An 8-year cycle in the rate of the global mean sea level
Global mean sea level (GMSL) over the altimetry era (1993-2020)

- GMSL is rising and accelerating
- GMSL rised by about 9 cm since 1993

Research question:
- How the rate of the GMSL evolved with time over the altimetry era?
Sea level budget

- GMSL budget equation:
  \[ \text{GMSL}(t) = \text{GMSL}_{\text{steric}}(t) + \text{GMSL}_{\text{ocean mass}}(t) \]
  - \( \text{GMSL}_{\text{steric}} \) refers to the contribution from the ocean thermal expansion
  - \( \text{GMSL}_{\text{ocean mass}} \) refers to the change in mass of the oceans

- Ocean mass term (water mass conservation in the climate system):
  \[ \text{M}_{\text{ocean}}(t) + \text{M}_{\text{glaciers}}(t) + \text{M}_{\text{GIS}}(t) + \text{M}_{\text{AIS}}(t) + \text{M}_{\text{TWS}}(t) + \text{M}_{\text{AWV}}(t) = 0 \]
  Representing temporal changes in the mass of glaciers, Greenland and Antarctica ice sheets (GIS, AIS), terrestrial water storage (TWS) and atmospheric water vapour (AWV).
GMSL budget components

- Land ice components exhibit slight interannual variability
- Thermal expansion and TWS components show significant interannual variability

**Objective:**
- Estimation of the temporal evolution of the GMSL rate after removing the interannual variability of all components of the GMSL budget.
Data

- GMSL from the European Space Agency (ESA) Climate Change Initiative (CCI) (01.1993-12.2015)
- GMSL from the Copernicus Marine Environment Monitoring Service (CMEMS) (01.2016-12.2016)
- GMSL from the Colorado University (01.1993-12.2016)
- Land ice (Antarctica and Greenland ice sheets and glaciers) data from the “Sea Level Budget Closure” ESA project (2020)
- Glaciers data from Zemp et al. (2019)
- TWS data from the WaterGap Hydrological Model (WGHM) from Goethe University Frankfurt
- TWS data from the Interaction Soil Biosphere Atmosphere-Total Runoff Integrating Pathways (ISBA-CTRIIP) from MetéoFrance (Toulouse)
- Ocean thermal expansion (steric component) from Dieng et al. (2017)
- Atmospheric Water Vapour (AWV) from ERA5 Atmospheric reanalysis
- GRACE data from Blazquez et al. (2019)
Interannual variability of GMSL

Method to separate between contributions:

• Isolate the interannual (natural) variability of each component of the GMSL budget

• Remove it from the GMSL before computing the time evolution of the rate
How to extract the interannual signal of the GMSL budget components?

The procedure is:

• To detrend the time series:
  • Quadratically for the steric and land ice components
  • Linearly for the TWS and AWV

• To remove the detrended time series (interannual variability/IV) from the initial GMSL time series:

\[
\text{GMSL}_{LT} = \text{GMSL} - \text{IV}_{\text{steric}} - \text{IV}_{\text{TWS}} - \text{IV}_{\text{glaciers}} - \text{IV}_{\text{AIS}} - \text{IV}_{\text{GIS}} - \text{IV}_{\text{AWV}}
\]

\( \text{GMSL}_{LT} \) is supposed to represent the long-term trend plus eventually some remaining interannual variability not included in the herein used observations.
GMSL, GMSL$_{LT}$ and interannual variability signal of all components of the GMSL budget
Rate of $\text{GMSL}_{\text{LT}}$ over 5-year windows shifted 1-year

$\text{GMSL}_{\text{LT}}$ shows a clear 8-year cycle superimposed on an increasing trend

Research question:
- What is the origin of the 8-year cycle?
What is the origin of the 8-year cycle?

• This 8-year periodicity is present in the GMSL$_{LT}$ time series in spite of the removal of the interannual variability of the GMSL budget components.

