# Churning the Ocean: Time variable gravity for ocean applications


Samudra Manthan, CC BY 3.0

*Roelof Rietbroek, 28 Sept. 2022*

# Analogies with today's talk

Find this presentation on https://github.com/strawpants/grace-hackweek-ocean

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- Snake Vasuki: Churning the ocean (forcing from wind stress, density contrasts)

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# Analogies with today's talk

- Mount Mandara: Adding mass to the ocean (e.g. melt water)
- Snake Vasuki: Churning the ocean (forcing from wind stress, density contrasts)
- Central Question: How can we use time variable gravity to observe ocean signals?

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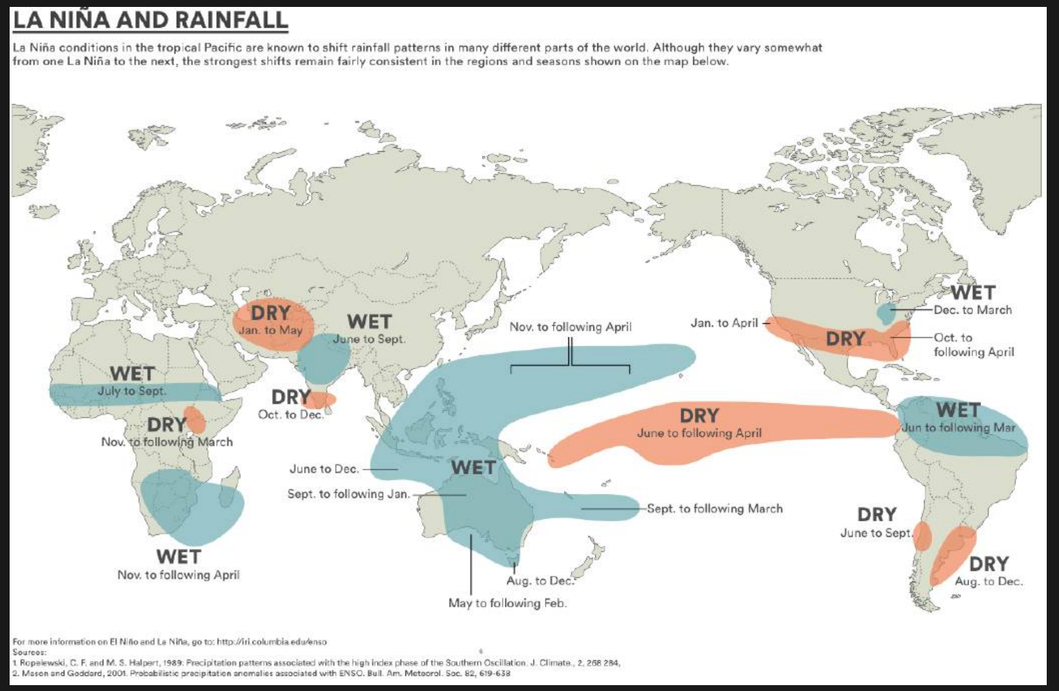
# Adding mass to the oceans (or removing it)


# Remember the 2010-2011 La Nina event?

Rockhampton, QLD. Photo by Salvation Army of Australia



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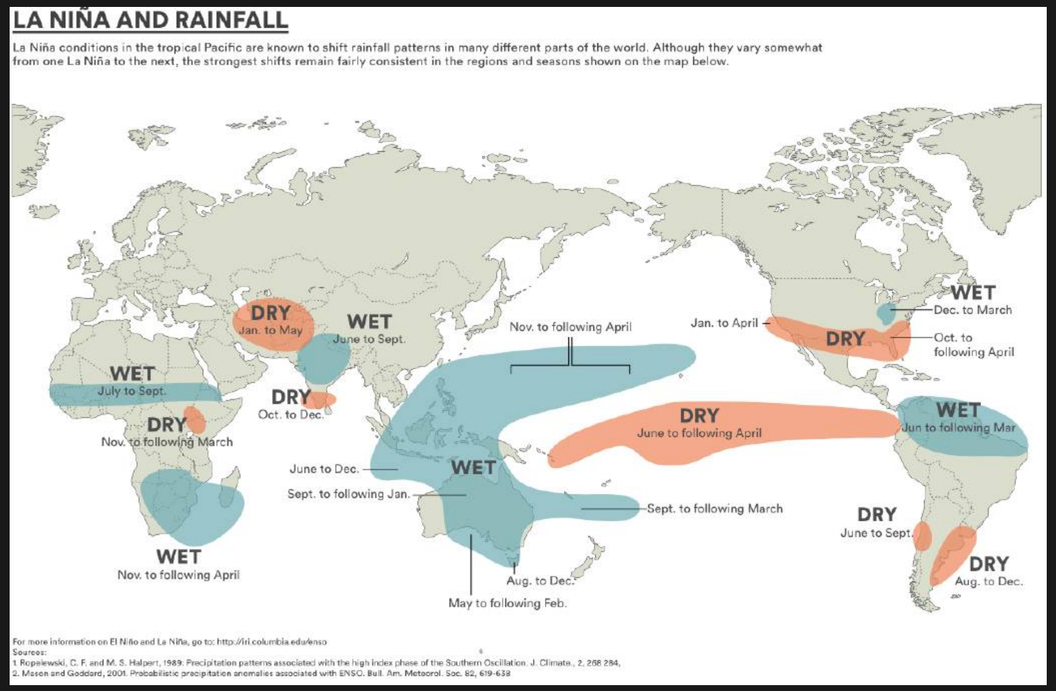


- Stronger trade winds result in warm ocean blob in the western Pacific

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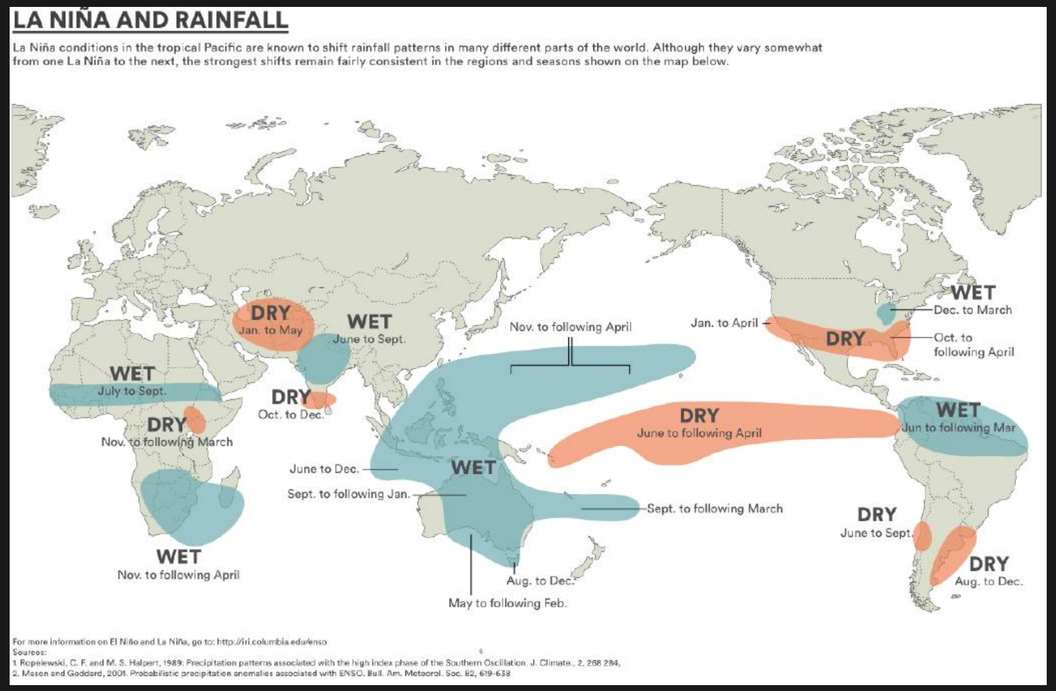


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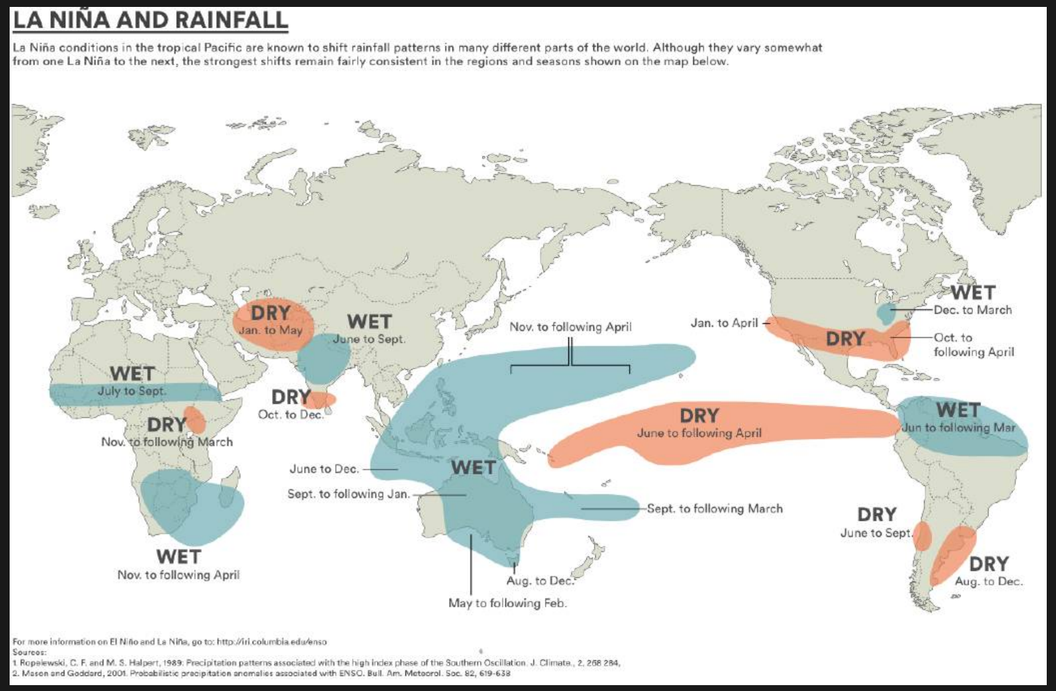


- Stronger trade winds result in warm ocean blob in the western Pacific
- Wet conditions in the West Pacific cause extreme precipitation
- Detectable in sea level?

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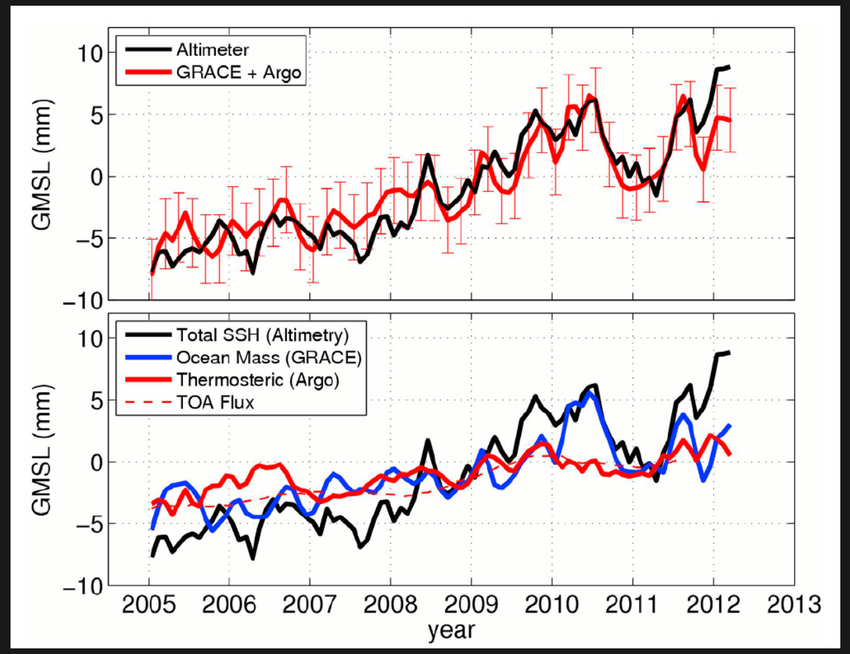
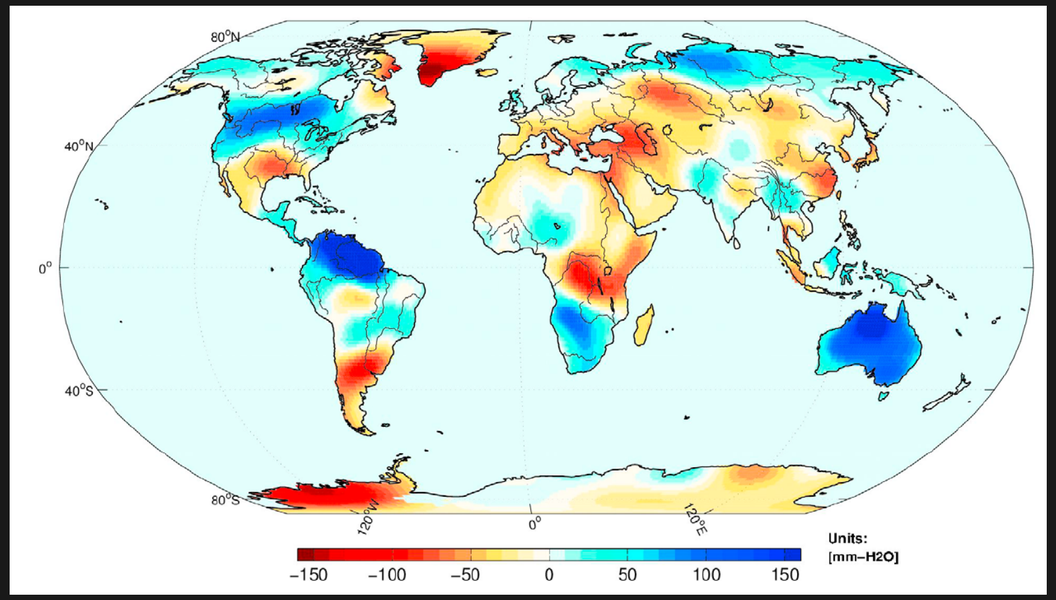



Global mean sea level variations (total, mass driven and 'steric'), From Böning et al. 2012

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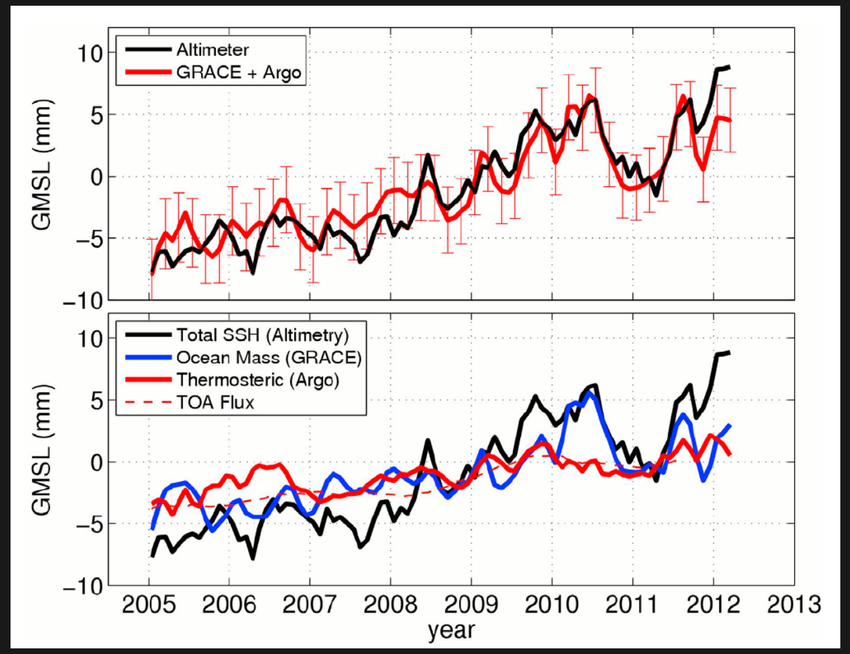


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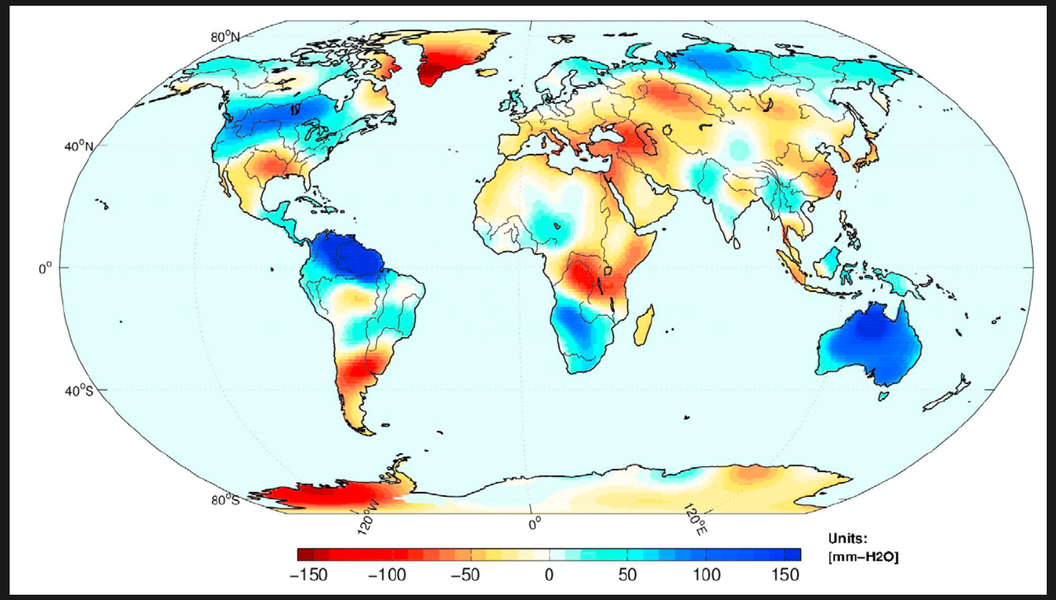
- Detectable with radar altimetry

