→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Sea Level and Climate

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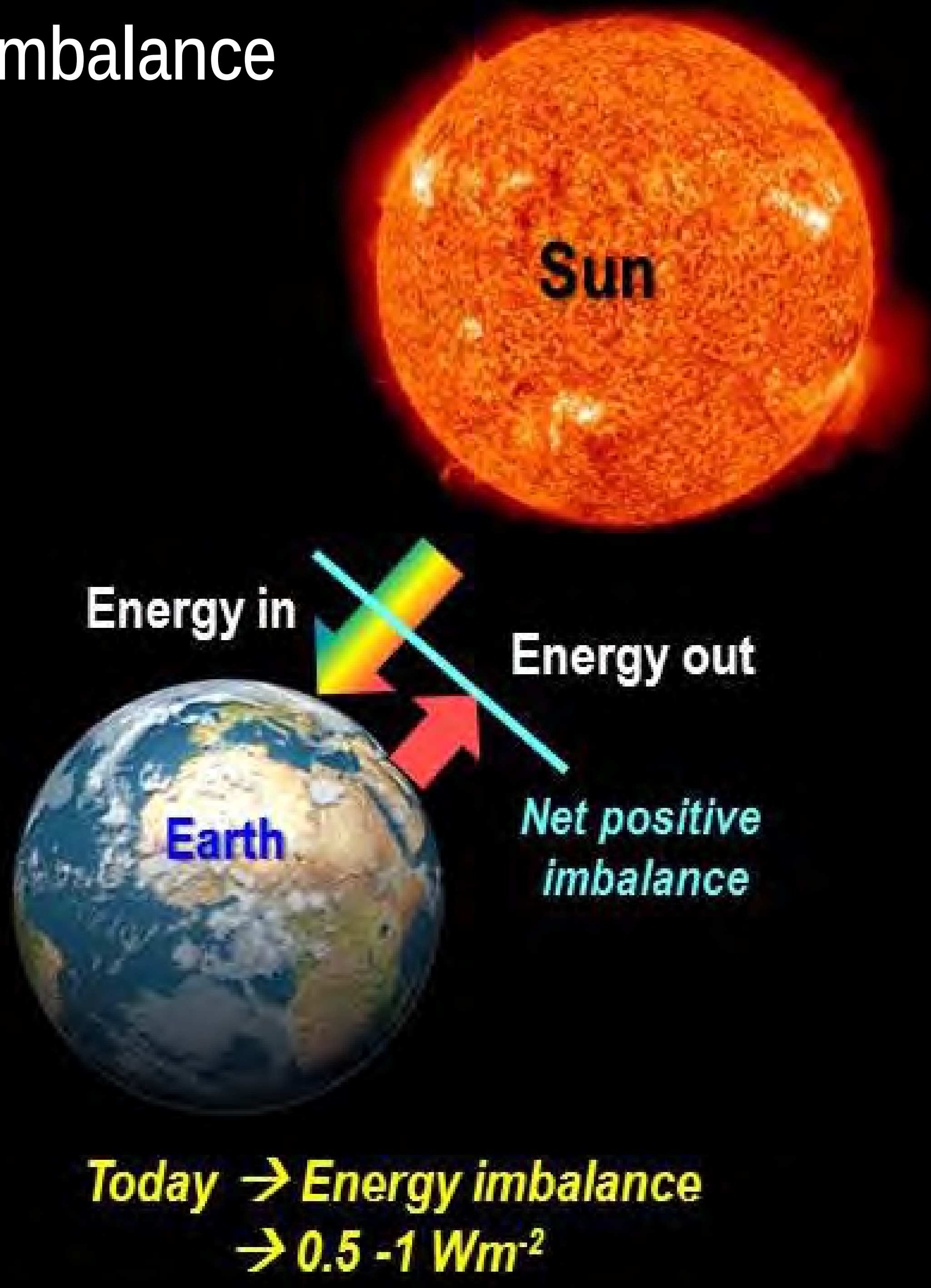
OUTLINE

