Earth Observations as Decision Support for Adaptation and Mitigation Strategies in Response to Coastal Sea Level Rise

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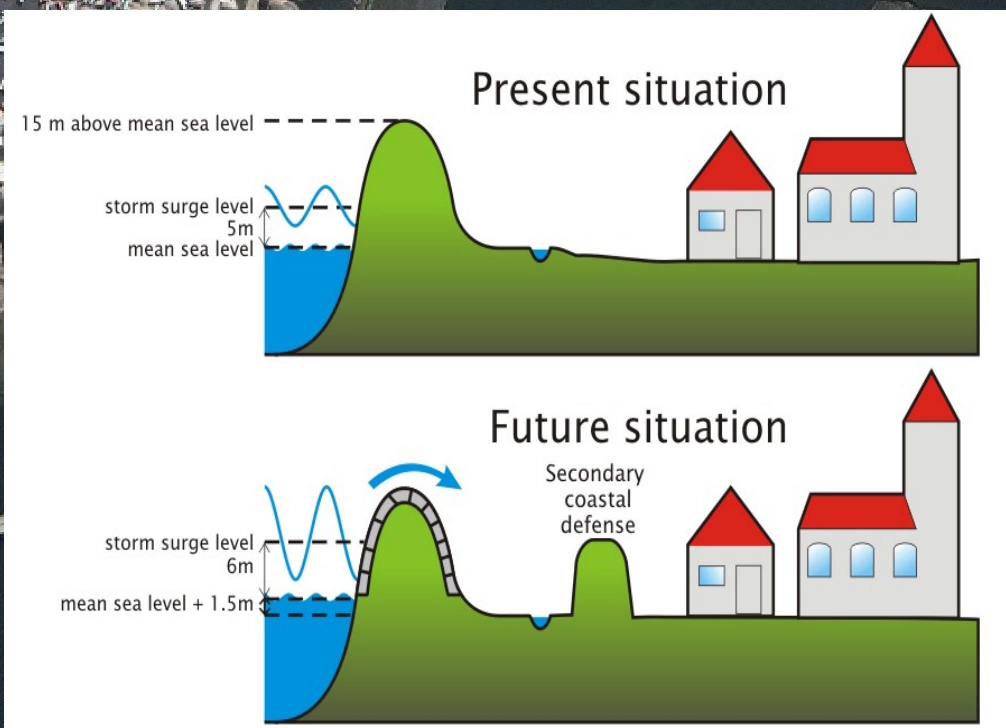
The potential threats:

- UN Development Program, 2008:
  332 million people in low-laying coastal zone
- Single disaster estimates: > $ 100 billion;
- World Bank, 2008: Disasters in two megacities in Asia could offset 20 years of global economic growth;

The challenges:

- Coastal defence: very high costs
- adaptation: relocation of settlements;
  Infrastructure (air ports, highways,pipelines, ...)



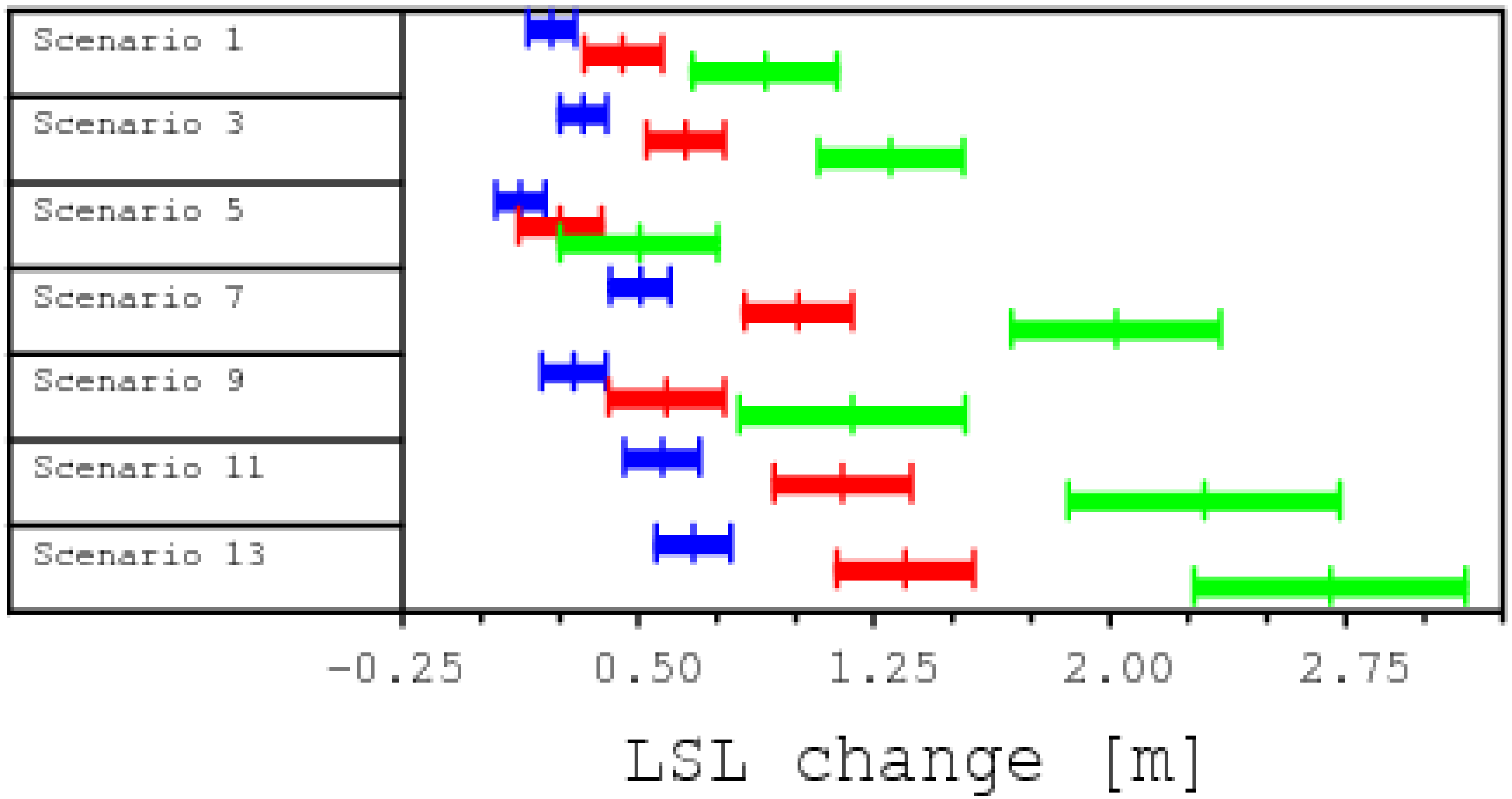
What is requested by policy makers?

