

Churning the Ocean: Time variable gravity for ocean applications



Analogies with today's talk



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



Analogy with today's talk

- Mount Mandara: Adding mass to the ocean (e.g. melt water)



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- Mount Mandara: Adding mass to the ocean (e.g. melt water)
- Snake Vasuki: Churning the ocean (forcing from wind stress, density contrasts)



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Analogyies 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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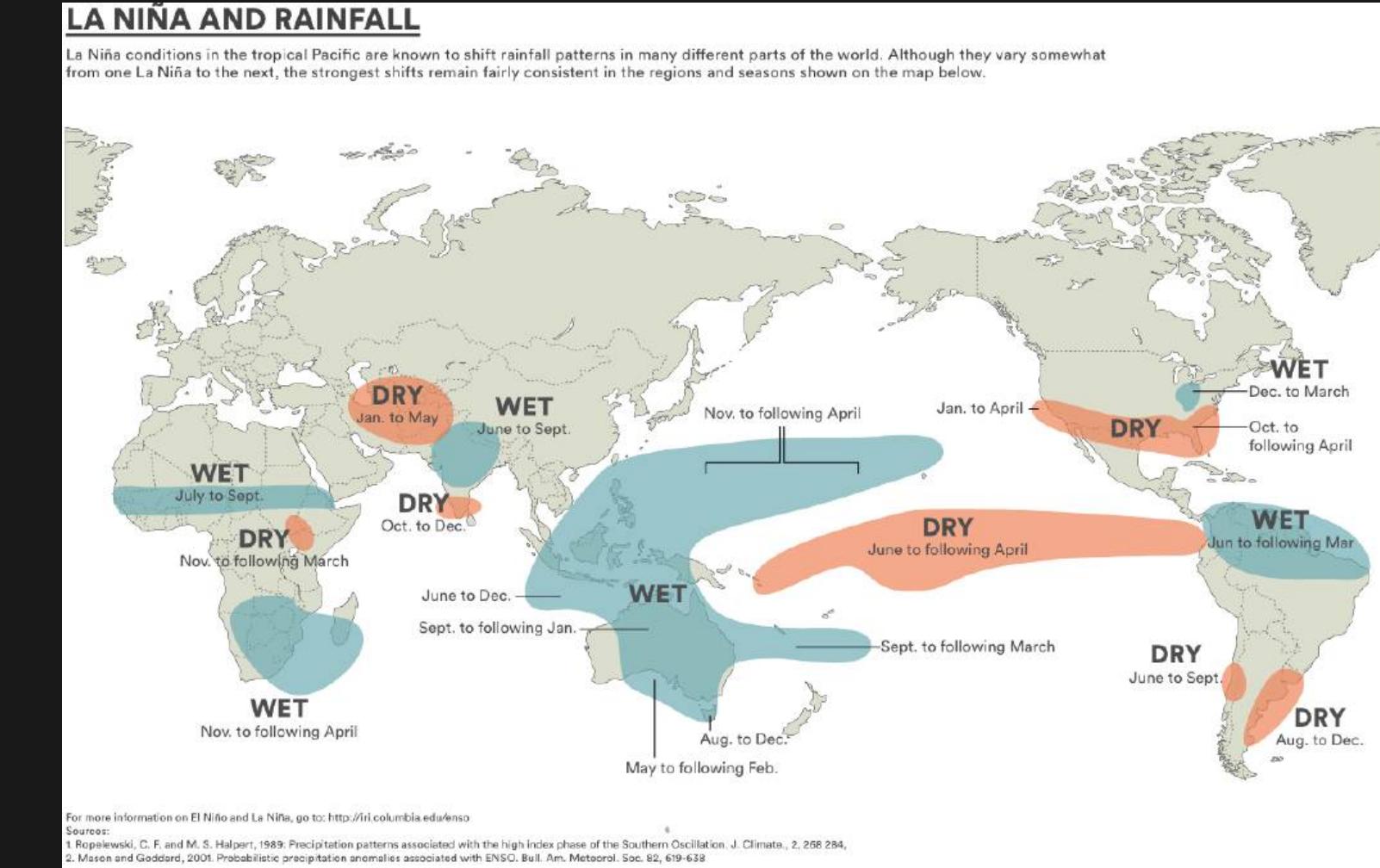
Adding mass to the oceans (or removing it)



Remember the 2010-2011 La Niña event?



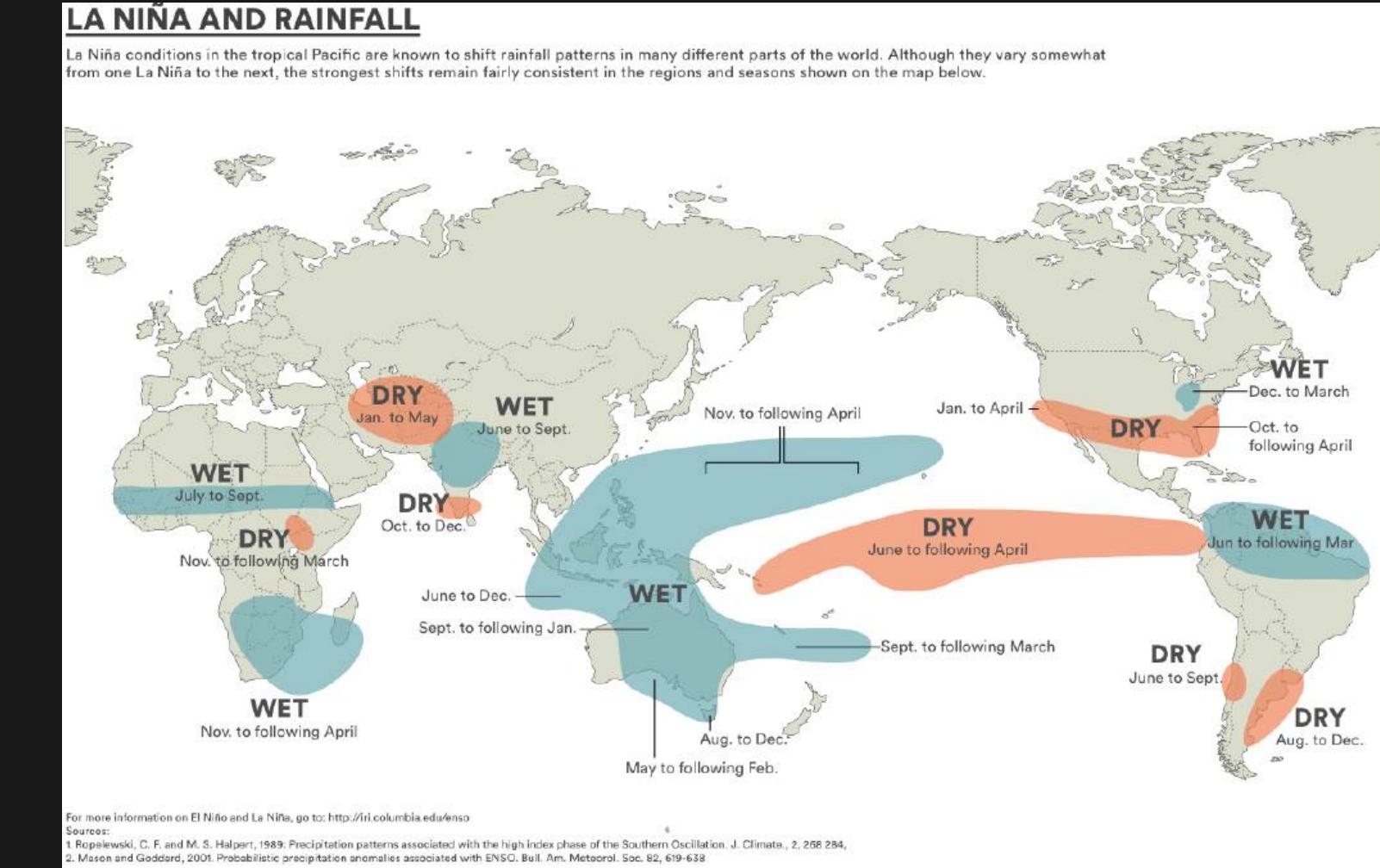
Rockhampton, QLD. Photo by Salvation Army of Australia



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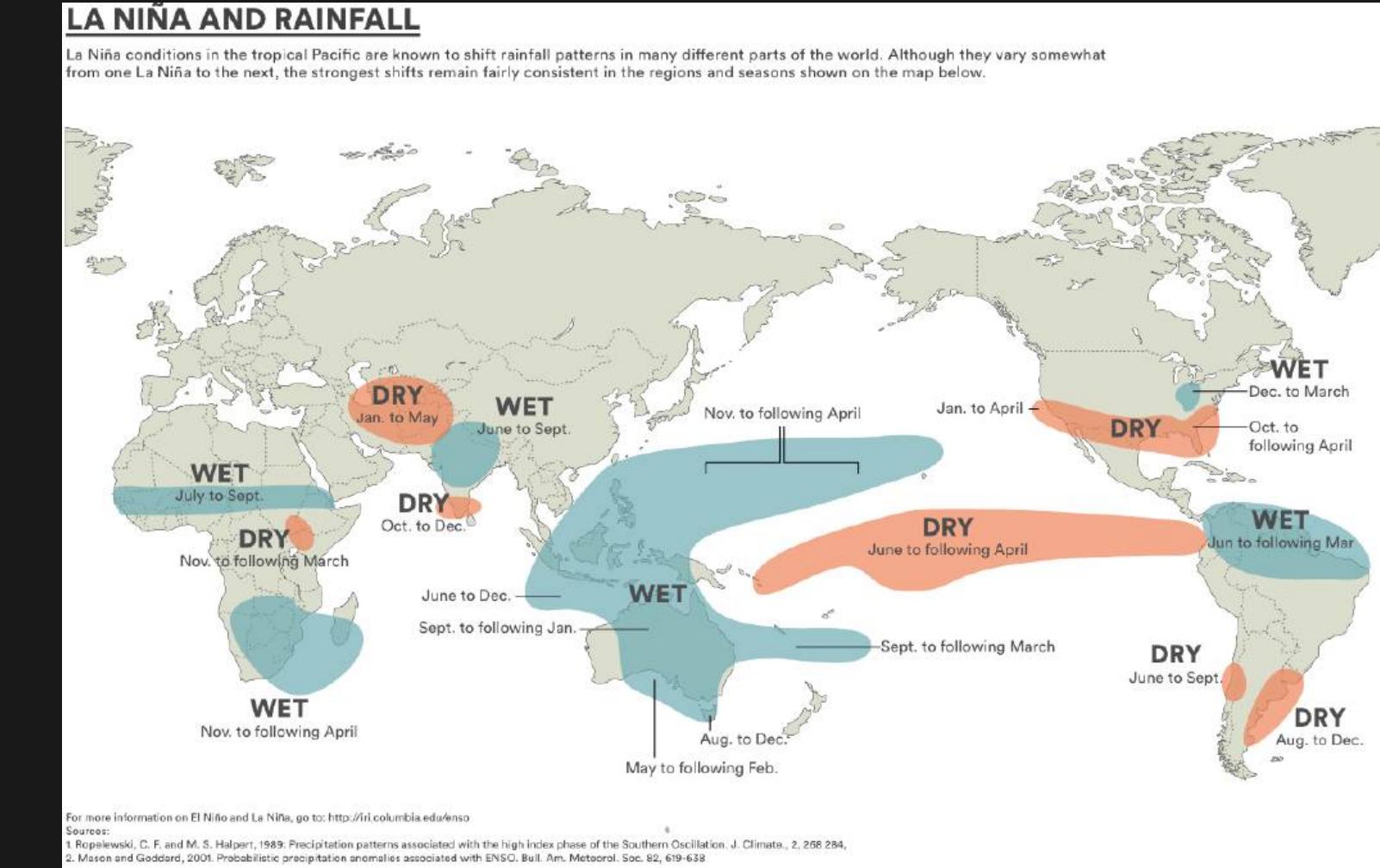
- Stronger trade winds result in warm ocean blob in the western Pacific



Remember the 2010-2011 La Niña event?



Rockhampton, QLD. Photo by Salvation Army of Australia



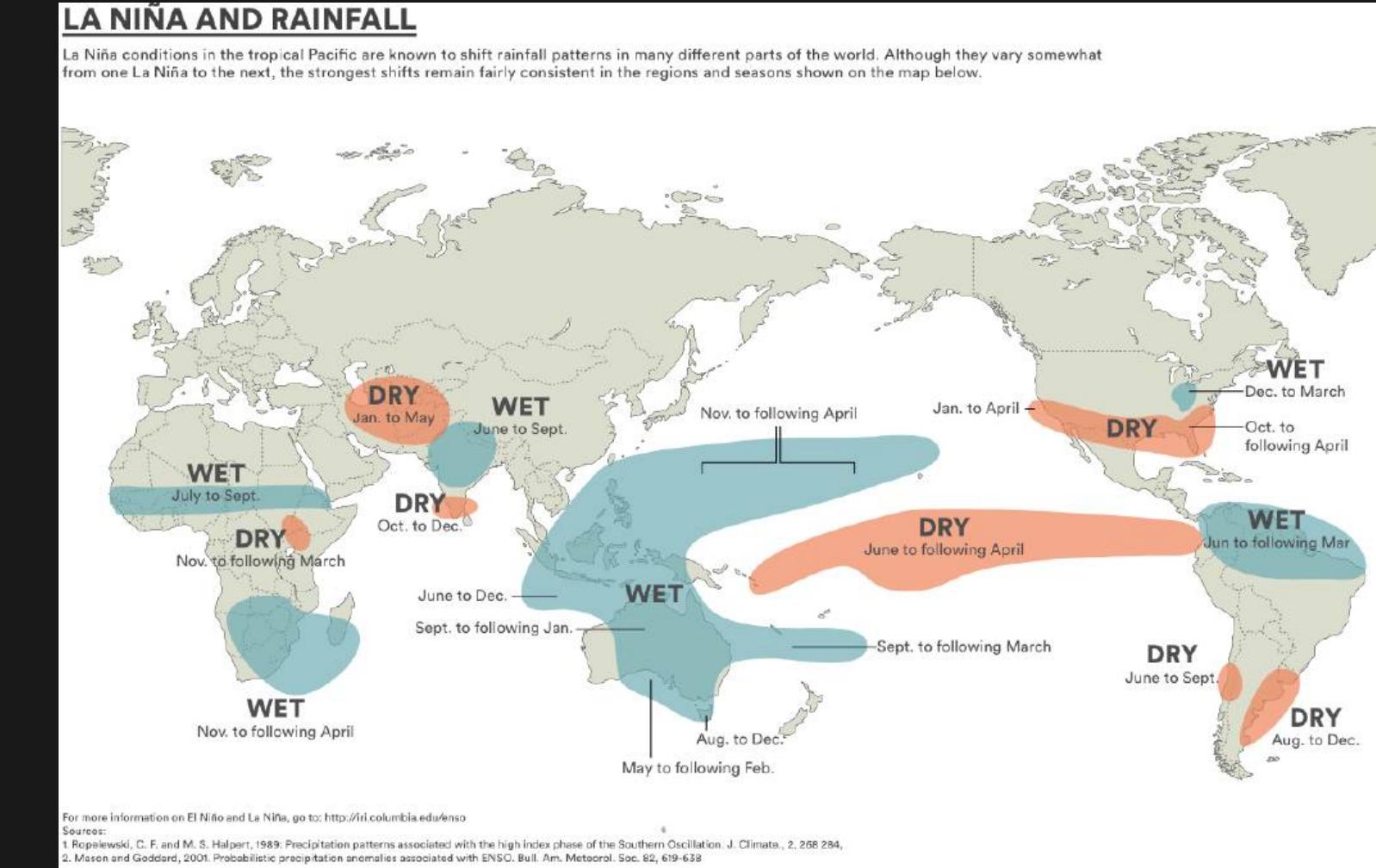
- Stronger trade winds result in warm ocean blob in the western Pacific
- Wet conditions in the West Pacific cause extreme precipitation



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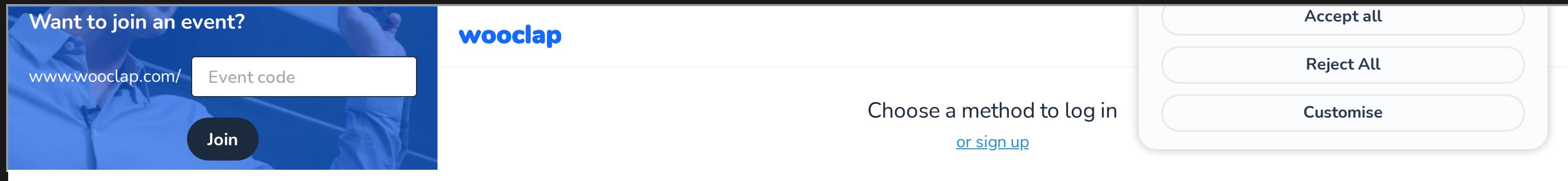
Rockhampton, QLD. Photo by Salvation Army of Australia



- 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?



Quiz time!



The image shows a Wooclap quiz interface on the left and a privacy pop-up on the right. The Wooclap interface features a blue background with a photo of people clapping. It has text 'Want to join an event?' and a URL 'www.wooclap.com/'. A white input field labeled 'Event code' is present, along with a dark button labeled 'Join'. The Wooclap logo is at the top right. To the right, a white pop-up window titled 'Choose a method to log in' offers three options: 'Accept all', 'Reject All', and 'Customise'.

Want to join an event?

www.wooclap.com/

Event code

Join

wooclap

Choose a method to log in

[or sign up](#)

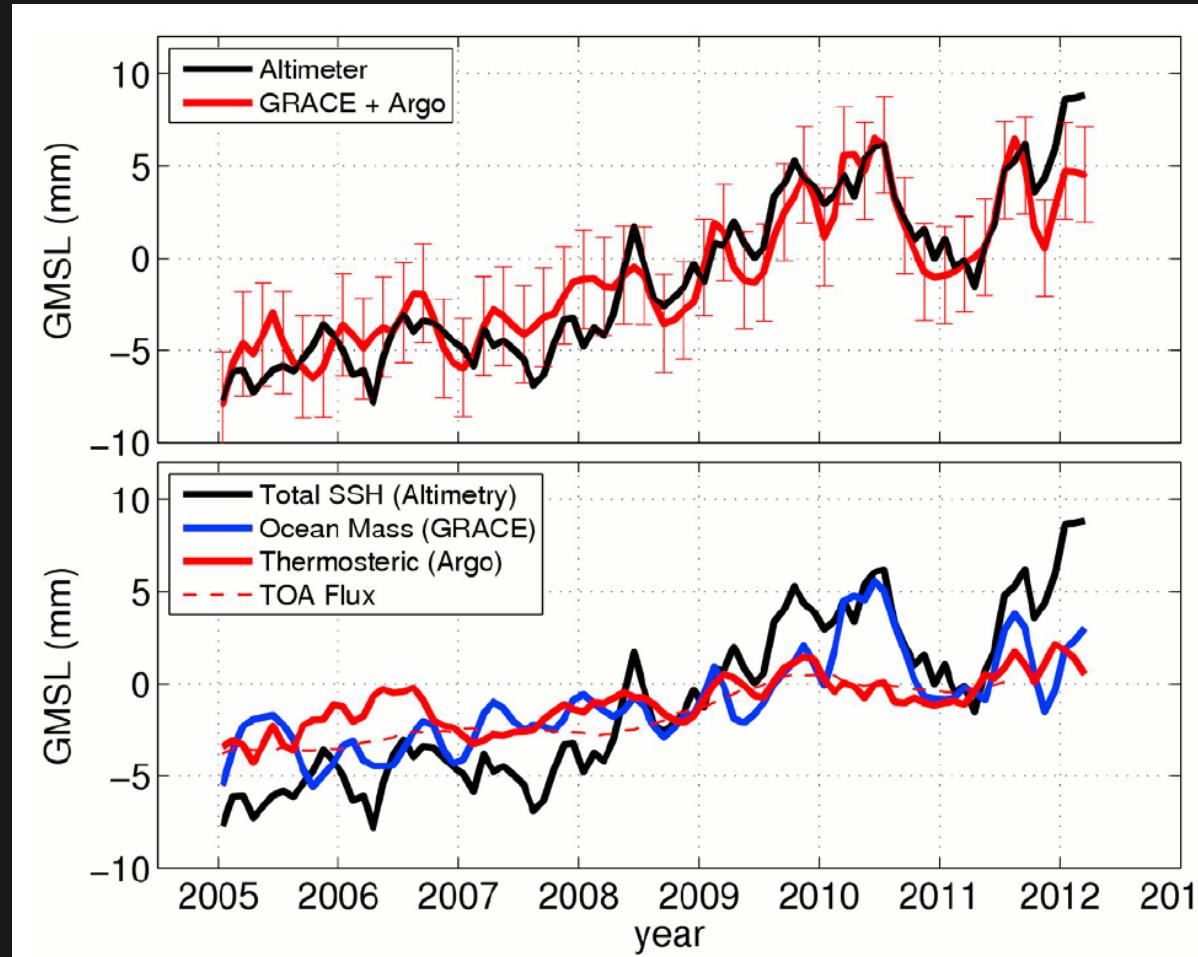
Accept all

Reject All

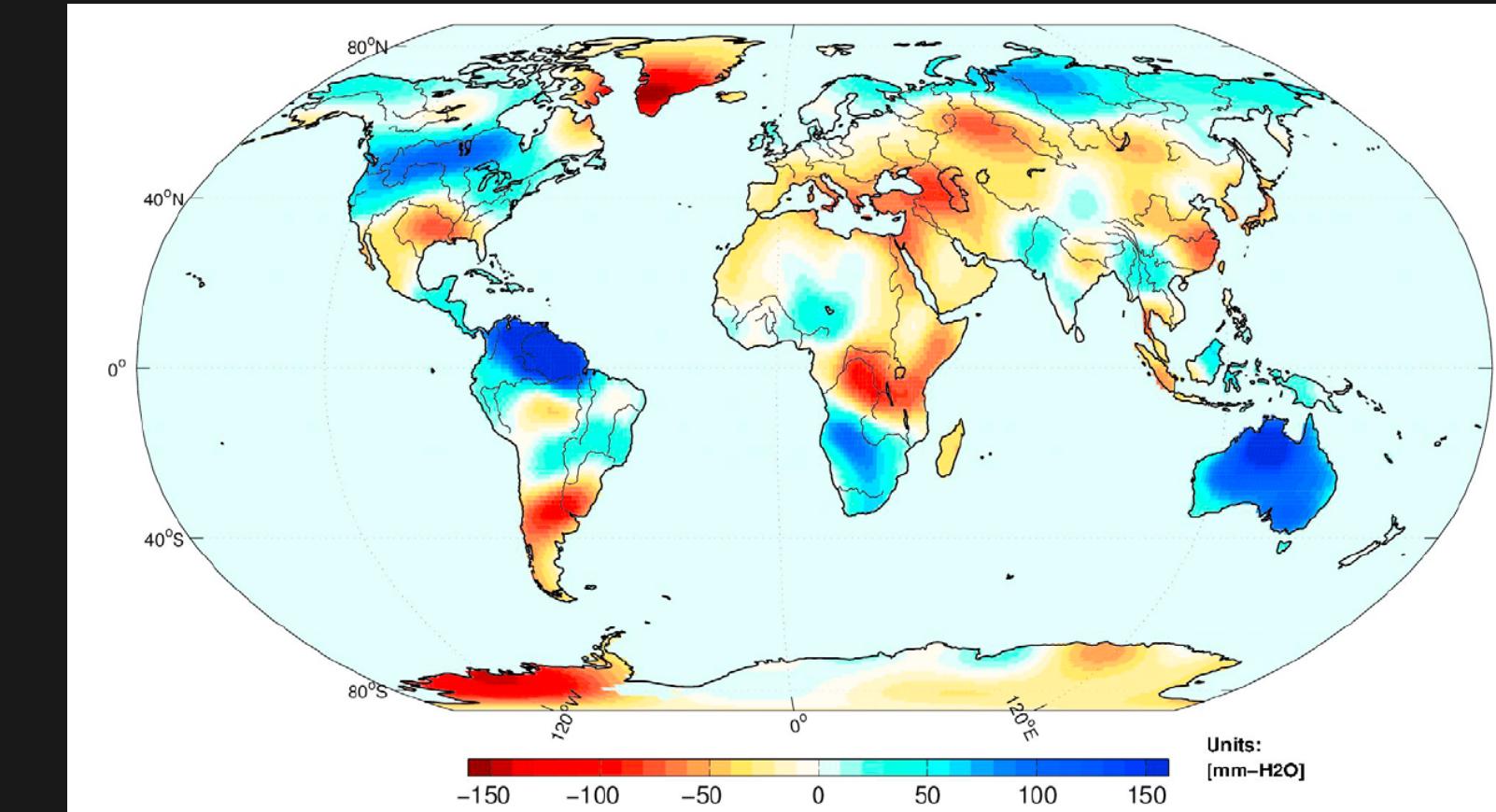
Customise



2010-2011 La Nina event (2)

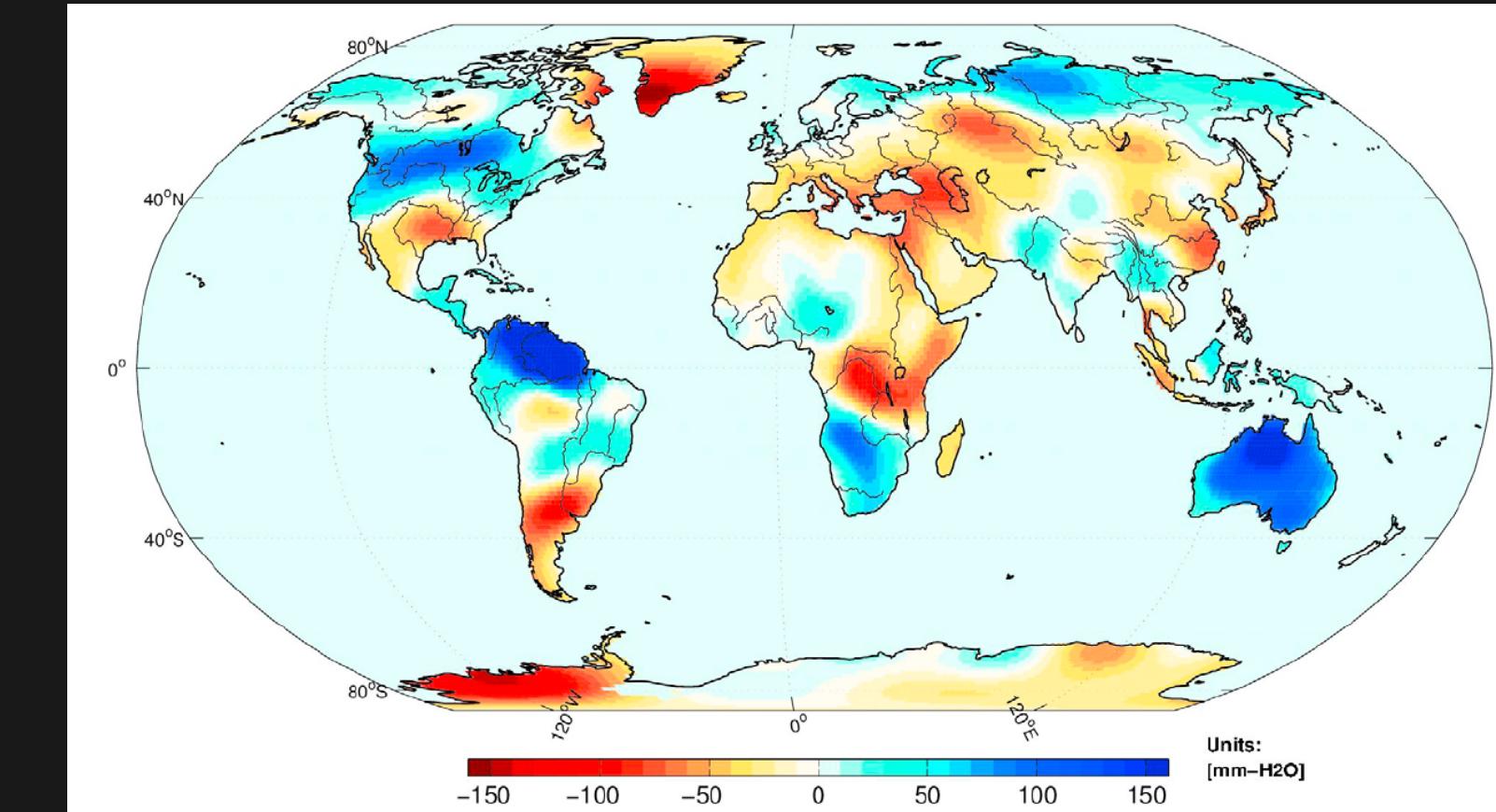
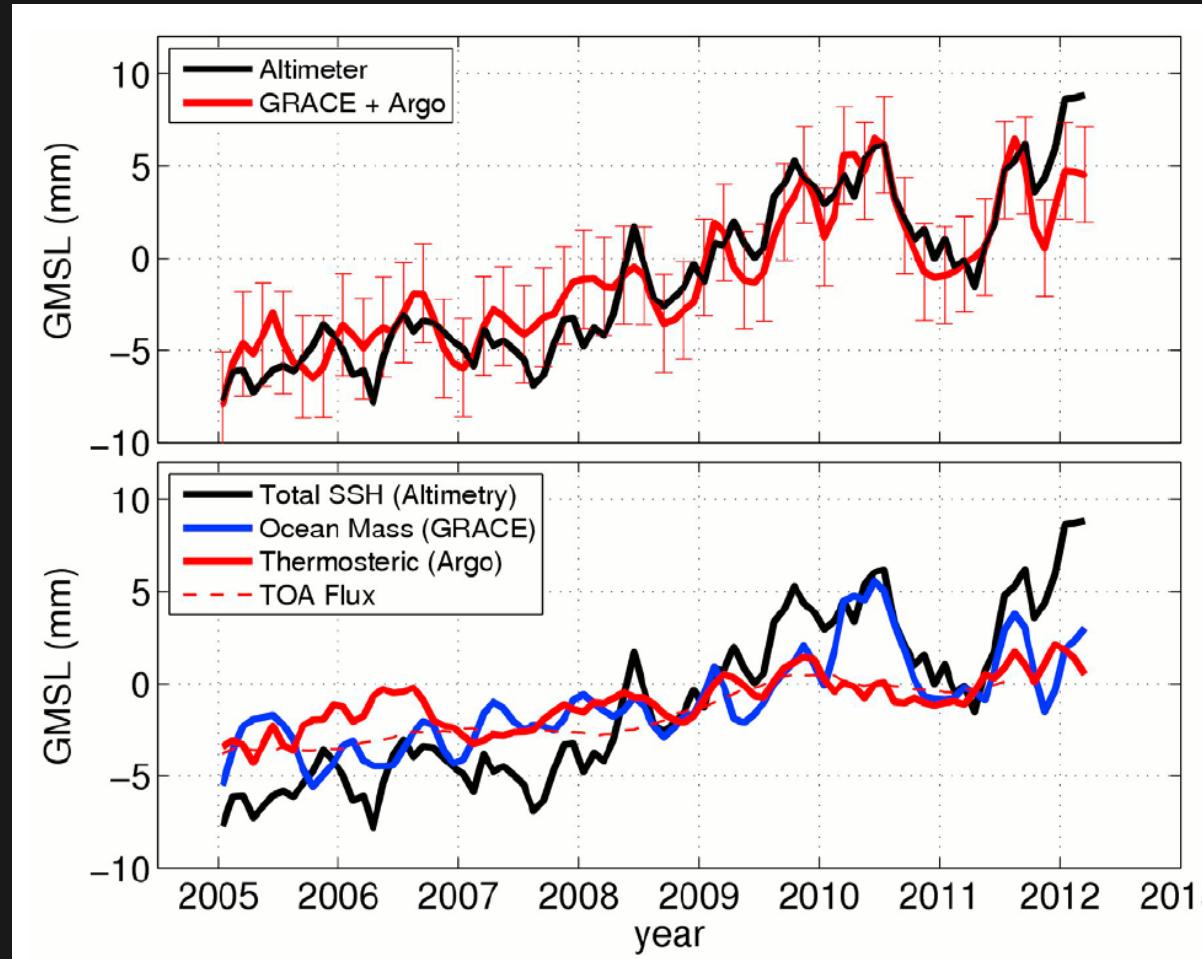


Global mean sea level variations (total, mass driven and 'steric'),
From Böning et al. 2012