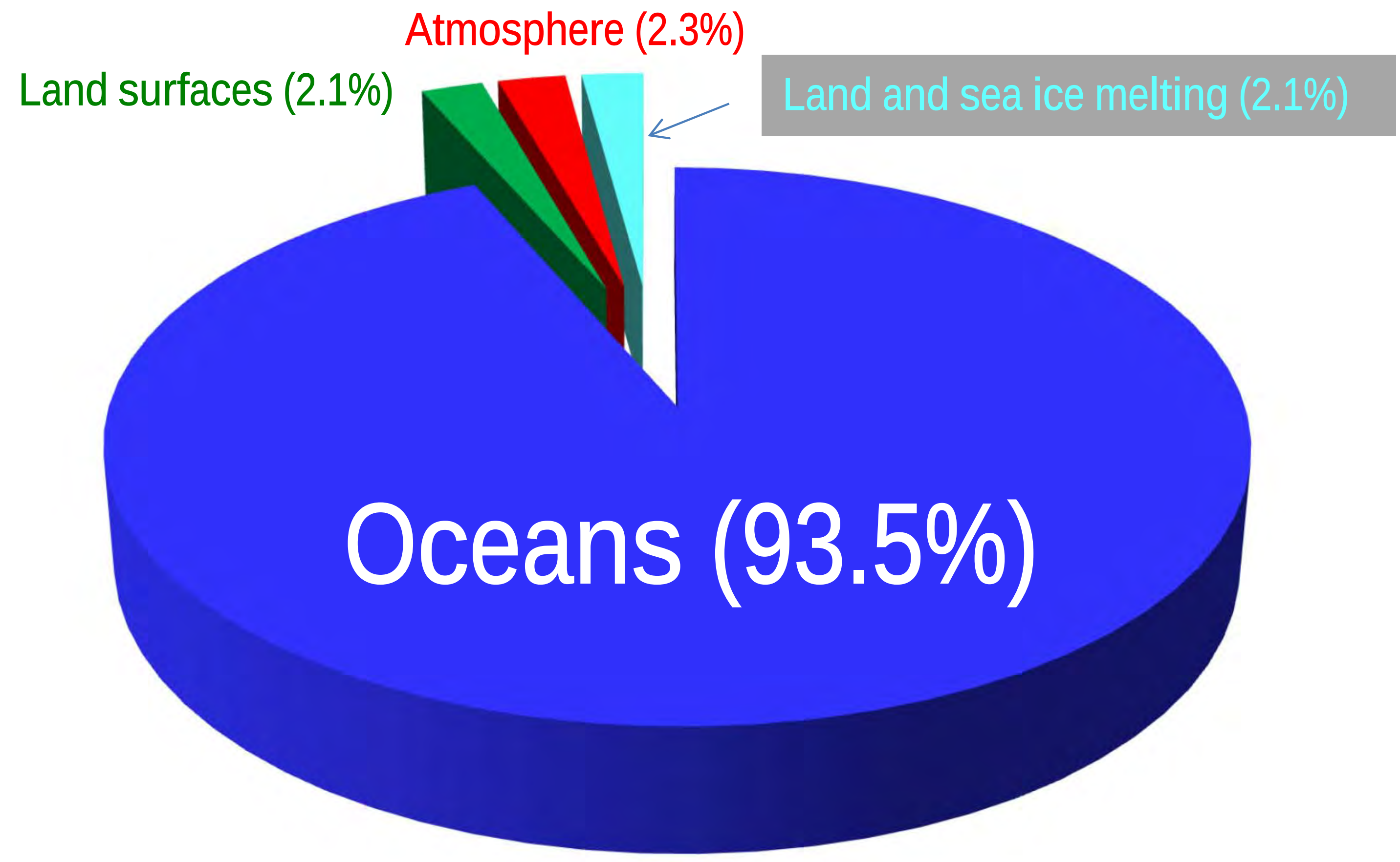
1. Introduction
2. Past sea level rise
3. Satellite altimetry and main applications
4. Sea level measured over the altimetry era
5. Recent improvements
6. Sea level budget (1993-present)
7. Sea level budget (Argo & GRACE era)
8. Interannual variability
9. Regional variability
10. Coastal sea level
11. Conclusions
12. A few relevant publications