- Local sea level (LSL) rise projections for the next 100 to 200 years, particularly high end;
- reliable uncertainties;
- full range of plausible LSL trajectories with probability density function (PDF);

Where do we stand?

- Projections give a wide range of LSL trajectories.
- no reliable PDFs.

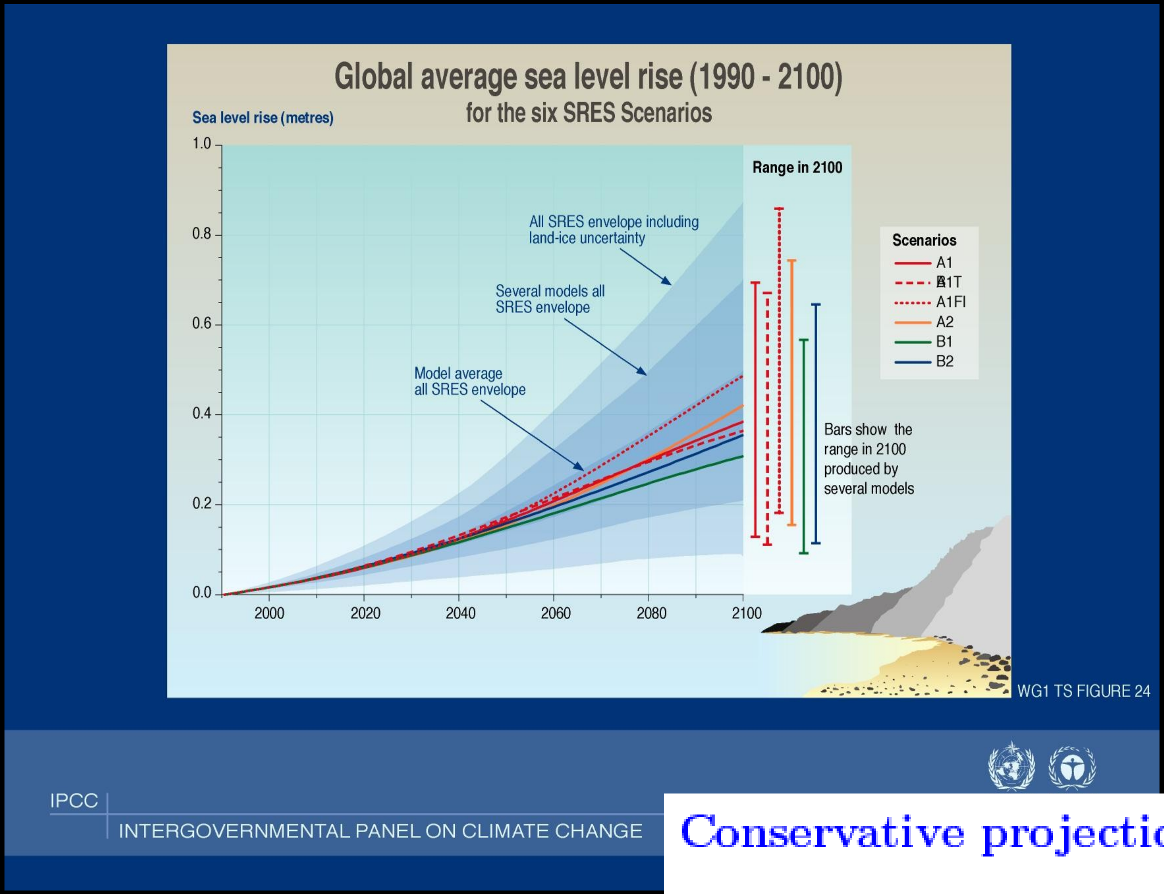
Blue: 2050
Red: 2100
Green: 2200



Recent examples: U.K., Venice, Dutch Coast, Southern Coasts of U.S.

How do we map the plausible range of LSL trajectories?

Mapping the Range of Plausible LSL Trajectories



“Localizing” global projections

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

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

Examples:

