Present-day sea level rise and climate change

Anny Cazenave (LEGOS-CNES) + many colleagues...

Special thanks to: B. Beckley, J. Benveniste, D. Chambers, J. Church, C. Domingues, M. Ishii, C.K. Shum, R. Sharroo, P. Woodworth

OSTST, Nice, Nov. 2008
Why are sea level studies important?

- Sea level rise: major consequence of global warming
- Sea level rise involves all components of the climate system (oceans, ice sheets, glaciers, land water reservoirs); even solid Earth is involved; complex response to global warming
- Sea level modelling: very difficult; future projections very uncertain due to lack of knowledge of future ice sheets behaviour; future regional variability very poorly known
- Future sea level rise: major impact in low-lying, highly-populated coastal areas
Submersion of coastal land under 1 m sea level rise

Source: Tyndall Center for Climate Change Research
In coastal regions, what does matter is ‘effective’ sea level change

- **Climate-related sea level change** (mean trend + regional variability)
- **Ground deformations** (subsidence, tectonics, ...)

'Effective 'sea level rise in large river deltas under contemporary conditions (~ 2mm/yr sea level rise)

From Ericson et al., 2006
Paleo and historical sea level (from Church et al., 2008)

Sea level rise during Holocene

Historical sea level
Global mean sea level rise during the 20th century

1.6-1.8 mm/yr

Tide gauges

Satellite altimetry

Holgate and Woodworth, 2004

Church et al., 2004, 2006
Global mean sea level evolution since 1993 from Topex/Poseidon and Jason-1 altimetry

Average rate of rise: 3.4 (+/- 0.4) mm/yr (1993-2008)
(GIA - Glacial Isostatic Adjustment - applied)

University of Colorado
**Topex+Jason global mean sea level curve (1993-2008)**

→ Comparison between 2 groups

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Univ. Colorado</td>
<td>3.4 mm/yr</td>
<td>3.6 mm/yr</td>
<td>2.5 mm/yr</td>
</tr>
<tr>
<td>CLS-Legos</td>
<td>3.35 mm/yr</td>
<td>3.45 mm/yr</td>
<td>2.45 mm/yr</td>
</tr>
</tbody>
</table>
Altimetry-based global mean sea level

Overall trend: 2.89 mm/yr
Common annual signal removed

Beckley et al. (2007)

C.K. Shum, Ohio State Univ.
<table>
<thead>
<tr>
<th>Source</th>
<th>Rate of sea level rise (GIA/-0.3 mm/yr and IB applied) unit: mm/yr</th>
<th>Time span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beckley et al. (2007)</td>
<td>3.6 +/- 0.4 (T/P + Jason)</td>
<td>1993-2007</td>
</tr>
<tr>
<td>S. Nerem (Univ. Colorado)</td>
<td>3.4 +/- 0.4 (T/P + Jason)</td>
<td>1993-2008</td>
</tr>
<tr>
<td>CLS-LEGOS</td>
<td>3.4 +/- 0.4 (T/P + Jason)</td>
<td>1993-2008</td>
</tr>
<tr>
<td>C.K. Shum (Ohio St. Univ.)</td>
<td>2.9 +/- 0.4 (T/P + Jason) 3.0 +/- 0.4 (multi sat)</td>
<td>1993-2008</td>
</tr>
<tr>
<td>R. Sharroo (TU Delft)</td>
<td>3.2 +/- 0.4 (multi sat)</td>
<td>1993-2008</td>
</tr>
</tbody>
</table>
# Global mean sea level trend: error budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Trend error (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit (Beckley et al., Ablain et al.)</td>
<td>0.25</td>
</tr>
<tr>
<td>Wet atmos. (TMR/JMR drift) (Ablain et al.)</td>
<td>0.3</td>
</tr>
<tr>
<td>Topex A-Topex B (Ablain et al.)</td>
<td>0.25</td>
</tr>
<tr>
<td>Dry atmos. (pressure fields) (Ablain et al.)</td>
<td>0.1</td>
</tr>
<tr>
<td>Sea state bias (Ablain et al.)</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Quadratic sum</strong></td>
<td><strong>0.45</strong></td>
</tr>
<tr>
<td>Tide gauge calibration (Micthum and Nerem; Beckley et al.; Ablain et al.)</td>
<td><strong>0.4</strong></td>
</tr>
</tbody>
</table>
Recommendation 1:

- Keep tight control on altimetric system performance (→ long term stability)
- Investigate the causes of differences in sea level trend estimates
- Implement a dedicated network of tide gauges equipped with GPS at <1 km distance
- Perform sea level budget studies (→ constraints on observed sea level rise)
Sea Level budget: Comparison between observed sea level change and sum of climate contributions (thermal expansion, land ice, land waters)

- 1950-2000
- 1993-2003
- 2003-2008
Change in Ocean Heat Content -past 50 years-

Domingues et al. (2008)

Ishii & Kimoto (2008)

1976 Climate regime change
Thermal budget of the climate system (last 50 years)

80% of heat in the climate system is stored in the oceans

After Levitus et al., 2005
### Contribution of thermal expansion

<table>
<thead>
<tr>
<th>Source</th>
<th>1961-2003 mm/yr</th>
<th>1993-2003 mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCC AR4 0-700m</td>
<td>0.35 +/- 0.06</td>
<td>1.6 +/- 0.25</td>
</tr>
<tr>
<td>Ishii &amp; Kimoto (2008) version 6.7 0-700 m</td>
<td>0.3 +/- 0.06 (1950-2005)</td>
<td>1.23 +/- 0.3 (1993-2005)</td>
</tr>
<tr>
<td>Domingues et al. (2008) 0-700 m</td>
<td>0.6 +/- 0.1</td>
<td>1.6 +/- 0.2</td>
</tr>
</tbody>
</table>
Land Ice contribution
Contribution of glacier melting to sea level rise

**Contribution to sea level:**
- 1961-2003: 0.5 +/- 0.18 mm/yr
- 1993-2003: 0.8 +/- 0.2 mm/yr

IPCC, 2007

Rate of ice mass loss by glacier melting (Gt/year)

Meier et al. (2007)

*Contribution to sea level:*
- 1961-2003: 0.5 +/- 0.18 mm/yr
- 1993-2003: 0.8 +/- 0.2 mm/yr

IPCC, 2007
Ice sheets Contribution (recent years)

Rignot & Thomas, 2002
Thomas et al., 2004
Krabill et al., 2004
Zwally et al., 2005
Johanessen et al., 2005
Davis et al., 2005
Rignot & Kanagaratnam, 2006
Rignot et al., 2006
Velicogna & Wahr (2005, 2006)
Ramillien et al. (2006)
Chen et al. (2006)
Lutchke et al. (2006)
Rignot et al. (2008)
Cazenave et al. (2008)
Wouters et al. (2008)
……….
Greenland ice sheet

Crevasses in ice...
Greenland and Antarctica mass balance

Ice mass loss (Gt/year)

Greenland contribution to sea level rise (1993-2003): 0.21 +/- 0.04 mm/yr (IPCC AR4)

Ice mass loss (Gt/year)

Antarctica contribution to sea level rise (1993-2003): 0.21 +/- 0.18 mm/yr (IPCC AR4)

Ice mass loss measured by remote sensing techniques
Land waters contribution
GRACE-based change in land water storage (2002-2007)

Net water loss:
- 60 ± 24 km³/yr
+ 0.2 mm/yr sea level rise

Ramillien et al. (2008)
SEA LEVEL BUDGET (1960-2000)
Land ice, waters and steric contributions to sea level rise

Observed rate of rise (tide gauges)

Glaciers
Ice sheets
Waters
Steric
Total climate

3 mm/yr
2 mm/yr
1 mm/yr
Sea Level Budget 1993–2003
Land ice, waters and steric contributions to sea level rise

- Glaciers: 1 mm/yr
- Ice sheets: 1 mm/yr
- Waters: steric
- Total climate: 3 mm/yr
- Observed rate of rise: 2 mm/yr
Sea Level Rise since 2003

New questions...
Steric sea level from ARGO

From Willis et al., 2008
Recent thermosteric sea level changes (Ishii and Kimoto, 2008)

Global (60°S–60°N) Annual Mean Thermosteric SL
0–700m Temp., err: 1σ

- Ishii and Kimoto (2008)
- Ishii et al. (2006)
- T/P + JASON-1 by AVISO

Observed sea level

Thermal expansion

Recent thermosteric sea level changes (Ishii and Kimoto, 2008)

Courtesy M. Ishii
Can we explain recent sea level rise by land ice only?

