New insights from the sea level budget

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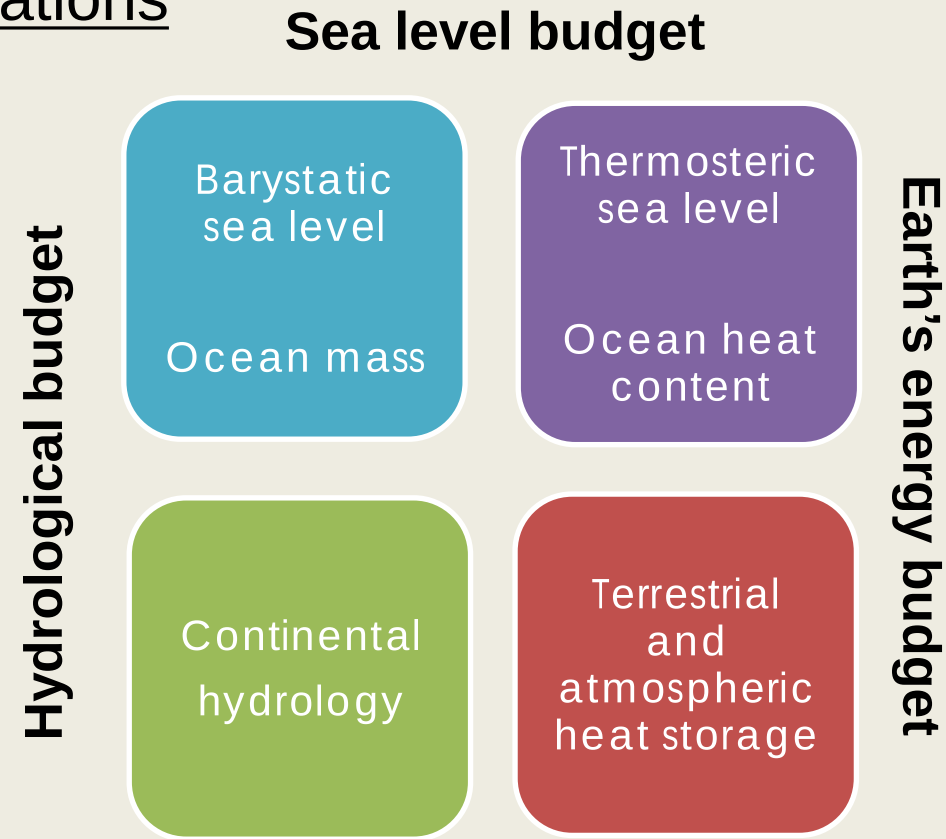
Relationships among the budgets

Connections among the observations

- Ocean heat content ⇔ thermosteric sea level.
- Ice sheet and glacial melt water and changes in continental water storage ⇔ the changes in ocean mass observed by GRACE

Outline:

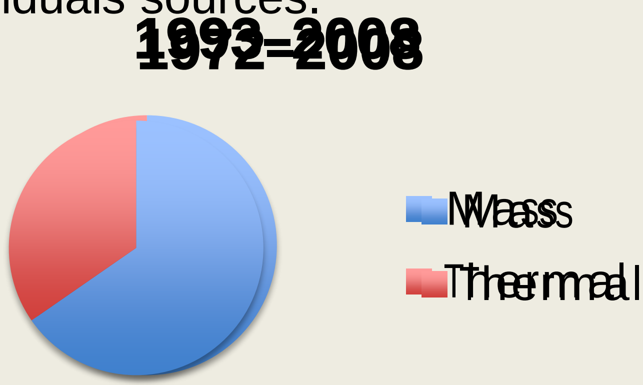
1. Review budgets
2. Regional sea level budgets
3. Residual errors in the observing systems
4. Status of the sea level budget observing system



Sea level budget from terrestrial sources

The sea level budget can be assessed with tide gauges, altimetry, hydrographic data, ice sheet estimates from GRACE, ICESat, CryoSat, airborne SAR, surveys of glaciers, reservoir data.

Relatively large uncertainties remain, in part because of the accumulation of errors from individuals sources.

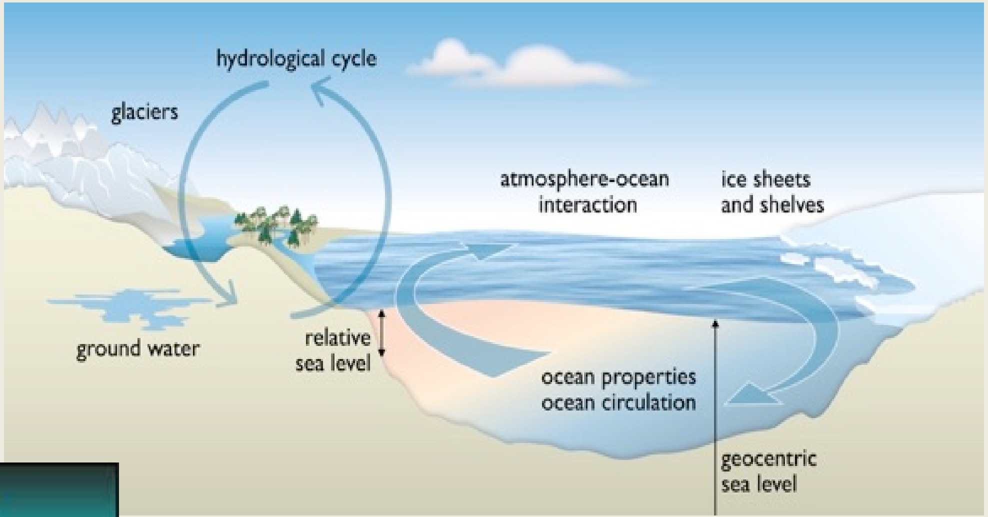


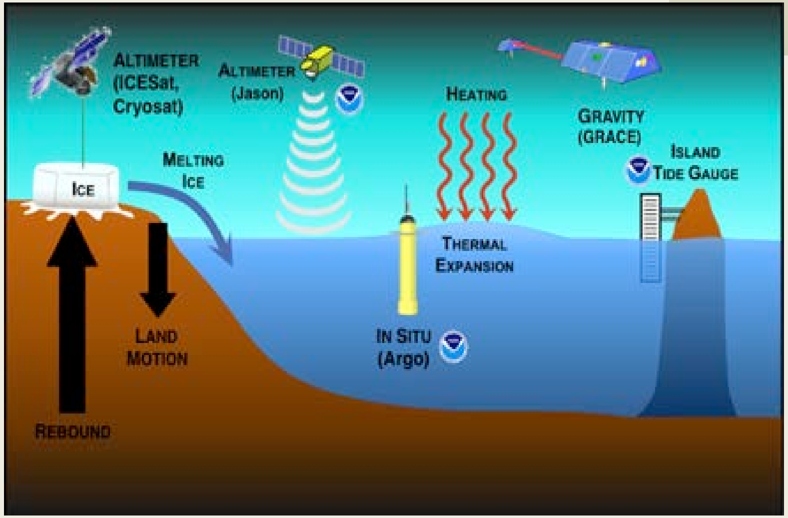
Component	1972 → 2008	1993 → 2008
Total s.l. (t.g. only)	**1.83 ± 0.18**[b]	**2.61 ± 0.55**
Total s.l. (t.g. + sat)	**2.10 ± 0.16**	**3.22 ± 0.41**
Shallow thermal (0–700m)	0.63 ± 0.09	0.71 ± 0.31
Deep thermal (700–3000m)	0.07 ± 0.10	0.07 ± 0.10
Abyssal thermal (3000m-bottom)	0.10 ± 0.06	0.10 ± 0.06
Total thermal (full depth)	**0.80 ± 0.15**	**0.88 ± 0.33**
Glaciers & Ice Caps	0.67 ± 0.03	0.99 ± 0.04
Greenland Ice Sheet	0.12 ± 0.17	0.31 ± 0.17
Antarctic Ice Sheet	0.30 ± 0.20	0.43 ± 0.20
Land ice (G&IC, GIS, AIS)	**1.09 ± 0.26**	**1.73 ± 0.27**
Thermal (full depth) + Land ice	**1.89 ± 0.30**	**2.61 ± 0.42**
Dam retention	−0.44 ± 0.15	−0.30 ± 0.15
Groundwater depletion	0.26 ± 0.07	0.35 ± 0.07
Natural terrestrial storage	0.07 ± 0.10	−0.14 ± 0.10
Total terrestrial storage	**−0.11 ± 0.19**	**−0.08 ± 0.19**
Total mass contributions	**0.98 ± 0.33**	**1.66 ± 0.33**
Total thermal + Mass	**1.78 ± 0.36**	**2.54 ± 0.46**
Residual (t.g. only)	**0.05 ± 0.40**	**0.08 ± 0.72**
Residual (t.g. + sat)	**0.32 ± 0.39**	**0.69 ± 0.62**

Church et al. 2010

Sea level rise observing system

Since 2005 the global ocean observing system has made great progress in monitoring the sea level budget and the hydrological cycle.