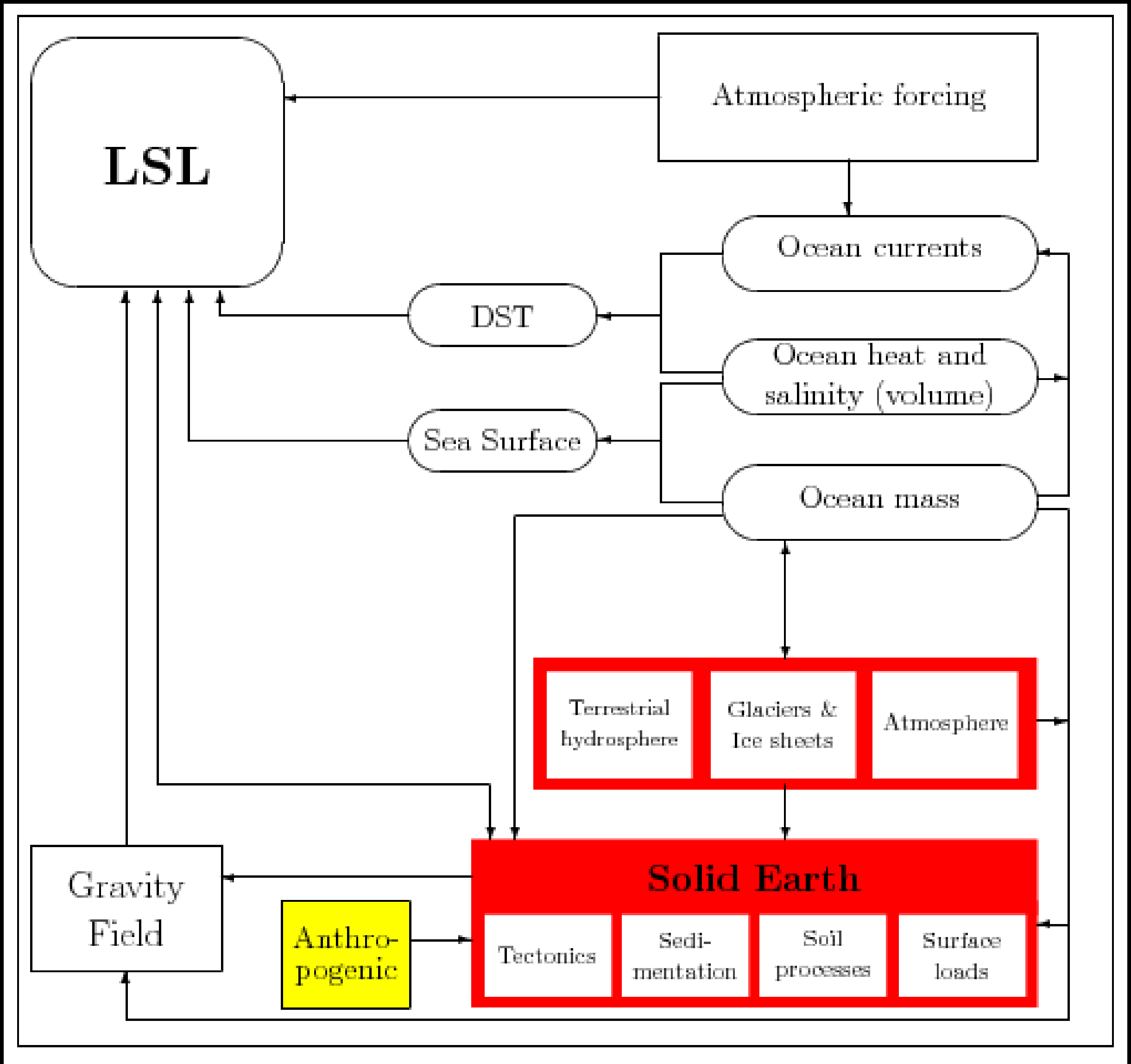
London: 1 m in mean sea level plus 2 m in surges

Germany and Netherlands: 1 m in mean

Denmark: 0.5 m in mean

Mapping the Range of Plausible LSL Trajectories

Local Sea Level (LSL): vertical distance between sea surface and land surface.



LSL is:
- Result of local, regional, and global processes;
- Earth system output

Modeling/preditions:
- Retrospective (modeling observed LSL): limited agreement
- Future LSL: Earth system model not available

Best practice:
- Local approach: sum of contributions from various processes

Mapping the Range of Plausible LSL Trajectories

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

Separation at periods of about 2 months

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

High-frequency LSL variations are the result of local and regional processes.

Mapping the Range of Plausible LSL Trajectories

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 (including freshening due to sea ice and land ice)
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 & Geoid changes
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

Low-frequency LSL Variations are the result of local, regional and global processes!

Mapping the Range of Plausible LSL Trajectories

Relation between mass changes in the water cycle and LSL:

Sea level equation (Farrell&Clark, 1976)

$$\xi(\vartheta,\lambda,t) = c(t) + O(\vartheta,\lambda,t)\int_{-\infty}^{t}\int_{0}^{\pi}\int_{0}^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t')$$
$$\frac{\mathrm{d}}{\mathrm{d}t'}\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda',t') + [1 - O(\vartheta',\lambda',t')]\,\rho_{\mathrm{L}}\eta(\vartheta',\lambda',t')\}\sin\vartheta'\mathrm{d}\lambda'\mathrm{d}\vartheta'\mathrm{d}t'.$$

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.

LSL change

Load on ocean areas

Loads on land areas

All mass movements
- change the geoid,
- displace the ocean bottom vertically
- redistribute water mass in the ocean

Mapping the Range of Plausible LSL Trajectories

Recent assessments: Sum of projections for each term in the LSL equation; combination of individual PDFs.

Problem: Different types of uncertainties (Manning and Petit, 2003):

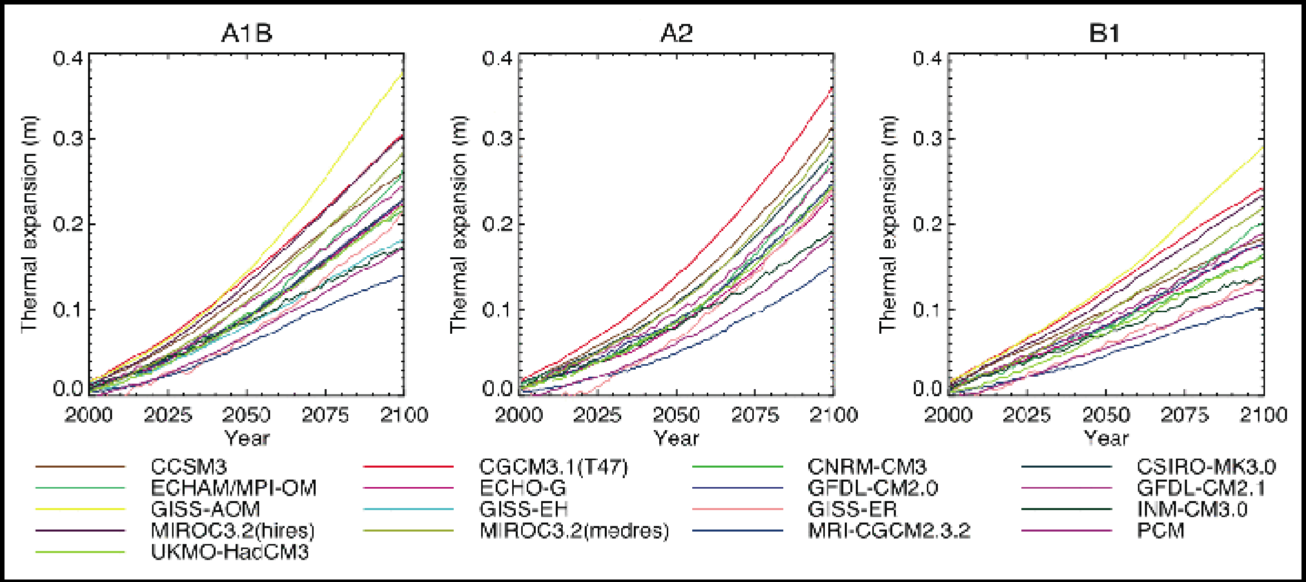
Uncertainty	Class	LSL forcing process
Incomplete or imperfect observations	aleatory	vertical land motion, reference frame, oceanographic observations;
Incomplete conceptual framework	epistemic	with respect to climate system: Yes; with respect to mass-LSL relation: No;
Inaccurate description of known processes	epistemic	one-dimensional models, incomplete mass redistribution, gravitationally inconsistent models, programming errors;
Chaos	epistemic	With respect to climate system (including ocean circulation): Yes; for mass-LSL relation: No;
Lack of predictability	epistemic	ice sheet behavior, mass exchange, ocean warming, circulation changes.