...
Ocean Mass Change from GRACE

GIA/ocean mass → Peltier, 2008: 1.9-2 mm/yr when rotational effects are accounted for

Source LEGOS
Observed sea level (altimetry) 1.9 +/- 0.1 mm/yr
Total ice + water. (GRACE / glaciers) 2.2 +/- 0.3 mm/yr
Ocean mass (GRACE) 1.9 +/- 0.1 mm/yr

Sea Level Change since 2003
Rate: 2.5 mm/yr
Contribution of glacier melting to sea level rise (recent years)

- Glaciers (2001-2004): 1.0 +/- 0.19 mm/yr  
  Kaser et al. (2006)

- Glaciers (2006): 1.1 +/- 0.24 mm/yr  
  Meier et al. (2007)
Space gravity mission **GRACE (2002-)**

→ temporal gravity variations → surface mass changes

**Greenland ice mass loss from GRACE**

**Trend:** -150 +/- 15 Gt/yr (0.35 mm/yr ESL)

Ramillien et al. (2008)

**Trend:** 179 +/- 25 Gt/yr (0.5 mm/yr ESL)

Wouters, Chambers, Schrama (2008)
Antarctica contribution to sea level (GRACE)

Trend: \( \sim 0 \)
Including GIA: 0.5 mm/yr

Source: LEGOS
GIA Models (Water Thickness Change)

ICE 5G (VM4); Peltier

Ivins-James

Wu RF3S20

Courtesy: C.K. Shum
Antarctica mass balance from INSAR (remote sensing)

2006 : 0.5 mm/yr (equivalent sea level)

Mass loss

Mass gain

Rignot et al., 2008
Comparaison Niveau mer observé et Contributions climatiques

ARGO

Trend: 0.37 +/- 0.1 mm/yr

Altimetry minus GRACE Ocean mass

Steric Sea Level

Trend : 0.3 +/- 0.15 mm/yr

Altimetry minus (ice + water)

ARGO

Trend: 0.37 +/- 0.1 mm/yr
Sea Level Budget 2003-2008
Land ice, waters and steric contributions to sea level rise

- Glaciers: 1 mm/yr
- Ice sheets: 1 mm/yr
- Waters: 2 mm/yr
- Steric: 2 mm/yr
- Total climate: 3 mm/yr
- Observed: 2 mm/yr
Recommendation 2:

• Improve GRACE products (ocean mass change, ice sheet mass balance)

• Improve GIA corrections (Grace-based ocean mass & ice sheets)

Data base of GRACE products (of interest for sea level studies) and associated GIA corrections based on expert group consensus (with regular updates)
Future Sea Level Rise...
Global mean sea level from 1800 to 2100

Accelerated ice mass loss in Greenland and West Antarctica...

Sea level change (mm)

Year

1800 1850 1900 1950 2000 2050 2100

Climate models (IPCC, 2007)

Projections of the future

IPCC, 2007

Observations

Climate models

(IPCC, 2007)

35 cm
Potential dynamical contribution of the ice sheets (ice dynamics) in 2100

1-2 m!

Pfeffer et al, Science, Sept. 2008
Sea level change (1700 - 2100)
Recommendation 3:

Improve climate model predictions of future sea level at global and regional scales

- Long time series of space – JASON-3 – and in situ observations (sea level + climate contributions) of crucial importance!

- Sea level budget studies

- Past sea level reconstructions
  (→ constraints on past regional variability)
Recommendation 4:

- Develop multidisciplinary impact studies in selected coastal regions using realistic regional sea level projections plus precise estimates of vertical crustal motions (subsidences, etc.), sediment supply from rivers, etc.
Future scientific Challenges

1. Detect any acceleration in the rate of sea level rise

2. Close the sea level budget

3. Understand the regional variability

4. Constrain (and improve) climate models

5. Study coastal impacts of sea level rise in selected coastal regions using realistic regional sea level projections plus precise estimates of vertical crustal motions (subsidence, etc.), sediment supply from rivers, etc.