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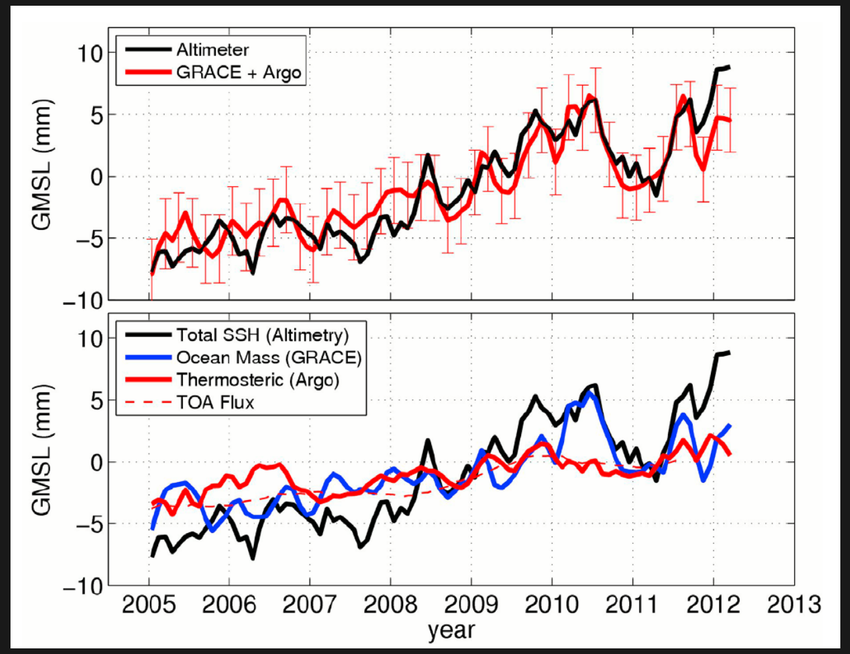


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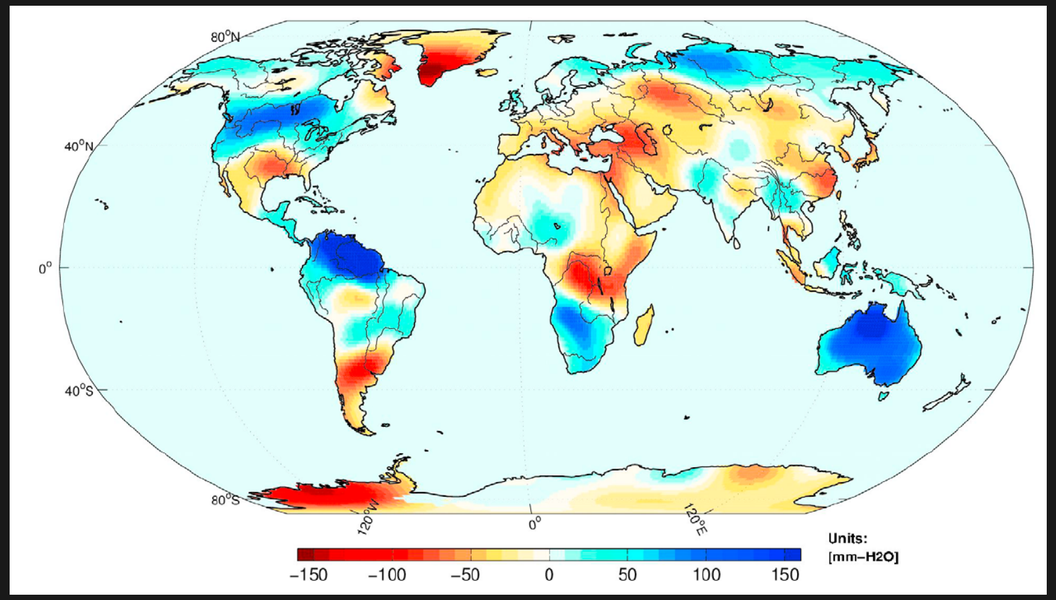


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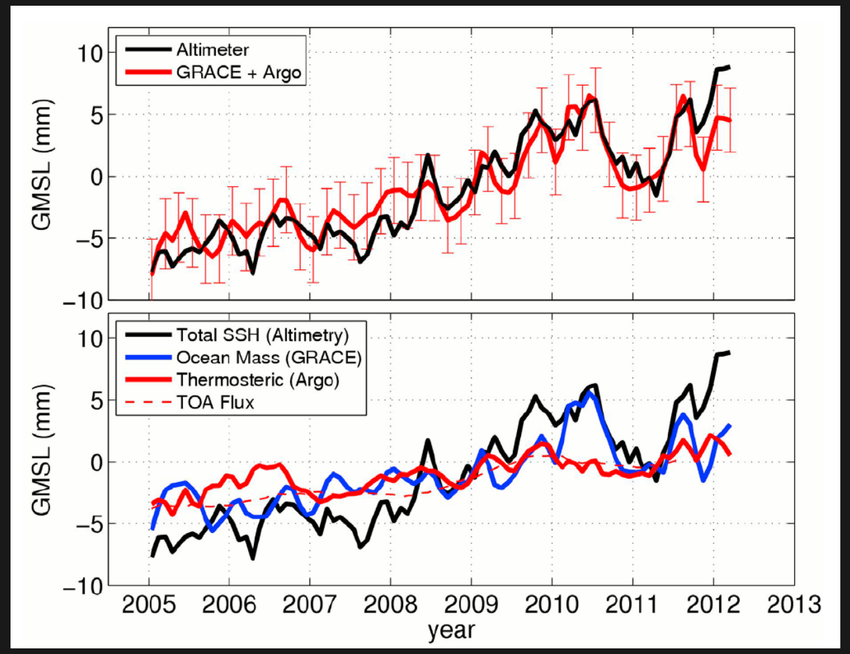


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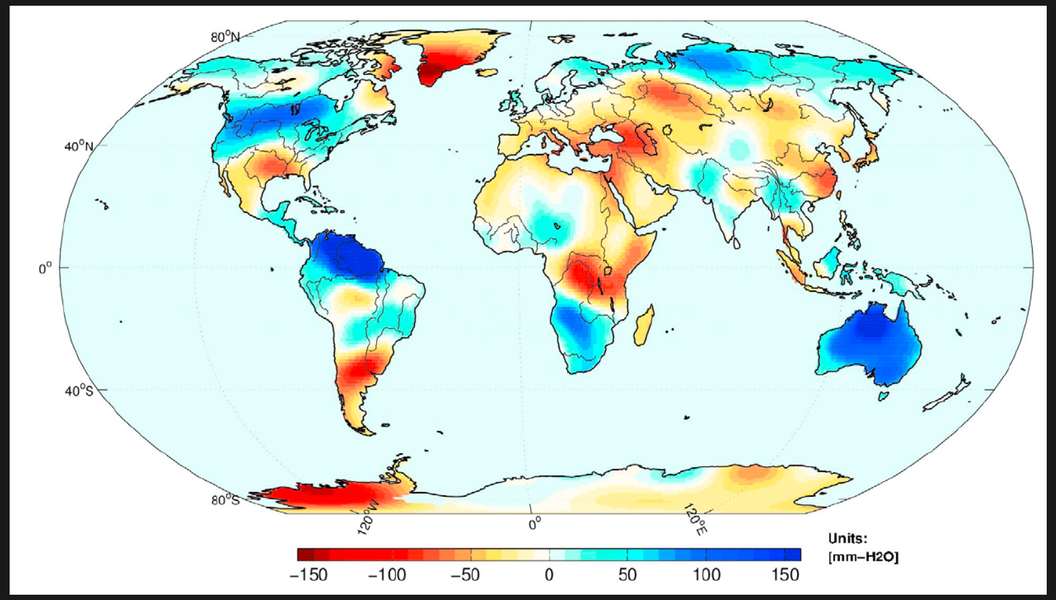
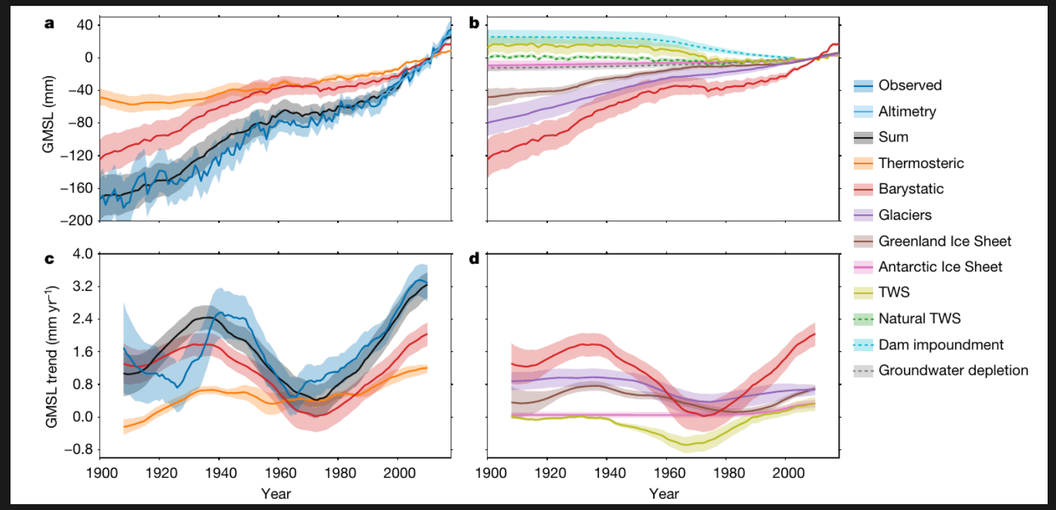



Terrestrial water storage change (2010-2011) from GRACE, From Böning et al. 2012

- Detectable with radar altimetry
- Can be explained by mass-driven sea level (GRACE)
- Hotspot:Australia

# Sea level contributions since 1900

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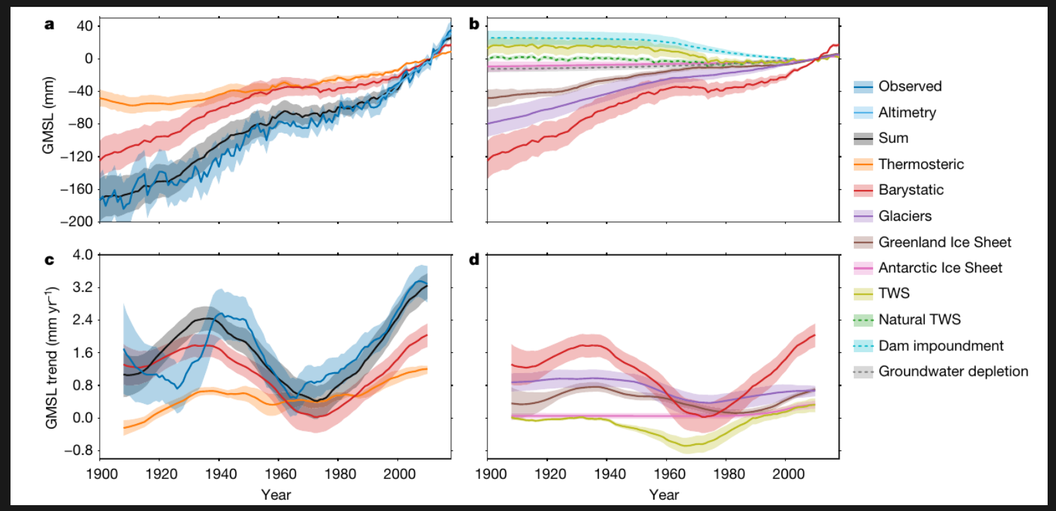


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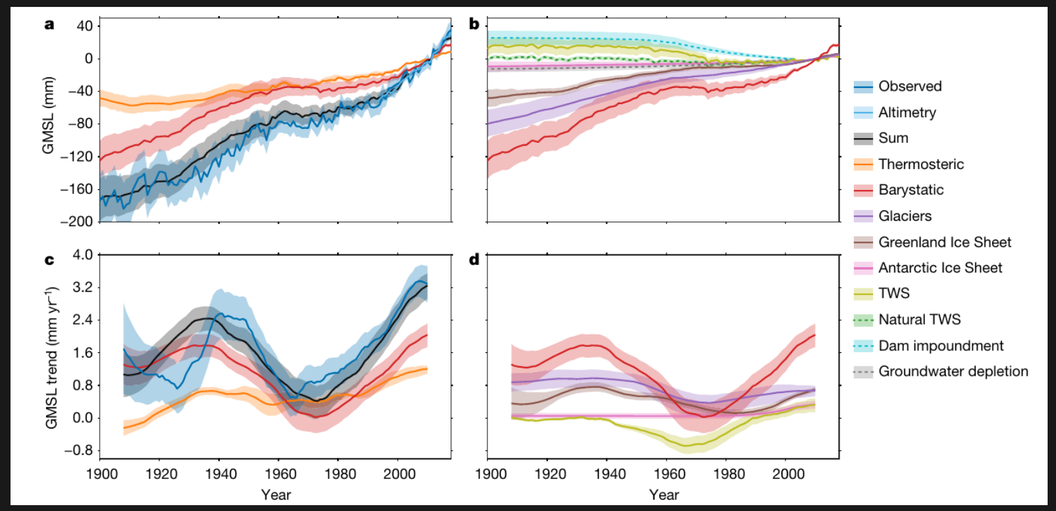


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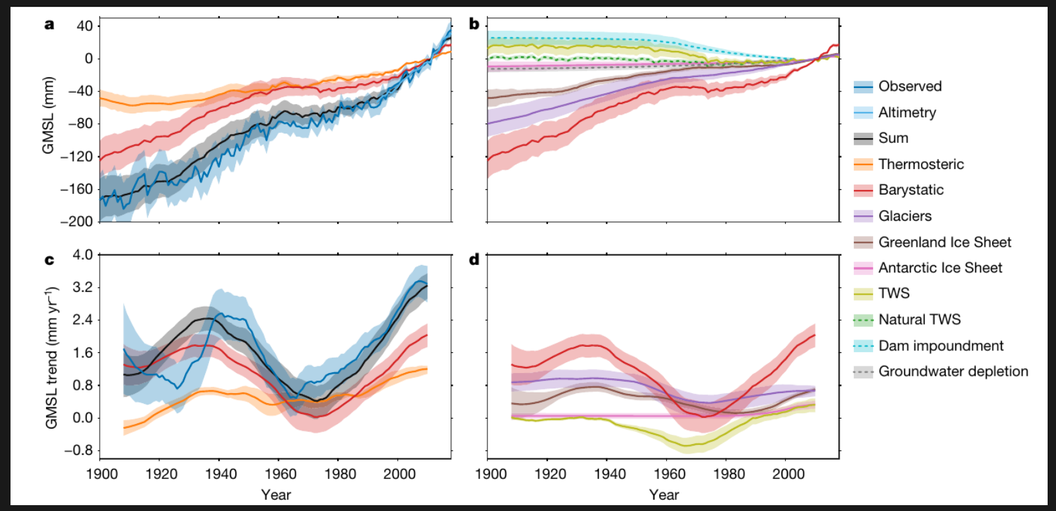


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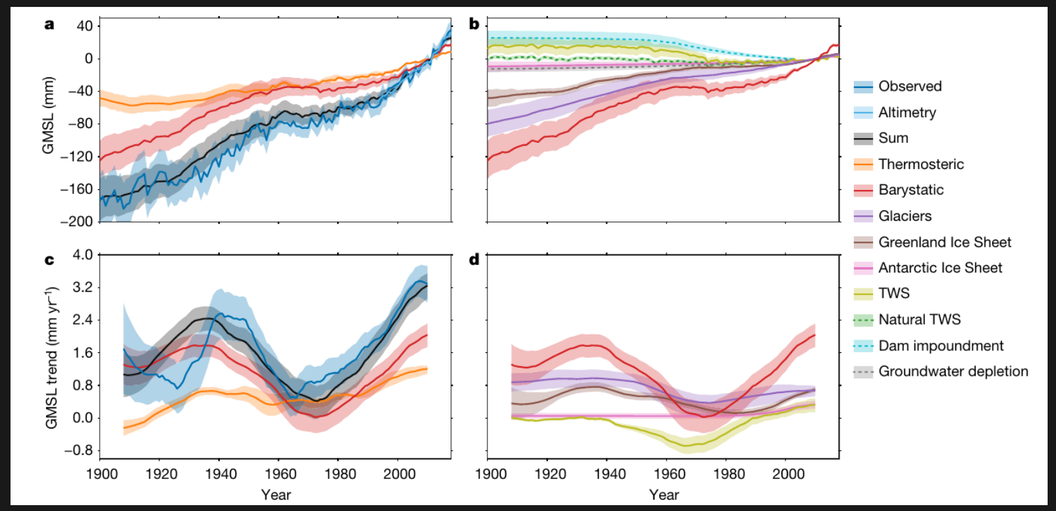


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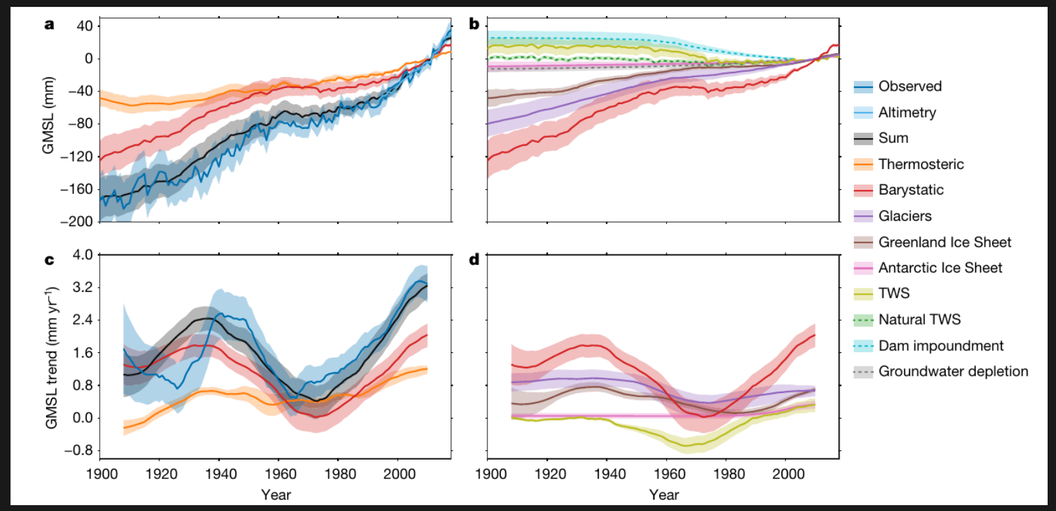


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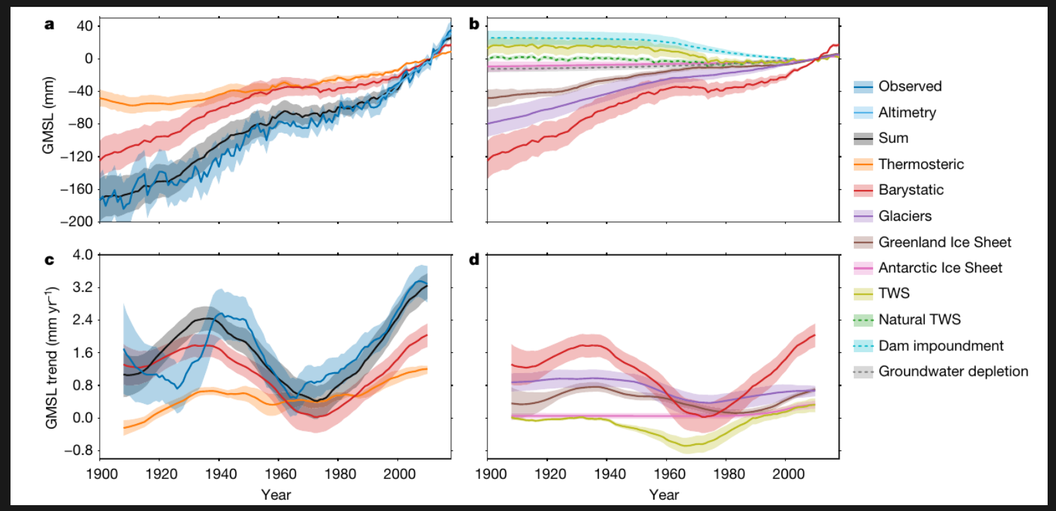


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- Recent accelerations from icesheets and glaciers -> (observable by GRACE since 2002)

# Ocean mass from GRACE (Theory)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. B9, 2193, doi:10.1029/2001JB000576, 2002

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Received 8 May 2001; revised 9 March 2002; accepted 14 March 2002; published 19 September 2002.

