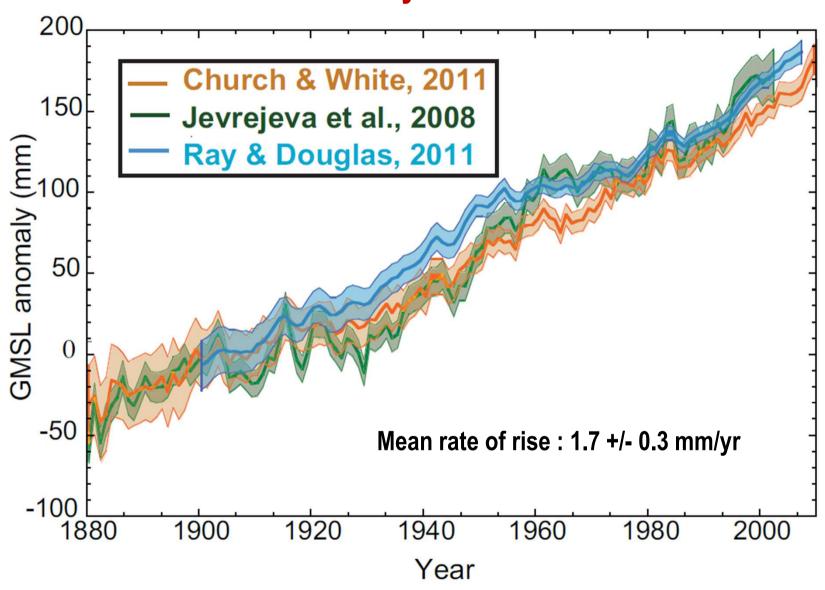


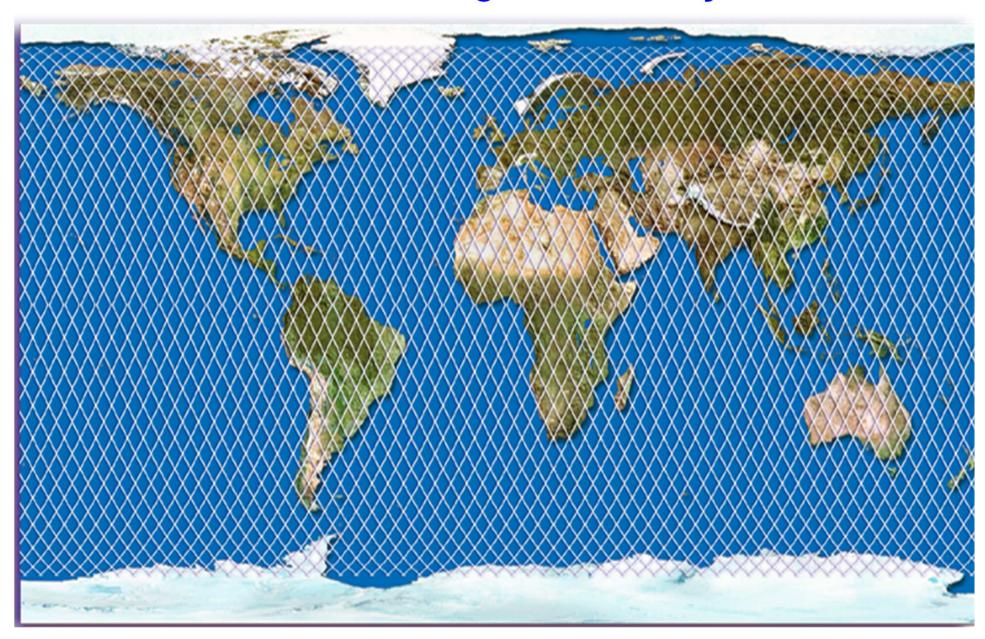
20th century sea level rise



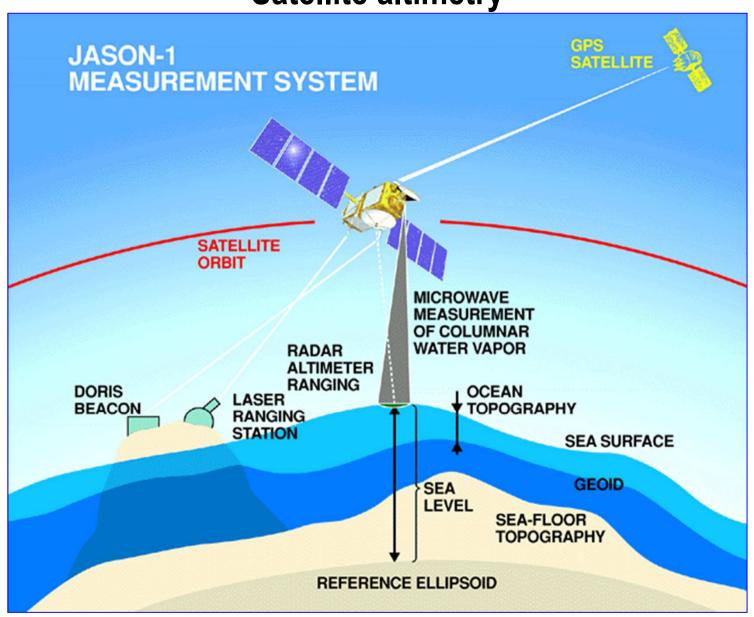
Sea level change now routinely measured by altimeter satellites

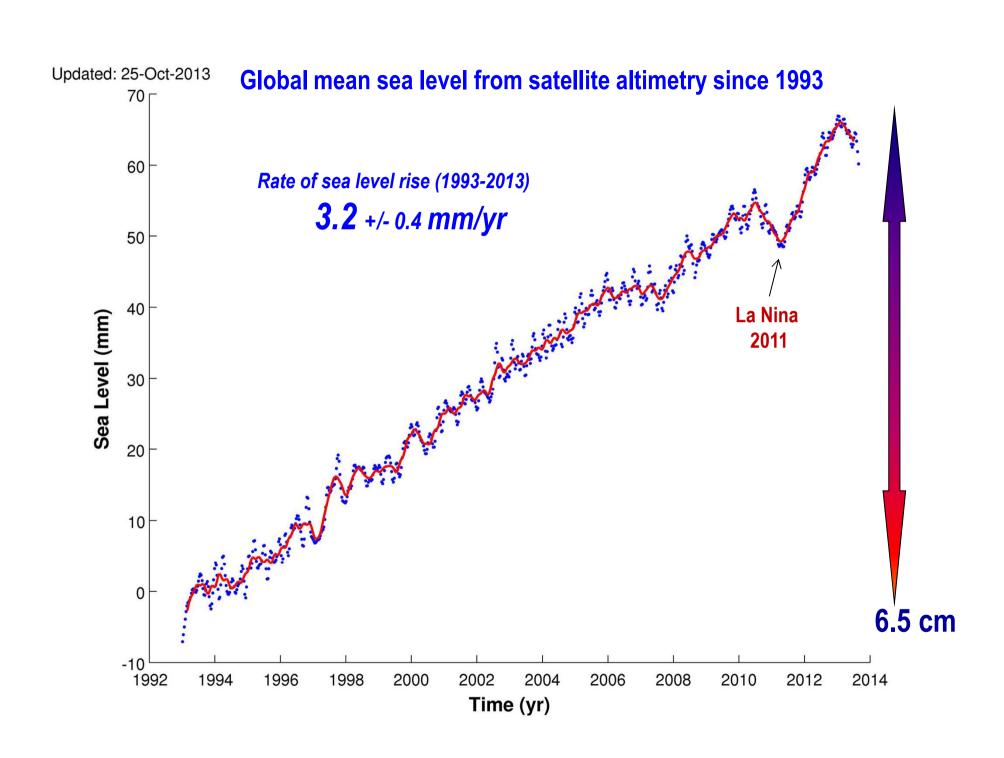


Global coverage in a few days



Satellite altimetry





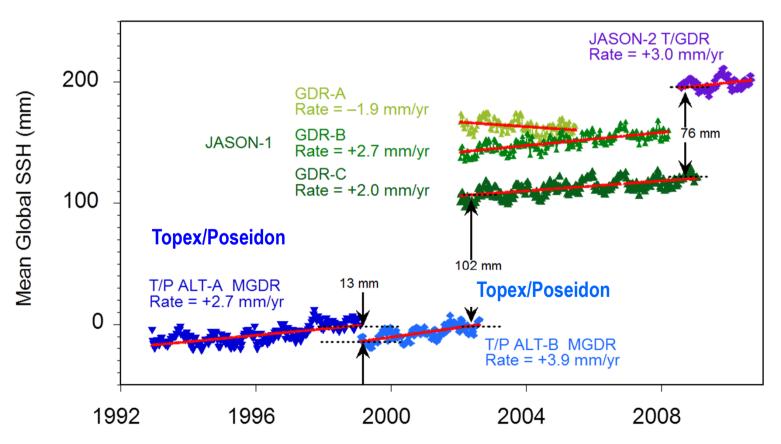
Sources of trend uncertainty

Source	Trend errors (mm/yr)
Orbit error	~0.25
Wet troposphere correction (instrumental drift of onboard radiometers)	~0.3
Intrumental altimeter bias (Topex A-Topex B)	~0.25
Dry troposphere correction (uncertainty of atm. surface pressure data)	~0.1
Sea state bias correction	~0.1
Total error	~0.4
Tide gauge calibration (e.g. Mitchum et al., 2010)	~0.4

