Sea Level « Essential Climate Variable », Climate Change Initiative and GCOS requirements

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Earth’s Energy Budget

Equilibrium

Today → Energy imbalance → 0.5 -1 Wm$^{-2}$
The ocean heat content is increasing

Change in global average upper ocean heat content

Ocean heat content = Ocean mass \times \text{Heat capacity of water} \times \text{Ocean mean temperature change}
Ice mass loss from Greenland and Antarctica measured by space techniques since 1990 (in Gt) → mass loss acceleration since early 2000s

Shepherd et al., 2012
IPCC AR5
Global Mean Sea Level (1993-2016)

Global Mean Sea Level from satellite altimetry multi missions

Rate of sea level rise (1993-2016)

$3.4 \pm 0.3 \text{ mm/yr}$
Observed sea level budget 1993-2010 (IPCC AR5)

Individual contributions (mm/yr)

- Observed sea level rise: 3.2 ± 0.4
- Sum of contributions: 2.8 ± 0.6
- Thermal E.: 1.1 ± 0.3
- Glaciers: 0.76 ± 0.36
- Greenland: 0.33 ± 0.08
- Antarctica: 0.27 ± 0.11
- LW: 0.38 ± 0.12
Regional Sea level Change

Rates of sea level rise observed by satellite altimetry over 1993-2014
IPCC-AR5 projections of Global Mean Sea Level Rise during the 21st century under two warming scenarios

Sea Level Rise

- Pessimistic scenario (RCP 8.5) - 75 cm
- Optimistic scenario (RCP 2.6) - 40 cm
Regional variability by 2100

Percentage of deviation from the global mean rise

(same values for all scenarios)
Why is it important to precisely monitor sea level changes?

1. Global mean sea level rise is an integrator of changes occurring in the climate system
   → provides an integrative view of present-day changes (land ice melt, ocean warming); one of the best indicators of climate change

2. Studying the sea level budget using different observing systems offers constraints on « missing contributions » (e.g. deep ocean warming) or poorly known components (e.g., ground water depletion in aquifers); also allows cross-validation of other ECVs (e.g., glaciers, ice sheets)

3. Observed sea level changes at global and regional scale help validating climate models used for projections and inform on detection/attribution issues

4. Observed sea level variations at the coast provide constraints on models of coastal impacts and shoreline erosion
Expected coastal impacts of future sea level rise:

- Stronger temporary flooding during extreme events
- Permanent flooding in low coastal areas
- Shoreline erosion
- Shoreline retreat
- Salt intrusion in coastal aquifers and estuaries
- Damages on coastal defences
- Negative impacts on coastal biodiversity
- .......
The World Climate Research Programme (World Meteorological Organization) has defined "Grand Challenges" in climate research. These challenges include:

1. Clouds, atmospheric circulation, and climate sensitivity
2. The cryosphere in a changing climate
3. Climate extremes
4. Sea level rise and coastal impacts
5. Changes in water availability
Uncertainty in sea level data and GCOS requirements

<table>
<thead>
<tr>
<th>Spatial Scales</th>
<th>Temporal Scales</th>
<th>GCOS Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Mean Sea Level</strong></td>
<td>Long-term trend (&gt; 10 years)</td>
<td>&lt;0.3 mm/yr</td>
</tr>
<tr>
<td></td>
<td>Interannual signals (&lt; 5 years)</td>
<td>0.5 mm (\text{over 1 year})</td>
</tr>
<tr>
<td><strong>Regional Sea Level</strong></td>
<td>Long-term trend (&gt;10 years)</td>
<td>&lt;1 mm/yr</td>
</tr>
<tr>
<td></td>
<td>Interannual signals (&lt;5 years)</td>
<td>Not Defined</td>
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</tbody>
</table>
### Uncertainty in sea level data (standard altimetry-based products)

<table>
<thead>
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<tbody>
<tr>
<td><strong>Global Mean Sea Level</strong></td>
<td>Long-term trend</td>
<td>0.7-0.8 mm/yr</td>
<td>~0.5 mm/yr</td>
</tr>
<tr>
<td></td>
<td>Interannual signals</td>
<td>&lt; 5 mm over 1 year</td>
<td>~2 mm over 1 year</td>
</tr>
<tr>
<td><strong>Regional Mean Sea Level</strong></td>
<td>Long-term trend</td>
<td>~4 mm/yr</td>
<td>2-3 mm/yr</td>
</tr>
<tr>
<td></td>
<td>Interannual signals</td>
<td>Not evaluated</td>
<td>Not evaluated</td>
</tr>
</tbody>
</table>
Regional trend patterns in sea level due to wet tropospheric correction error

From Legeais et al., Ocean Sciences, 2014
Regional trend patterns in sea level due to orbit error

Source: Couhert et al., 2015
ESA Climate Change Initiative
13 CCI ECVs, 14 projects
The CCI Sea Level Project