Earth's Energy Imbalance



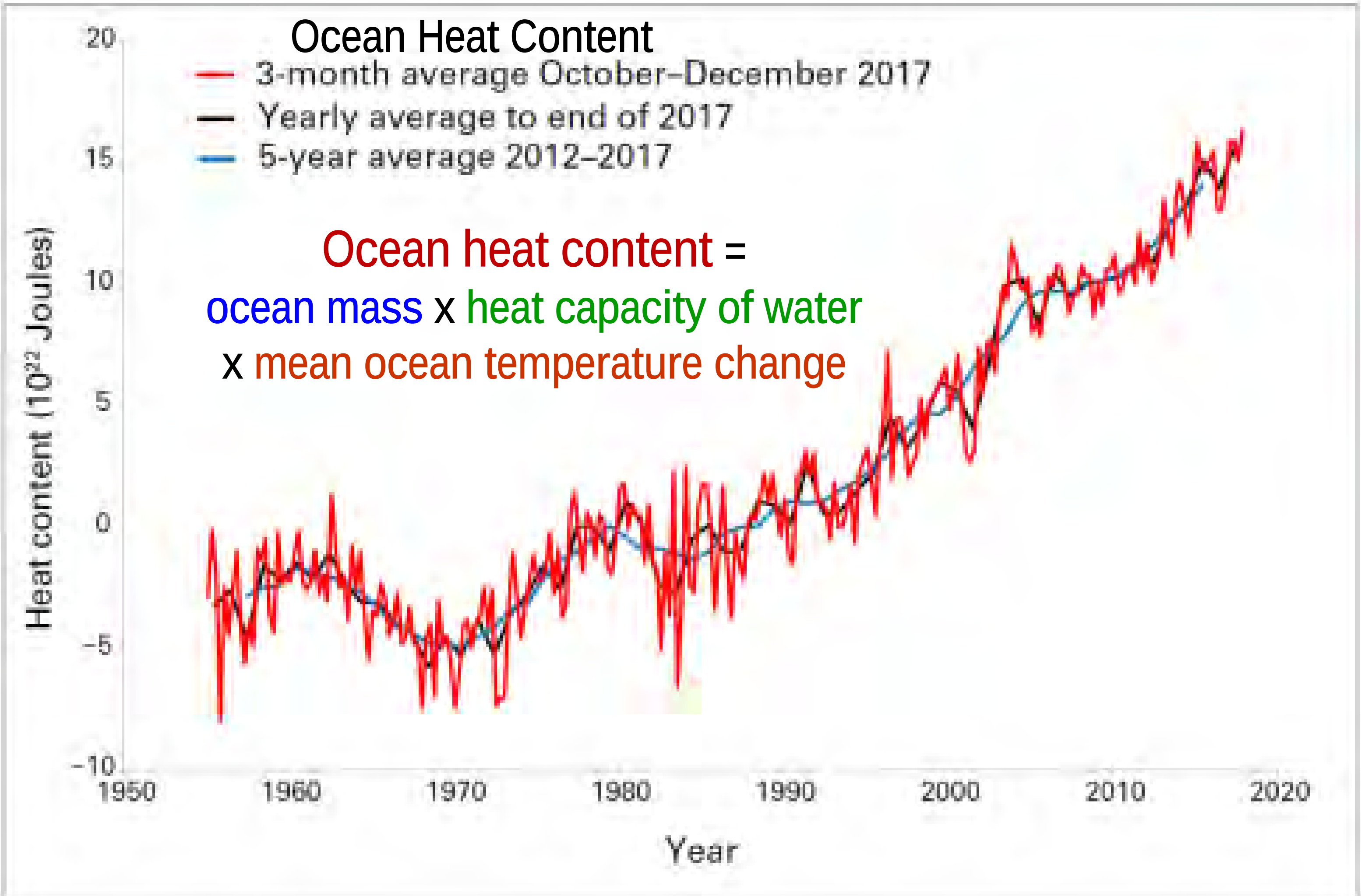
Heat excess in the climate system:

Percentage of heat accumulated
in the different reservoirs over the last 50 years