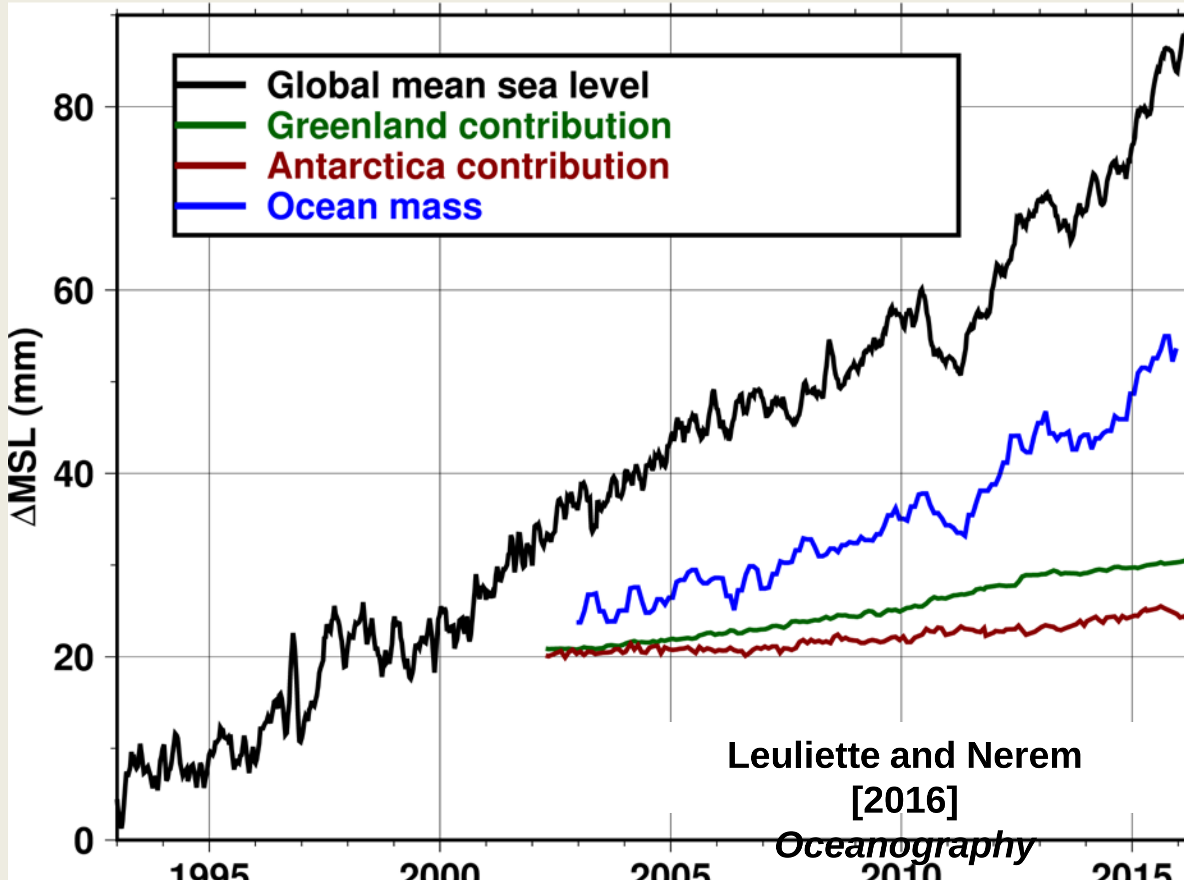




- ► Climate-quality altimetry record
- ► Water mass transport from GRACE
- ► Argo array with 3000+ floats
- ► Ice sheet monitoring from SAR, ICESat, CryoSat, etc.
- ► Tide gauges with vertical land motion estimates
- ► Glacial isostatic adjustment modeling

Sea level budget: ocean mass contributions

GRACE enables us to estimate the relative contributions of ice sheet melt, glaciers, and ground water storage changes to the ocean mass component of recent sea level change.



The sea level budget may be expressed as height changes from the main components of sea level change:

$$\Delta SSH = \Delta SH + \Delta OM$$

SSH = sea surface height, SH = steric height, *OM* = ocean mass

Argo measures temperature and salinity short of the abyssal ocean (roughly 44 to 75% of Argo profiles are from 2000m).

$$\Delta SH = \Delta SH_{(0\text{–}2000m)} + \Delta SH_{(2000m\text{–}\infty)}$$

We can estimate a residual from observations:

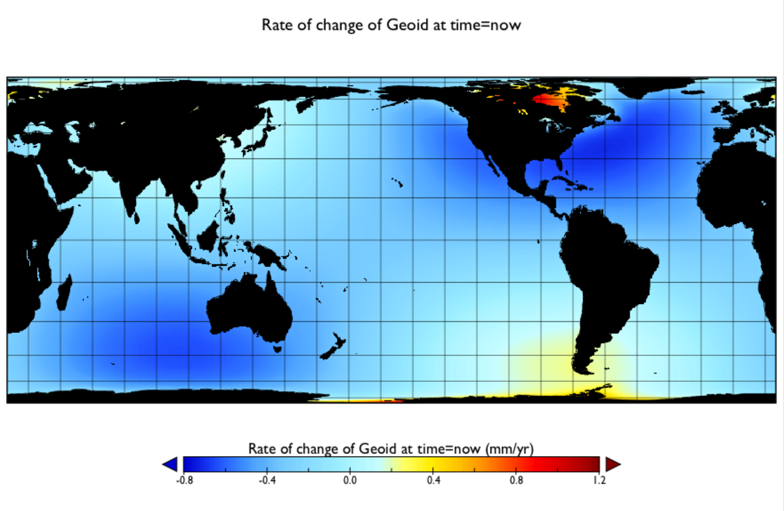
$$\Delta SL_{residual} = \Delta SSH - \Delta SH_{(0\text{–}2000m)} - \Delta OM$$

$$\Delta SL_{residual} = \Delta SH_{(2000m\text{–}\infty)} + Error$$

Altimetry

For total sea level we use Jason-1, Jason-2 and Jason-3 data from RADS (Radar Altimeter Database System)

- GOT4.10 tide model; Desai [2015] pole tide
- GIA radial geoid rates Peltier ICE5Gv1.3 [2012].
  - Average correction increases SLR by +0.25 mm/year.



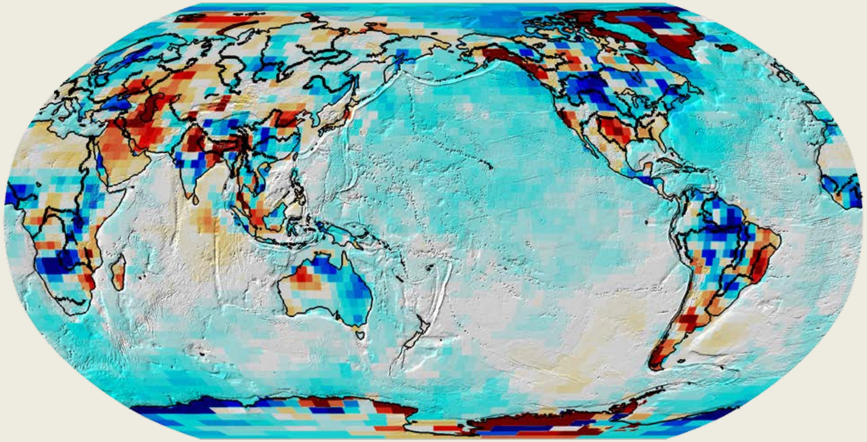
For Argo, we use gridded temperature and salinity fields from:

- IPRC: UH International Pacific Research Center
- JAMSTEC: Japan Agency for Marine-Earth Science and Technology
- SIO: Roemmich-Gilson

GRACE JPL-Mascons

GRCTellus JPL-Mascons

- “Monthly” global mass grids
- Fit tracking data to 4,551 equal-area 3° x3° spherical caps
- Includes crustal loading
- Two solutions
  - With and without a Coastline Resolution Improvement (CRI) filter
  - Previous GRACE studies of ocean mass needed masks/filters near the coast, forward modeling of land hydrology, or other “mascon” solutions



10.5067/TEMSC-OCL05 Watkins et al. (2015)

Modifications

- Mean atmosphere
- Pole tide (Wahr 2015)

Glacial Isostatic Adjustment

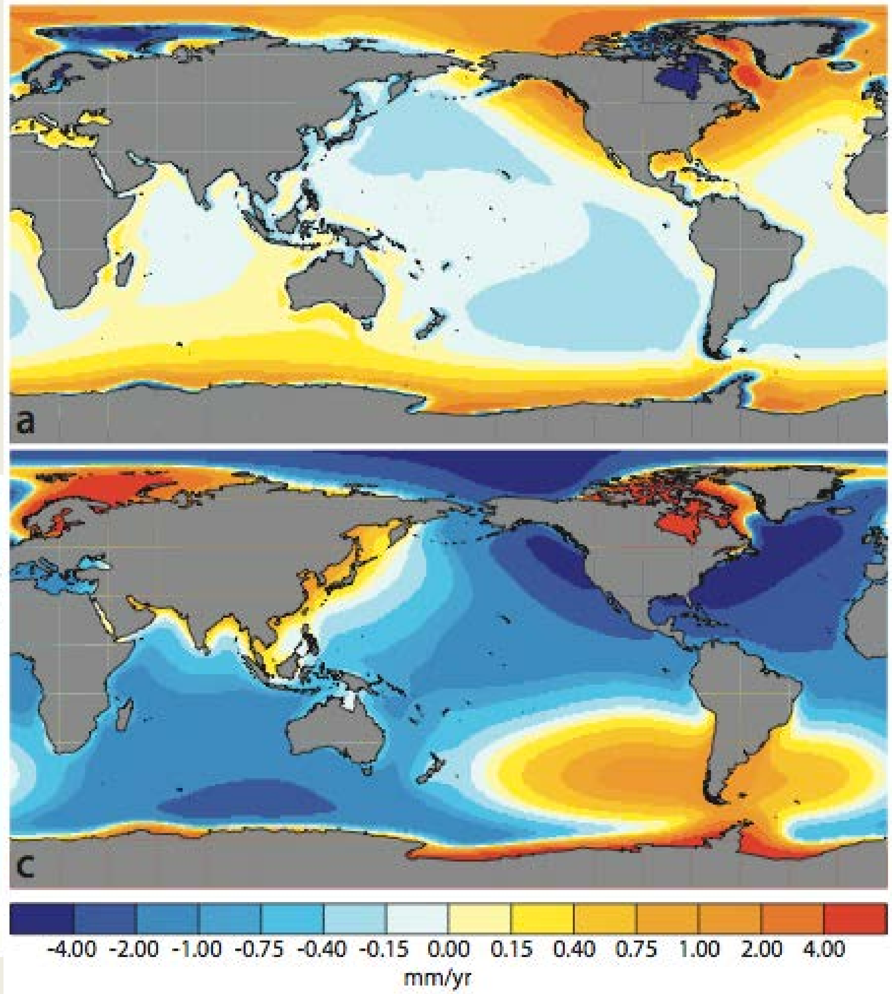
The GIA correction differs for

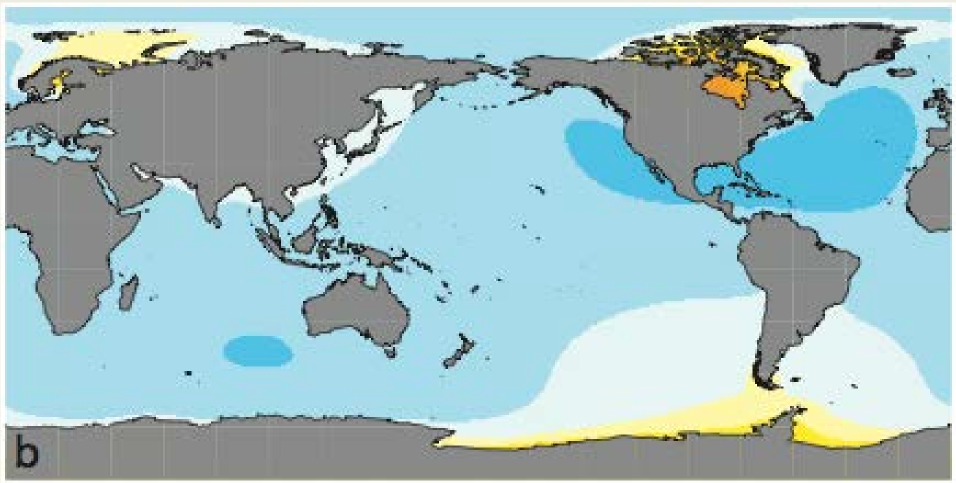
a) Relative sea level from tide gauges (vertical motion of the crust)

b) Absolute sea level from altimetry (geoid)

c) Ocean mass from GRACE (equivalent mass from geoid change)

