Sea level rise and the Earth's energy imbalance

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Outline

- **What do we mean by « sea level »?**

(What is in the sea level signal at climatic time scales?)

- **Contemporary Sea level rise**

(Is the current sea level rise unusual? Is sea level rise accelarating?)

- **Causes of contemporary sea level rise**

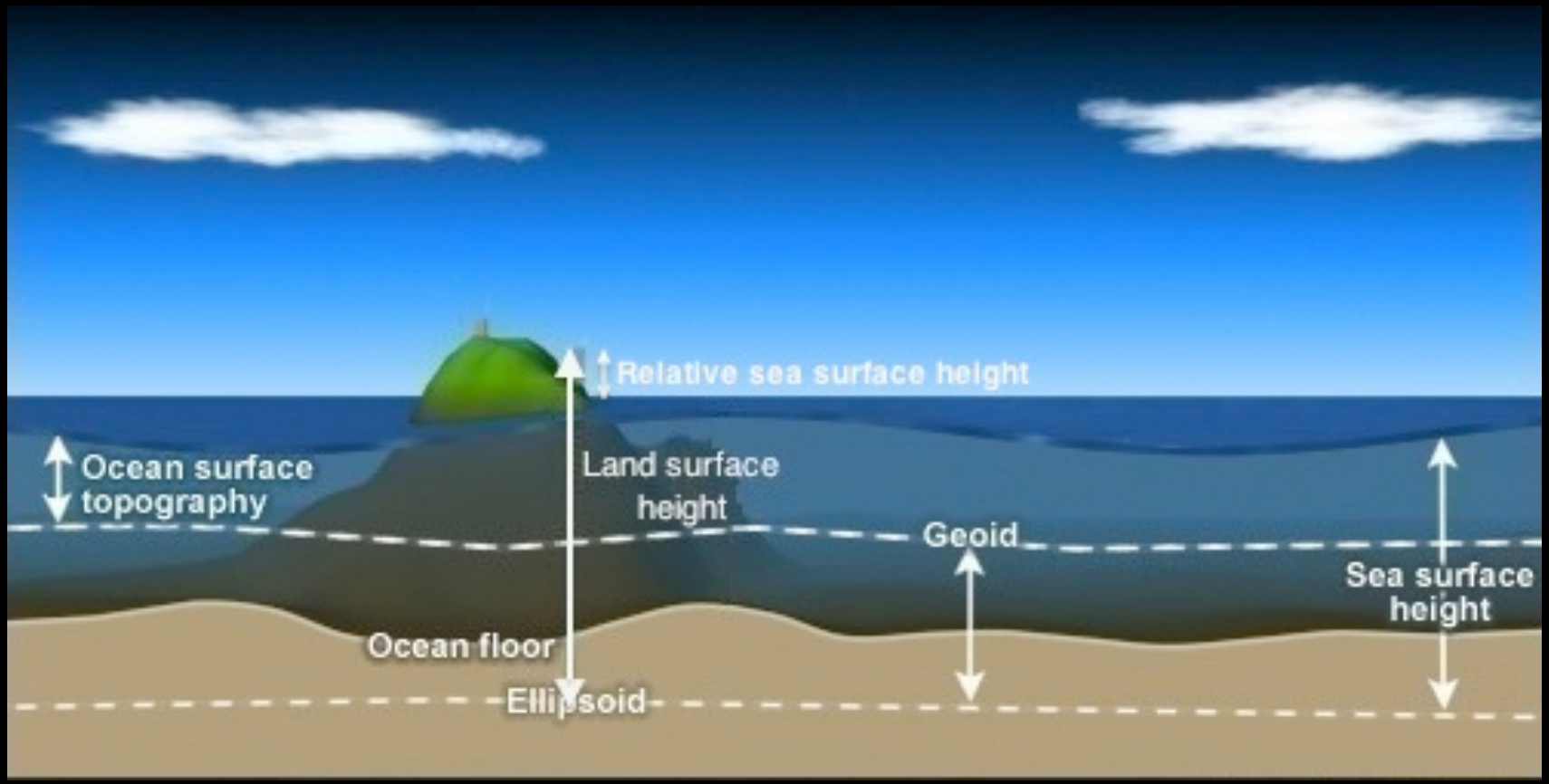
(can we explain the present sea level rise and close the sea level budget?)

- **Implications for the Earth's energy budget**

(Can sea level rise observations give a constraint on TOA imbalance?)

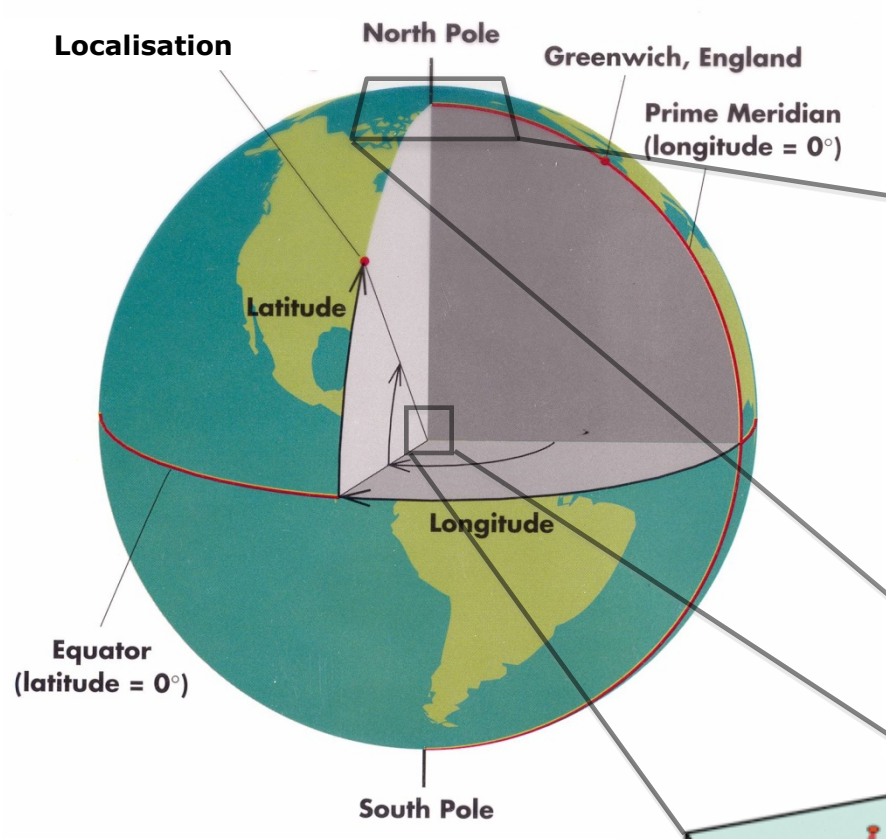
What do we mean by sea level?

absolute sea level and relative sea level

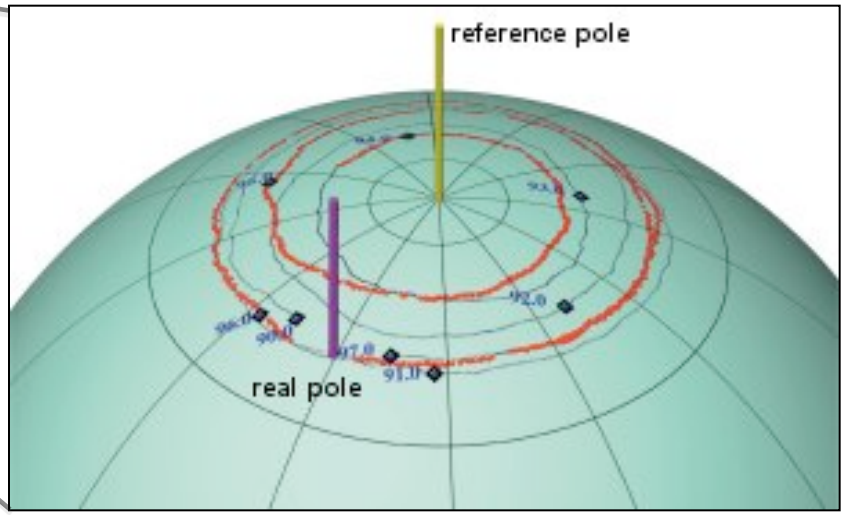


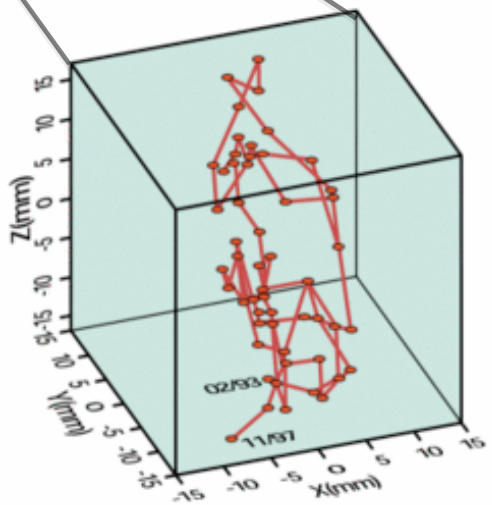
relative SSH = absolute SSH – absolute LSH

International Terrestrial Reference System:



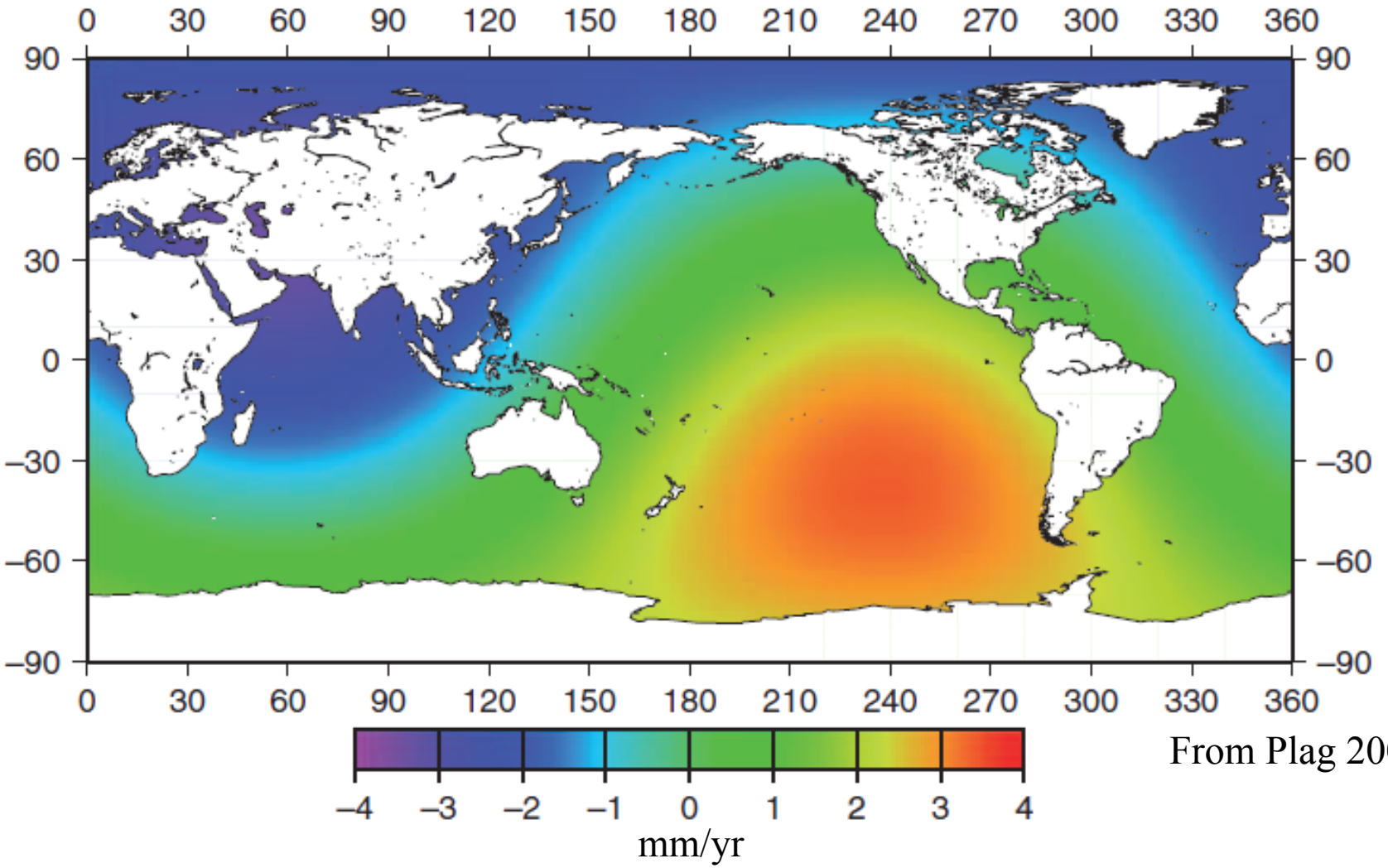
Pole Motion wrt the Earth surface (crust)





Geocenter (center of mass) motion
wrt the center of figure

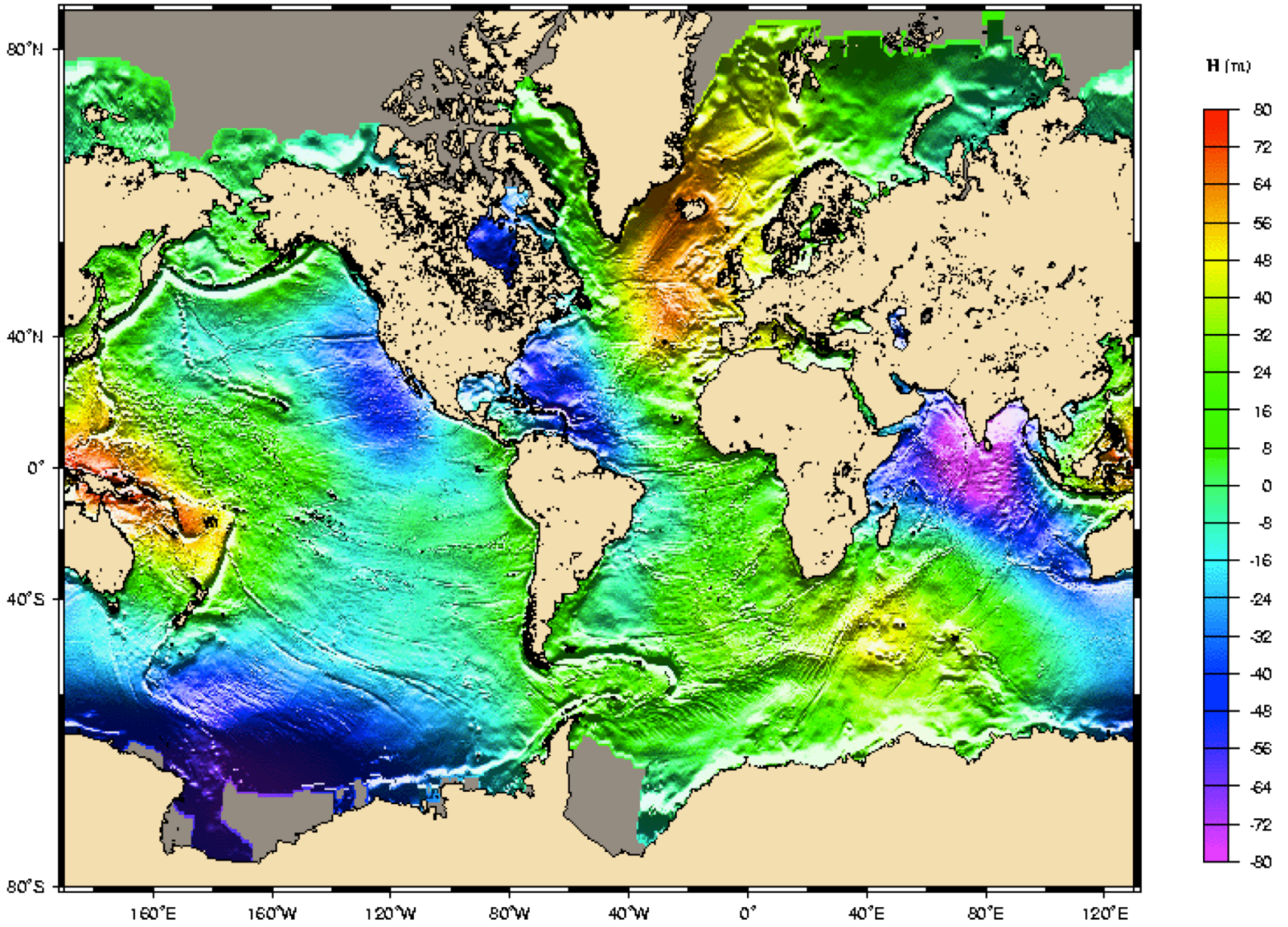
International Terrestrial Reference Frame uncertainty:



