Revisited sea level budget over 2005-2015 indicates a large Earth energy imbalance

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GEWEX conference, May 2018, Canmore
Energy storage in the climate system

From Von Schuckmann et al. 2016
OHC estimation from Argo since the 2000s

Global coverage on the 4th of May 2018

global OHC from Argo $0.6 \pm 0.5 \text{W.m}^{-2}$ ($1.65 \sigma$, i.e. 90% CL)
Earth Energy imbalance: 2005-2013

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

- 0.9 ± 0.6 mm/yr (Thermal expansion)
- 1.9 ± 0.5 mm/yr (GRACE-based ocean mass)

(from Dieng et al. 2015)
Sea level rise from Altimetry = \(2.8 \pm 0.4\) mm/yr

Land ice melting processes (from Dieng et al. 2015)

Thermal expansion

GRACE-based ocean mass

Sea level rate

Heating rate

Earth Energy imbalance: 2005-2013
Earth Energy imbalance: 2005-2013

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

Sea level rise
3 mm/yr
2.8 mm/yr
2 mm/yr
1 mm/yr

Thermal expansion
0.9 ± 0.6 mm/yr

GRACE-based ocean mass
1.9 ± 0.5 mm/yr

Ocean heat uptake
0.74 ± 0.5 W/m²

Land ice melt processes
0.01 W/m²

Land ice
(from Dieng et al. 2015)
Resulting Earth energy imbalance = 0.77 ± 0.52 W/m² (1.65 $\sigma$) (from Dieng et al. 2015)

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

Ocean heat uptake

Land ice melt processes

GRACE-based ocean mass

Thermal expansion

Sea level rate

0.9 ± 0.6 mm/yr

0.01 W/m²

0.74 ± 0.5 W/m²

0.02 W/m²

Land ice

Heating rate

0.5 W/m²

1 W/m²
Earth Energy imbalance: 2005-2013

Resulting Earth energy imbalance = $0.77 \pm 0.52 \text{ W/m}^2$ (1.65 $\sigma$) 
(from Dieng et al. 2015)

imbalance = $0.69 \pm 0.6 \text{ W/m}^2$ (1.65 $\sigma$) 
(from Llovel et al. Oct 2014)

Sea level rise from Altimetry = $2.8 \pm 0.4 \text{ mm/yr}$

Dieng et al.

Llovel et al.

Thermal expansion

$0.9 \pm 0.6 \text{ mm/yr}$

$0.8 \pm 0.8 \text{ mm/yr}$

GRACE-based ocean mass

$1.9 \pm 0.5 \text{ mm/yr}$

$2.0 \pm 0.7 \text{ mm/yr}$

Land ice

$0.01 \text{ W/m}^2$

$0.01 \text{ W/m}^2$

atmosphere + continent + sea ice

$0.02 \text{ W/m}^2$

$0.02 \text{ W/m}^2$

Heating rate

$1 \text{ W/m}^2$

$0.5 \text{ W/m}^2$

Sea level

$3 \text{ mm/yr}$

$2.8 \text{ mm/yr}$

$2 \text{ mm/yr}$

$1 \text{ mm/yr}$

Heating rate

$1 \text{ W/m}^2$

$0.5 \text{ W/m}^2$
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>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>0.41</td>
</tr>
<tr>
<td><strong>Tide gauge calibration</strong> (Mickett and Nerem; Beckley et al.; Ablain et al.)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Updated from Ablain et al. 2015
Resulting Earth energy imbalance = $0.77 \pm 0.52 \text{ W/m}^2$ (1.65 $\sigma$) 
(from Dieng et al. 2015) 
imbalance = $0.69 \pm 0.6 \text{ W/m}^2$ (1.65 $\sigma$) 
(from Llovel et al. Oct 2014) 

Sea level rise from Altimetry = $2.8 \pm 0.4 \text{ mm/yr}$ 

1.9 ± 0.5 mm/yr (Dieng et al.) 
2.0 ± 0.7 mm/yr (Llovel et al.) 

0.9 ± 0.6 mm/yr (Dieng et al.) 
0.8 ± 0.8 mm/yr (Llovel et al.) 

Thermal expansion 

Sea level rate 
3 mm/yr 
2.8 mm/yr 
2 mm/yr 
1 mm/yr 

GRACE-based ocean mass 

0.01 W/m$^2$ (Land ice) 
0.66 ± 0.6 W/m$^2$ (atmosphere + continent + sea ice) 
0.74 ± 0.5 W/m$^2$ (atmosphere + continent + sea ice) 
0.02 W/m$^2$ (atmosphere + continent + sea ice)
## Uncertainty in Ocean mass changes from GRACE

<table>
<thead>
<tr>
<th>(mmSLE/yr)</th>
<th>GOM</th>
<th>Greenland</th>
<th>Antarctica</th>
<th>Arctic islands</th>
<th>Glacier &amp; TWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing center</td>
<td>0.08</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>Geocenter motion</td>
<td>0.55</td>
<td>0.05</td>
<td>0.17</td>
<td>0.04</td>
<td>0.63</td>
</tr>
<tr>
<td>$C_{2,0}$</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Filtering</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Leakage correction</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>GIA</td>
<td>0.23</td>
<td>0.01</td>
<td>0.13</td>
<td>0.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

| Total Uncertainty         | 0.52     | 0.06       | 0.18       | 0.06           | 0.56          |
| RMS Uncertainties         | 0.60     | 0.06       | 0.22       | 0.06           | 0.64          |
| Interaction               | 0.08     | <0.01      | 0.03       | <0.01          | 0.08          |

From Blazquez et al. in revision
Resulting Earth energy imbalance = 0.77 ± 0.52 W/m² (1.65 σ)
(from Dieng et al. 2015)
imbalance = 0.69 ± 0.6 W/m² (1.65 σ)
(from Llovel et al. Oct 2014)

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Sea level rate

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

GRACE-based ocean mass

Thermal expansion

0.9 ± 0.6 mm/yr
0.8 ± 0.8 mm/yr

Llovel et al.