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

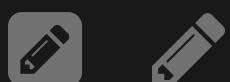
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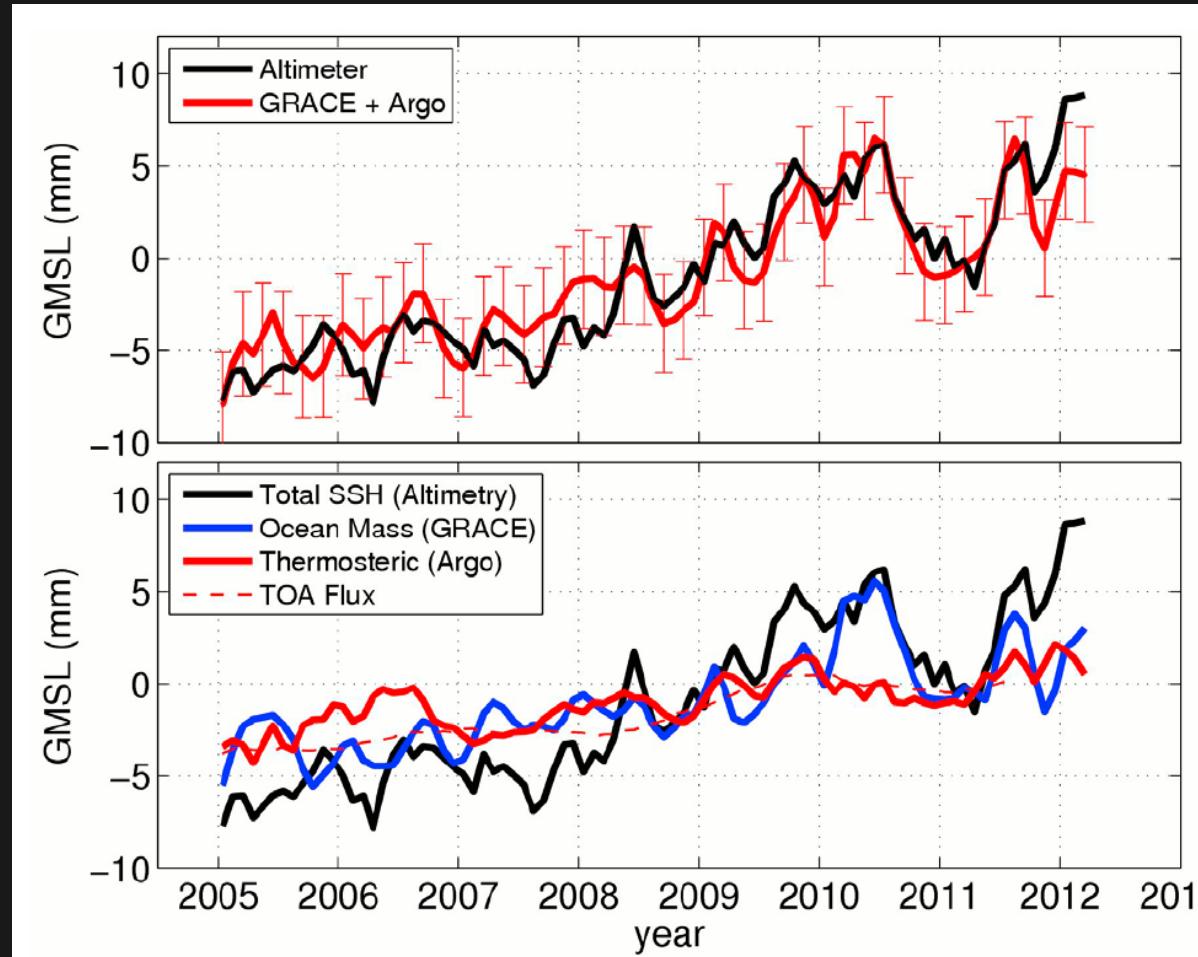
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- Detectable with radar altimetry

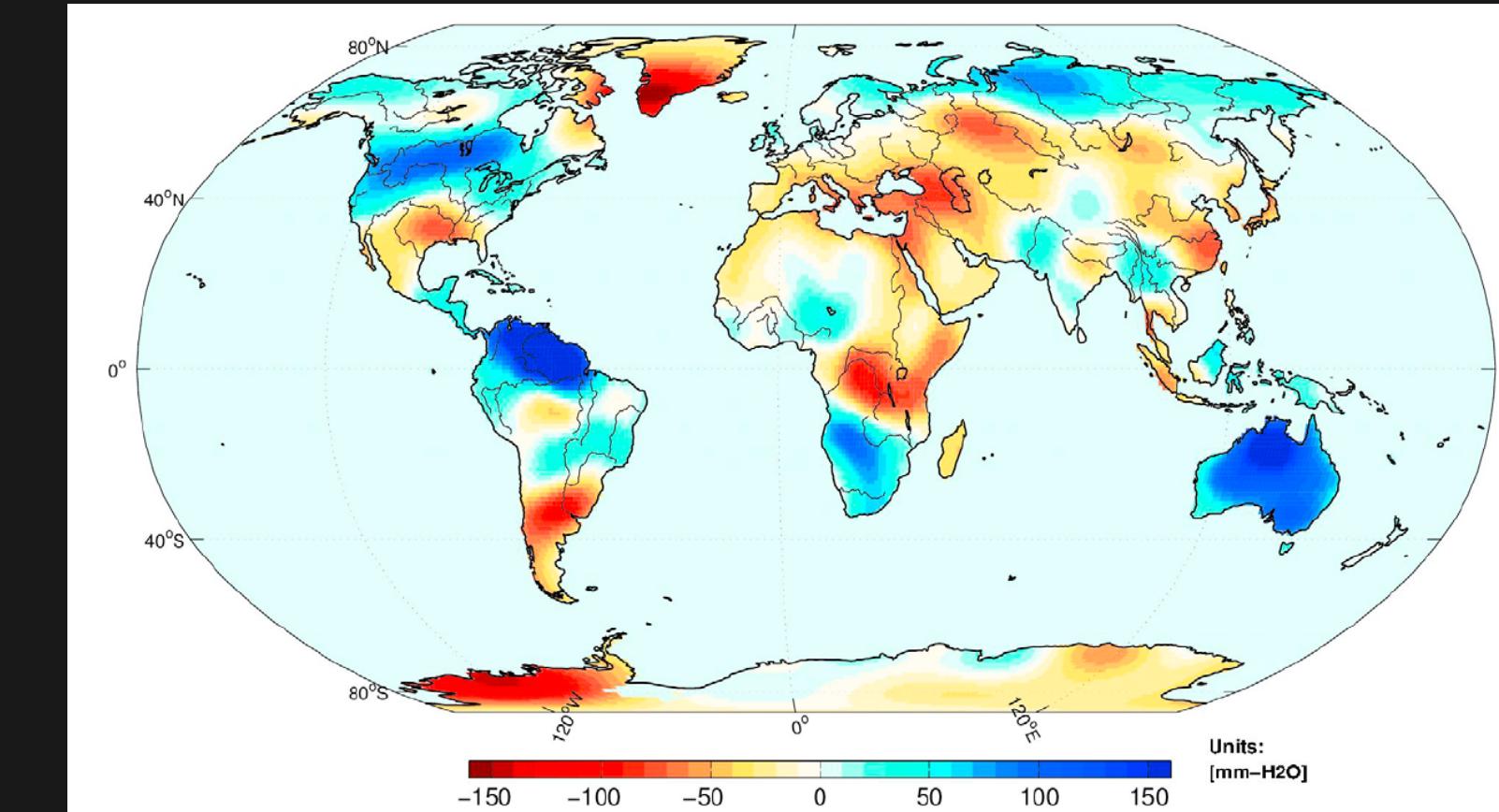


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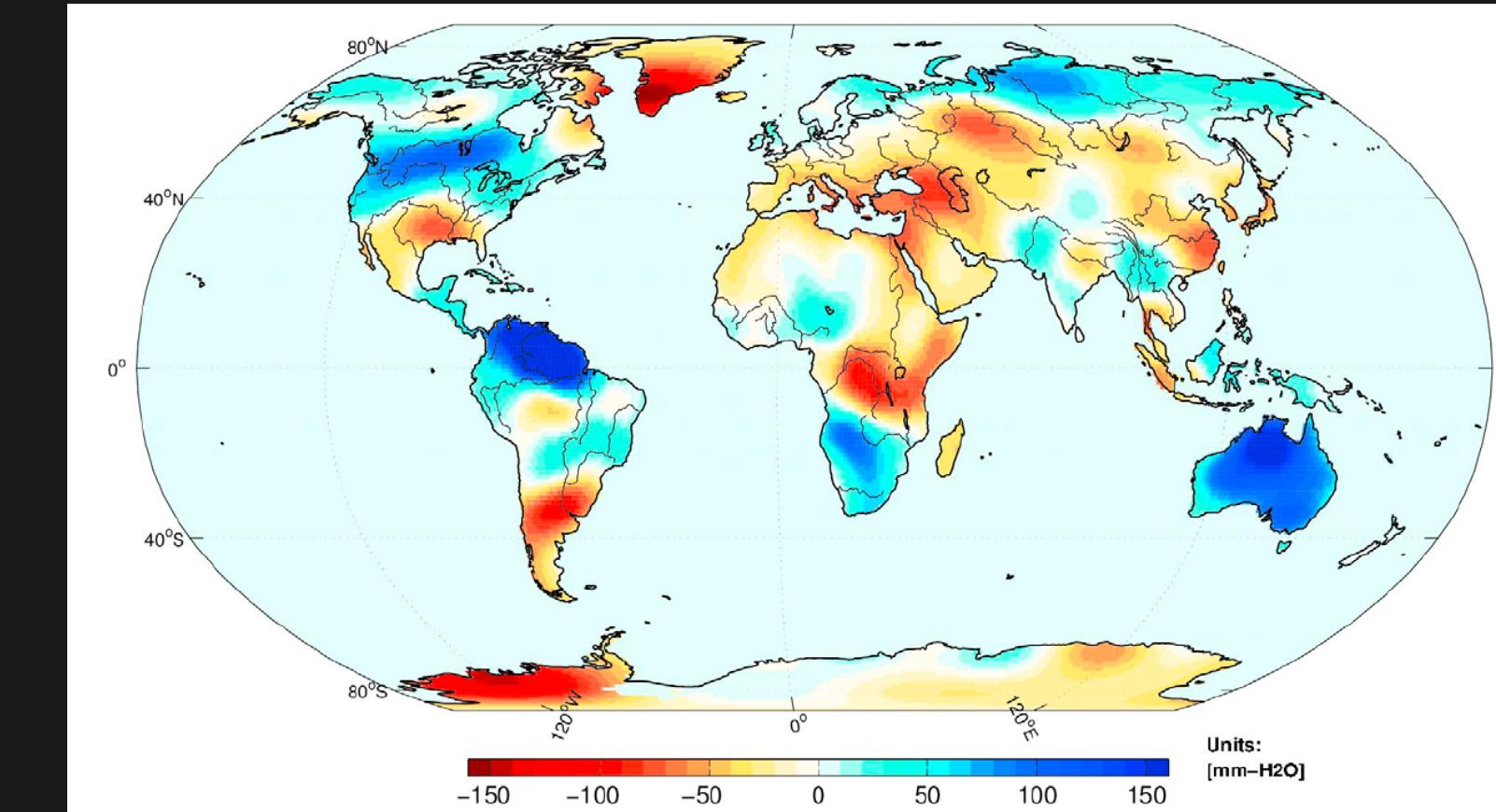
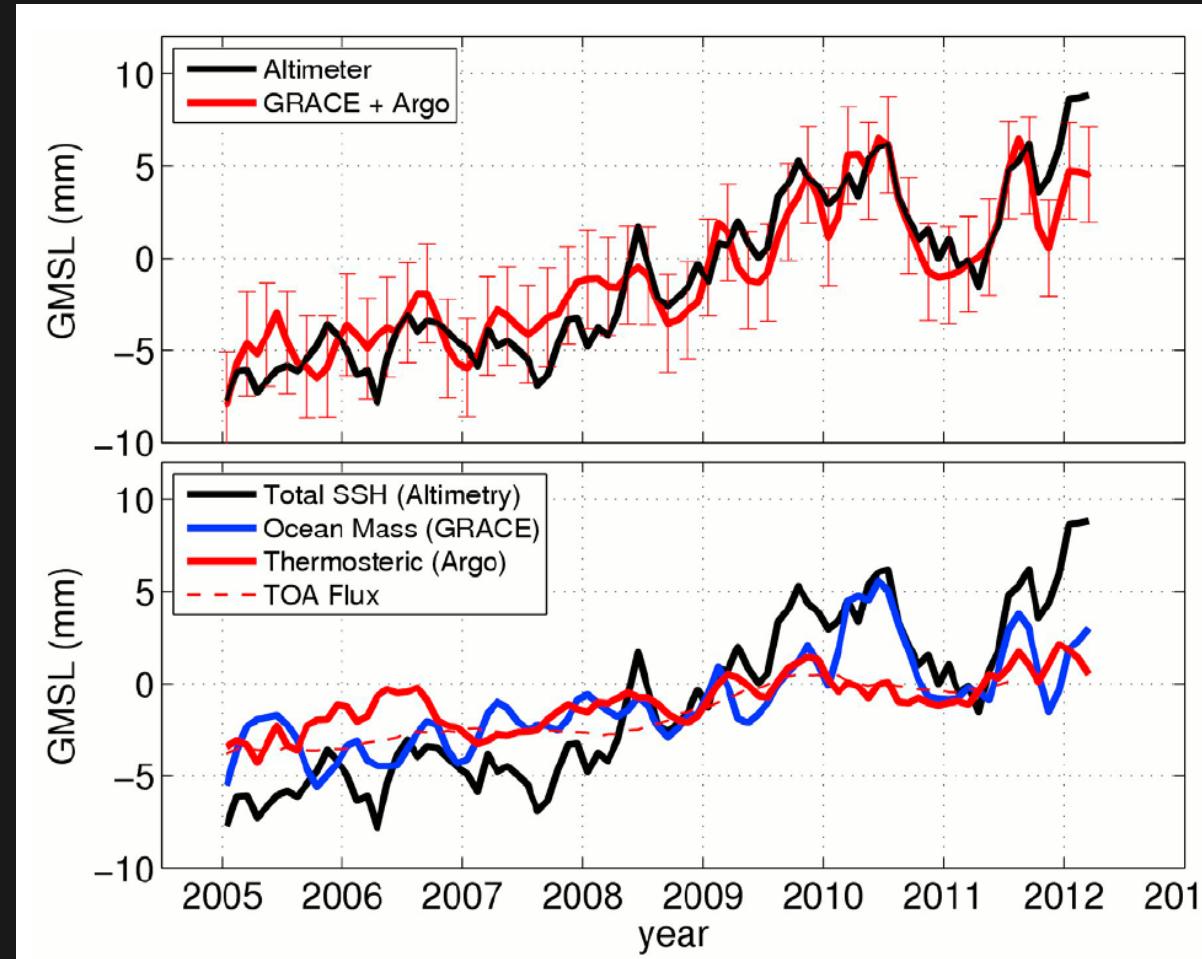
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- Detectable with radar altimetry
- Can be explained by mass-driven sea level (GRACE)



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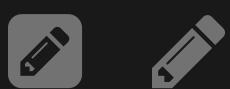
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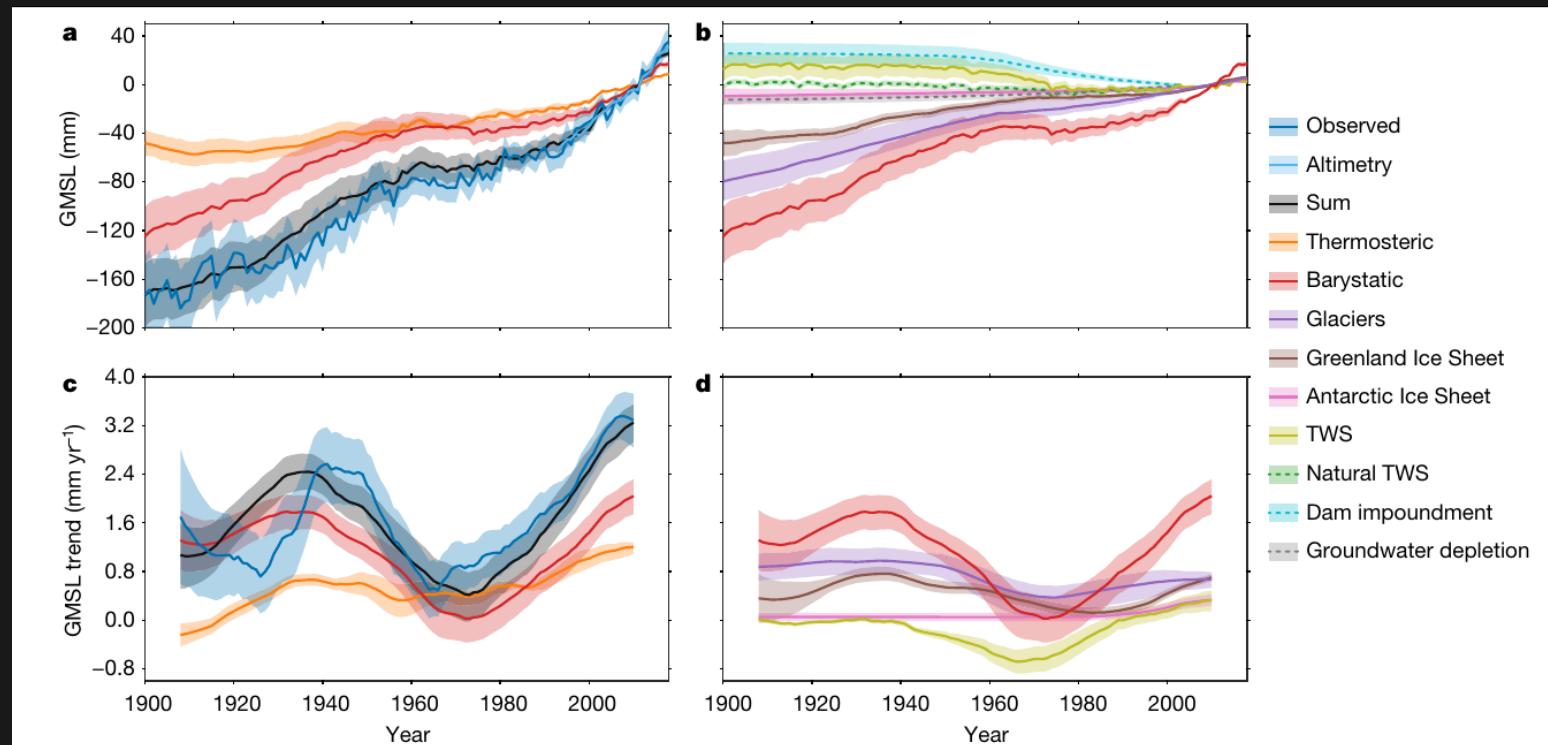
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- Can be explained by mass-driven sea level (GRACE)
- Hotspot: Australia



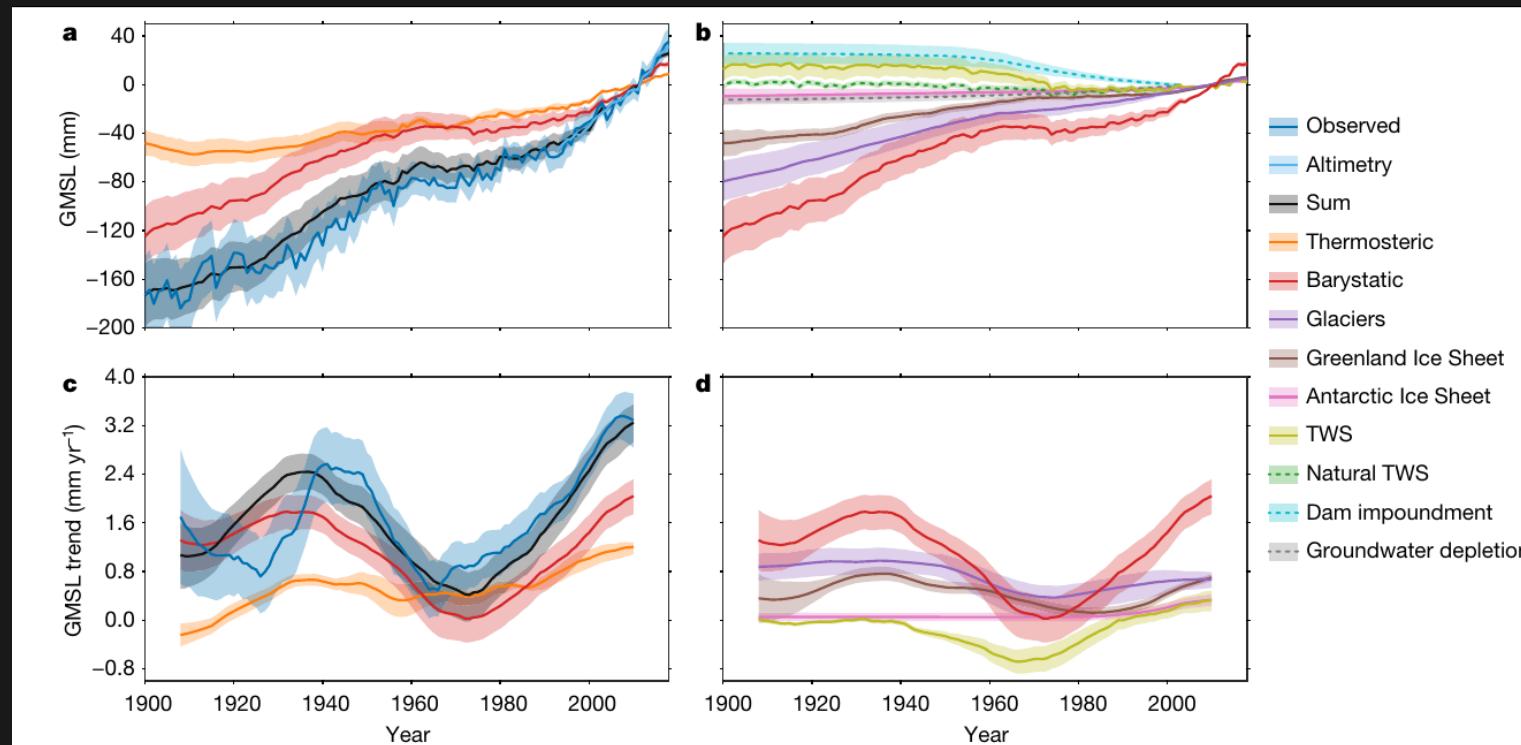
Sea level contributions since 1900



Historic sea level can be largely explained with different (modelled) sea level contributions. From Frederikse et al. 2020



Sea level contributions since 1900

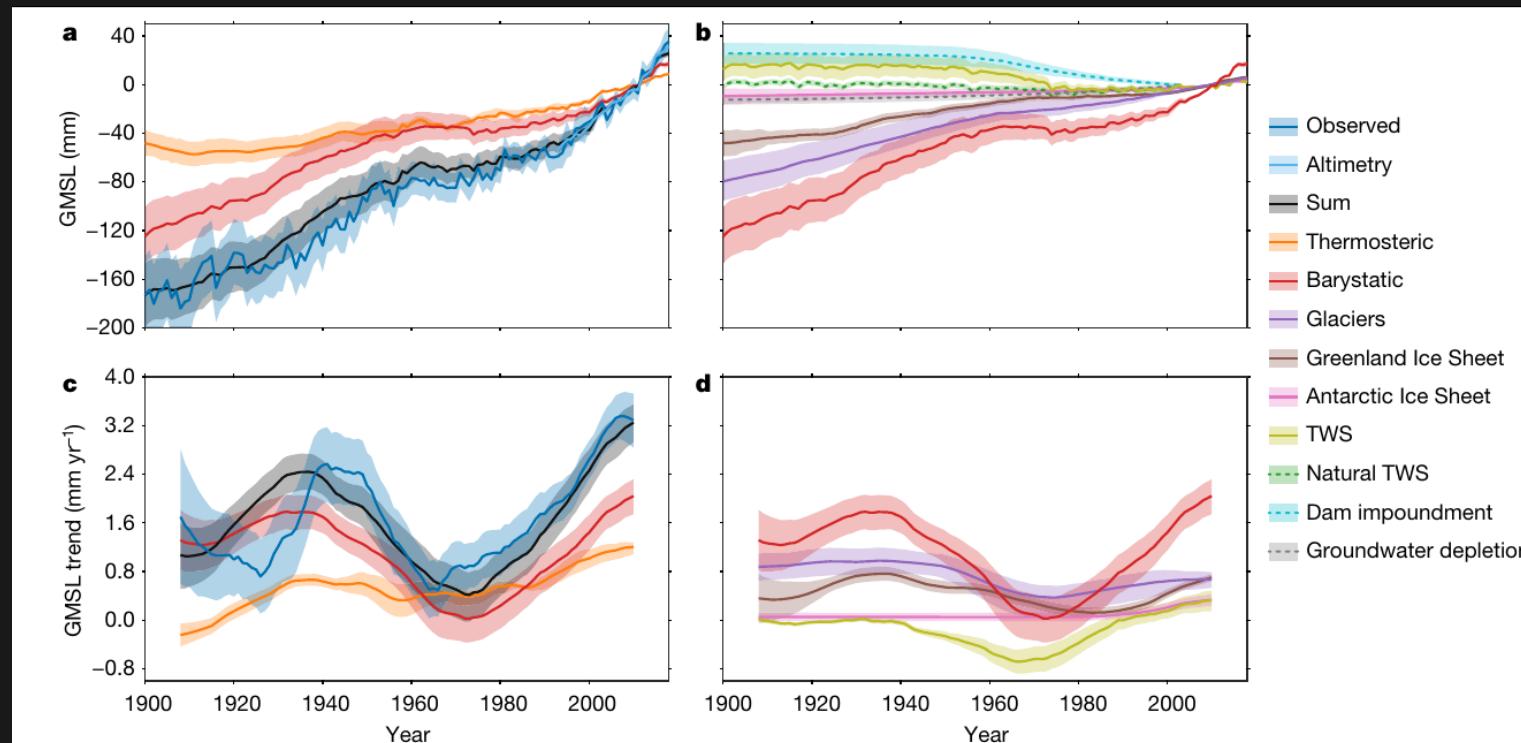


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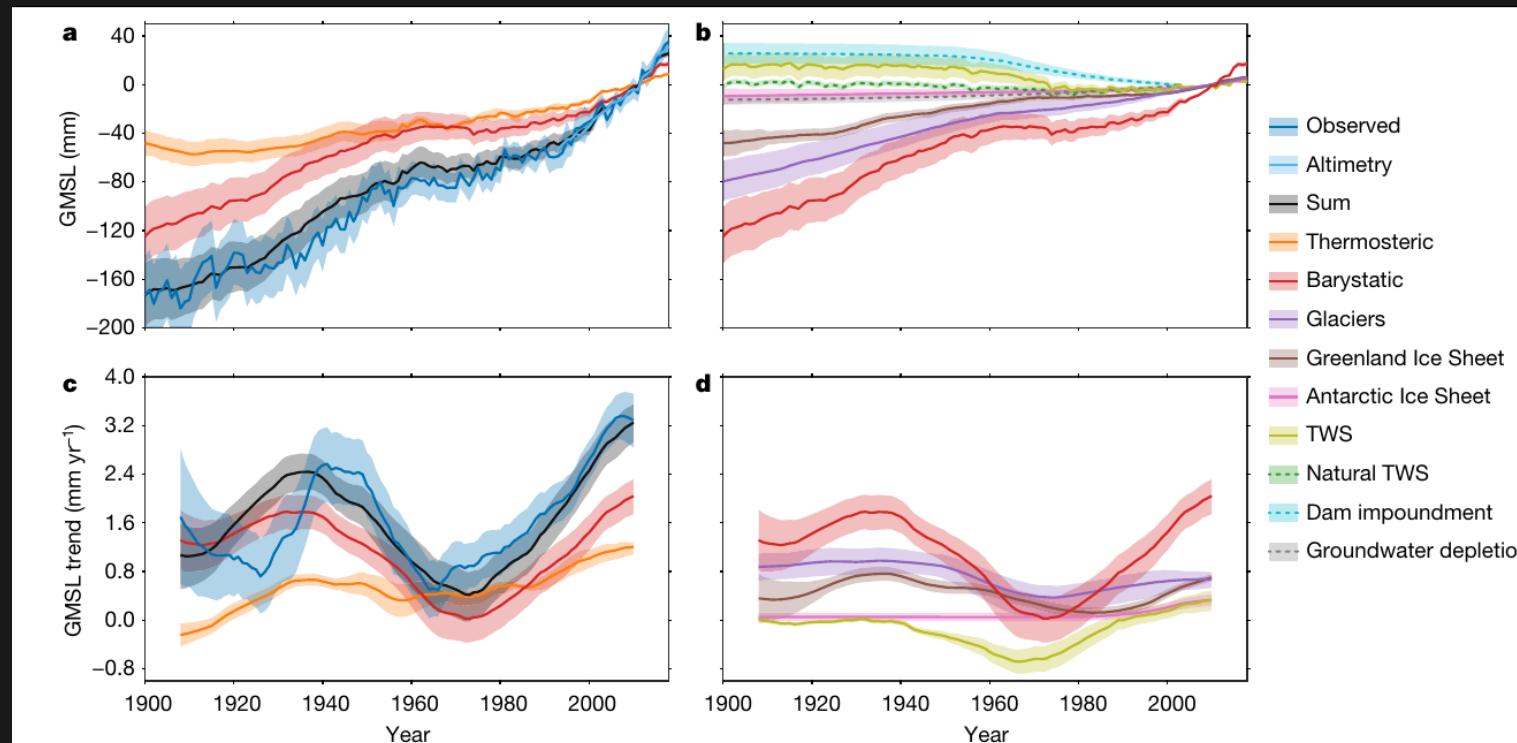


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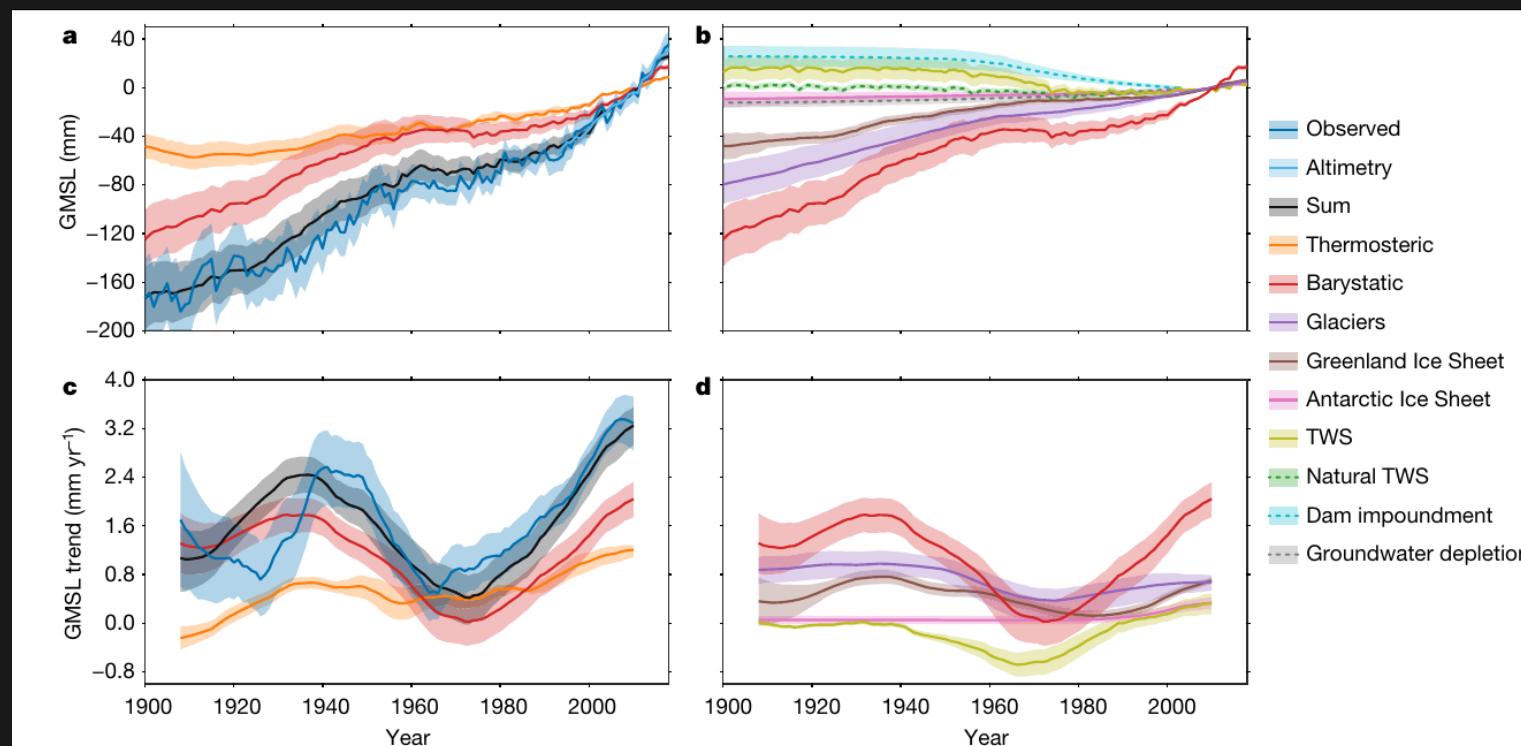