From Plag 2006

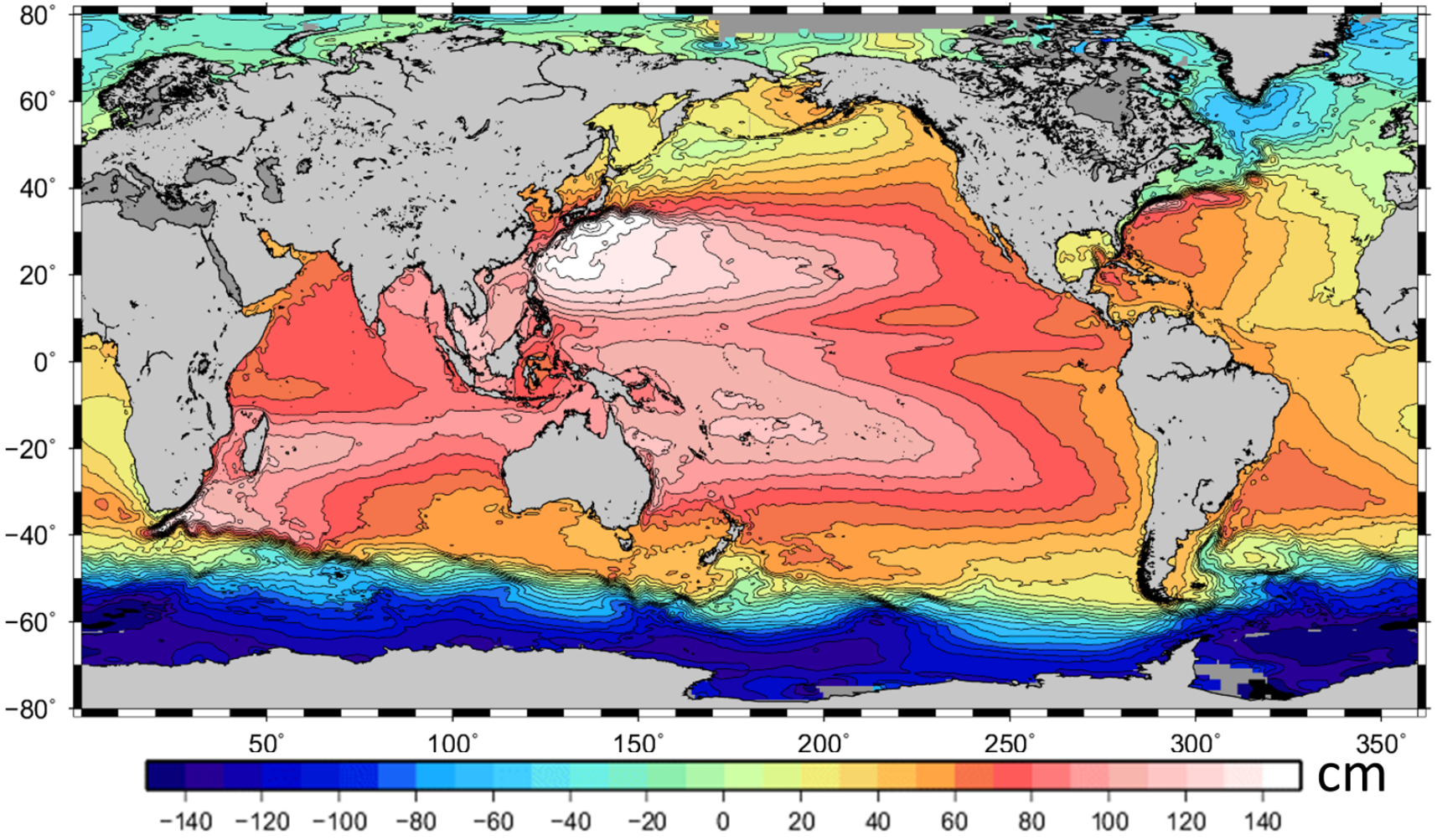
Sea level trend generated by an uncertainty in the ITRF geocenter of (-1.5,-2.2,-2.1) mm/yr between 2000 and 2006 (ITRF2000 – IGS ppp). 0.4 mm/yr in GMSL

What is in the sea level signal?
SSH = geoid+MDT+SLA



CNES,CLS, 2012

What is in the sea level signal: SSH-geoid = MDT+SLA



From Rio et al. 2011

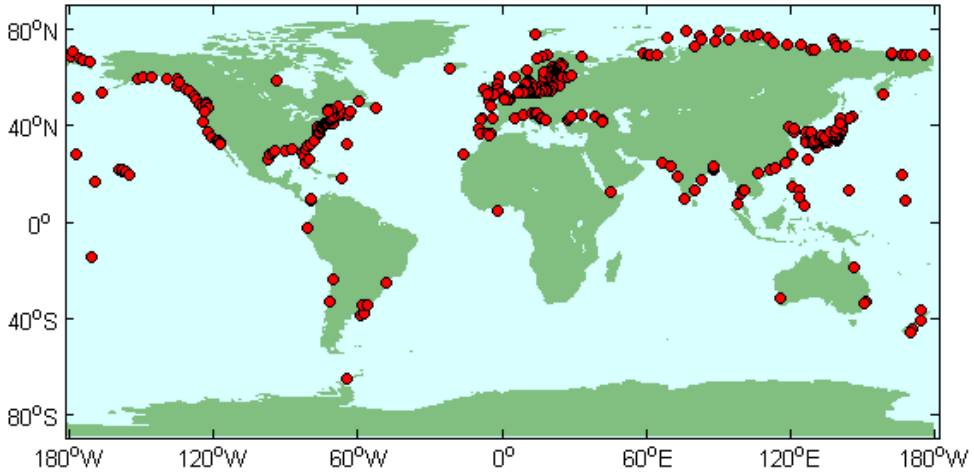
Sea level anomaly from satellite altimetry over 1993-2013

CNES,CLS, 2014

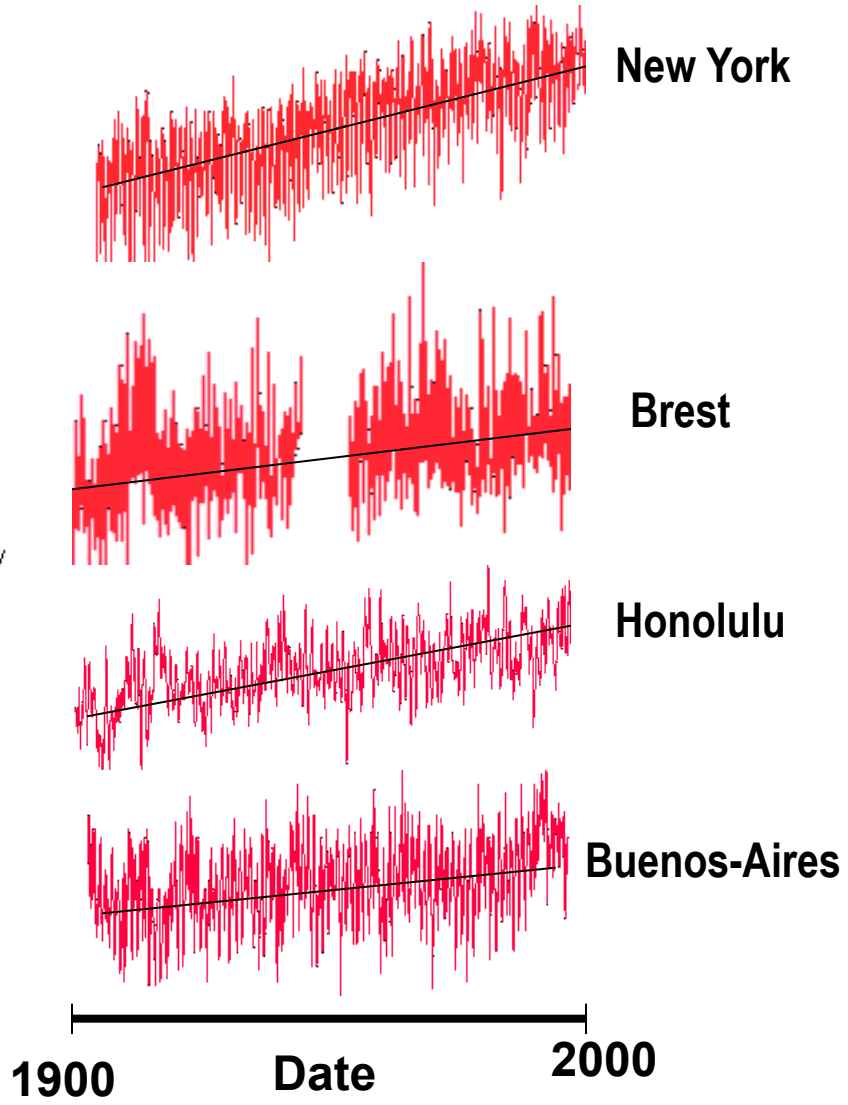
What is the Contemporary sea level rise and how do we measure it?

Instrumental era (since mid/late-19th century)

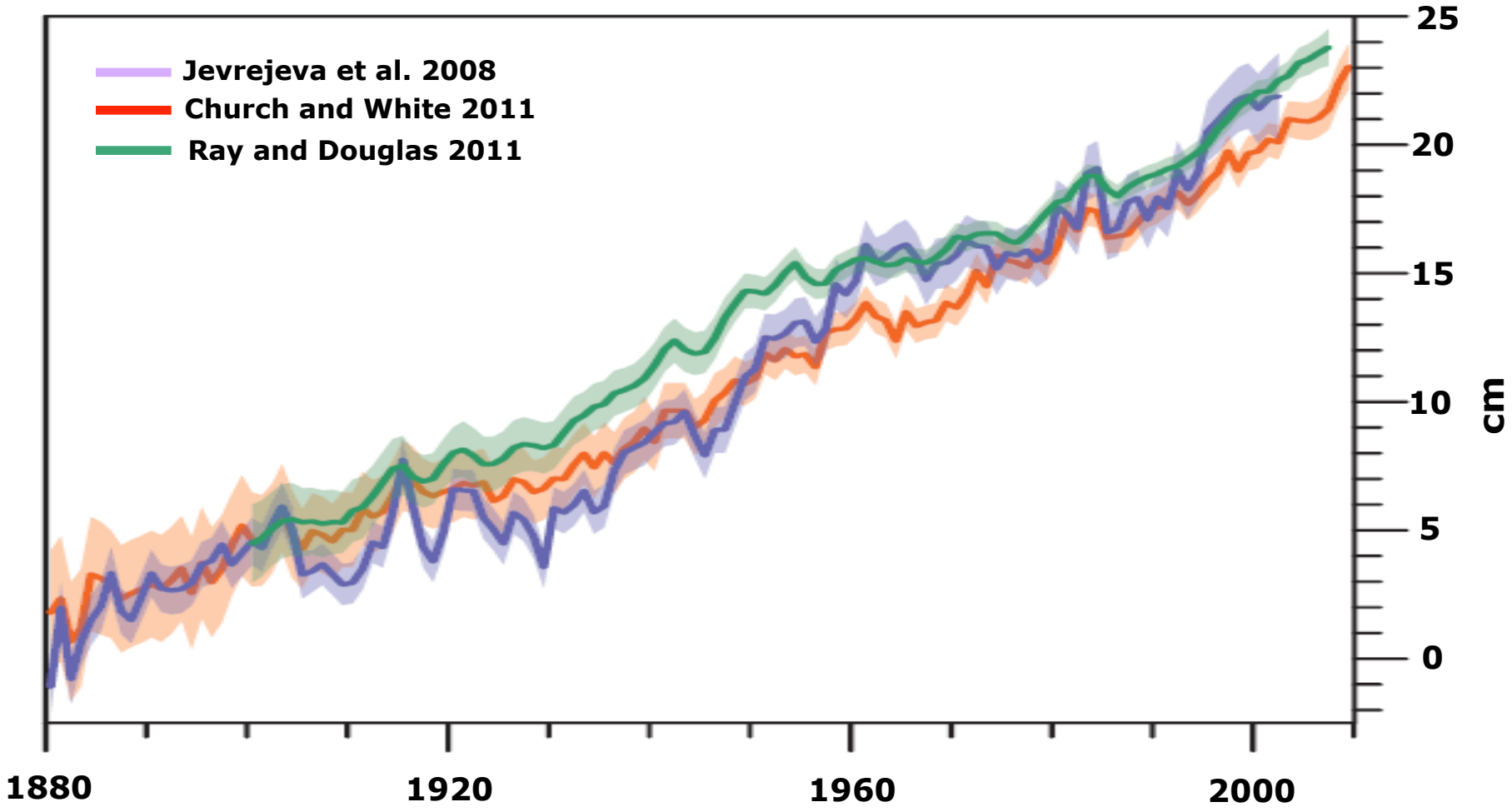
Tide gauge distribution with records > 40 years