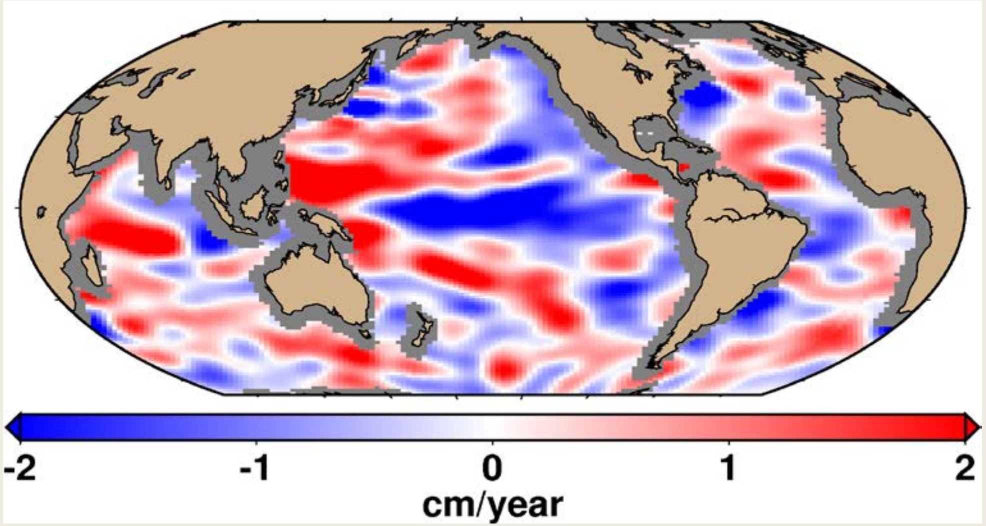
GIA effect must correctly account for Earth rotation changes and have no net mass change.



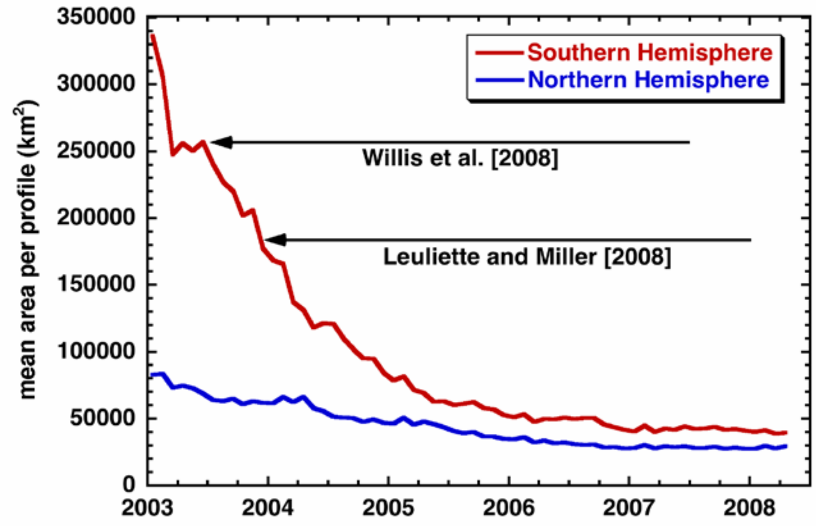


Steric sea level rise

Argo data can be used to produce monthly fields of steric sea level variations

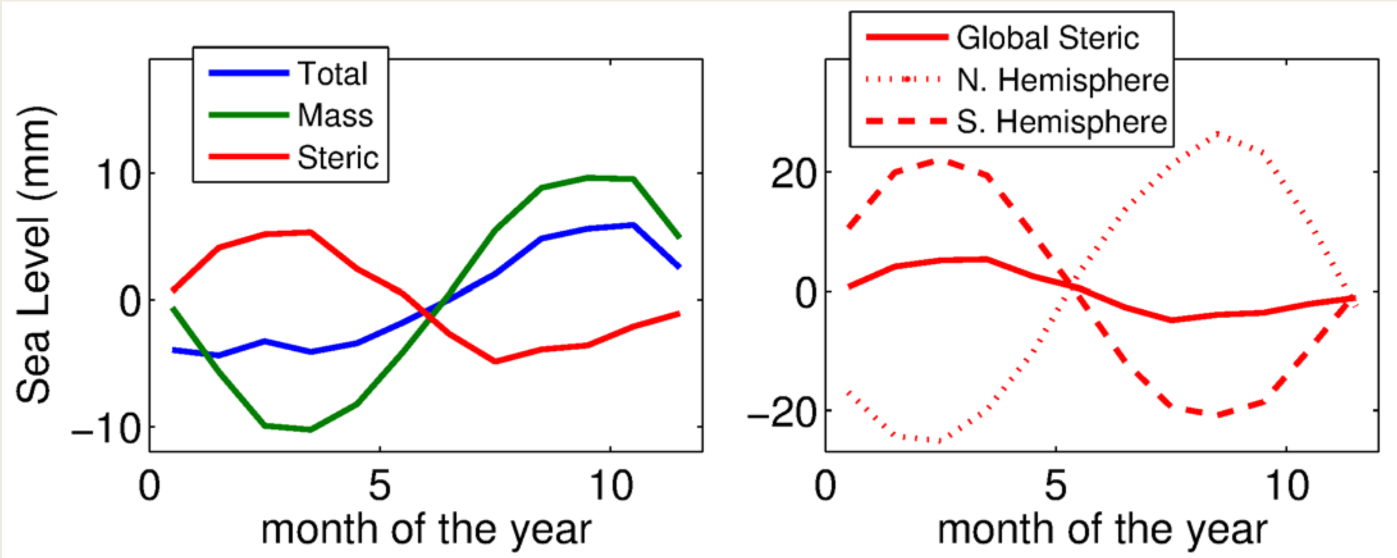


Trends in steric sea level 2004 – 2008



The budget analysis in Leuliette and Miller [2009] excluded 2003 because of poor coverage of the Southern Hemisphere.

Annual cycle of the budget



Leuliette and Willis [2011]

The seasonal cycle of globally averaged sea level and its components (left panel). Strong cancellation occurs in the global average of the steric signal due to out-of-phase seasonal heating between the hemispheres. The right panel shows the steric signal in each hemisphere. Note the difference in the vertical scale.

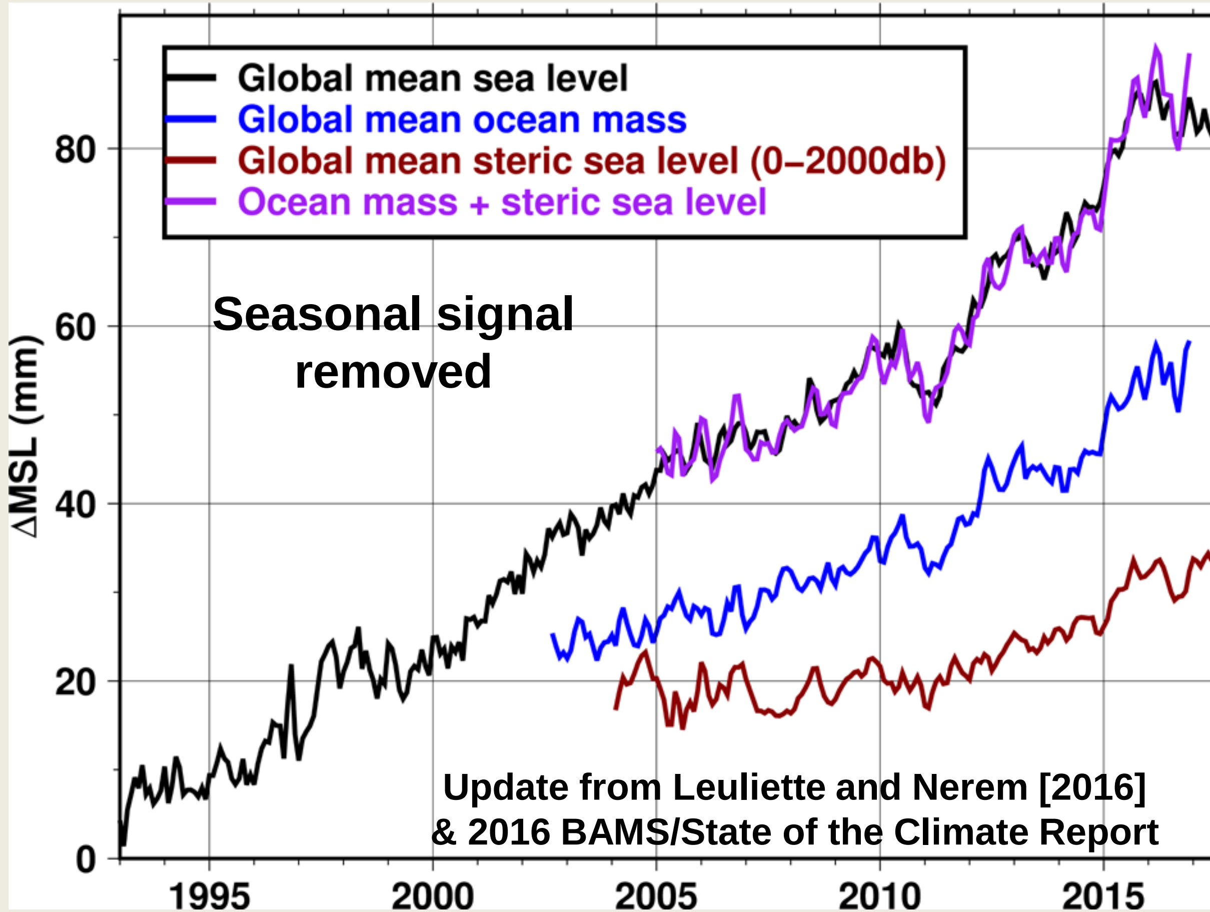
Global and regional sea level budgets

Global sea level budgets can be closed within the estimated errors

Bounds size of deep (> 2000 m) ocean warming

(e.g. Llovel et al. 2014)

