An 8-year cycle in the rate of the global mean sea level

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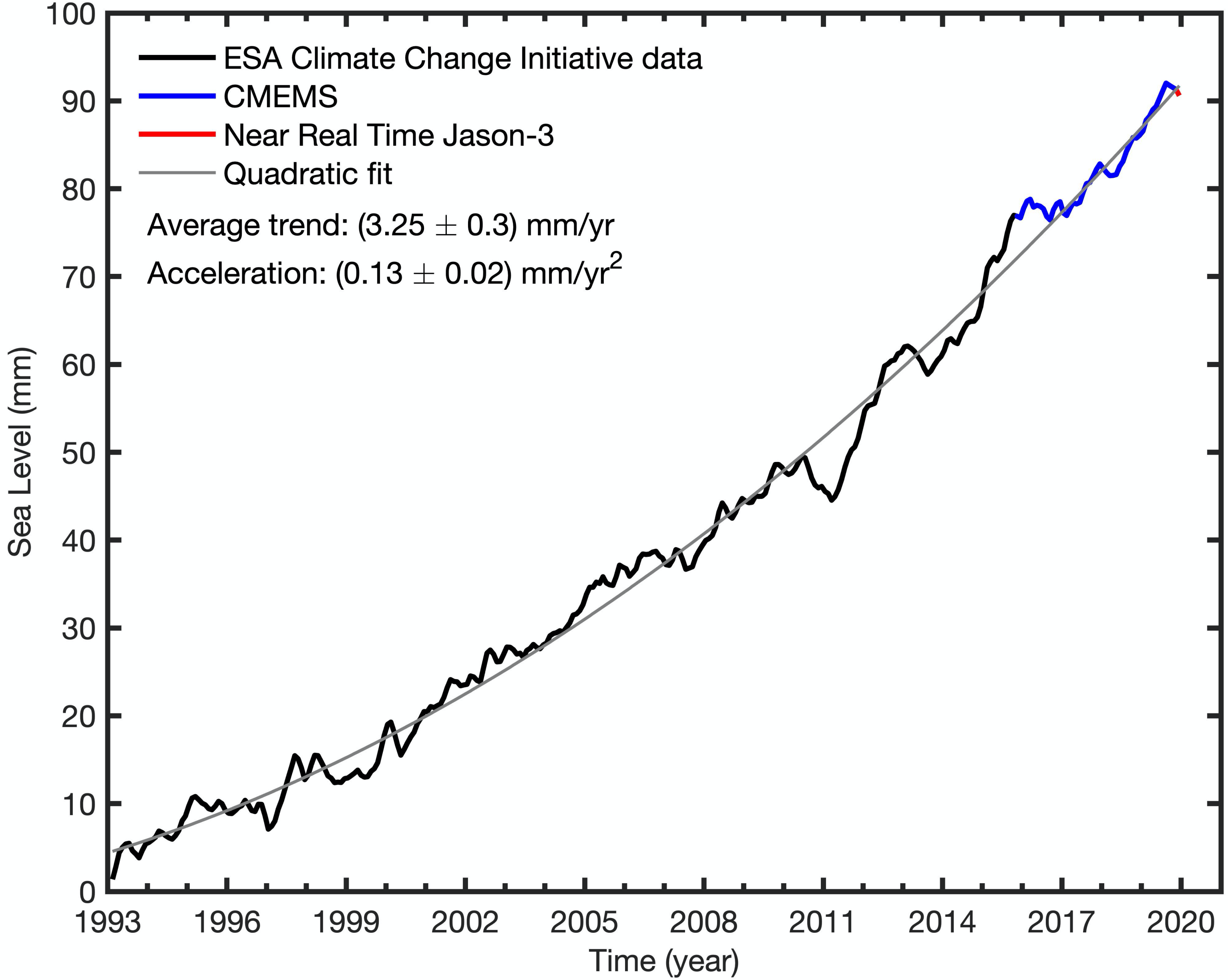
Global mean sea level (GMSL) over the altimetry era (1993-2020)



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

<u>Research question:</u>

- How the rate of the GMSL evolved with time over the altimetry era?

Sea level budget

- GMSL budget equation:

$$GMSL(t) = GMSL_{steric}(t) + GMSL_{ocean\ mass}(t)$$

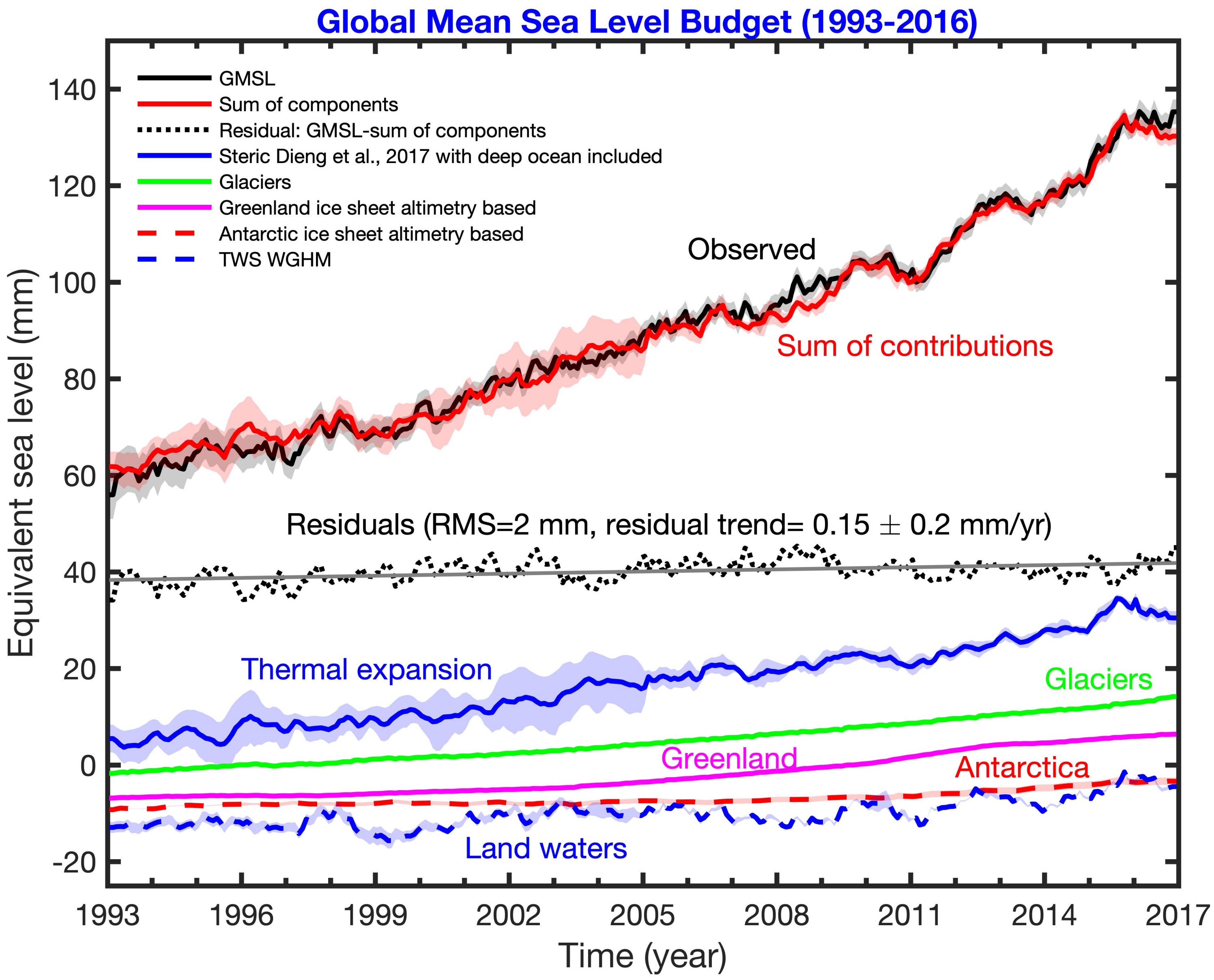
  - $GMSL_{steric}$ refers to the contribution from the ocean thermal expansion
  - $GMSL_{ocean\ mass}$ refers to the change in mass of the oceans