Tide gauge

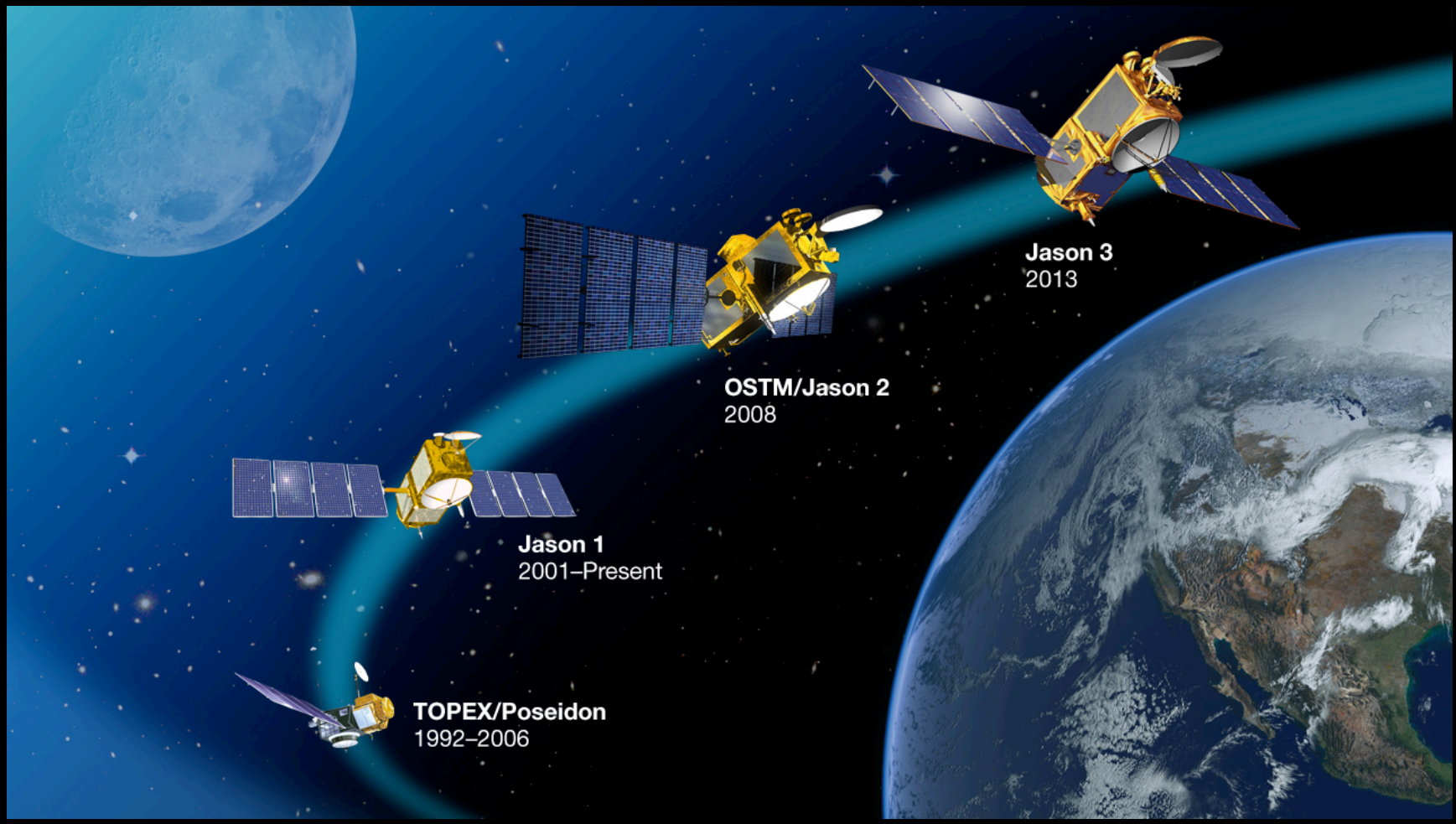


Global mean sea level (20th century) from tide gauge records

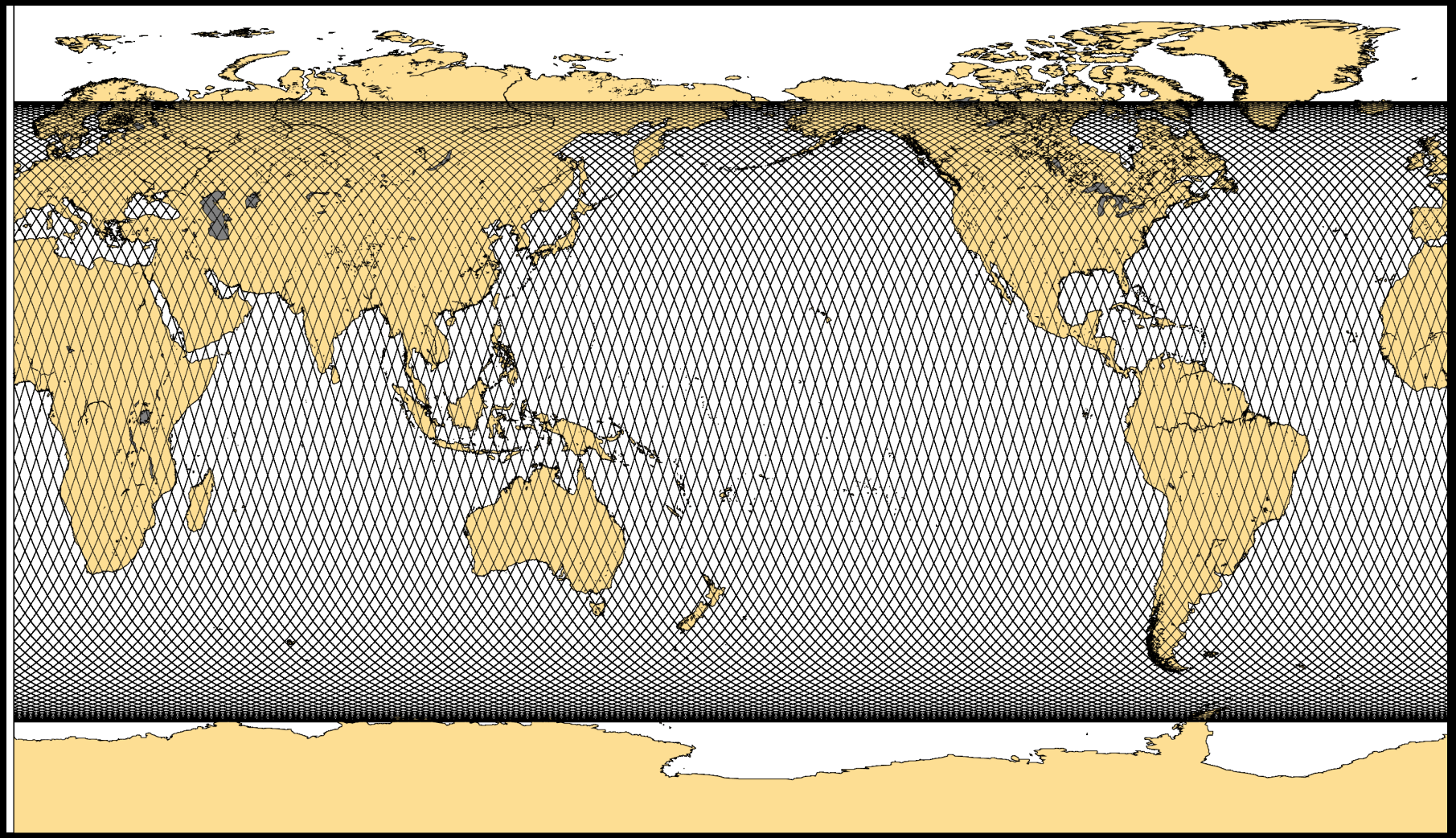


Rate of sea level rise (20th century) : 1.8 +/- 0.3 mm/yr

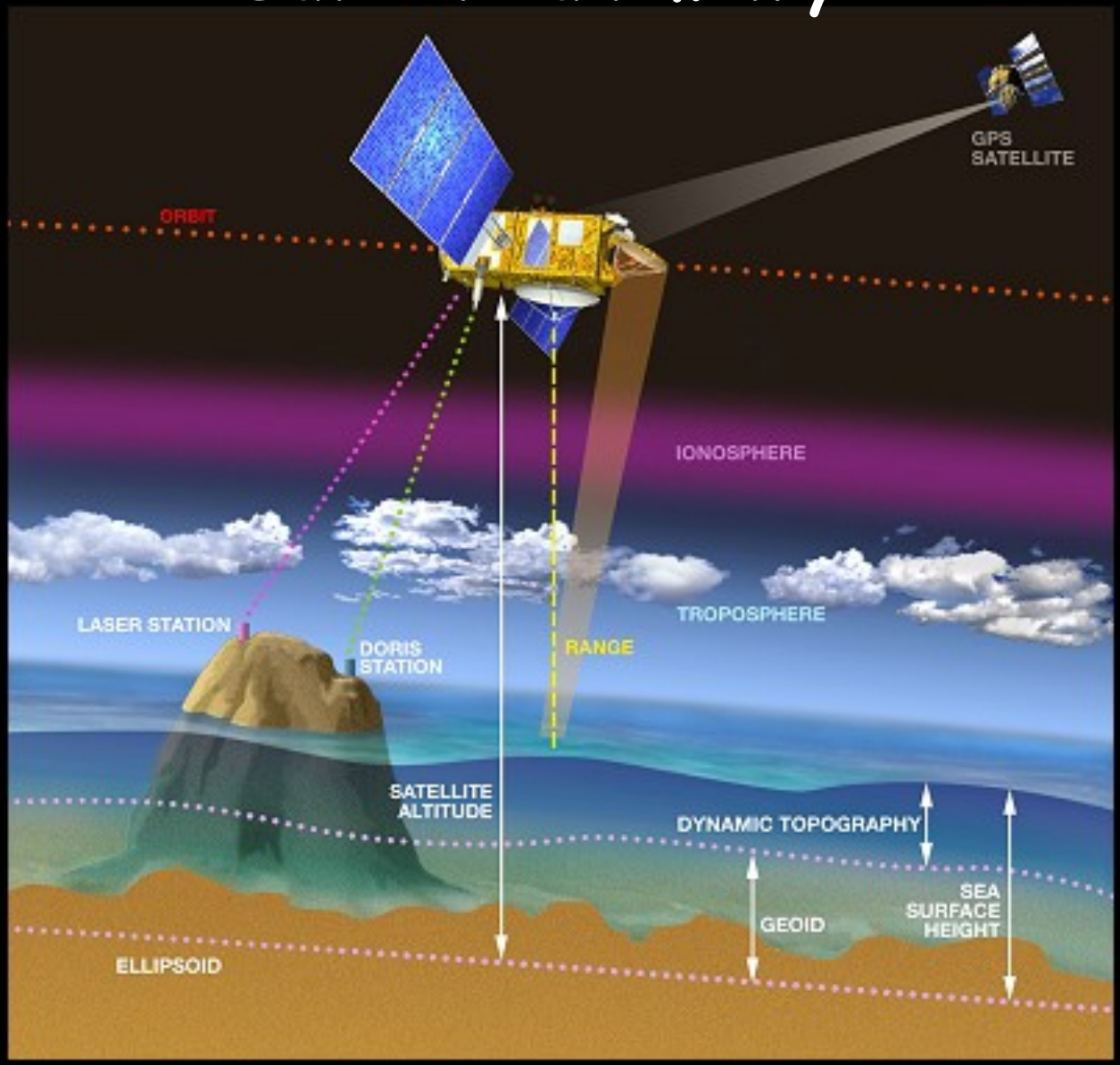
Sea level change now measured by satellites

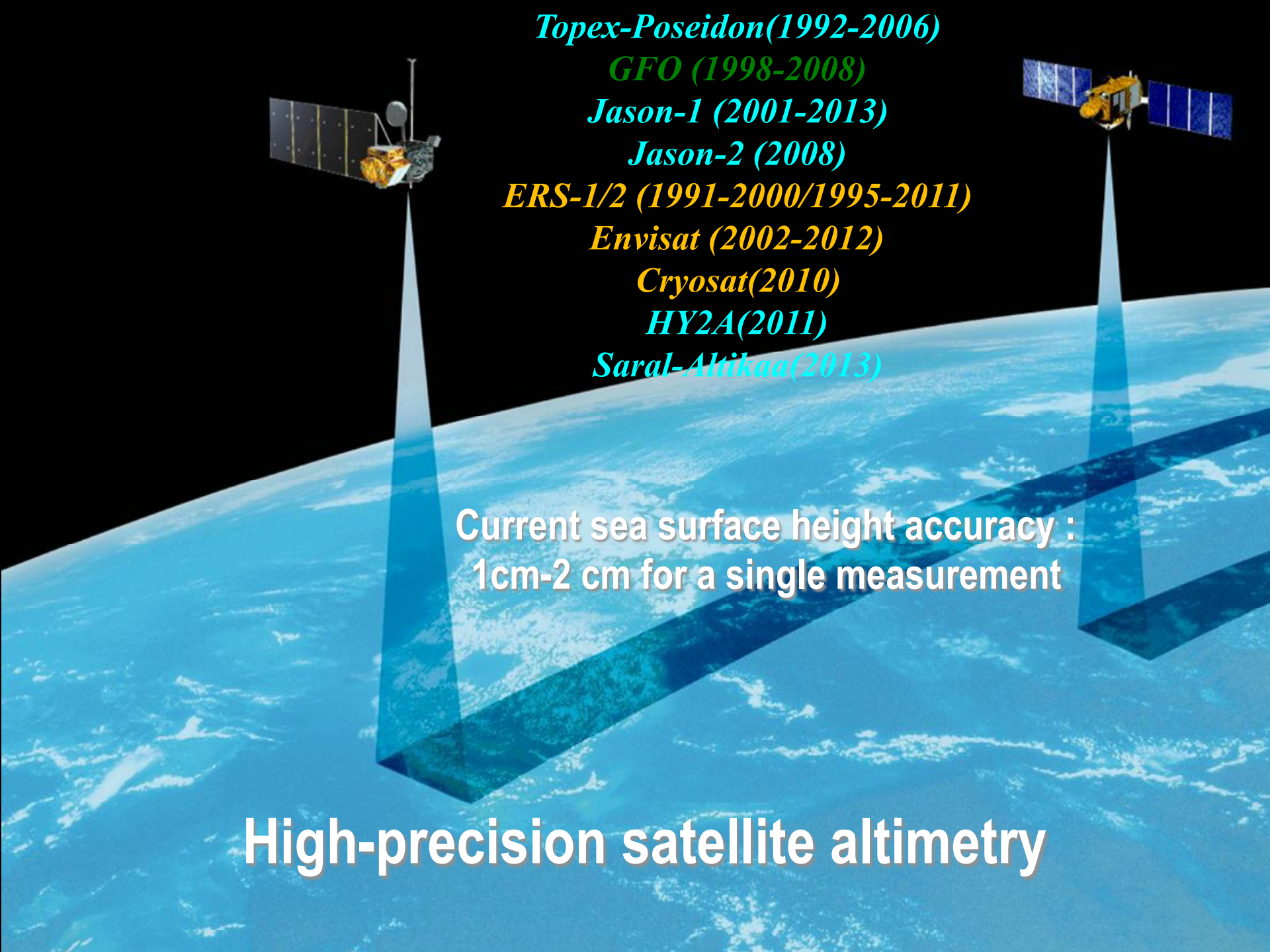


Global coverage of the Earth in a few days



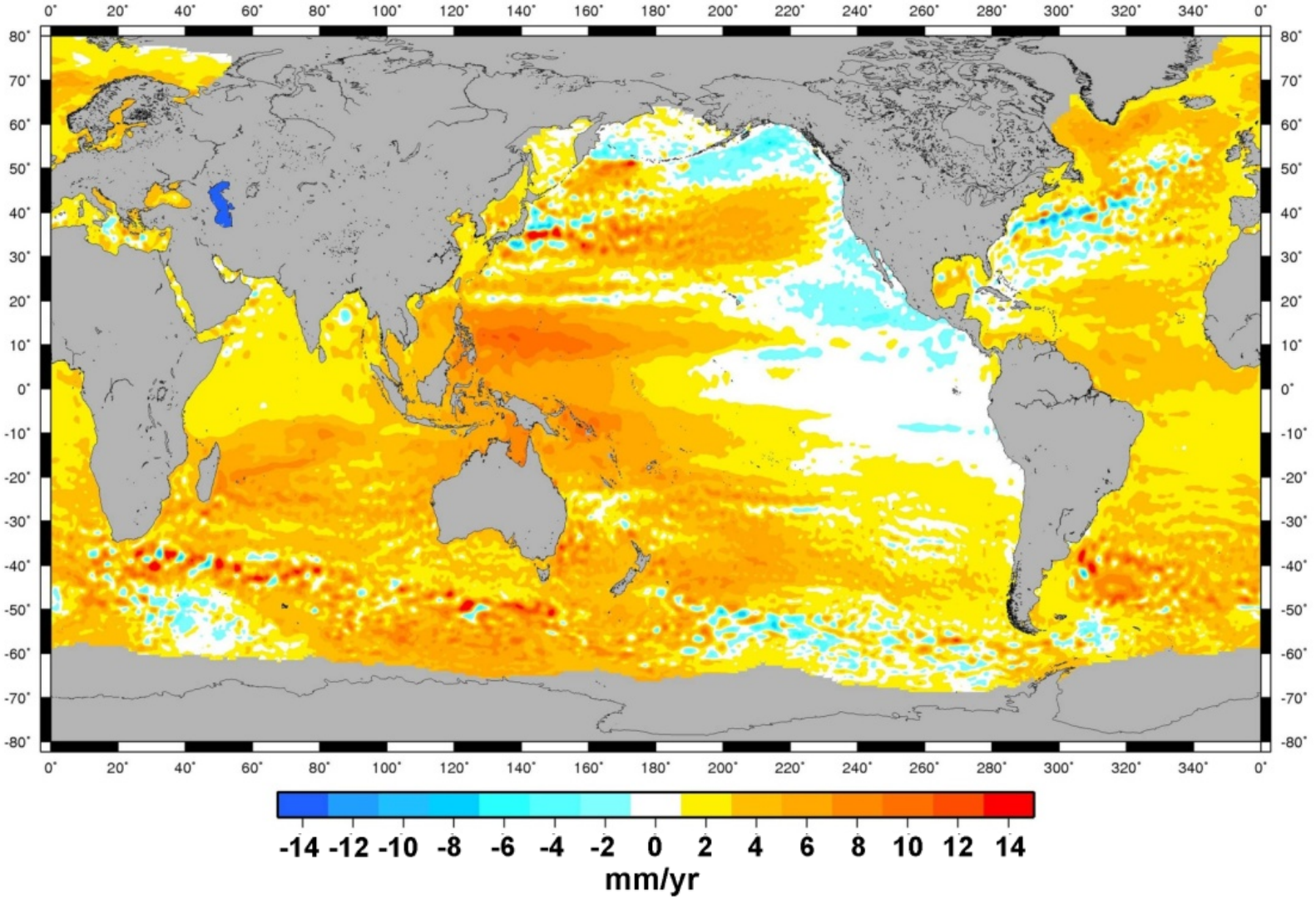
Satellite altimetry



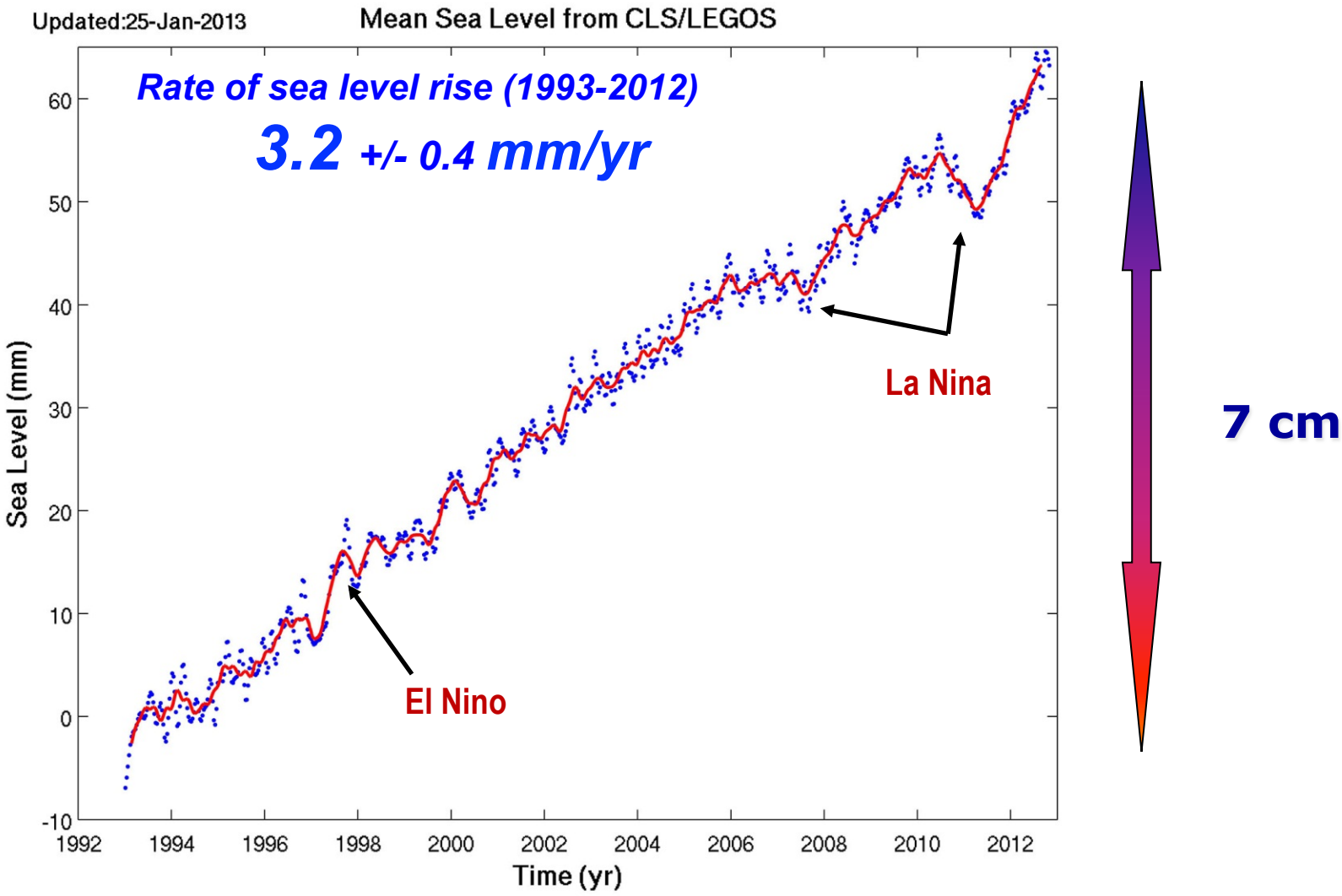

Topex-Poseidon(1992-2006)
GFO (1998-2008)
Jason-1 (2001-2013)
Jason-2 (2008)
ERS-1/2 (1991-2000/1995-2011)
Envisat (2002-2012)
Cryosat(2010)
HY2A(2011)
Saral-Altikaa(2013)
Current sea surface height accuracy :
1cm-2 cm for a single measurement
High-precision satellite altimetry

Regional sea level: Sea level does not rise uniformly!