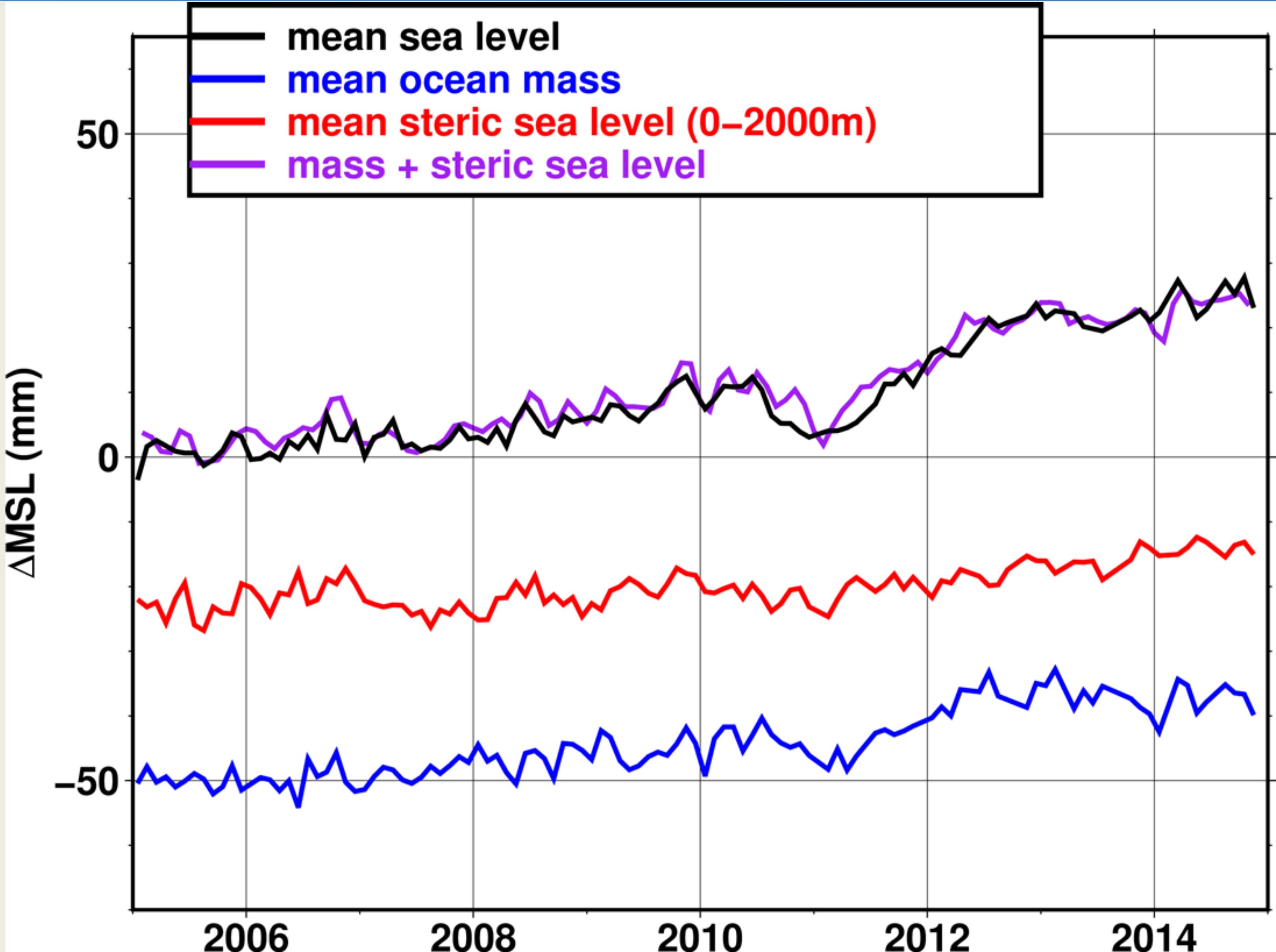
What do regional sea level budgets tell us?



http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/budget.php

Global mean sea level budget

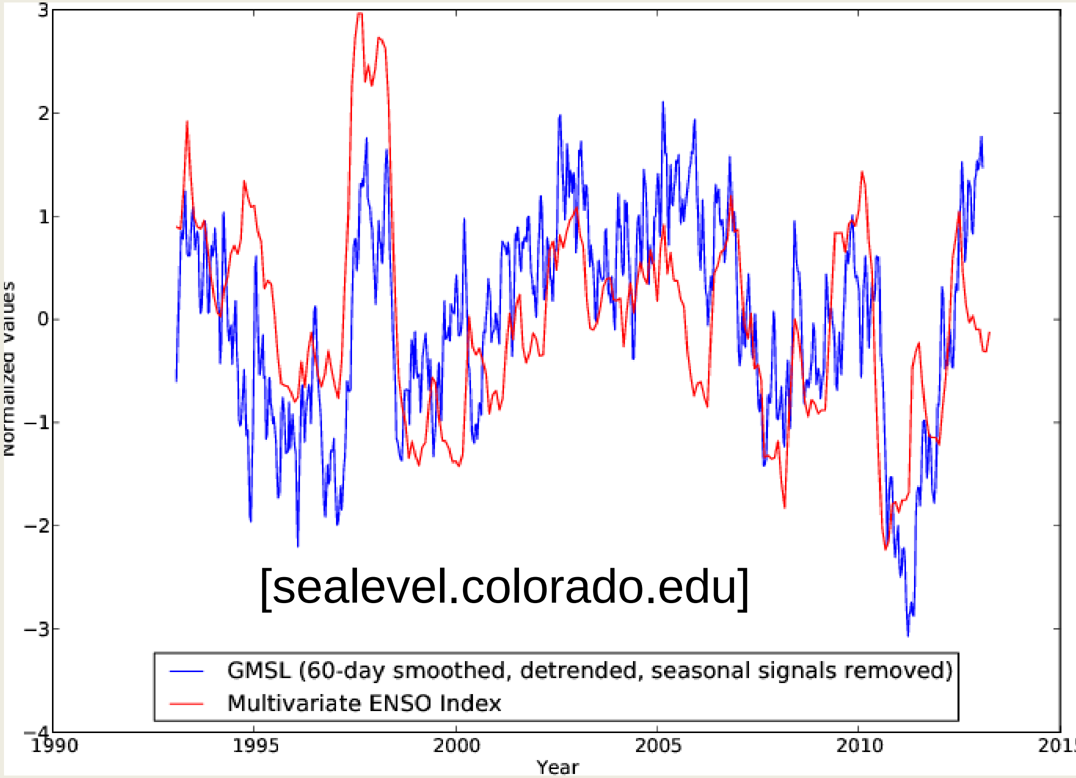
	mm/yr
Jason	2.63
GRACE +Argo	2.42
Argo	0.83
GRACE	1.63



Water storage, recent sea level change

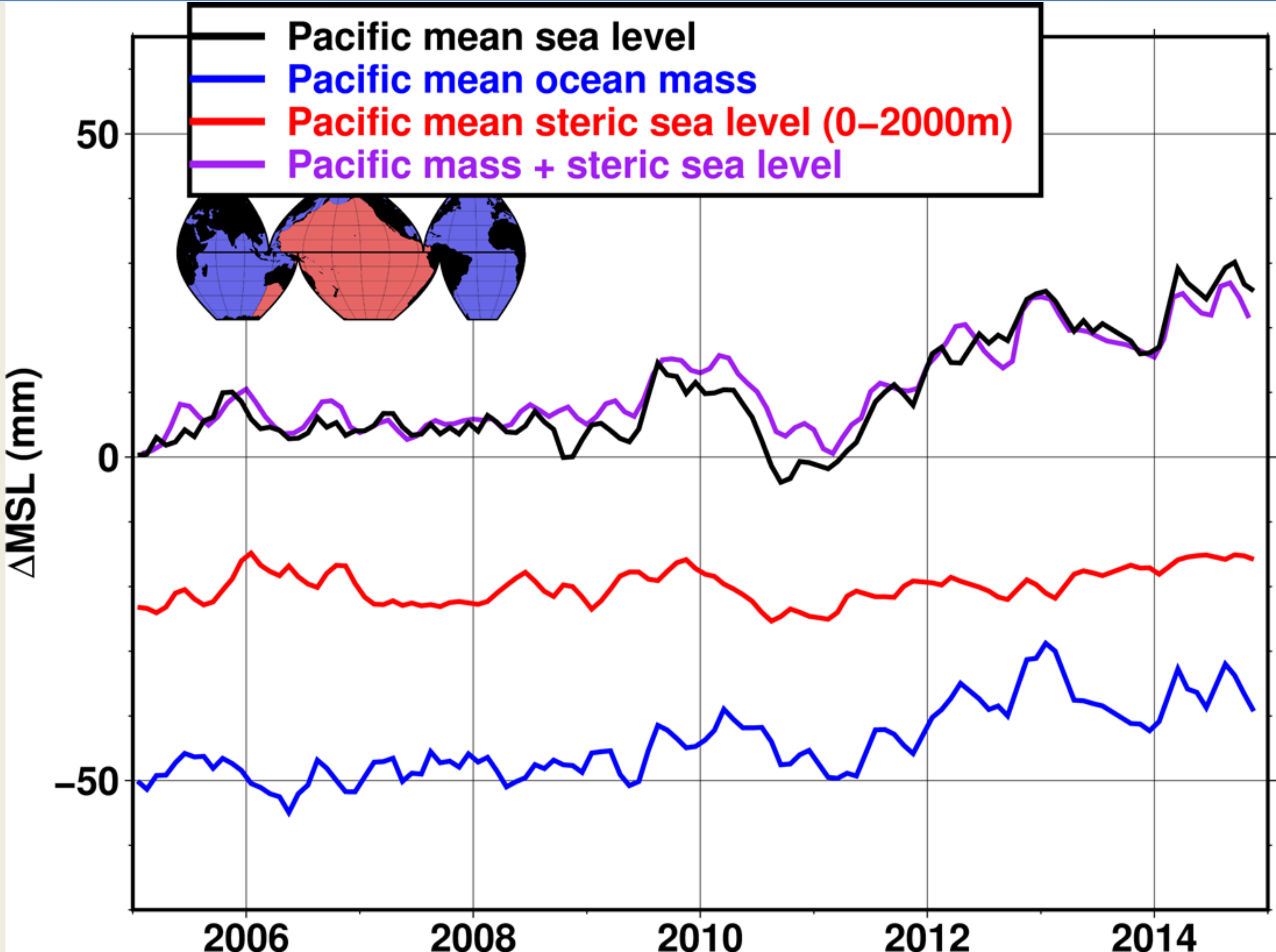
- Altimetry shows a significant decrease in mean sea level from 2010 to the middle of 2011.
- GRACE demonstrated a large increase in water storage in northern South America and Australia [Boening et al. 2012].
- Further study indicated that the longevity of the anomaly could be attributed to water storage in closed drainage basins in Australia [Fasullo et al. 2013].