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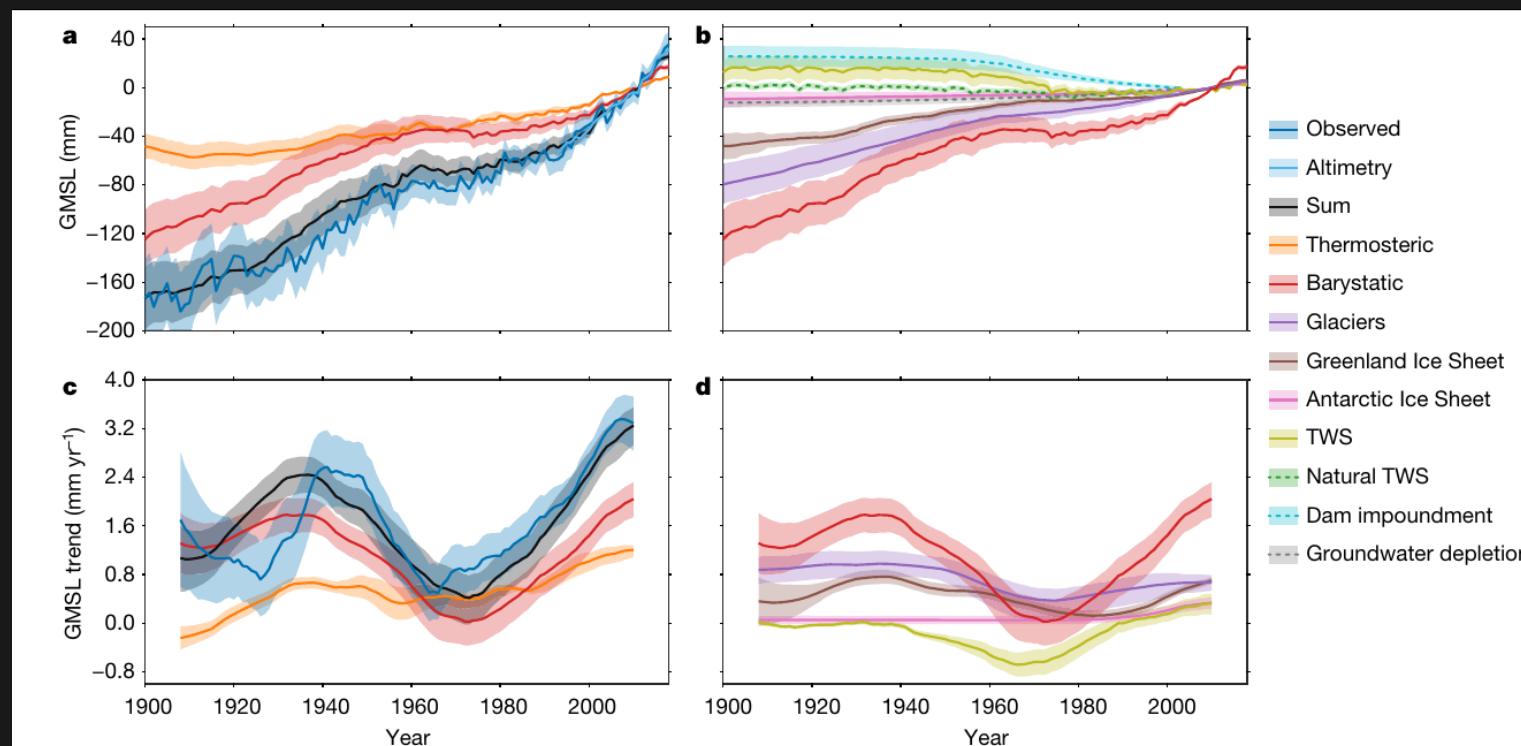


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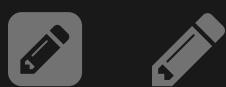


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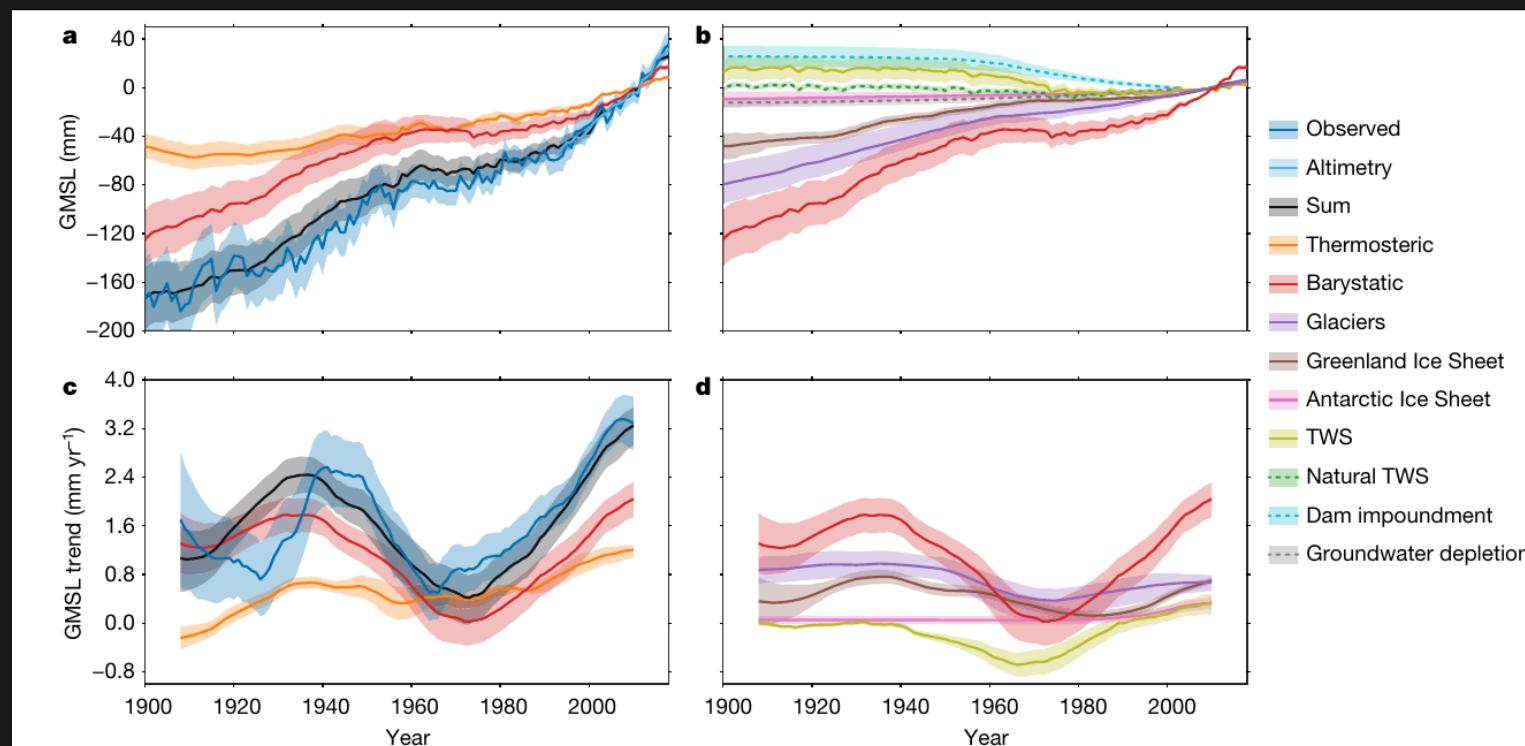


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- Recent accelerations from icesheets and glaciers -> (observable by GRACE since 2002)



Ocean mass from GRACE (Theory)

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

Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity

Sean Swenson and John Wahr

Department of Physics and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, USA

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

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$$\widetilde{\Delta\sigma}_{\text{region}} = \sum_{l,m} \frac{K_l}{\Omega_{\text{region}}} (W_{lm}^c \Delta C_{lm} + W_{lm}^s \Delta S_{lm}). \quad (27)$$



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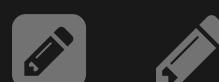
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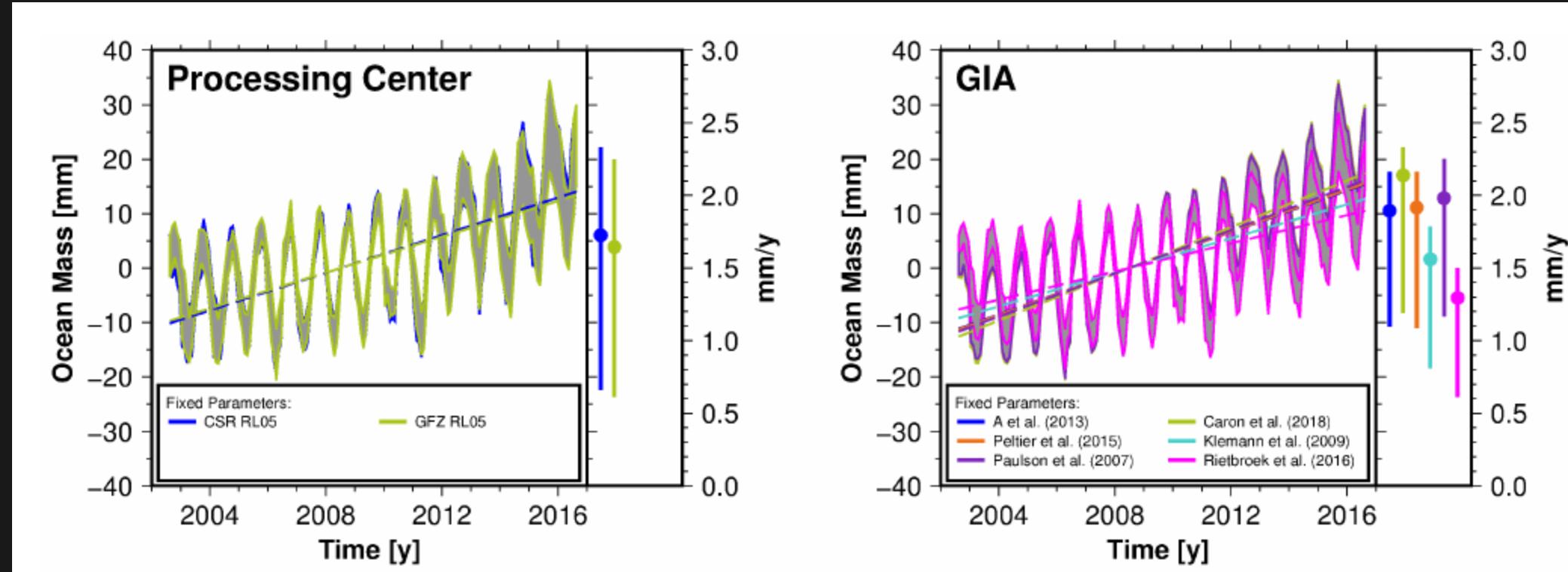
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 - dot product of smoothed basin coefficients with GRACE-TWS coefficients



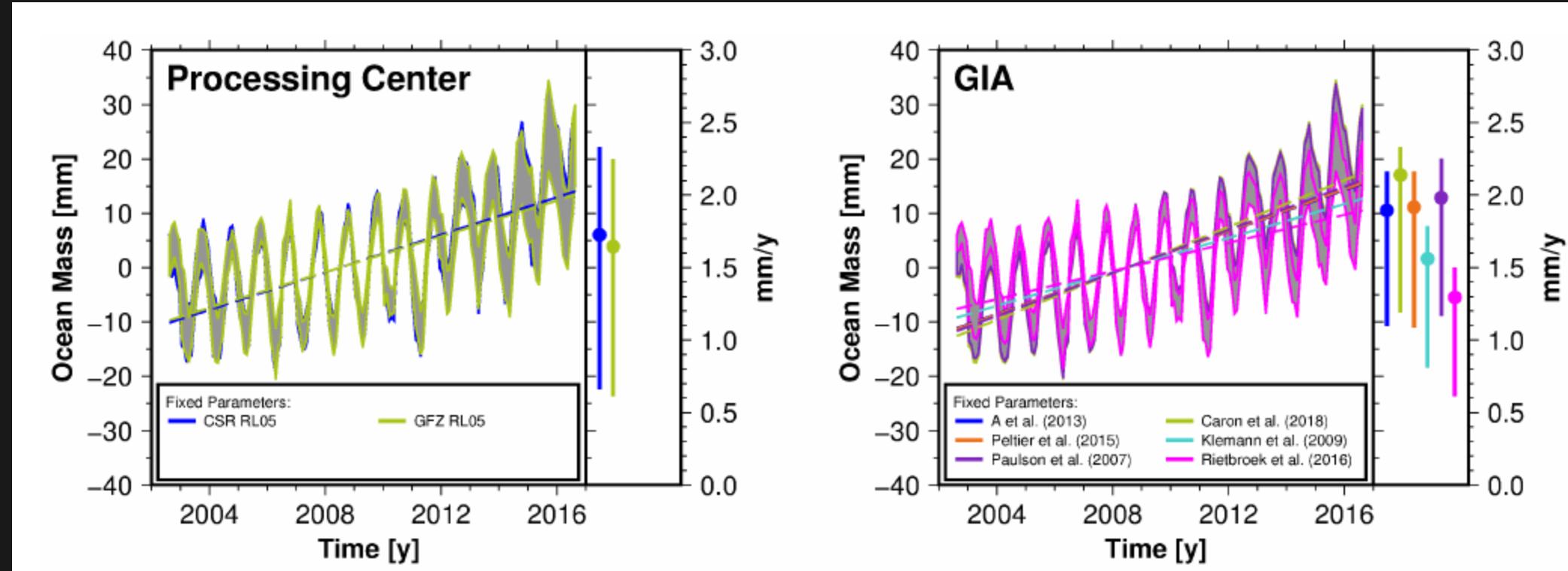
Ocean mass from GRACE (Praxis)



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

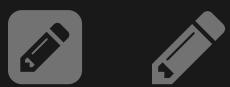


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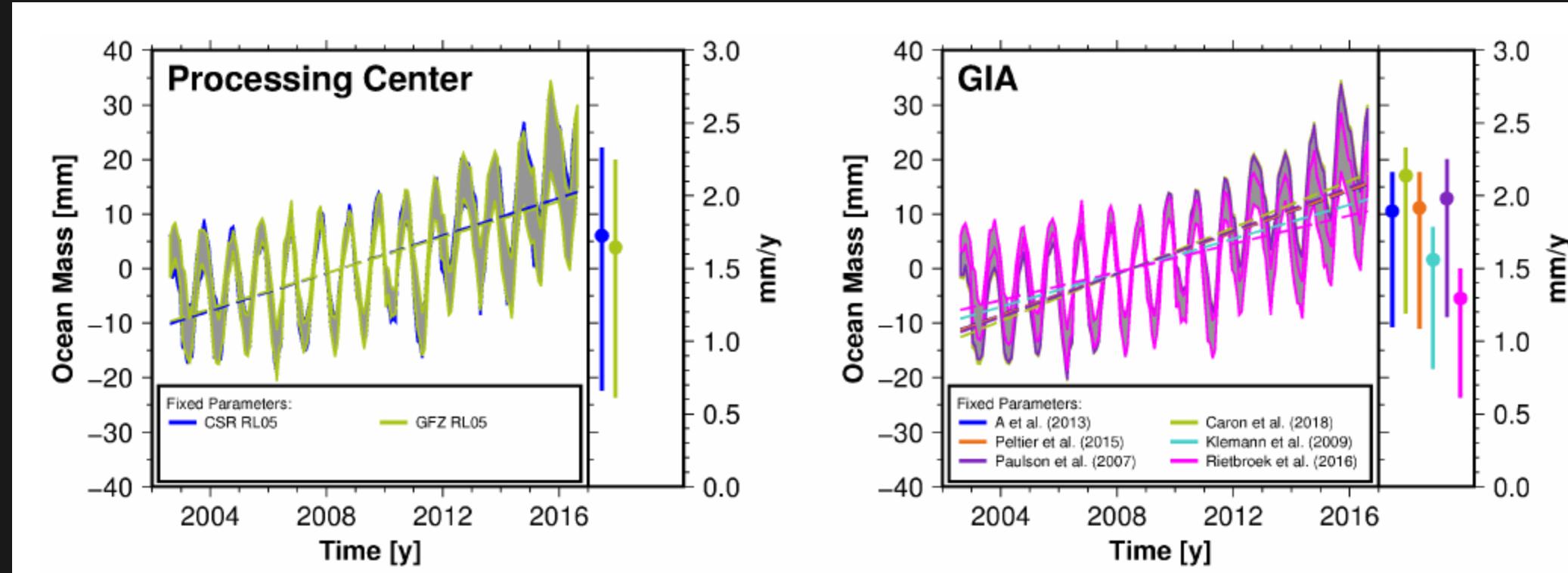


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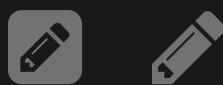


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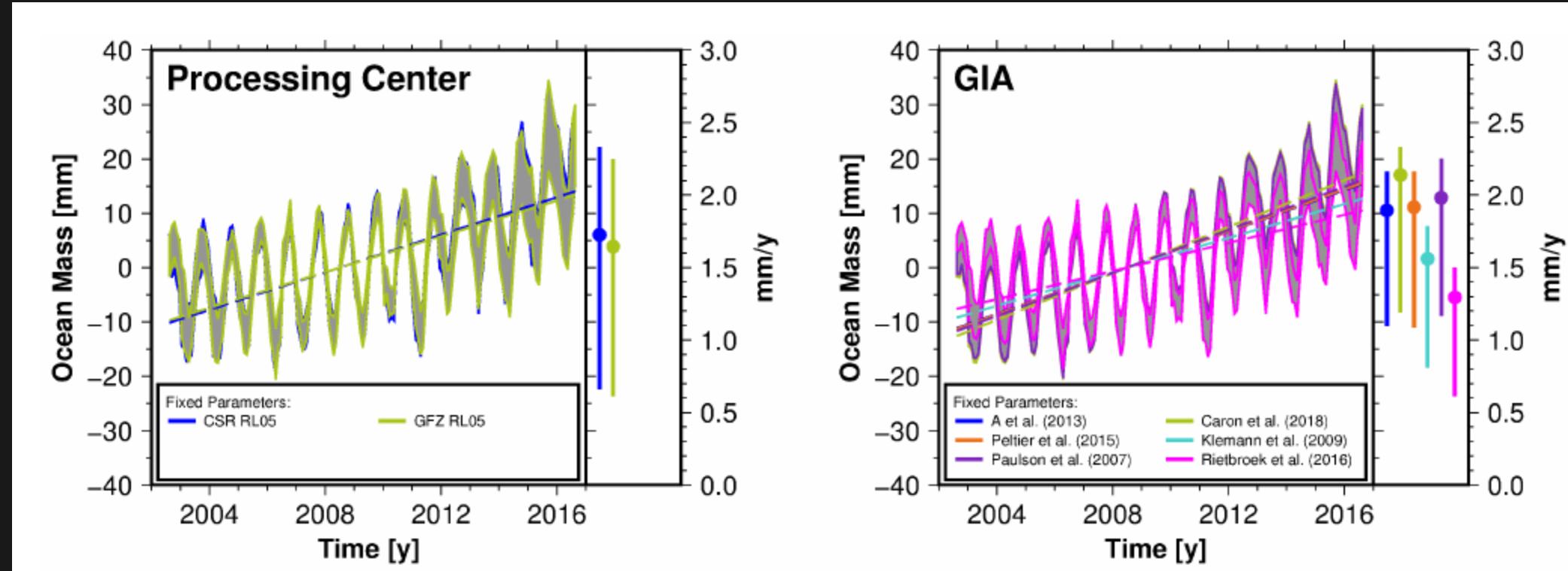


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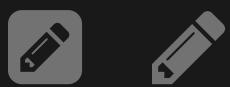


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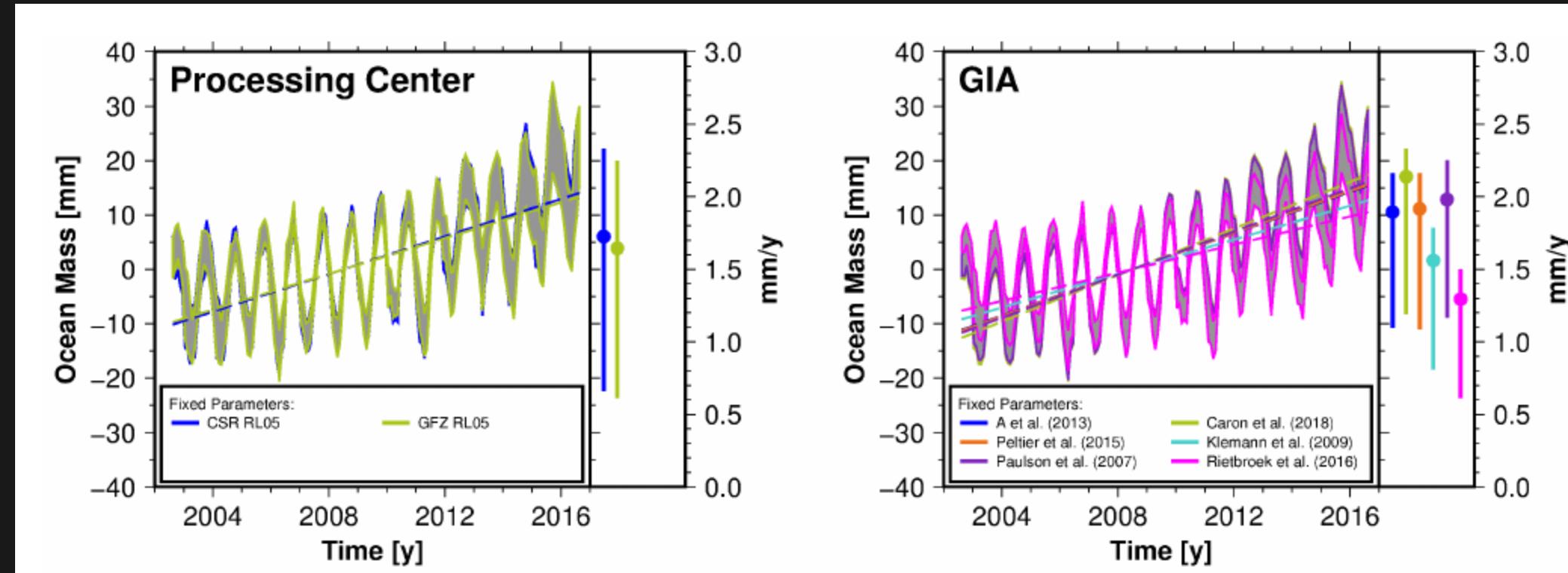


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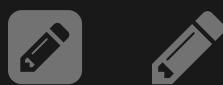


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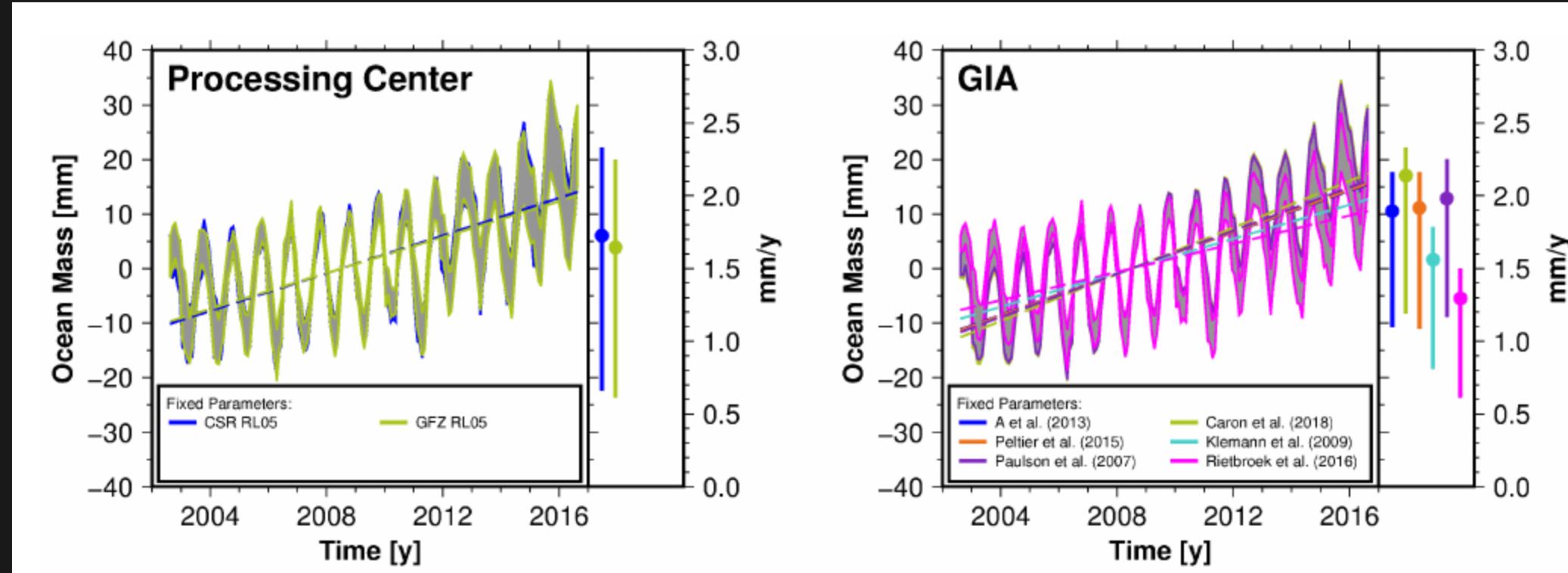


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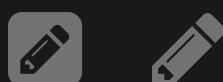


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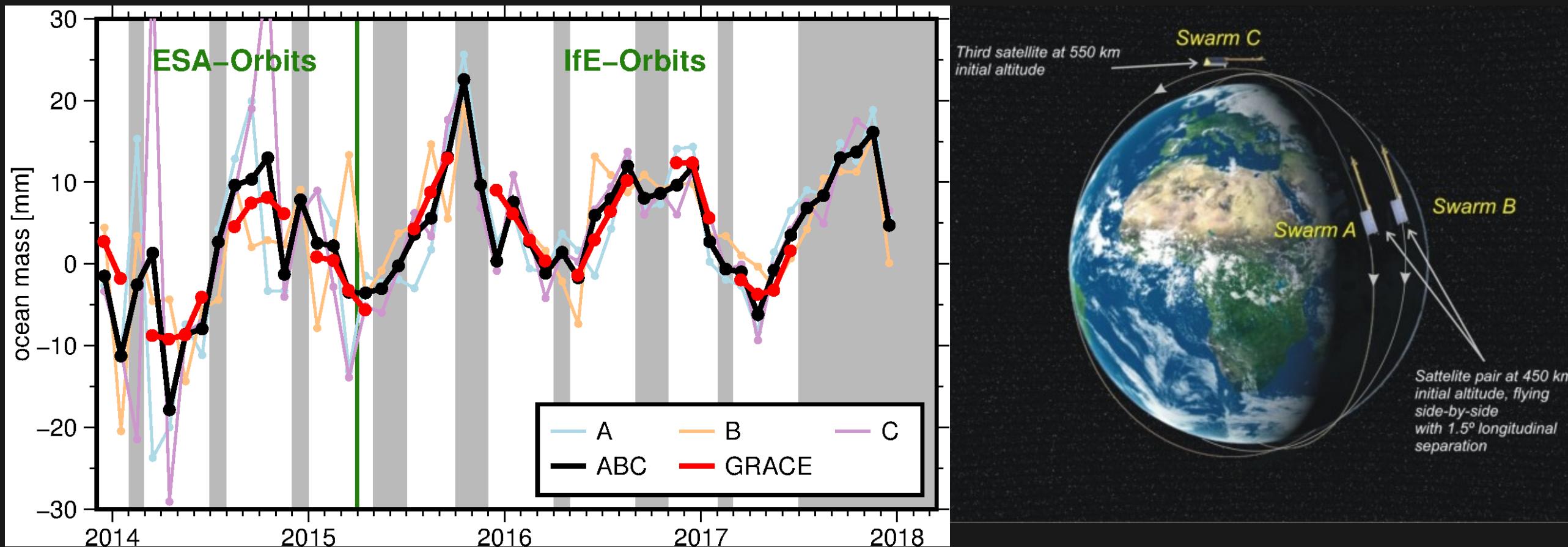


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 - Current mass trends ~1.5-2mm/yr (c.f. total trend ~3.3 mm/yr)

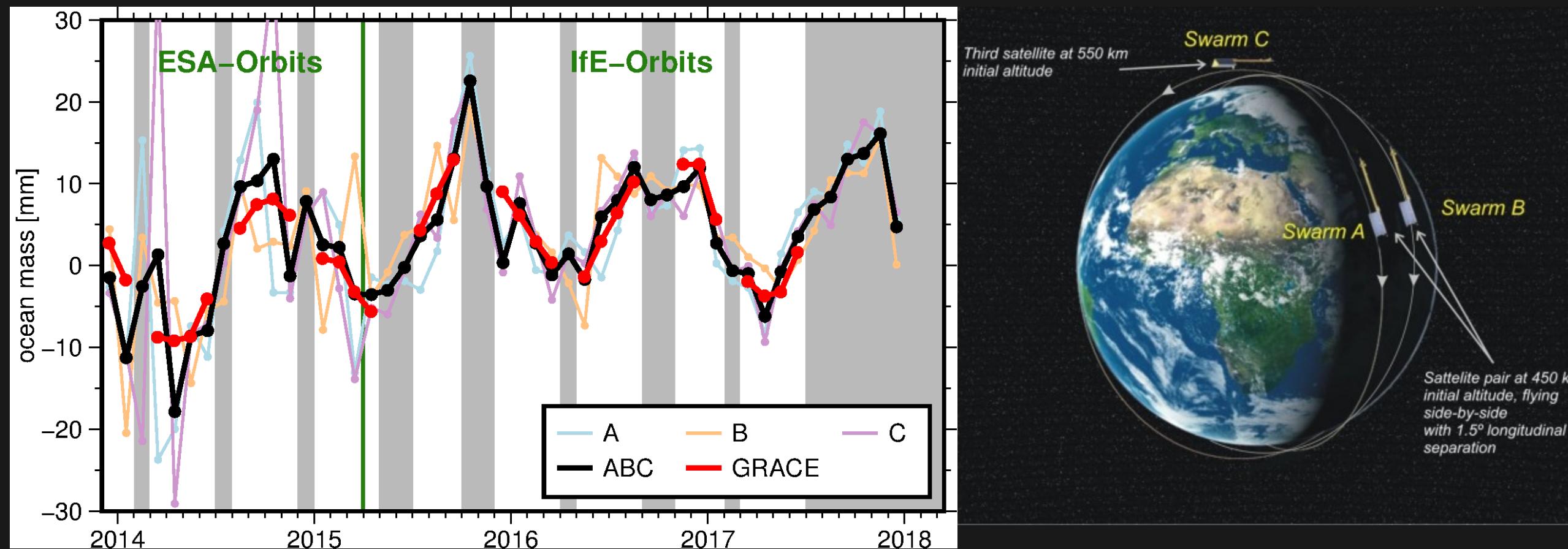


Ocean mass can also be retrieved from the SWARM Mission



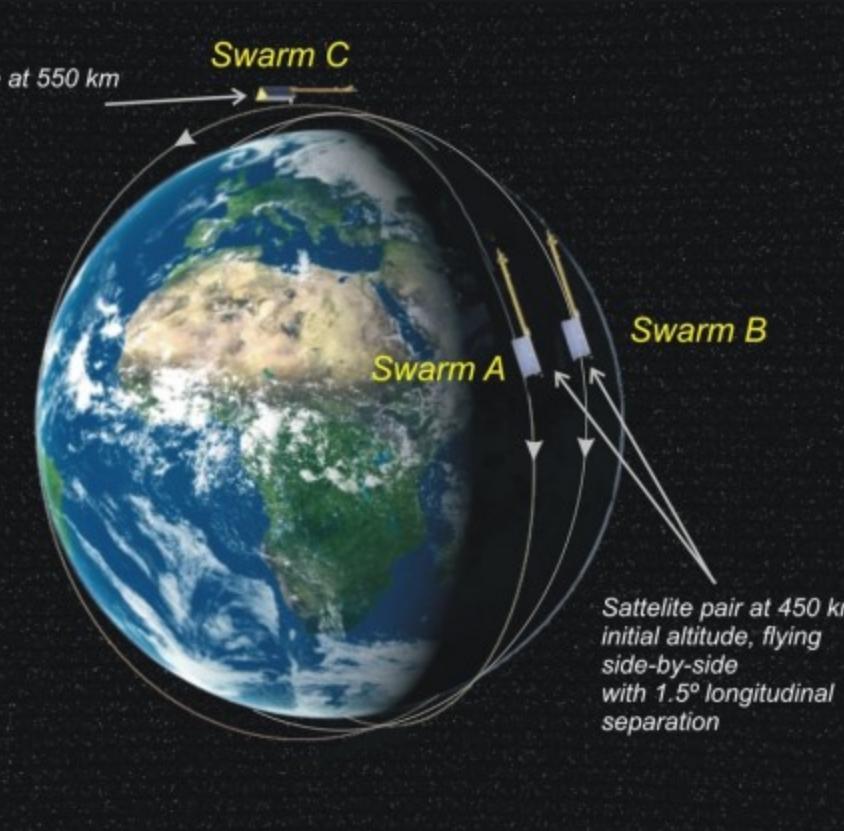
Comparison of ocean mass from GRACE and the SWARM (A,B,C satellites). Update of Luck et al. 2018

