusions

- LSL is the coastal impact parameter, which depends on local, regional and global processes
- Uncertainties in predictions of future LSL result mainly from epistemic uncertainties concerning the climate system, in particular ocean circulation, thermal expansion, and the response of the ice sheet to climate forcing
- Incomplete and insufficient observations aggravate the problems in understanding past, present and future LSL changes
- Reducing the uncertainties requires better global monitoring: GEOSS, IGWCO, GOOS, GLOSS, GGOS, ...