Mean sea level residuals and the Multivariate ENSO Index



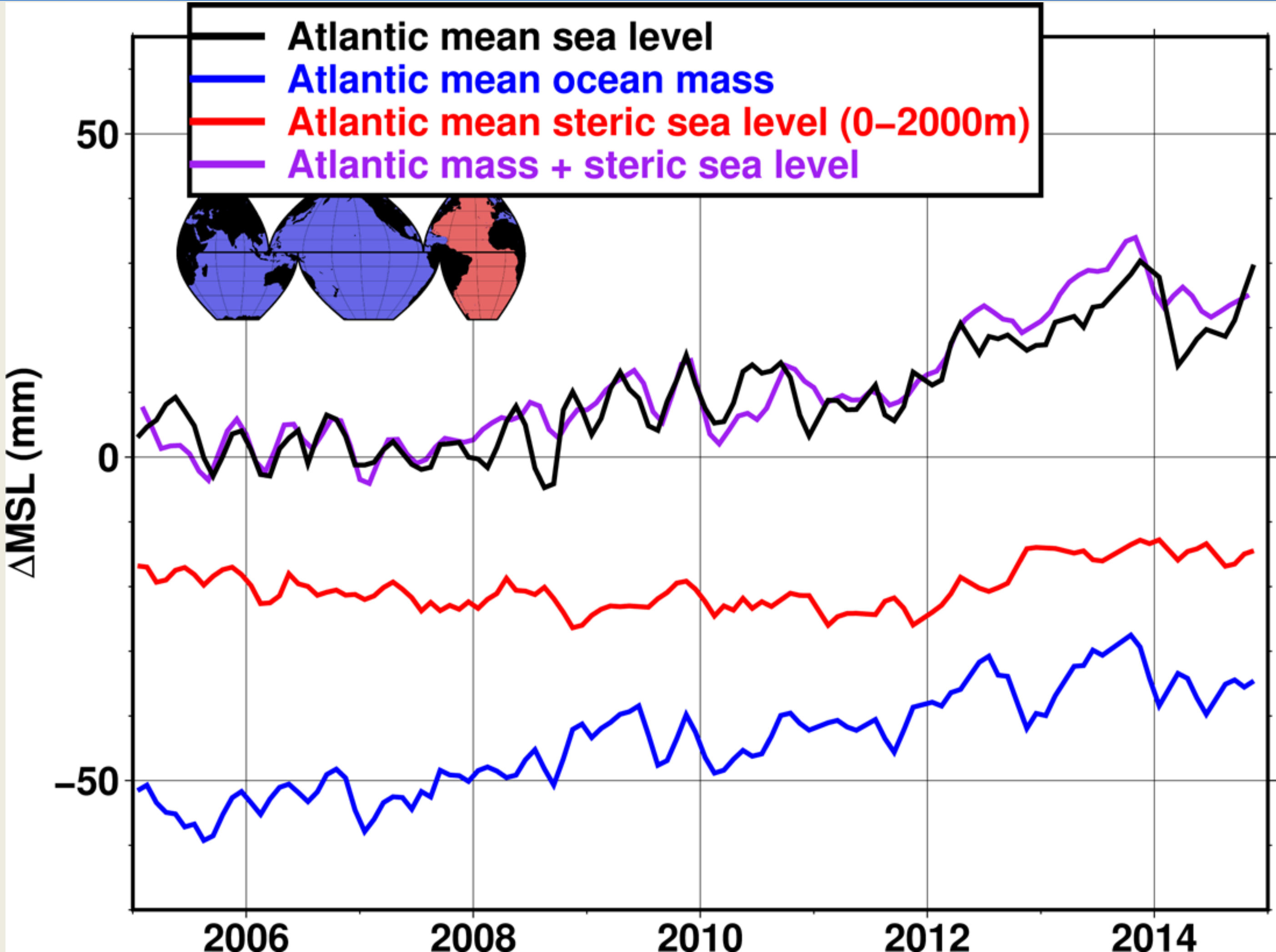
Pacific Ocean sea level budget

	mm/yr
Jason	2.18
GRACE +Argo	1.92
Argo	0.26
GRACE	1.61



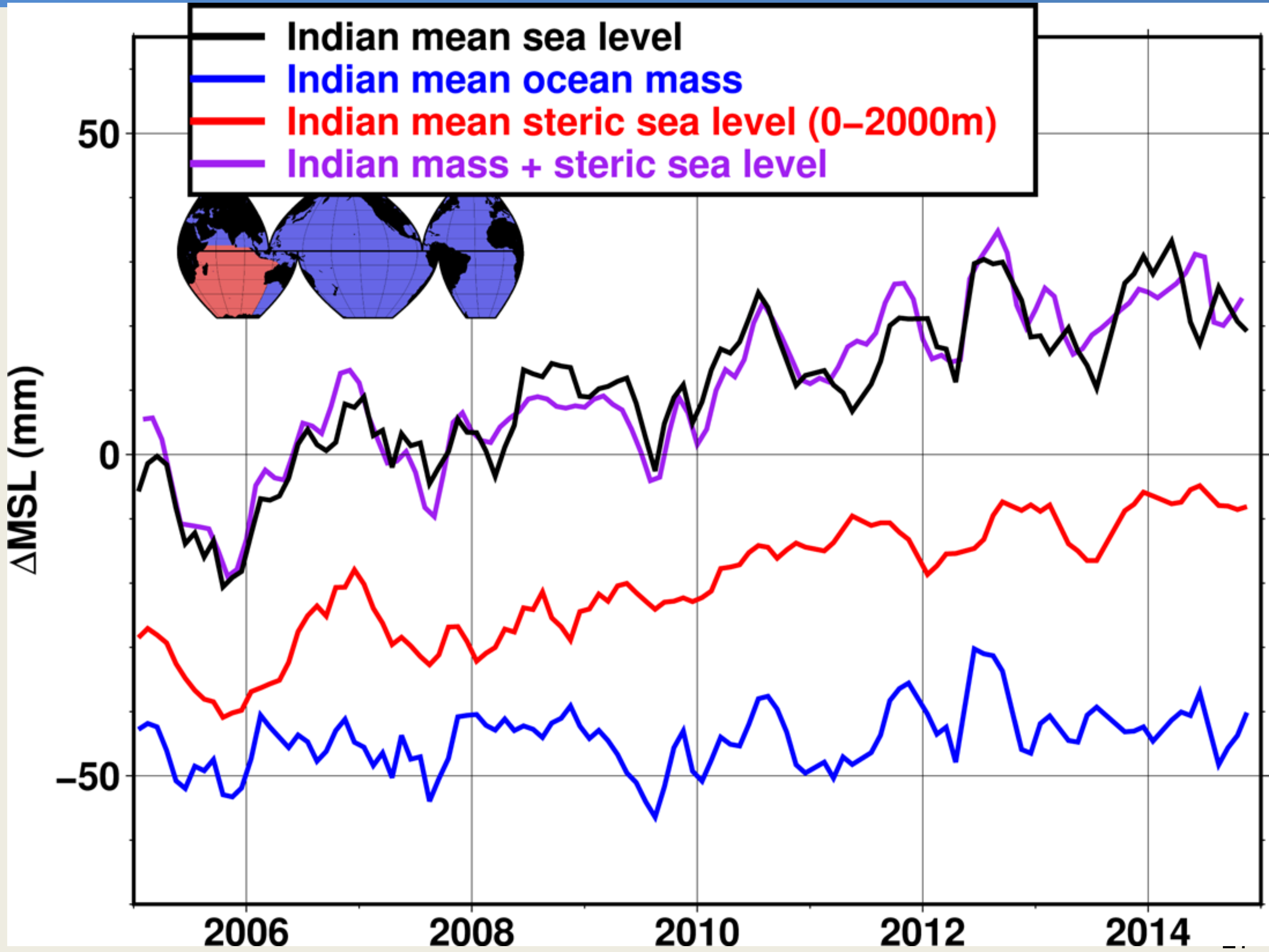
Atlantic Ocean sea level budget

	mm/yr
Jason	2.41
GRACE +Argo	2.72
Argo	0.39
GRACE	2.39



Indian Ocean sea level budget

	mm/yr
Jason	3.67
GRACE +Argo	3.55
Argo	3.00
GRACE	0.65

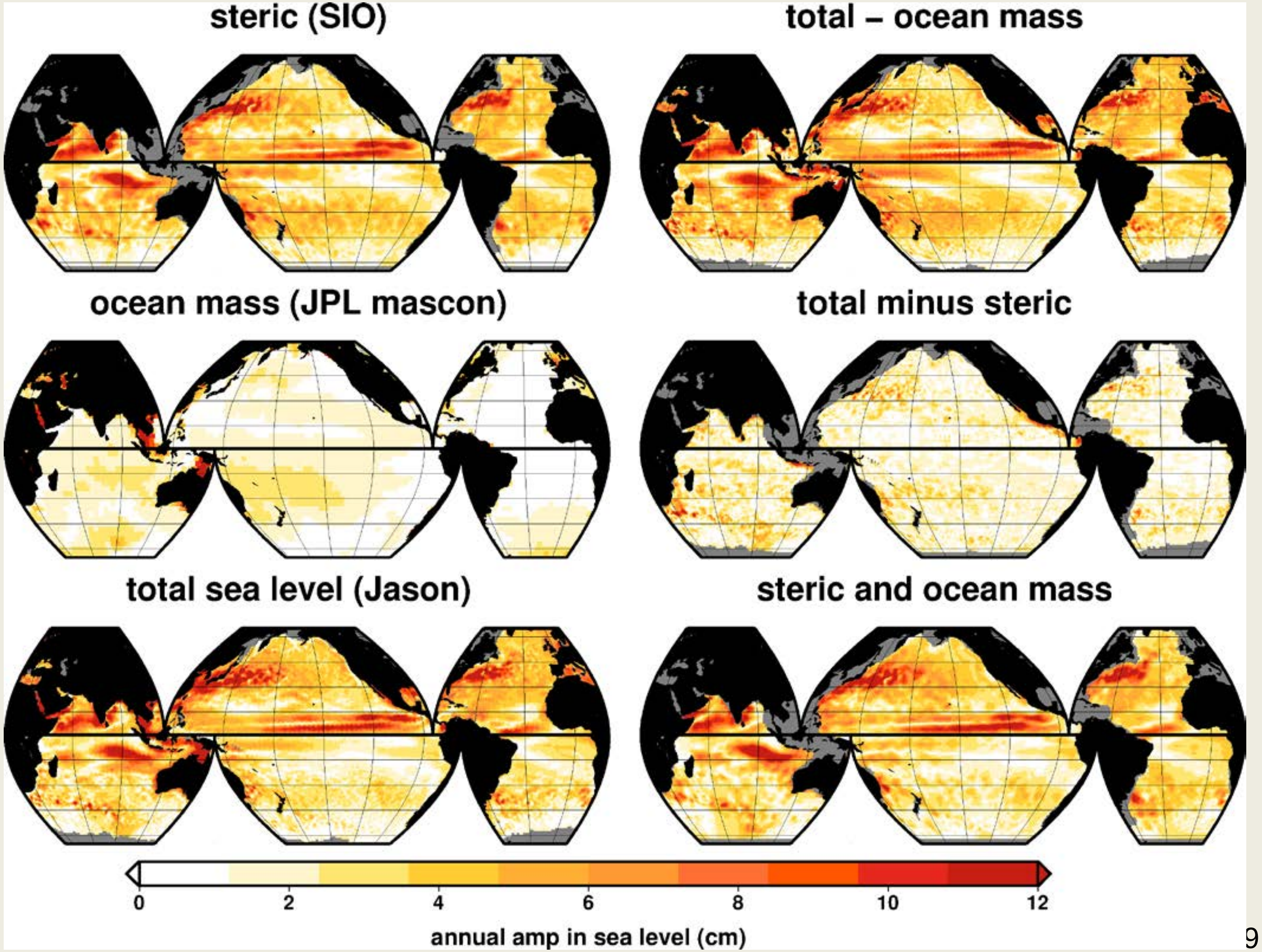


Sea level trends Jan 2005 to Nov 2014

(mm/year)		Total sea level	Steric sea level	Ocean mass
Global	direct	2.63	0.83	1.63
	indirect	2.42	1.05	1.77
Pacific	direct	2.18	0.26	1.61
	indirect	1.92	0.54	1.99
Atlantic	direct	2.41	0.39	2.39
	indirect	2.72	0.09	2.01
Indian	direct	3.67	3.00	0.65
	indirect	3.55	3.25	0.60