IPCC AR5; Von Schuckmann et al., 2016

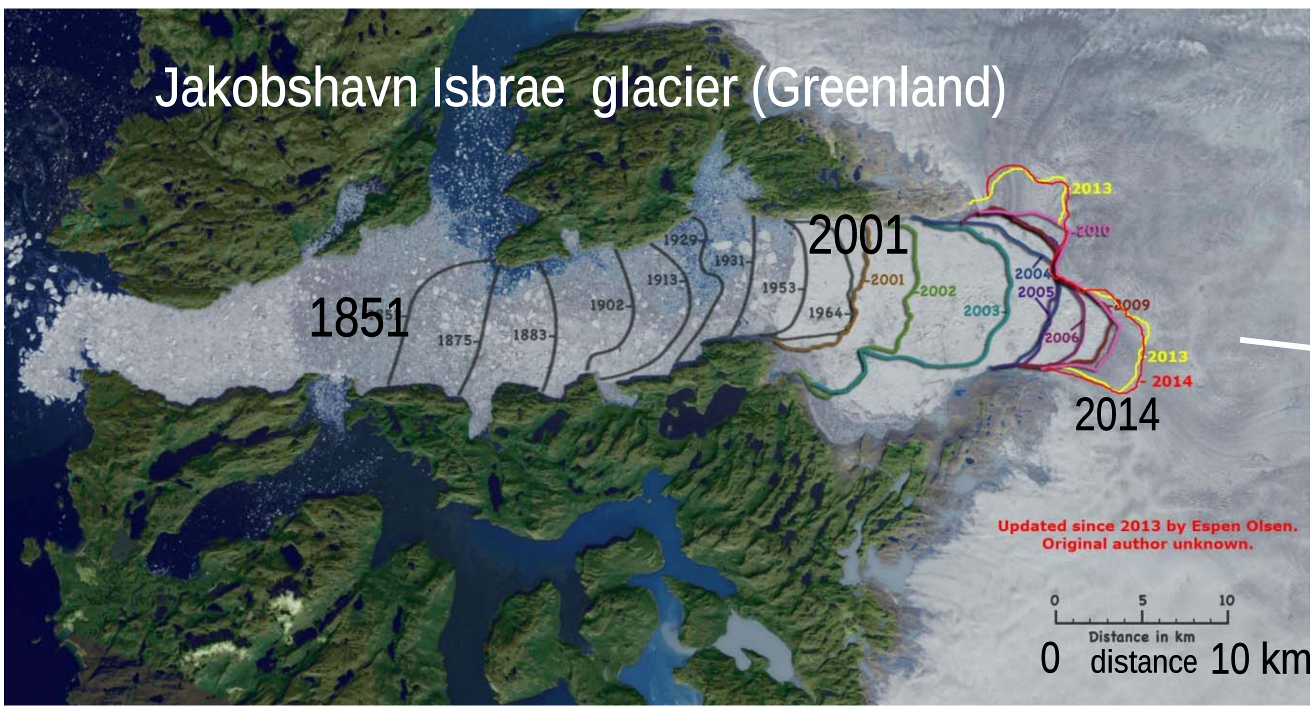
The ocean heat content is increasing

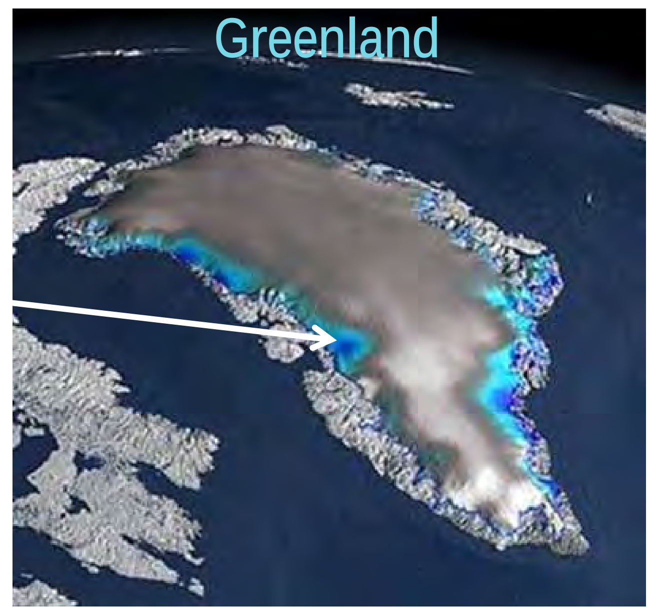