- Ocean mass term (water mass conservation in the climate system):

$$M_{ocean}(t) + M_{glaciers}(t) + M_{GIS}(t) + M_{AIS}(t) + M_{TWS}(t) + M_{AWV}(t) = 0$$

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



(Source: ESA CCI Global Mean Sea Level Budget project, 2020)

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

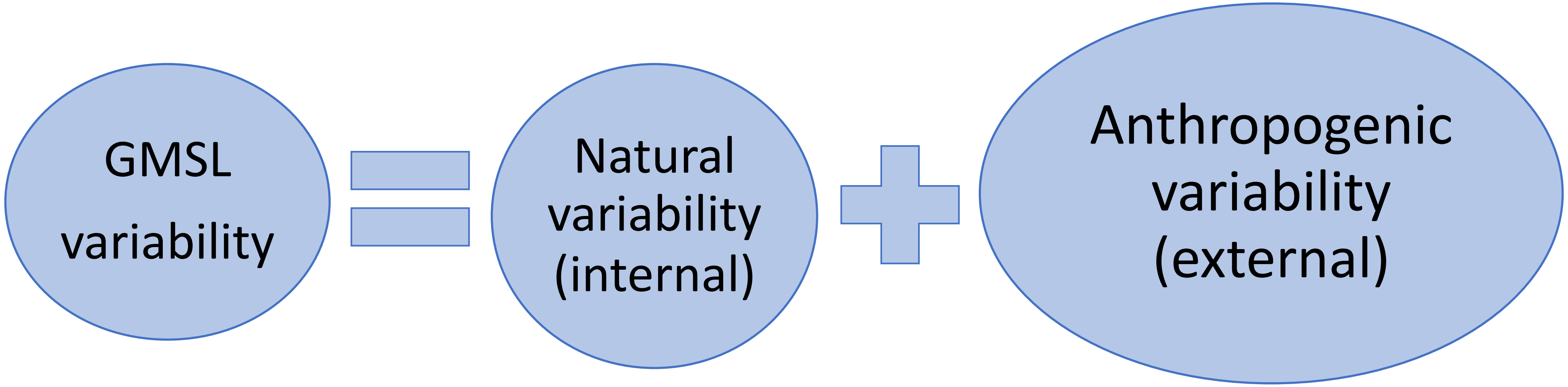
Objective:

- 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-CTRIP) 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



<u>Method to separate between contributions:</u>

- 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?

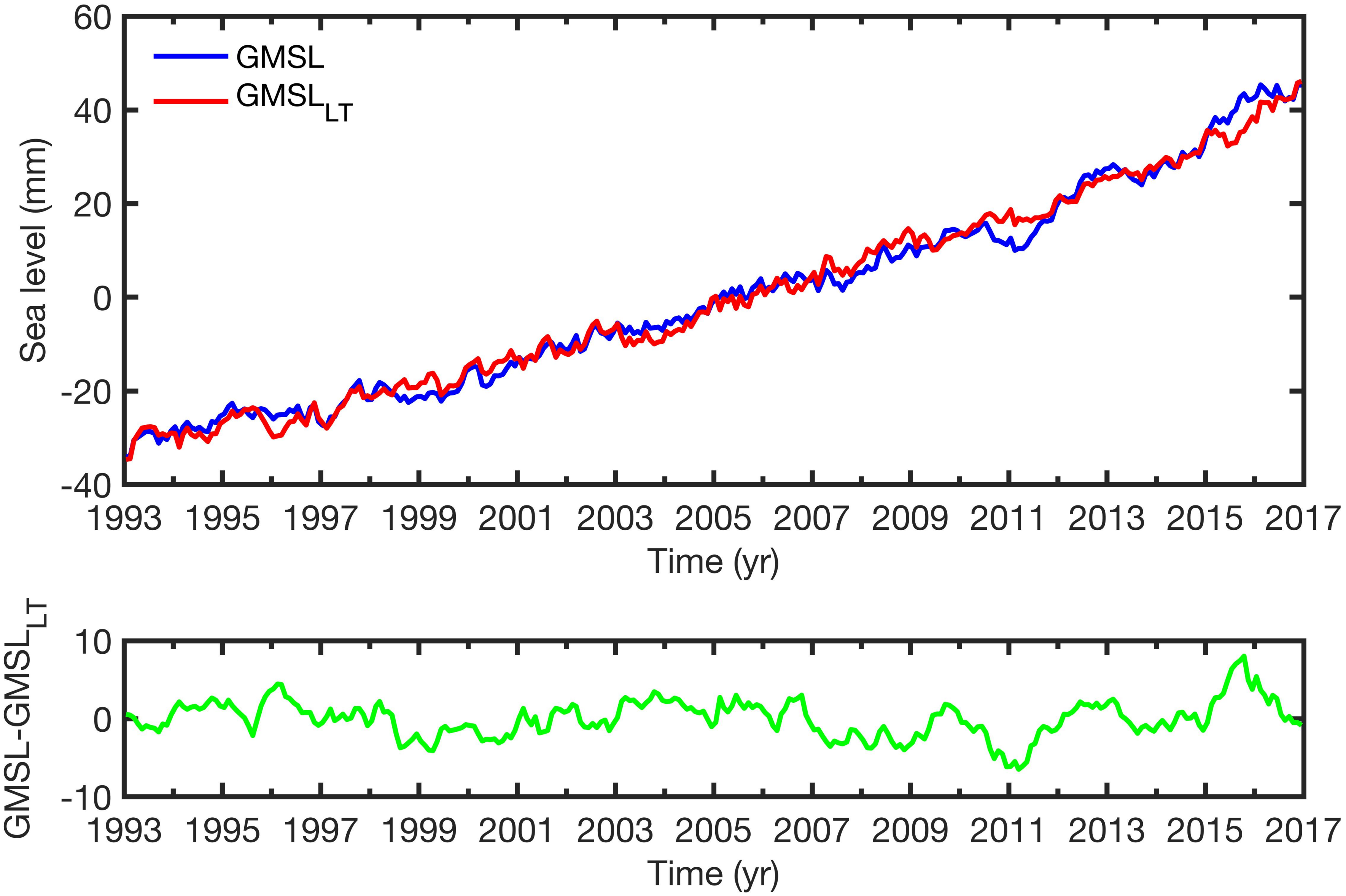
The procedure is:

- 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:

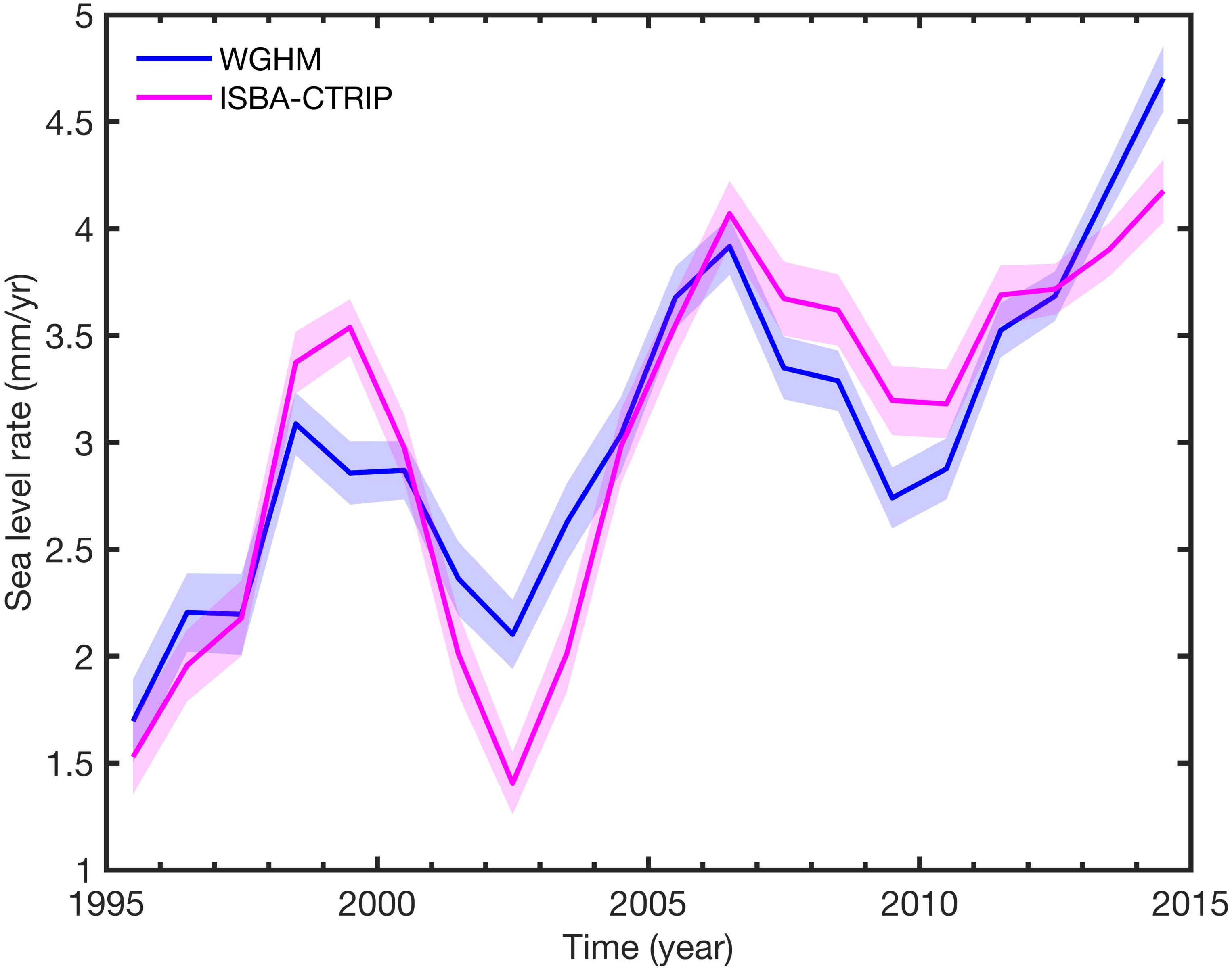
$$GMSL_{LT} = GMSL - IV_{steric} - IV_{TWS} - IV_{glaciers} - IV_{AIS} - IV_{GIS} - IV_{AWV}$$

$GMSL_{LT}$ 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 $GMSL_{LT}$ over 5-year windows shifted 1-year



