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

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Potential impact: Example Florida

Today

1 m

2 m

4 m

[Maps and images of Florida depicting potential impact areas with varying elevations]
Potential impact: Example Bangladesh

Today

1 m

2 m

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

IPCC, AR4
(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).
Basic Terms and Concepts in Sea Level Studies

Local Sea Level (LSL):

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

\( r_0 \) and \( r_1 \): geocentric positions of the sea floor and sea surface, respectively.

\( \phi, \theta \): geographical longitude and latitude, respectively.

- LSL is an absolute quantity (i.e. reference frame independent).
- Sea Surface Height (SSH) is a relative quantity.

Global Ocean Volume (GOV):

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

Global Ocean Mass (GOM):

\[
M_O = \int_0^R \rho dV
\]

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

Comments on the relation between mass changes (exchange and redistribution) and LSL.
What causes the sea level to change?

- Terrestrial water storage, extraction of groundwater, building of reservoirs, changes in runoff, and seepage into aquifers
- Subsidence in river delta region, land movements, and tectonic displacements
- Surface and deep ocean circulation changes, storm surges
- As the ocean warms, the water expands
- Exchange of the water stored on land by glaciers and ice sheets with ocean water
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:

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

Important for projection of maximum flood levels

Result of local and regional processes.
Low-frequency part of LSL equation:

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

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

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

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!
Relation between mass changes in the water cycle and LSL:

Sea level equation (Farrell & Clark, 1976)

\[ \xi(\theta, \lambda, t) = c(t) + O(\theta, \lambda, t) \int_0^{\infty} \int_0^{2\pi} G(\theta, \lambda, \theta', \lambda', t - t') \]

\[ \frac{d}{dt'} \left\{ O(\theta', \lambda', t') \rho_W \xi(\theta', \lambda', t') + [1 - O(\theta', \lambda', t')] \rho_L \eta(\theta', \lambda', t') \right\} \sin \theta' d\lambda' d\theta' d t'. \]

\( \xi \): local sea level change (distance to the deformable solid Earth surface),
\( G \): Green's function for sea level,
\( O \): ocean function,
\( \eta \): cumulated water/ice load change due to mass added or removed from land,
\( \rho_W \) and \( \rho_L \): densities of the ocean water and the load (water or ice), respectively,
\( c(t) \): quantity to ensure mass conservation.

All mass movements
- change the geoid,
- displace the ocean bottom vertically
Forcing: Postglacial Rebound

Postglacial rebound: present-day signal in sea level

<table>
<thead>
<tr>
<th>N</th>
<th>Author</th>
<th>Model</th>
<th>$N_0$</th>
<th>$d$</th>
<th>$\eta_a$</th>
<th>$\eta_r$</th>
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<td>P</td>
<td>VM4</td>
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<tr>
<td>P13</td>
<td>S</td>
<td>S1</td>
<td></td>
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</table>
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)
Forcing: Thermo-Steric Changes

Levitus et al., 2000

Ishii et al., 2003

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Oceanographic data</th>
<th>Depth</th>
<th>Temporal</th>
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<tr>
<td>&quot;L500&quot;</td>
<td>Ishii et al. (2003)</td>
<td>500 m</td>
<td>1 month</td>
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<tr>
<td>&quot;L500&quot;</td>
<td>Levitus et al. (2000)</td>
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<td>1 year</td>
</tr>
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</tr>
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<td>&quot;L700&quot;</td>
<td>Levitus et al. (2000)</td>
<td>700 m</td>
<td>1 year</td>
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</table>

\[
\text{mm/yr}\]

\[
\text{mm/yr}\]

\[
\text{mm/yr}\]
Observations: Local Sea Level Trends

Plag, 2006
Reconstruction of Local Sea Level Trends

Global models consistent with tide gauges

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

Levitus et al., 2000

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

Ishii et al., 2003

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:

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

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

\[h_{\text{GPS}}: \text{has to be given with respect to the Center of Mass of the Earth System!}\]