Sea level trend patterns from satellite altimetry (1993-2012)



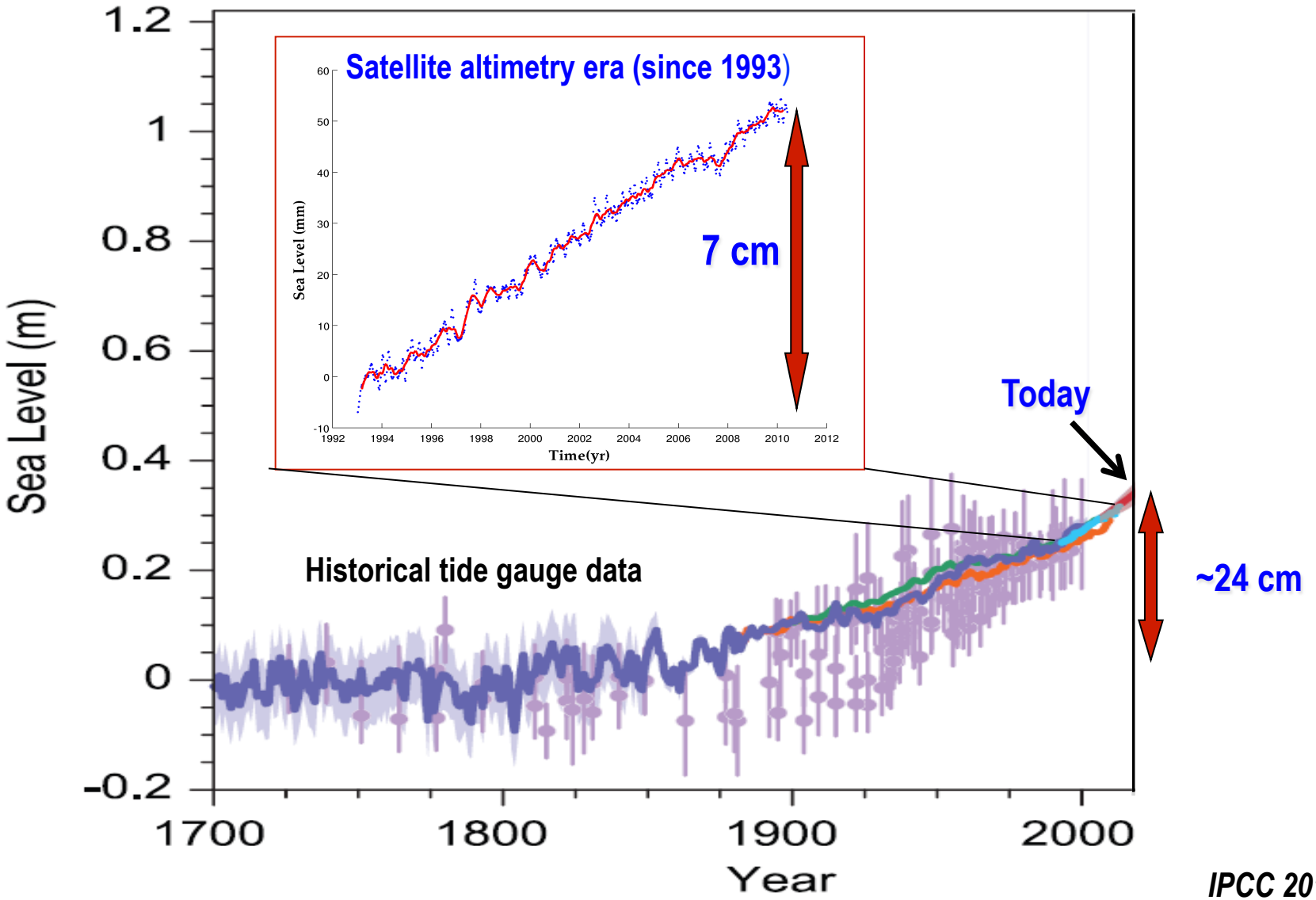
Global Mean Sea Level Rise measured by altimeter satellites since 1993



Global mean sea level trend: error budget

Source	Trend error (mm/yr)
Orbit (Beckley et al., Ablain et al.)	0.25
Wet atmos. (TMR/JMR drift) (Ablain et al.)	0.3
Topex A-Topex B (Ablain et al.)	0.25
Dry atmos. (pressure fields) (Ablain et al.)	0.1
Sea state bias (Ablain et al.)	0.1
Quadratic sum	*0.44*
Tide gauge calibration (Micthum and Nerem; Beckley et al.; Ablain et al.)	0.4

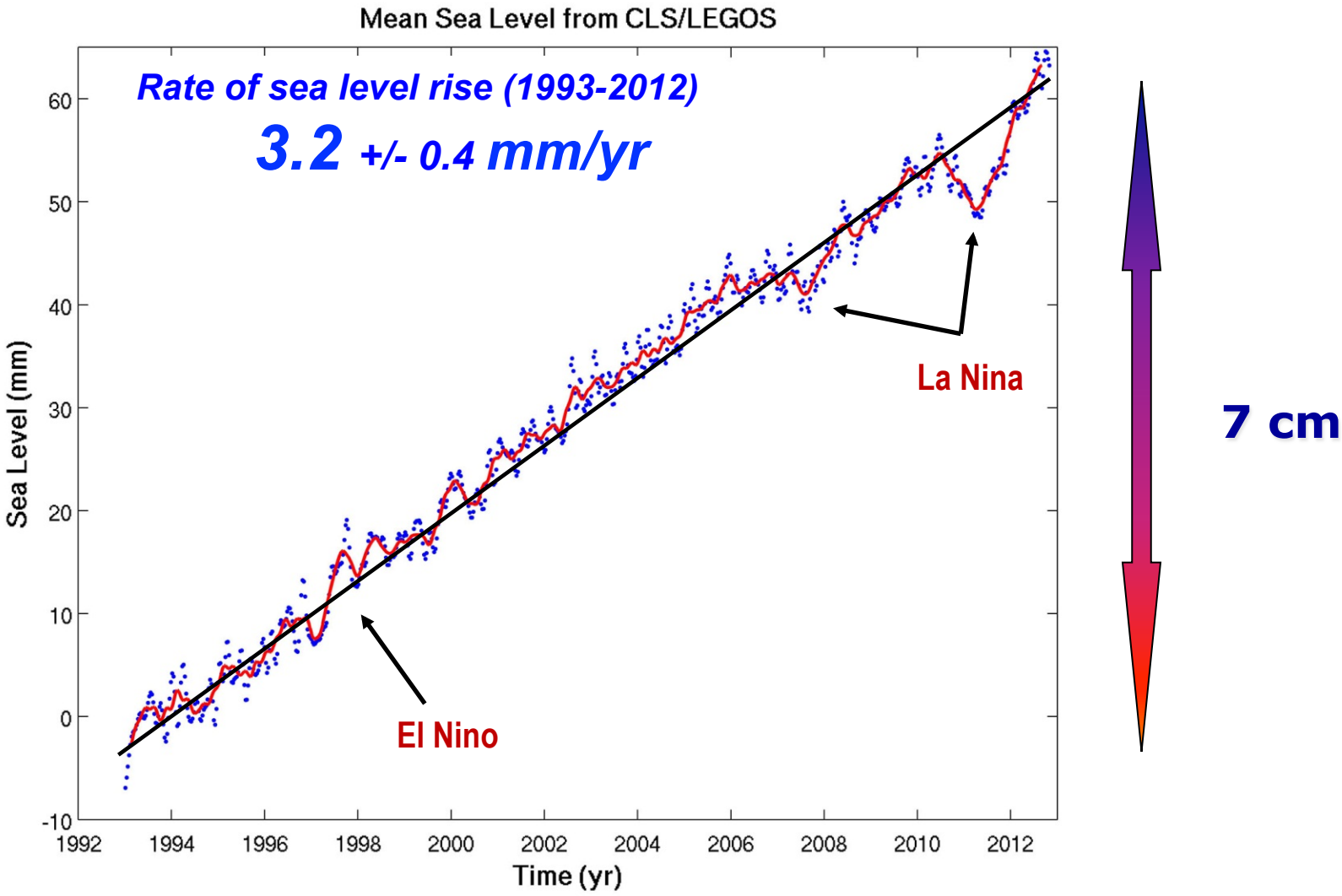
Summary of the Global mean sea level evolution



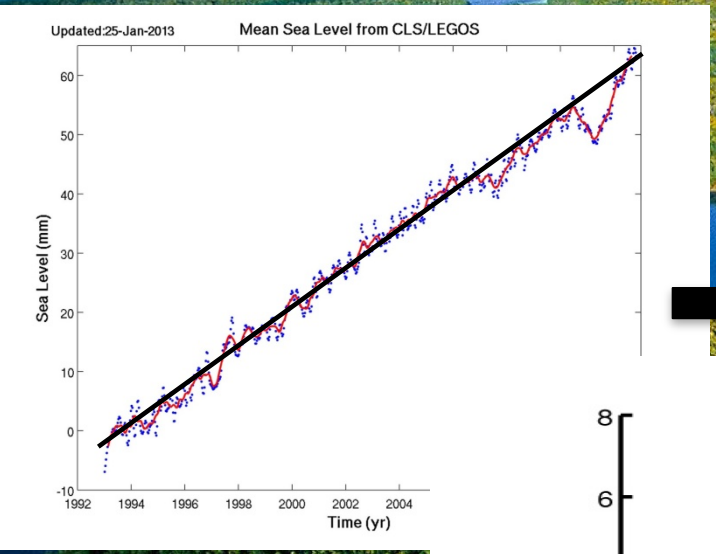
IPCC 2013

What causes contemporary sea level rise?

Global Mean Sea Level Rise measured by altimeter satellites since 1993

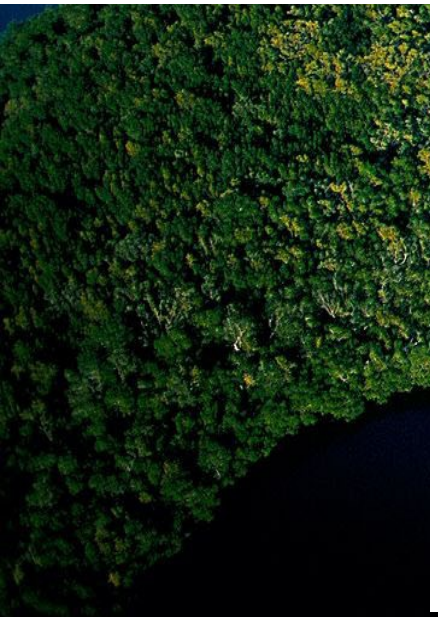


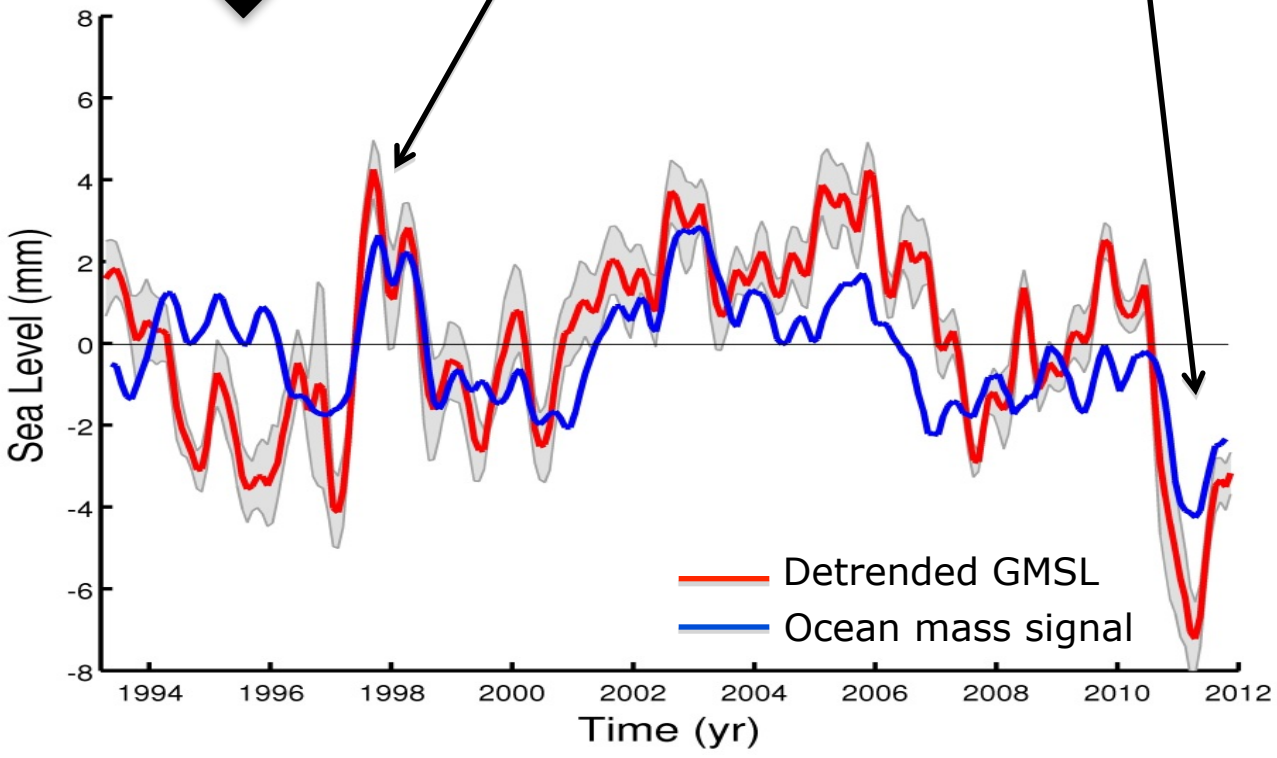
Global Mean Sea Level Rise measured by altimeter satellites since 1993



El Niño 97/98
Essentially Amazon basin water storage

La Niña 10/11
Essentially Australian basins water storage

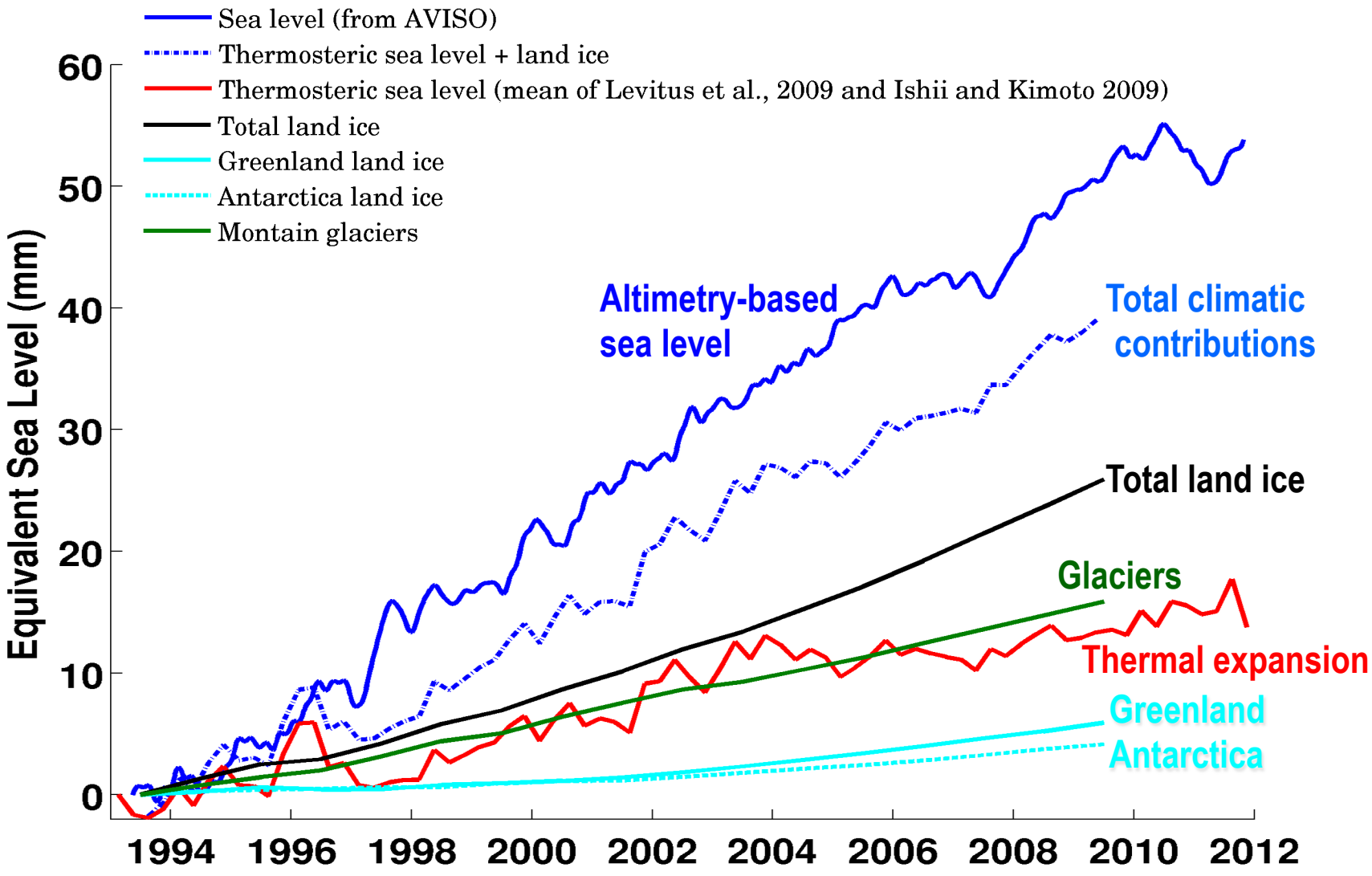




Llovel et al. 2011, Cazenave et al. 2012, Boening et al. 2012

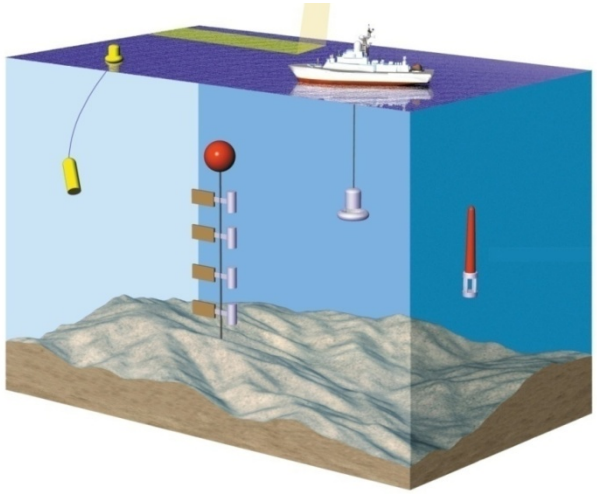
Can we explain the observed sea level rise?