- $GMSL_{LT}$ shows a clear 8-year cycle superimposed on an increasing trend

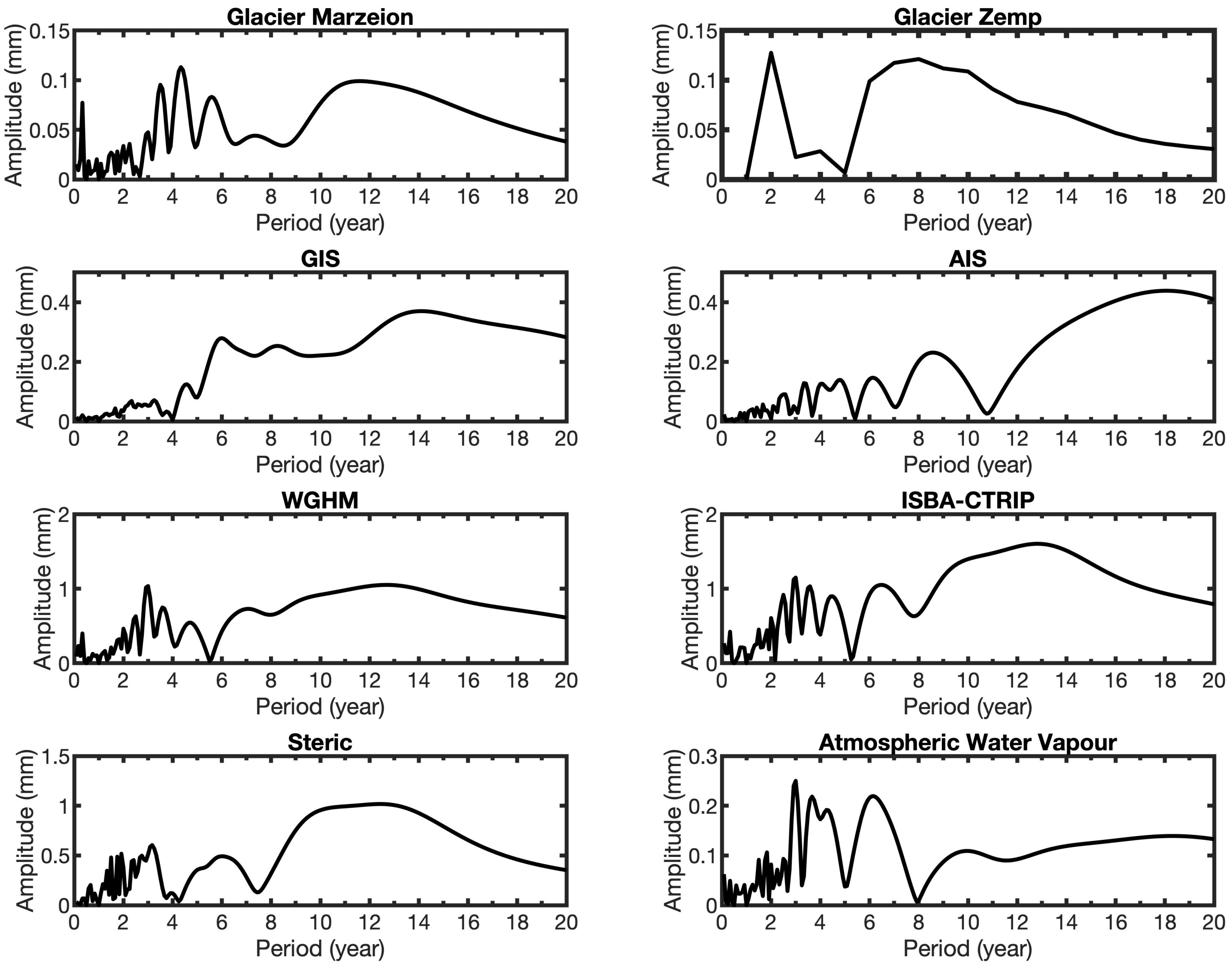
<u>Research question:</u>

- 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 posible 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

<u>Hypothesis:</u>

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

<u>Research question:</u>

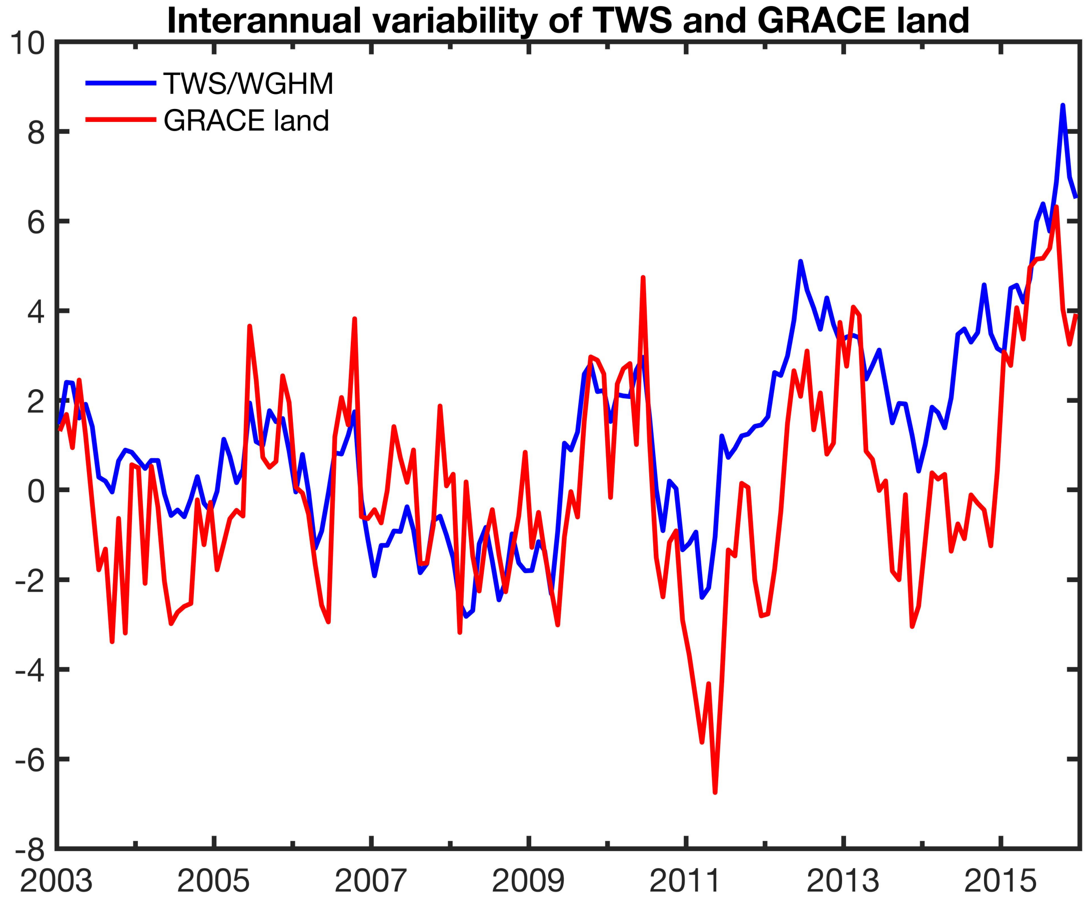
- Could a missed glacier contribution be responsible for the observed 8-year cycle?

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:

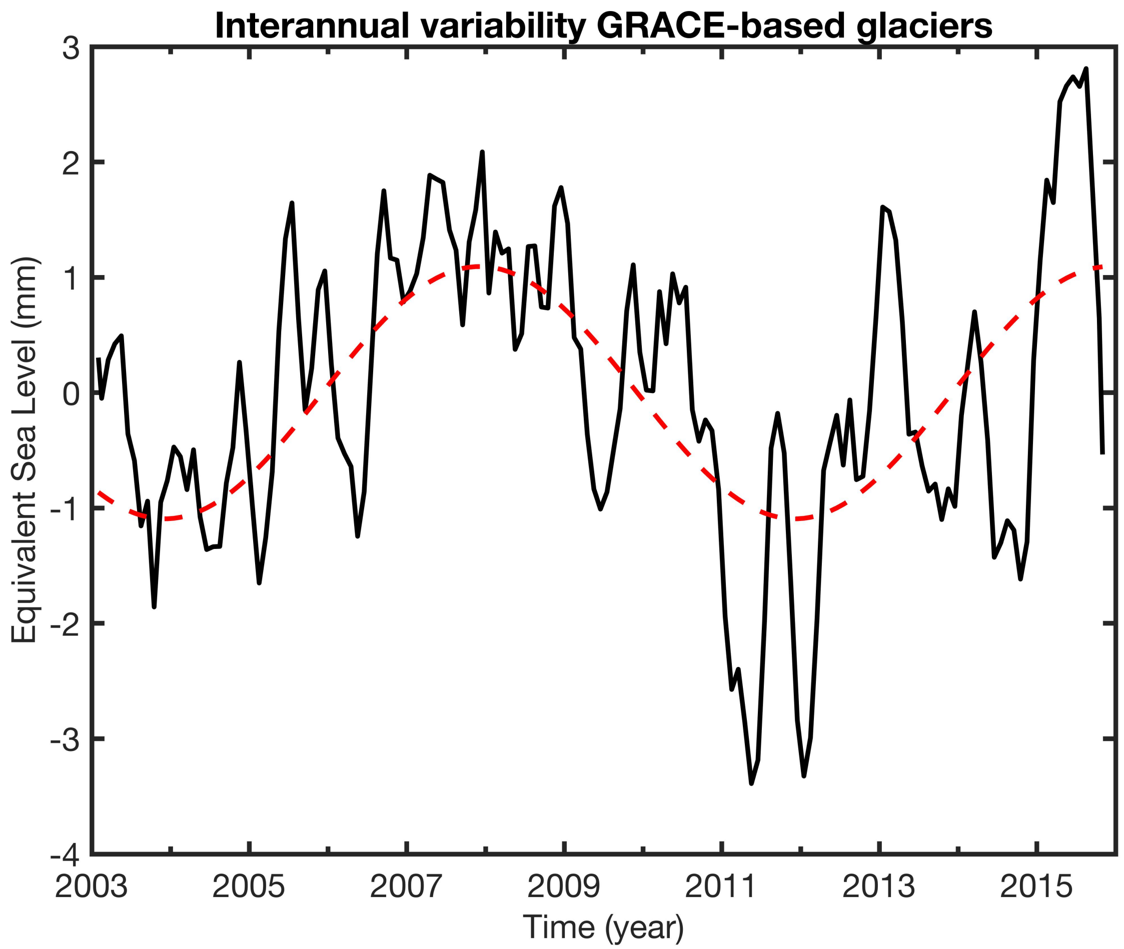
$$GRACE_{land} = Glaciers + TWS$$

$$\text{GRACE-based glaciers} = GRACE_{land} - TWS$$

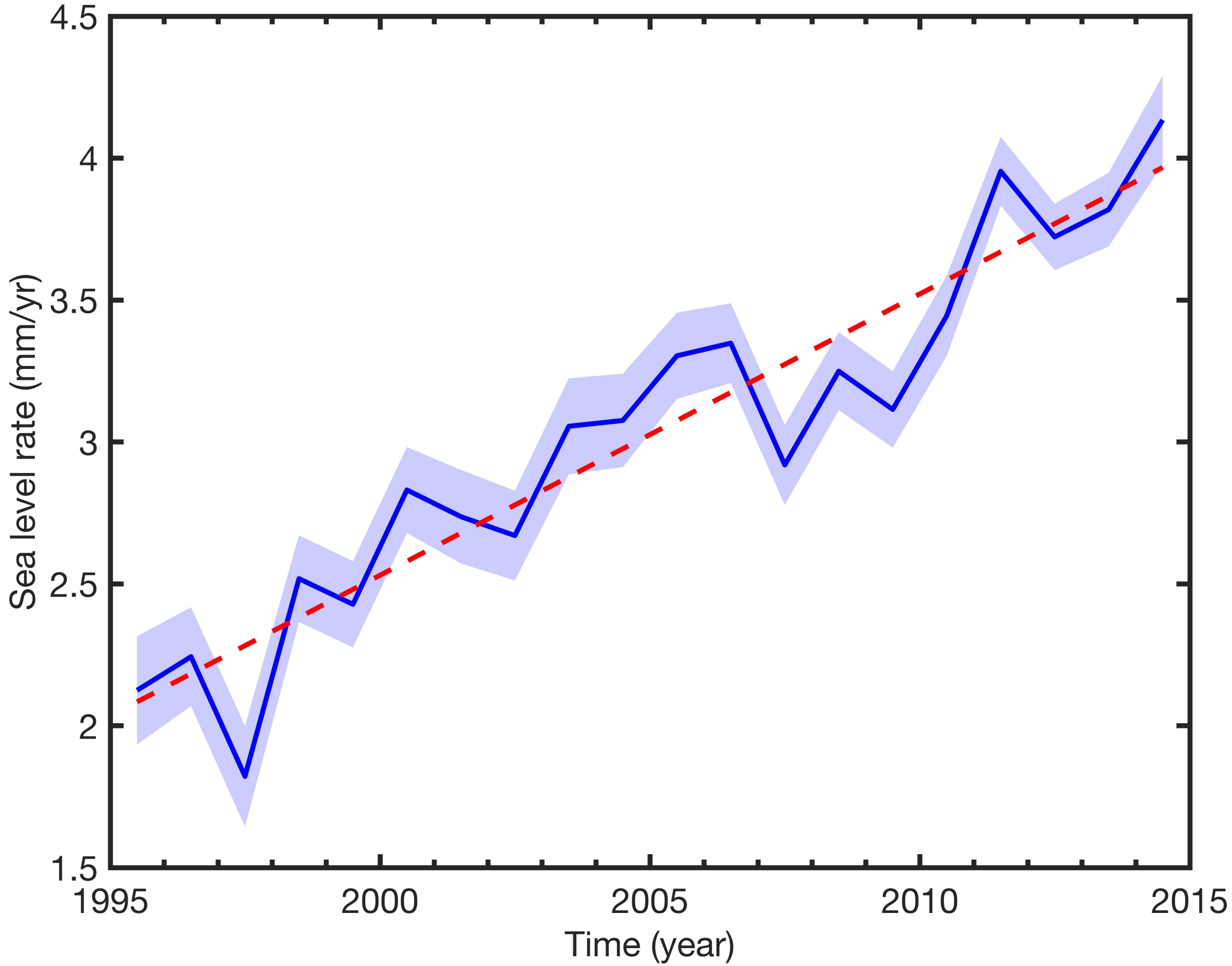


GRACE-based glacier interannual variability

- 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 $GMSL_{LT}$:

$$GMSL_{LT} = GMSL - Iv_{steric} - IV_{TWS} - Iv_{glaciers} - IV_{AIS} - IV_{GIS} - IV_{AWV} - (8\text{-year cycle})$$

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

Acceleration of GMSL

- Acceleration of $GMSL_{LT}$:

  $A_{GMSL\ (1993\text{-}2016)}=(0.11 \pm 0.02)\ mm/yr^2$

- Comparison with other published values:
  - Nerem *et al.* (2018):

    $A_{GMSL\ (1993\text{-}2017)}=(0.085 \pm 0.025)\ mm/yr^2$

  - Veng and Andersen (2019):