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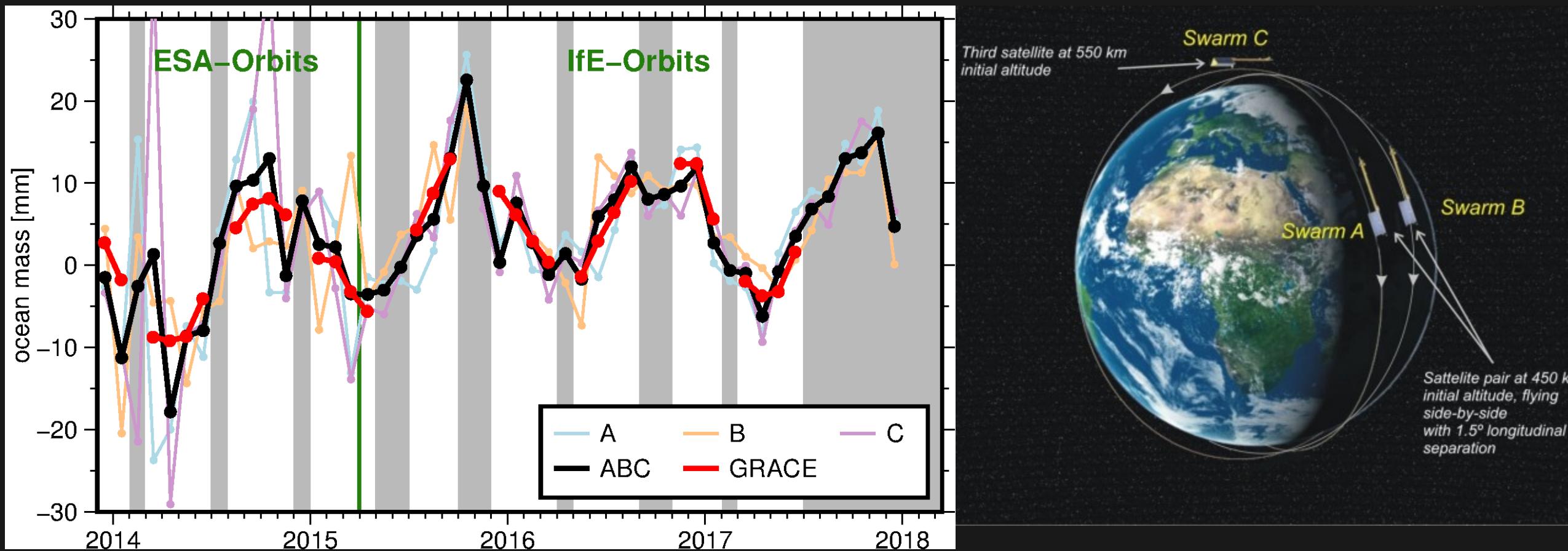


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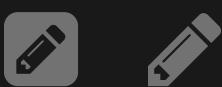


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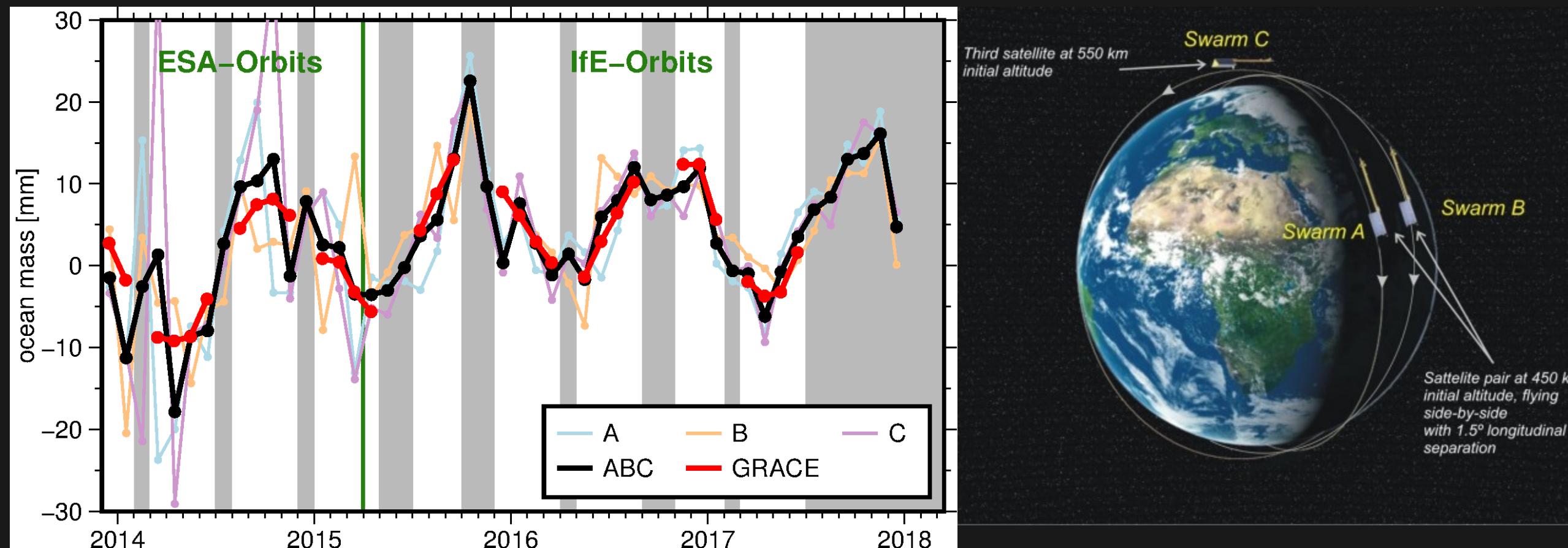


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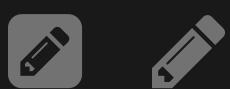


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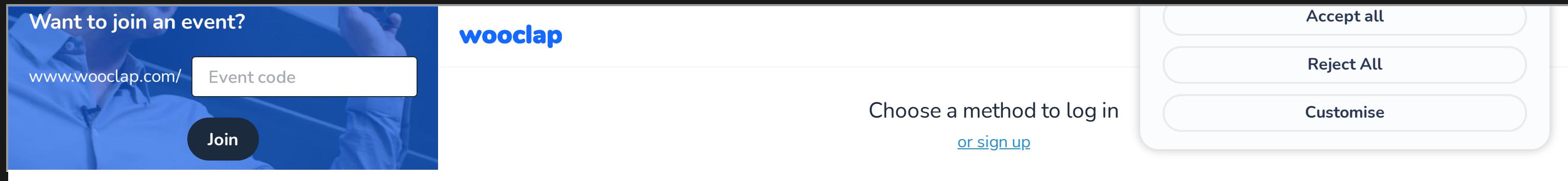


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- Precise (kinematic) orbits contain information on low-resolution gravity changes -> ocean scales
- Principle is useful for filling gaps and potentially pre-GRACE era



Regional sea level



The image shows a screenshot of a Wooclap event page titled "Regional sea level". On the left, there's a blue banner with the text "Want to join an event?" and a URL "www.wooclap.com/". Below the URL is a white input field labeled "Event code" and a dark blue "Join" button. To the right of the banner is the Wooclap logo. In the center, there's a call to action "Choose a method to log in or sign up". A white rounded rectangle on the right side contains three options: "Accept all", "Reject All", and "Customise", each with a small circular icon.

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www.wooclap.com/ Event code

Join

wooclap

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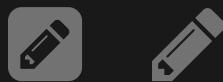
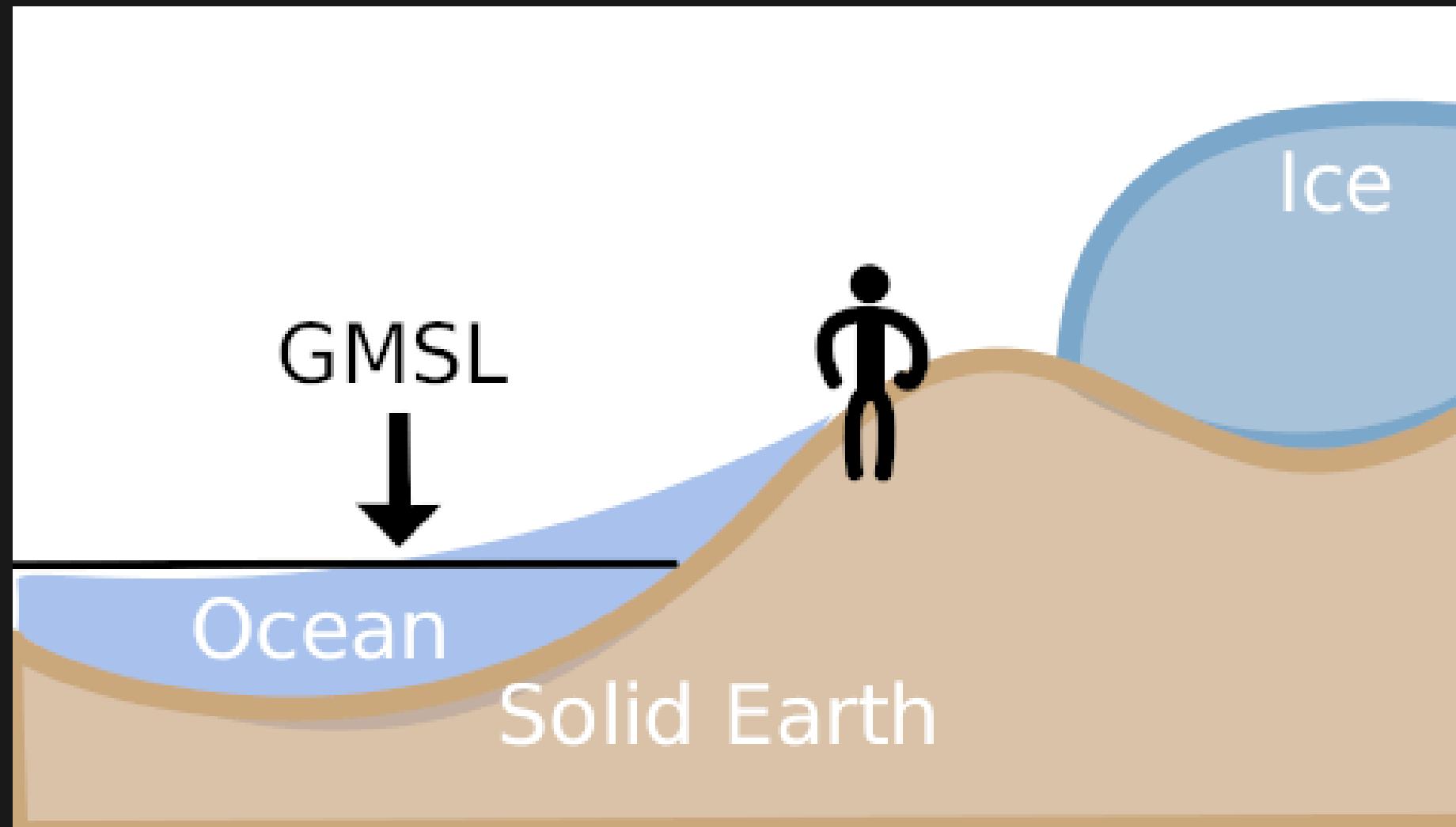
Accept all

Reject All

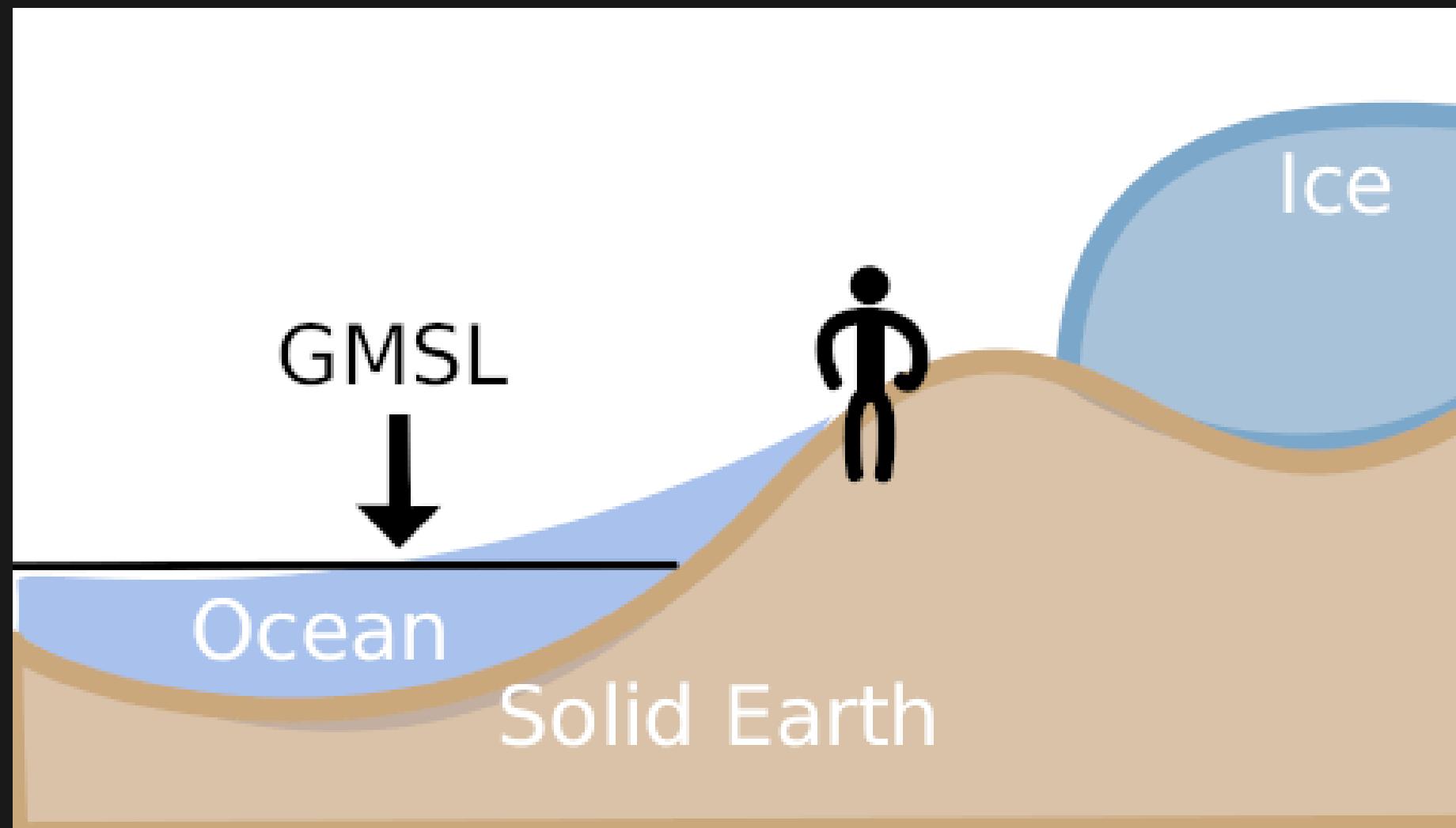
Customise



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

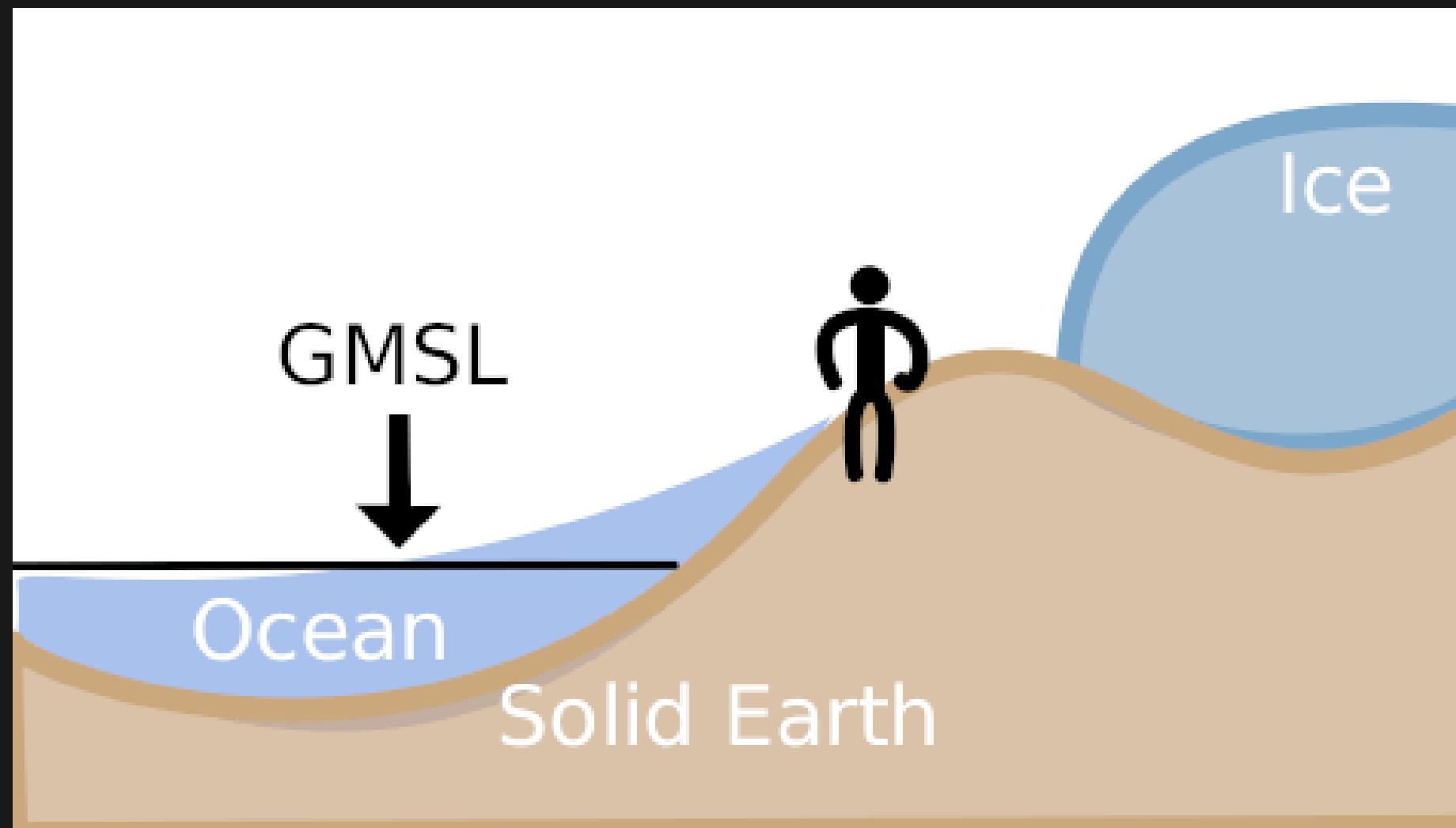


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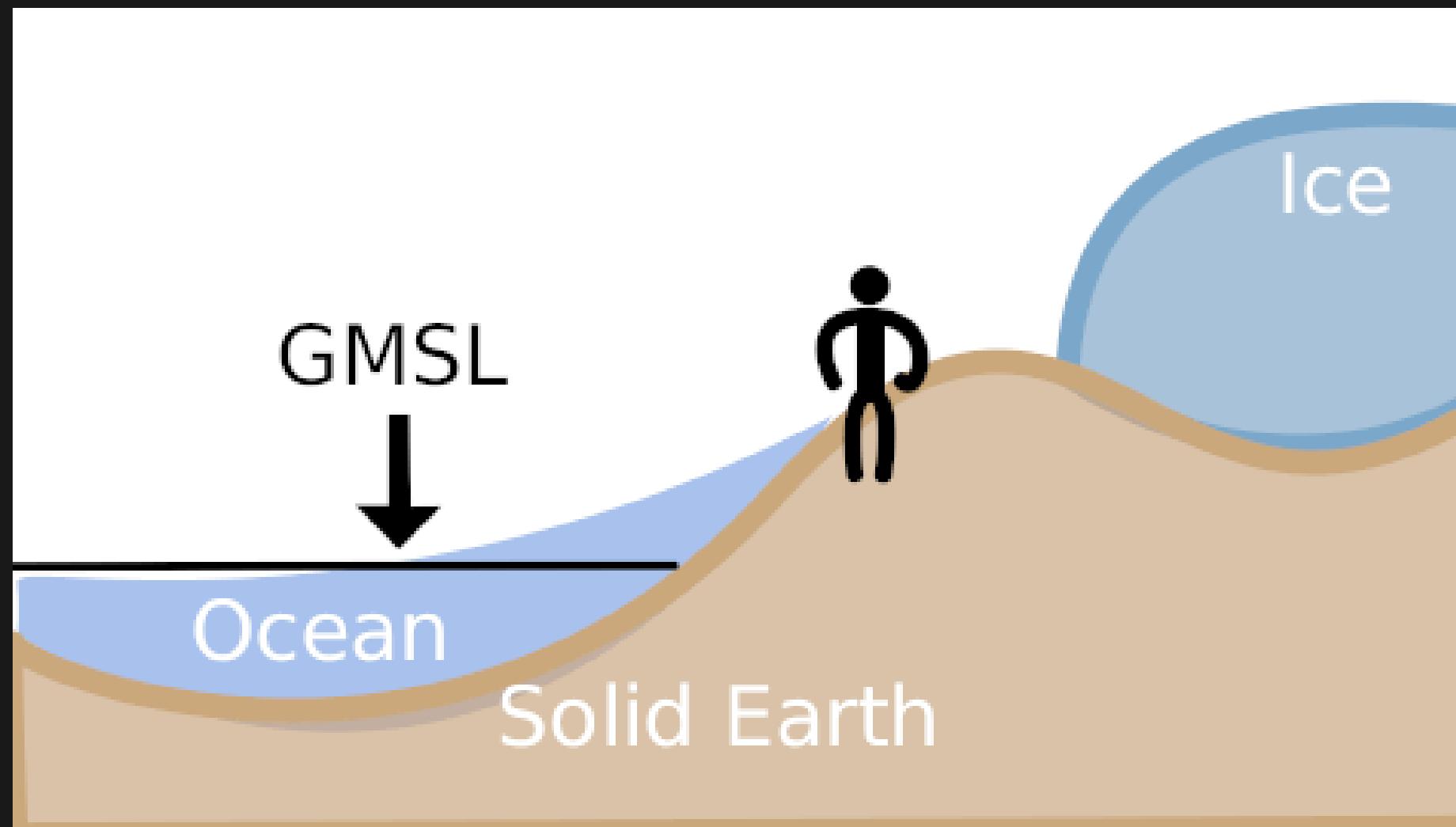
- Theory goes back to 1888
(Woodward)

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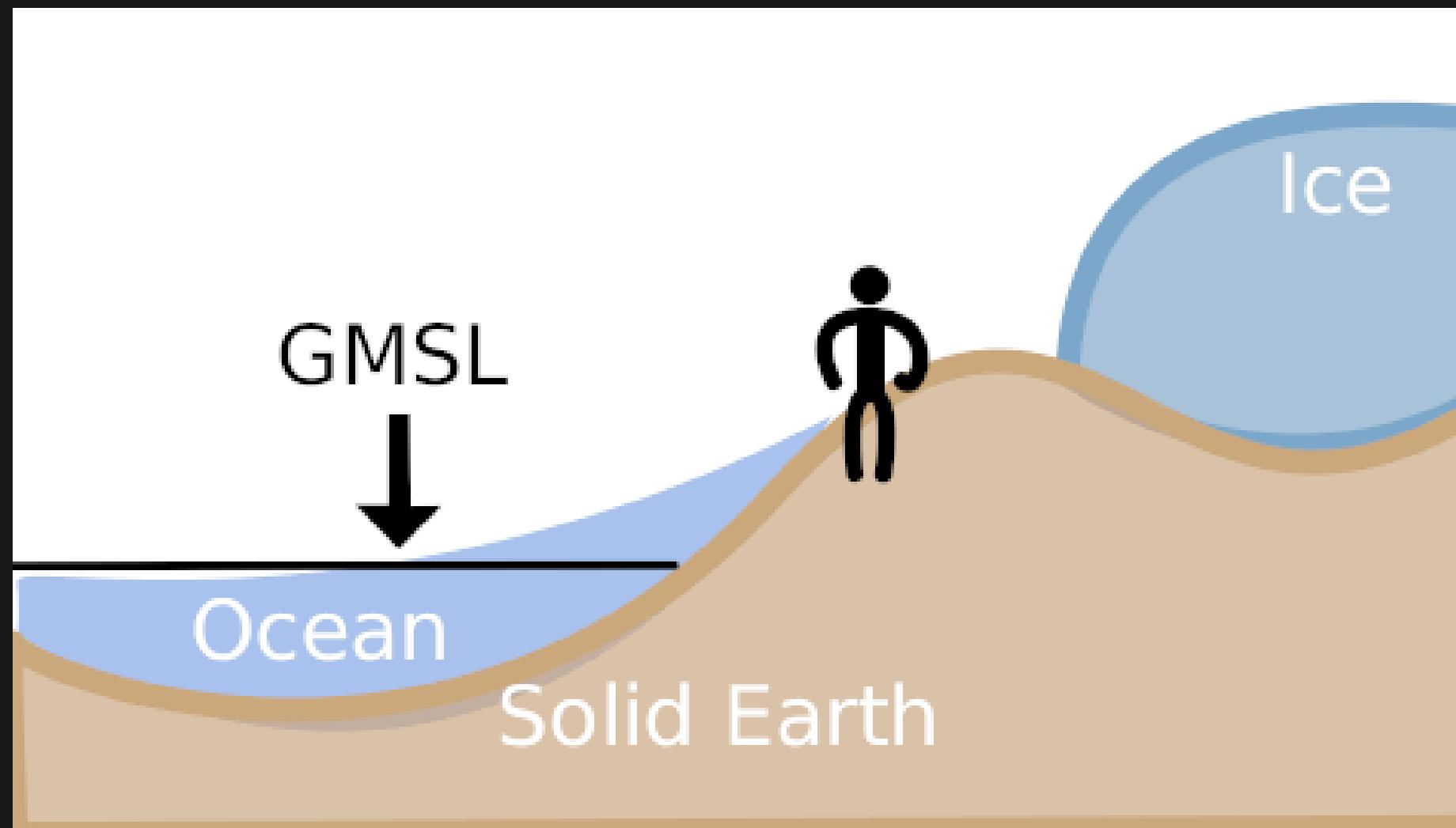
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- Modelled as a passive ocean response (no currents)

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



- Theory goes back to 1888 (Woodward)
- Modelled as a passive ocean response (no currents)
- mass conserving

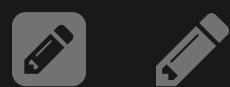
Relative sea level is affected by self attraction and loading (SAL)..



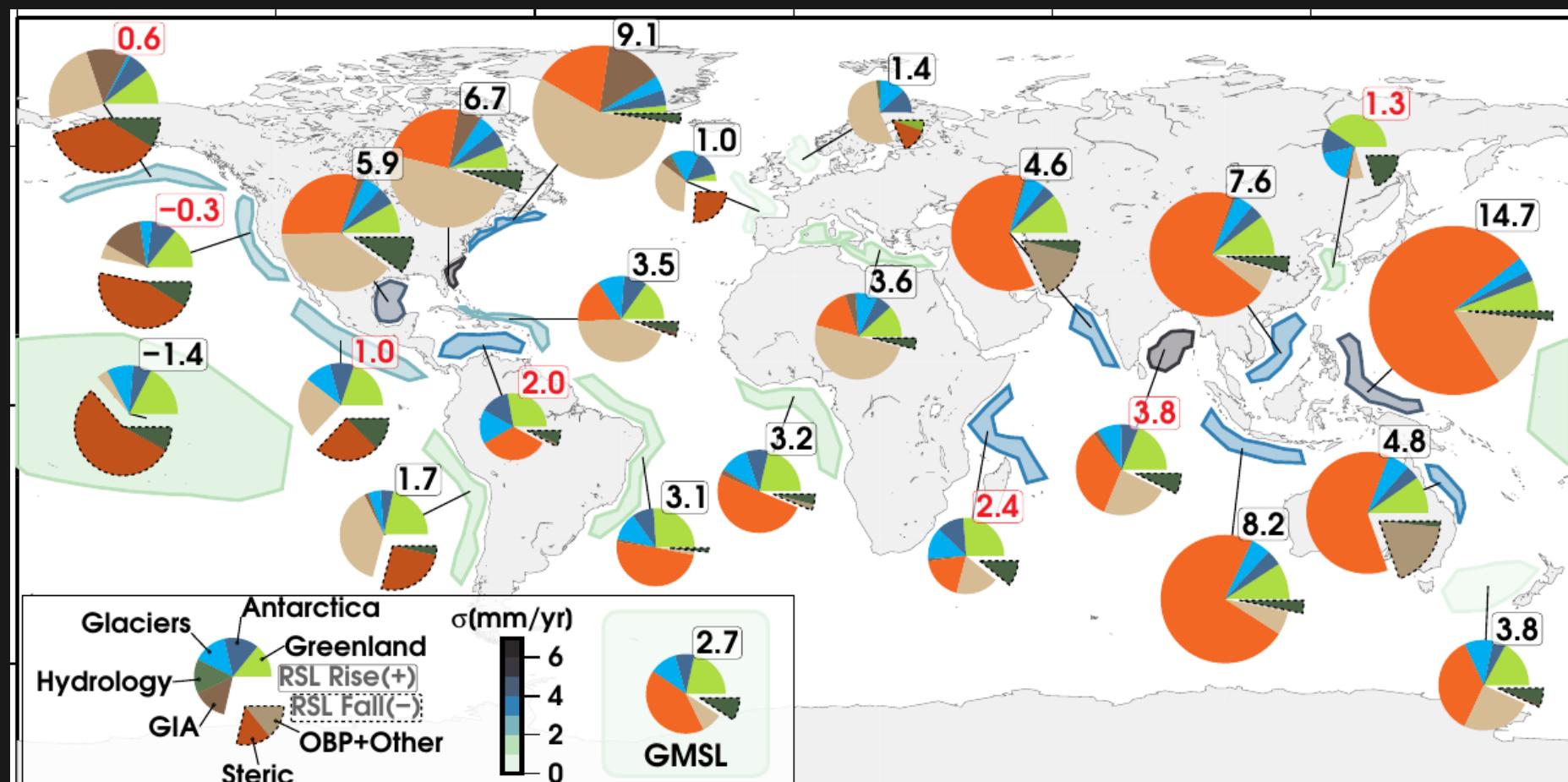
- Theory goes back to 1888 (Woodward)
- Modelled as a passive ocean response (no currents)
- mass conserving
- Takes into account the deformation of the Earth

Other factors affecting relative sea level?