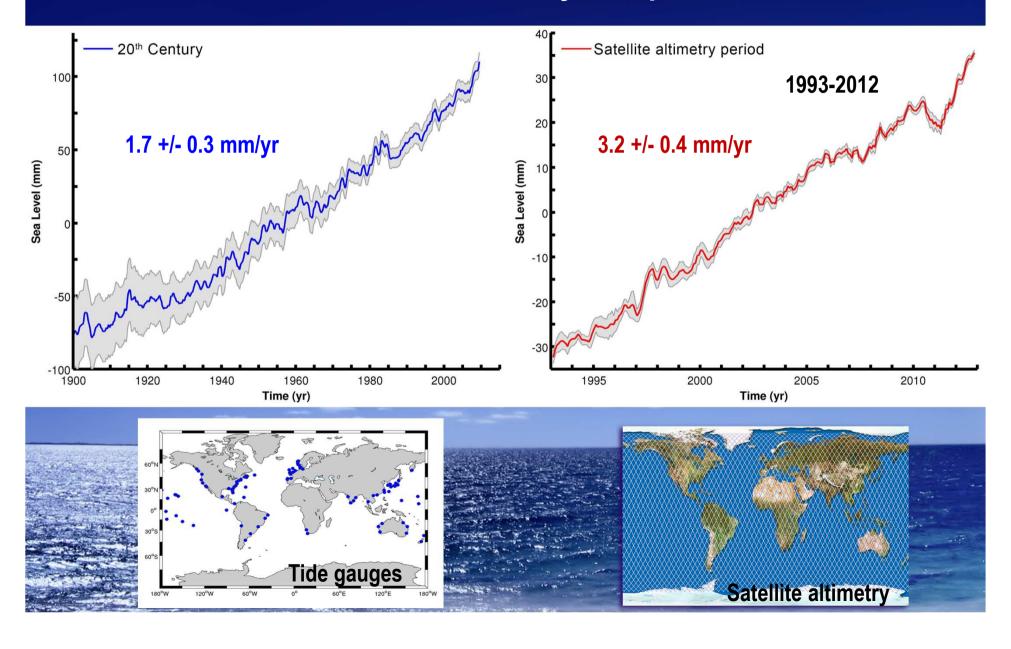
Sea level: most demanding application of satellite altimetry

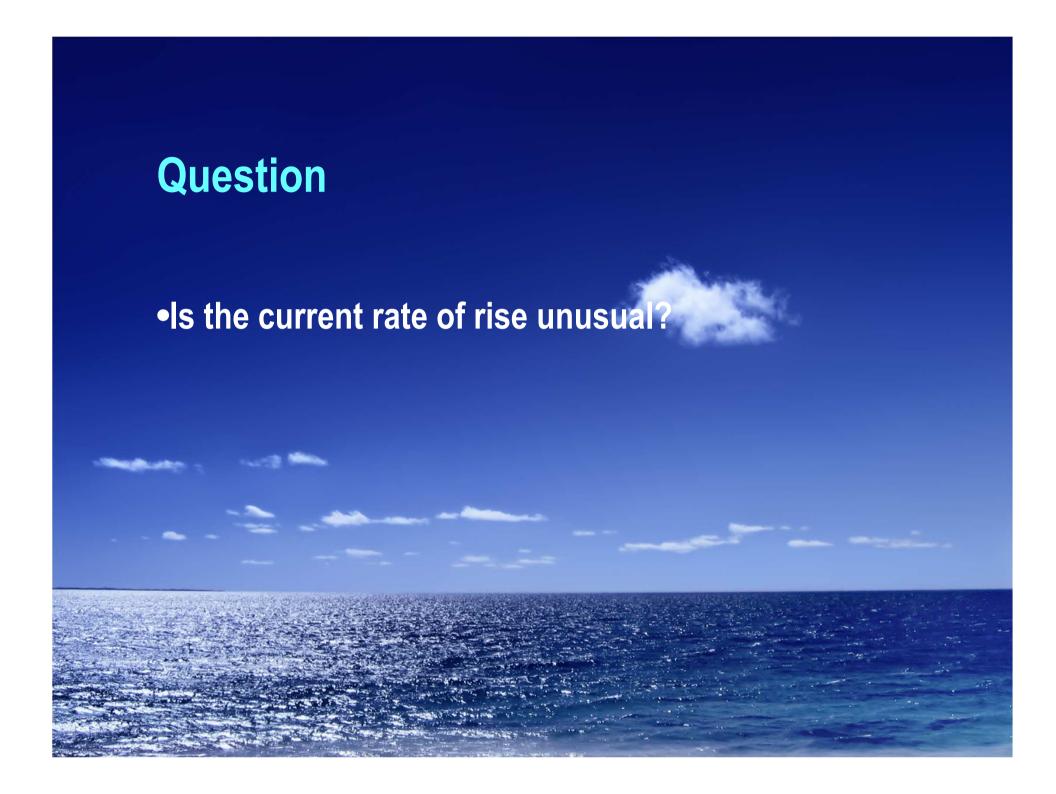
Example of sea surface height bias between successive missions (Topex/Poseidon, Jason-1, Jason-2) → calibration very important! Need for overlap between successive missions (tandem missions)

Global Sea Level from T/P, Jason-1 and Jason-2: **UNCALIBRATED** Record for 1992—2010

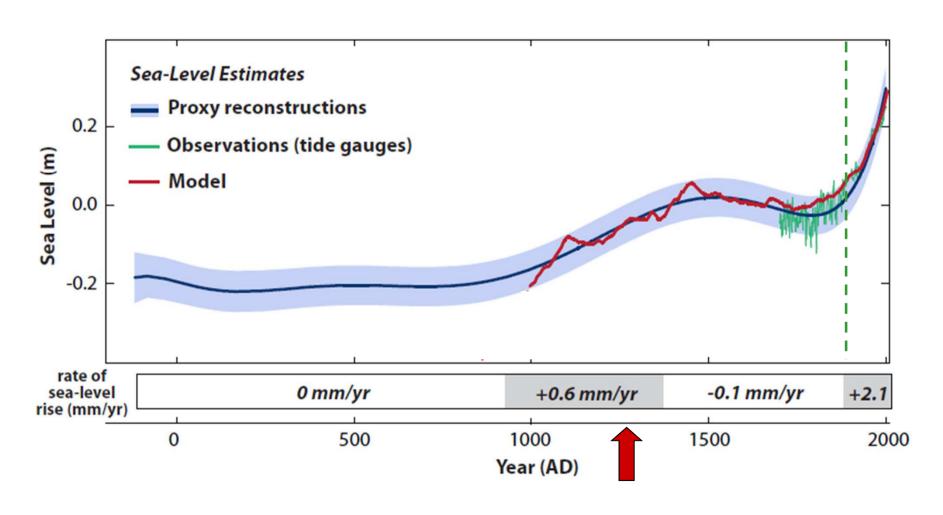


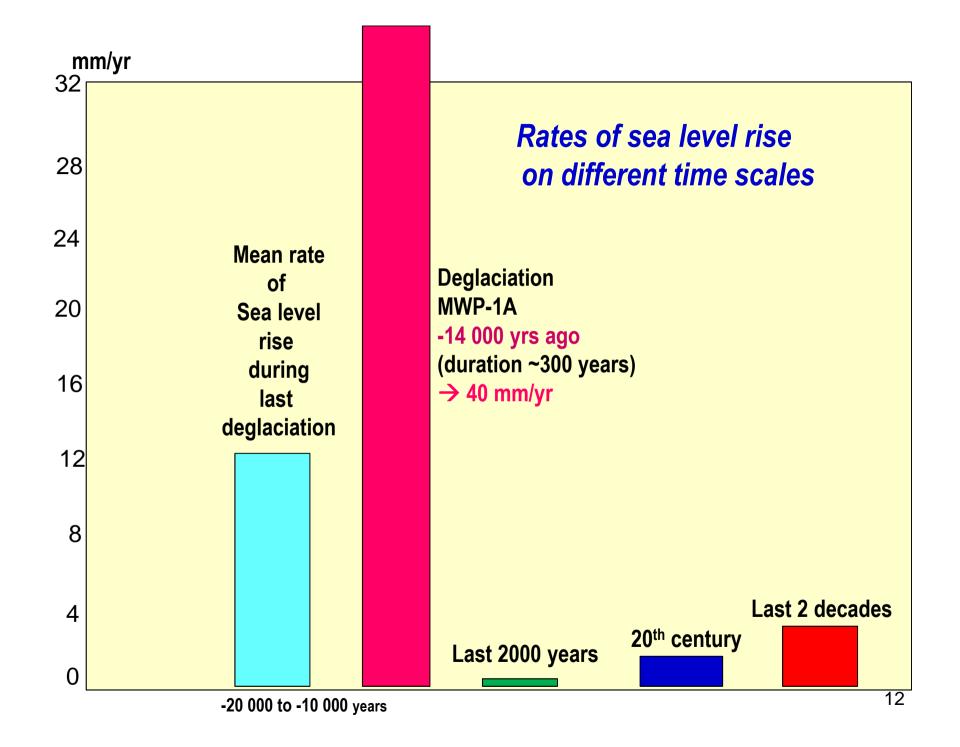
Sea level rise: 20th century and past 2 decades