    $A_{GMSL\ (1993\text{-}2017)}=(0.093 \pm 0.014)\ mm/yr^2$

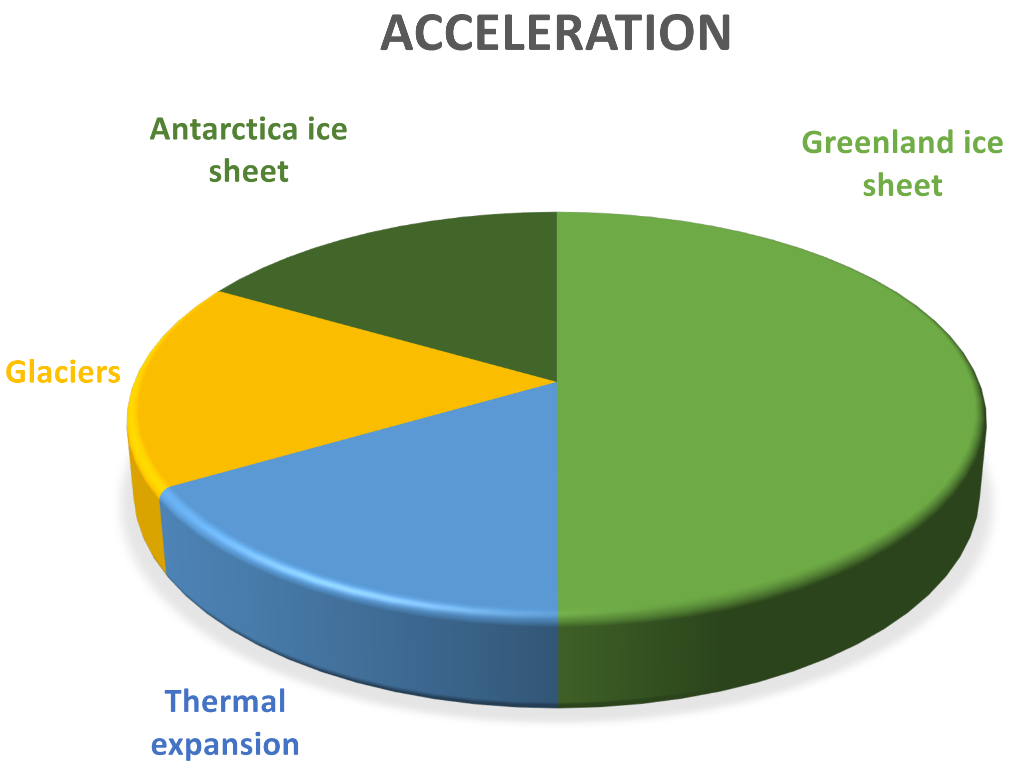
- The $GMSL_{LT}$ acceleration is slightly larger than other estimations reported but it is still within the error bars

Acceleration of GMSL budget components

- Acceleration of $GMSL_{LT}$:

  A_{GMSL}=(0.11 ± 0.02) mm/yr^2

- Acceleration of GMSL budget components:
  - $A_{glaciers}$=(0.027 ± 0.001) mm/yr^2
  - A_{GIS}=(0.055 ± 0.001) mm/yr^2
  - A_{AIS}=(0.026 ± 0.001) mm/yr^2
  - A_{steric}=(0.028 ± 0.004) mm/yr^2
  - A_{AWV}=(-0.004 ± 0.001) mm/yr^2
- Sum of all components:
  - A_{Total}=(0.13 ± 0.01) 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!

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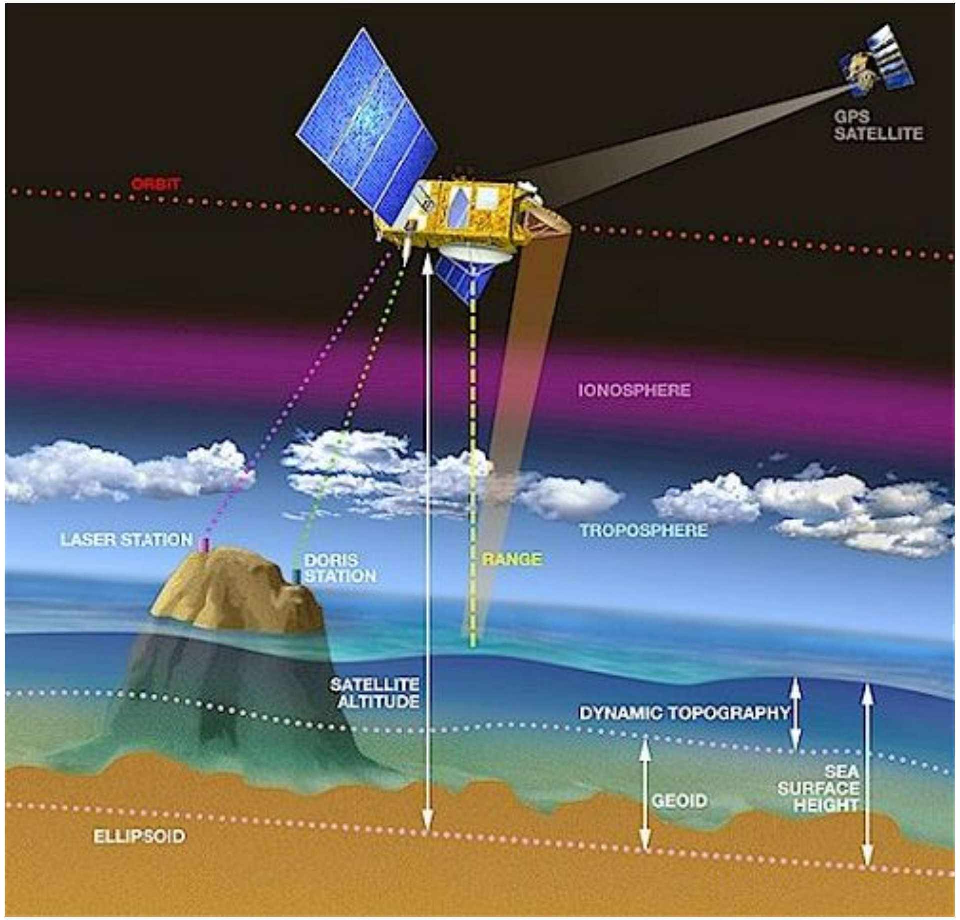
References

- Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. and Cogley, J. G. (2019), Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 382-389, 568, https://doi.org/10.1038/s41586-019-1071-0.
- Nerem, S., Ablain, M. and Cazenave, A. (2018). A 25-year long satellite altimetry-based global mean sea level record; Closure of the sea level budget & missing components. In: Stammer, Cazenave (Eds.), Satellite Altimetry over Oceans and Land Surfaces. CRC Press.
- Veng, T. and Andersen, O. B. (2020), Consolidating Sea Level Acceleration Estimates from Satellite Altimetry, *Advances in Space Research*, in press.