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

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

Effect on LSL +- 2 mm/yr

ITRF97 minus ITRF2000

ITRF2000 minus ITRF2005

mm/yr
Example Dutch Coast: Spatial Pattern of Past LSL Trends

Observed LSL Trends
Upper: All data
Lower: Data for 1950 - 2008
Example Dutch Coast: Past LSL Trends, Summary

**Observed Trends:**
* Considerable spatial variability (order $\pm 2$ mm/yr)
* Considerable temporal variability from 5 to more decades (order $\pm 1$ 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?
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.
Global average sea level rise (1990 - 2100) for the six SRES Scenarios

Sea level rise (metres)

Range in 2100

Scenarios
- A1
- B1T
- A1FI
- A2
- A2
- B1
- B2

Bars show the range in 2100 produced by several models

All SRES envelope including land-ice uncertainty

Several models all SRES envelope

Model average all SRES envelope

Years:
- 2000
- 2020
- 2040
- 2060
- 2080
- 2100
Conservative scenario (Hulme et al., 2002; Nicholls, 2005):

\[
h_{\text{future~mean}} = \text{IPCC projection} + 50\% \text{ regional/local amplification} \\
= 1.5 \times h_{\text{IPCC}}(t = 2100)
\]

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
Scenarios of Future Sea Levels

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

\[
h_{\text{future maximum}} = h_{lf}(t = t_P) + \max(h_{lf}(t = t_P))
\]

For \( h_{lf} \):

<table>
<thead>
<tr>
<th>Factor</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>...</th>
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<td>Steric</td>
<td></td>
<td></td>
<td>local to regional</td>
<td></td>
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<tr>
<td>Ocean currents</td>
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<td></td>
<td>local to regional</td>
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<tr>
<td>Atmosphere</td>
<td></td>
<td></td>
<td>Order of a few cm over a century</td>
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<tr>
<td>Greenland</td>
<td></td>
<td></td>
<td>Depends on ice scenario and location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antarctica</td>
<td></td>
<td></td>
<td>Depends on ice scenario and location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glaciers</td>
<td></td>
<td></td>
<td>Depends on ice scenario and location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terr. Hydro.</td>
<td></td>
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<td>Depends on load scenario and location</td>
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<tr>
<td>Land</td>
<td></td>
<td></td>
<td>Depends on reference frame and location</td>
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Forcing Scenarios and Projections of Future LSLs

### PDFs

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<th>90% boundaries</th>
<th>Remarks</th>
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<td>0 mm</td>
<td>±50 mm</td>
<td>Oscillatory nature, times scales of 50-100 years</td>
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<td>50 mm</td>
<td>±50 mm</td>
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<td>±2 mm/yr</td>
<td>Mean shift in wind and air pressure</td>
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<td>-1.25 mm/yr</td>
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<td>At Dutch coasts</td>
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<td>LSL trend</td>
<td>-1 to 3 mm/yr</td>
<td>±1 mm/yr</td>
<td>Spatially variable</td>
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</table>
Forcing Scenarios and Projections of Future LSLs

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

<table>
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<td>Atmosphere</td>
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<td>0 ± 50</td>
<td>0 ± 50</td>
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<td></td>
<td></td>
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<tr>
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<td>44 ± 22</td>
<td>88 ± 22</td>
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<tr>
<td>5</td>
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<td>11</td>
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<td>300 ± 100</td>
<td>600 ± 200</td>
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<tr>
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<td>S5 1+2+3+5+8+9+10+11</td>
<td>126 ± 137</td>
<td>323 ± 277</td>
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</tr>
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<td>S6 1+2+3+6+8+9+10+11</td>
<td>157 ± 147</td>
<td>456 ± 329</td>
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<tr>
<td></td>
<td>S7 1+2+3+6+8+9+10+12</td>
<td>358 ± 147</td>
<td>856 ± 329</td>
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</tr>
</tbody>
</table>

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**LSL Projections**
Forcing Scenarios and Projections of Future LSLs

S7
S6
S5
S4
S3
S2
S1

Blue: 2050
Red: 2100
Green: 2200

LSL change [m]
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