Climatic contributions to the global mean sea level (1993-2012)

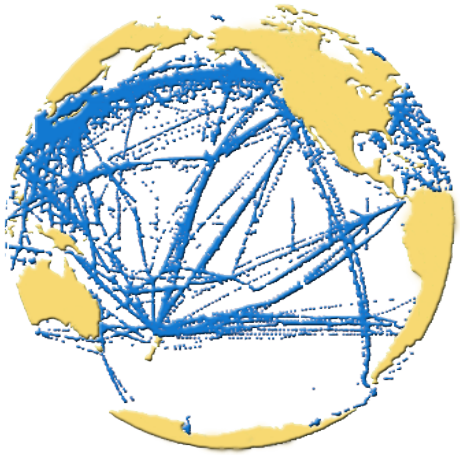


Meyssignac et Cazenave, 2012

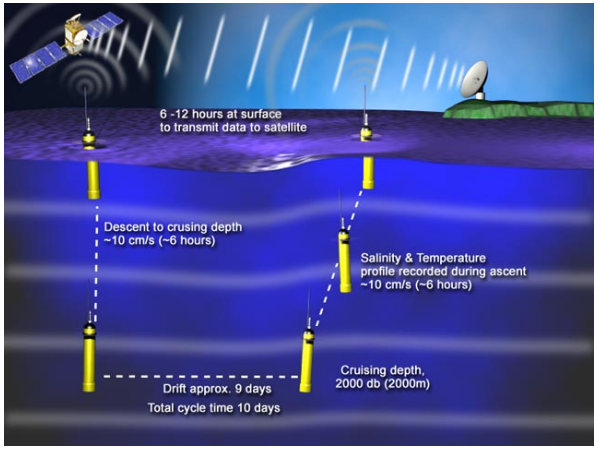
Ocean temperature measurements (XBT, CTD, Argo)

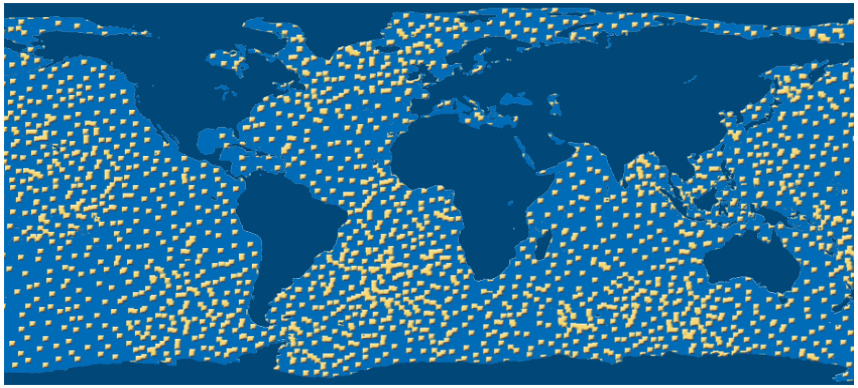


Past few decades: coverage mainly along commercial roads

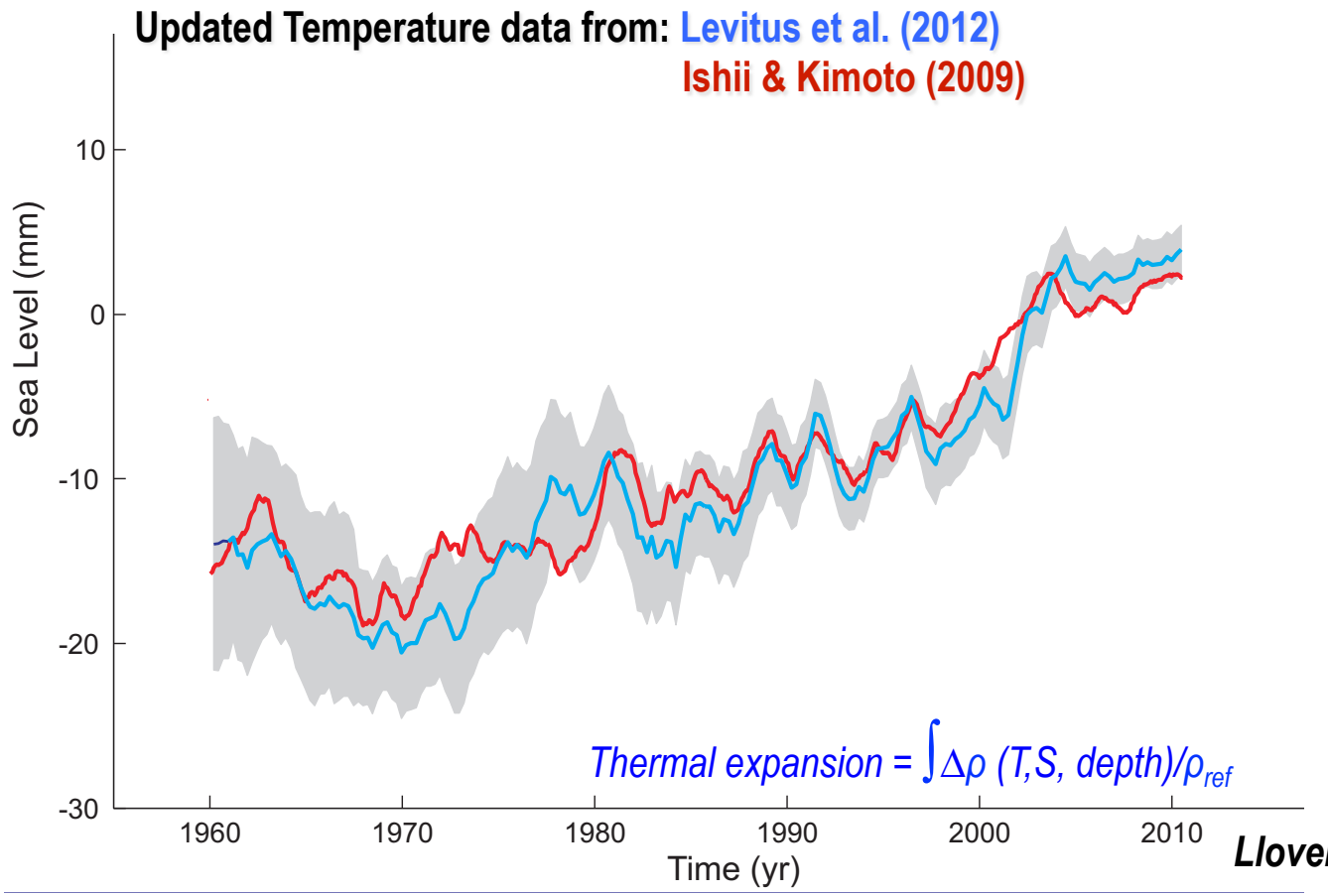


Since about 2003 → 'Argo' profiling floats



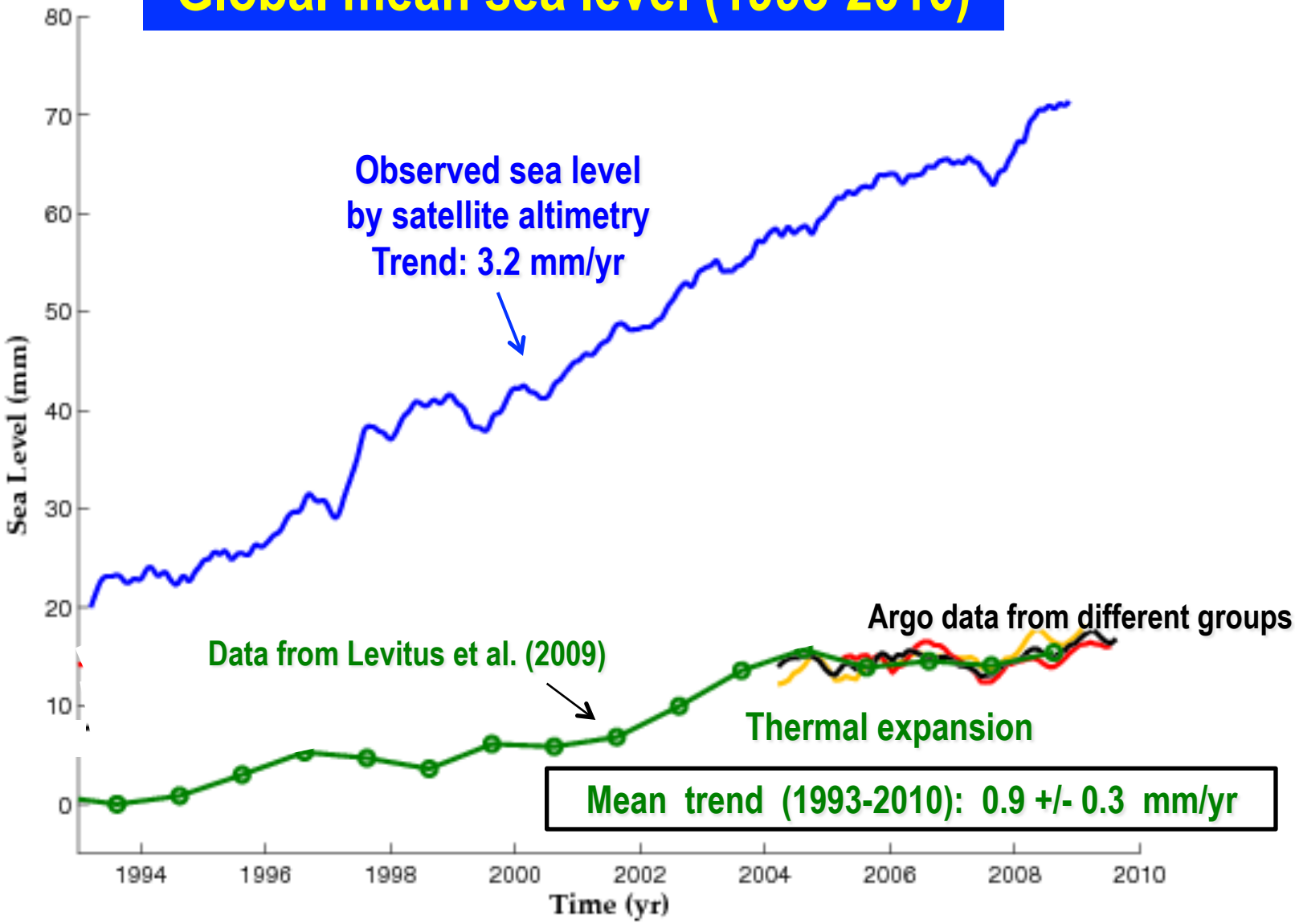


Upper ocean thermal expansion (0-700 m)
1960-2011



Llovel et al. 2012

Global mean sea level (1993-2010)



Deep ocean warming → contribution poorly known but estimated to ~ 20%

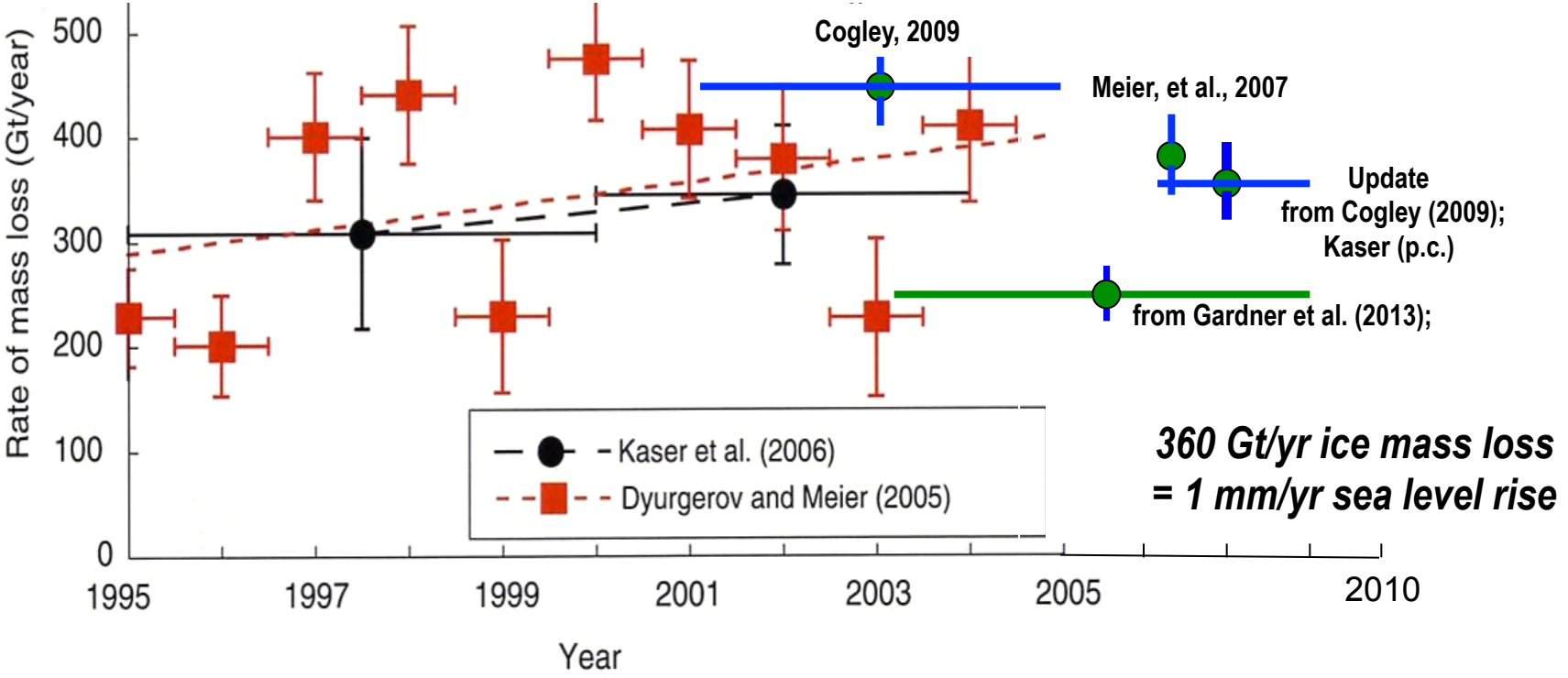
Contribution of glacier melting to sea level rise

Image SPOT 5
du massif
du Mont Blanc

GRACE space gravimetry

Contribution of glacier melting to sea level rise

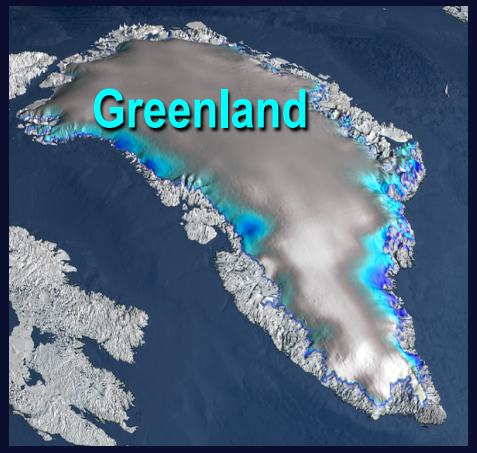
Annual Ice mass loss by glacier melting (Gt/year)



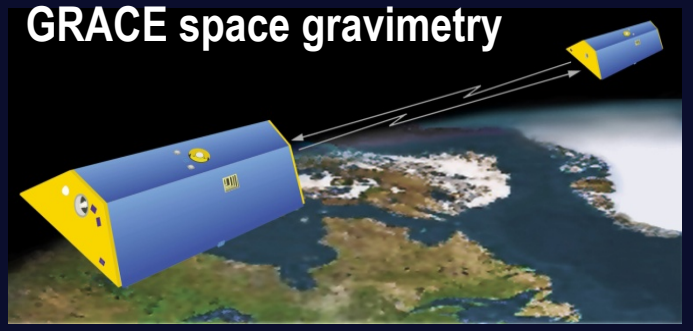
Glacier contribution to sea level rise: (1993-2010): 0.9. +/- 0.2 mm/yr
(2005-2010) : 0.7 +/- 0.15 mm/yr