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    - dot product of smoothed basin coefficients with GRACE-TWS coefficients

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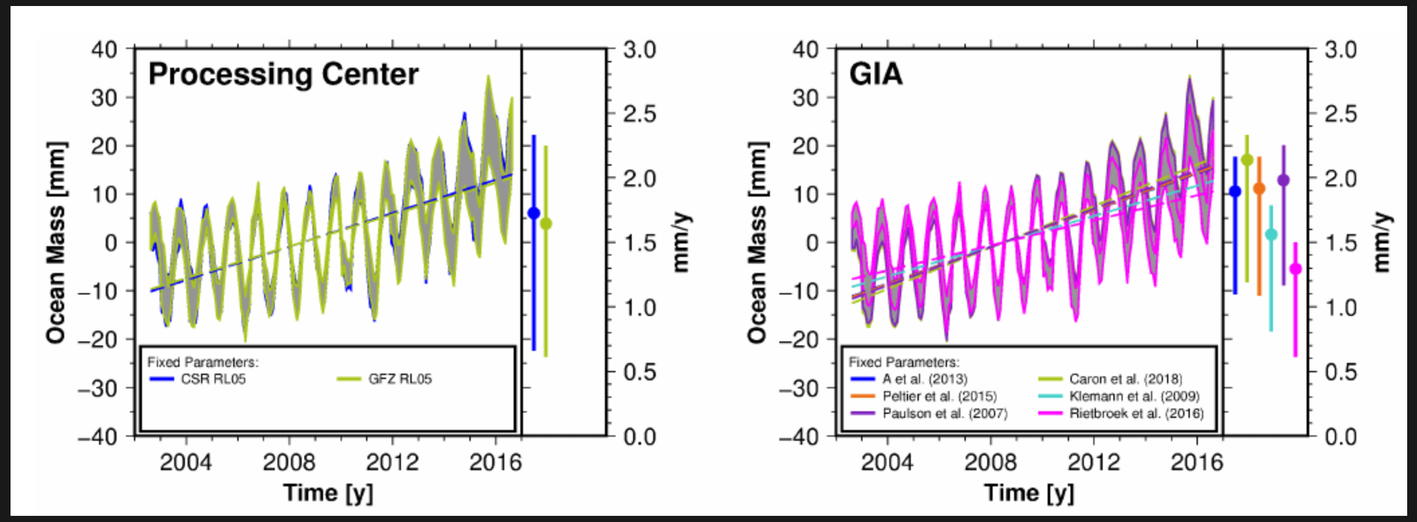


Effect of different processing choices on ocean mass estimates, from Uebbing et al. 2019

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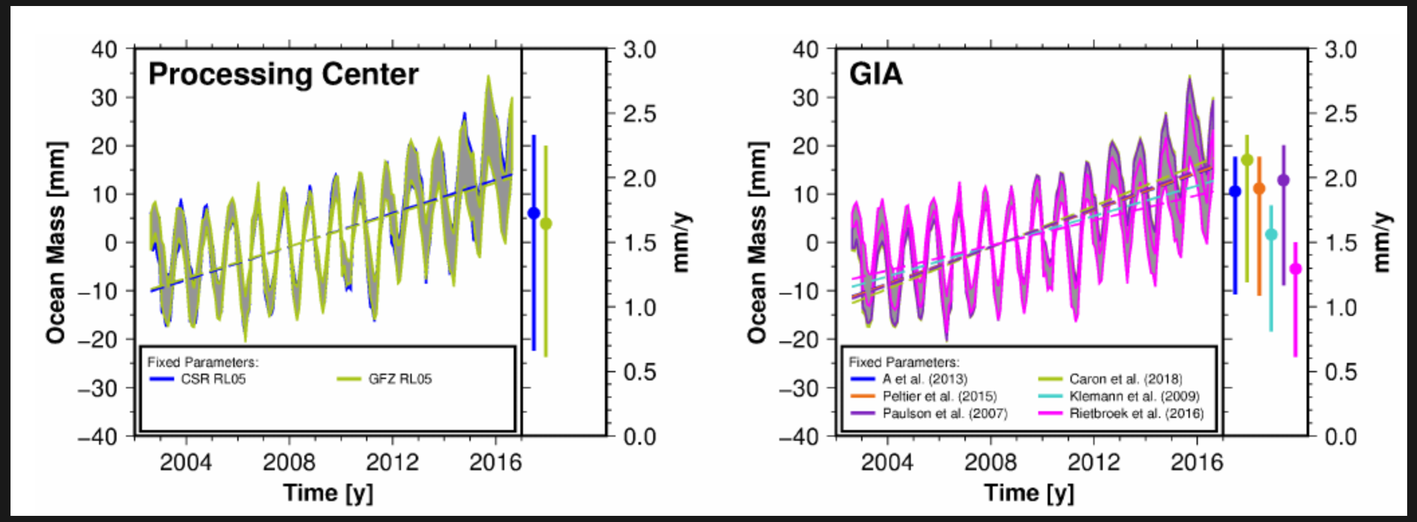


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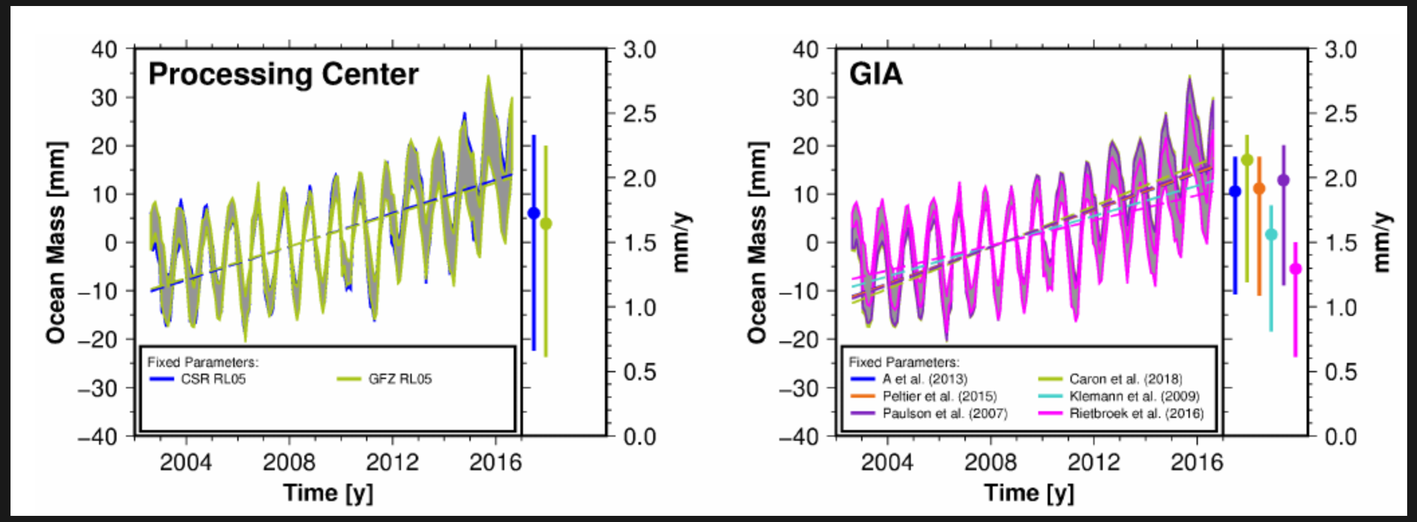


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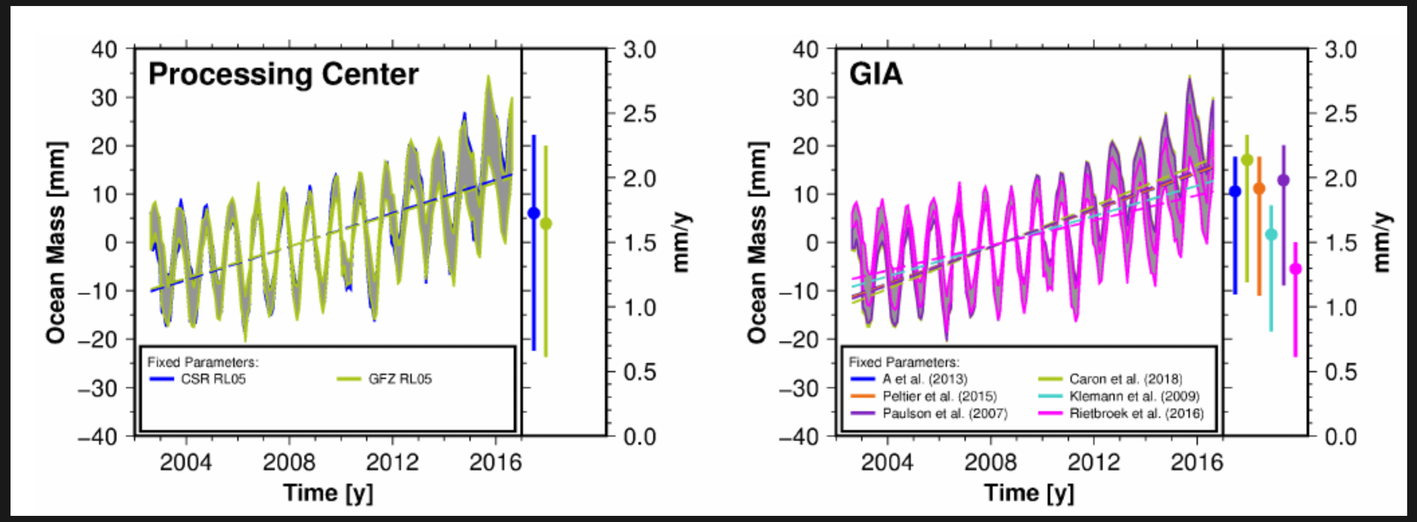


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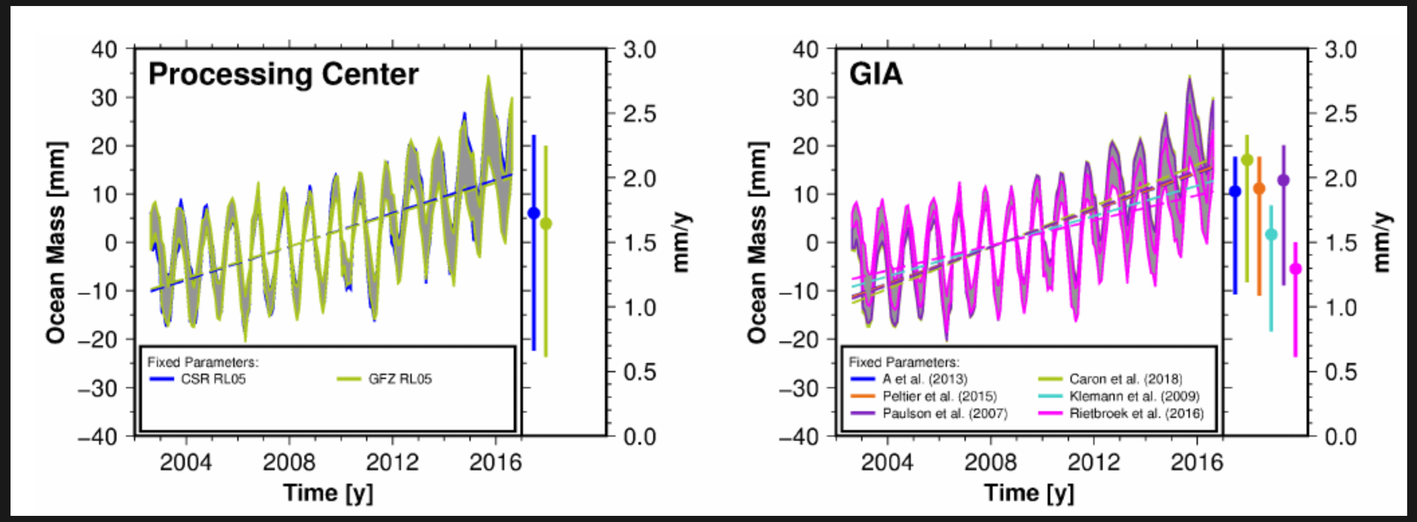


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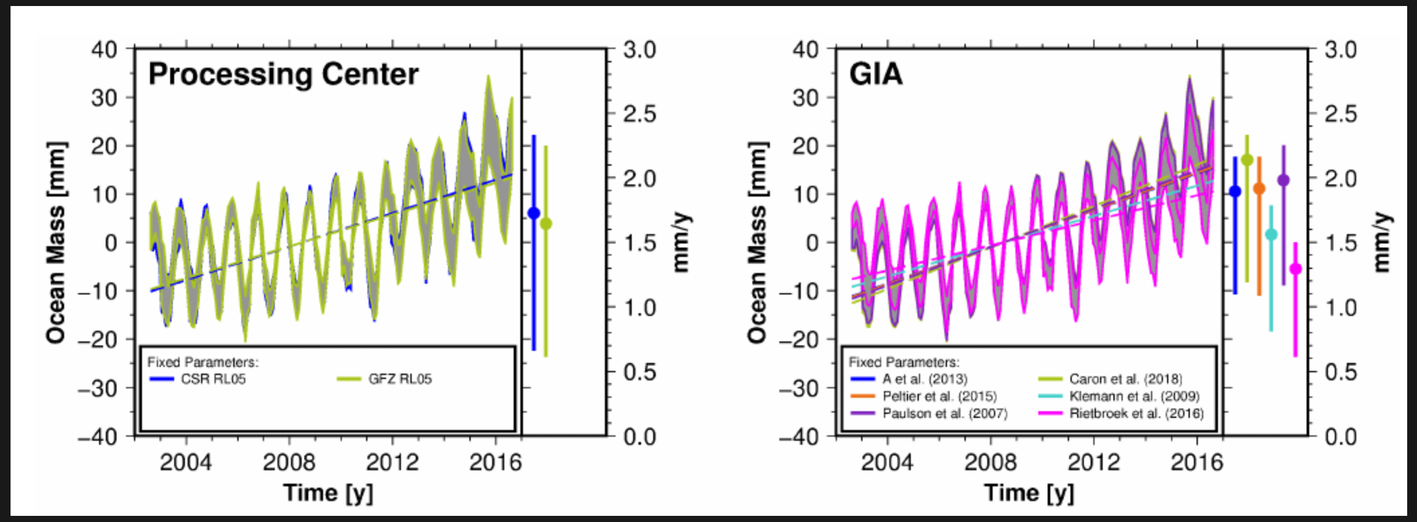


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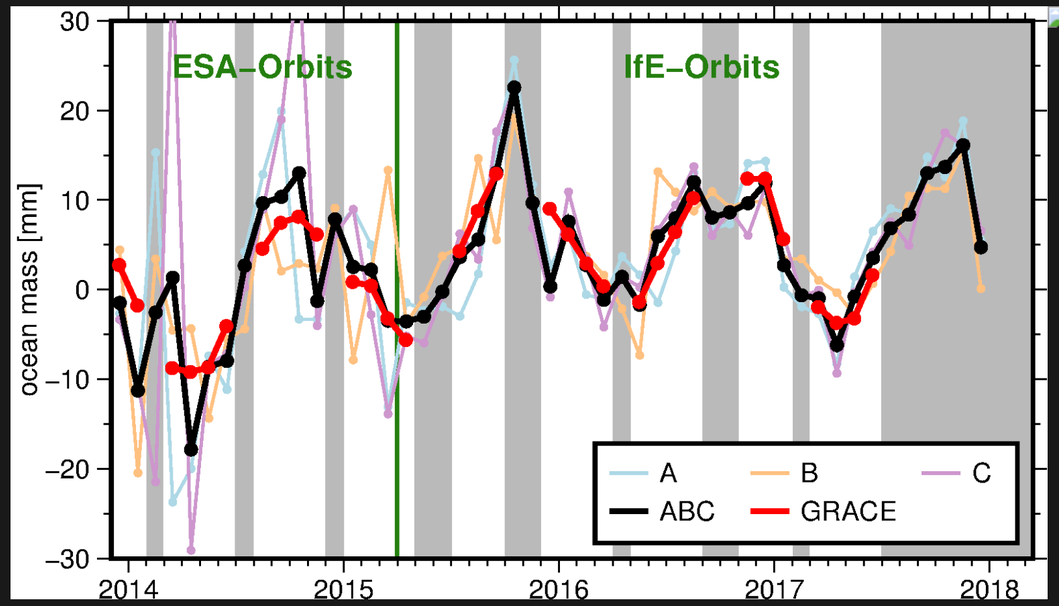
  - Current mass trends ~1.5-2mm/yr (c.f. total trend ~3.3 mm/yr)