• Two possible reasons:
  • A missing component not considered in the GMSL budget
  • Inadequate data for representing the GMSL budget components

• Approach:
  • Option 1: Indonesian Sea Region not covered by Argo, but it does not show an 8-year periodicity
  • Option 2: Try to find GMSL budget component that has an 8-year cycle

• Research question:
  • Which component of the GMSL budget has an 8-year periodicity?
Peridograms of the GMSL budget components

- Only land ice components show a peak around 8 years
- Glacier Zemp data peak at 8 years is 10% of the amplitude of the GMSL$_{LT}$ peak
- Land ice component time series’ are generally very smoothed and display small interannual variability

Hypothesis:
- The glacier component could be responsible for the 8-year cycle

Research question:
- Could a missed glacier contribution be responsible for the observed 8-year cycle?
Method to investigate if glaciers could contribute to the 8-year cycle

GRACE data averaged over all land (excluding the ice sheets) provides the change in water mass due to the combined effect of glaciers and TWS:

$$\text{GRACE}_{\text{land}} = \text{Glaciers} + \text{TWS}$$

GRACE-based glaciers = GRACE$_{\text{land}}$ - TWS
GRACE-based glacier interannual variability

- The GRACE-based glacier time series shows an 8-year cycle.
- Its amplitude (1mm) is the same as the one observed at GMSL$_{LT}$ and 10 times larger than the one observed in the Zemp et al. (2019) data.
- Glacier component is a strong candidate to explain the 8-year cycle reported by GMSL$_{LT}$.
- However, error contributions in the TWS component coming from the hydrological models can also have an impact.
Sea level rate over 5-year windows shifted 1-year based on GMSL$_{LT}$ minus the 8-year cycle

- Rate of GMSL$_{LT}$:
  \[
  \text{GMSL}_{LT} = \text{GMSL} - \text{Iv} \text{steric} - \text{IV}_{\text{TWS}} - \text{Iv}_{\text{glaciers}} - \text{IV}_{\text{AIS}} - \text{IV}_{\text{GIS}} - \text{IV}_{\text{AWV}} - (8\text{-year cycle})
  \]

- GMSL rate increases by a factor of 2 from 1995 to 2015
Acceleration of GMSL

• Acceleration of GMSL_{LT}:
  \[ A_{GMSL\ (1993\text{-}2016)} = (0.11 \pm 0.02) \text{ mm/yr}^2 \]

• Comparison with other published values:
  • Nerem et al. (2018):
    \[ A_{GMSL\ (1993\text{-}2017)} = (0.085 \pm 0.025) \text{ mm/yr}^2 \]
  • Veng and Andersen (2019):
    \[ A_{GMSL\ (1993\text{-}2017)} = (0.093 \pm 0.014) \text{ mm/yr}^2 \]

• The GMSL_{LT} acceleration is slightly larger than other estimations reported but it is still within the error bars
Acceleration of GMSL budget components

- Acceleration of GMSL$_{LT}$:
  \[ A_{\text{GMSL}} = (0.11 \pm 0.02) \text{ mm/yr}^2 \]

- Acceleration of GMSL budget components:
  - \( A_{\text{glaciers}} = (0.027 \pm 0.001) \text{ mm/yr}^2 \)
  - \( A_{\text{GIS}} = (0.055 \pm 0.001) \text{ mm/yr}^2 \)
  - \( A_{\text{AIS}} = (0.026 \pm 0.001) \text{ mm/yr}^2 \)
  - \( A_{\text{steric}} = (0.028 \pm 0.004) \text{ mm/yr}^2 \)
  - \( A_{\text{AWV}} = (-0.004 \pm 0.001) \text{ mm/yr}^2 \)

- Sum of all components:
  - \( A_{\text{Total}} = (0.13 \pm 0.01) \text{ mm/yr}^2 \)
Conclusions and outlook

• Discovery of an unexpected 8-year cycle present in the GMSL record corrected for the interannual variability of all the components of the sea level budget

• Attribution of the 8-year signal to the interannual variability of the glacier component

• Good agreement with acceleration results reported in other publications

• Further research is needed to understand the processes causing the reported 8-year cycle
Thank you for your attention!
References


Satellite altimetry

- Radar altimeters on board the satellites transmit signals at high frequencies to Earth and receive the echoes from the Surface.
- The ultimate goal is to measure surface height relative to a terrestrial reference frame.
- Sea Level Anomalies = (Satellite Altitude) – (Mean Sea Level)
  - The altitude of the satellite is the satellite’s distance with respect to an arbitrary reference (e.g. the reference ellipsoid, a rough approximation of the Earth’s surface).
  - The mean sea level is the sea surface height averaged across all the oceans of the globe.

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Periodograms of $\text{GMSL}_{LT}$ rate and $\text{GMSL}_{LT}$
Quadratically detrended CCI/CMEMS and CU GMSL
Interannual variability of TWS from WGHM and ISBA-CTRIP
Periodograms of climate modes

- NAO
- AMO
- SAM
- MEI
- IOD
- PDO