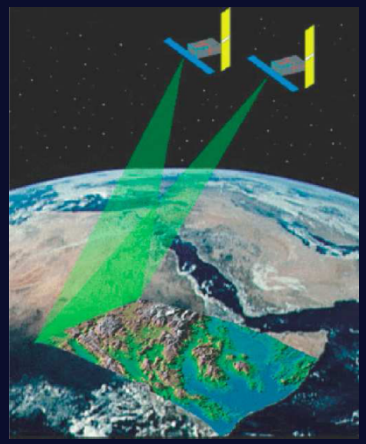
(Updated from IPCC 2013)

Ice sheet mass balance measured by remote sensing over the last 2 decades

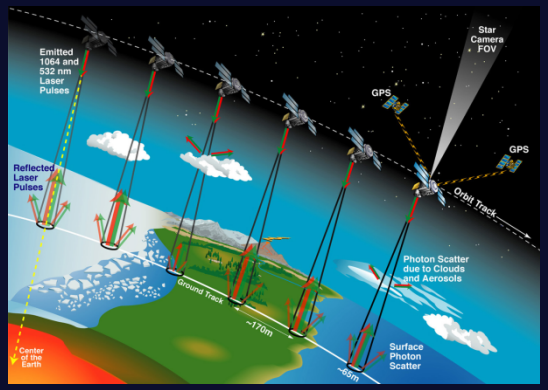


GRACE space gravimetry





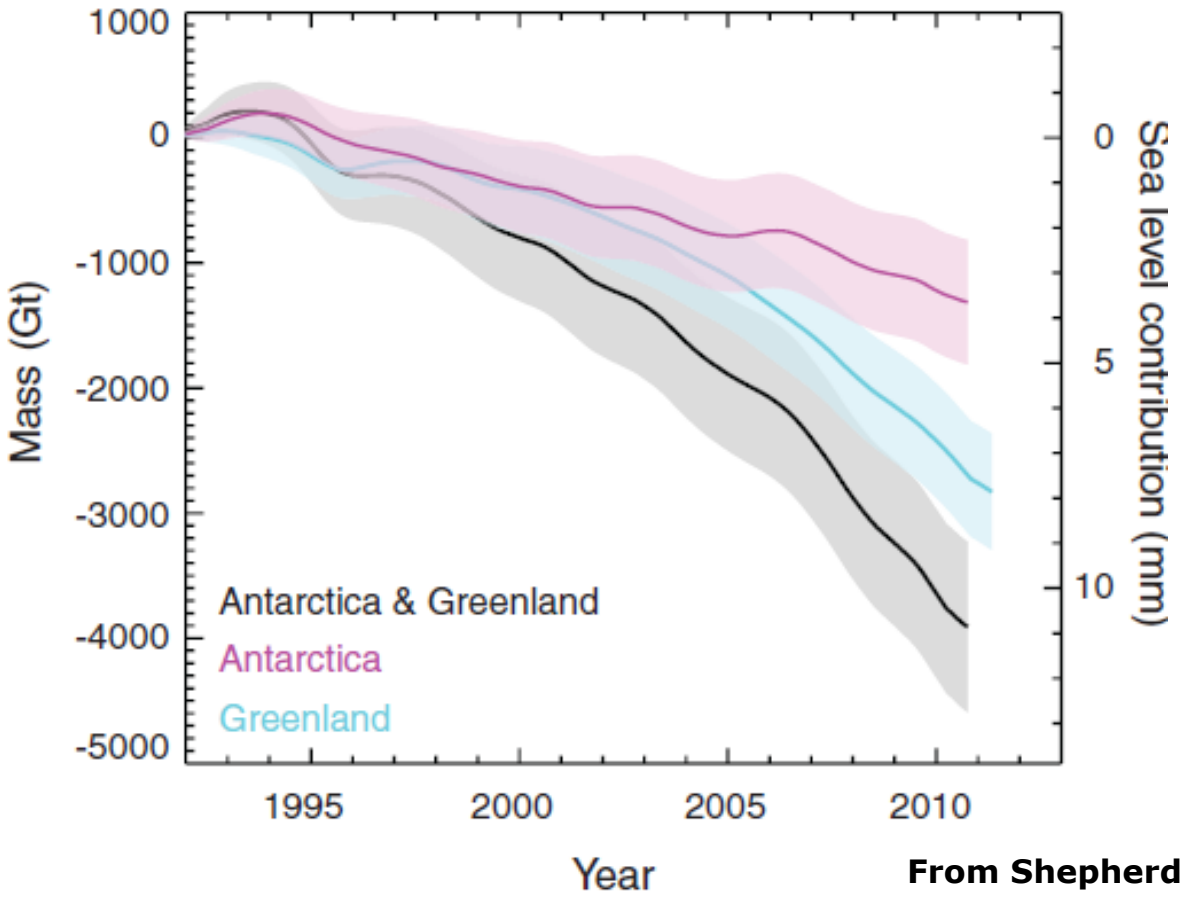
InSAR



Radar and laser altimetry

Contribution of ice sheets to sea level rise

Annual ice mass loss (Gt/yr) over 1993-2010

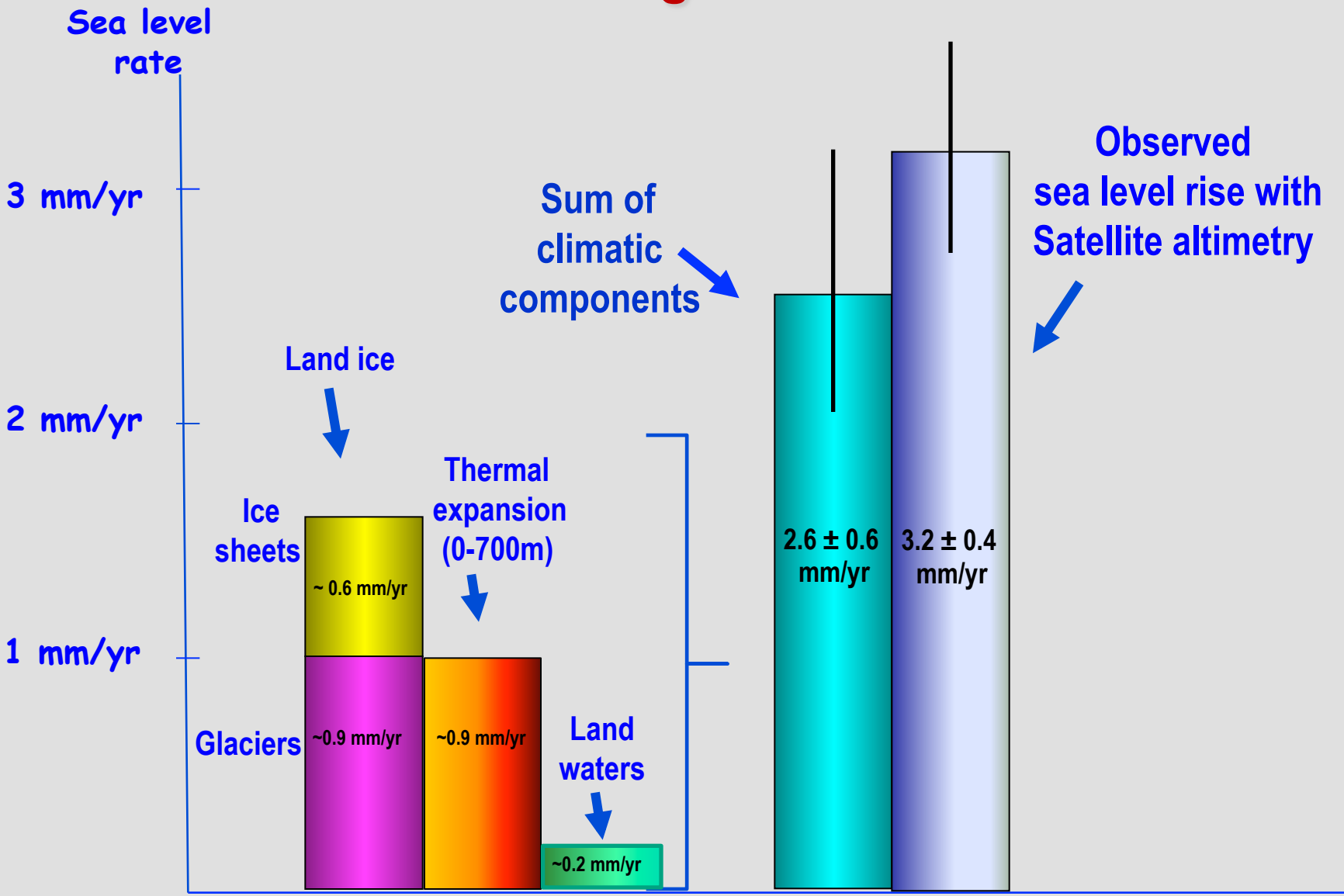


From Shepherd et al. 2012

Greenland + Antarctica contributions: (1993-2010) → 0.6 +/- 0.3 mm/yr

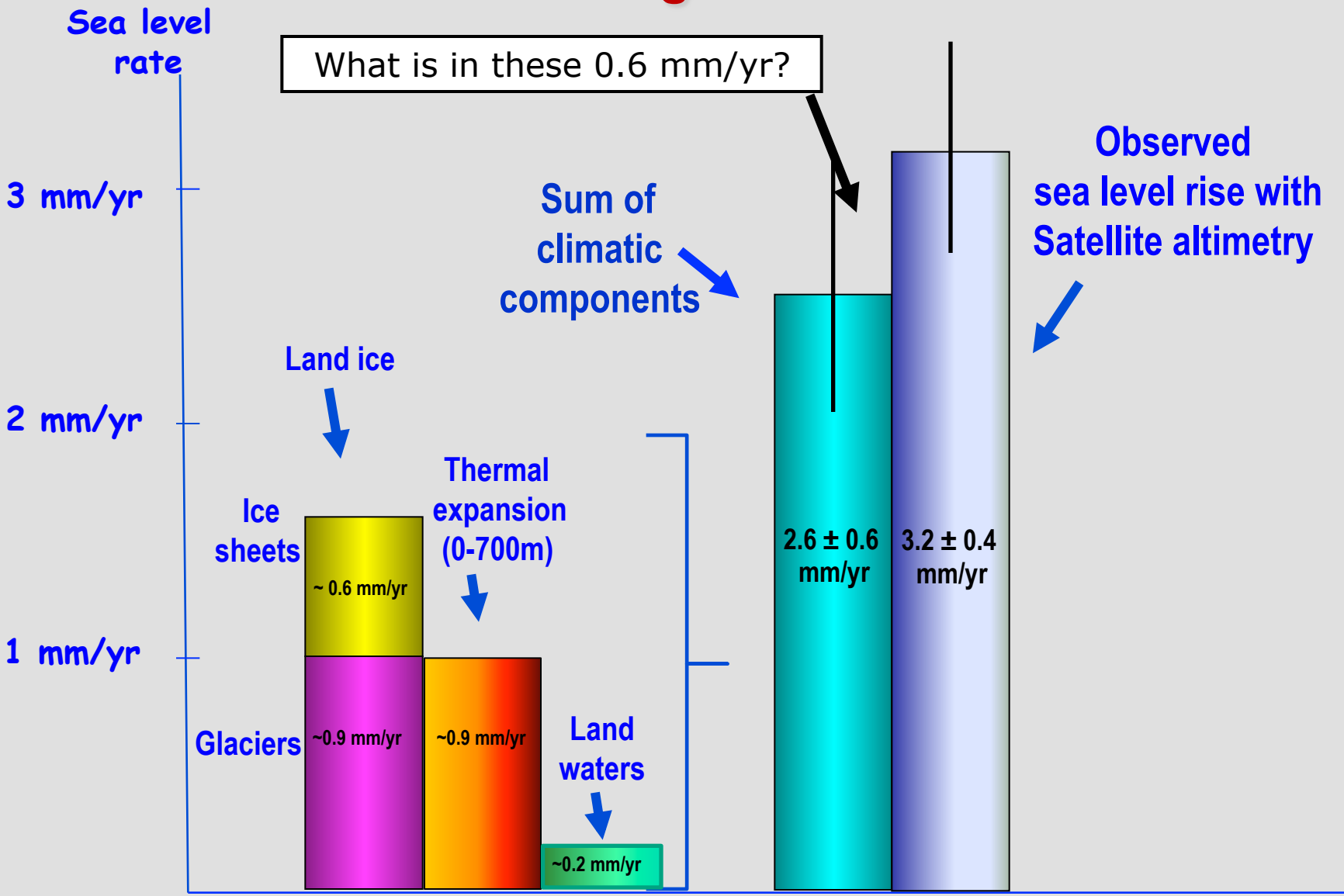
(2005-2010) → 1. +/- 0.2 mm/yr

Sea Level Budget: 1993-2010



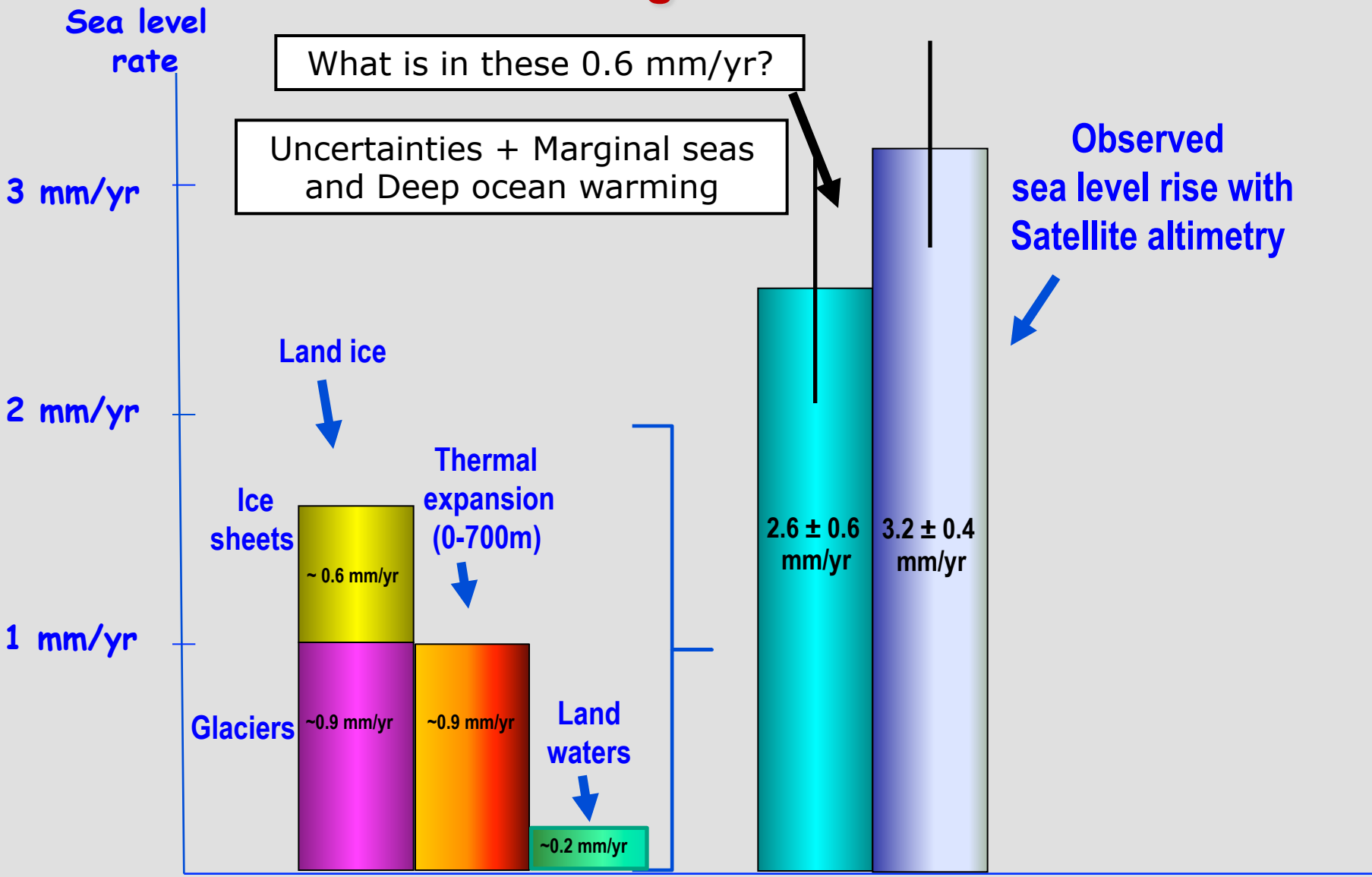
(Updated from IPCC 2013)

Sea Level Budget: 1993-2010



(Updated from IPCC 2013)