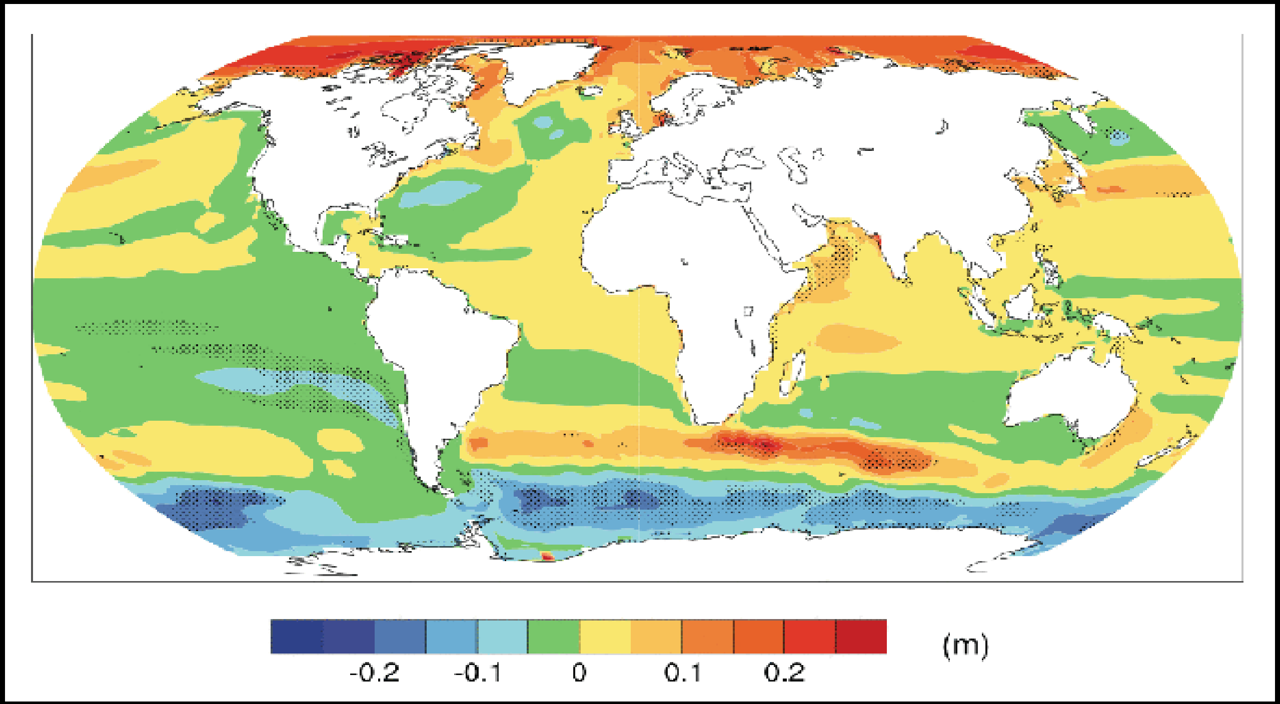
Treatment of uncertainties in the mapping of plausible LSL trajectories:

- Aleatory: values and PDF estimates from past observations;

- Epistemic: research; scenario approach: realistic assumptions concerning forcing; Ensemble studies (chaos, lack of predictability)

Uncertainties





Thermal expansion

Method:

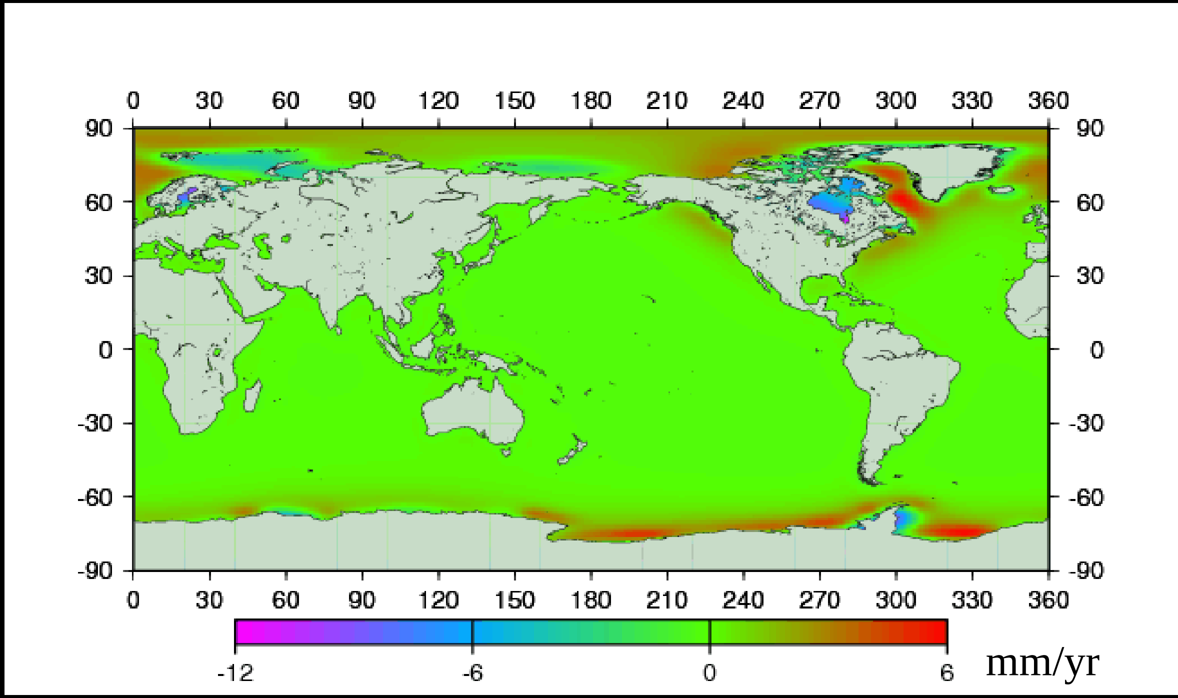
IPCC Emission Scenarios and Ensemble studies:

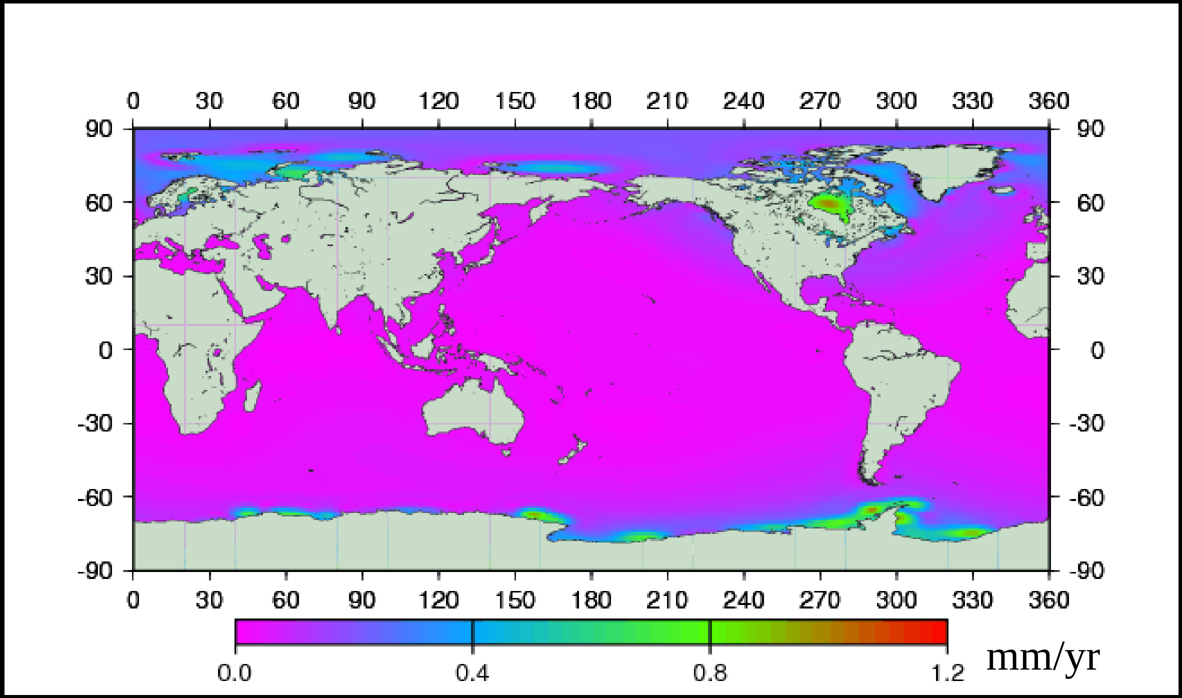
- GSL rise due to steric effect : 1.0 – 3.5 mm/yr

Regional variations:

- IPCC: ±2.0 mm/yr
- Some regional studies: ±4.0 mm/yr

Uncertainties





Postglacial rebound:

Method:
Extrapolation of predicted present-day signal in sea level;

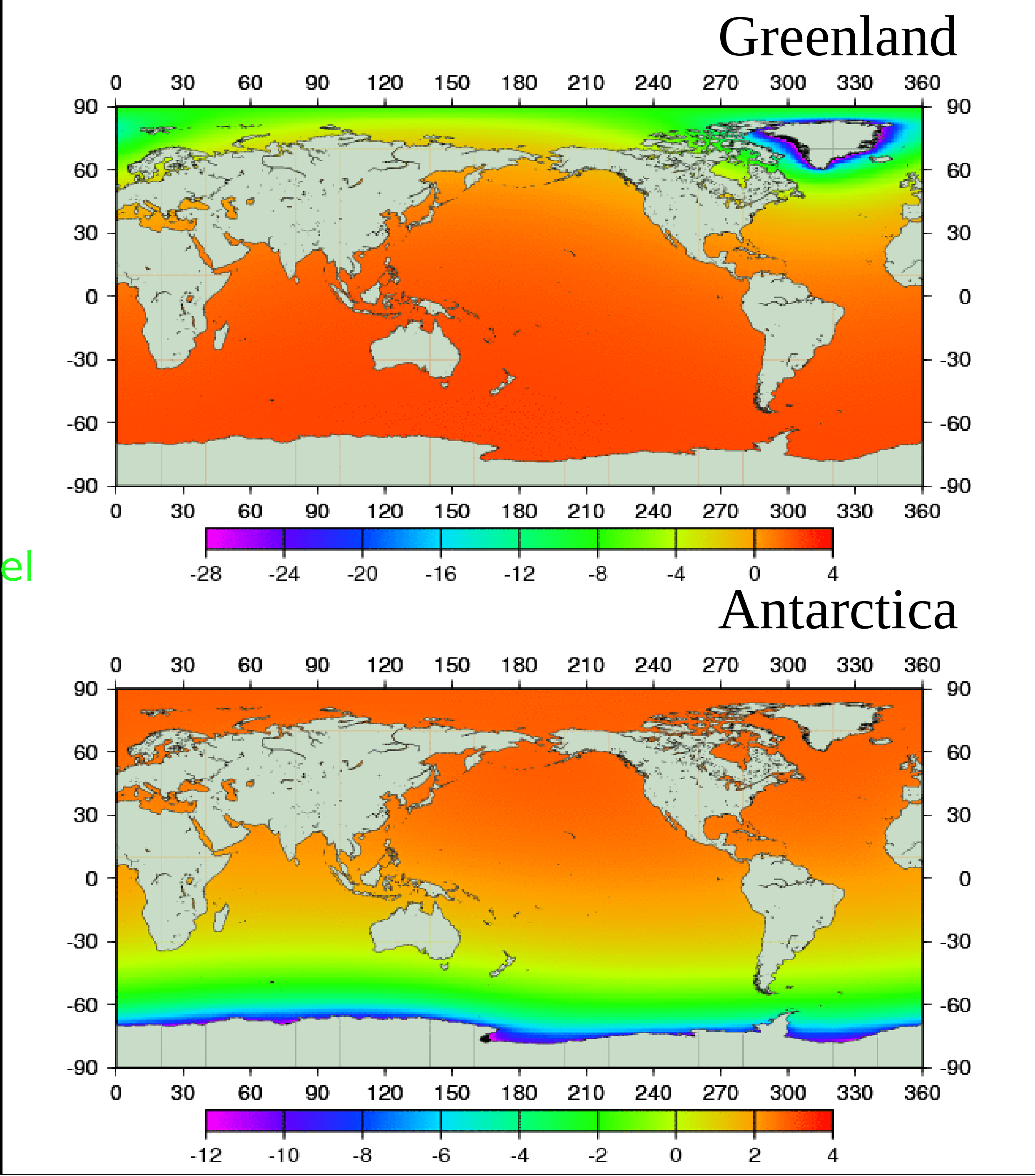
Mean of many predictions
Example: 14 different predictions
Signal: -10 to 5 mm/yr