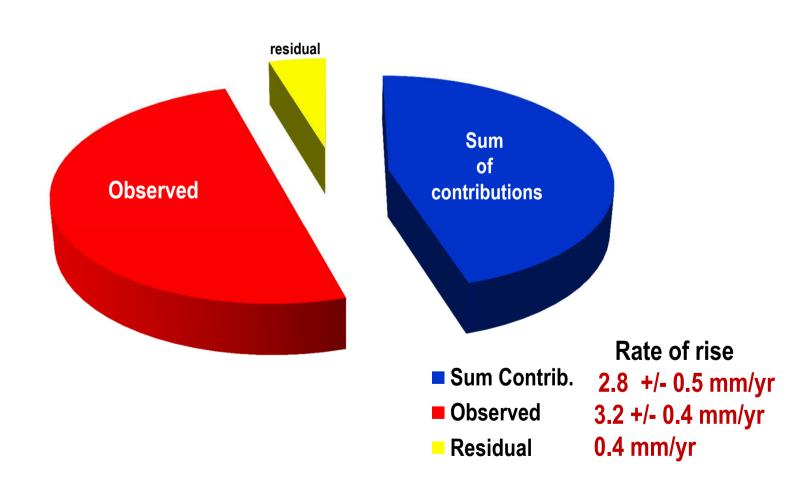
Evolution of the mean sea level over the last 2000 years



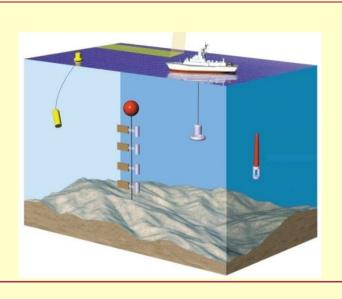




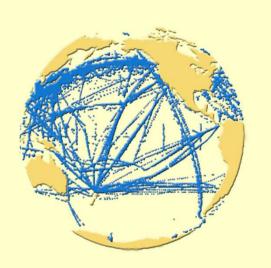
Observed sea level budget during the altimetry era (1993-2010) IPCC AR5



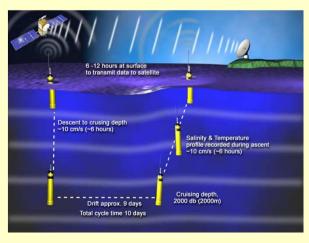
Ocean temperature measurements (XBT, Argo)

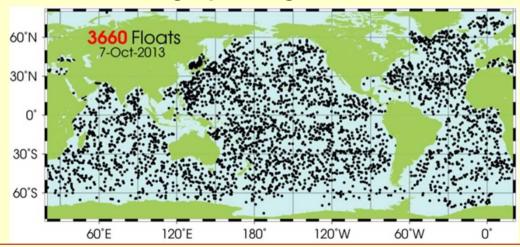


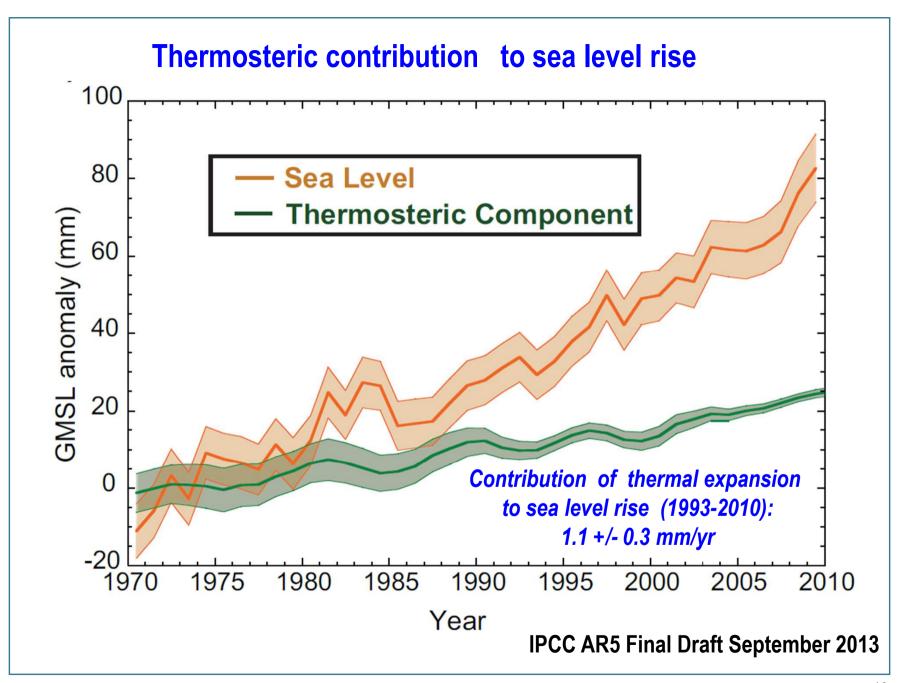
Past few decades: coverage mainly along trade roads



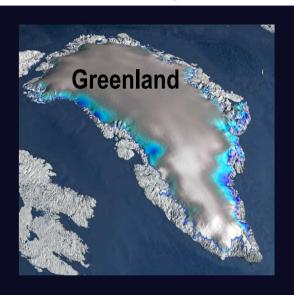
Since about 2003 → 'Argo' profiling floats

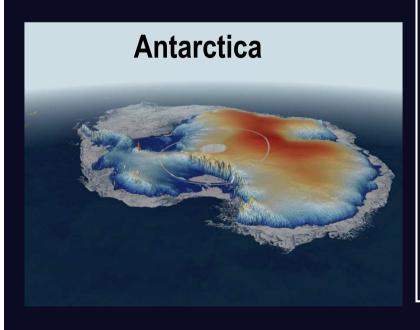




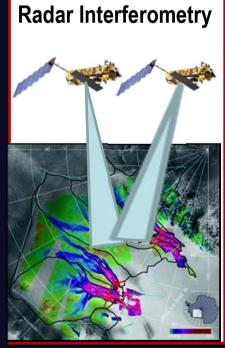


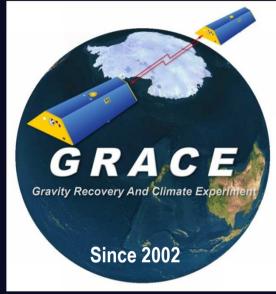
Since the early 1990s, ice sheet mass change measured from space

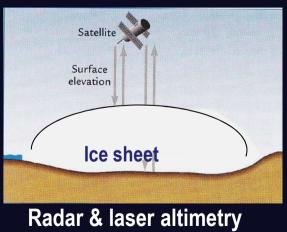




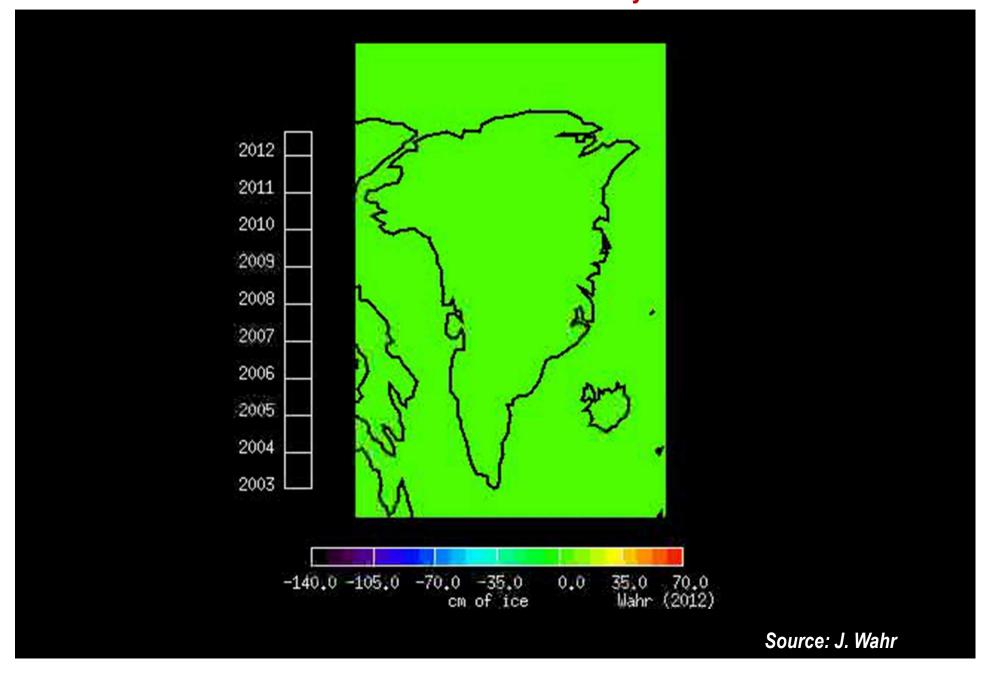




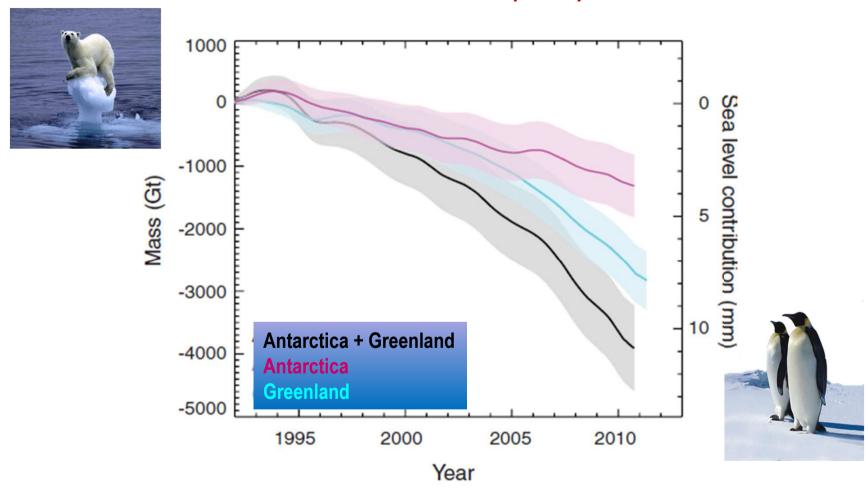




Ice mass loss of the Greenland ice sheet (blue-violet-black) between 2003 and 2012 observed by GRACE