# Ocean mass can also be retrieved from the SWARM Mission

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Comparison of ocean mass from GRACE and the SWARM (A,B,C satellites). Update of Luck et al. 2018

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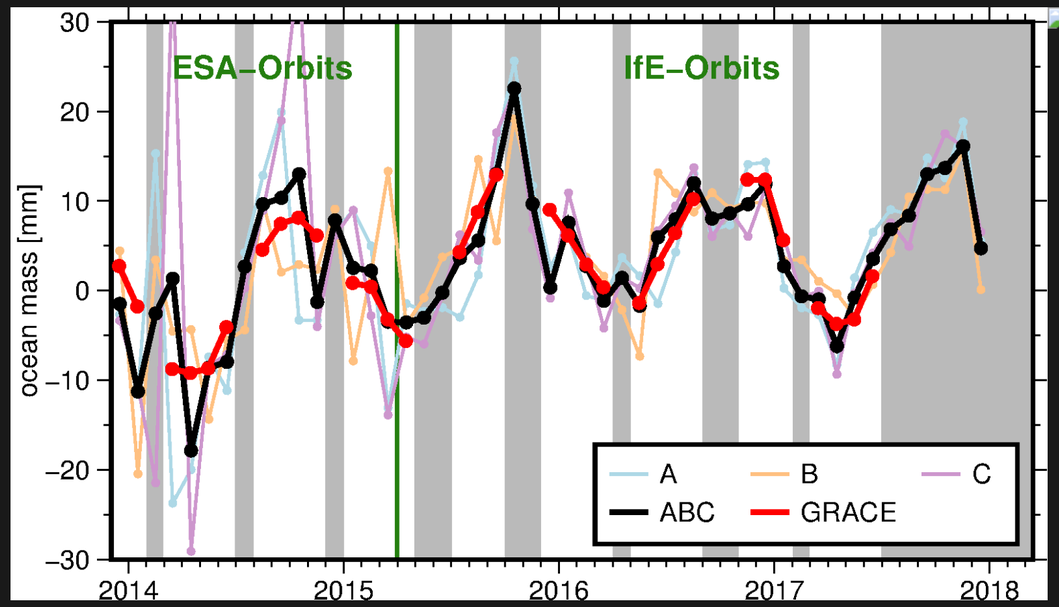


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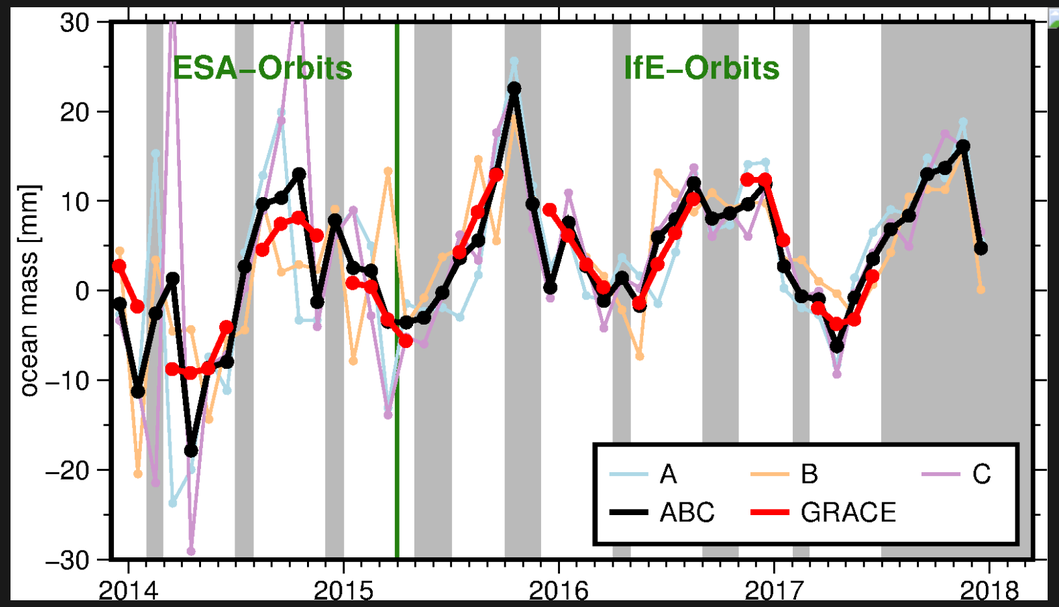


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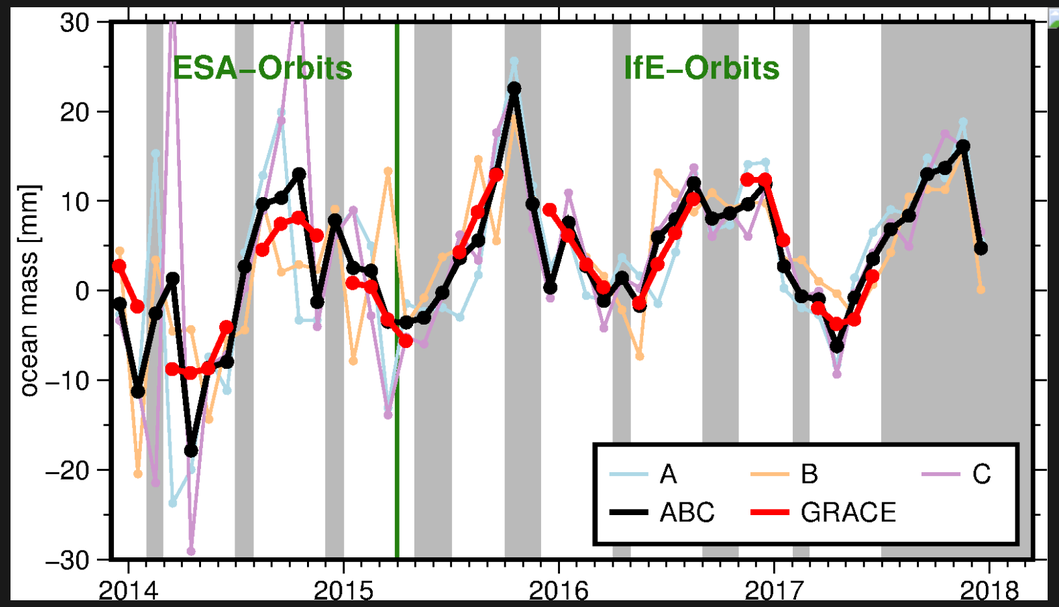


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- Precise (kinematic) orbits contain information on low-resolution gravity changes -> ocean scales
- Principle is useful for filling gaps and potentially pre-GRACE era

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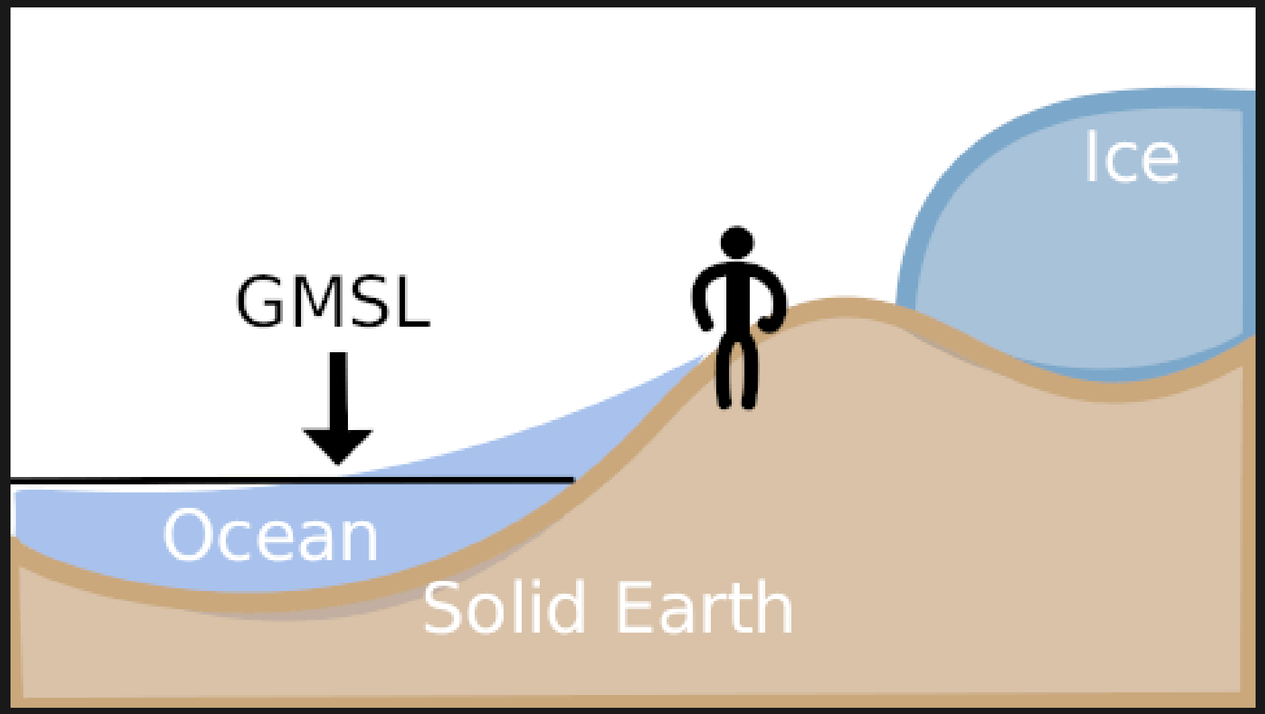
# Relative sea level is affected by self attraction and loading (SAL)..





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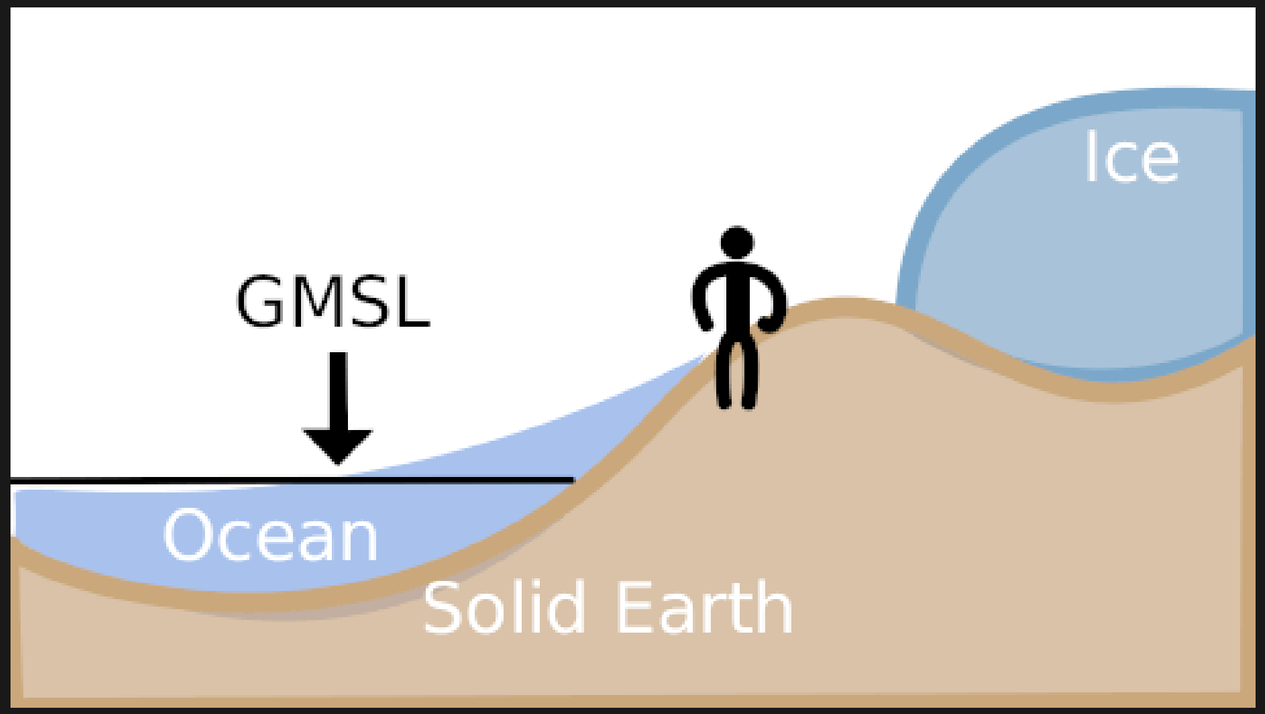


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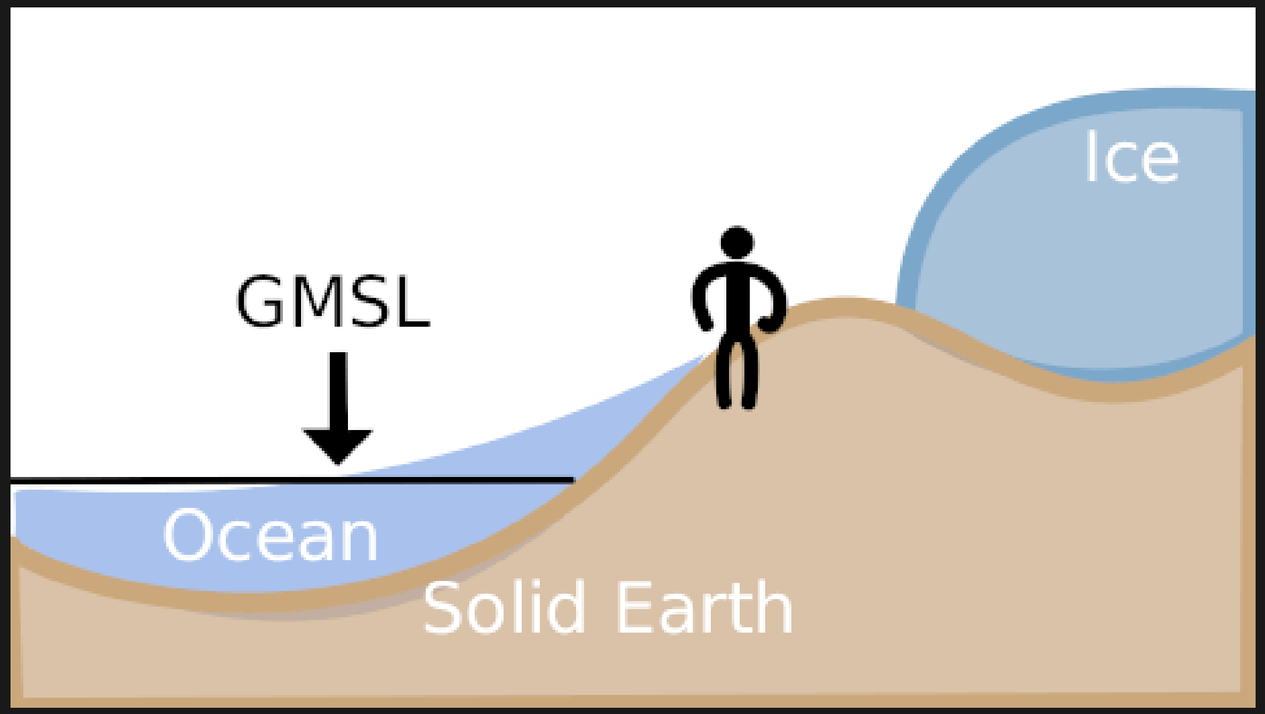


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- Modelled as a passive ocean response (no currents)

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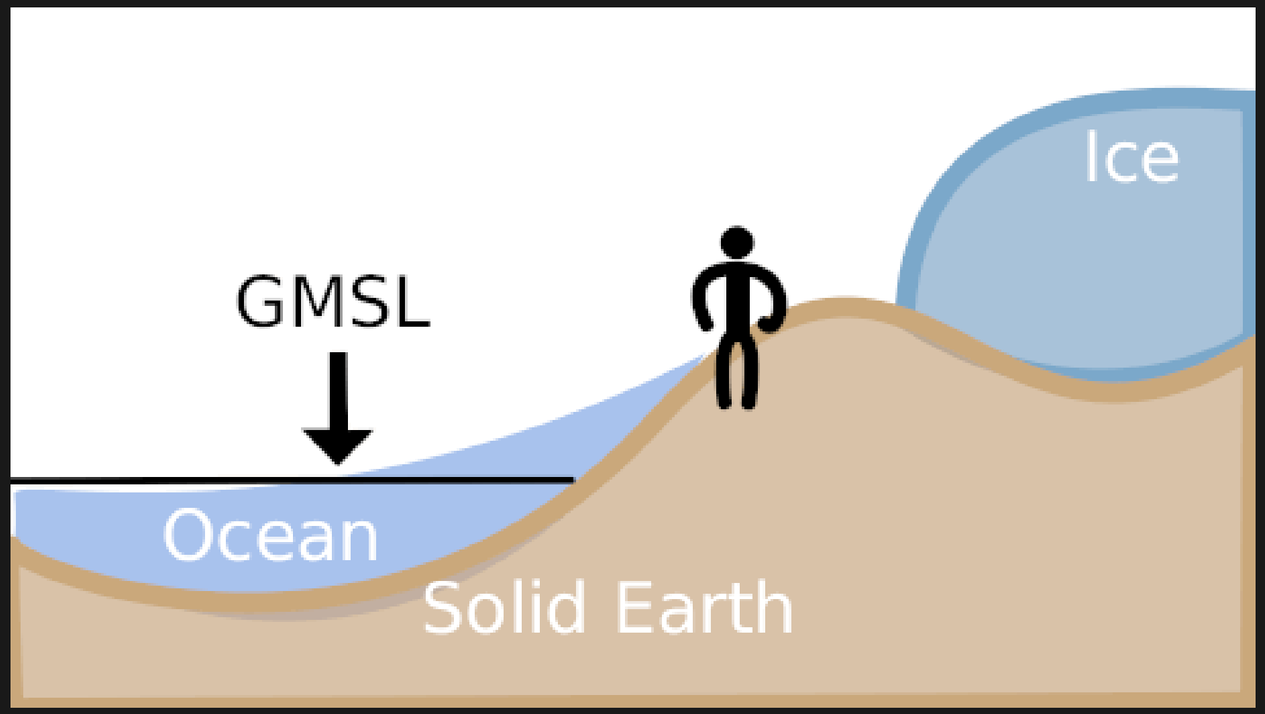