Sea Level Budget: 1993-2010

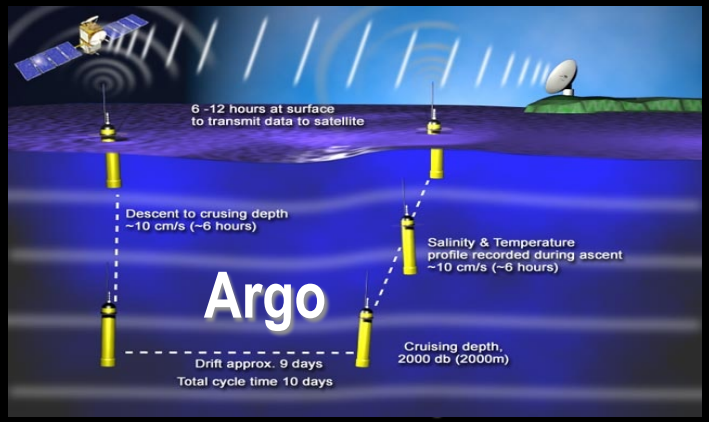


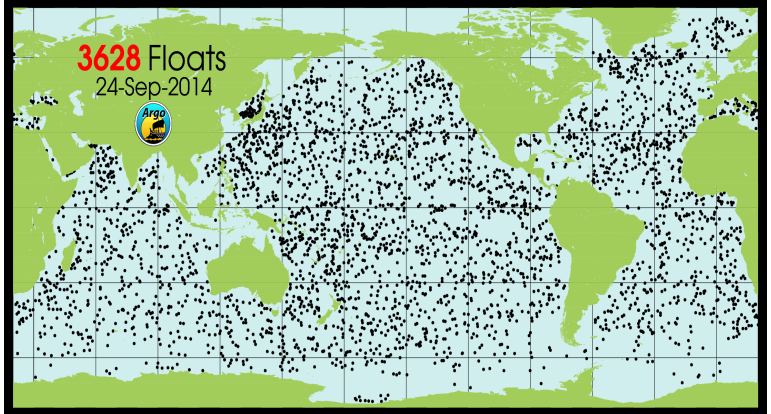
(Updated from IPCC 2013)

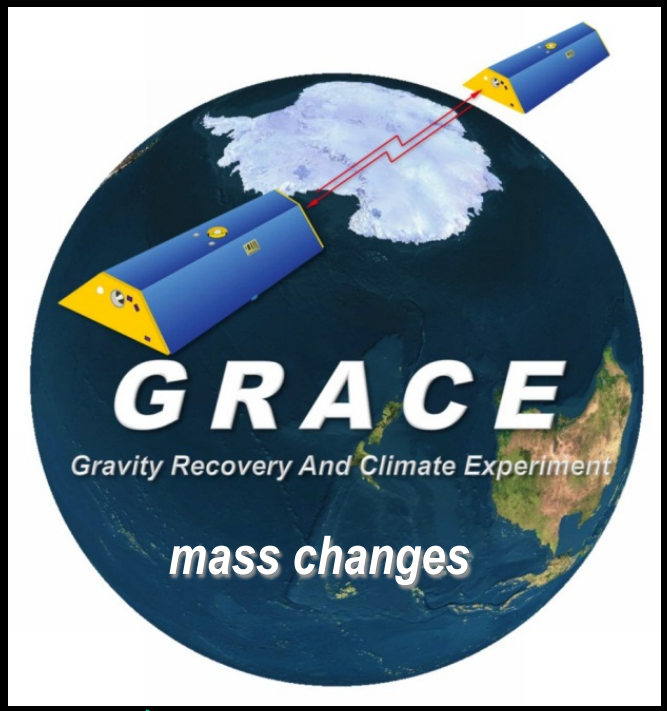
What are implications for the Earth energy budget?

Since ~ 2005, Argo + GRACE → upper ocean thermal expansion + ocean mass

Thermal expansion of the upper ocean (0-2000 m)



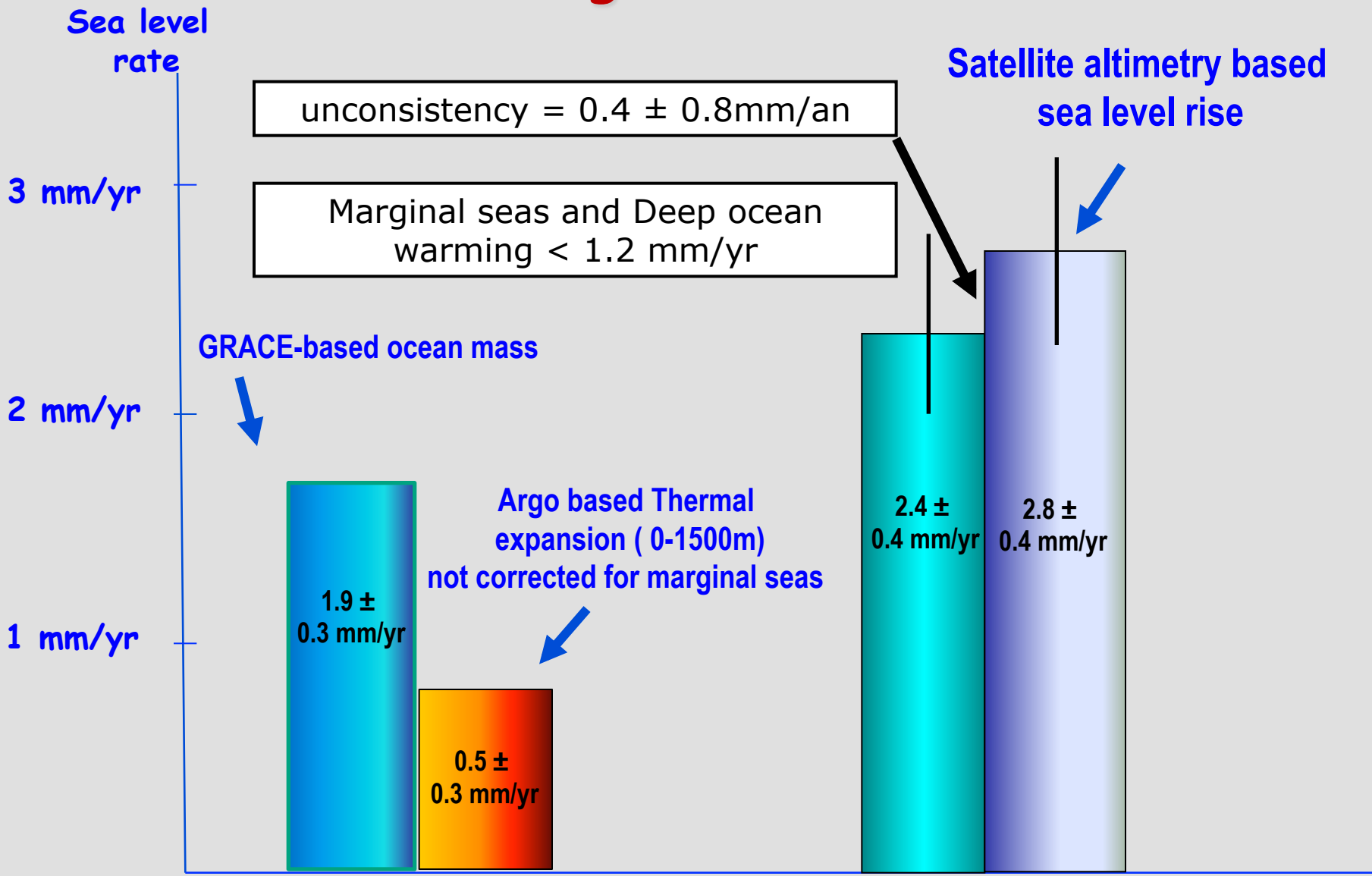




ocean mass

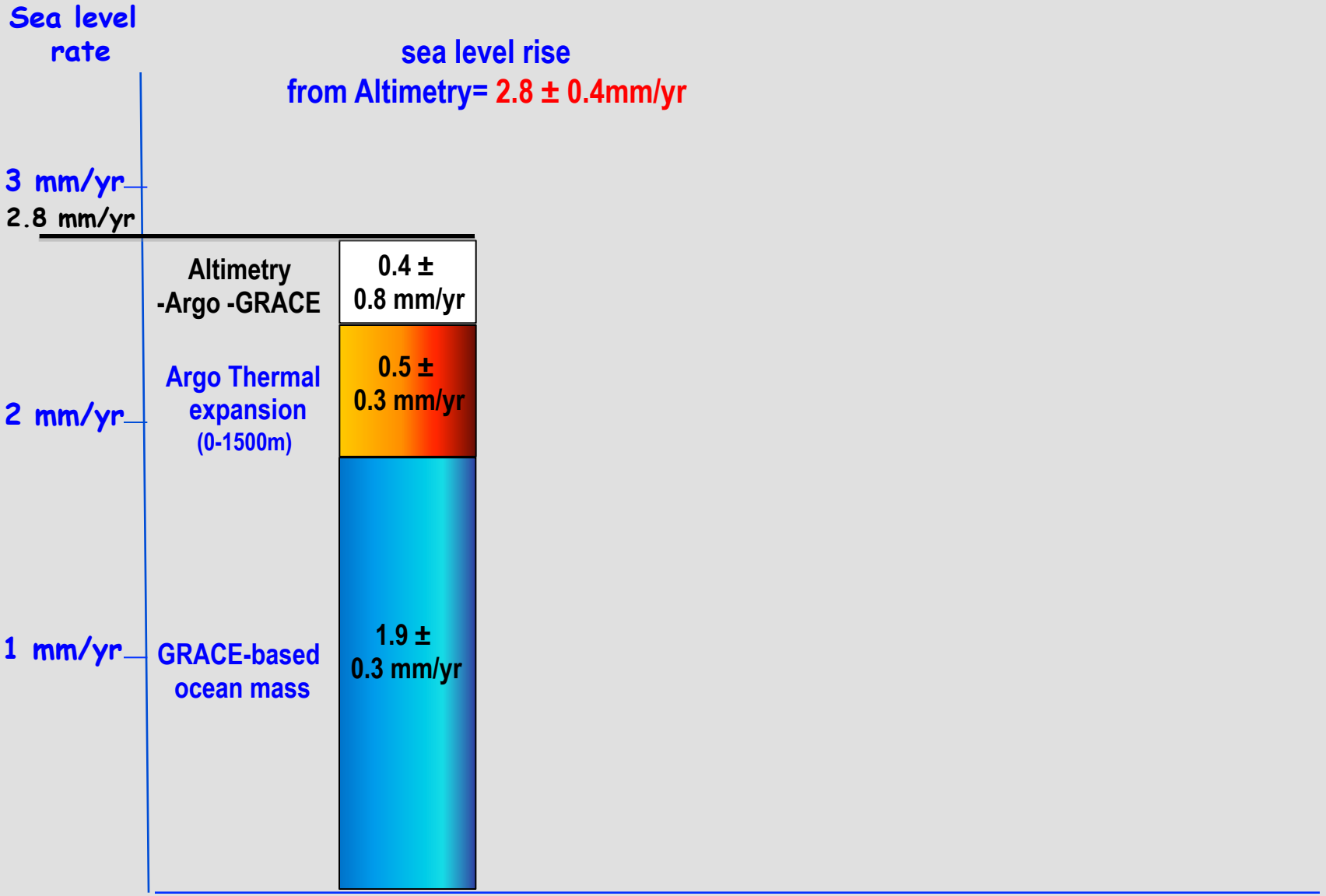
Glaciers, ice sheets, land waters

Sea Level Budget: 2005-2013



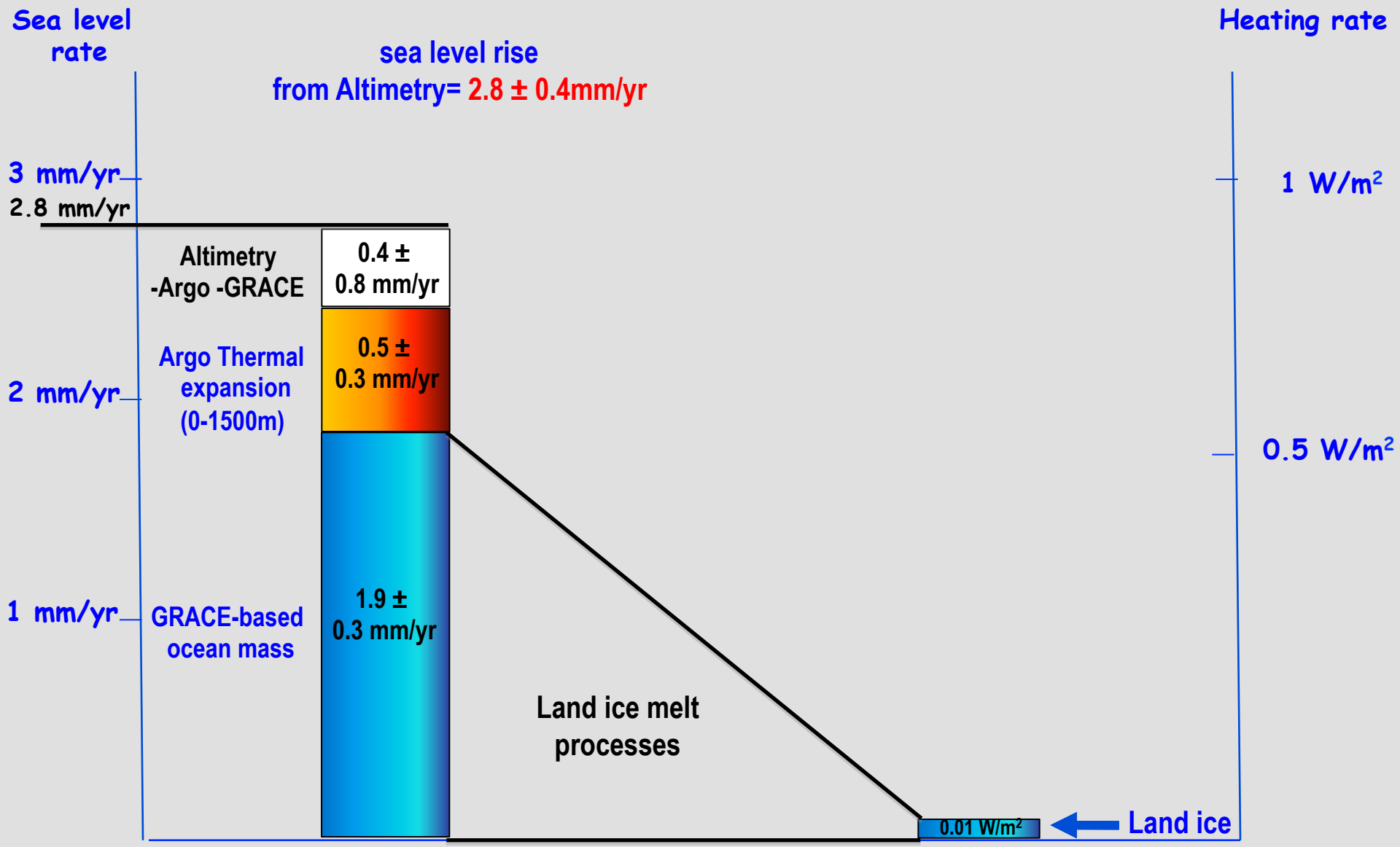
(from Dieng et al. In revision)

implications for the Earth heat budget: 2005-2013



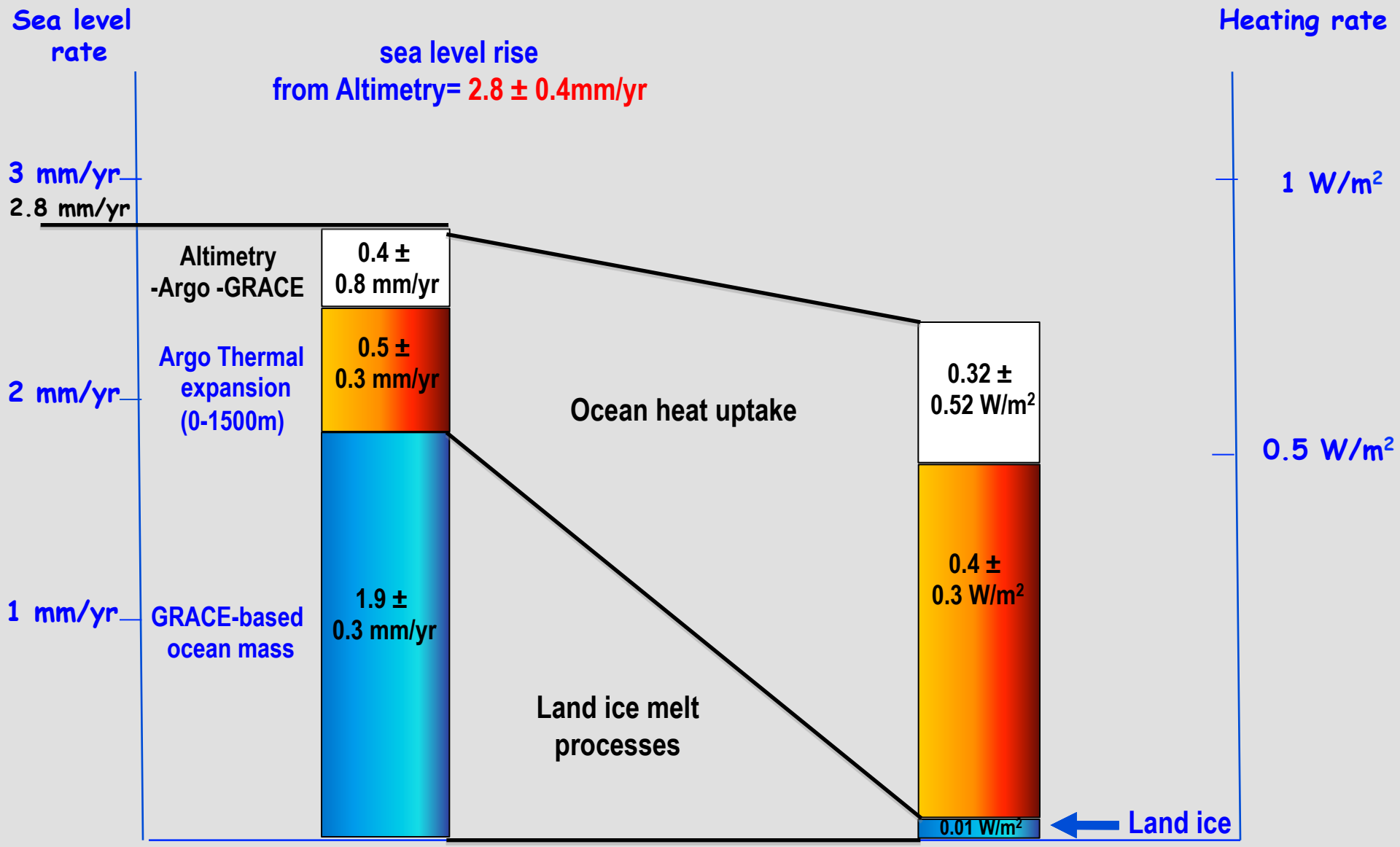
(from Dieng et al. In revision)