- 7 altimeter missions (re)processed: T/P, Jason1/2, ERS-1/2, ENVISAT & GFO (CryoSat-2 and SARAL/AltiKa soon included)
- Period: [1993-2014]
- 70 cumulated years of data (re)processed

Level 2 product

Input data acquisition

Pre-Processing
Orbit, Instrum. & Geophysical corr, including CCI corrections

Multimission calibration
Orbit / Longwavelength Errors including the new CCI methodology

Mapping
including the new CCI methodology

Computation of Sea level products

Ablain et al., 2015

From along-track data to gridded products....
• CCI Sea Level Products V1.1: based on new altimeter corrections developed to increase homogeneity between missions and reduce main sources of errors

• A full reprocessing of the Sea Level ECV will start in summer 2016 (V2.0), based on:
  
  • New ocean tides corrections
  • New orbit solutions
  • New atmospheric fields:
    
    From model and the JRA-55 reanalysis
    From radiometer correction (univ. of Porto)
  • New Pole tide correction (Desai et al., 2015)
  • New altimeter missions included:
    
    CryoSat-2, SARAL/AltiKa
    In the future: Jason-3 and Sentinel-3
Uncertainty of CCI Sea Level Products

Regional sea level trend errors

Source: Prandi et al., 2016
## Sea Level Uncertainty of CCI products

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<tr>
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<th>Errors of CCI products</th>
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<td>Long-term trend</td>
<td>&lt;0.3 mm/yr</td>
<td>~ 0.3 mm/yr</td>
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<td></td>
<td>Interannual signals</td>
<td>0.5 mm over 1 year</td>
<td>&lt; 2 mm over 1 year</td>
</tr>
<tr>
<td><strong>Regional Sea Level</strong></td>
<td>Long-term trend</td>
<td>&lt;1 mm/yr</td>
<td>&lt;2 mm/yr (except for western boundary currents)</td>
</tr>
<tr>
<td></td>
<td>Interannual signals</td>
<td>Not Defined</td>
<td>Not evaluated</td>
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Source: Ablain et al., 2015
Additional GCOS requirements (needed to fulfill the accuracy requirements)

- At least 1 high-precision altimeter mission operating at all times
- Combined and intercalibrated multi satellite missions
- Long-term climate-related sea level record
- Altimeter missions with high inclination orbits (Arctic sea level)
- In situ observing systems (tide gauges + GPS, Argo)
- Continuity of space gravimetry missions
- Geodetic infrastructure + improved ITRF
- Regular reprocessing to benefit improvements in geophysical corrections, models, etc.
- Specific processing of altimetry data in coastal areas

- and ....
- Intercomparison of sea level products provided by different groups; reduction of discrepancies
- Improvement of the collaboration between observers and modellers
- Promotion of the use in synergy of different space & in situ observing systems (→ sea level budget and Earth energy imbalance studies)
Altimetry-based sea level time series (2003-2013) from different processing groups
(referred to the CCI sea level time series)
Sea Level Budget → Another method to estimate sea level products error:

**Observed Global Mean Sea Level Rise**

= 

**Ocean Thermal Expansion + Ocean Mass**

\[ \Delta M_{\text{ocean}} = - \Delta M_{\text{LI}} - \Delta M_{\text{LW}} - \Delta M_{\text{WV}} - \Delta M_{\text{Snow}} \]

\[ \Delta = \text{Time variation} \]

\[ M = \text{Masse} \]

\[ LI = \text{Land Ice (glaciers + ice sheets)} \]

\[ LW = \text{Land Waters} \]

\[ WV = \text{Water Vapour} \]
Observed CCI-Based Global Mean Sea Level (3.07 mm/yr) =
  Argo-based Thermal Expansion (1.1 +/- 0.12 mm/yr)
  + GRACE-based Ocean Mass (1.86 +/- 0.1 mm/yr)
  Sum -> 2.97 +/- 0.15 mm/yr

Black: CCI altimetry-based Global Mean Sea Level
Red: Sum of Thermal Exp.+ Mass

Ocean Mass from GRACE
Thermal Expansion (Argo-based T/S -> 2000m)

Source: Dieng et al., 2016
ESA Climate Change Initiative
13 CCI ECVs, 14 projects
Conclusions & Next Steps

• Significant improvement of errors characterisation & reduction in sea level products owing to the CCI project

• But GCOS requirements not yet fully reached (suggestion: revise GCOS requirements depending on applications)

• More work to be done on intercomparison of sea level products provided by different groups; improve understanding and reduce discrepancies

• Regular reprocessing needed to improve the sea level ‘climate’ record

• Importance of improving coastal sea level data for impact studies

• More work needed on use in synergy of different space & in situ observing systems
  → study of sea level budget and Earth’s energy imbalance
  → cross-calibration of different observing systems provides additional info on sea level data uncertainty

• Closing the global sea level budget or estimating all single components entering into the budget remains a challenge
  → significant work still needed to reduce uncertainties of all components of the sea level budget