Annual amplitude of sea level components

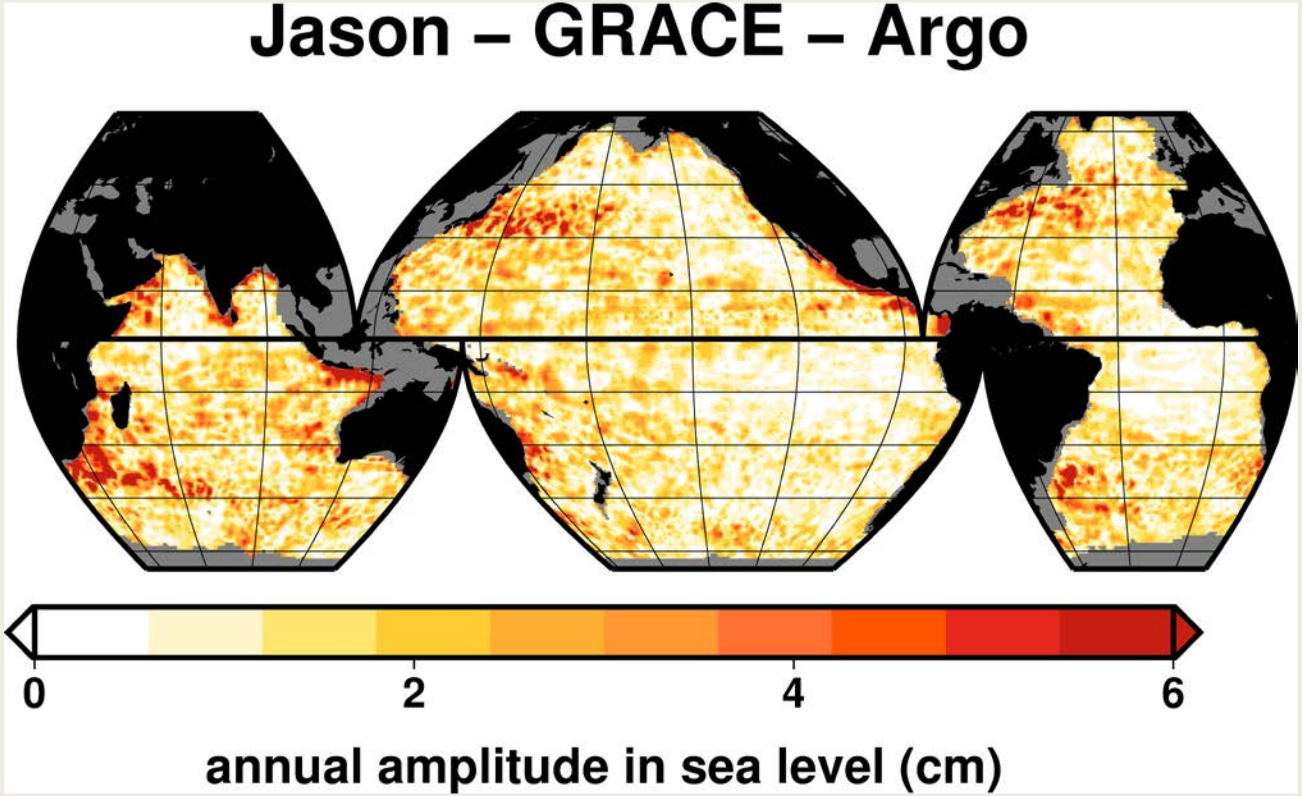
The seasonal sea level budget is closed in most regions.



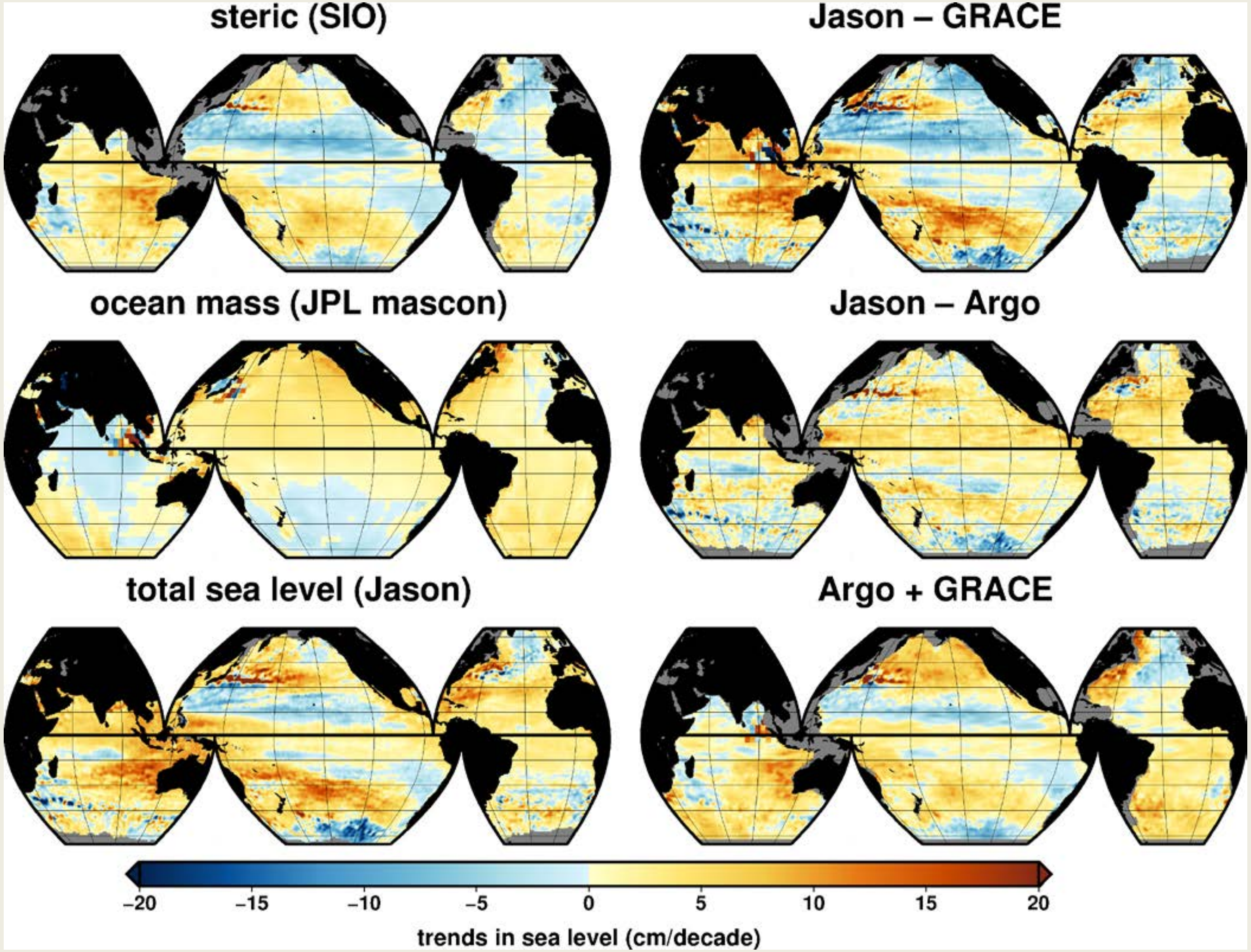
Residual seasonal signal

The residual annual signal is significant mainly in mesoscale regions.

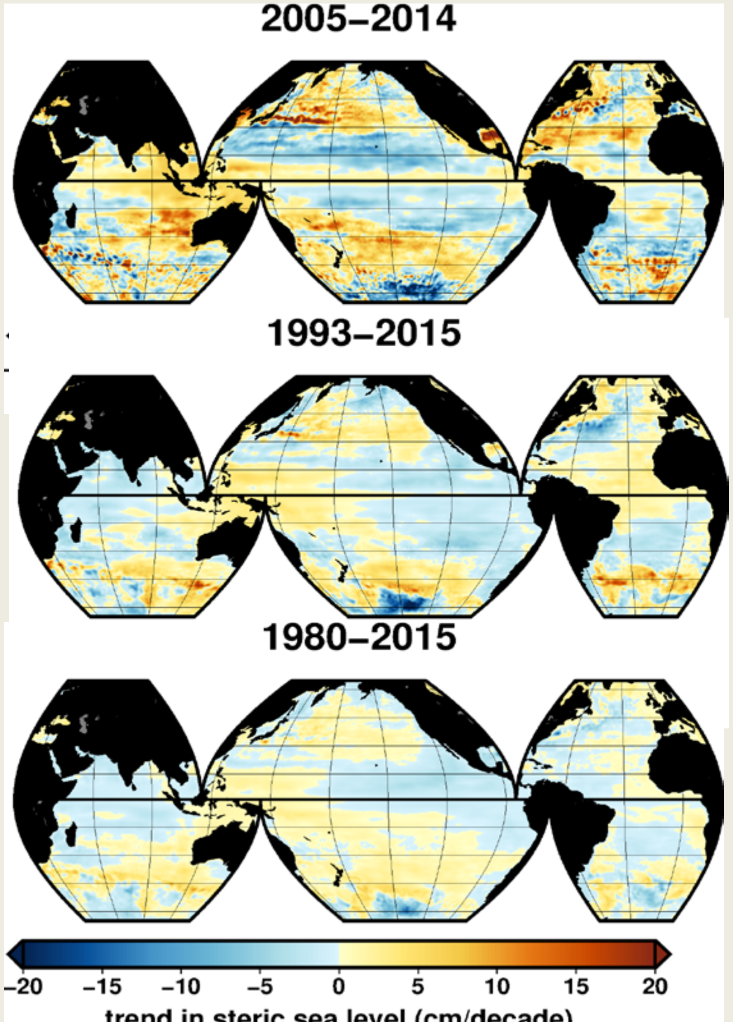
[Note change in scale.]