Uncertainty from standard deviation:
Max. ± 1.2 mm/yr, relative: ~15%

Uncertainties

Present-day mass exchange:

- Ice sheets
- Glaciers
- Land water storage



For known mass changes: Solution of the static sea level equation

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

Fingerprint admittance functions: *describe the effect of a unit ice mass change in a given area on sea level.*

Uncertainties:
- *in mass change predictions;*
  * *total amount;*
  * *spatial distribution*
- *in admittance functions.*

Uncertainties

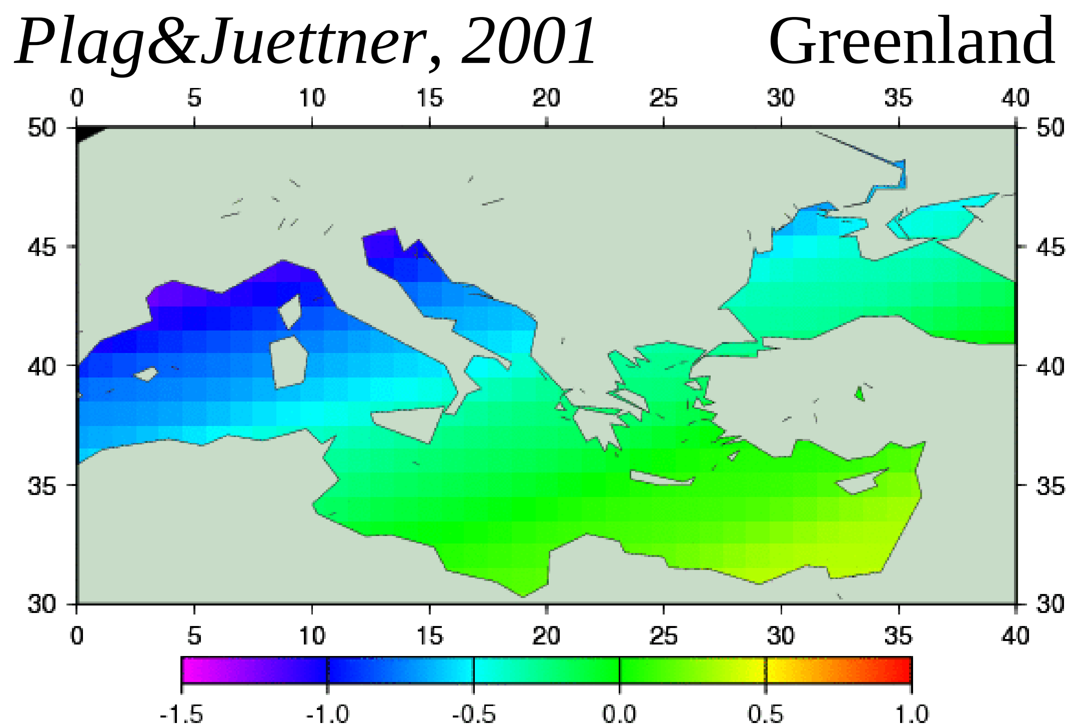
Uncertainties in Mass Changes:

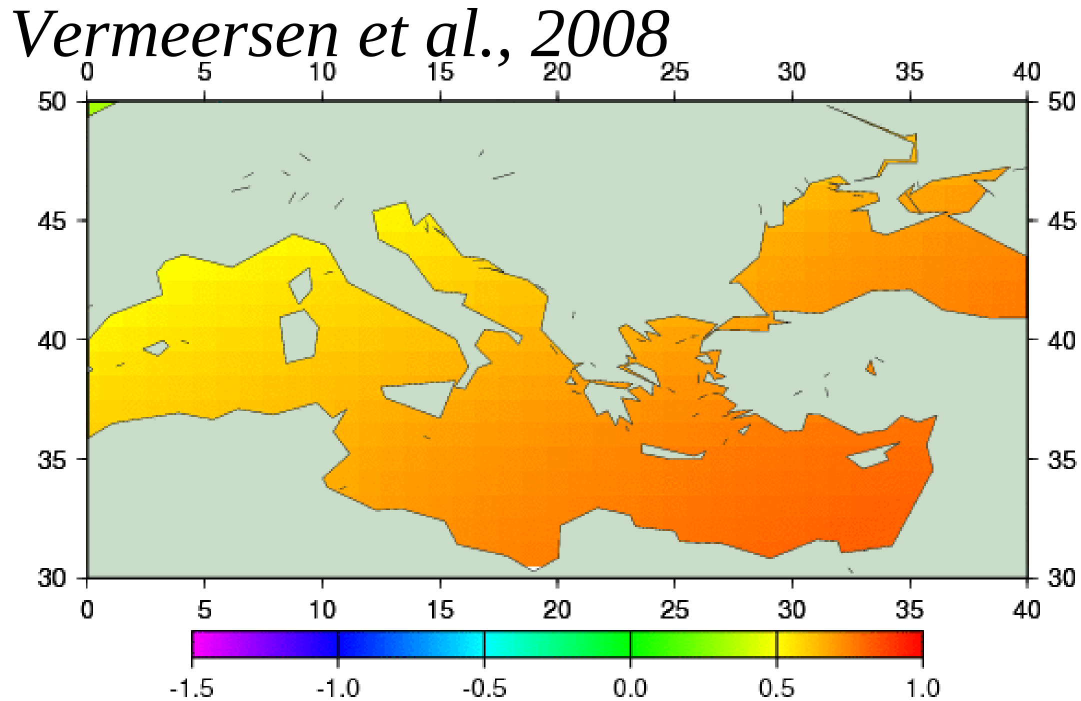
- Ice Sheets:
  * IPCC estimates may be too small;
  * impact of increased surface melt;
  * interaction of LSL rise and shelf ice;
  * dynamic response to warming.
- Glaciers:
  * IPCC estimates may be too small.
- Land hydrology:
  * large uncertainties in spatial distrib.