WMO, State of Climate , 2018

Land ice is melting

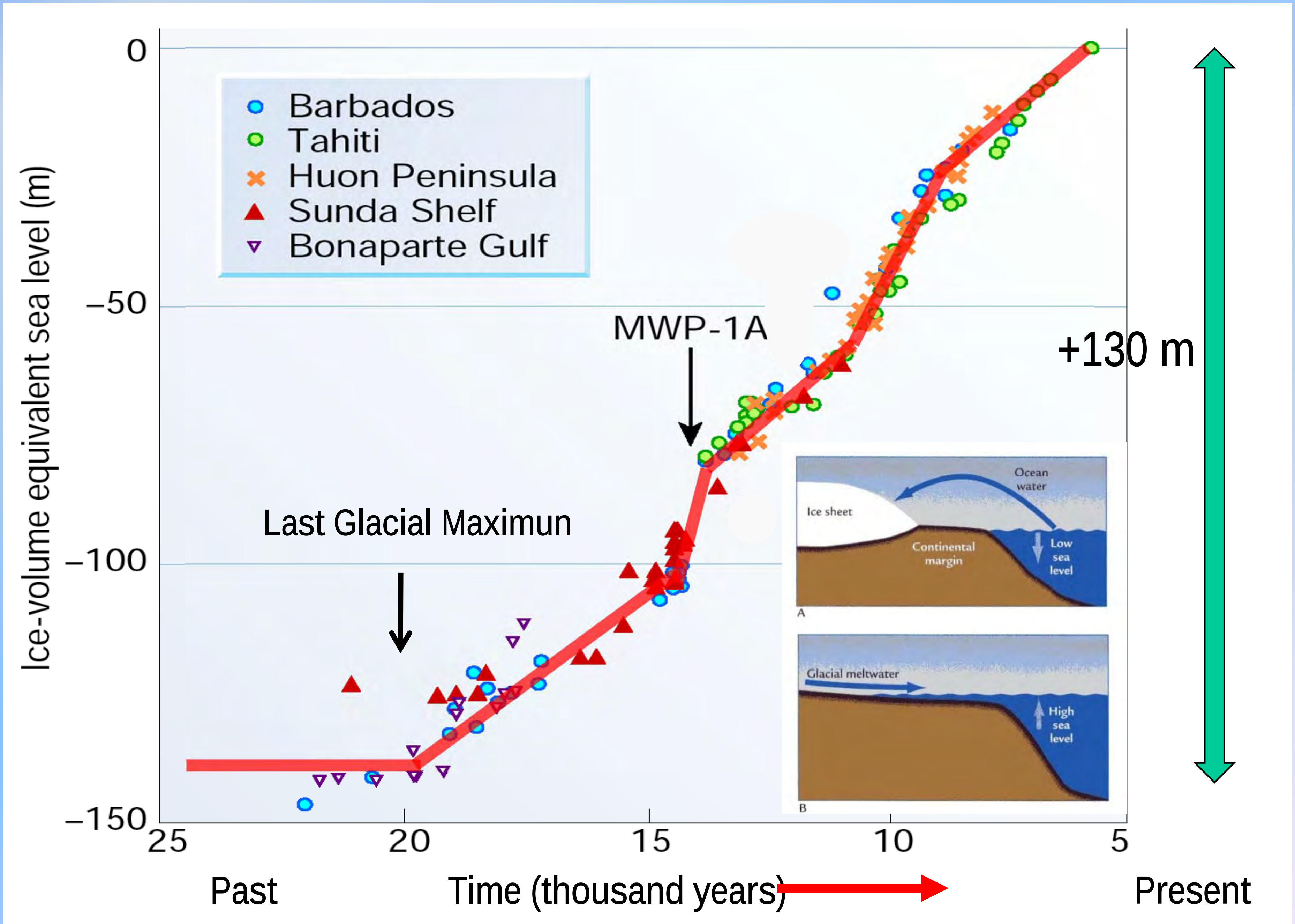
Rhone Glacier (Swiss Alps)