Local sea level budget trends



Steric trends from SODA

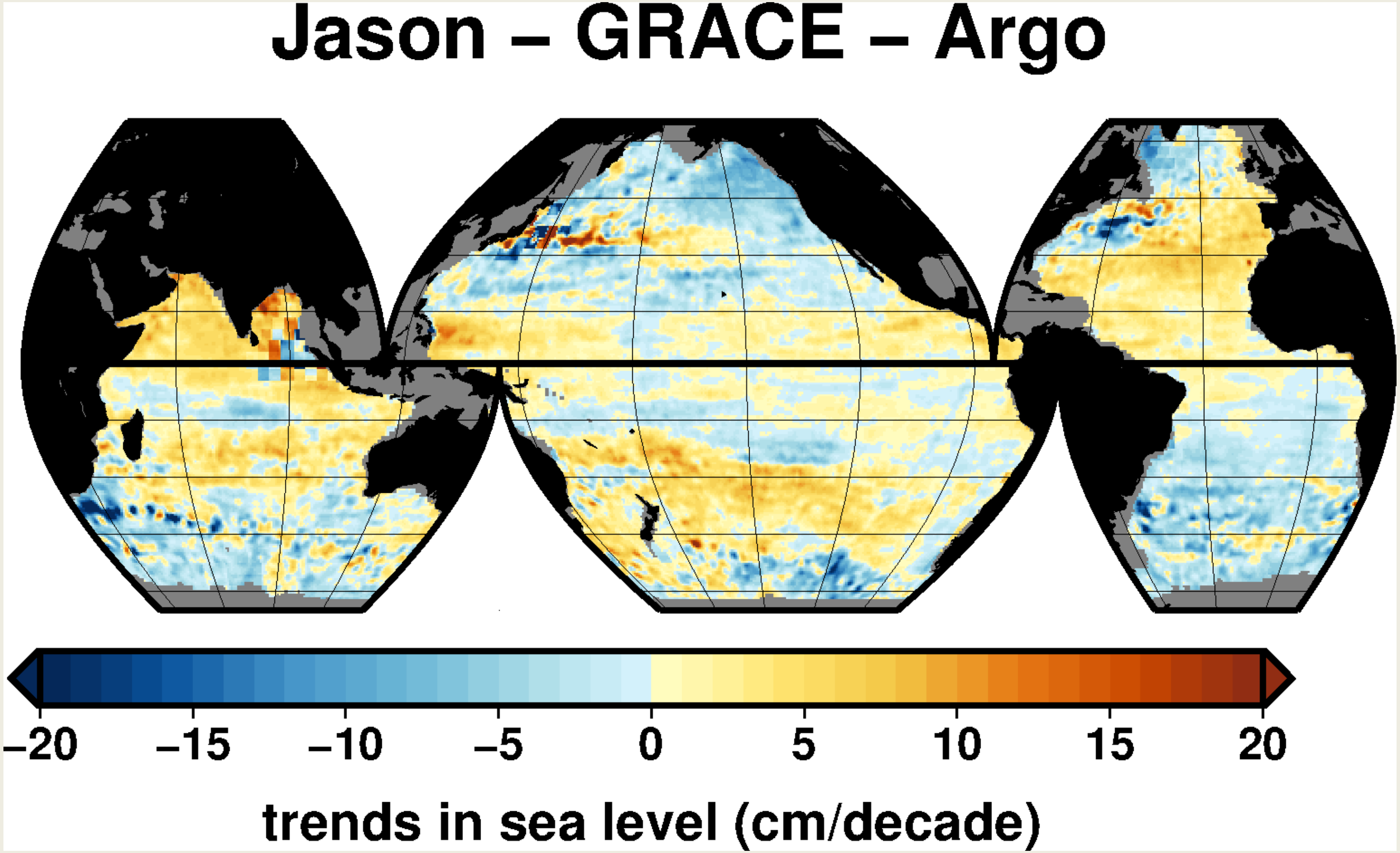


Regional trends in the steric component of sea level from the SODA3.3.1 reanalysis a) the same time period as Figure 2, b) the altimetry era, and c) the entire reanalysis period.

The steric trends from the SODA 3.3.1 reanalysis for 2005-2014 show a similar pattern to the Argo/SIO trends, but exhibit higher magnitudes such as those inferred from Jason-GRACE trends.

This suggests that our analysis of the SIO/Argo steric trends may underestimate the regional trends, despite the excellent agreement in the global mean.

Residual trends



Spectrum of residual trends

We transformed the residual trends into weighted spherical harmonics to find the degree variances.

The sea level budget closes:

At basin scales:

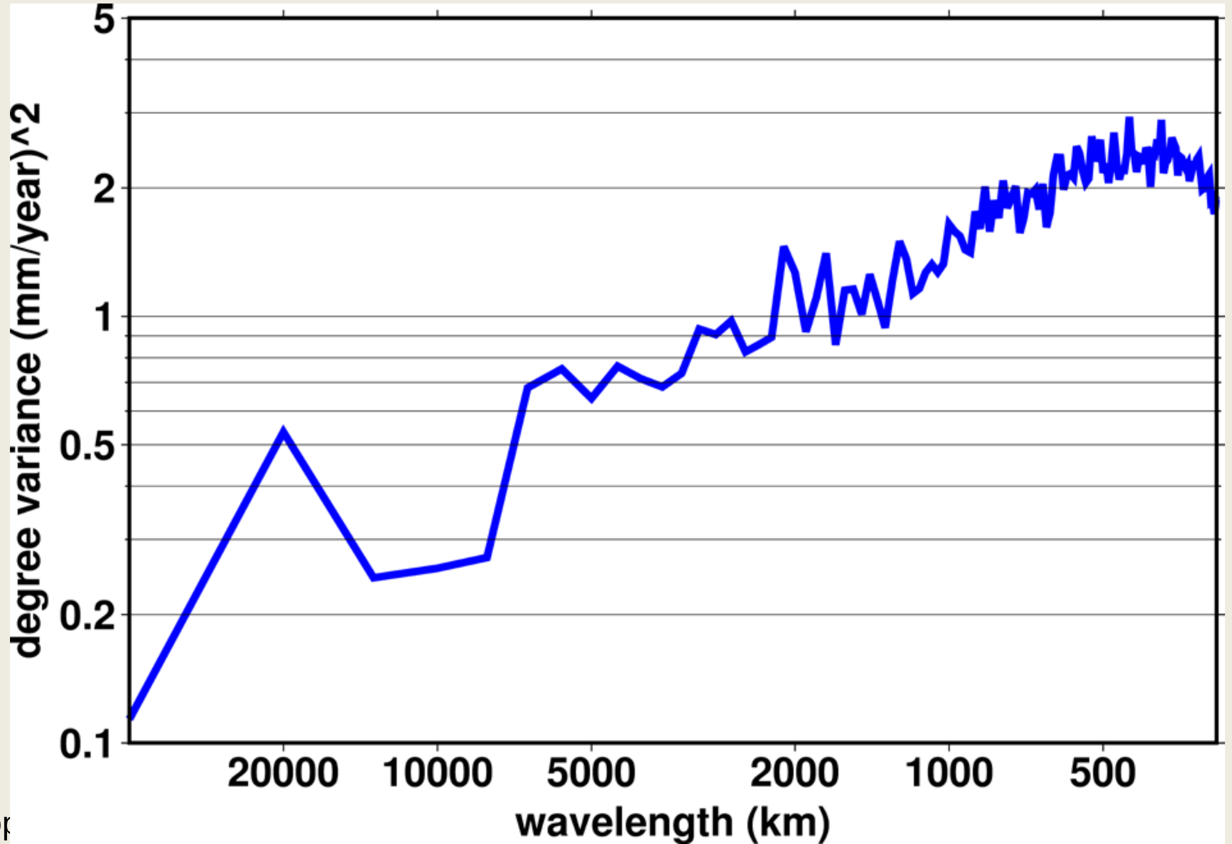
<0.5 (mm/year)^2

For scales 2000km:

~1 (mm/year)^2

For scales <1000km:

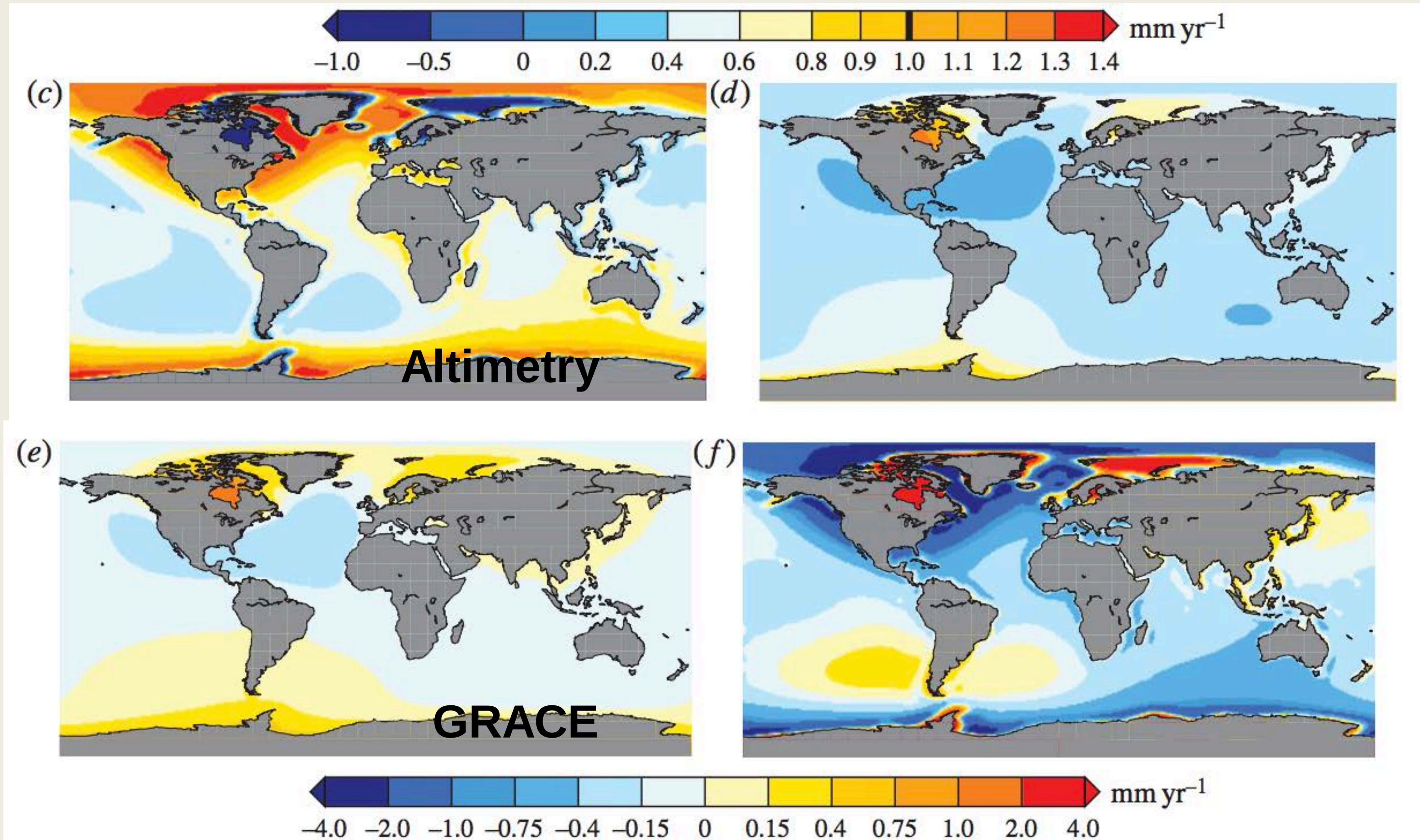
1–3 (mm/year)^2



Sea level fingerprints?