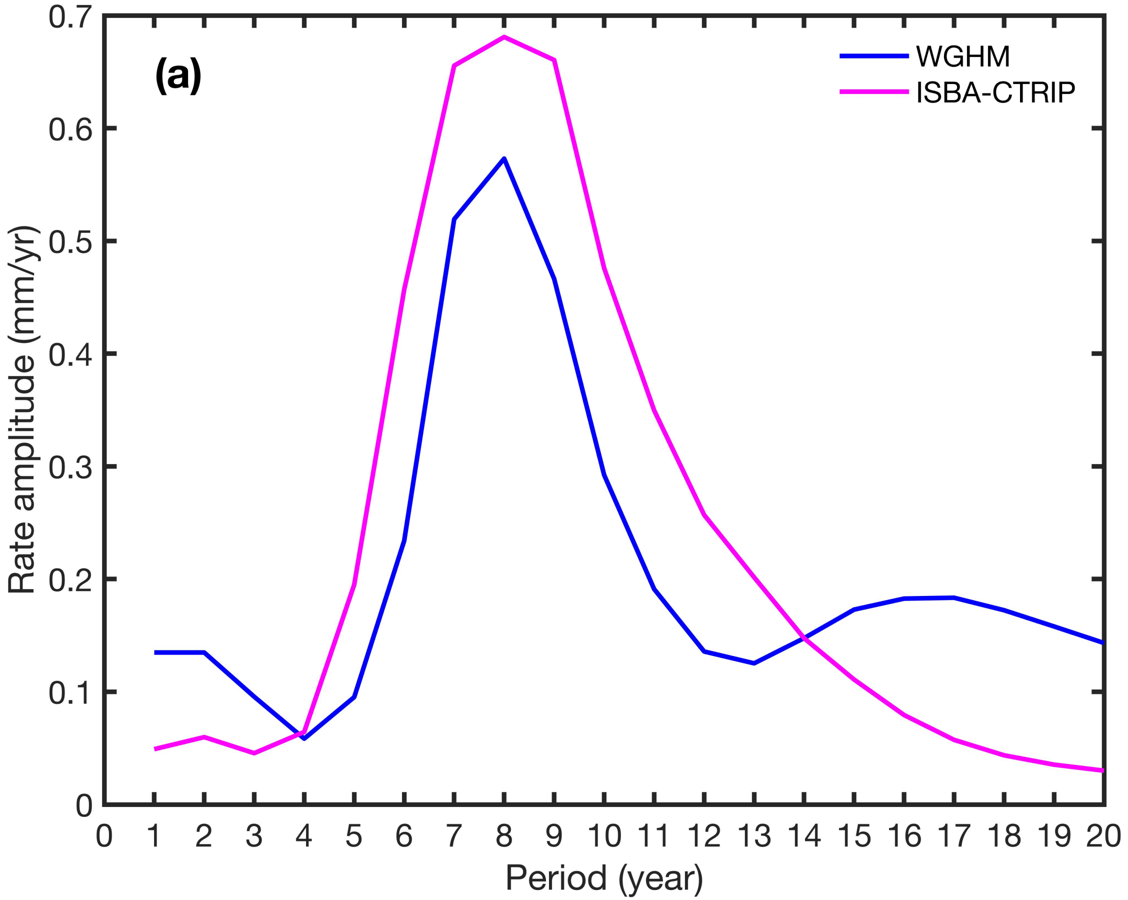
Satellite altimetry

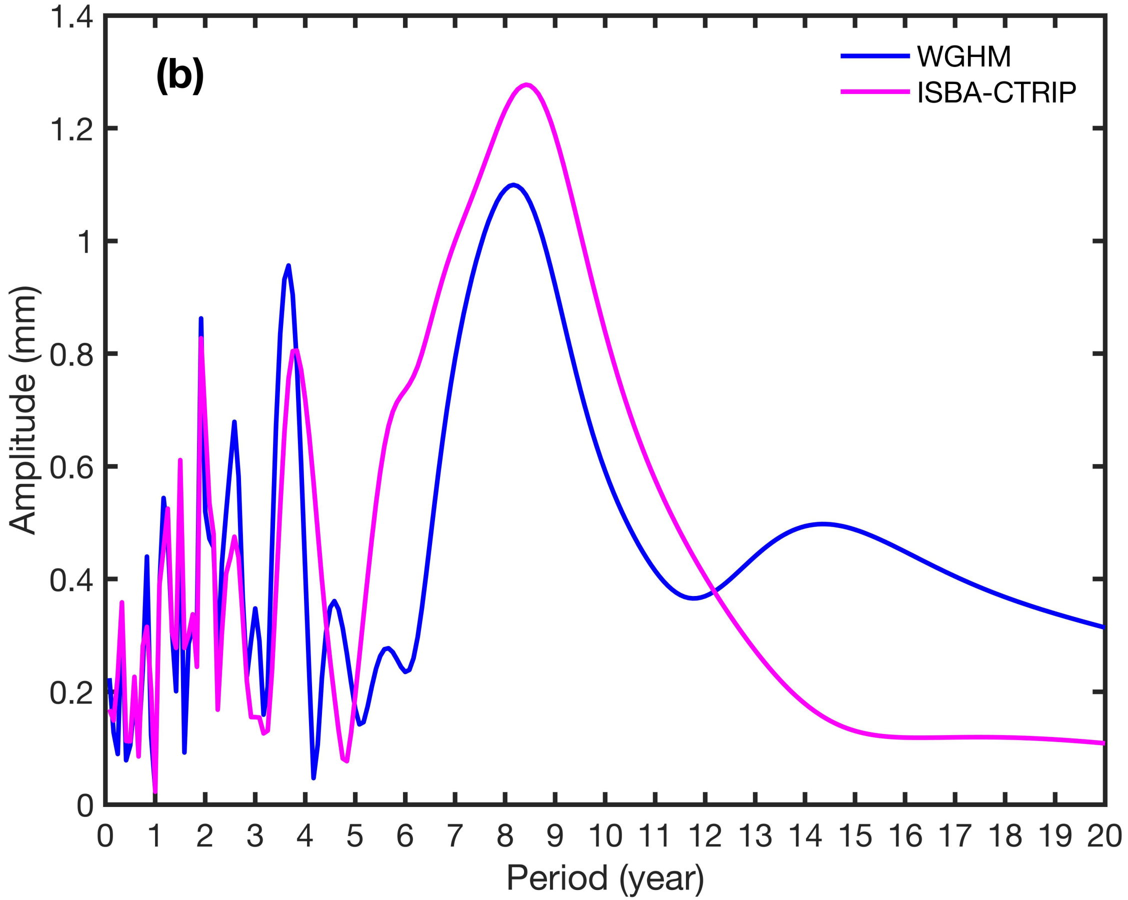


(Credits CNES/D. Ducros)