Uncertainties in Admittance Functions:

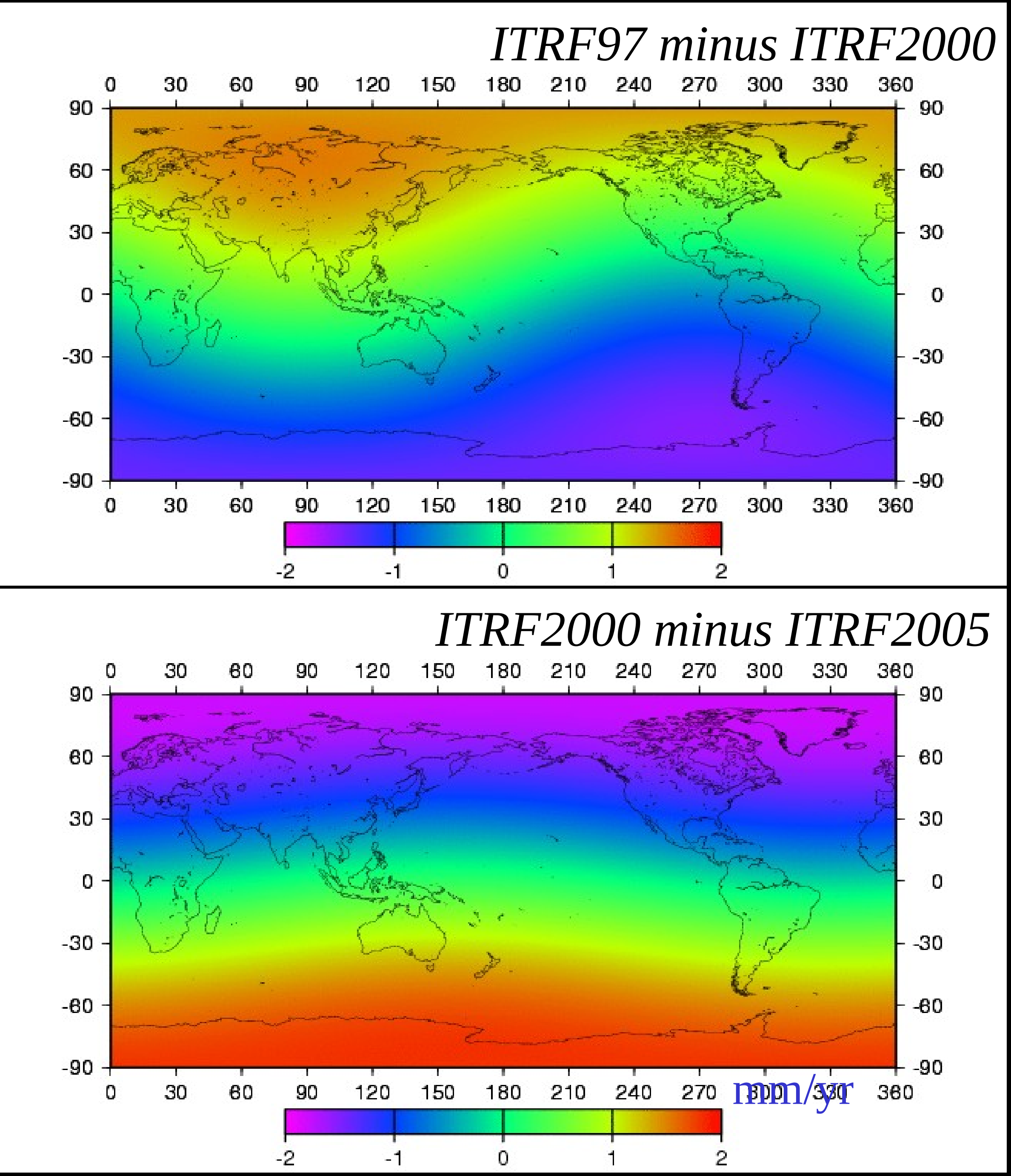
- Large intermodel differences.

- admittance functions not validated against observations;
- Recent observations from Greenland and Svalbard indicate large spatial variability in admittance functions.





Uncertainties



Vertical land motion:
- Observed vertical rate:
  * typical errors 0.1 – 0.3 mm/yr;
  * Uncertainty in reference frame: ±2 mm/yr.

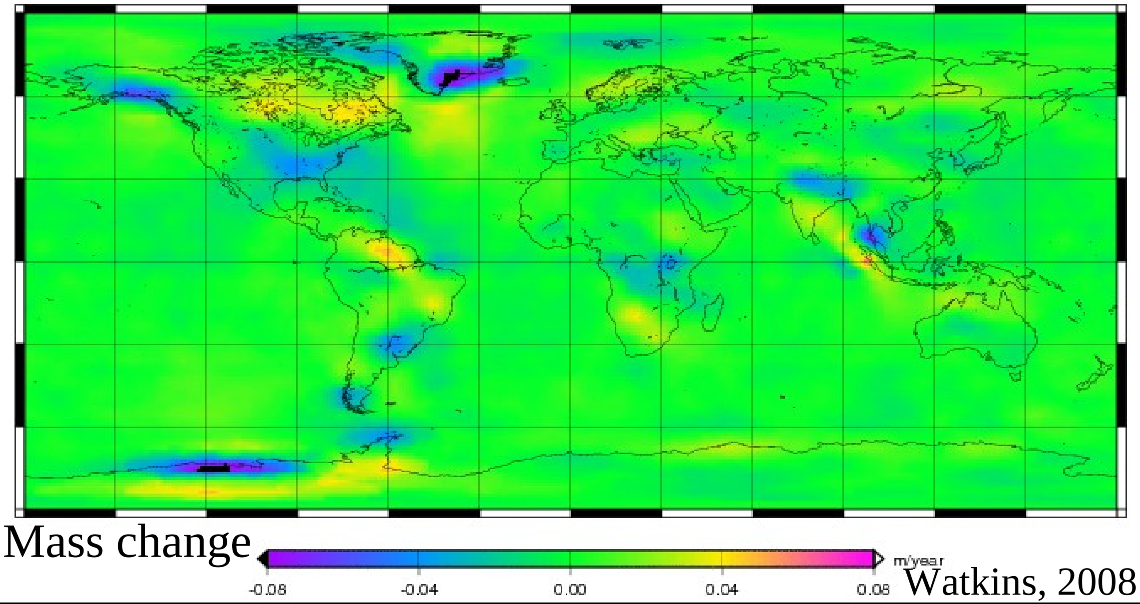
Problems for projections:
- high spatial variability;
- large gaps in spatial coverage;
- attribution to causes;
- non-linear contribution from present-day mass changes.

