Sea level rise
and the Earth’s energy imbalance

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Outline

• What do we mean by « sea level »?
  (What is in the sea level signal at climatic time scales?)

• Contemporary Sea level rise
  (Is the current sea level rise unusual? Is sea level rise accelerating?)

• Causes of contemporary sea level rise
  (can we explain the present sea level rise and close the sea level budget?)

• Implications for the Earth’s energy budget
  (Can sea level rise observations give a constraint on TOA imbalance?)
What do we mean by sea level?

**absolute sea level** and **relative sea level**

Relative SSH = Absolute SSH – Absolute LSH

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Ocean surface topography

Land surface height

Geoid

Sea surface height
International Terrestrial Reference System:

- Localisation
- North Pole
- Greenwich, England
- Prime Meridian (longitude = 0°)
- Latitude
- Longitude
- South Pole
- Equator (latitude = 0°)

Pole Motion wrt the Earth surface (crust)

Geocenter (center of mass) motion wrt the center of figure
International Terrestrial Reference Frame uncertainty:

Sea level trend generated by an uncertainty in the ITRF geocenter of (-1.5, -2.2, -2.1) mm/yr between 2000 and 2006 (ITRF2000 – IGS ppp). 0.4 mm/yr in GMSL

From Plag 2006
What is in the sea level signal?

$$SSH = \text{geoid} + \text{MDT} + \text{SLA}$$
What is in the sea level signal:

SSH-geoid = MDT+SLA

From Rio et al. 2011
Sea level anomaly from satellite altimetry over 1993-2013
What is the Contemporary sea level rise and how do we measure it?
Instrumental era (since mid/late-19th century)

Tide gauge distribution with records > 40 years

New York

Brest

Honolulu

Buenos-Aires

Tide gauge

20 cm

1900  Date  2000
Rate of sea level rise (20th century) : 1.8 +/- 0.3 mm/yr

Global mean sea level (20th century) from tide gauge records

Data from Church and White (2011)

Jevrejeva et al. 2008
Church and White 2011
Ray and Douglas 2011
Sea level change now measured by satellites
Global coverage of the Earth in a few days
Satellite altimetry
High-precision satellite altimetry

*Topex-Poseidon (1992-2006)*
*GFO (1998-2008)*
*Jason-1 (2001-2013)*
*Jason-2 (2008)*
*Envisat (2002-2012)*
*Cryosat (2010)*
*HY2A (2011)*
*Saral-Altika (2013)*

Current sea surface height accuracy: 1cm-2 cm for a single measurement
Regional sea level: Sea level does not rise uniformly!

Sea level trend patterns from satellite altimetry (1993-2012)
Global Mean Sea Level Rise measured by altimeter satellites since 1993

Rate of sea level rise (1993-2012)

3.2 +/- 0.4 mm/yr

La Nina

El Nino

7 cm
## Global mean sea level trend: error budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Trend error (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit</strong> (Beckley et al., Ablain et al.)</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Wet atmos. (TMR/JMR drift)</strong> (Ablain et al.)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Topex A-Topex B</strong> (Ablain et al.)</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Dry atmos. (pressure fields)</strong> (Ablain et al.)</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Sea state bias</strong> (Ablain et al.)</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Quadratic sum</strong></td>
<td>0.44</td>
</tr>
<tr>
<td><strong>Tide gauge calibration</strong> (Micthum and Nerem; Beckley et al.; Ablain et al.)</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Summary of the Global mean sea level evolution

Satellite altimetry era (since 1993)

Historical tide gauge data

Sea Level (m)

-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0
1.2

1700 1800 1900 2000

Year

IPCC 2013

~24 cm

7 cm
What causes contemporary sea level rise?
Global Mean Sea Level Rise measured by altimeter satellites since 1993

Rate of sea level rise (1993-2012)

3.2 ± 0.4 mm/yr

La Nina

El Nino

7 cm
Global Mean Sea Level Rise measured by altimeter satellites since 1993

- El Niño 97/98: Essentially Amazon basin water storage
- La Niña 10/11: Essentially Australian basins water storage

Can we explain the observed sea level rise?