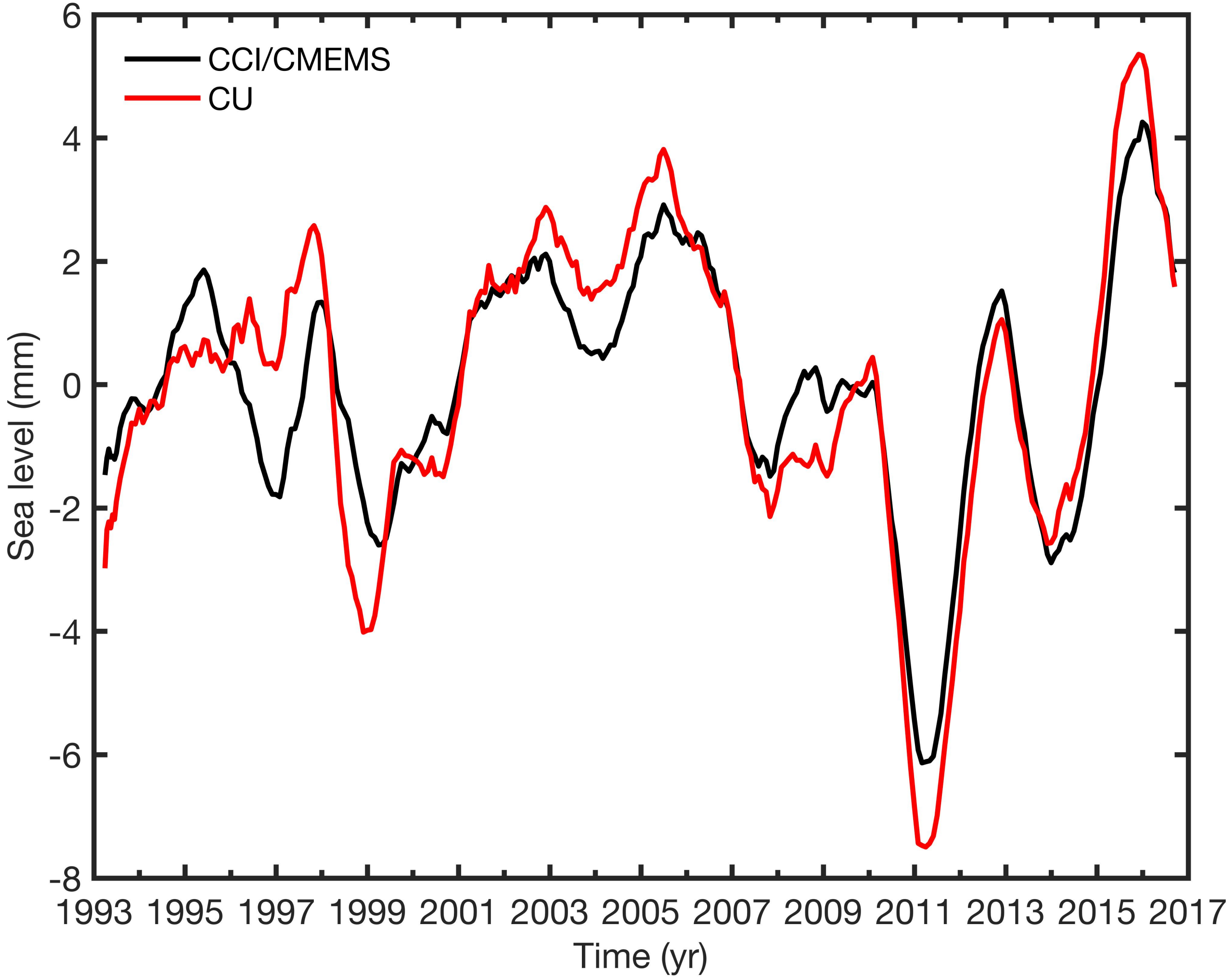
- Radar altimeters on board the satellites transmit signals at high frequencies to Earth and receive the echoes from the Surface
- The ultimate goal is to measure surface height relative to a terrestrial reference frame
- Sea Level Anomalies = (Satellite Altitude) – (Mean Sea Level)
    - The altitude 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

Periodograms of $GMSL_{LT}$ rate and $GMSL_{LT}$

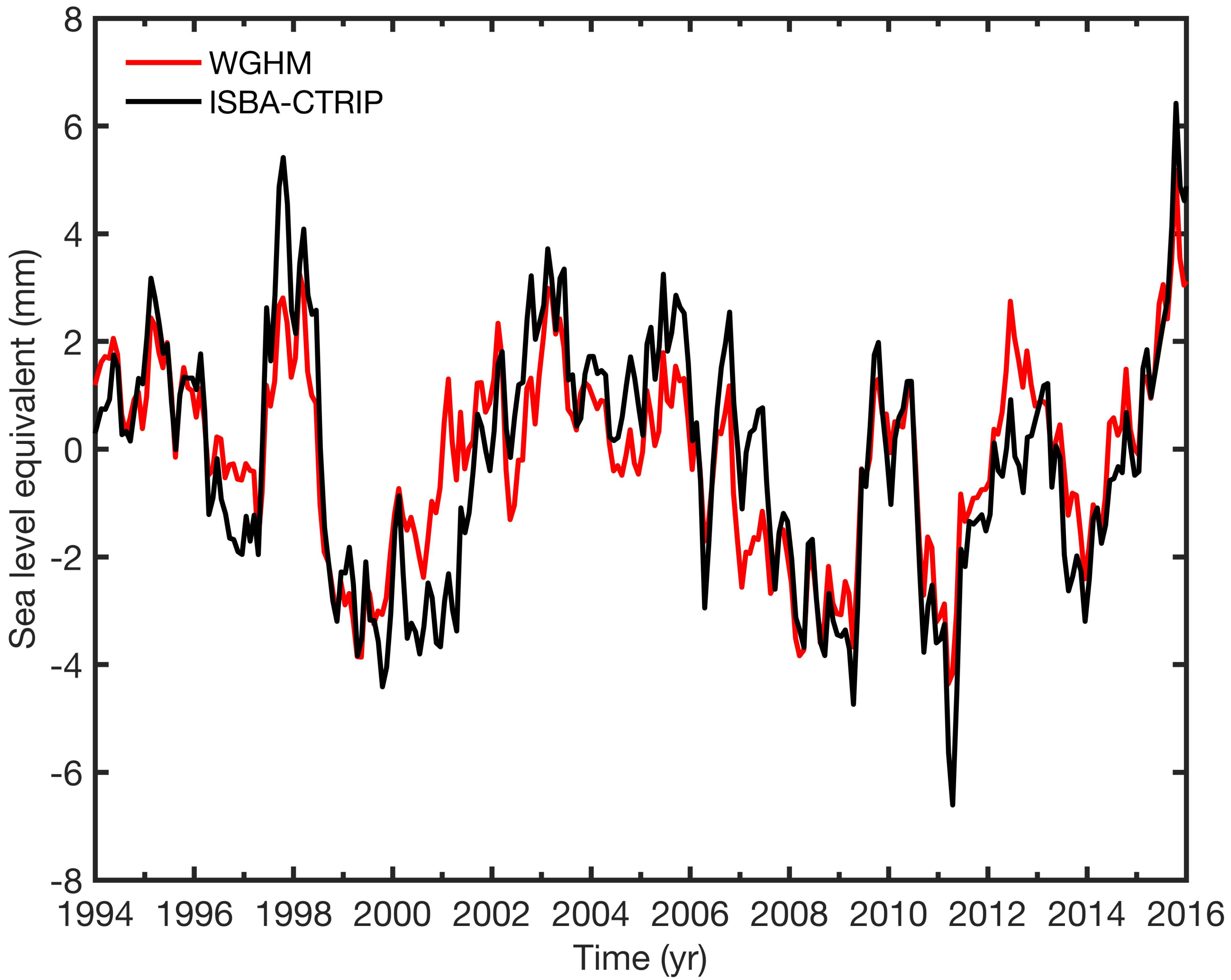




Quadratically detrended CCI/CMEMS and CU GMSL



Interannual variability of TWS from WGHM and ISBA-CTRIP



Periodograms of climate modes