Reducing the Uncertainties

Uncertainties:

- steric contribution (thermal expansion):
  * separation of mass and steric contribution (gravity, sea surface).
- mass exchange:
  * ice sheets: improved observational constraints (ice and land surfaces, gravity);
  * glaciers: more observations of LSL, land surface and mass balance for coastal glaciers;
  * land hydrology: improved observational constraints (land surface and gravity).
- validation of admittance functions:
  * improved observations close to large, rapidly changing ice loads (LSL, land surface, gravity).
- vertical land motion:
  * improved tie between reference frame origin and center of mass;
  * observations in high risk areas (in particular, coastal mega cities).

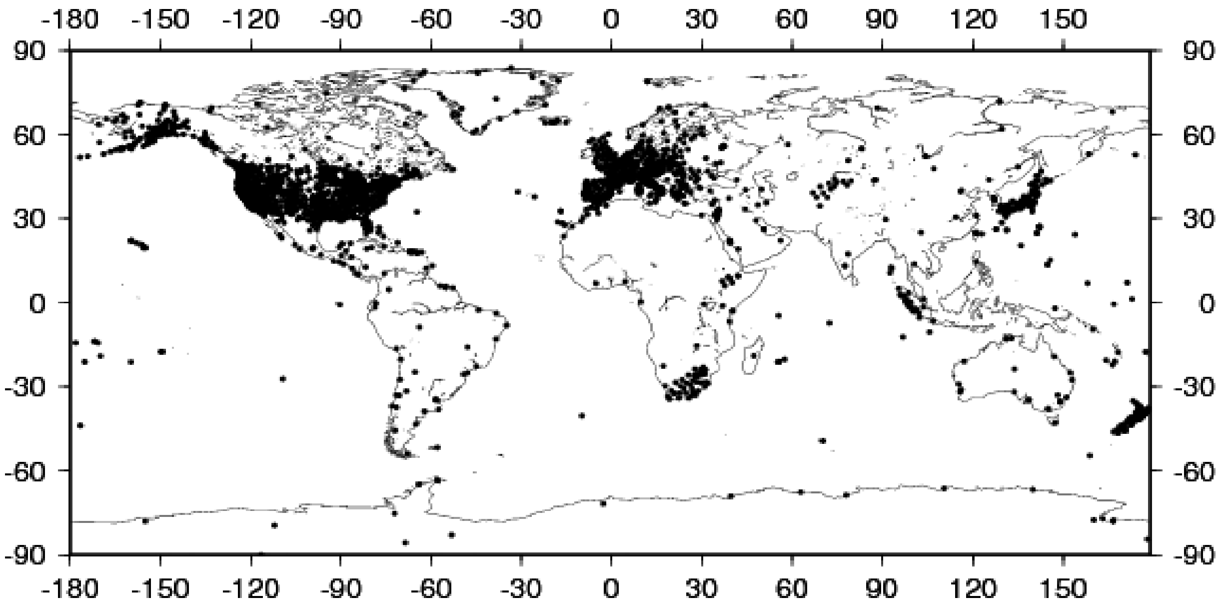
Reducing the Uncertainties



Mass change

Watkins, 2008

GPS site locations, ~4,000 sites



Blewitt and Kreemer, 2008

Validation of Admittance Function, mass change models, ice sheet dynamics models:

Increased observations (surface displacements, gravity, mass balance) in areas with large mass changes, in particular:

- Greenland;
- Svalbard;
- Antarctica and southern South America .

Reducing the Uncertainties

If successful, what will we get?

Improved retrofit: Yes

Reduced range of plausible LSL trajectories: Hardly

"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).

Decision Support for Climate Change Impact

What do decision and policy makers mostly expect?

Science-based approach:
- first predict, then react/adapt
- Basic assumption: system can be described by a set of equations, and, if initial conditions are known, predicted (Reductionism)

Limitations:
- complex system for which future is unpredictable with narrow uncertainties
- Present is already different from the last 650,000 years
- Future is going to be different from the past (paleo-results cannot be used to explore the future)

Important contribution: Monitoring and understand the trajectory of the system through well-observed, emerging properties (emergence)

Decision Support for Climate Change Impact

Problem: Policy making, mitigation, and adaptation in the face of large, and mostly unreducable uncertainties

Contribution of the Scientist:

- understand and respect the uncertainties (type, quantity)
- map the range of plausible futures,
  * use reductionism where appropriate;
  * use ensemble and scenario approach where necessary;
- monitor (in particular) those characteristics and components that are not predictable;
- develop assimilation models with limited (in time) predictive capabilities to support rapid response to new developments

Decision Support for Climate Change Impact

Problem: Policy making, mitigation, and adaptation in the face of large, and mostly unreducable uncertainties

Contribution of decision/policymakers:

- respect the uncertainties (and scientific limitations)
- plan flexible adaptation based on the range of plausible futures
- adjust as needed
- Plan to be prepared for surprising trajectories (hopefully within the space of plausible futures): reduce vulnerability, increase resilience;
- Ensure (through framework conditions and funding) sufficient monitoring of the Earth system and relevent research.

Applied to LSL changes:

- flexible planning with contingency for future developments
- frequent reassessments using a widely accepted systematic approach
- building (increasingly more expensive) protections where possible
- slow retreat from coastal zone areas prone to inundation and/or


Thank you for your attention!