Climatic contributions to the global mean sea level (1993-2012)

- Altimetry-based sea level
- Total climatic contributions
- Total land ice
- Thermosteric sea level (mean of Levitus et al., 2009 and Ishii and Kimoto 2009)
- Greenland land ice
- Antarctica land ice
- Montain glaciers

Meyssignac et Cazenave, 2012
Since about 2003 → ‘Argo’ profiling floats

Ocean temperature measurements
(XBT, CTD, Argo)

Past few decades:
coverage mainly along commercial roads
Upper ocean thermal expansion (0-700 m) 1960-2011


Thermal expansion = $\int \Delta \rho (T, S, \text{depth})/\rho_{\text{ref}}$

Llovel et al. 2012
Observed sea level by satellite altimetry
Trend: 3.2 mm/yr

Global mean sea level (1993-2010)

Thermal expansion
Mean trend (1993-2010): 0.9 +/- 0.3 mm/yr

Deep ocean warming → contribution poorly known but estimated to ~ 20%
Contribution of glacier melting to sea level rise

**Satellite imagery**

*Image SPOT 5 du massif du Mont Blanc*

**GRACE space gravimetry**

**1900**

*In situ measurements*

**Present**
Contribution of glacier melting to sea level rise

Annual Ice mass loss by glacier melting (Gt/year)

Glacier contribution to sea level rise: (1993-2010): 0.9. +/- 0.2 mm/yr
(2005-2010): 0.7 +/- 0.15 mm/yr

360 Gt/yr ice mass loss = 1 mm/yr sea level rise

(Updated from IPCC 2013)
Ice sheet mass balance measured by remote sensing over the last 2 decades

Greenland

Antarctica

GRACE space gravimetry

InSAR

Radar and laser altimetry
Contribution of ice sheets to sea level rise

Annual ice mass loss (Gt/yr) over 1993-2010

From Shepherd et al. 2012

**Greenland + Antarctica contributions:**

- (1993-2010) → 0.6 +/- 0.3 mm/yr
- (2005-2010) → 1. +/- 0.2 mm/yr
**Sea Level Budget: 1993-2010**

- **Observed sea level rise with Satellite altimetry**
  - 3 mm/yr
  - 2 mm/yr
  - 1 mm/yr

- **Sum of climatic components**
  - 2.6 ± 0.6 mm/yr
  - 3.2 ± 0.4 mm/yr

- **Land ice**
  - ~0.9 mm/yr

- **Thermal expansion (0-700m)**
  - ~0.2 mm/yr

- **Ice sheets**
  - ~0.6 mm/yr

- **Glaciers**
  - ~0.9 mm/yr

- **Land waters**
  - ~0.9 mm/yr

*Updated from IPCC 2013*
Sea Level Budget: 1993-2010

What is in these 0.6 mm/yr?

- Thermal expansion (0-700m) ~0.2 mm/yr
- Ice sheets ~0.6 mm/yr
- Glaciers ~0.9 mm/yr
- Land ice ~0.9 mm/yr
- Land waters ~0.2 mm/yr
- Sum of climatic components ~0.6 mm/yr
- Observed sea level rise with Satellite altimetry

(Updated from IPCC 2013)
Sea Level Budget: 1993-2010

Sea level rate

3 mm/yr

2 mm/yr

1 mm/yr

Observed sea level rise with Satellite altimetry

What is in these 0.6 mm/yr?

Uncertainties + Marginal seas and Deep ocean warming

Land ice

Ice sheets

~ 0.6 mm/yr

~ 0.9 mm/yr

~ 0.9 mm/yr

~ 0.2 mm/yr

Glaciers

Land waters

2.6 ± 0.6 mm/yr

3.2 ± 0.4 mm/yr

Satellite altimetry

(Updated from IPCC 2013)
What are implications for the Earth energy budget?
Since ~ 2005, Argo + GRACE ➞ upper ocean thermal expansion + ocean mass

**Thermal expansion of the upper ocean (0-2000 m)**

- Argo
- 6-12 hours at surface to transmit data to satellite
- Descent to cruising depth ~10 days (~6 hours)
- Cruising depth 2000 m (2000m)
- Total cycle time 10 days
- 3628 Floats 24-Sep-2014