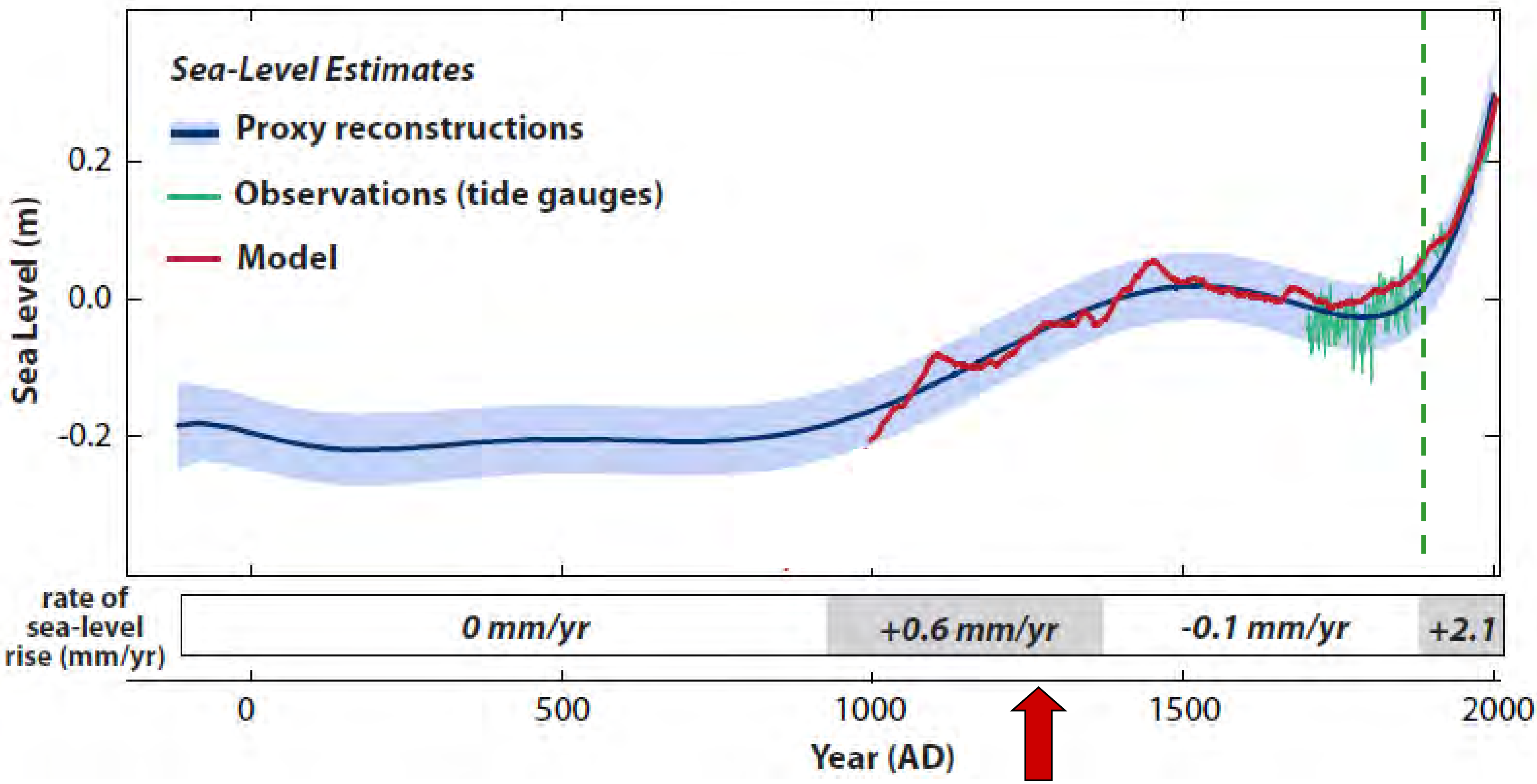
→ Sea level is rising

Global mean sea level rise since the Last Glacial Maximum (- 20 000 years)