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- mass conserving

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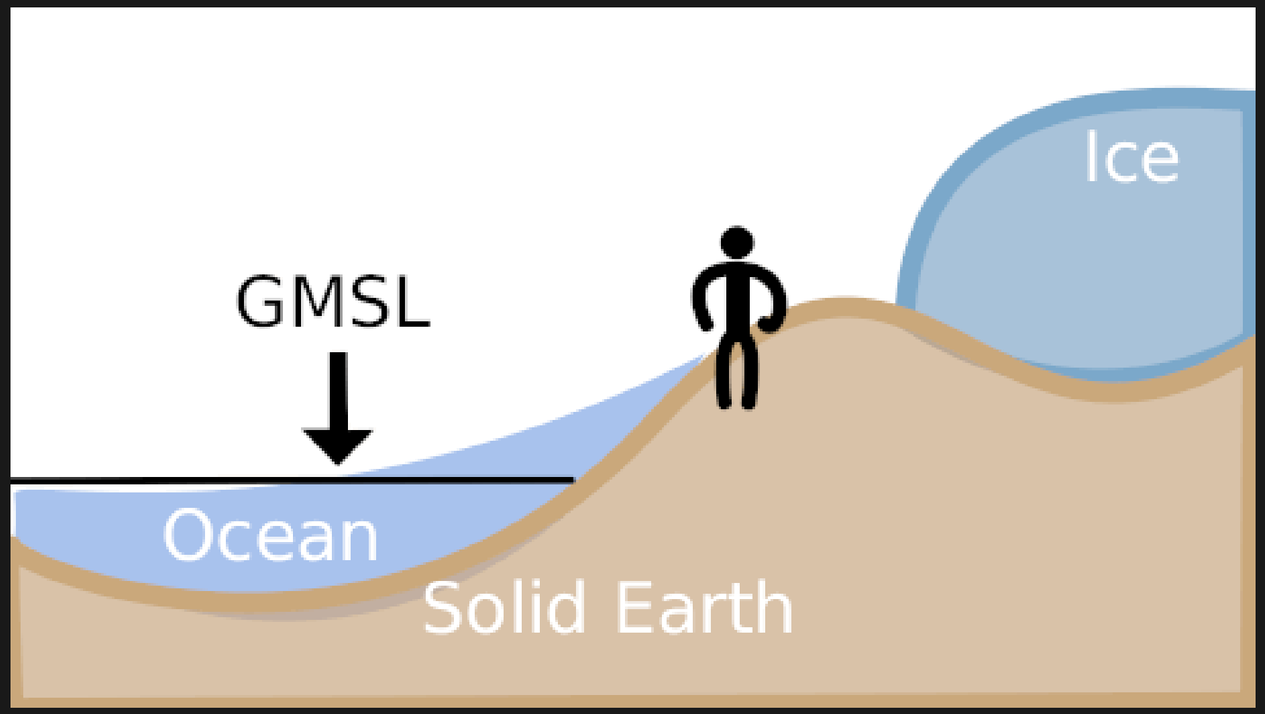
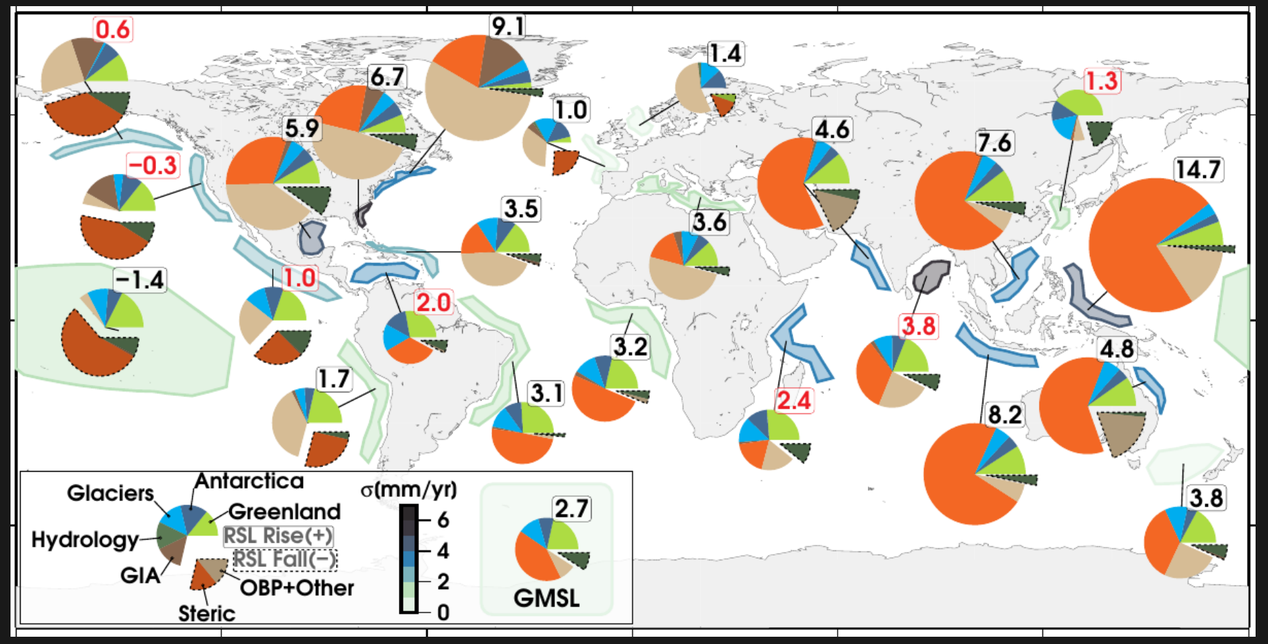



- Theory goes back to 1888 (Woodward)
- Modelled as a passive ocean response (no currents)
- mass conserving
- Takes into account the deformation of the Earth

In [ ]:
```
sld=FlexSlide("Other factors affecting relative sea level?")
sld.addIframe("https://app.wooclap.com/events/IDGQJT/questions/6163594df830731203b4299c")
sld.display()
```


# Regional sea level budgets




Regional sea level budgets from Rietbroek et al. 2016

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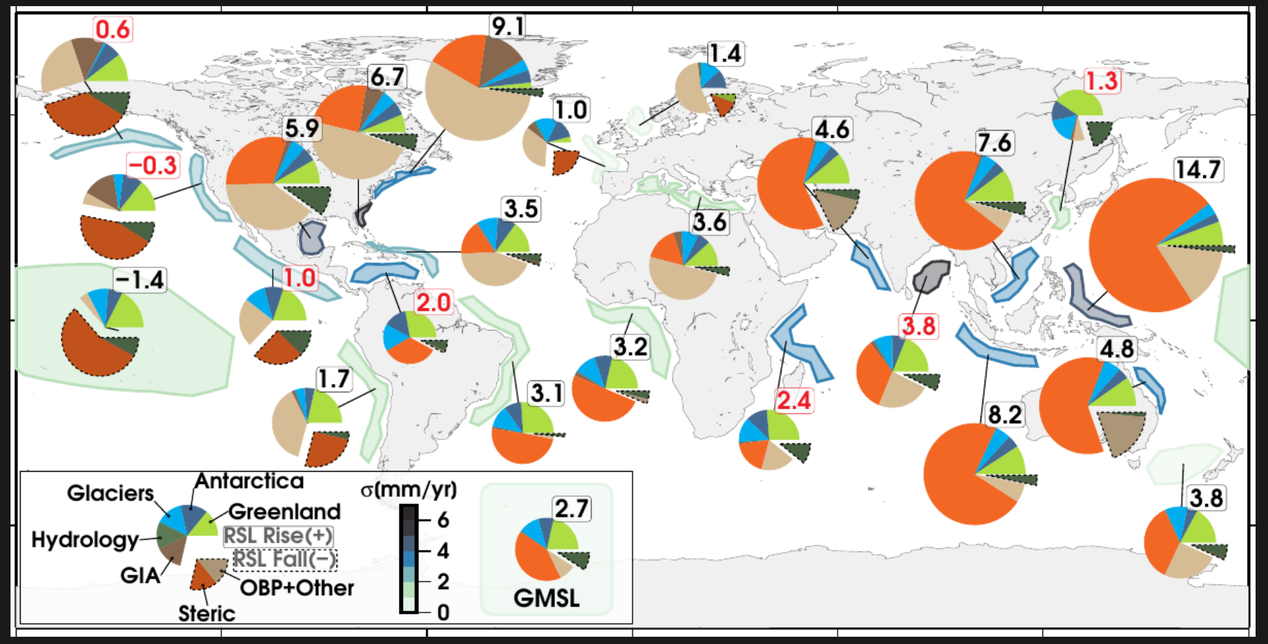


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- Sea level rise is not uniform

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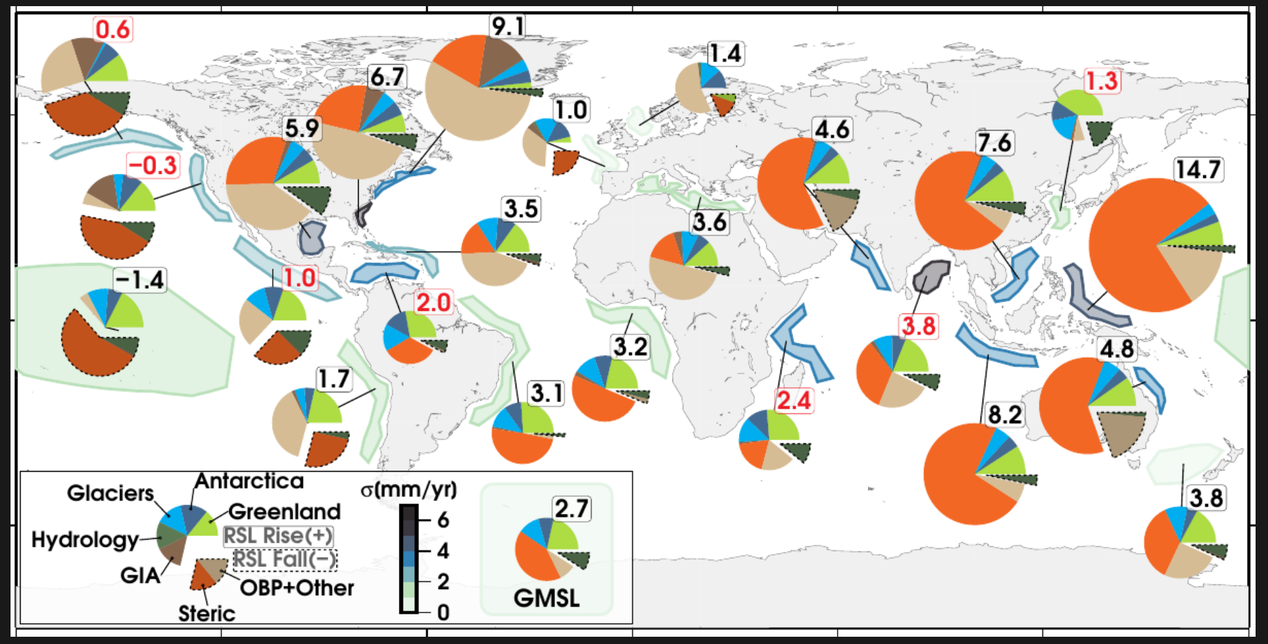


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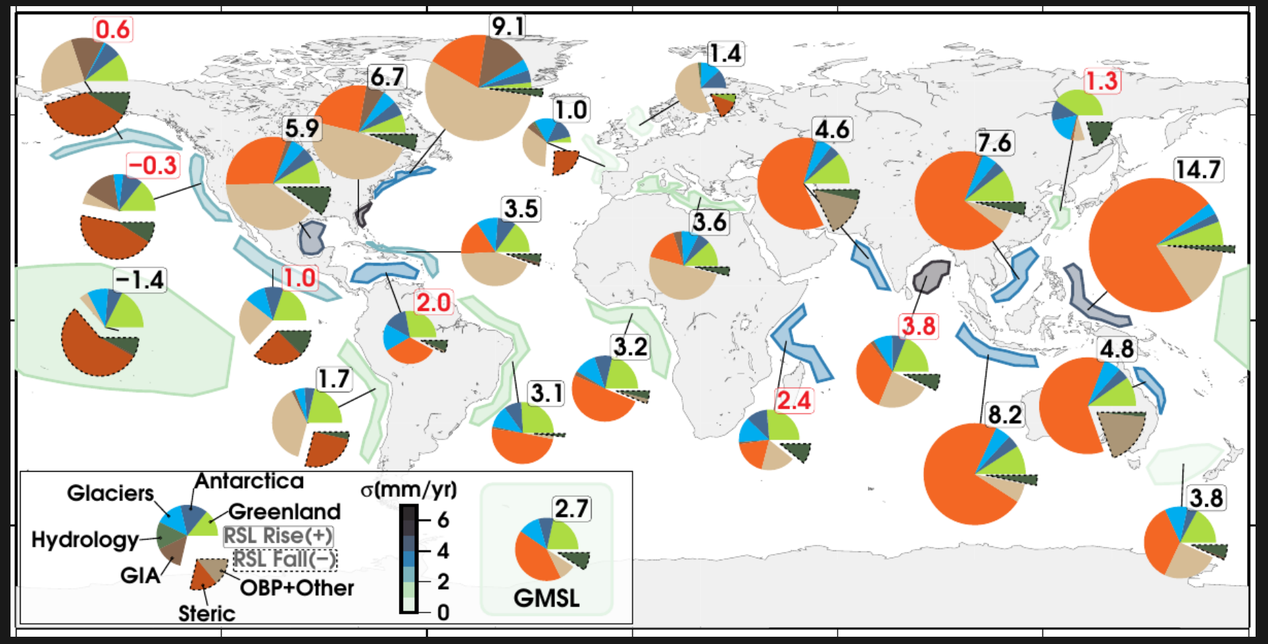



Regional sea level budgets from Rietbroek et al. 2016

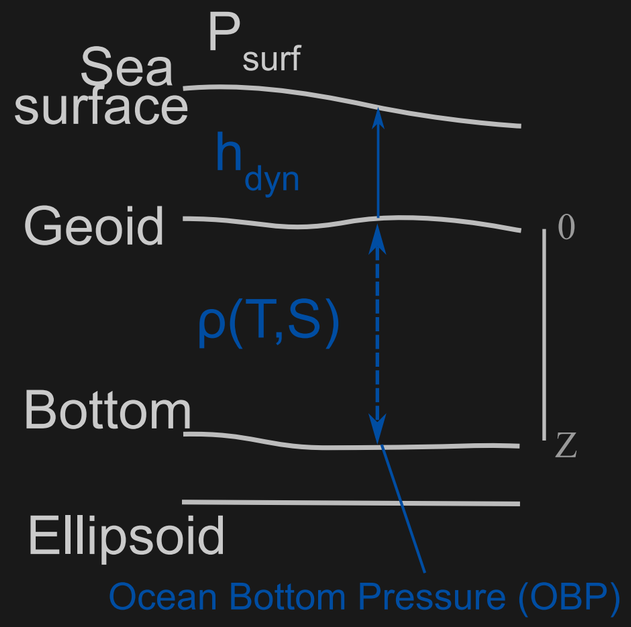
- Sea level rise is not uniform
- SAL effects
- Thermosteric and ocean bottom pressure changes play a larger role in the regional budgets

# Churning the ocean (forcing from wind stress, density contrasts)



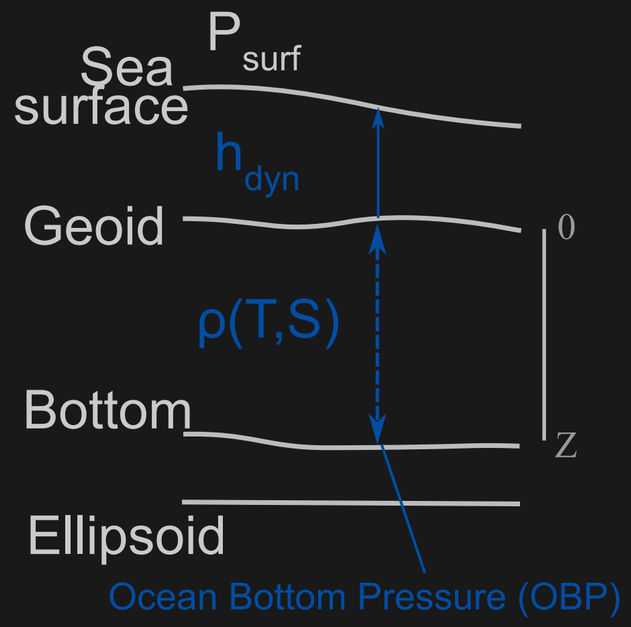
UNIVERSITY OF TWENTE. | ITC

# Integrating the water column to obtain ocean bottom pressure



# Integrating the water column to obtain ocean bottom pressure

$$P_{OBP} = P_{surf} + g \int_{-Z}^{0} \rho(z, T, S) dz + g \rho_{sea} h_{dyn}$$



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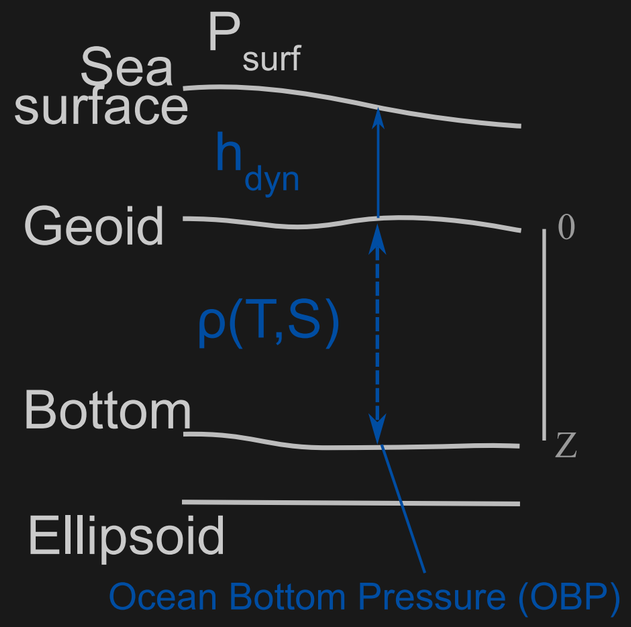