Ice mass loss from Greenland and Antarctica measured by space techniques since 1992 (in Gt)

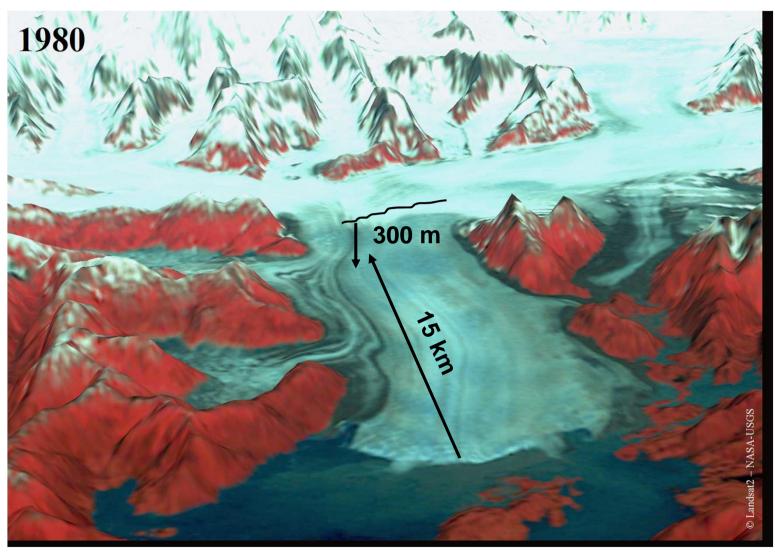


Sum of the 2 ice sheets:

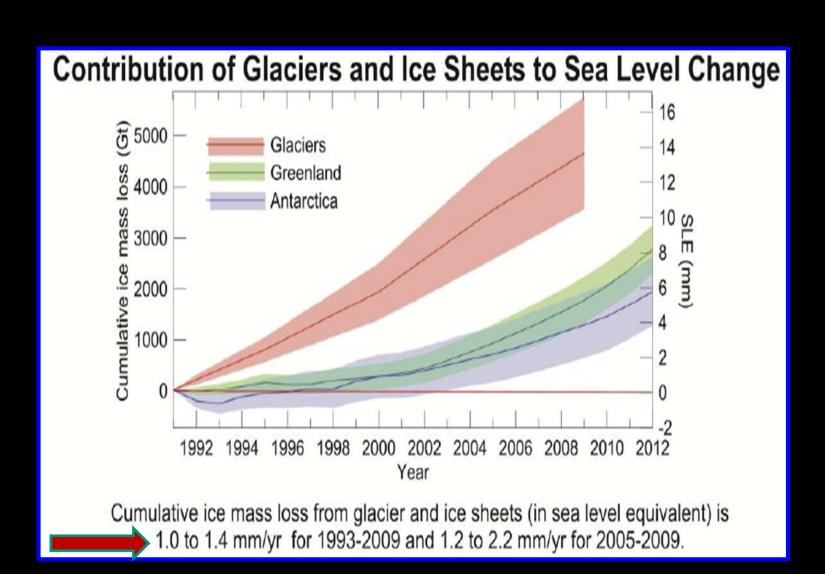
Shepherd et al. (2012)

 $(1993-2010) \rightarrow 0.6 +/- 0.2 \text{ mm/yr}$ $(2005-2010) \rightarrow 0.96 +/- 0.13 \text{ mm/yr}$

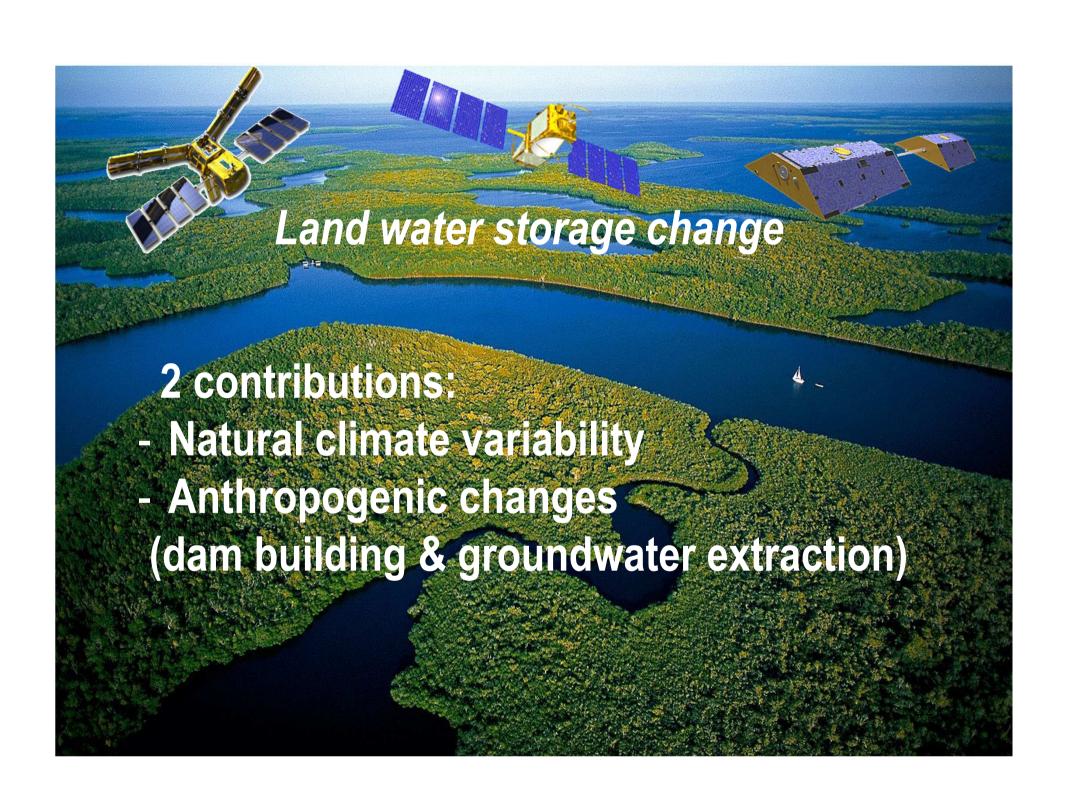
Thinning & retreat of mountain glaciers observed by satellite imagery