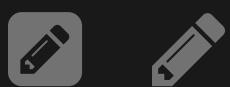
The image shows a Wooclap poll interface. On the left, there's a blue background with a person's hands raised, and text asking "Want to join an event?". It includes a URL "www.wooclap.com/" and a text input field for an "Event code". A "Join" button is visible. In the center, the Wooclap logo is displayed. Below it, there's a "Choose a method to log in" section with a "or sign up" link. On the right, a white callout box contains three options: "Accept all", "Reject All", and "Customise".



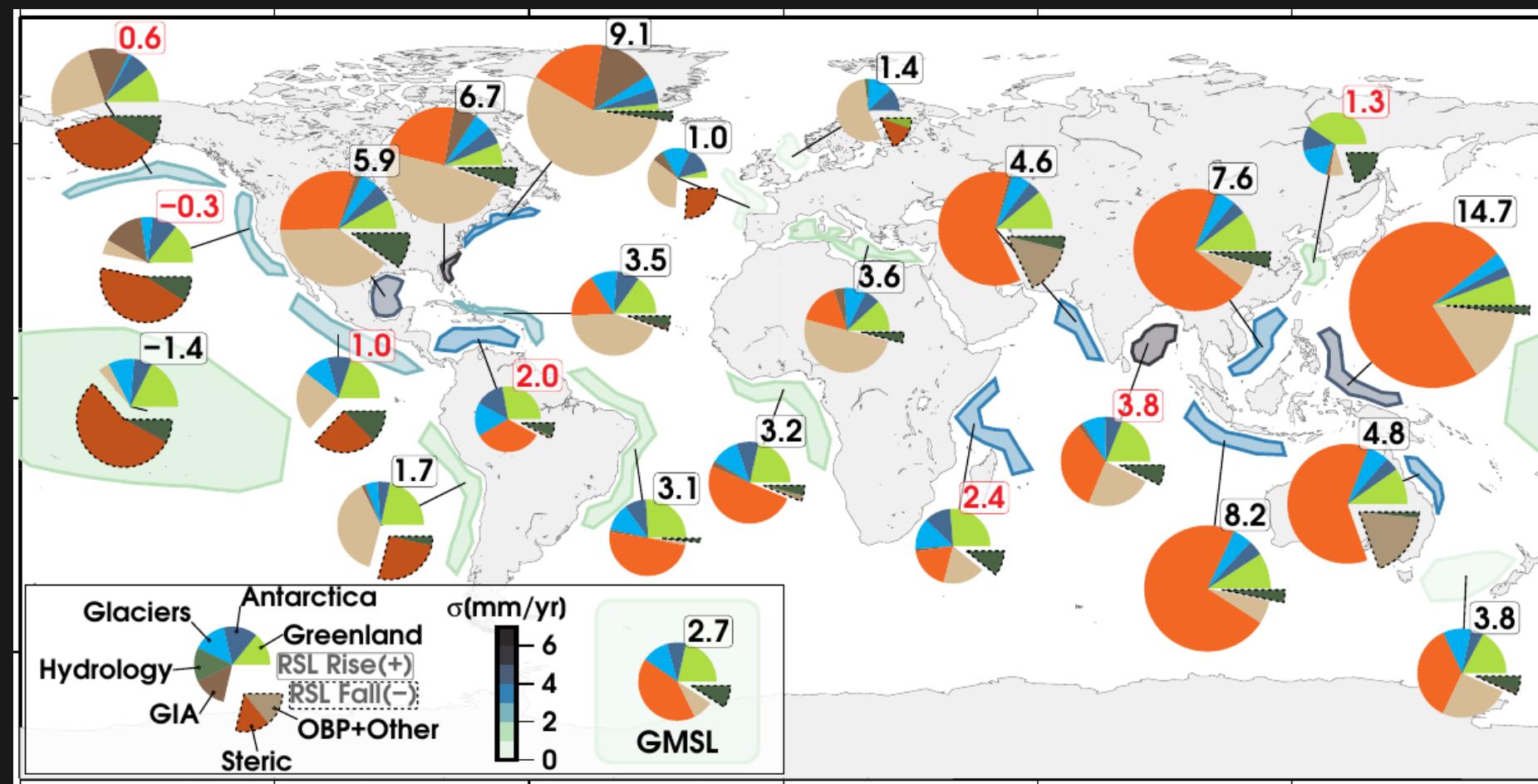
Regional sea level budgets



Regional sea level budgets from Rietbroek et al. 2016

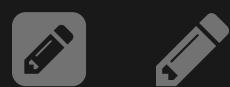


Regional sea level budgets

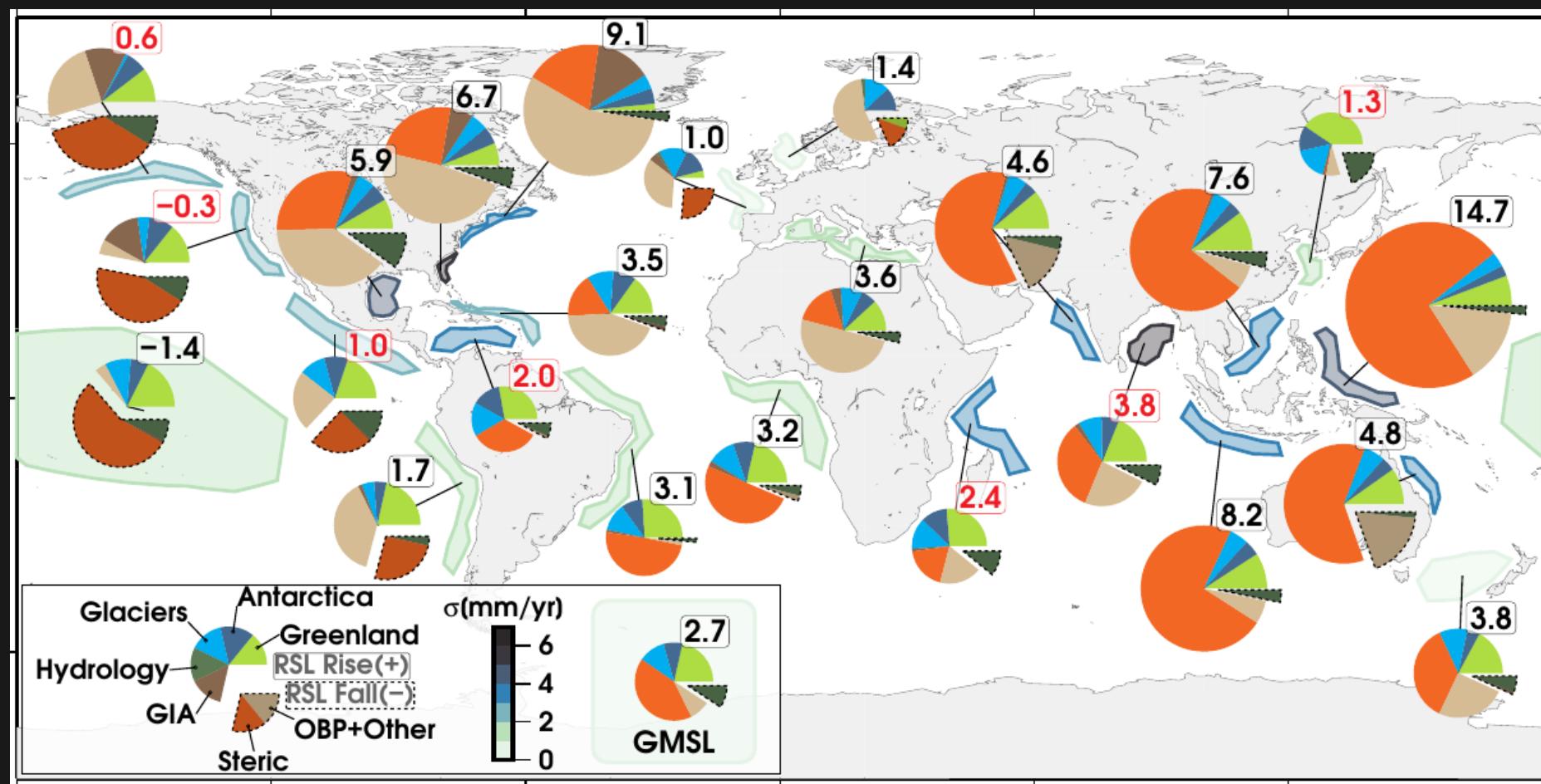


Regional sea level budgets from Rietbroek et al. 2016

- Sea level rise is not uniform

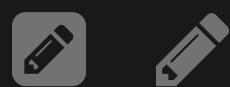


Regional sea level budgets

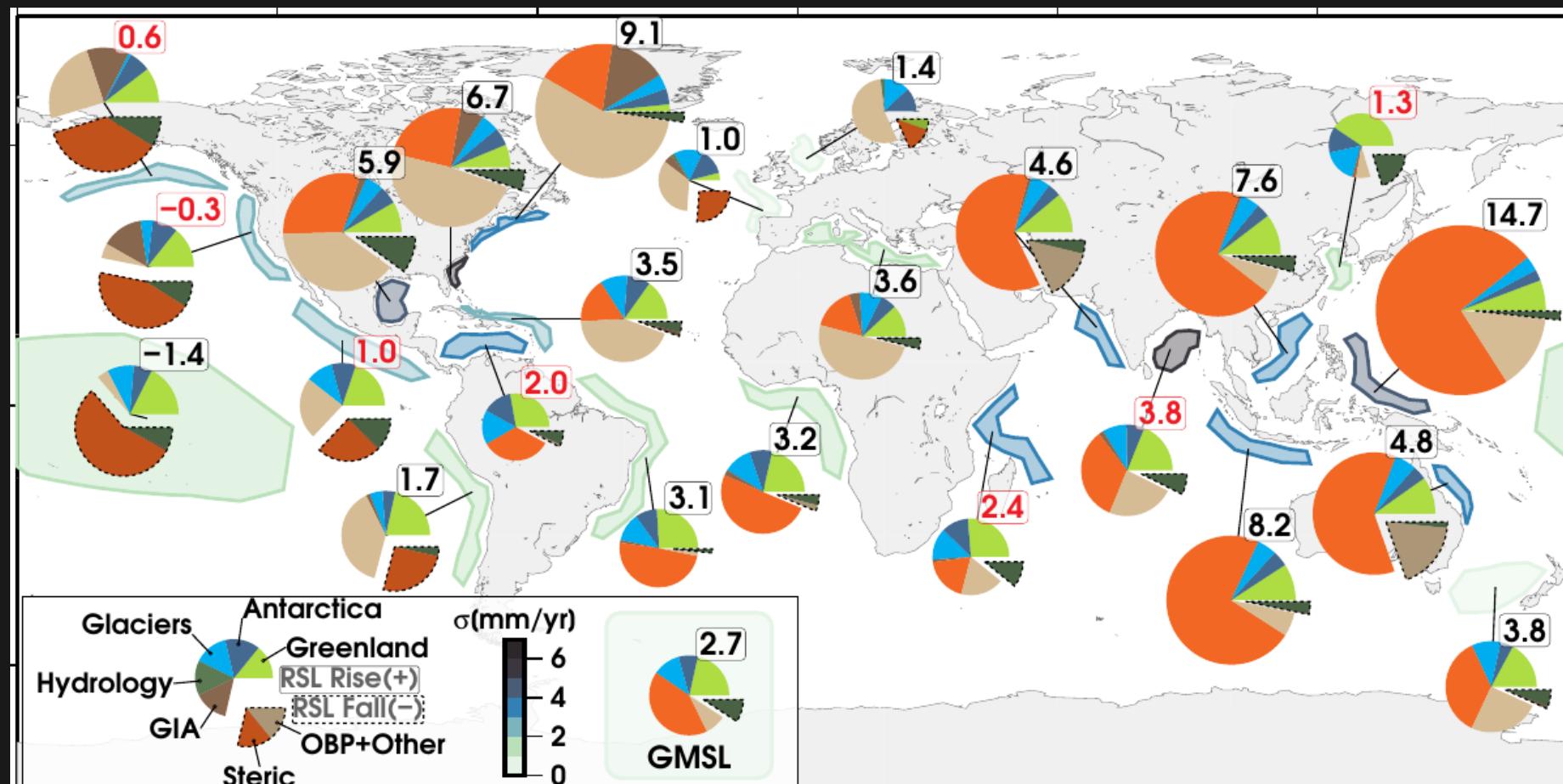


Regional sea level budgets from Rietbroek et al. 2016

- Sea level rise is not uniform
- SAL effects



Regional sea level budgets



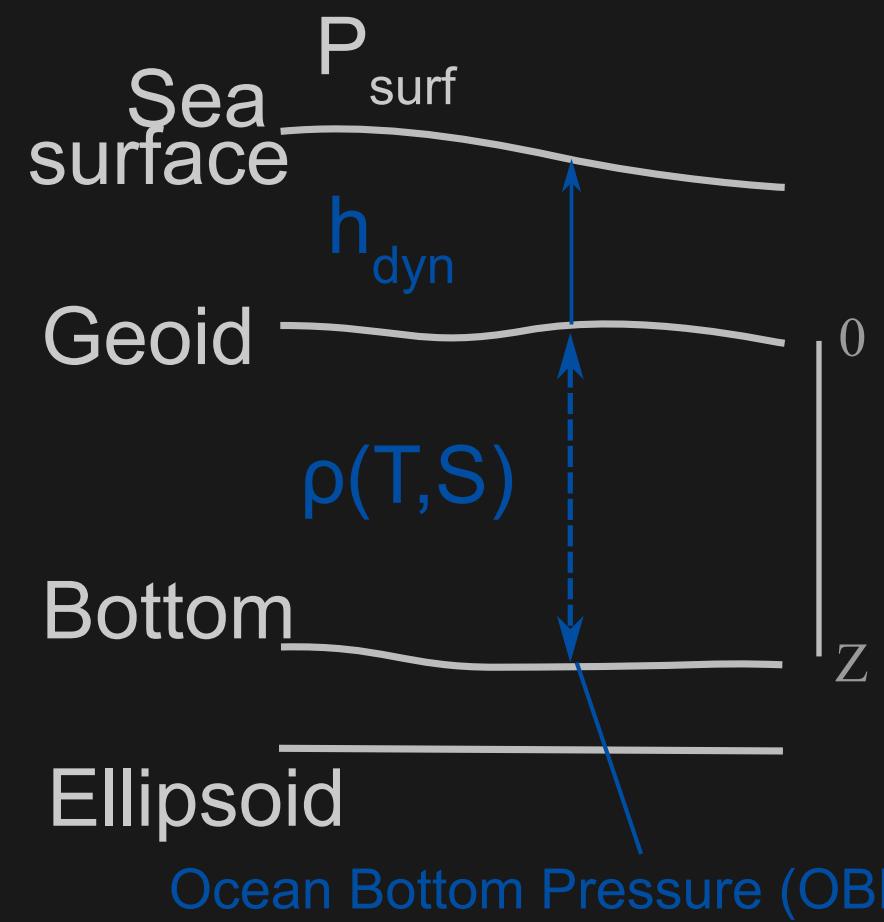
Regional sea level budgets from Rietbroek et al. 2016

- 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)

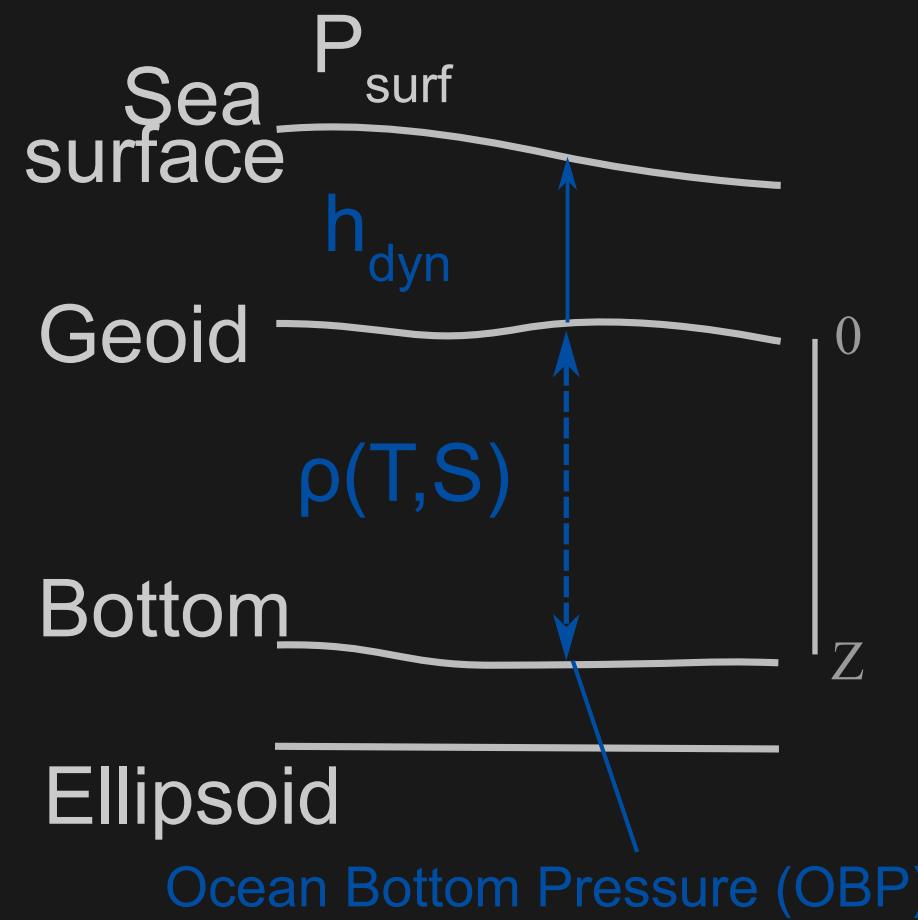


Integrating the water column to obtain ocean bottom pressure

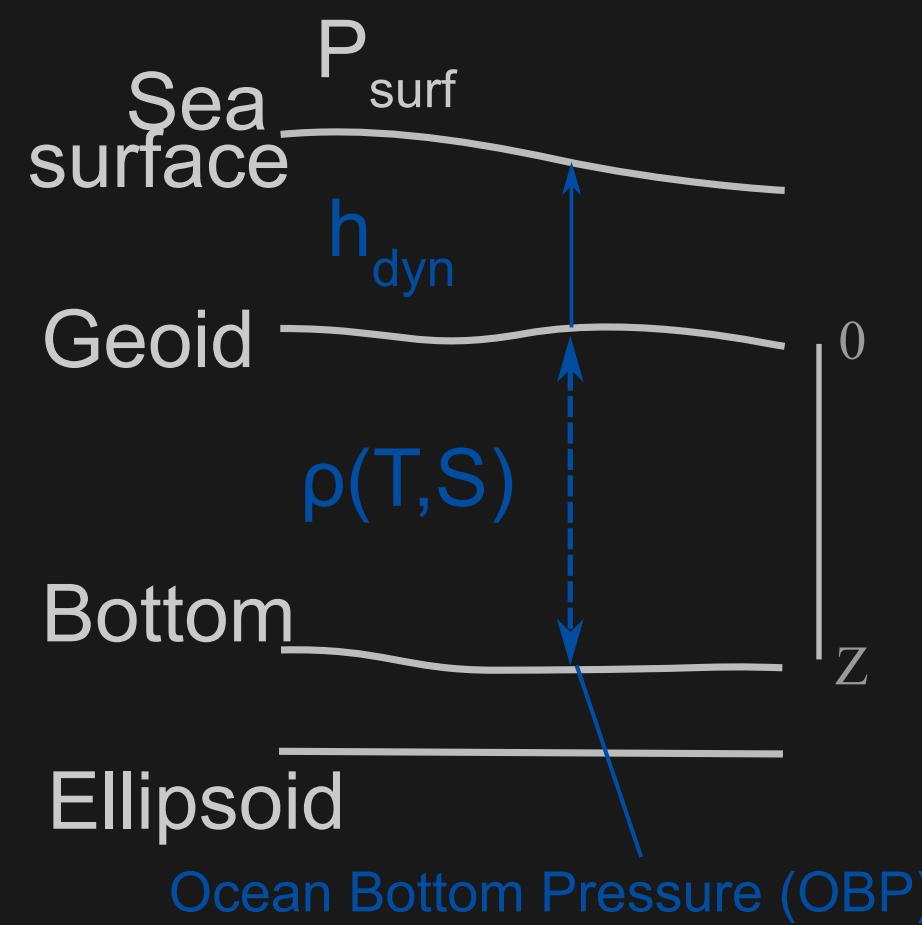


Integrating the water column to obtain ocean bottom pressure

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



Integrating the water column to obtain ocean bottom pressure

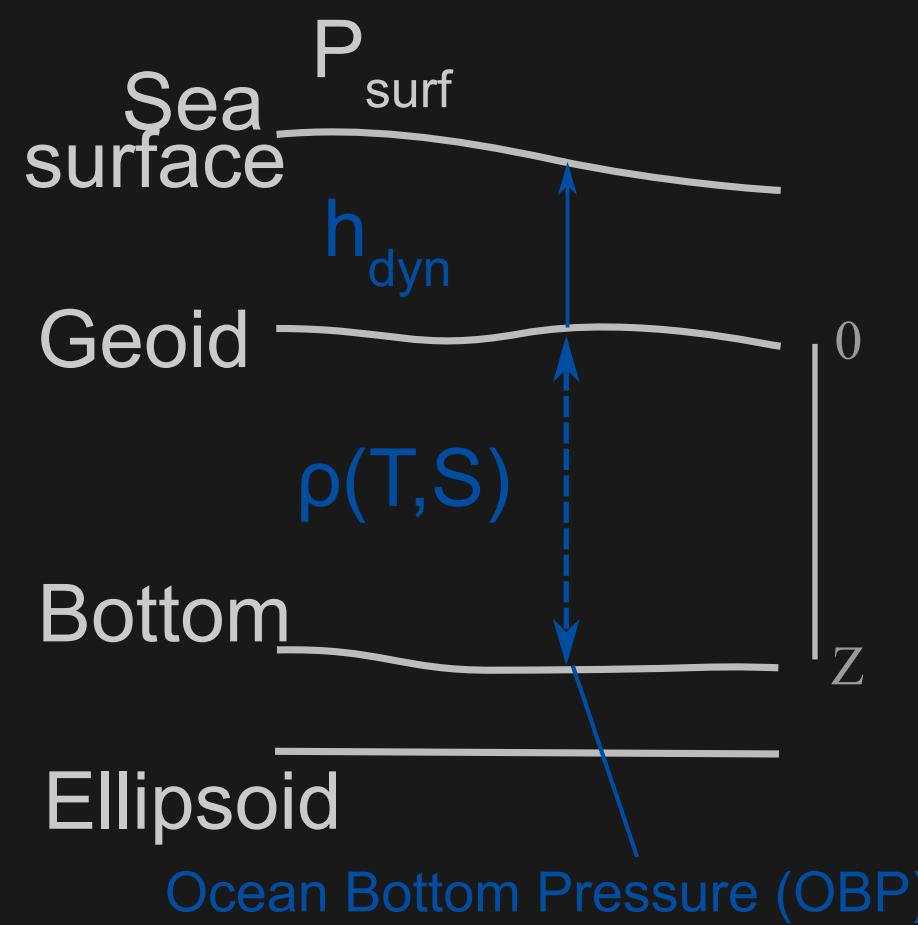


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Steric **change** only (no OBP change):

$$0 = g \int_{-Z}^0 \delta\rho(z, T, S) dz + g\rho_{sea} \delta h_{ster}$$

Integrating the water column to obtain ocean bottom pressure



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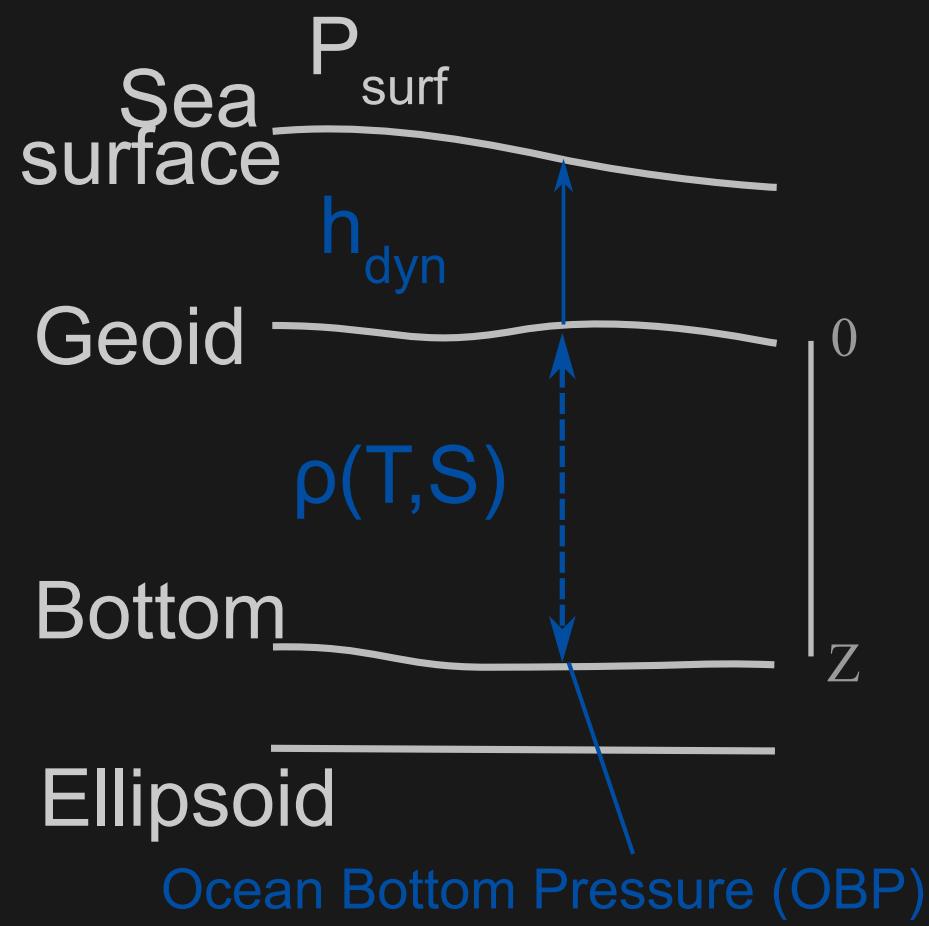
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Results in:

$$\delta h_{ster} = -\frac{1}{\rho_{sea}} \int_{-Z}^0 \delta\rho(z, T, S) dz$$

Integrating the water column to obtain ocean bottom pressure



$$P_{OBP} = P_{surf} + g$$

$$\int_{-Z}^0 \rho(z, T, S) dz$$

$$+ g\rho_{sea} h_{dyn}$$

Steric **change** only (no OBP change):

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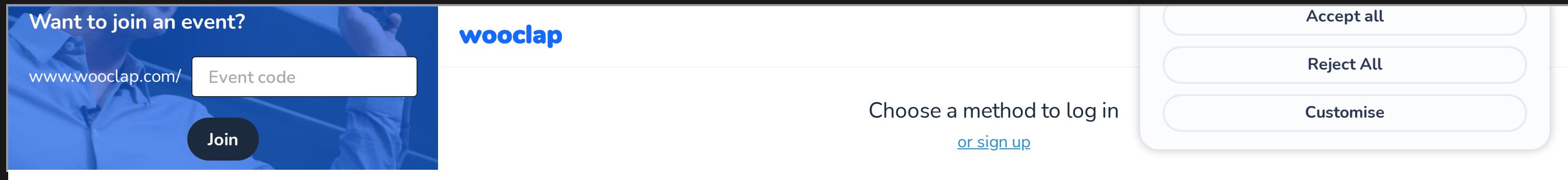
$$\int_{-Z}^0 \delta\rho(z, T, S) dz$$

- 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:



Quiz time! (again)



The image shows a Wooclap quiz interface on the left and a privacy pop-up on the right.