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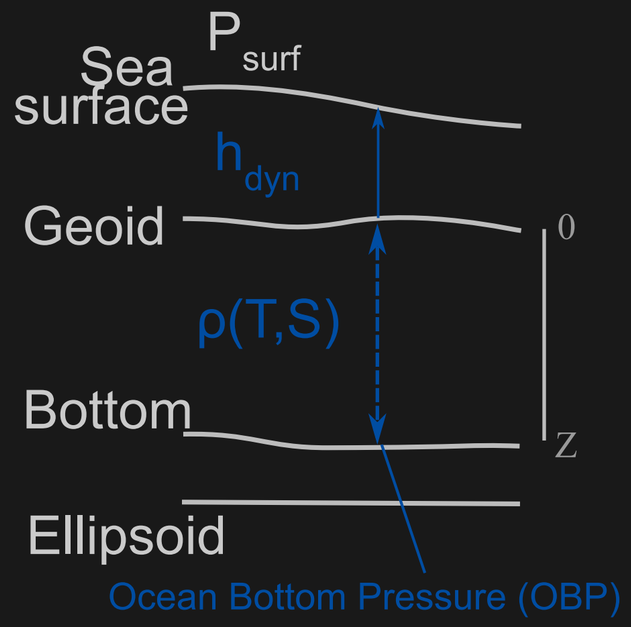


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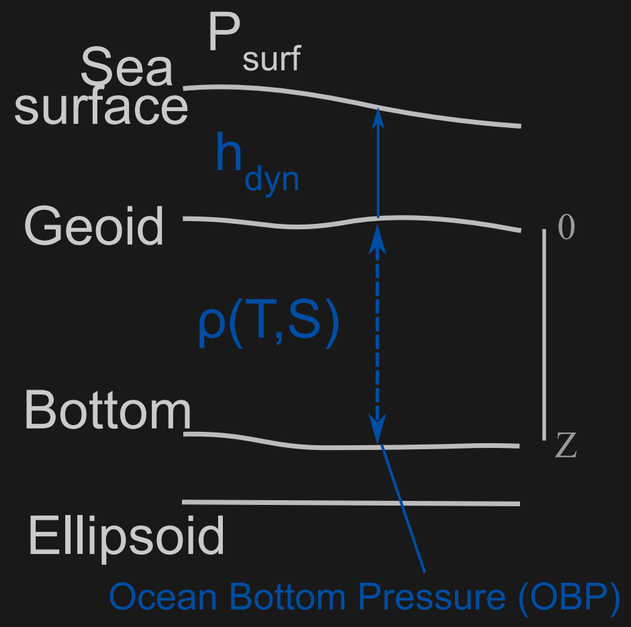


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Results in:

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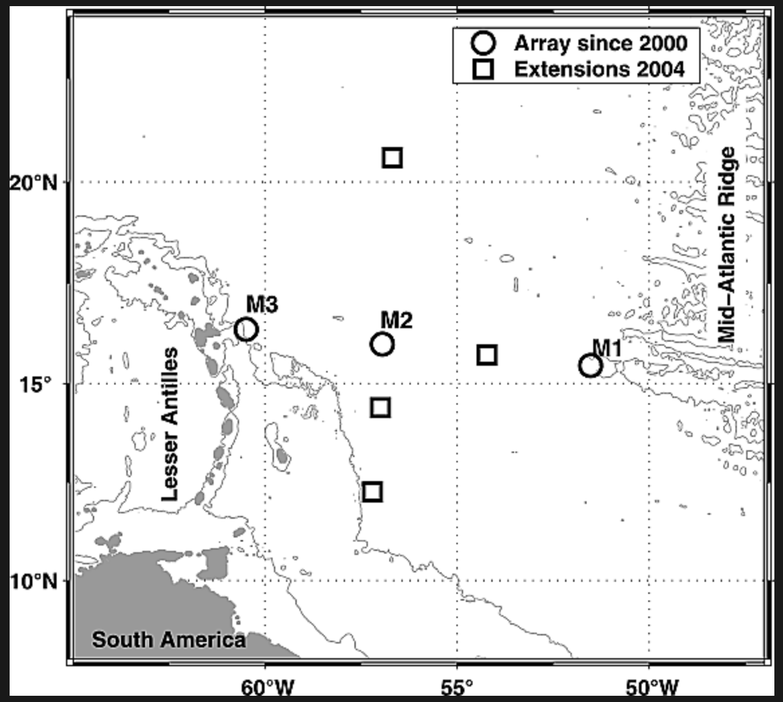
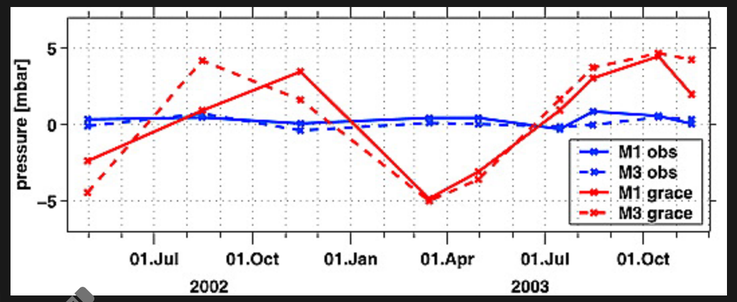
- Invisible to GRACE-like satellites! (Assumes no ocean bottom pressure change)
- But visible by radar altimetry!
- Density increase results in lowering of sea level

Generally:

In [ ]:
```
sld=FlexSlide("Quiz time! (again)")
sld.addIframe("https://app.wooclap.com/events/IDGQJT/questions/6163faf07a387711dec8d093")
sld.display()
```


# Early GRACE validation of ocean bottom pressure changes (Kanzow et al. 2005)



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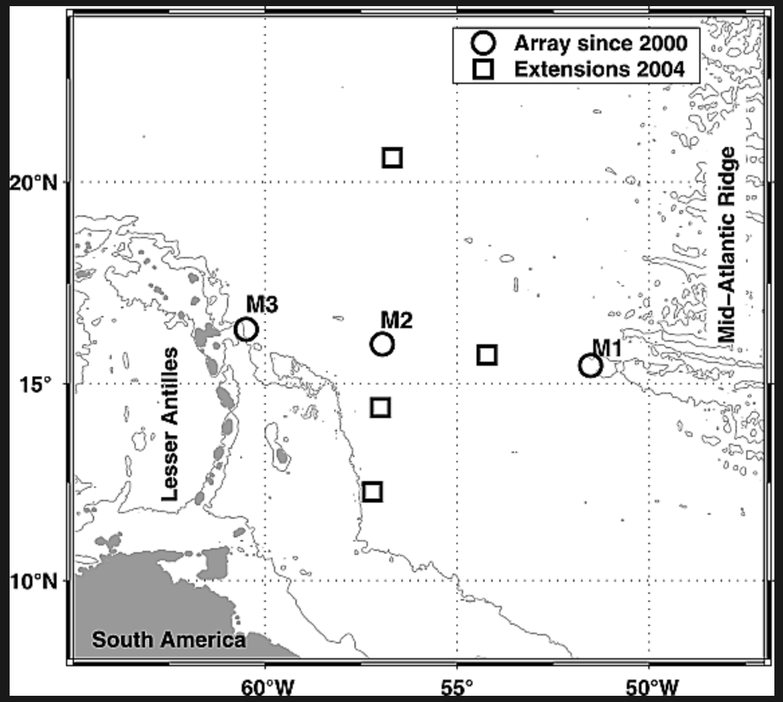


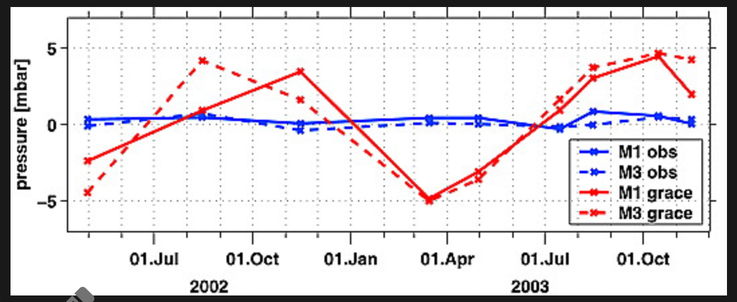

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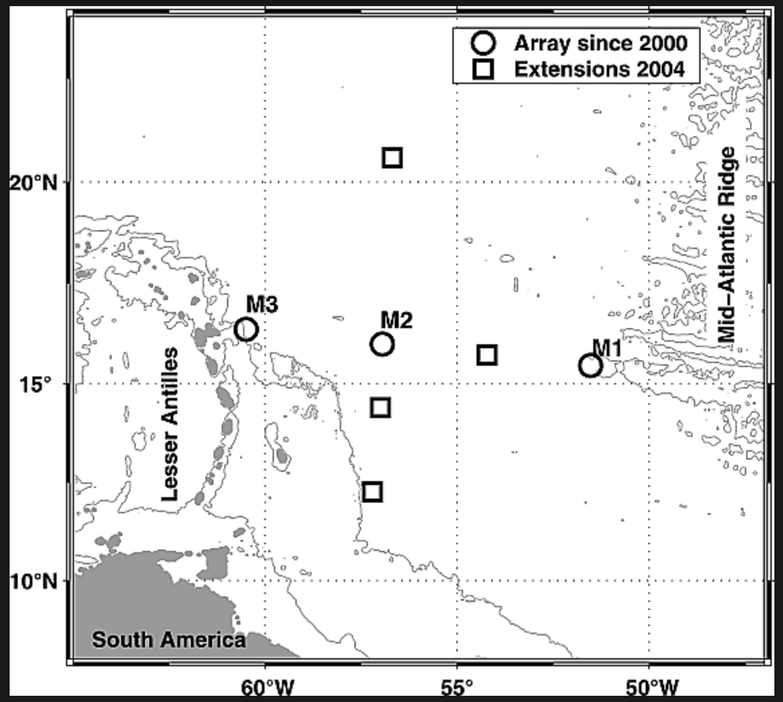


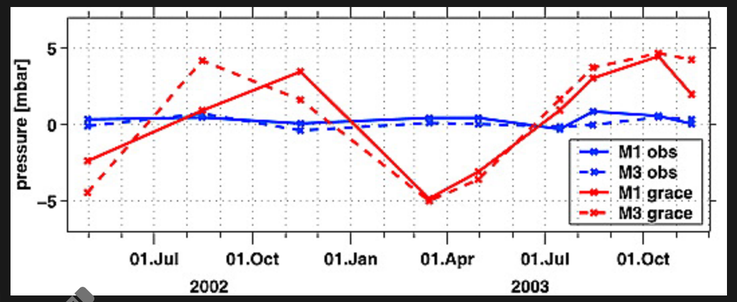

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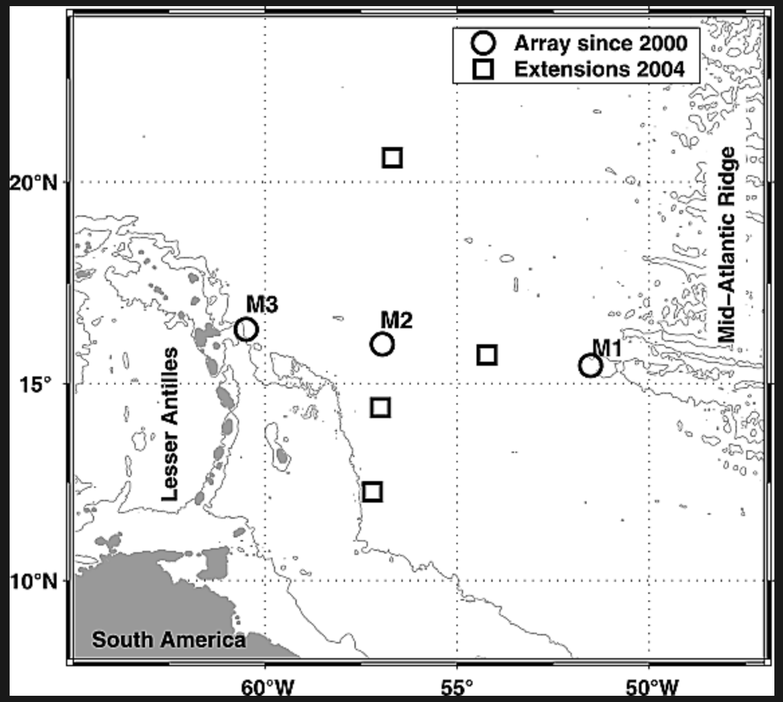
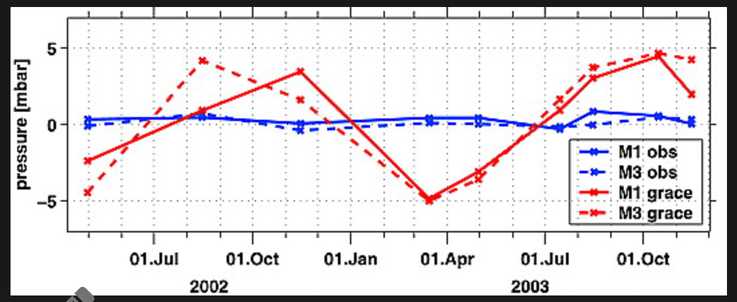
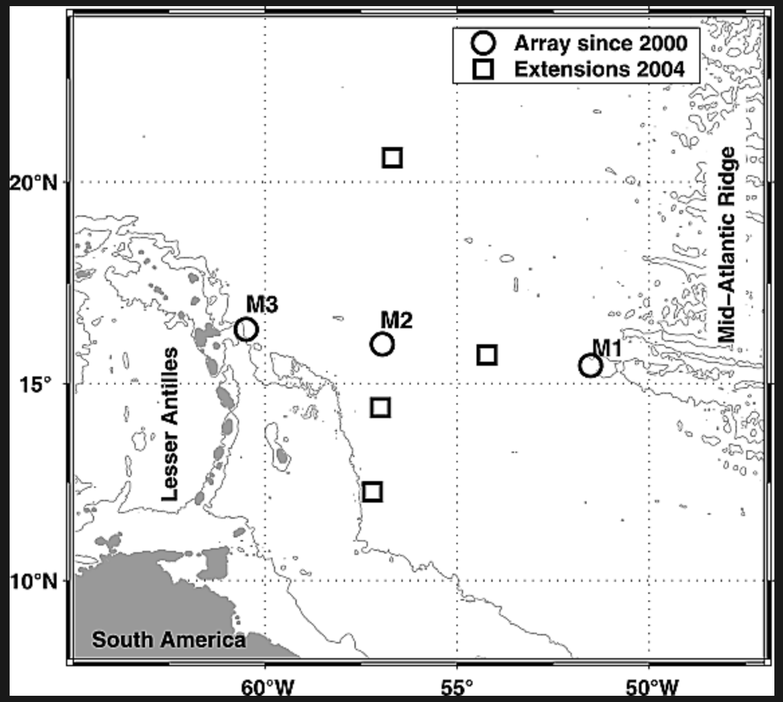
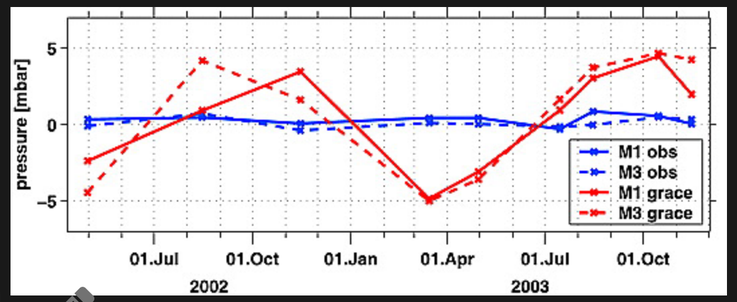


# Early GRACE validation of ocean bottom pressure changes (Kanzow et al. 2005)

- In situ validation with pressure sensors
- GRACE fluctuations were too large
  - Signal leakage
  - Processing errors