Dieng et al.

Sea level rate

0.66 ± 0.6 W/m²
0.74 ± 0.5 W/m²
0.01 W/m²
0.01 W/m²
0.02 W/m²
0.02 W/m²

Heating rate

1 W/m²
0.5 W/m²

atmosphere + continent + sea ice

Land ice

Thermal expansion

0.9 ± 0.6 mm/yr
0.8 ± 0.8 mm/yr

Llovel et al.

Dieng et al.

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0.8 ± 0.8 mm/yr

Llovel et al.

Dieng et al.
Revisit of the sea level budget


2. Improved orbit, improved wet-tropo corrections and improved intersatellite calibration allow to decrease the uncertainty in the global sea level trend from satellite altimetry

3. Sea level budget closure assessed in the center of mass of the Earth (as close as possible).
Revisited sea level budget (centre of mass) and Earth Energy imbalance: 2005-2015

Sea level rise from Altimetry = 3.47 ± 0.33 mm/yr

Resulting Earth energy imbalance = 1.33 ± 0.23 W/m² (1.65 σ)
(from Blazquez et al. in prep)

Ocean heat uptake

GRACE-based ocean mass

1.88 ± 0.22 mm/yr

Land ice melt processes

1.59 ± 0.28 mm/yr

Thermal expansion

0.02 W/m²

Atmosphere + continent + sea ice

Land ice

0.01 W/m²

0.5 W/m²

1 W/m²

Heating rate

Sea level rate
Revisited sea level budget (centre of mass) and Earth Energy imbalance: 2005-2015

Resulting Earth energy imbalance = $1.33 \pm 0.23 \text{ W/m}^2$ (1.65 $\sigma$) 
(from Blazquez et al. in prep)

Sea level rise from Altimetry = $3.47 \pm 0.33 \text{ mm/yr}$

Land ice melt processes

Ocean heat uptake

Thermal expansion

GRACE-based ocean mass

Heating rate

atmosphere + continent + sea ice

Land ice

0.5 W/m$^2$

1 W/m$^2$

0.01 W/m$^2$

0.02 W/m$^2$

0.32 $\pm 0.24 \text{ W/m}^2$

0.98 $\pm 0.3 \text{ W/m}^2$

0.01 W/m$^2$
Conclusions

1. Sea level (from satellite altimetry) minus ocean mass (from space gravimetry) is a satellite alternative to Argo for the OHC estimation

2. The revisited sea level budget in the center of mass of the Earth suggest that past OHC estimates (0.73±0.6 W.m⁻²) are biased low. Our current best estimate over 2005-2015 is 1.3±0.23 W.m⁻²

3. Comparison with Argo down to 2000 m depth suggests that this EEI is consistent with a significant deep ocean warming of 0.3±0.24 W.m⁻² (below 2000m)

4. The residual error bar is essentially due to the wet tropo correction in altimetry and GIA correction in GRACE. The error bar in Altimetry is backed up by TG records (high confidence). No external validation for GRACE error bars (medium confidence)

Caution Note: when reporting errors from other studies it is important to translate them to the same level of confidence
Perspectives

1. The salt budget in the ocean can give a new constraint on the ocean mass estimate and help in validating the error budget in GRACE

2. Improvement of the wet tropospheric correction in altimetry should allow to further reduce the error bars (down to 0.2 W.m\(^{-2}\))

3. Regional estimates from satellites will allow to determine where the heat goes in the ocean (horizontally): important for interannual to decadal climate variability (like the hiatus)
Earth Energy imbalance: 2005-2013

Resulting Earth energy imbalance = $0.77 \pm 0.52 \text{ W/m}^2$

(from Dieng et al. 2015)

imbalance = $0.69 \pm 0.6 \text{ W/m}^2$

(from Llovel et al. 2014)

Sea level rise from Altimetry = $2.8 \pm 0.4 \text{ mm/yr}$

$\begin{array}{ccc}
\text{Altimetry - Argo - GRACE} & 0.4 \pm 0.8 \text{ mm/yr} \\
\text{Argo Thermal expansion (0-1500m)} & 0.5 \pm 0.3 \text{ mm/yr} \\
\text{GRACE-based ocean mass} & 1.9 \pm 0.5 \text{ mm/yr} \\
\end{array}$

$\begin{array}{ccc}
\text{Dieng et al.} & 0.9 \pm 0.2 \text{ mm/yr} \\
\text{Llovel et al.} & 0.09 \pm 0.43 \text{ W/m}^2 \\
\text{Land ice} & 0.02 \text{ W/m}^2 \\
\end{array}$

atmosphere + continent + sea ice

$\begin{array}{ccc}
\text{Heating rate} & 1 \text{ W/m}^2 \\
0.5 \text{ W/m}^2 \\
0.5 \text{ W/m}^2 \\
\end{array}$