Wooclap Quiz Interface:

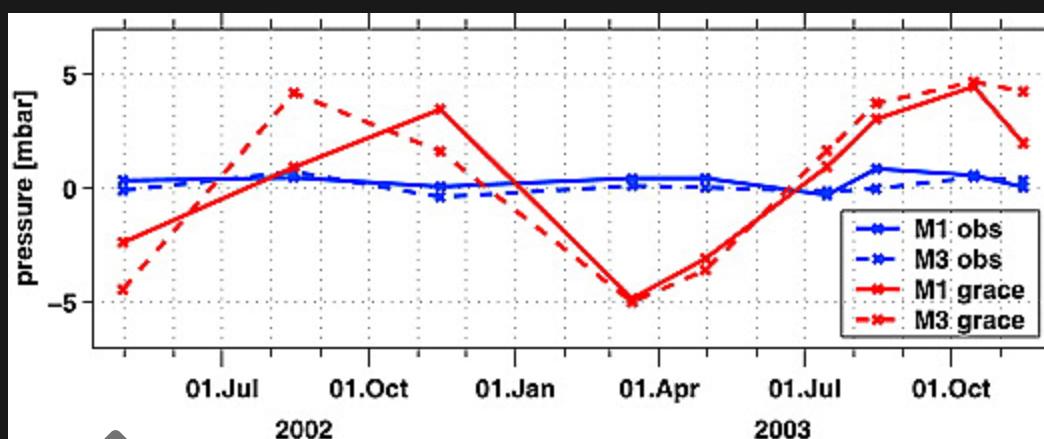
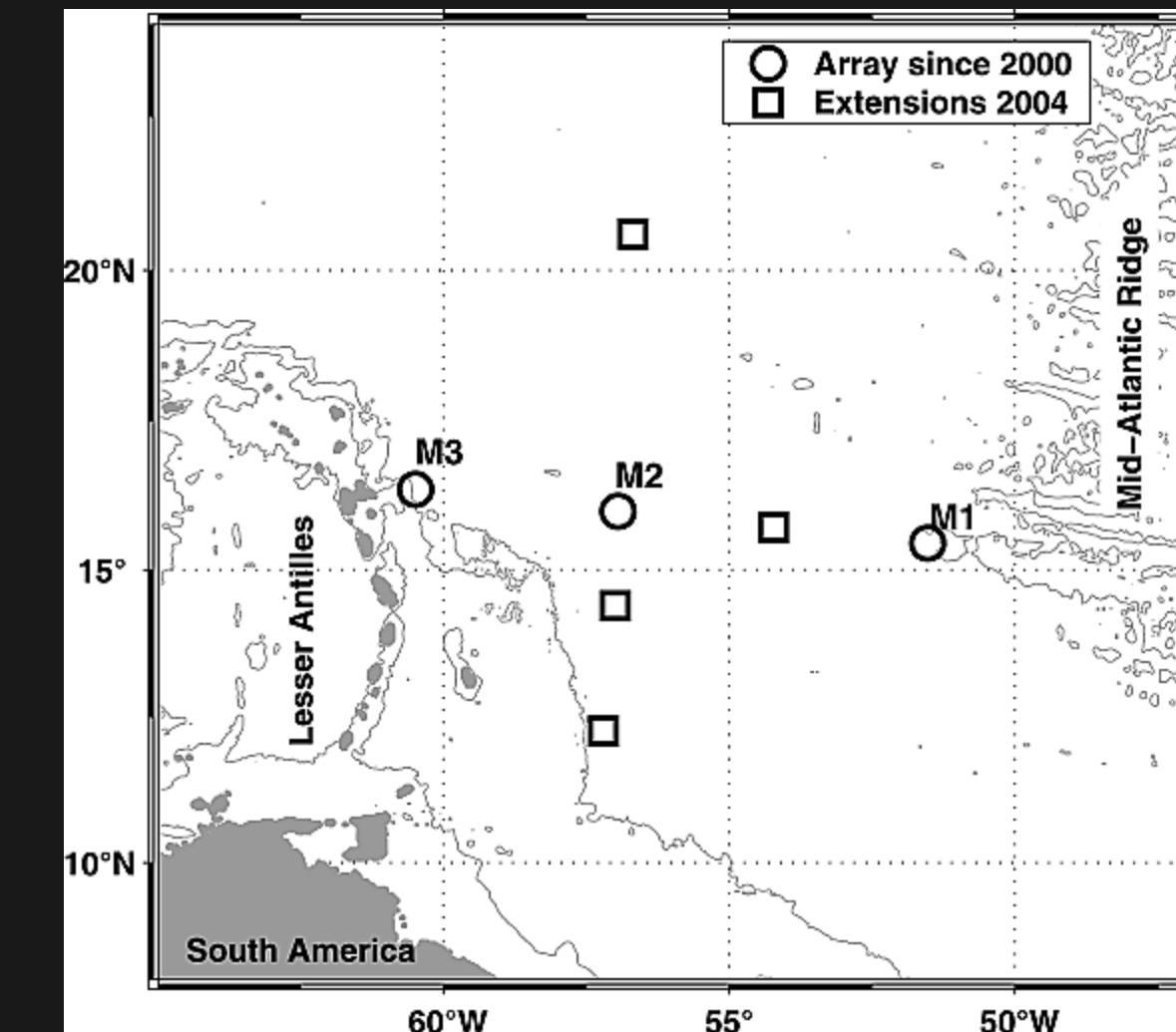
- Header: "Want to join an event?"
- Text input field: "www.wooclap.com/ [Event code]"
- Button: "Join"
- Wooclap logo: "wooclap"

Privacy Pop-up:

- Header: "Choose a method to log in or sign up"
- Buttons:
 - Accept all
 - Reject All
 - Customise

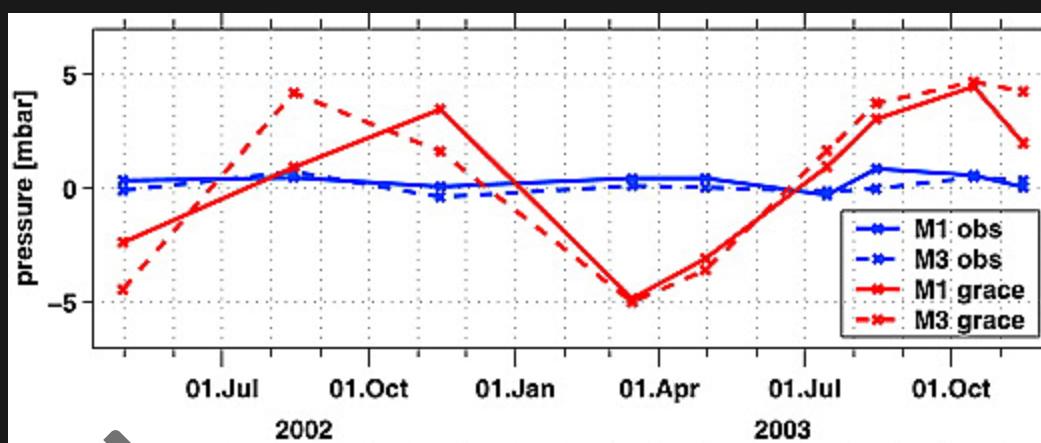
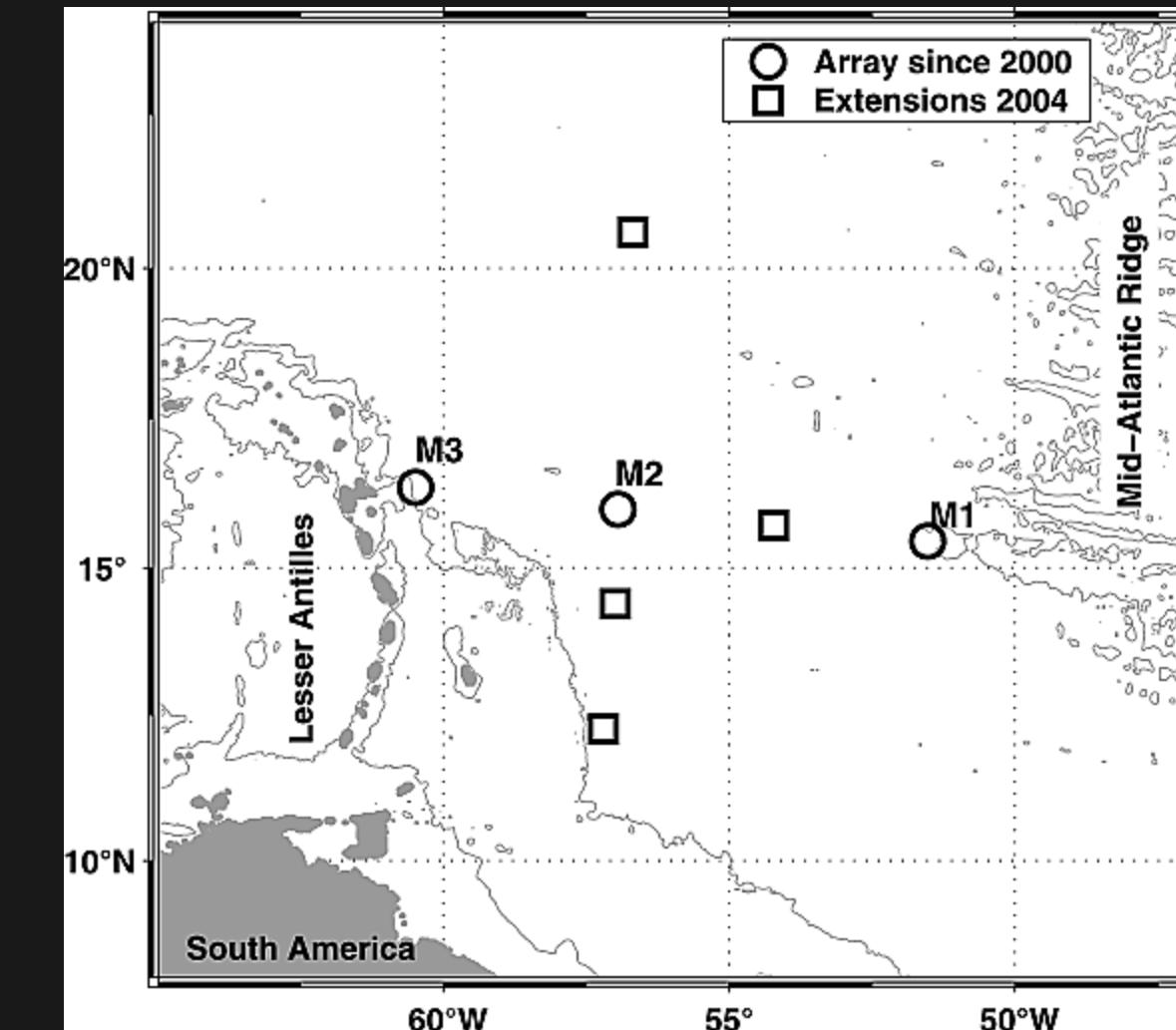


Early GRACE validation of ocean bottom pressure changes (Kanzow et al. 2005)



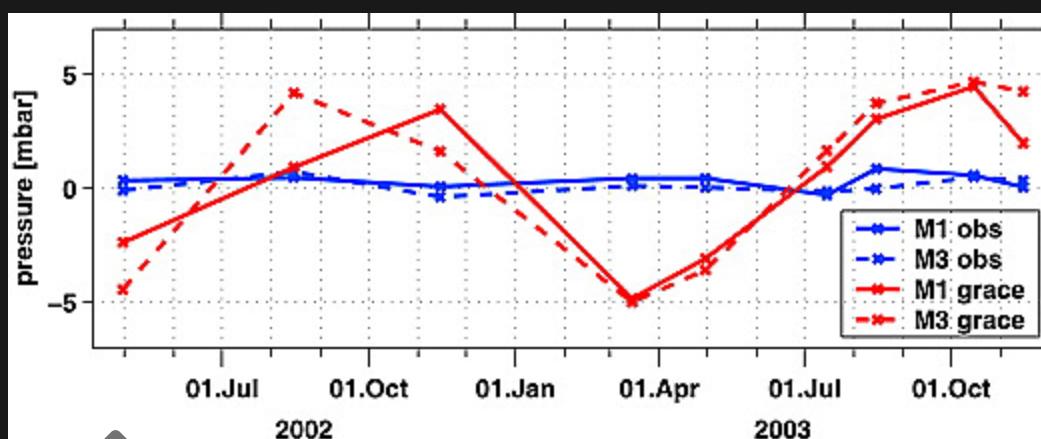
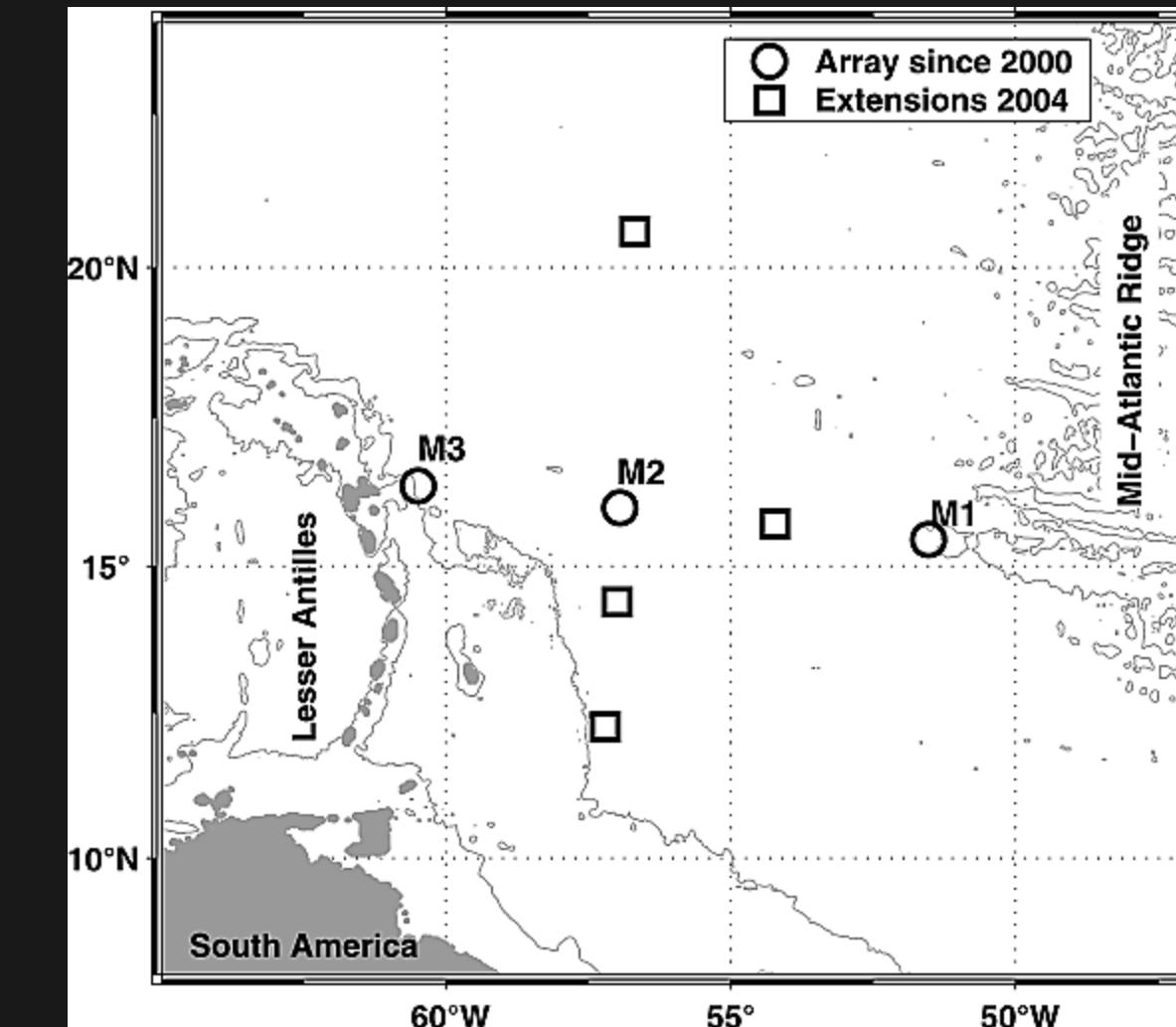
Early GRACE validation of ocean bottom pressure changes (Kanzow et al. 2005)

- In situ validation with pressure sensors



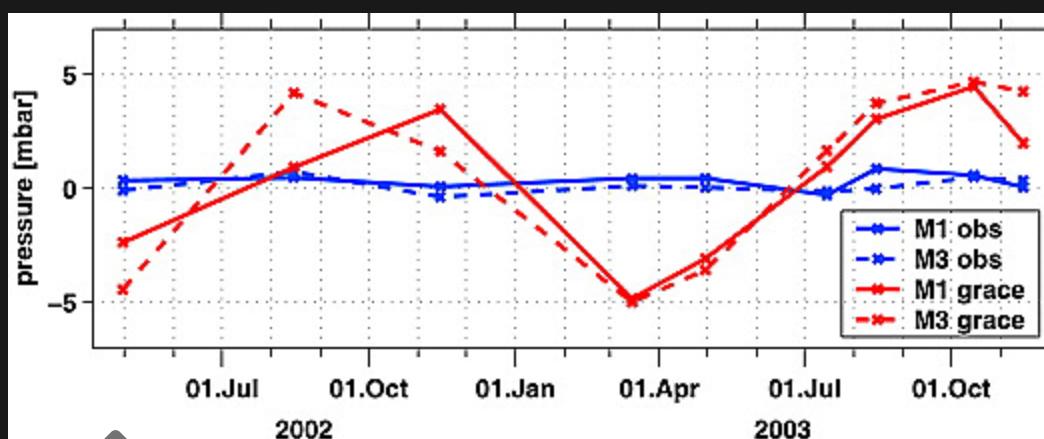
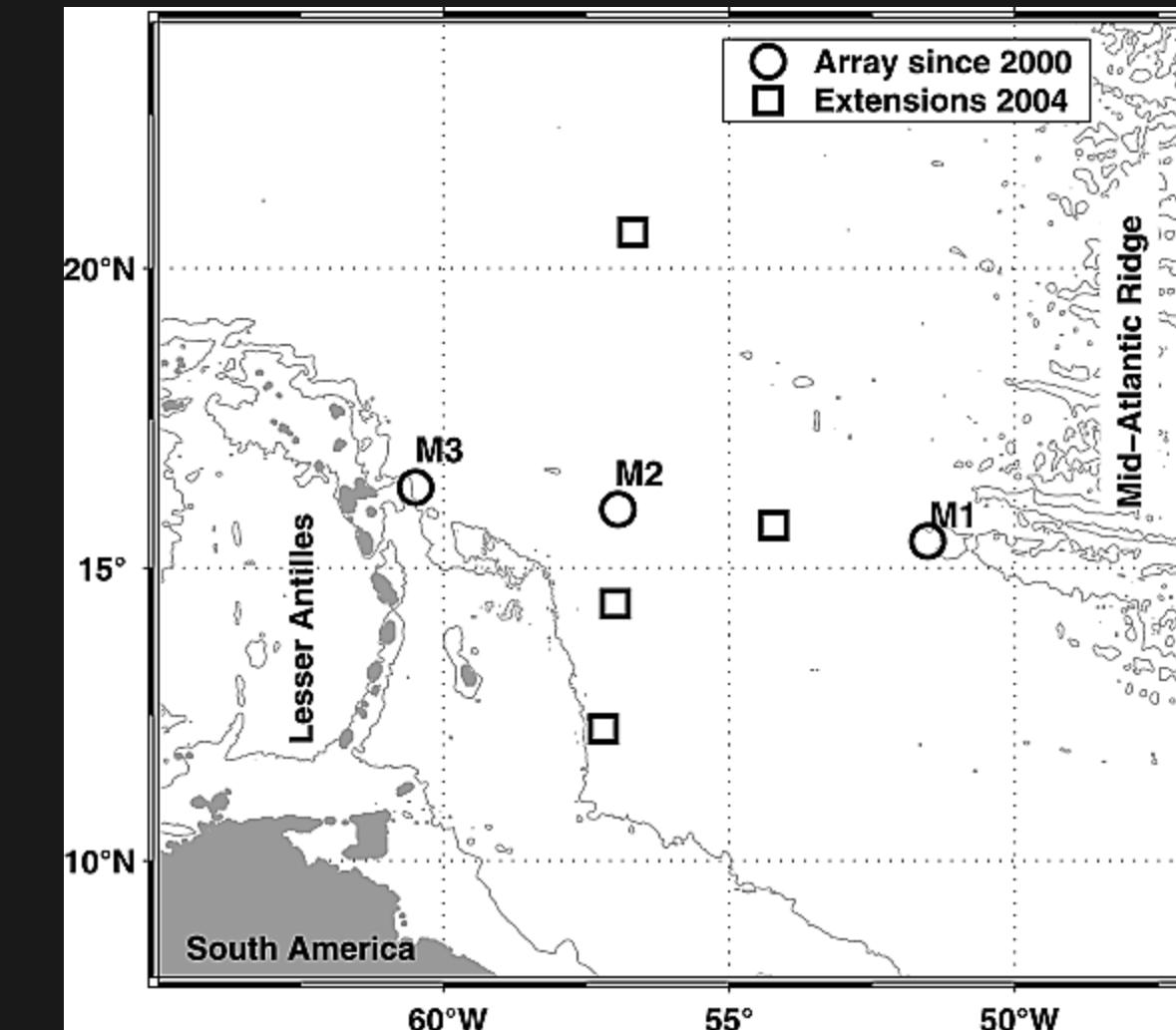
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- In situ validation with pressure sensors
- GRACE fluctuations were too large



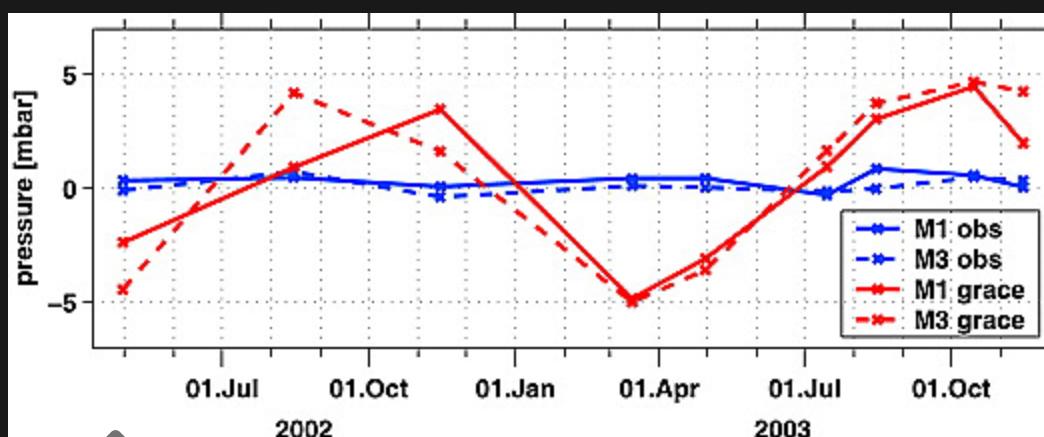
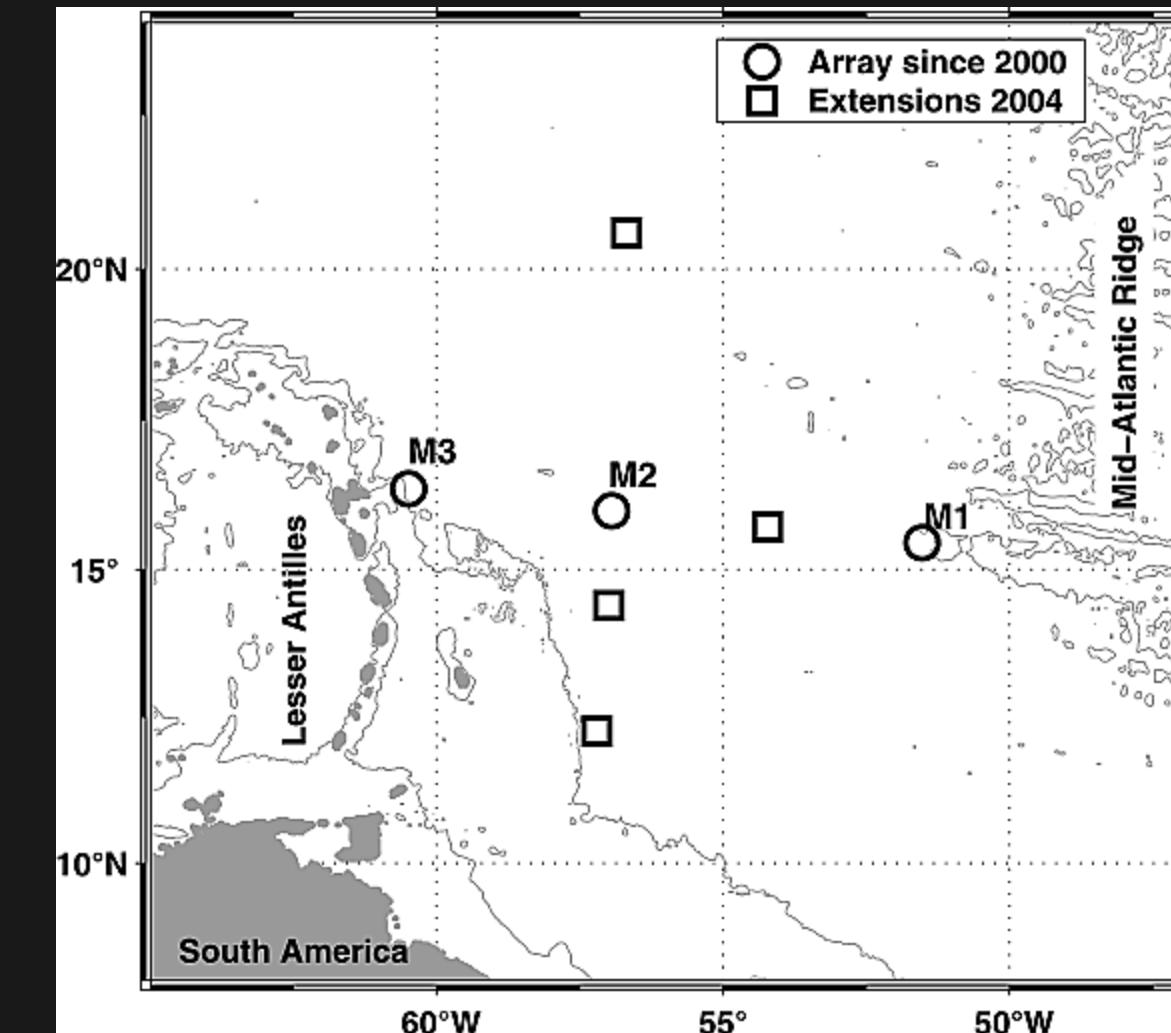
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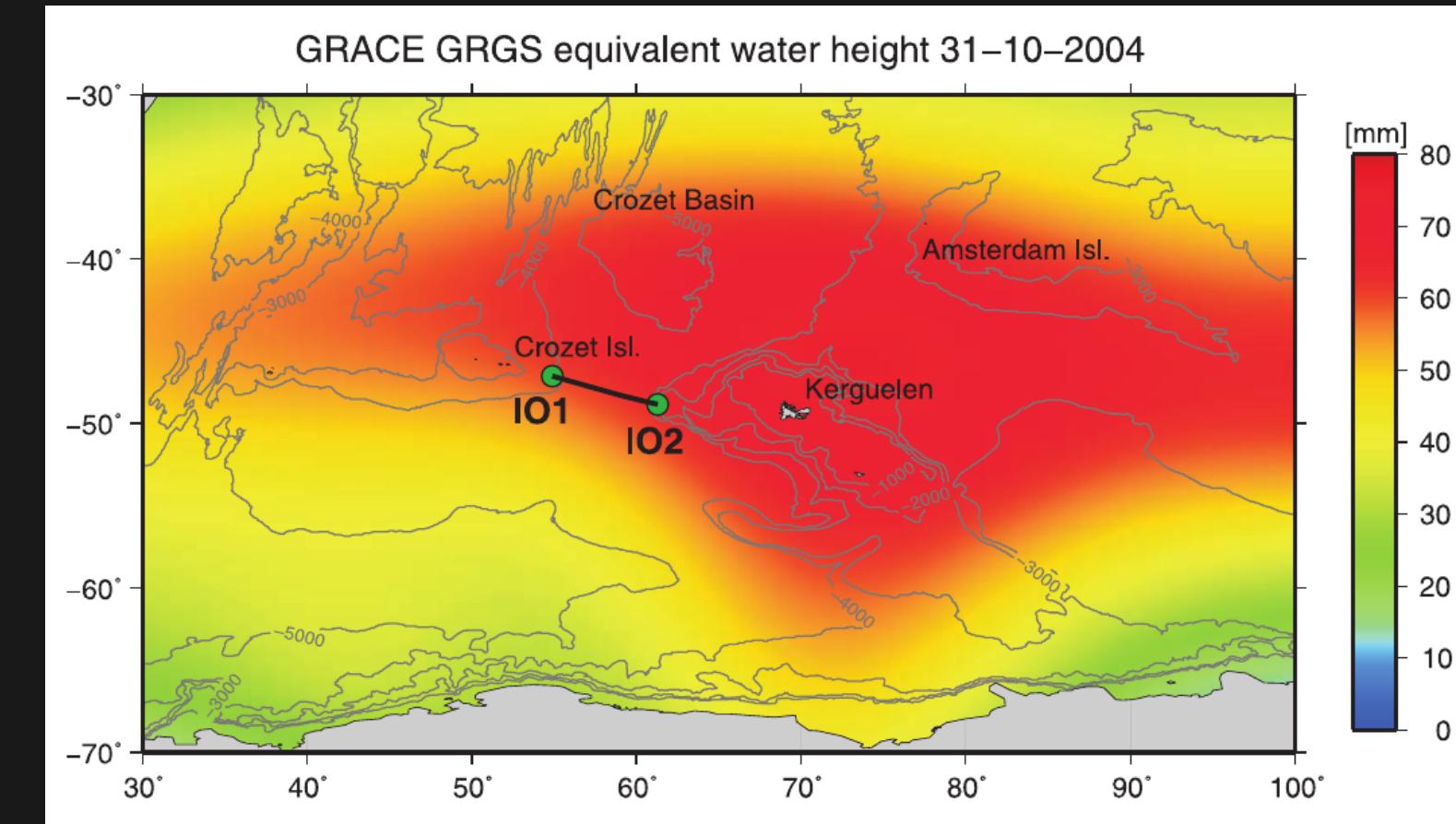
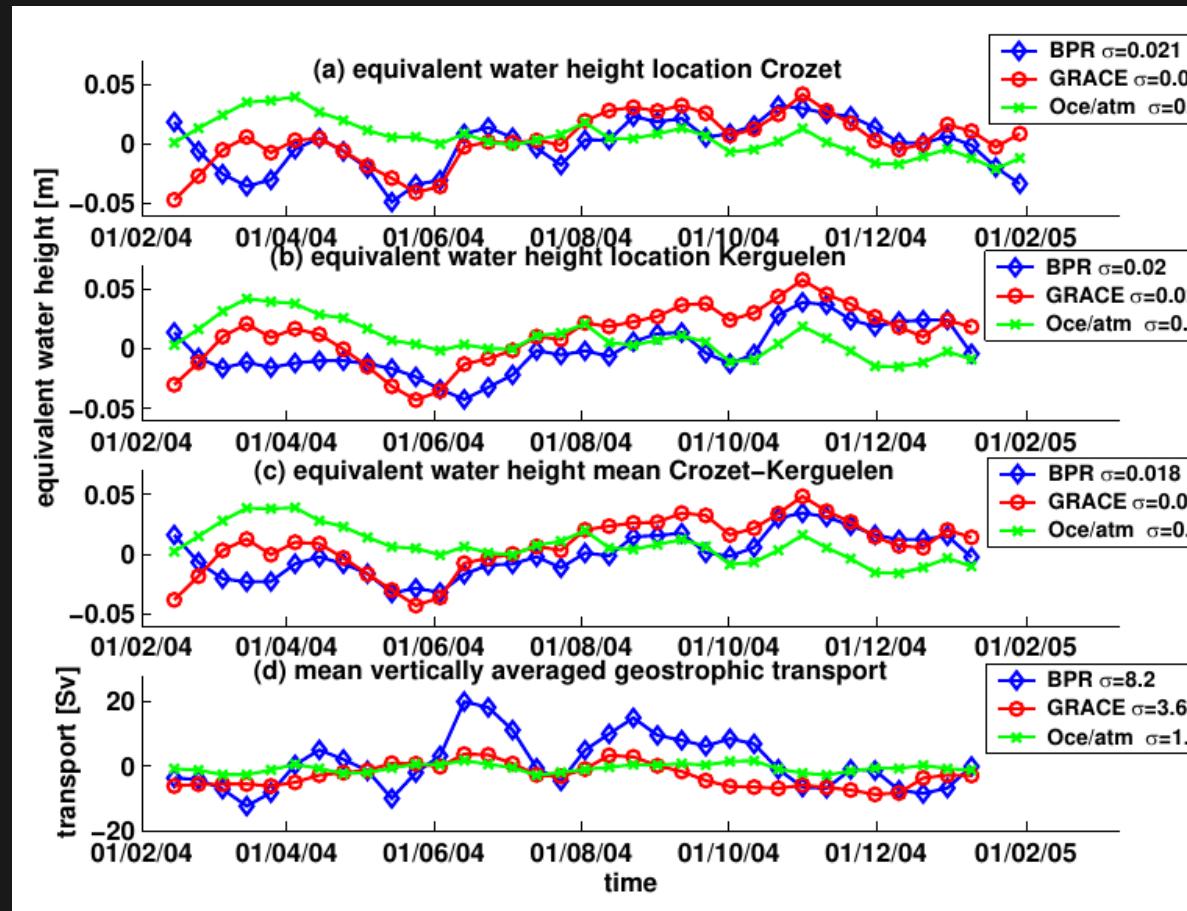


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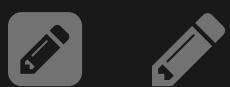
- In situ validation with pressure sensors
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 - Processing errors