**GRACE**

- Gravity Recovery And Climate Experiment
- Mass changes

**Ocean mass**

- Glaciers, ice sheets, land waters
Sea Level Budget: 2005-2013

Sea level rise 3 mm/yr

Sea level rise 2 mm/yr

Sea level rise 1 mm/yr

GRACE-based ocean mass

Argo based Thermal expansion (0-1500m) not corrected for marginal seas

Marginal seas and Deep ocean warming < 1.2 mm/yr

Satellite altimetry based sea level rise

unconsistency = 0.4 ± 0.8 mm/yr

2.4 ± 0.4 mm/yr

2.8 ± 0.4 mm/yr

0.5 ± 0.3 mm/yr

1.9 ± 0.3 mm/yr

(from Dieng et al. In revision)
implications for the Earth heat budget: 2005-2013

Sea level rate

3 mm/yr
2.8 mm/yr
2 mm/yr
1 mm/yr

sea level rise
from Altimetry= 2.8 ± 0.4 mm/yr

Argo Thermal expansion (0-1500m)

Altimetry -Argo -GRACE

0.4 ± 0.8 mm/yr

0.5 ± 0.3 mm/yr

GRACE-based ocean mass

1.9 ± 0.3 mm/yr

(from Dieng et al. In revision)
implications for the Earth heat budget: 2005-2013

Sea level rise from Altimetry = 2.8 ± 0.4 mm/yr

1 mm/yr
2 mm/yr
3 mm/yr

2.8 mm/yr
0.4 ± 0.8 mm/yr
0.5 ± 0.3 mm/yr
1.9 ± 0.3 mm/yr

Argo Thermal expansion (0-1500m)

0.01 W/m²

Land ice melt processes

GRACE-based ocean mass

Altimetry - Argo - GRACE

Heating rate

0.5 W/m²
1 W/m²

Land ice

(from Dieng et al. In revision)
implications for the Earth heat budget: 2005-2013

Sea level rate

3 mm/yr
2.8 mm/yr
2 mm/yr
1 mm/yr

Altimetry - Argo - GRACE

Argo Thermal expansion (0-1500m)

GRACE-based ocean mass

Land ice melt processes

Ocean heat uptake

Land ice

Heating rate

1 W/m²
0.5 W/m²

Sea level rise from Altimetry = 2.8 ± 0.4 mm/yr

1 mm/yr
2 mm/yr
3 mm/yr

0.4 ± 0.8 mm/yr
0.5 ± 0.3 mm/yr

0.01 W/m²
0.32 ± 0.52 W/m²
0.4 ± 0.8 W/m²

(From Dieng et al. In revision)
Implications for the Earth heat budget: 2005-2013

Sea level rate

- 3 mm/yr
- 2.8 mm/yr
- 2 mm/yr
- 1 mm/yr

Sea level rise from Altimetry = 2.8 ± 0.4 mm/yr

Resulting Earth energy imbalance = 0.75 ± 0.52 W/m² (from Dieng et al. In revision)

Heating rate

- 1 W/m²
- 0.5 W/m²
- 0.02 W/m²
- 0.01 W/m²

Altimetry - Argo - GRACE

Argo Thermal expansion (0-1500m)

GRACE-based ocean mass

Ocean heat uptake

0.4 ± 0.8 mm/yr

0.5 ± 0.3 mm/yr

1.9 ± 0.3 mm/yr

Land ice melt processes

0.32 ± 0.52 W/m²

0.4 ± 0.3 W/m²

0.01 W/m²

Land ice
implications for the Earth heat budget: 2005-2013

Resulting Earth energy imbalance = \(0.75 \pm 0.52\) W/m\(^2\) (from Dieng et al. In revision)

Sea level rise from Altimetry = \(2.8 \pm 0.4\) mm/yr

- **Altimetry**
  - 3 mm/yr
  - 2.8 mm/yr

- **Argo Thermal expansion (0-1500m)**
  - 0.4 ± 0.8 mm/yr

- **GRACE-based ocean mass**
  - 1.9 ± 0.3 mm/yr

Heating rate

- **atmosphere + continent + sea ice**
  - 1 W/m\(^2\)
  - 0.5 W/m\(^2\)

- **Land ice**
  - 0.4 ± 0.3 W/m\(^2\)

- **GRACE-based ocean mass**
  - 0.02 W/m\(^2\)

- **Argo Thermal expansion (0-1500m)**
  - 0.32 ± 0.52 W/m\(^2\)