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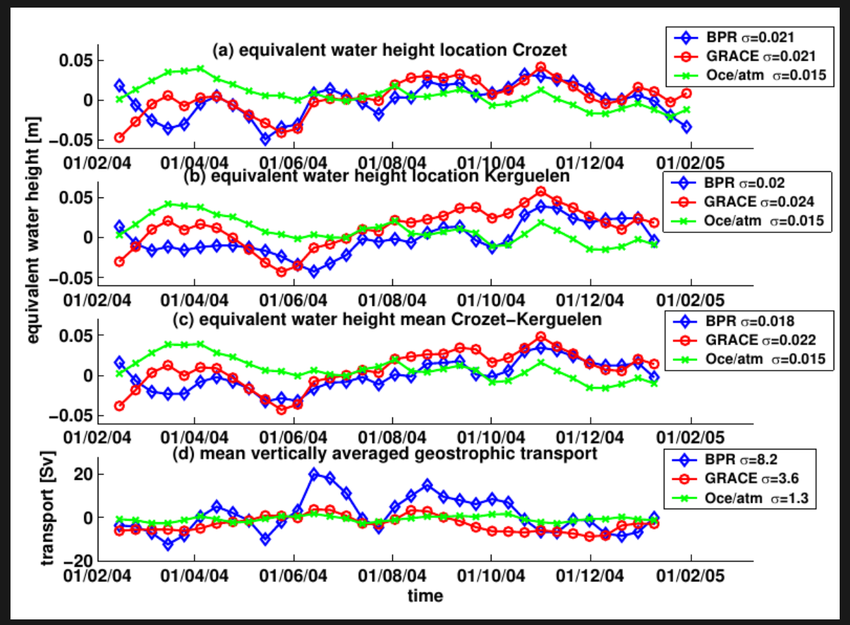
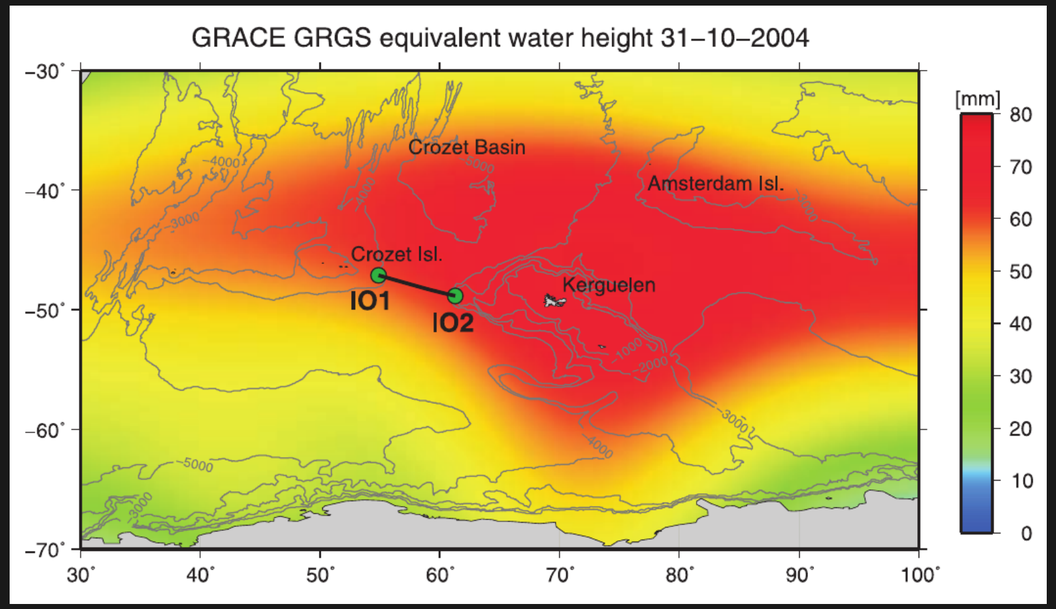



From Rietbroek et al. 2016



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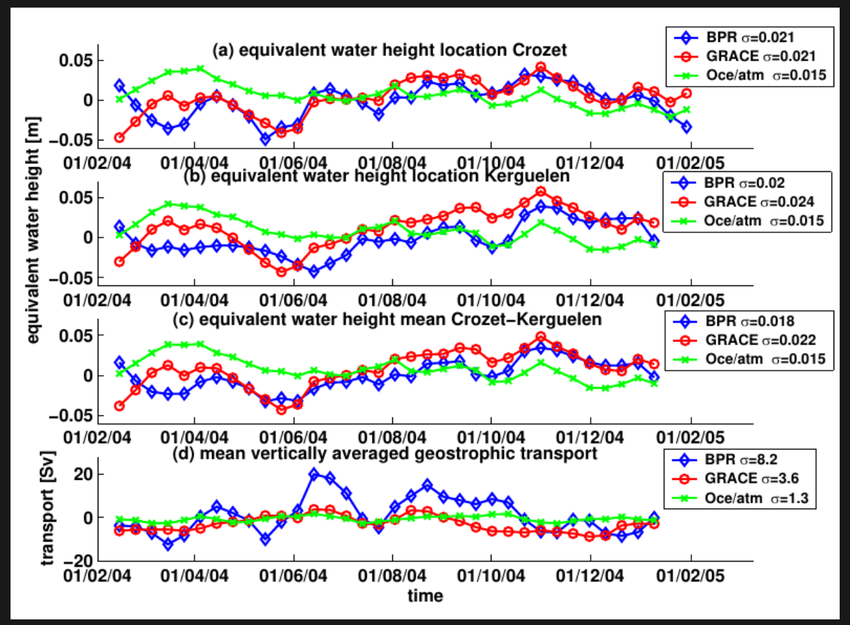


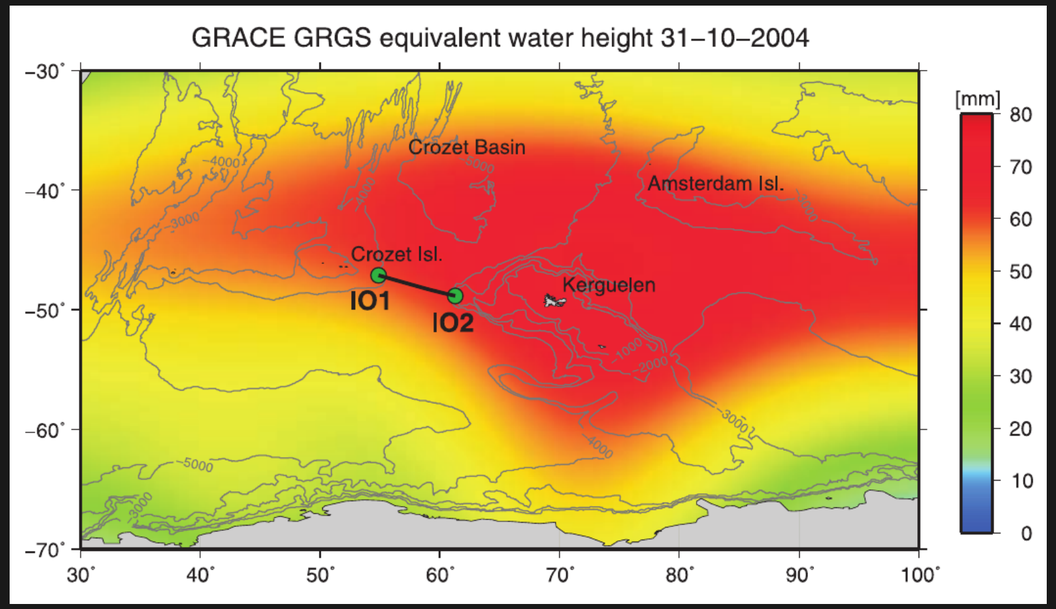


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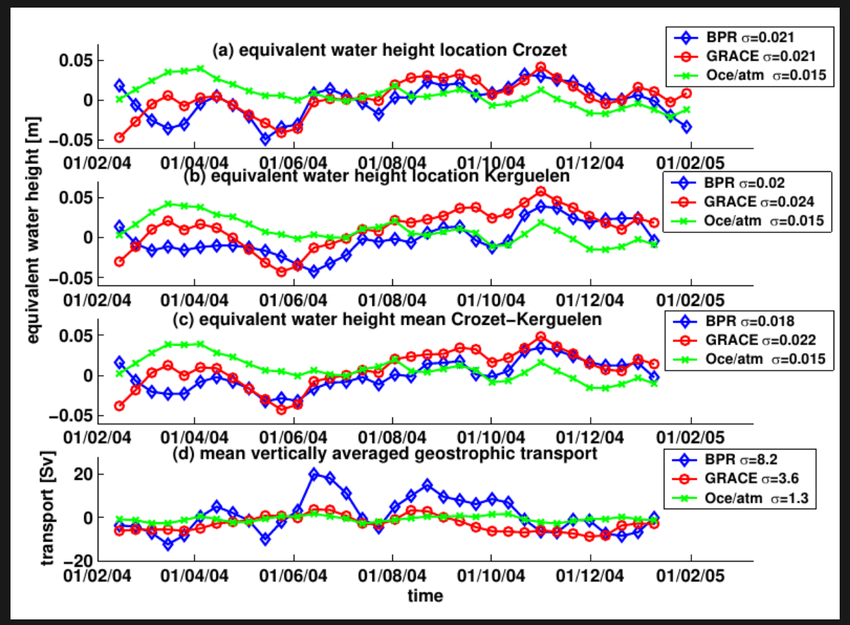


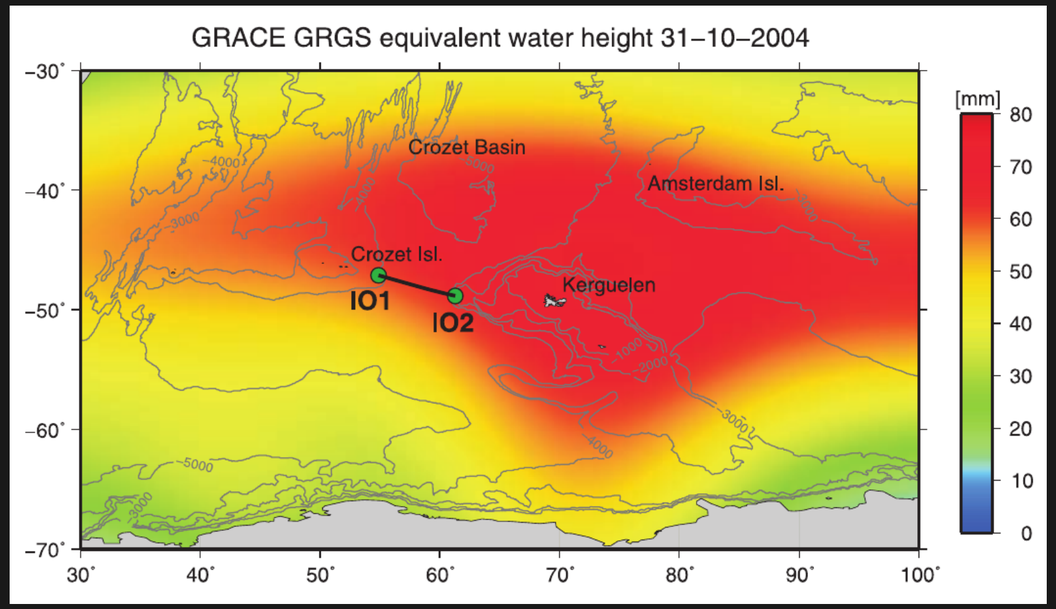


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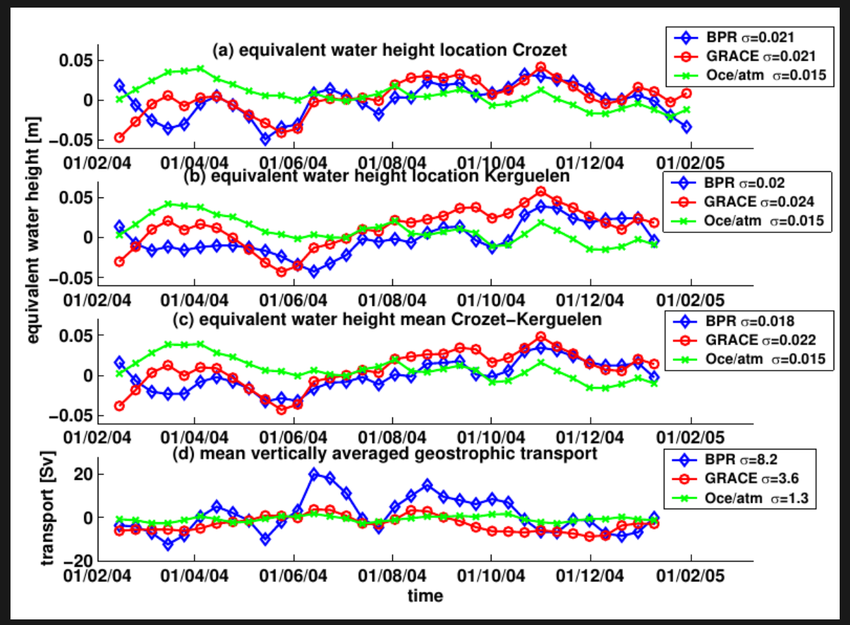


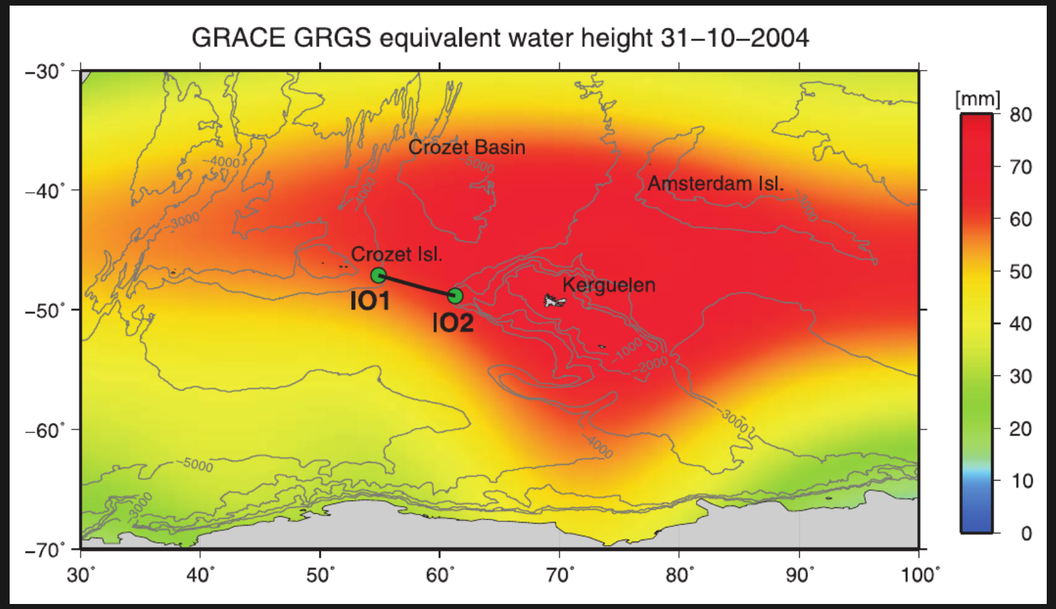


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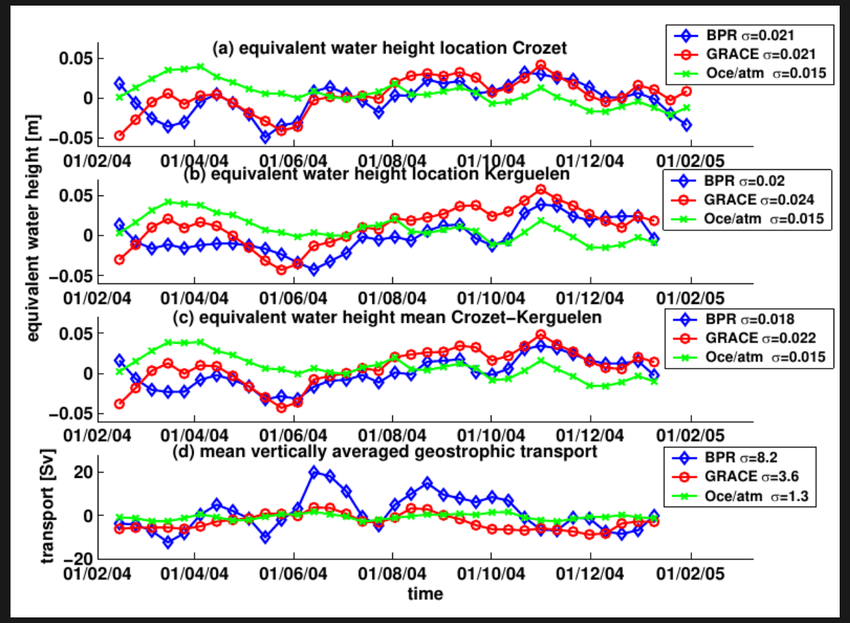


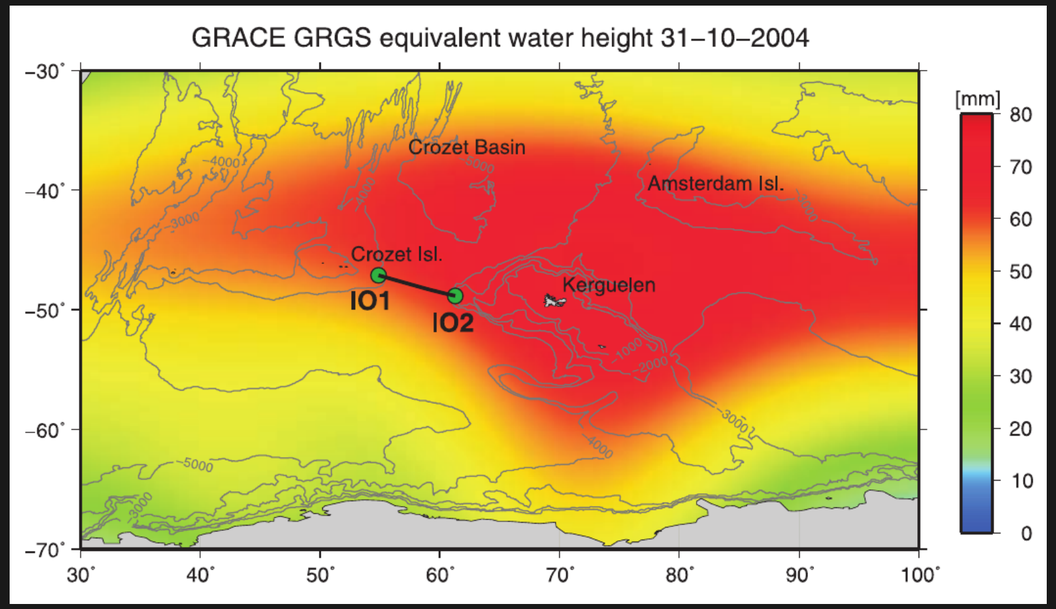


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- In situ validation with pressure sensors
- 10-day GRACE solution was better than background model
- Large scale ocean signals picked up
- Due to smoothing geostrophic bottom currents not resolved