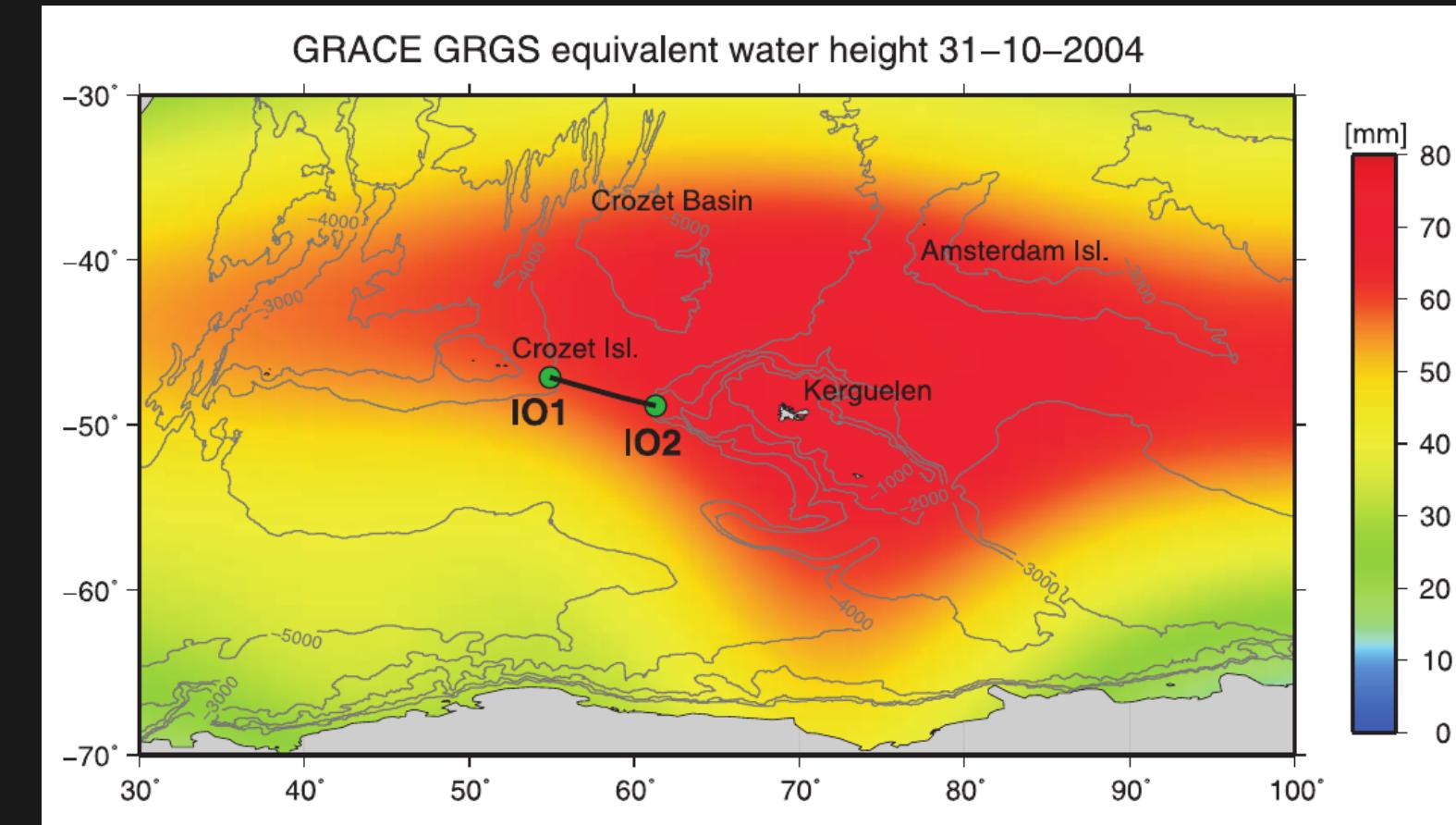
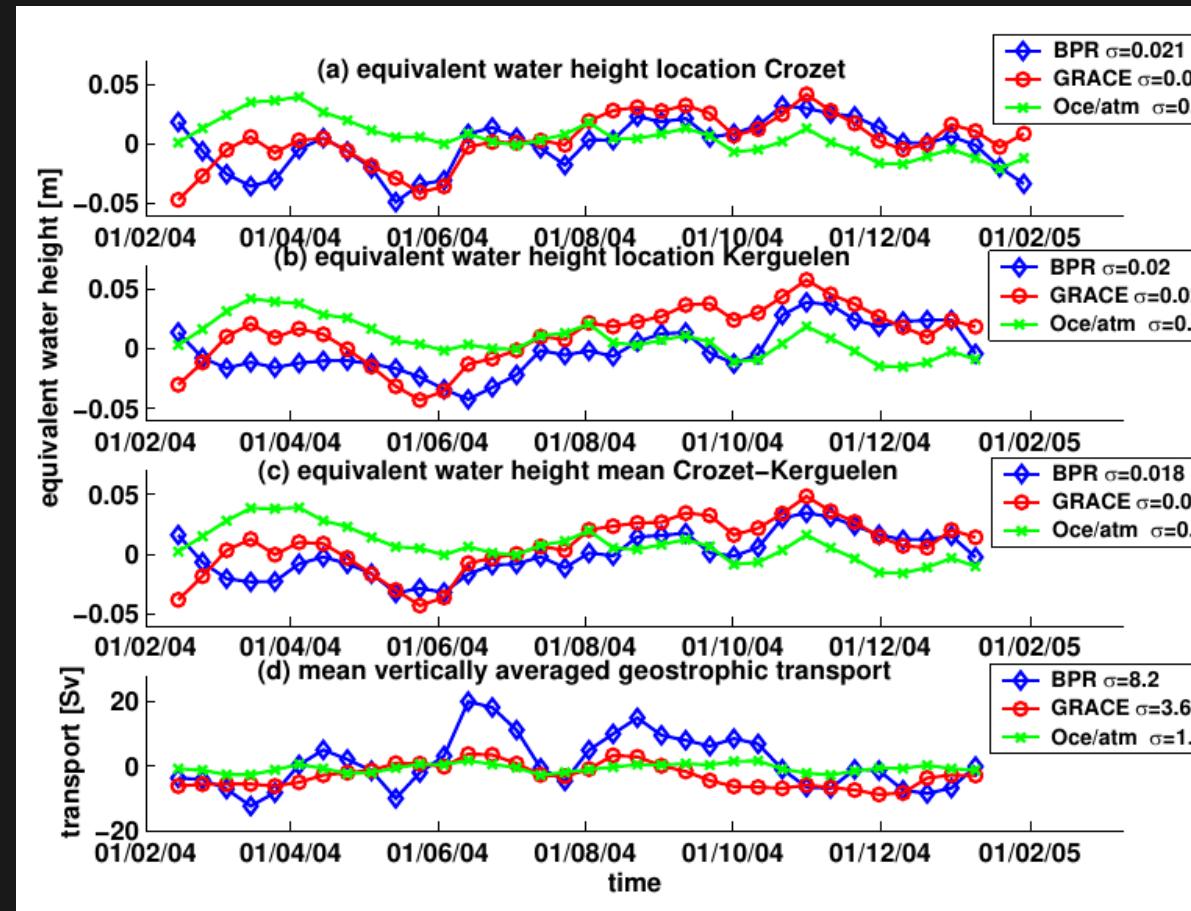
Validation in the Southern Ocean



From Rietbroek et al. 2016



Validation in the Southern Ocean

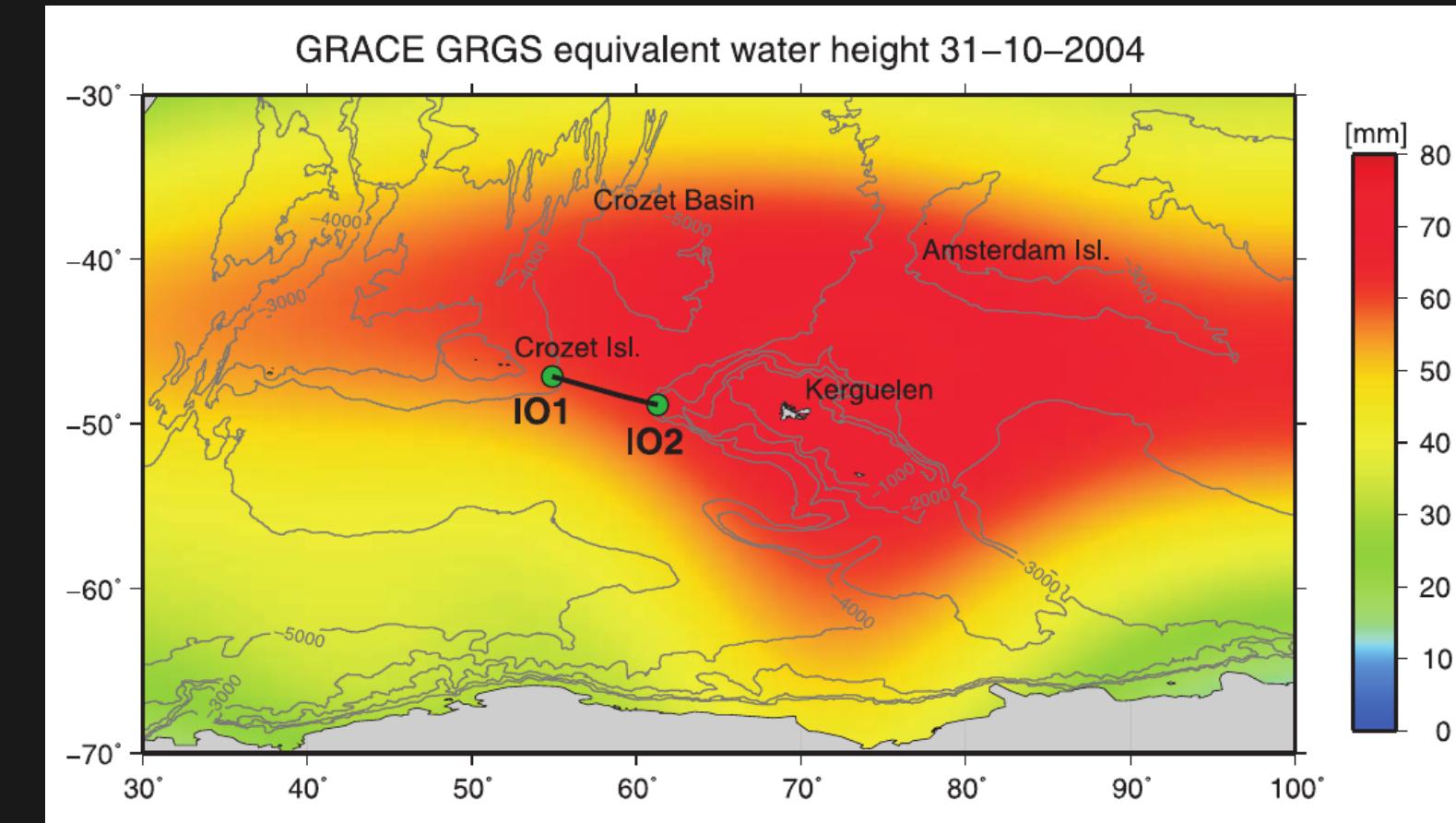
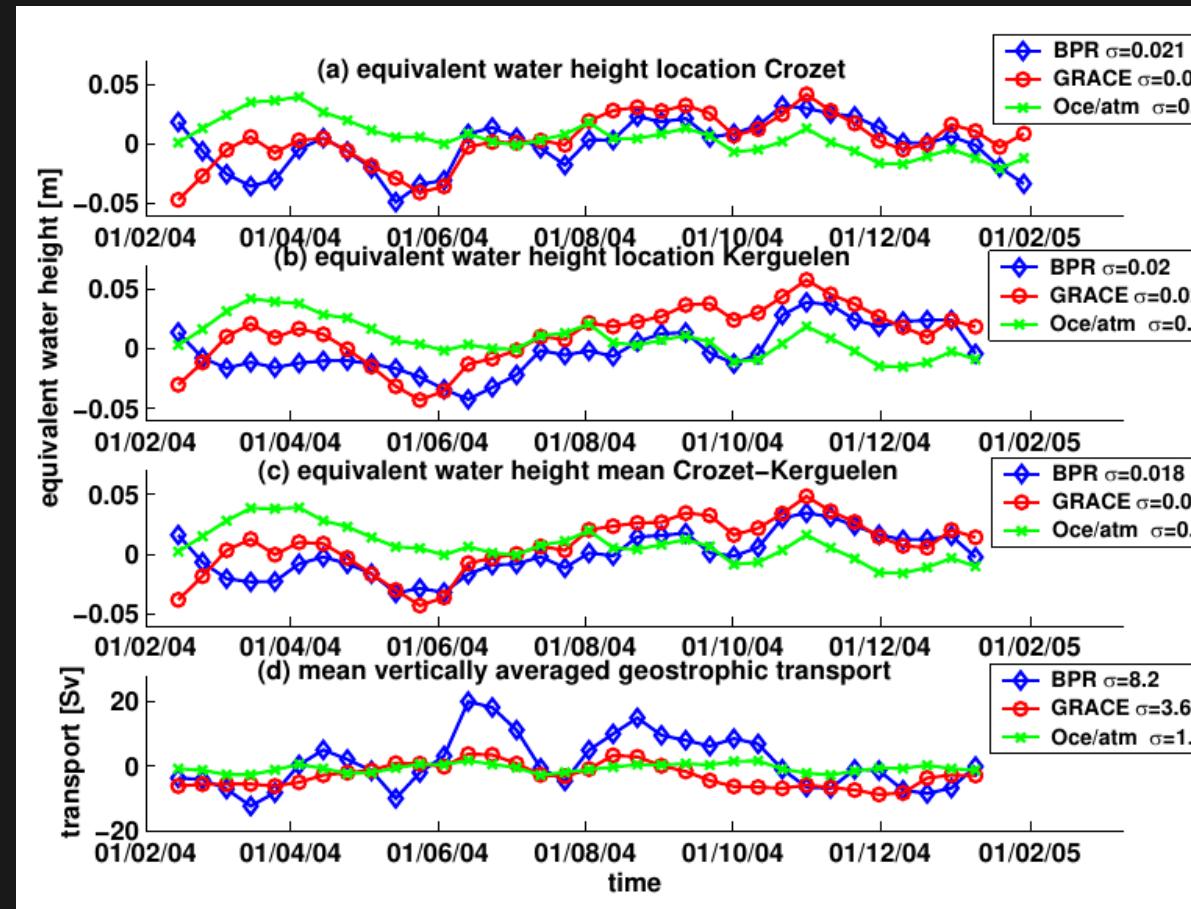


From Rietbroek et al. 2016

- In situ validation with pressure sensors



Validation in the Southern Ocean

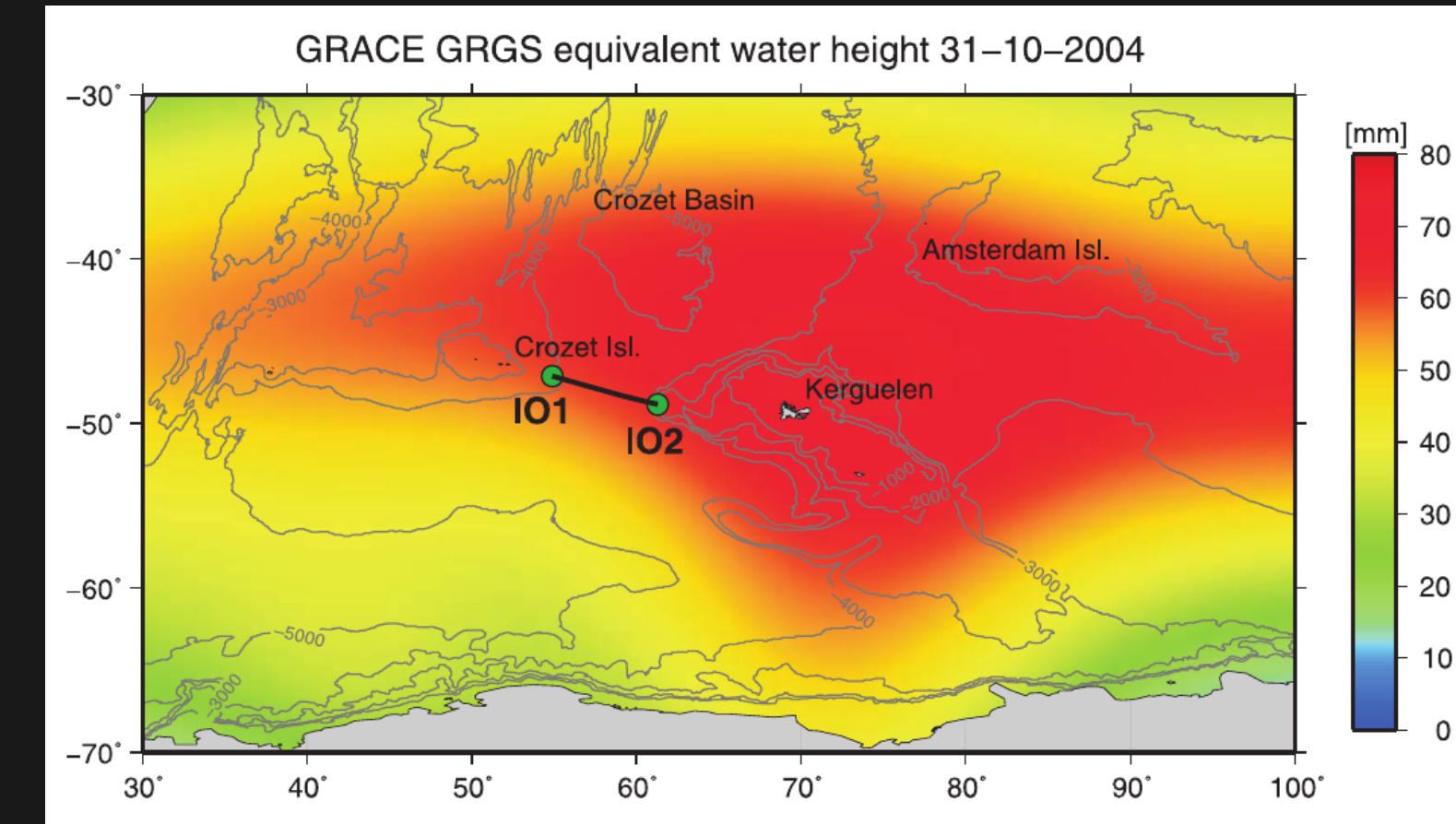
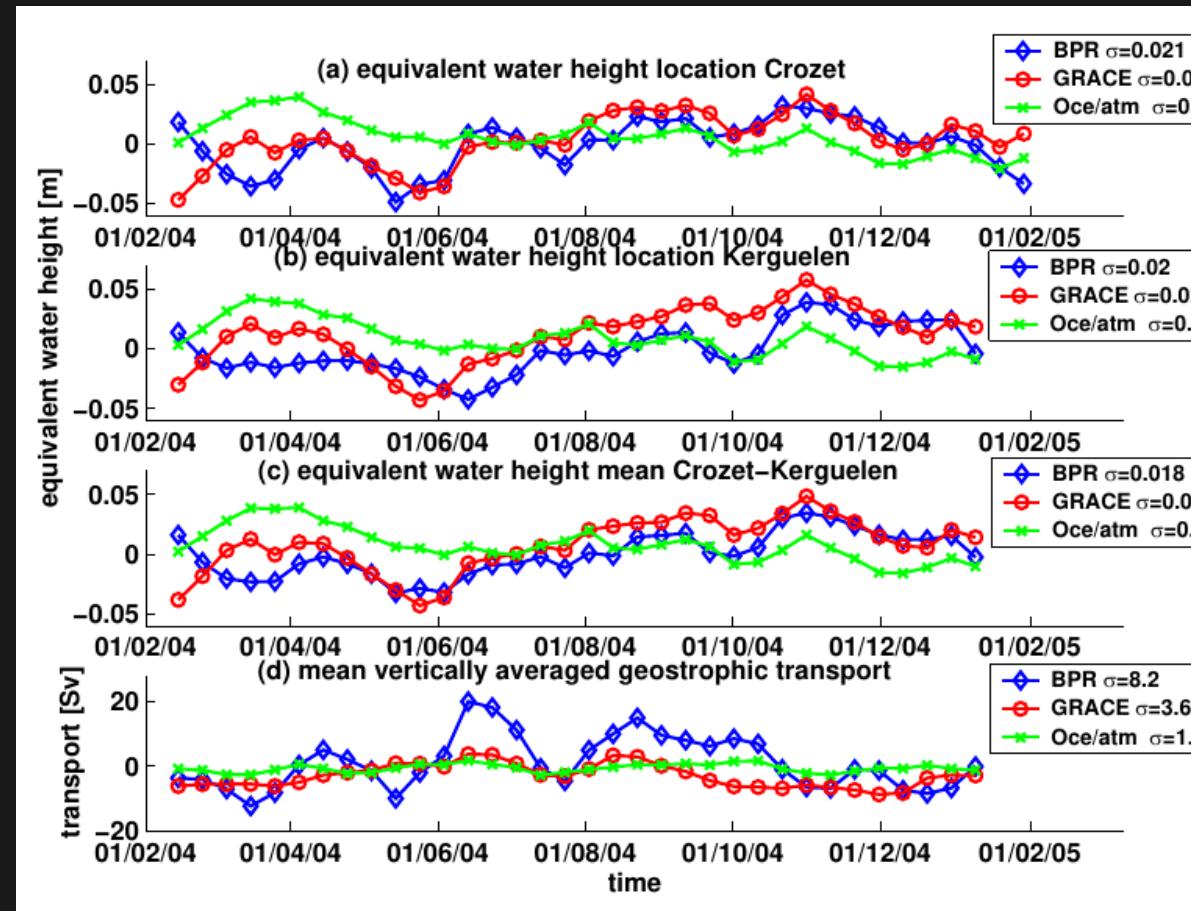


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- In situ validation with pressure sensors
- 10-day GRACE solution was better than background model

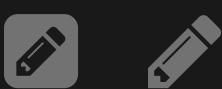


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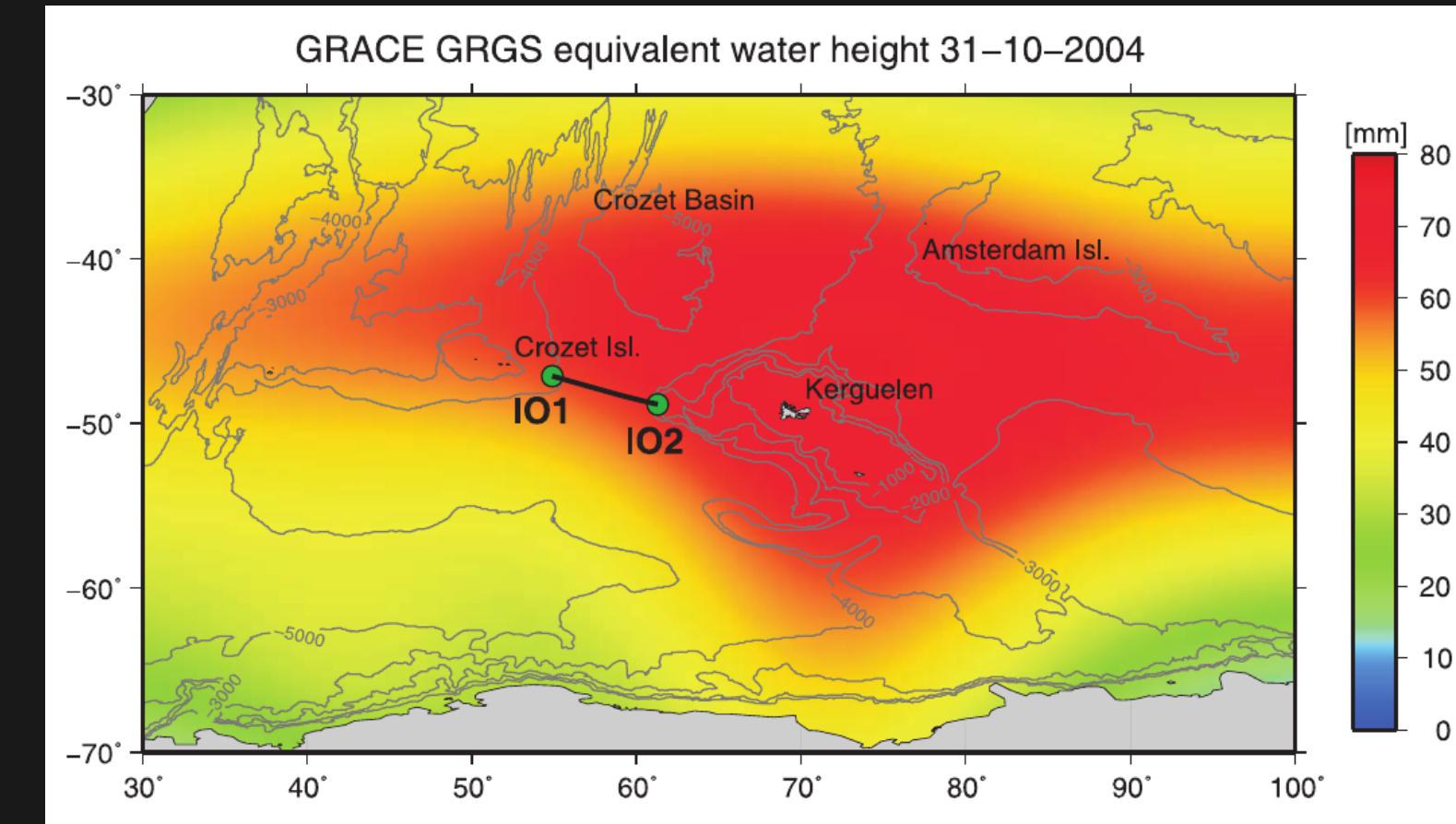
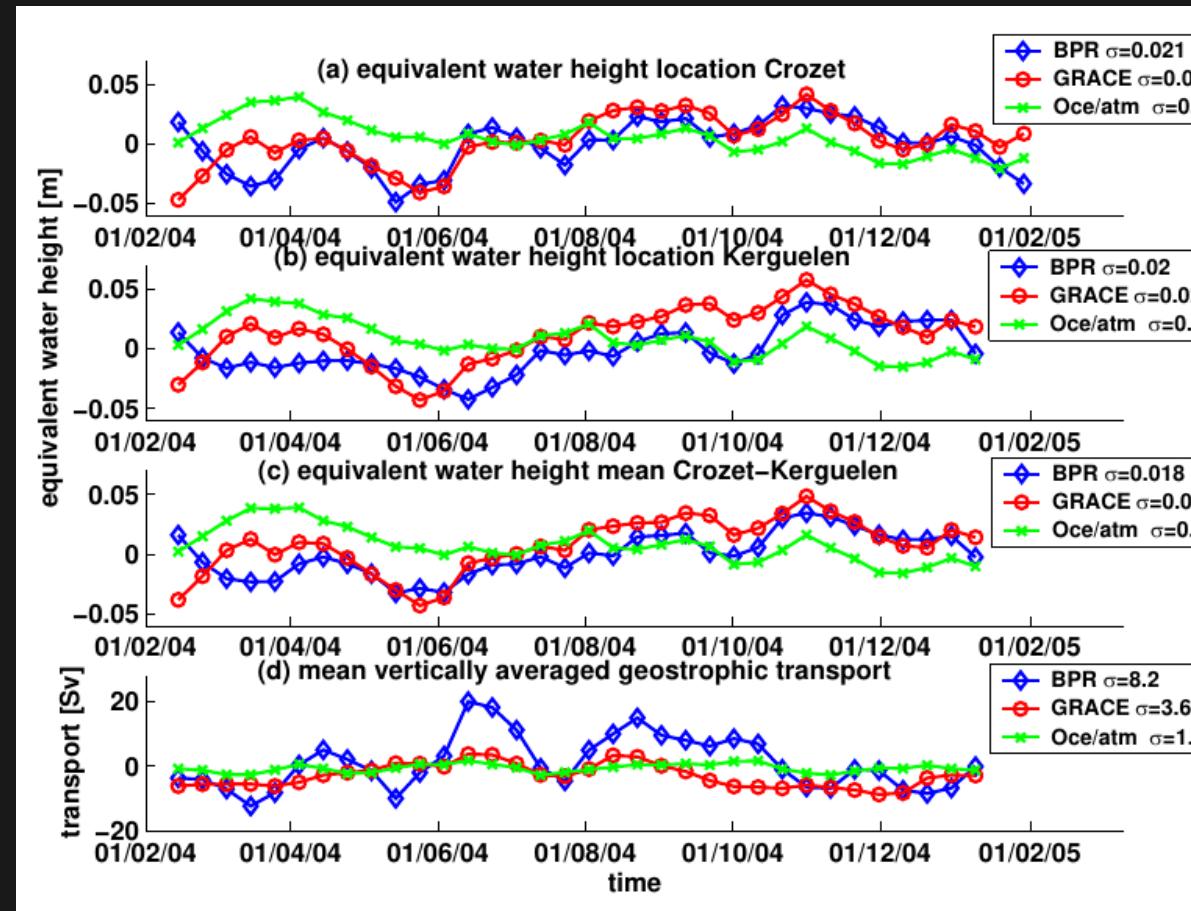


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- Large scale ocean signals picked up

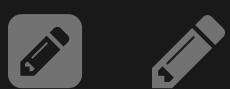


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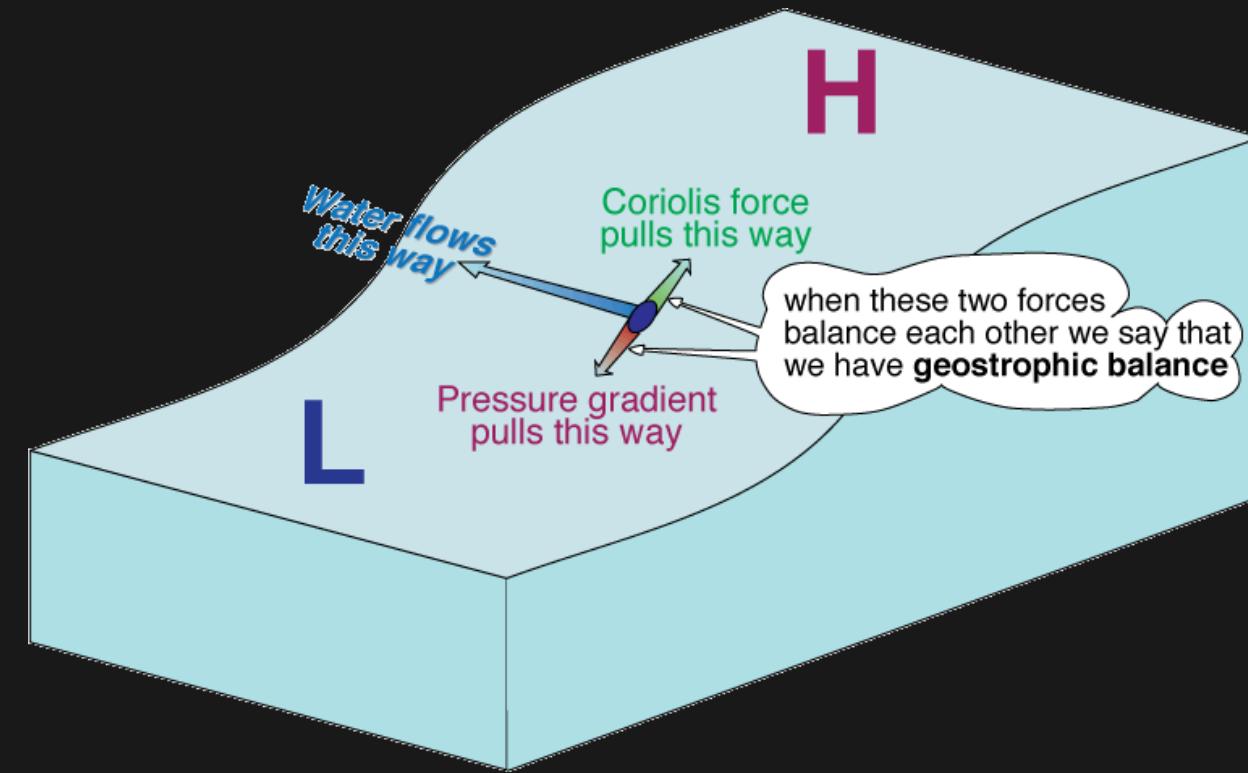
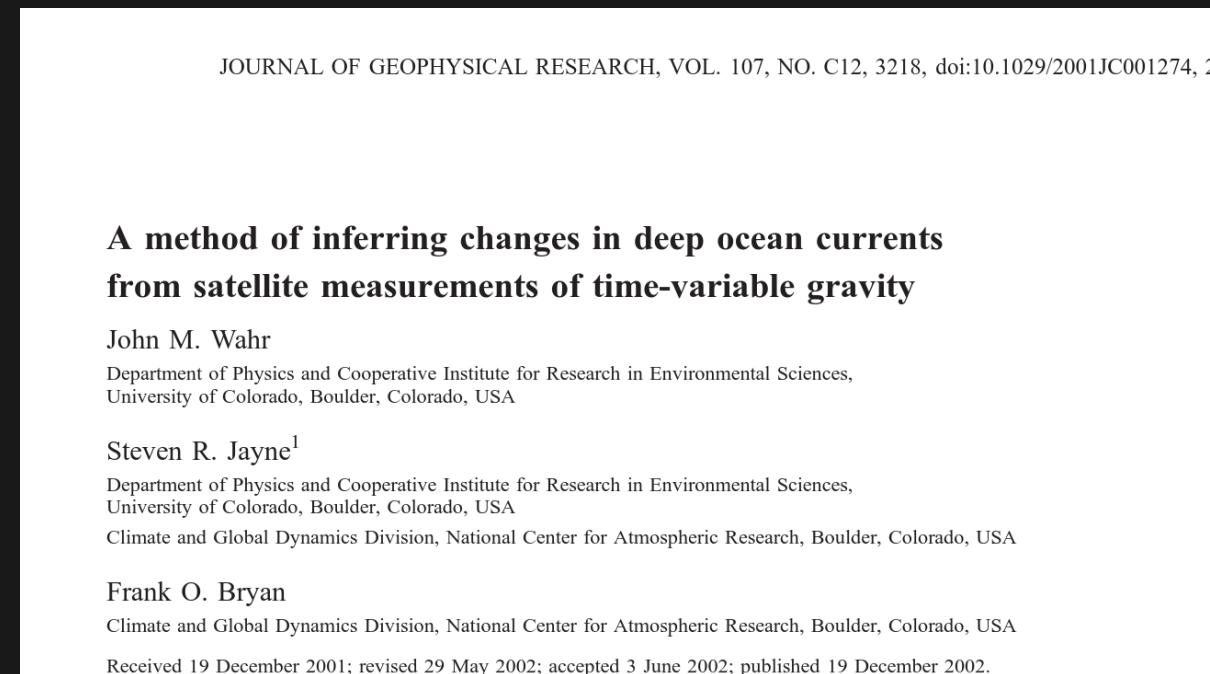