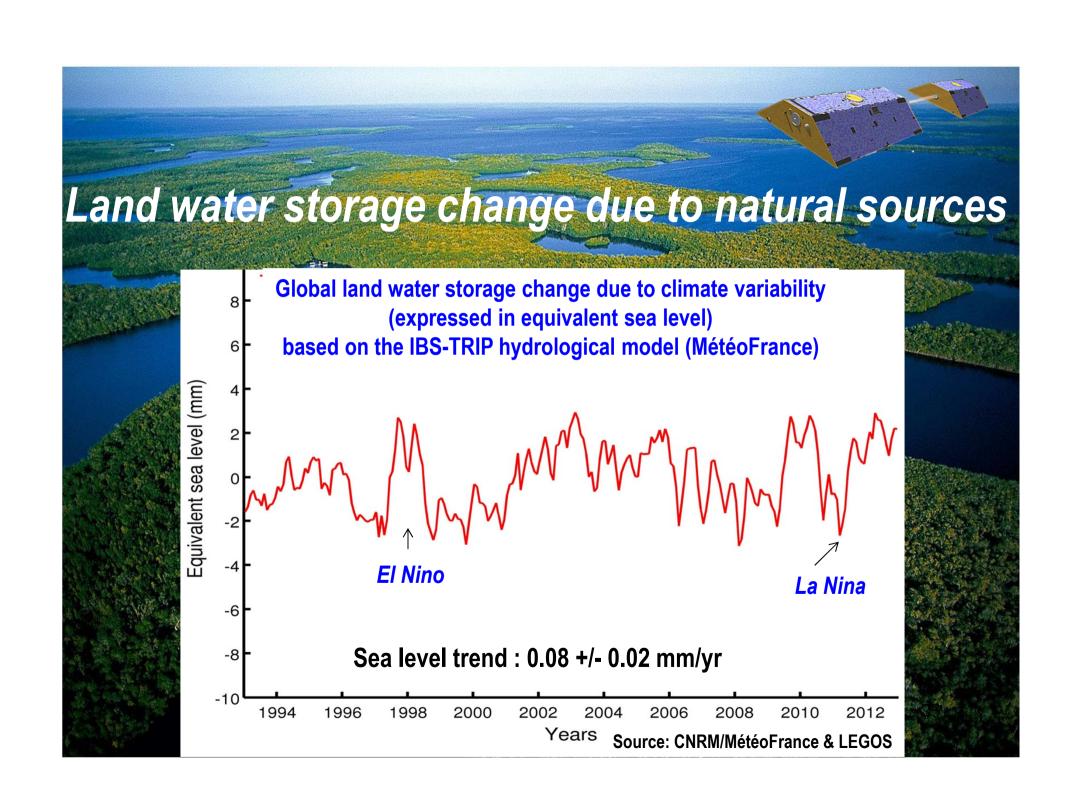


Columbia glacier (Alaska) 1980 and 2007

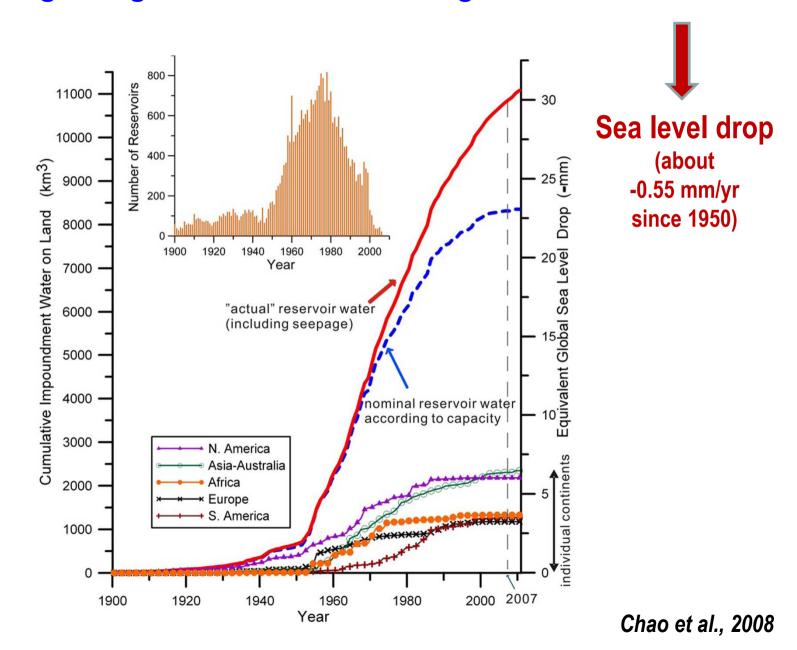


Ice sheet contribution (1993-2010) : 0.6 +/- 0.2 mm/yr
IPCC AR5 Final Draft September 2013

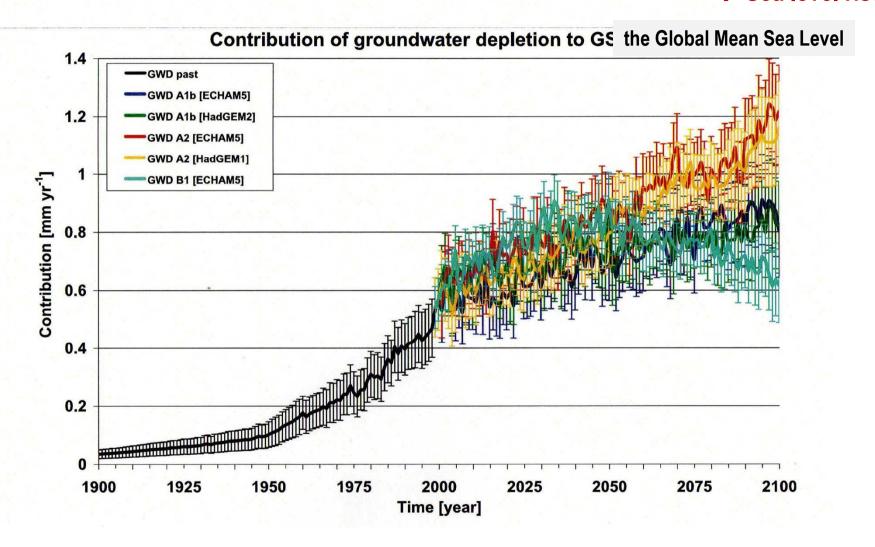




Dam building along rivers : effect on the global mean sea level



WADA ET AL.: PAST AND FUTURE GROUNDWATER DEPLETION → Sea level rise



Other recent estimates: Wada et al., 2010 Konikow, 2011

Y. Wada (personal communication, Oct 2013)

Anthropogenic land water storage (1993-2012)

Dam building: -0.3 +/- 0.03 mm/yr

Ground waters: + 0.56 +/- 0.1 mm/yr

Net effect: +0.26 +/- 0.11 mm/yr

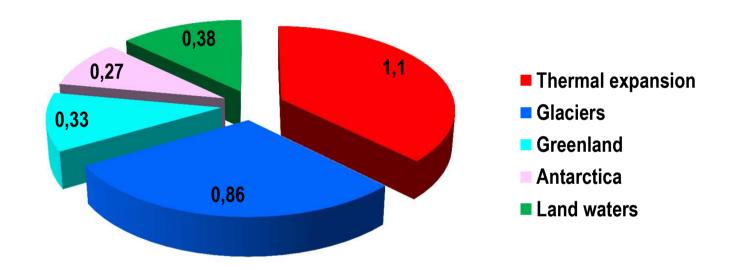
Natural land water storage: 0.08 +/- 0.02 mm/yr

Total: 0.34 +/- 0.15 mm/yr

IPCC AR5 -anthropogenic only- (1993-2010): 0.38 +/- 0.12 mm/yr

Observed sea level budget 1993-2010 (IPCC AR5)

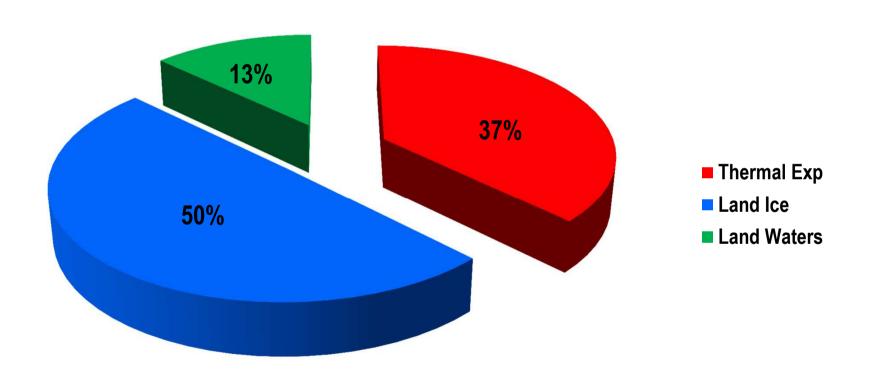
Individual contributions (mm/yr)