# Geostrophic currents from time variable gravity

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. C12, 3218, doi:10.1029/2001JC001274, 2002

**A method of inferring changes in deep ocean currents from satellite measurements of time-variable gravity**

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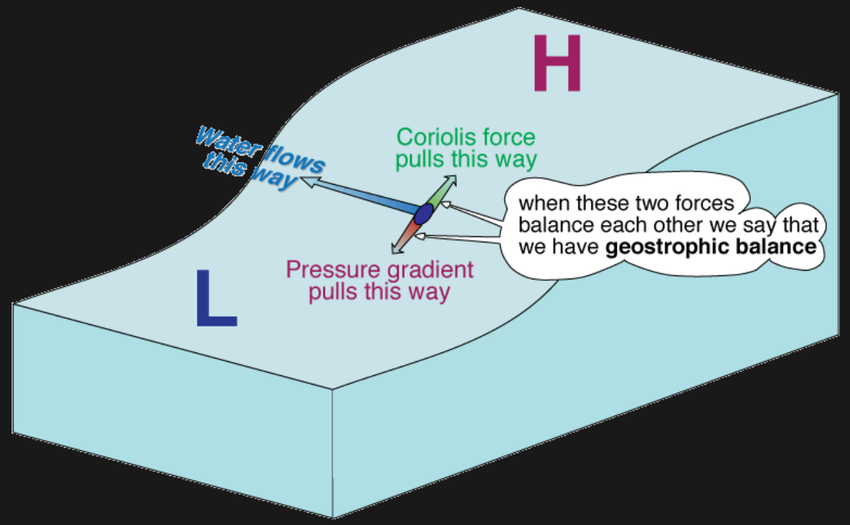


CC-NC-SA, https://www.seos-project.eu

the effects of friction and external forcing are less important, (1) reduces to the geostrophic approximation:

Pressure gradient

$$2\rho_0 \Omega \times \mathbf{v} \approx -\nabla P \qquad (2)$$

Earth rotation vector

velocity

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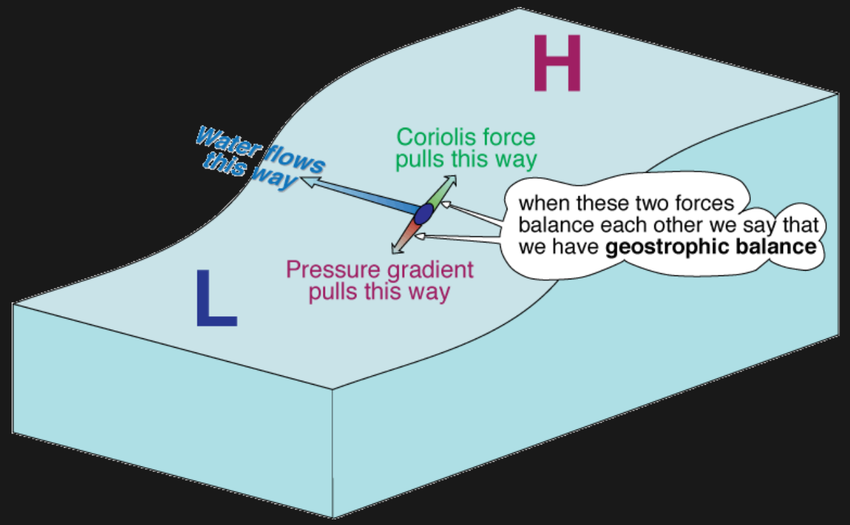


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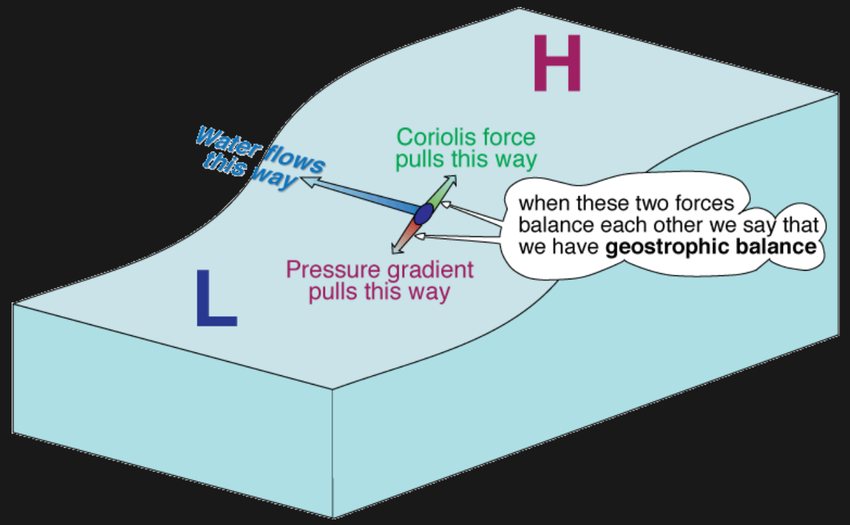


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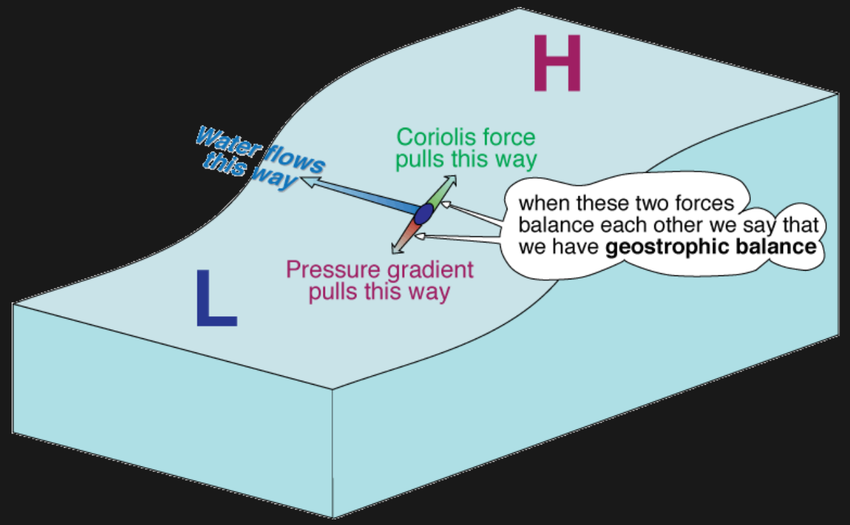


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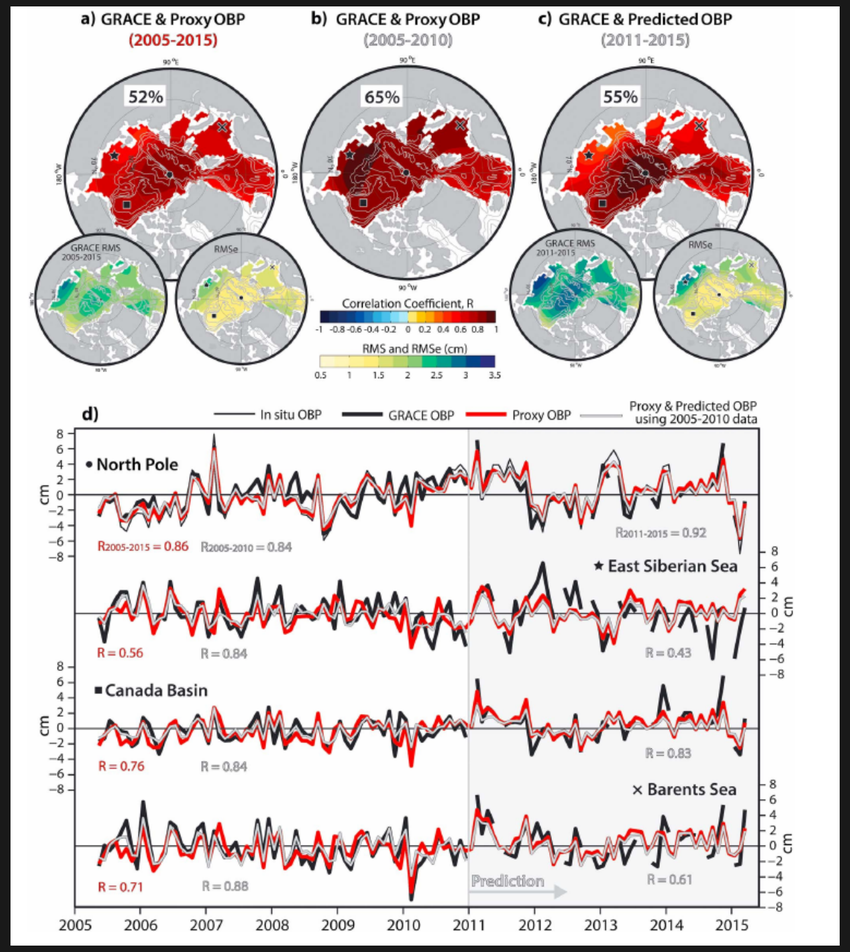
Earth rotation vector

velocity

- Assume horizontal constant velocities
- cross-product -> latitude dependency
- Velocity is orthogonal to gradient!

# Arctic Ocean Bottom pressure variations well captured by GRACE




From Peralta-ferriz et al. 2016

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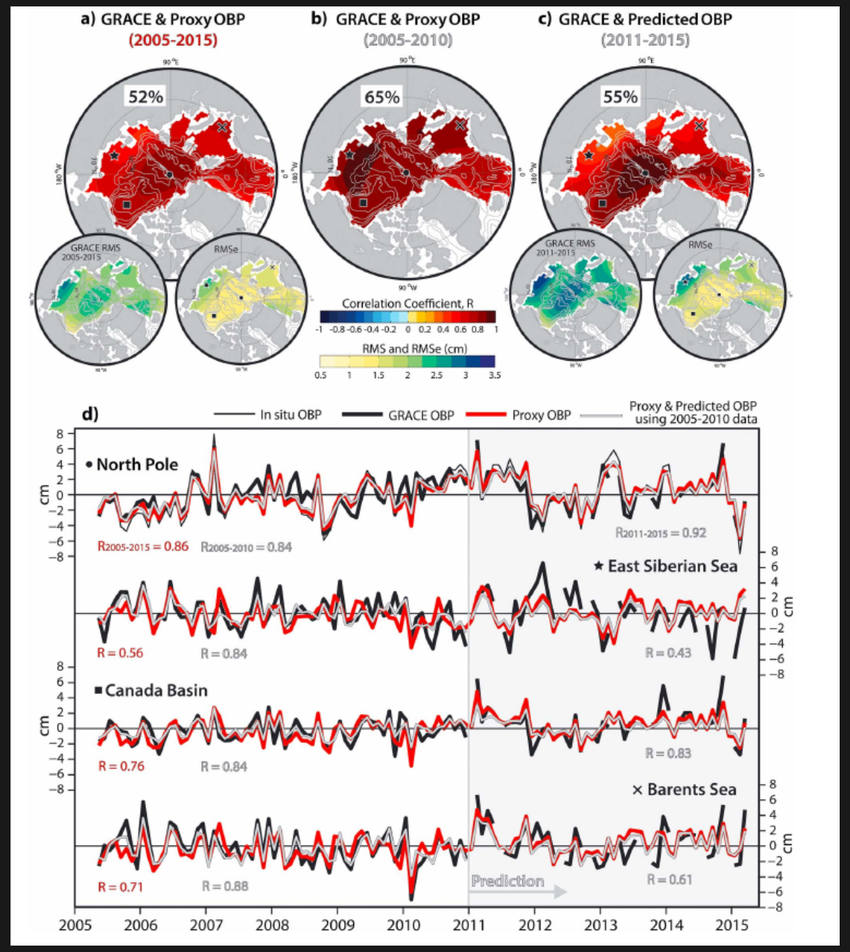


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- In situ OBP well captured by GRACE

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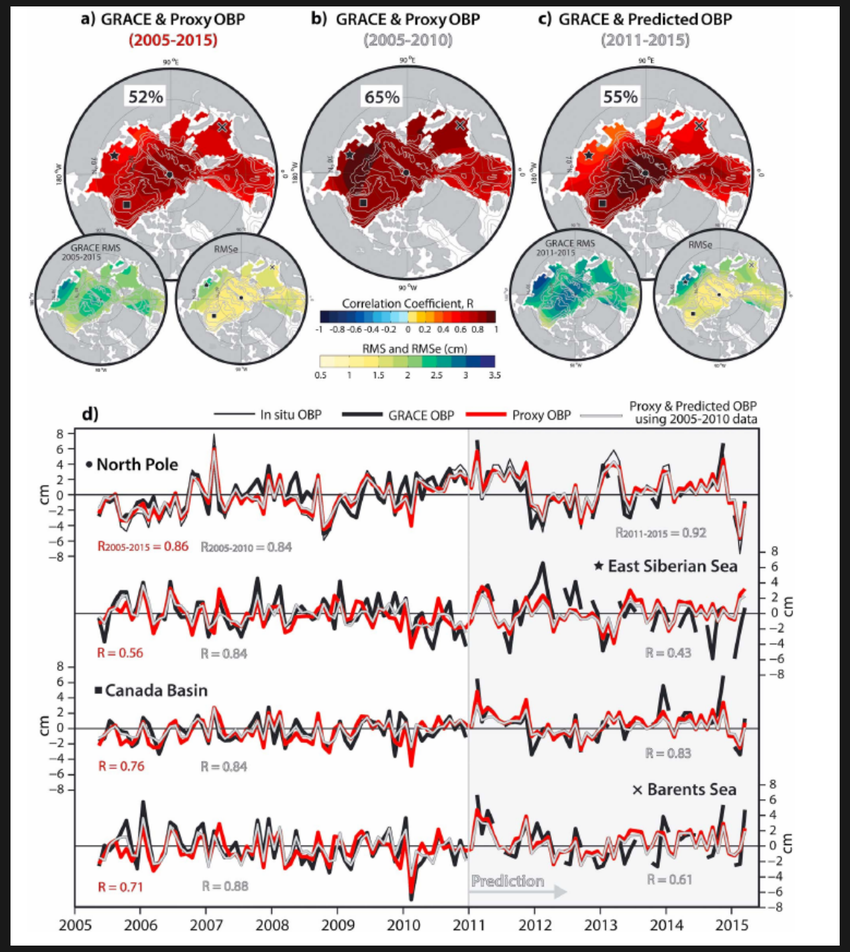


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- Coherent OBP signals in the Arctic

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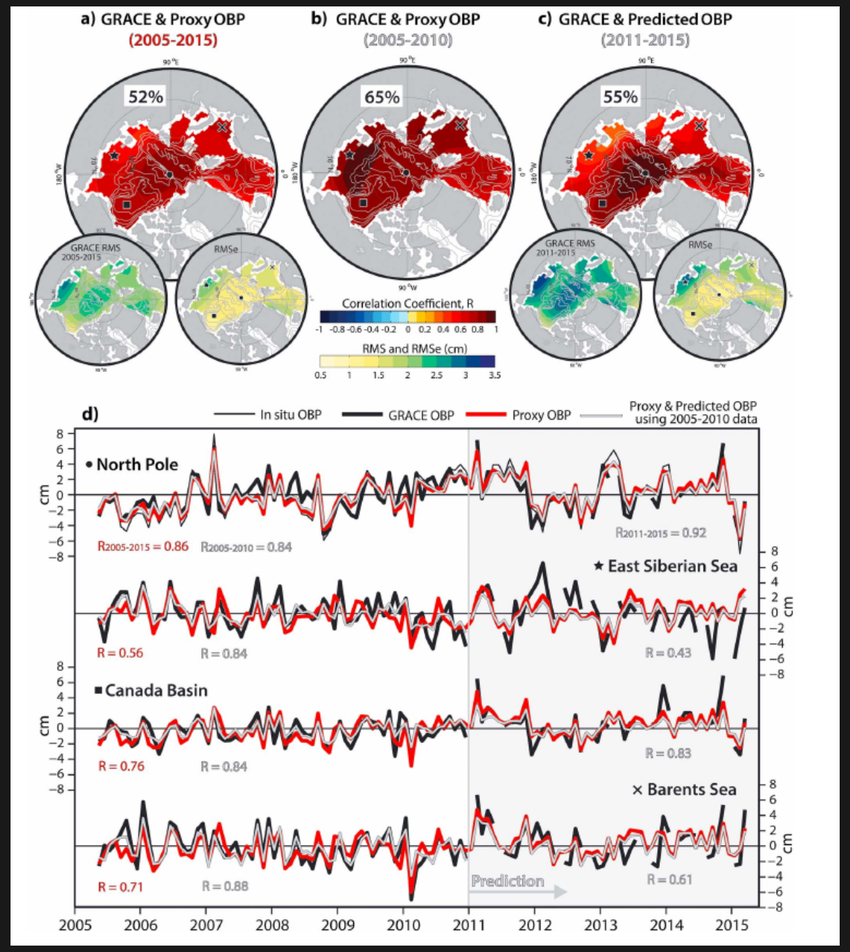


From Peralta-ferriz et al. 2016

- In situ OBP well captured by GRACE
- Coherent OBP signals in the Arctic
- Comparison showed that a single in situ OBP can serve as proxy for the entire Arctic

# What have you learned?

- Adding mass to the ocean
    - Observable with time-variable gravity
    - GRACE (1.5 - 2 mm/yr global mean ocean mass change)
    - Different causes have non-uniform contributions (Ice sheets, hydrology, dams,
    - Regional sea level also influenced by: Self attraction and loading, forcing from wind stress
- Churning the Ocean
    - Integration of the water column -> OBP
    - OBP changes due to dynamic height differences
    - Steric sea level: density driven dynamic height changes under the assumption of no OBP change
    - Pressure gradients cause circulation (surface gradient may be different from bottom)

**Outlook**

- Still many ocean applications unexplored (geostrophic currents!)
- Added value comes from combined interpretation with altimetry, Argo, etc.