From Rietbroek et al. 2016

- 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



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

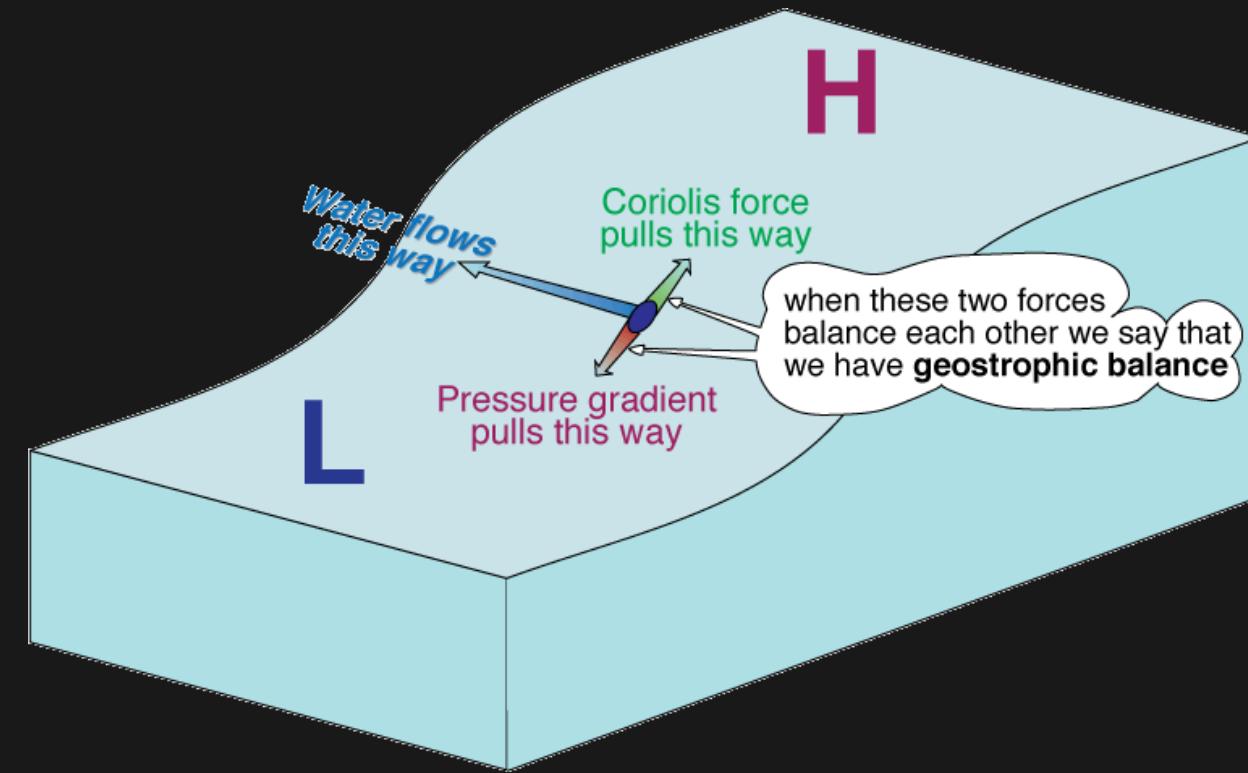
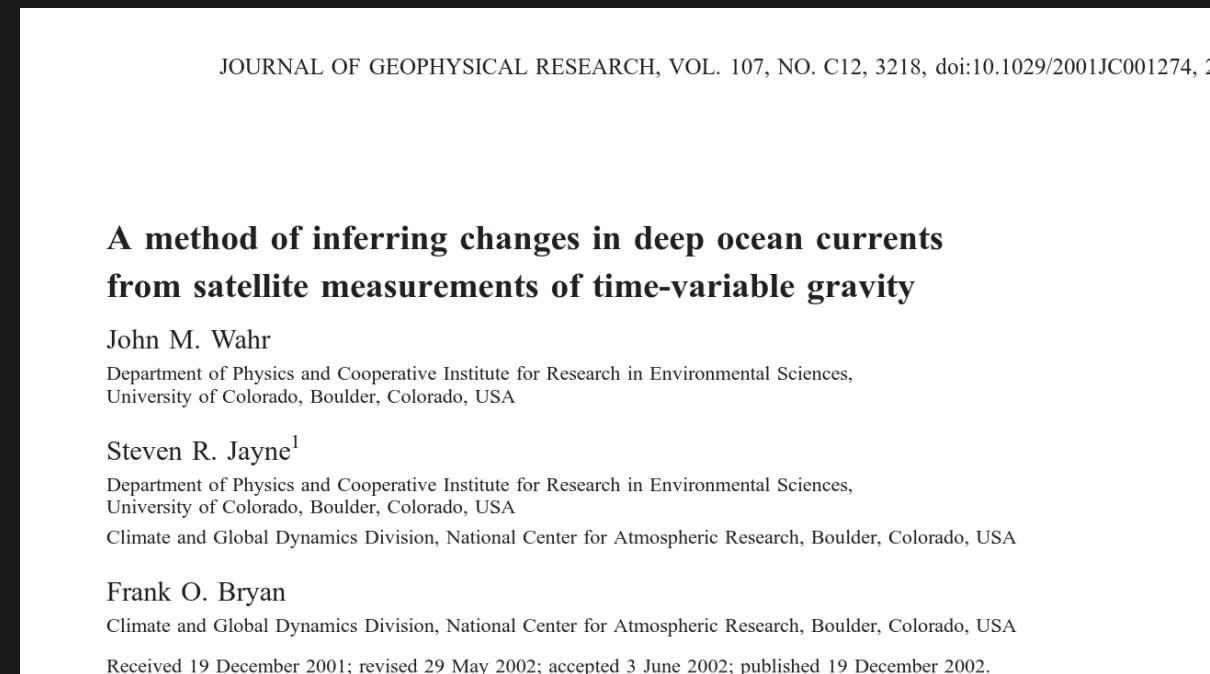
the effects of friction and external forcing are less important,
(1) reduces to the geostrophic approximation:

$$\text{Pressure gradient} \\ 2\rho_0 \Omega \times \mathbf{v} \approx -\nabla P \quad (2)$$

Earth rotation vector ↑ velocity



Geostrophic currents from time variable gravity



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

- Assume horizontal constant velocities

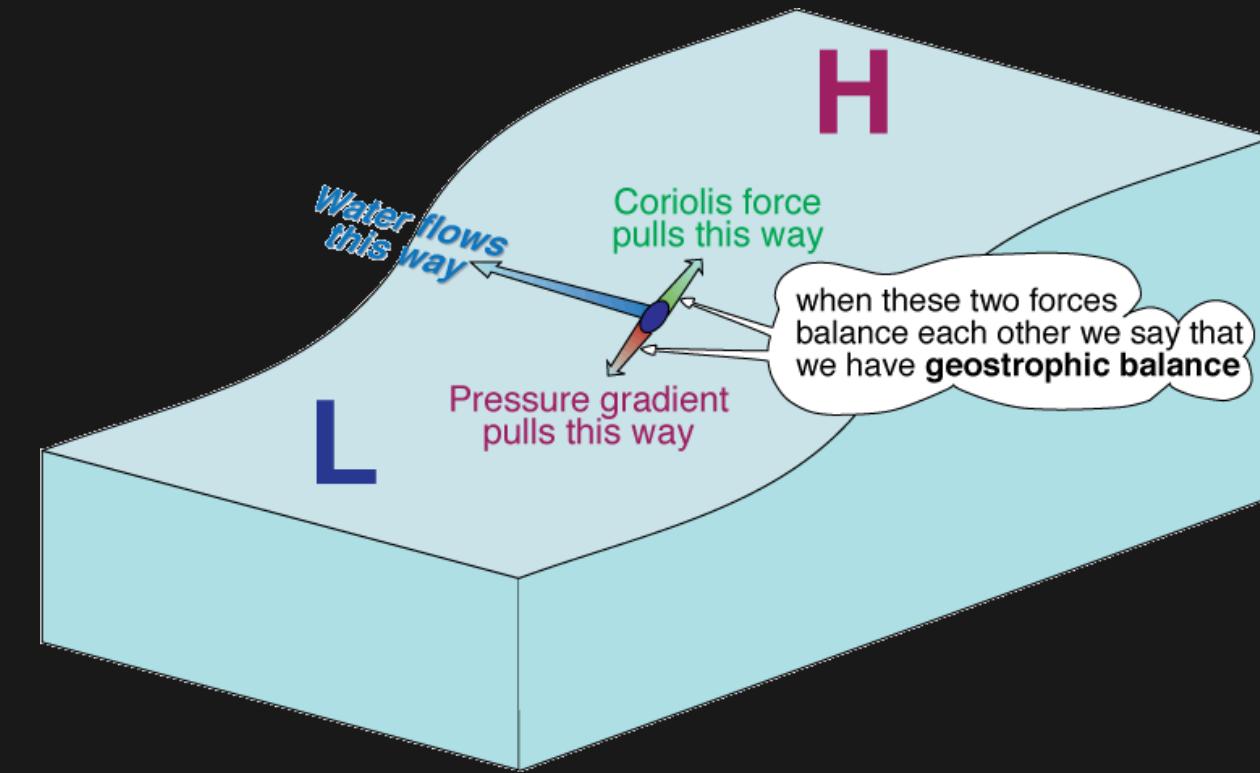
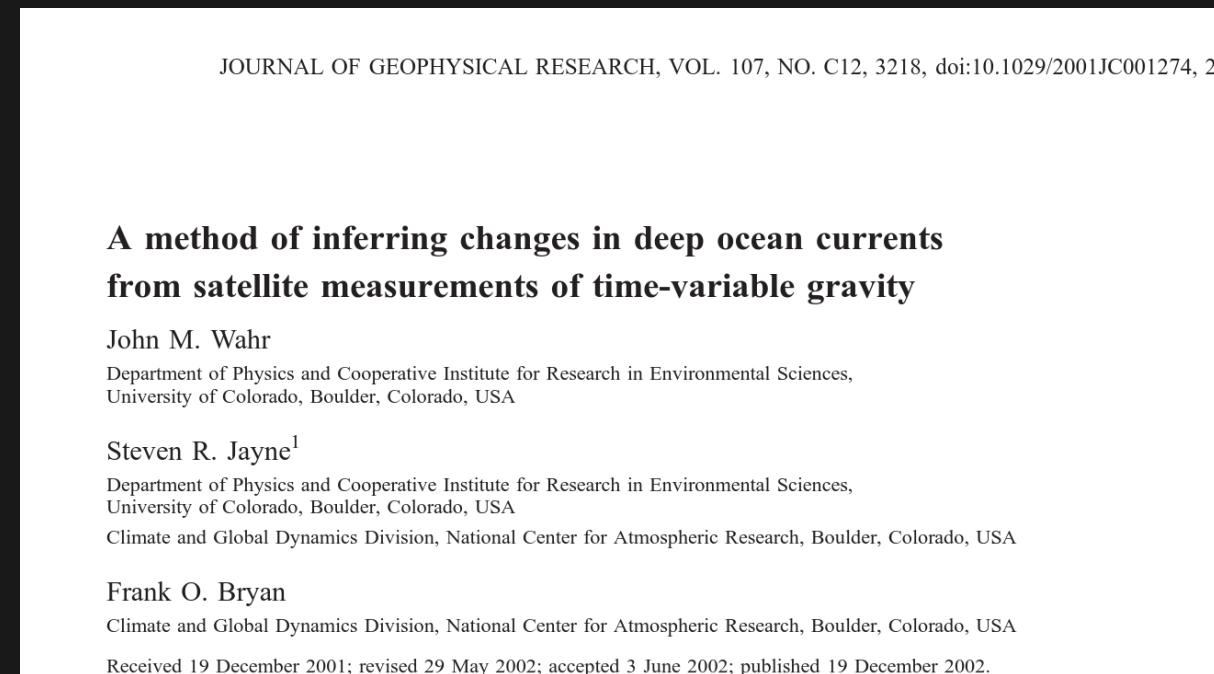
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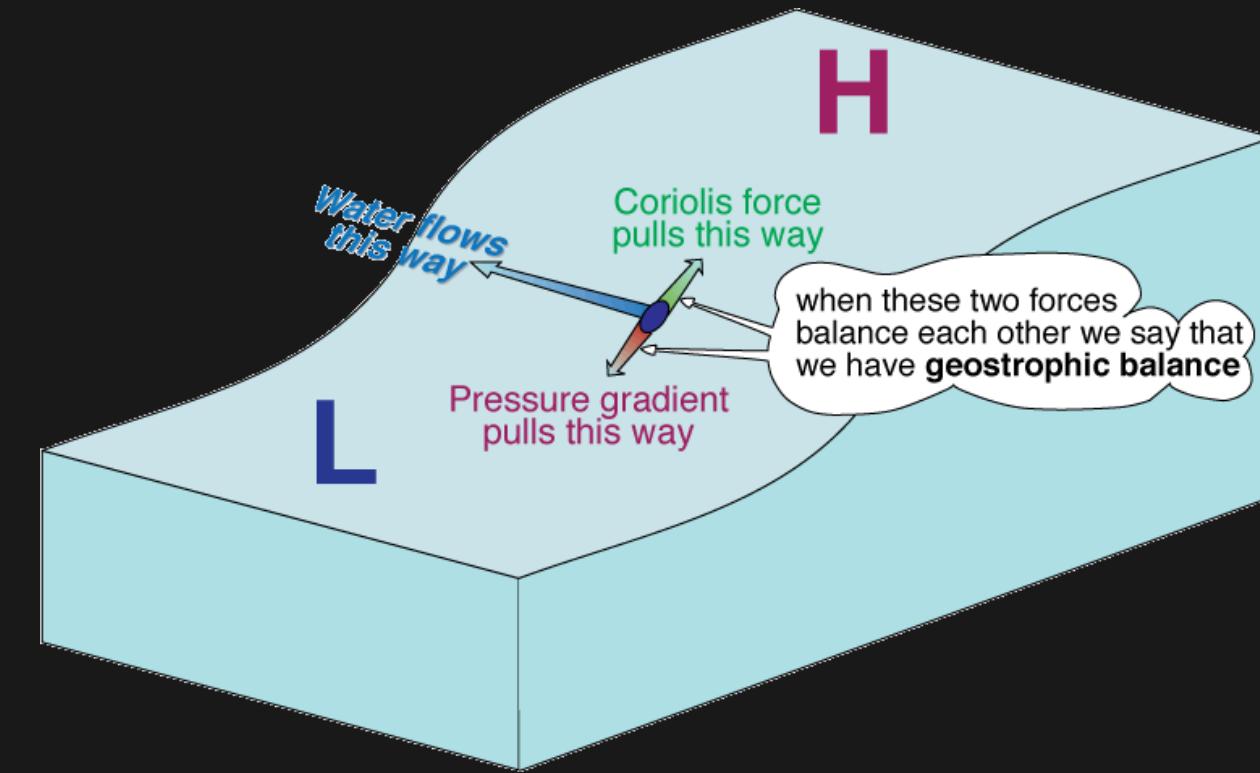
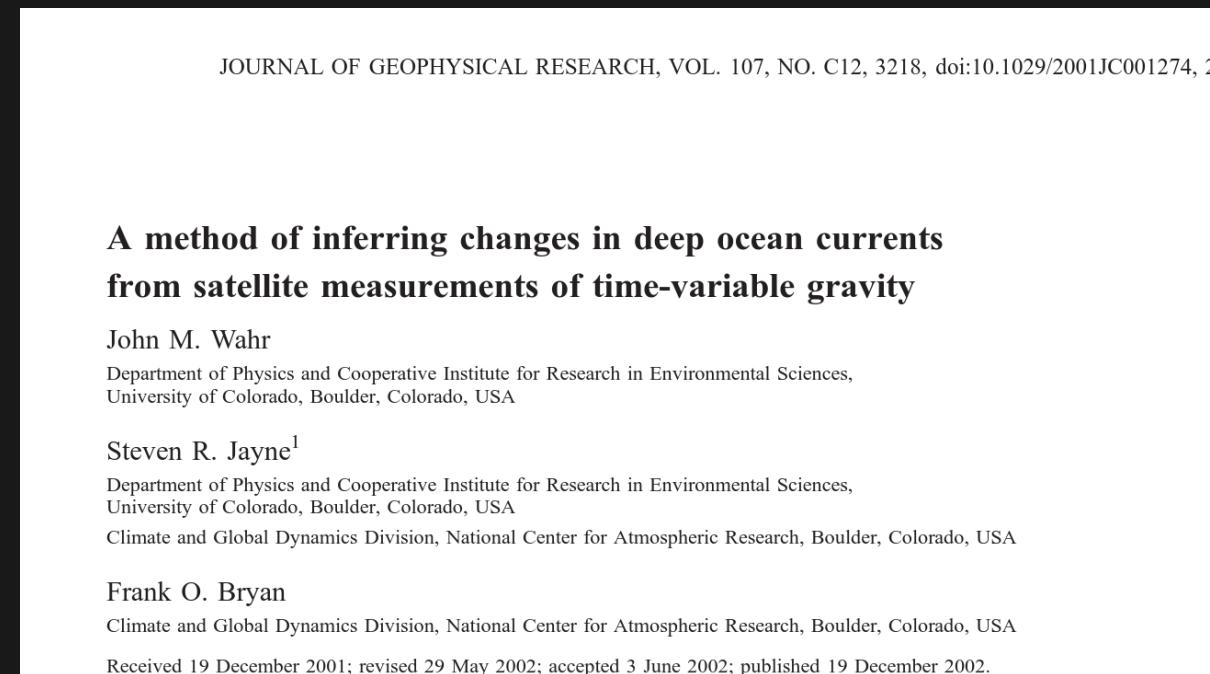
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Earth rotation vector ↑ velocity

- Assume horizontal constant velocities
- cross-product -> latitude dependency



Geostrophic currents from time variable gravity



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

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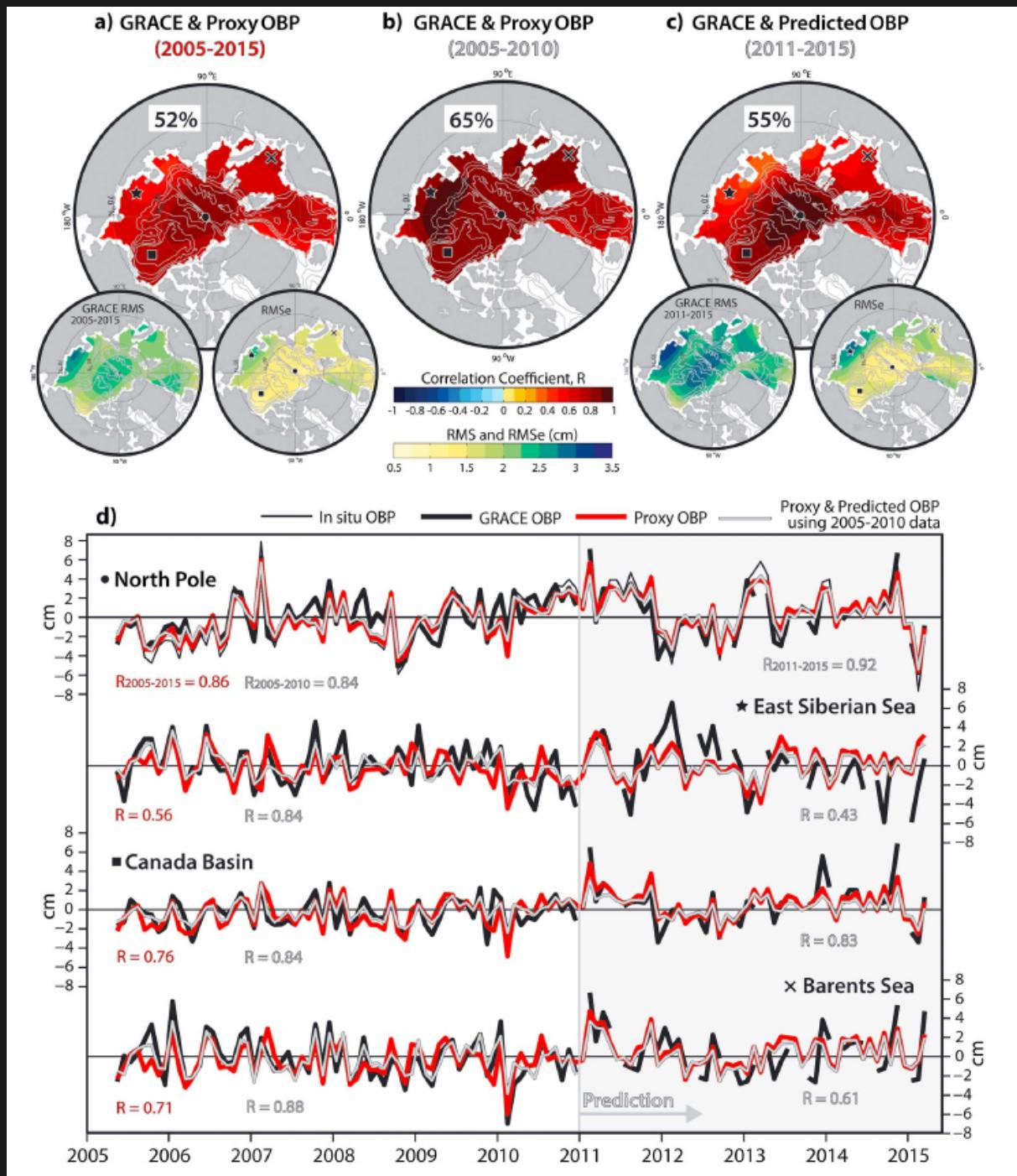
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Earth rotation vector
velocity

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

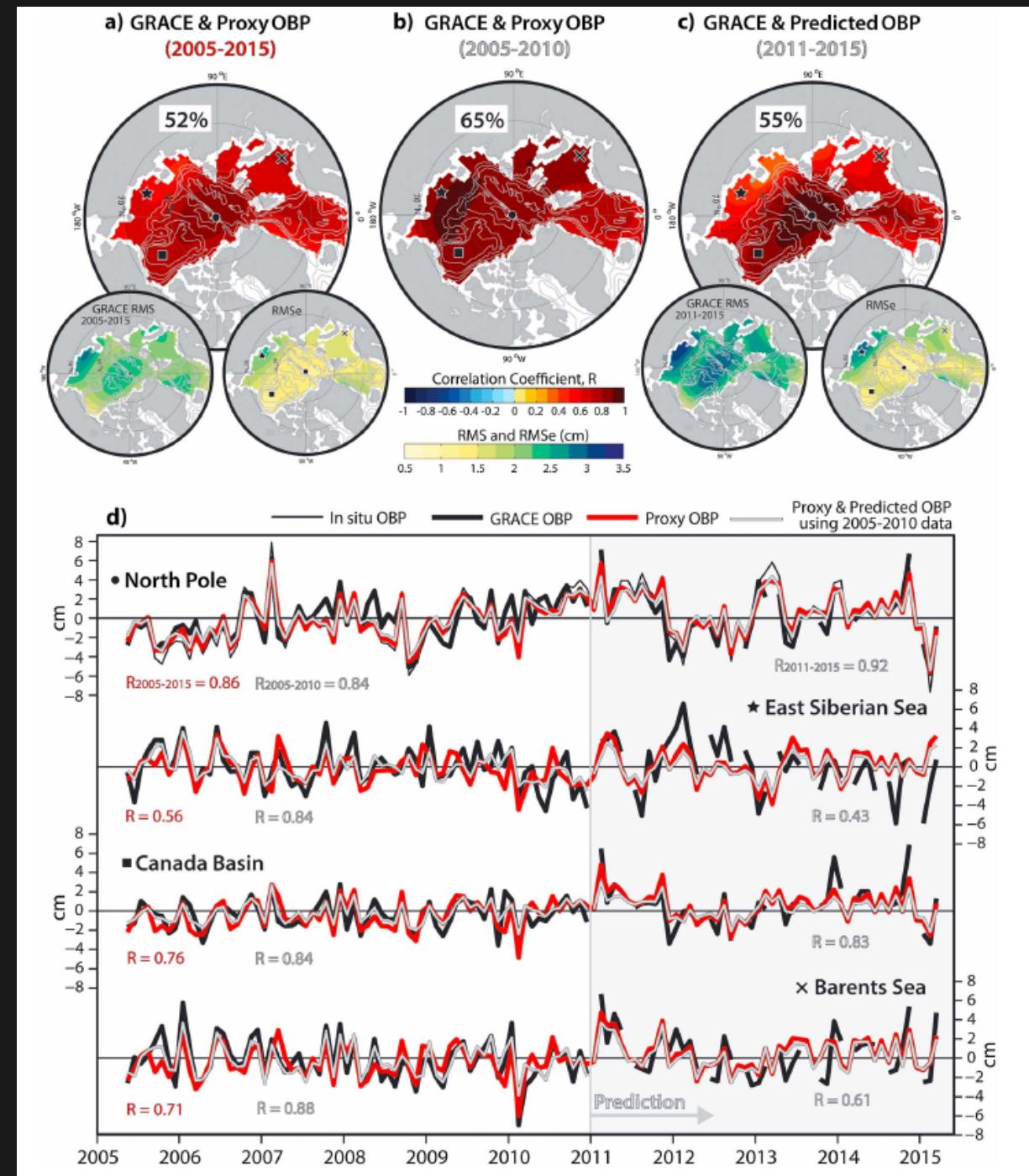


Arctic Ocean Bottom pressure variations well captured by GRACE



From Peralta-ferriz et al. 2016

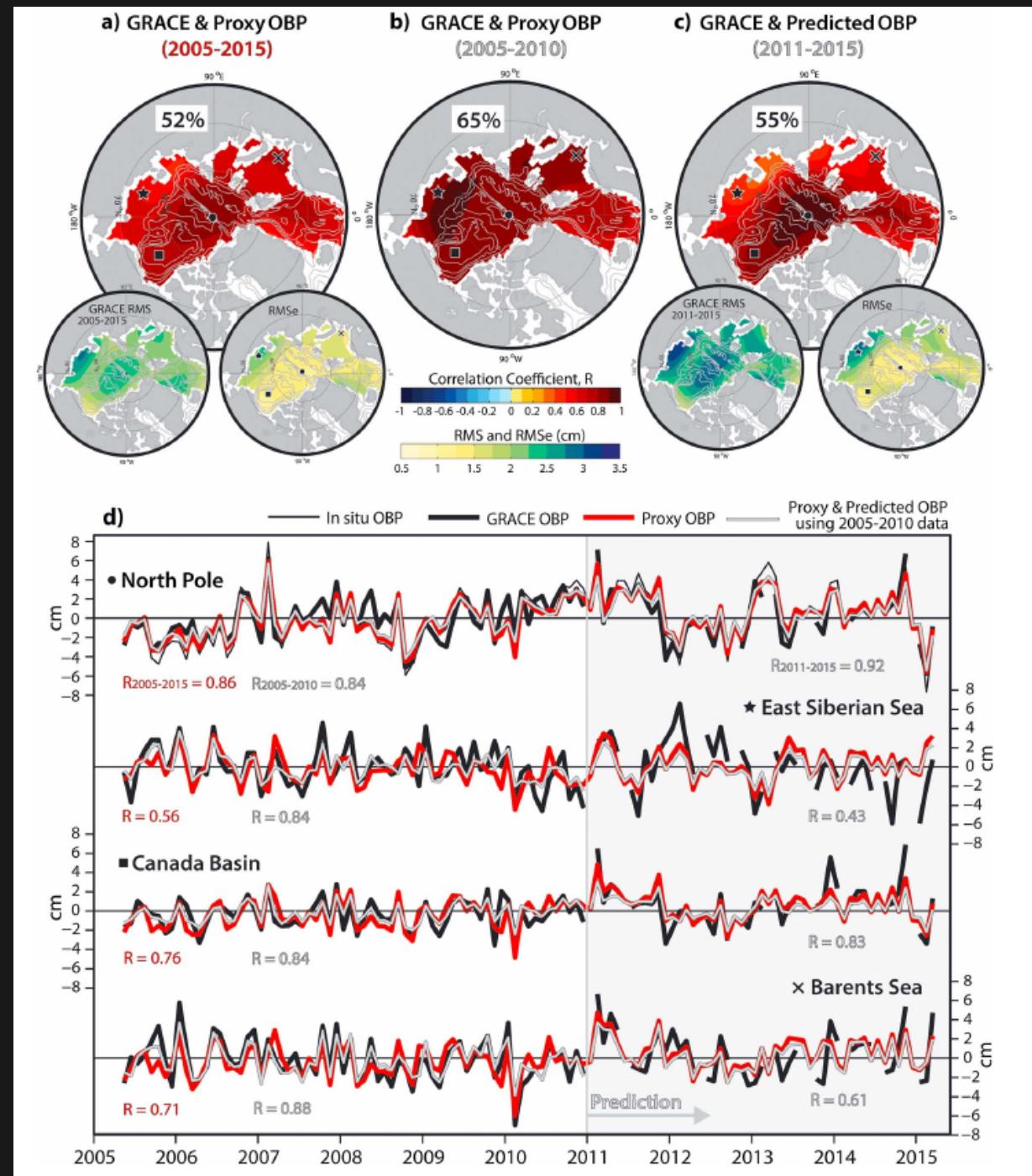
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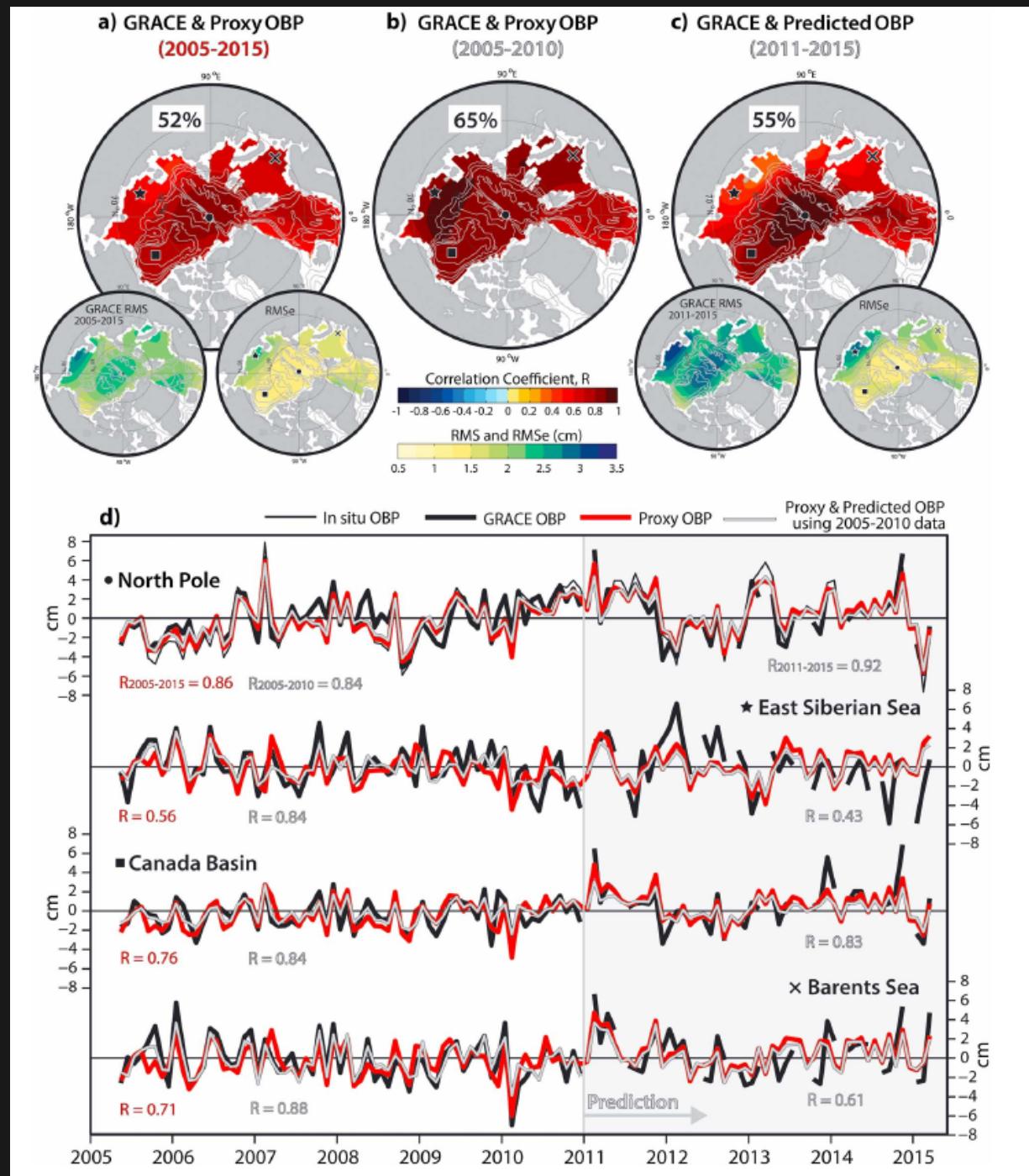


From Peralta-ferriz et al. 2016

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- Coherent OBP signals in the Arctic

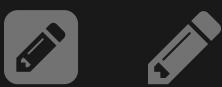


Arctic Ocean Bottom pressure variations well captured by GRACE



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.