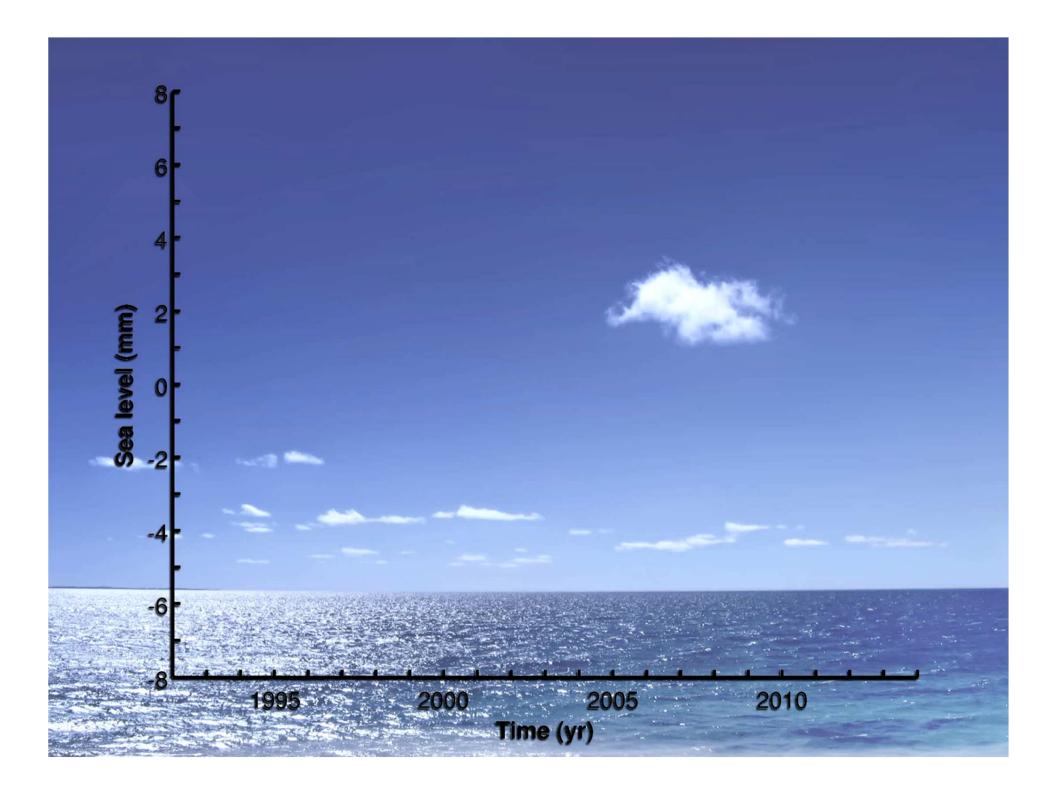
Sum of contributions: 2.8 +/- 0.5 mm/yr

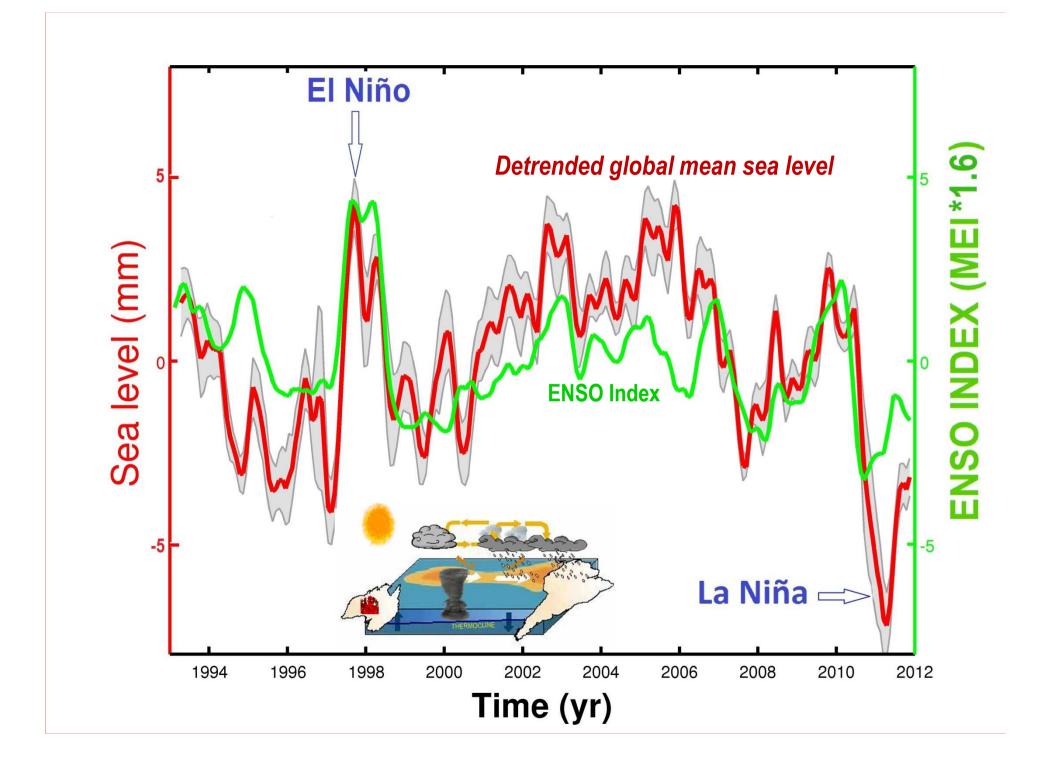
Observed rate of rise: 3.2 +/- 0.4 mm/yr

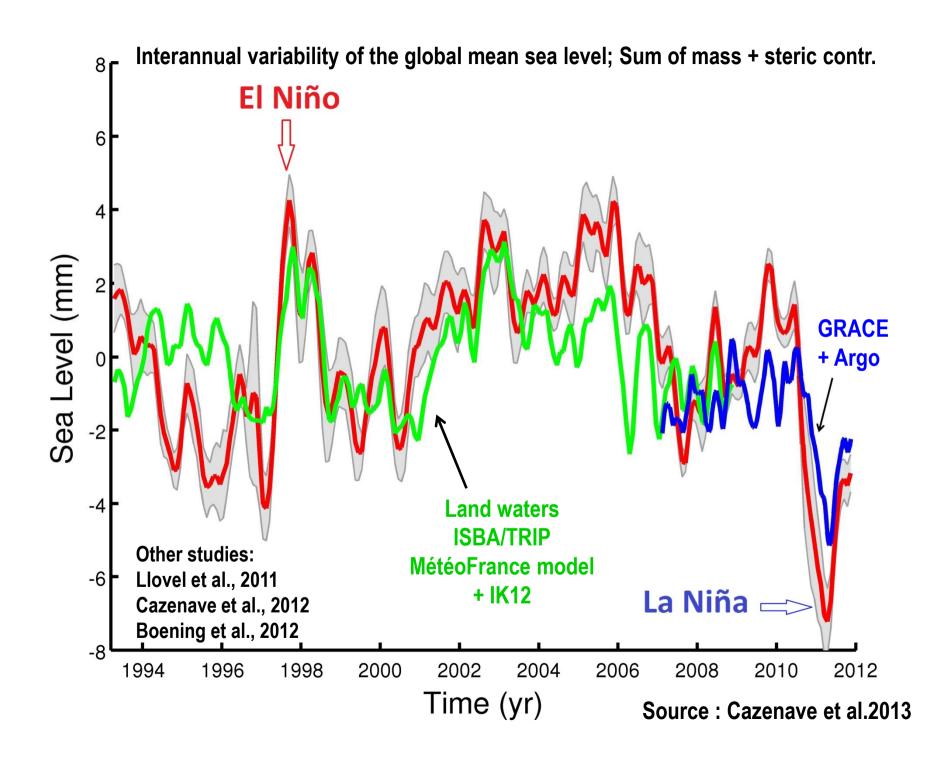
Sea level budget 1993-2010 (IPCC AR5) Individual contributions (%)