implications for the Earth heat budget: 2005-2013



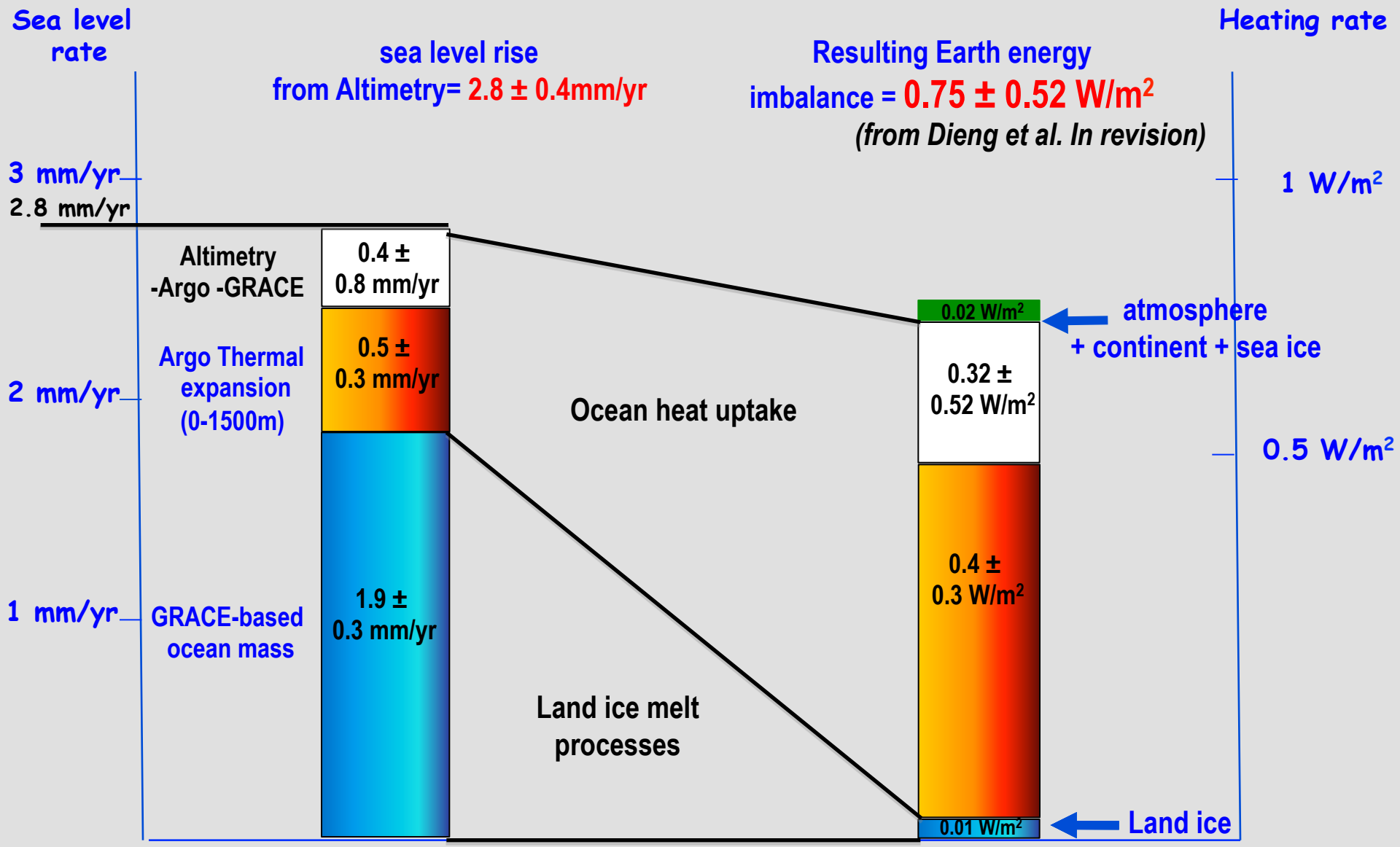
(from Dieng et al. In revision)

implications for the Earth heat budget: 2005-2013

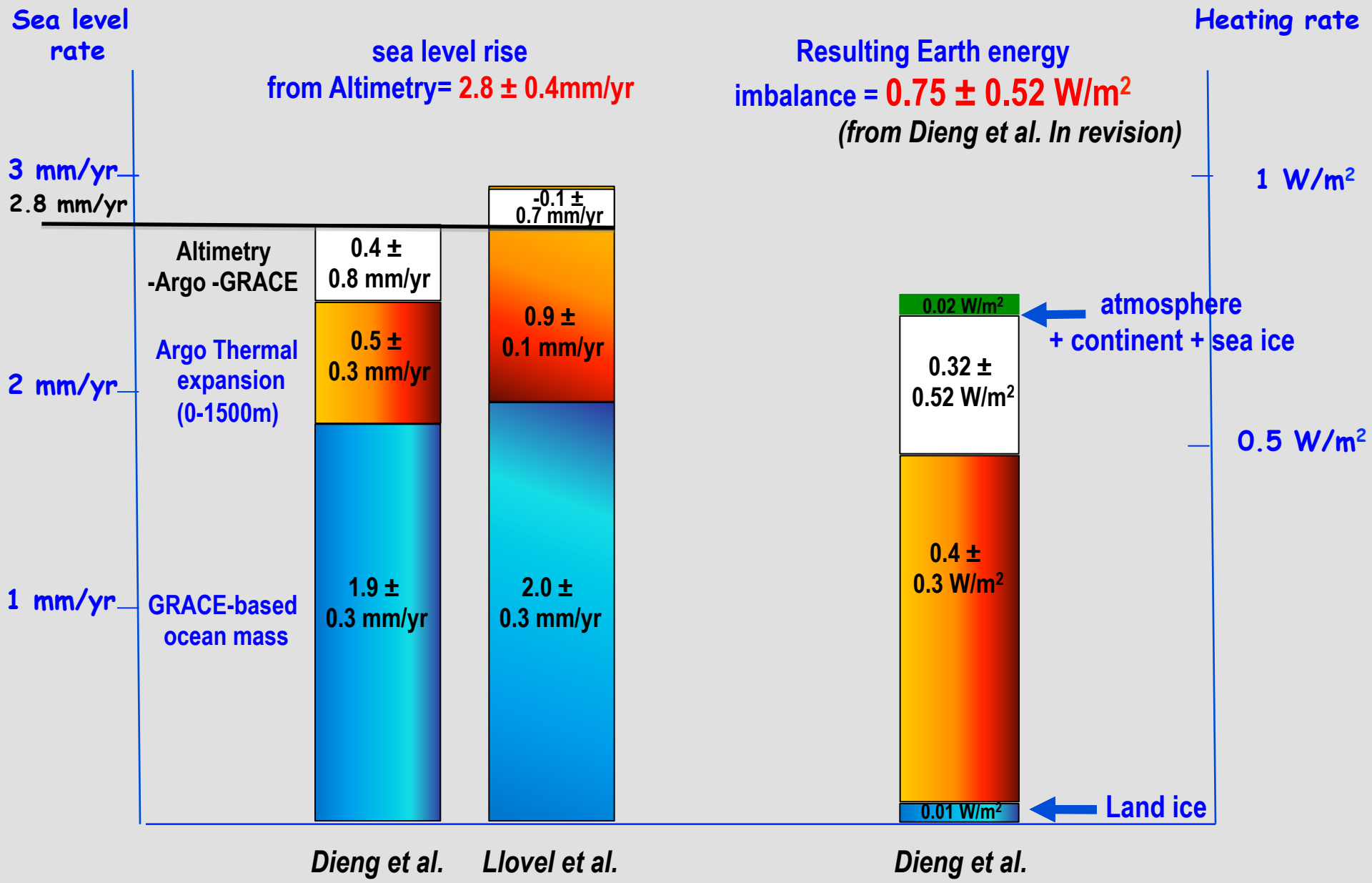


(from Dieng et al. In revision)

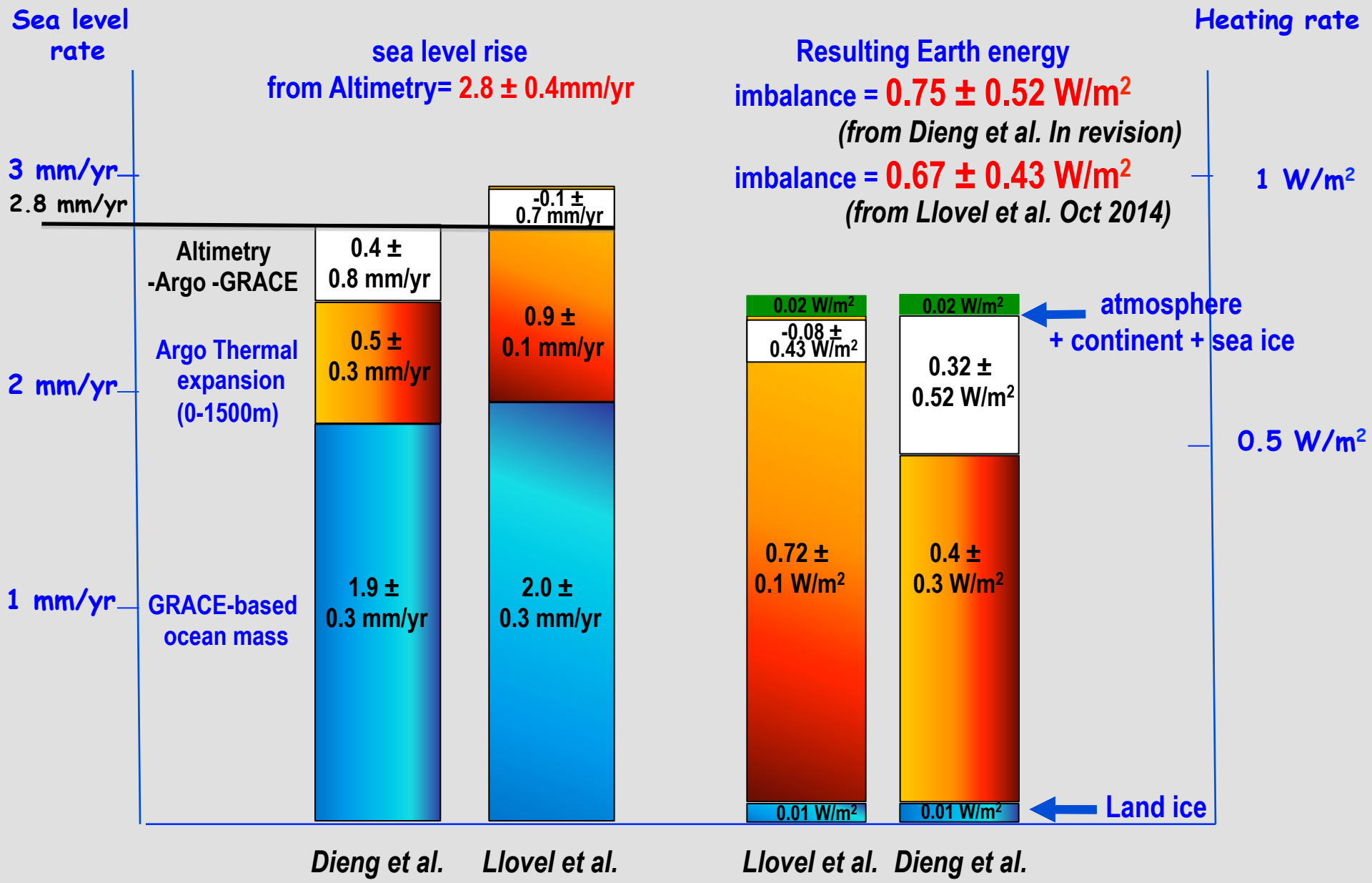
implications for the Earth heat budget: 2005-2013



implications for the Earth heat budget: 2005-2013



implications for the Earth heat budget: 2005-2013



Conclusions I

-Current global mean sea level is rising fast compared to the last century and previous millenia

-It rises in response to ocean warming and land ice melt

-Inferred estimate from Argo and GRACE explain most of the observed sea level rise since 2005

-However an unconsistency of a 0.4 mm/yr remains. It is due to uncertainties in the observing system + Marginal seas and deep ocean warming not observed by Argo

-Closing the sea level budget enable to infer marginal seas and deep ocean warming within the uncertainties of the observing system.

- It suggest a radiative imbalance around 0.7 ± 0.5 W/m^2 over 2005- 2013

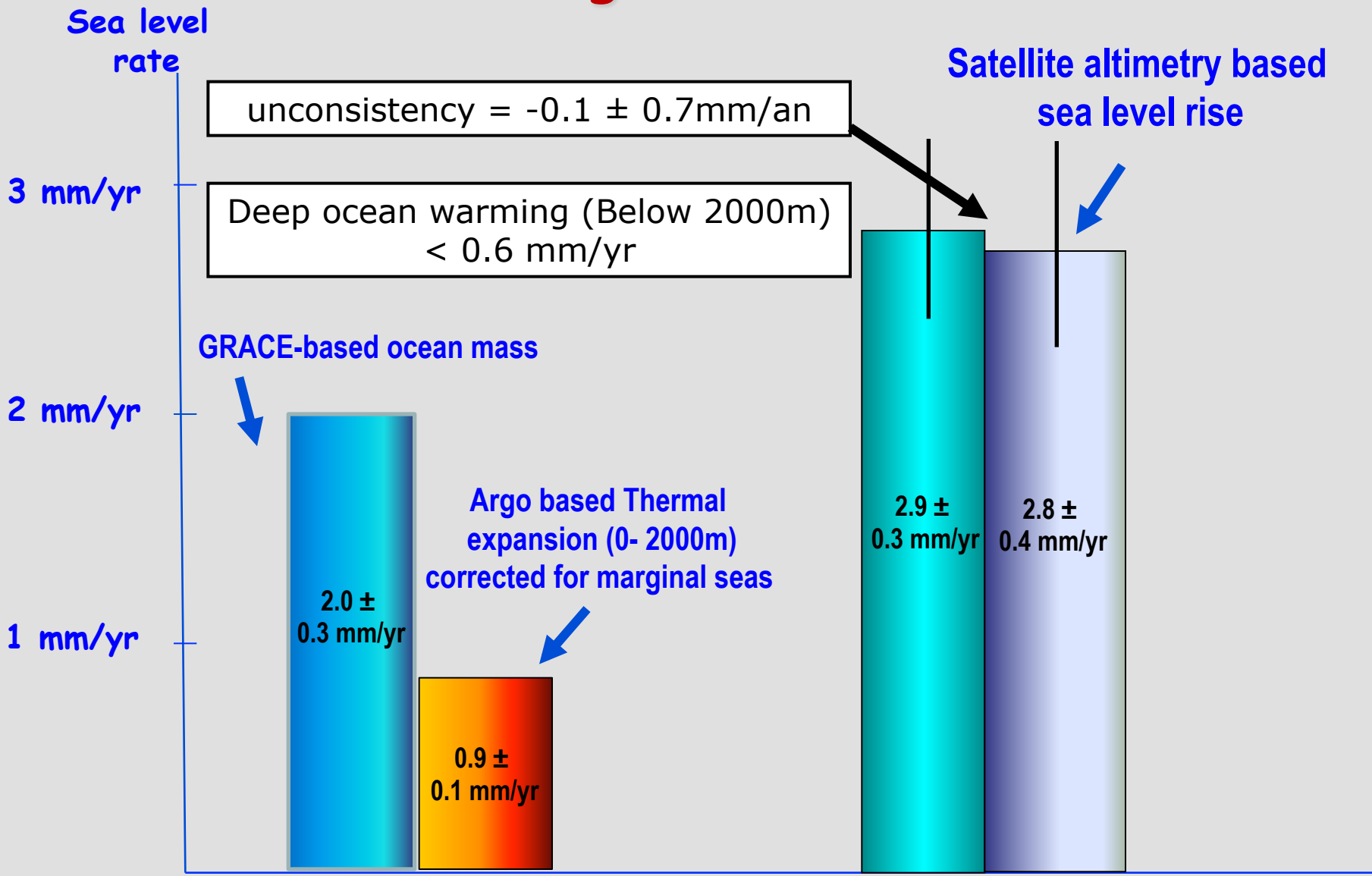
Conclusions I I

-Biases and uncertainties in ocean temperature estimates and land ice melt estimates before Argo and GRACE make the energy imbalance estimate very uncertain before 2005.

-Future challenge:
* reduce the uncertainty in the sea level budget
* estimate the interannual variability in TOA and its relationship to global OHC and sea level rise

Extra slides

Sea Level Budget: 2005-2013



(from Llovel et al. Oct. 2014)