- **Dieng et al.**
  - 0.4 ± 0.3 mm/yr
  - 0.32 ± 0.52 mm/yr
  - 0.01 W/m\(^2\)

- **Llovel et al.**
  - 0.9 ± 0.1 mm/yr
  - 1.9 ± 0.3 mm/yr
  - 0.4 ± 0.8 mm/yr

Sea level rise from Altimetry = \(2.8 ± 0.4\) mm/yr

- **Dieng et al.**
  - 0.5 ± 0.3 mm/yr
  - 1.9 ± 0.3 mm/yr
  - 0.4 ± 0.8 mm/yr

- **GRACE-based ocean mass**
  - 1 mm/yr
  - 2 mm/yr
  - 3 mm/yr
implications for the Earth heat budget: 2005-2013

Resulting Earth energy imbalance = 0.75 ± 0.52 W/m$^2$
(from Dieng et al. In revision)
imbalance = 0.67 ± 0.43 W/m$^2$
(from Llovel et al. Oct 2014)

Sea level rate

- 3 mm/yr = 2.8 mm/yr
- 2 mm/yr = 0.5 W/m$^2$
- 1 mm/yr = 0 W/m$^2$

Sea level rise from Altimetry = 2.8 ± 0.4 mm/yr

- 0.4 ± 0.8 mm/yr
- 0.5 ± 0.3 mm/yr
- 0.9 ± 0.1 mm/yr
- 0.02 W/m$^2$
- 0.08 ± 0.43 W/m$^2$
- 0.02 W/m$^2$
- 0.32 ± 0.52 W/m$^2$
- 0.72 ± 0.1 W/m$^2$
- 0.72 ± 0.1 W/m$^2$
- 0.4 ± 0.3 W/m$^2$

Sea level rise from Altimetry = 2.8 ± 0.4 mm/yr

- 0.01 W/m$^2$
- 0.01 W/m$^2$
- 0.01 W/m$^2$
- 0.01 W/m$^2$

Argo Thermal expansion (0-1500m)

- 0.4 ± 0.8 mm/yr
- 0.5 ± 0.3 mm/yr
- 0.9 ± 0.1 mm/yr
- 0.72 ± 0.1 W/m$^2$
- 0.08 ± 0.43 W/m$^2$
- 0.32 ± 0.52 W/m$^2$
- 0.4 ± 0.3 W/m$^2$

GRACE-based ocean mass

- 1.9 ± 0.3 mm/yr
- 2.0 ± 0.3 mm/yr
- 0.72 ± 0.1 W/m$^2$
- 0.32 ± 0.52 W/m$^2$
- 0.4 ± 0.3 W/m$^2$

Land ice

atmosphere + continent + sea ice
Conclusions I

-Current global mean sea level is rising fast compared to the last century and previous millenia

-It rises in response to ocean warming and land ice melt

-Inferred estimate from Argo and GRACE explain most of the observed sea level rise since 2005

-However an unconsistency of a 0.4 mm/yr remains. It is due to uncertainties in the observing system + Marginal seas and deep ocean warming not observed by Argo

-Closing the sea level budget enable to infer marginal seas and deep ocean warming within the uncertainties of the observing system.

-It suggest a radiative imbalance around $0.7 \pm 0.5 \text{ W/m}^2$ over 2005-2013
Conclusions II

- Biases and uncertainties in ocean temperature estimates and land ice melt estimates before Argo and GRACE make the energy imbalance estimate very uncertain before 2005.

- Future challenge:
  * reduce the uncertainty in the sea level budget
  * estimate the interannual variability in TOA and its relationship to global OHC and sea level rise
Extra slides
Sea Level Budget: 2005-2013

Sea level rate

3 mm/yr

2 mm/yr

1 mm/yr

GRACE-based ocean mass

Satellite altimetry based sea level rise

Unconsistency = -0.1 ± 0.7 mm/an

Deep ocean warming (Below 2000m) < 0.6 mm/yr

2.9 ± 0.3 mm/yr

2.8 ± 0.4 mm/yr

2.0 ± 0.3 mm/yr

0.9 ± 0.1 mm/yr

Argo based Thermal expansion (0-2000m) corrected for marginal seas

(from Llovel et al. Oct. 2014)