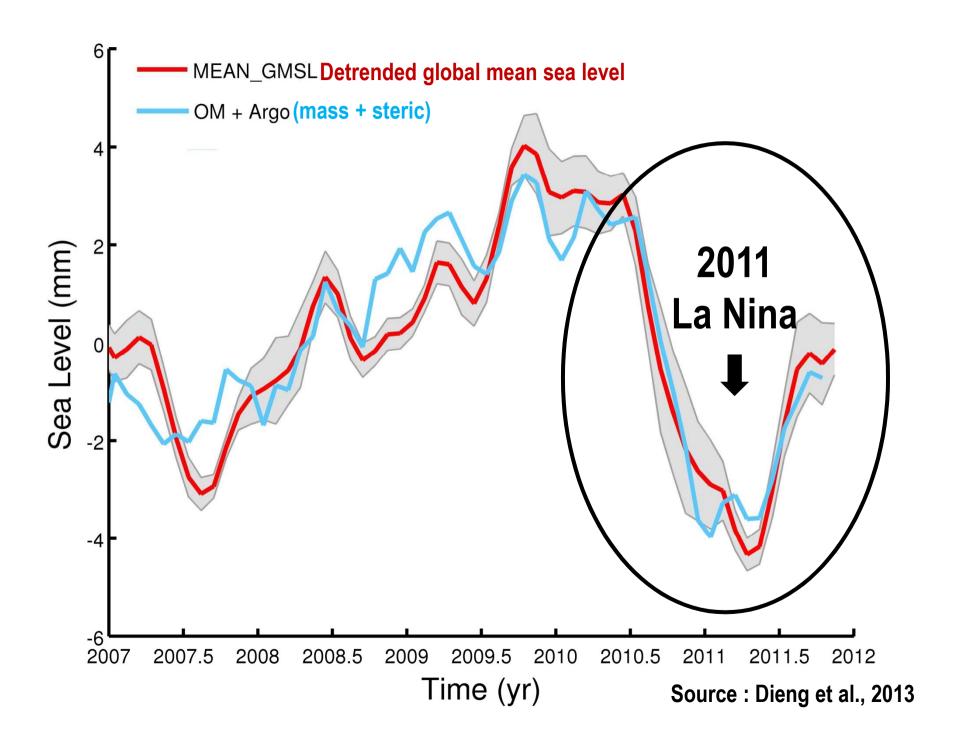


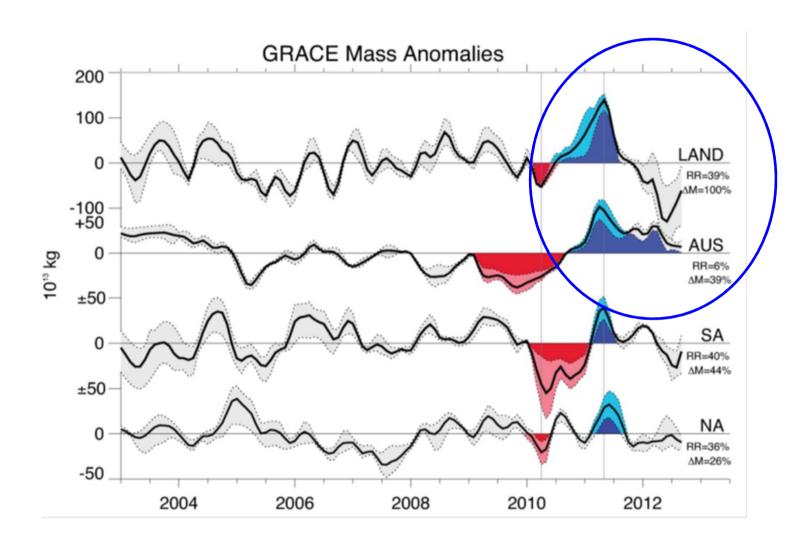


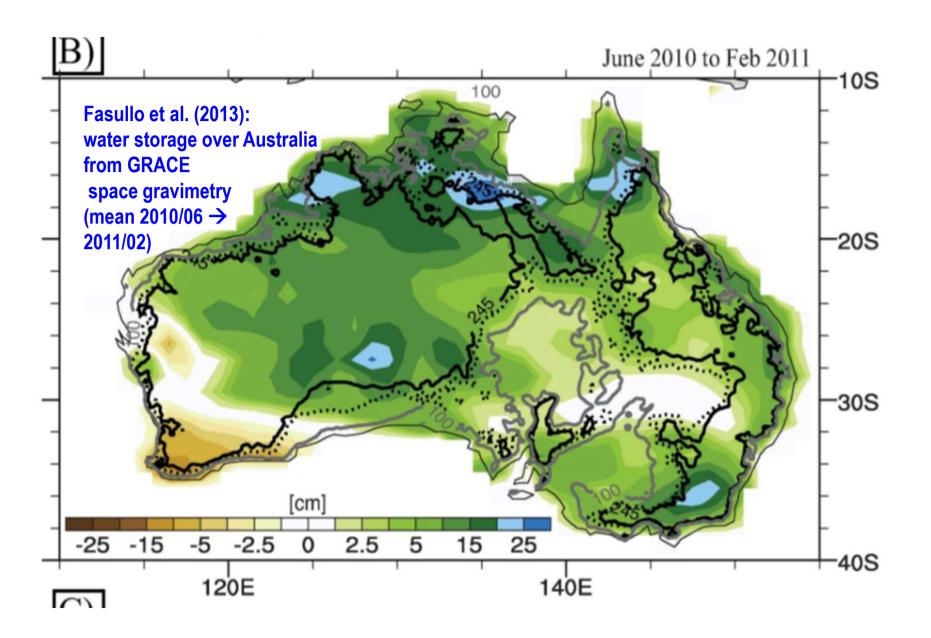






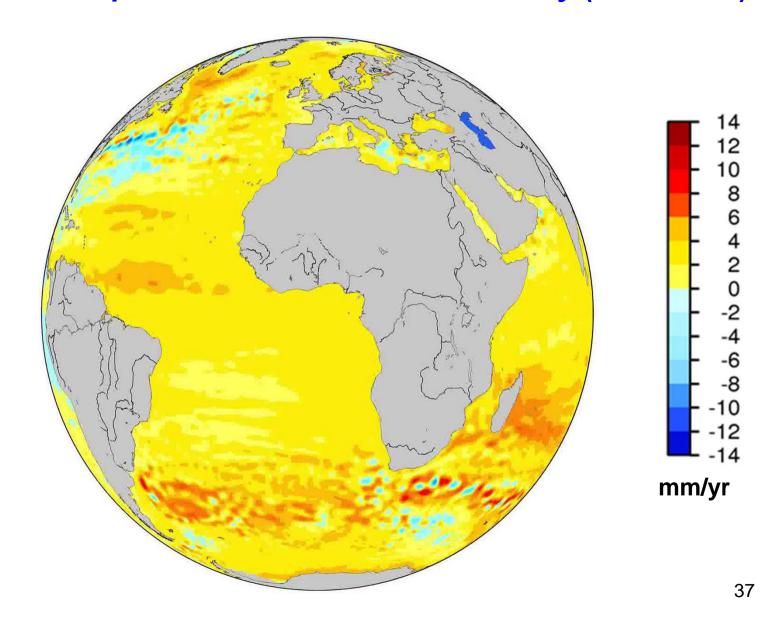




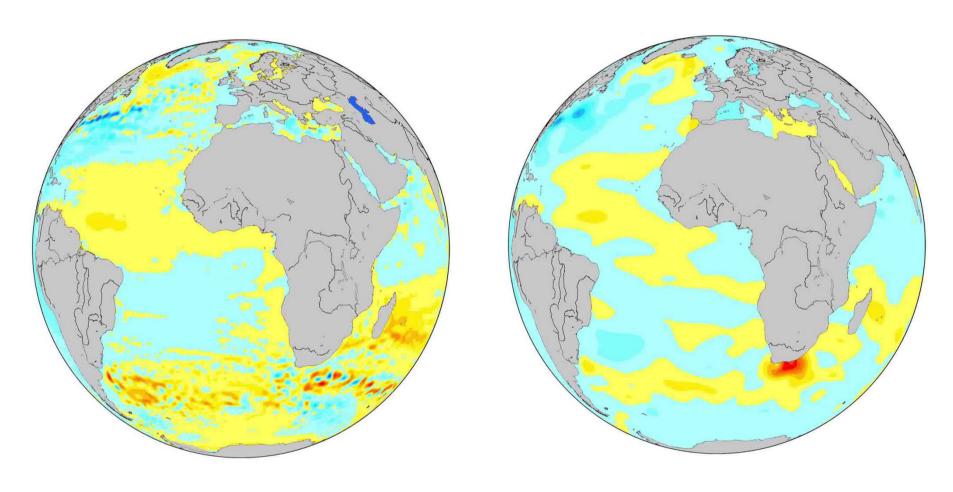




Sea level trend patterns from satellite altimetry (1993-2012)



Regional variability of the rates of sea level change over 1993-2012 (global mean rise removed)



Observed sea level by satellite altimetry

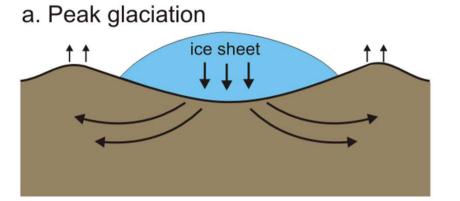
Observed thermal expansion + salinity changes 38

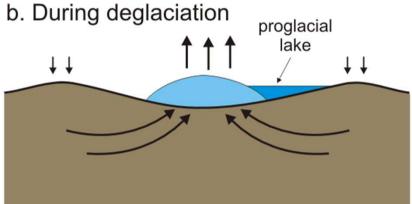
Another source of regional variability in sea level rise → large-scale water mass redistribution due to land ice melt deforms ocean basins because the Earth mantle is viscous and the crust is elastic

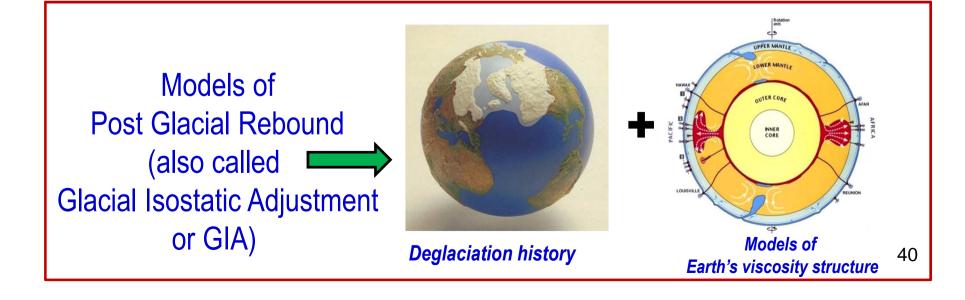


Post Glacial Rebound



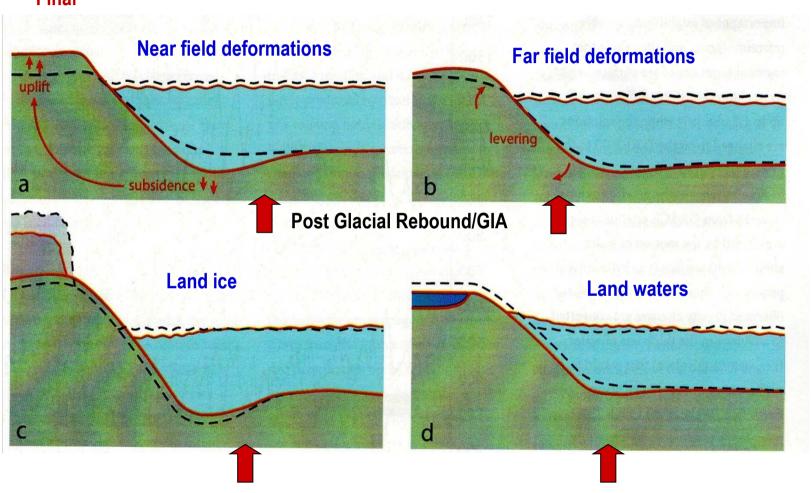






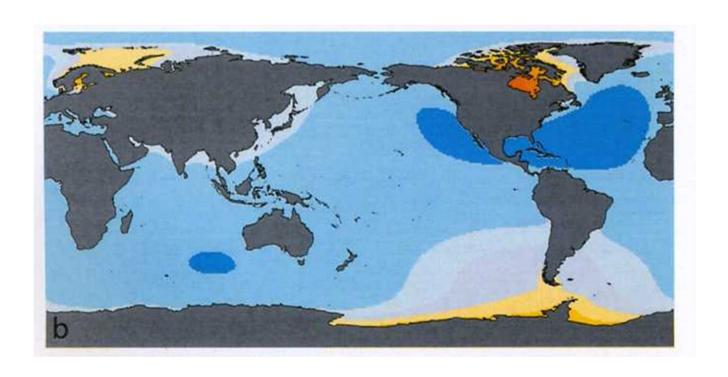
Regional variability in sea level due to GIA and ongoing & future land ice melt