Predicted spatial patterns of relative sea level change caused by a mass loss equivalent to a 1 mm/yr globally averaged SLR.

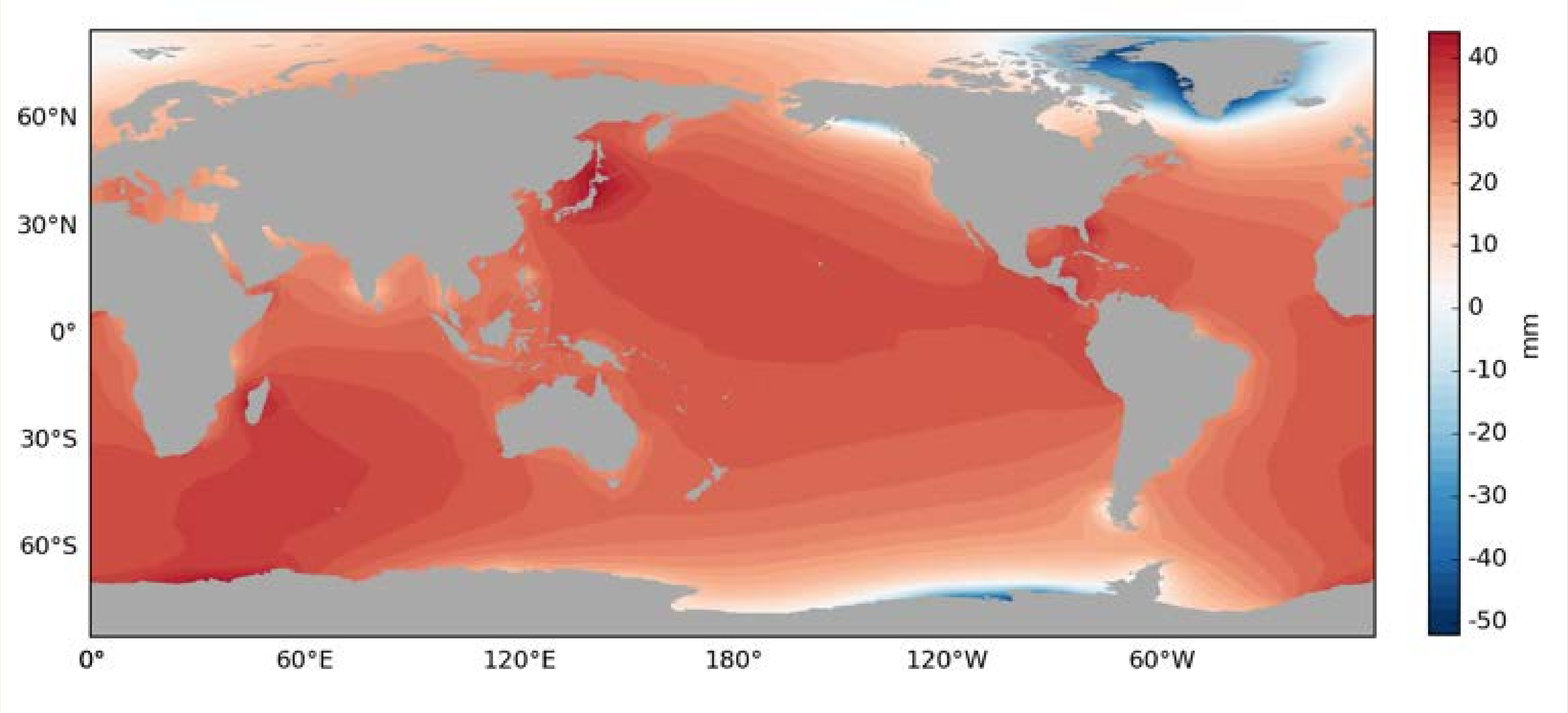
Greenland **West Antarctica**



Tamisiea and Mitrovica [2011]

Sea level fingerprints

Cumulative sea level fingerprint estimated from GRACE estimates of continental mass change [Watkins et al., 2015] since 2002.



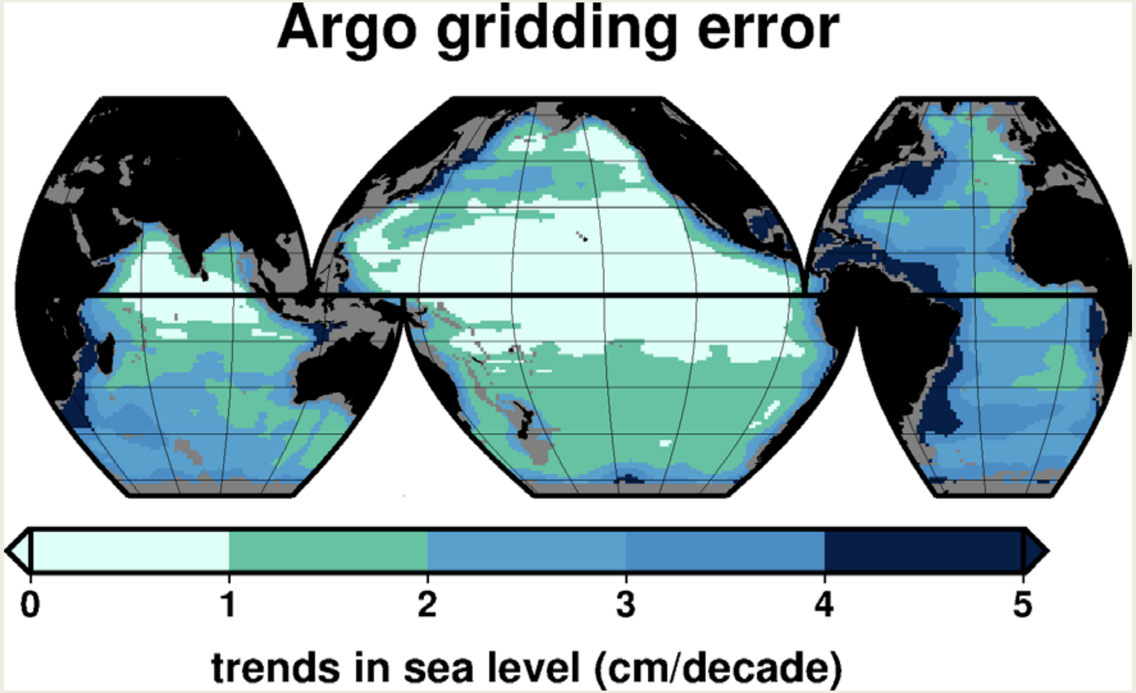
Adhikari et al., 2015

Residual trends and Argo errors

We use the estimated gridding errors from the JAMSTEC monthly grids of Argo temperature and salinity to infer the error in the Argo trends.

We assume errors in depth are correlated.

Errors are generally higher in the Atlantic and the Southern Ocean.



95% significance

GRACE Follow-on

After 15 years, the GRACE mission ended in October.

To continue measuring time-variable gravity, a GRACE Follow-on mission is scheduled for launch in spring 2018, again with a nominal 5-year lifetime.

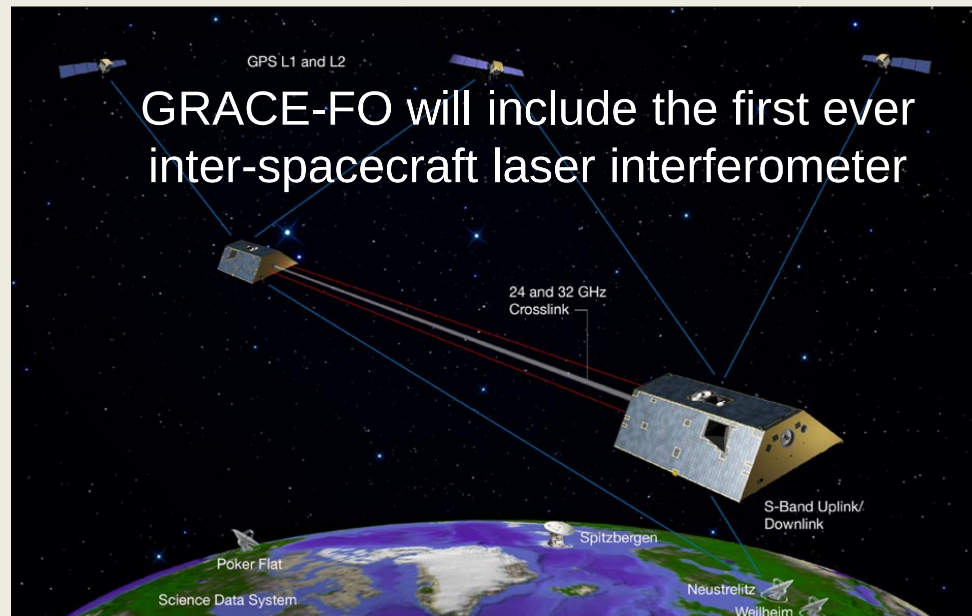
SPACENEWS

GRACE mission comes to an end

by **Jeff Foust** — October 27, 2017

The GRACE Earth science mission used two spacecraft flying in formation to measure changes in the local gravitational field linked to weather and climate. Credit: NASA

WASHINGTON — An Earth science mission launched more than 15 years ago has finally come to an end, slightly earlier than previously expected, NASA announced Oct. 27.



Conclusions

- The seasonal level budget and the sea level rise budget both close globally and on basin scales.
- With the current observing system, we can expect budgets to close < 1 mm/year at scales > 2000 km or better.
- Budget closure should improve as the observing system expands:
  - Altimetry
    - 2018 and beyond: five or more active altimeters
  - GRACE Follow-on
    - Consistent monthly ocean mass measurements (2018-2023+)
  - Argo
    - Core network + augmentation + Deep Argo