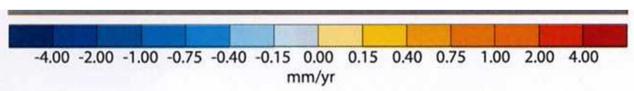
Final — — — Initial



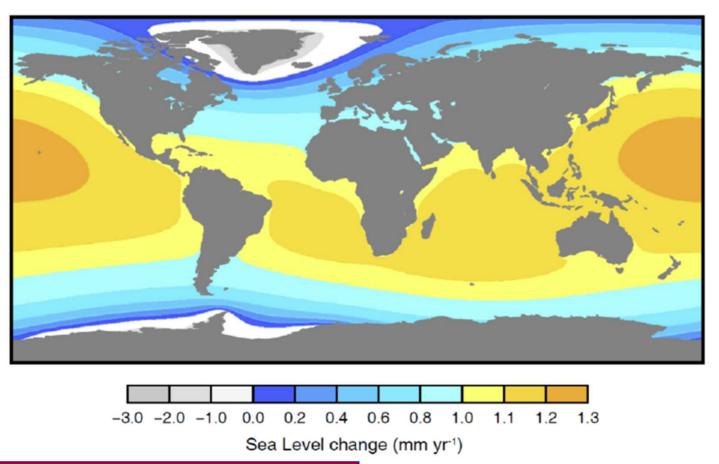
Present& future land ice melt & land water storage loading

Absolute sea level due to Post Glacial Rebound (effect on absolute sea level as measured by satellite altimetry)





Effects on regional 'relative' sea level due to solid Earth's deformation and self gravitation in response to ongoing (& future) ice sheet melting (Greenland: 0.5 mm/yr; west Antarctica: 0.5 mm/yr)

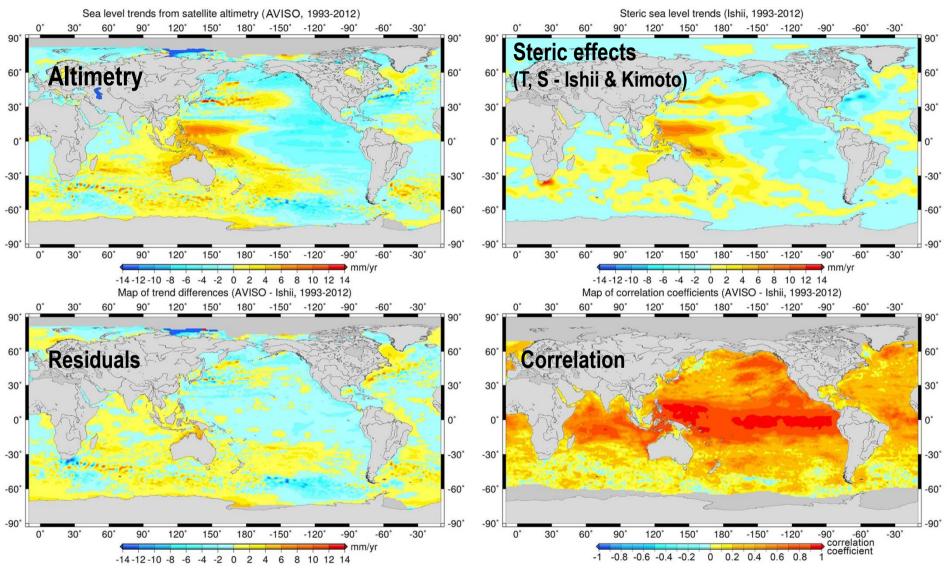


Amplification in the tropics by 20%-30%

IPCC AR5

also Mitrovica, 2009; Milne et al., 2009 $_{\rm 43}$ Tamisiea & Mitrovica, 2011, Spada et al., 2013

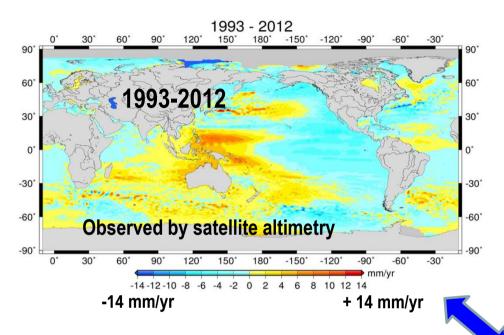
Spatial trend patterns: comparison altimetry –steric effects (1993-2012)

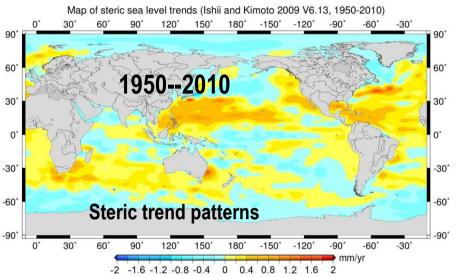


Source: LEGOS

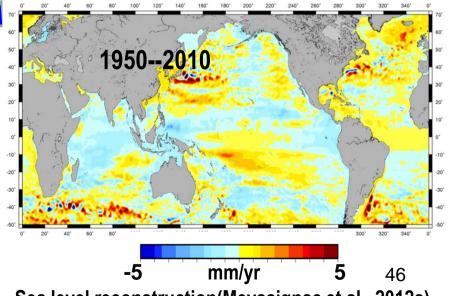


Spatial trend patterns in sea level (global mean rise removed)



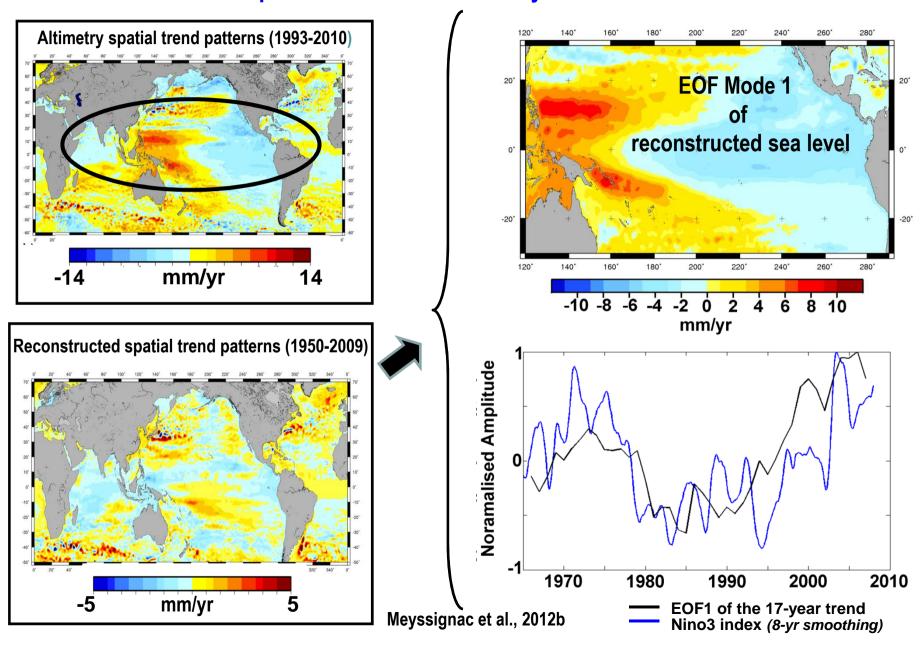


The spatial trend patterns oscillate in space and time in response to natural (internal) climatic modes (ENSO, PDO, NAO, ...)
(e.g., Bindoff et al., 2007, Stammer et al., 2013, Meyssignac et al., 2012a, Hamlington et al., 2013)



Sea level reconstruction(Meyssignac et al., 2012a)

Spatial trend patterns of the sea level reconstruction computed over successive 18-year windows



Conclusions

- Global mean sea level rise is likely accelerating
- Sea level budget (altimetry era) almost closed
- Global mean sea level rise likely a consequence of anthropogenic global warming
- Regional variability (spatial trend patterns) still dominated by natural (internal) modes of climate variability

Grand challenges for the coming years

- Insure continuity of space-based & in situ observing systems (+ new observations)
- → satellite altimetry (sea level & ice sheets)
- → space gravimetry (GRACE Follow On)

 (ice sheet mass balance, glaciers, land waters)
- → Argo + Argo deep ocean
- → Tide gauges + GPS
- Improve past sea level reconstructions & OGCMs
- Reprocess long time climatic time series (e.g., ESA CCI for 'Essential Climate Variables') → climate services
 - Perform systematic comparisons between observations and climate model hindcasts......