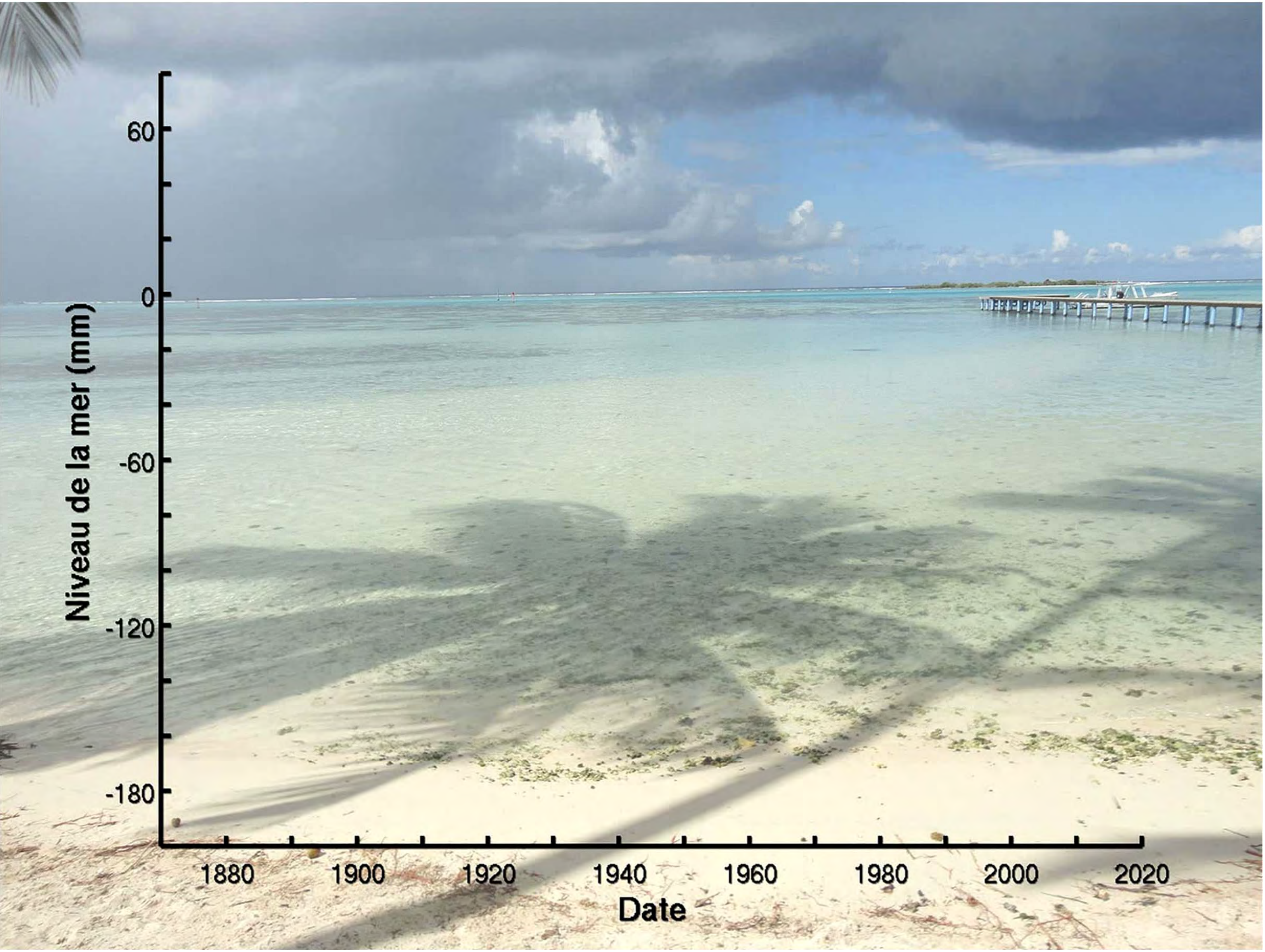


From Lambeck et al., 2002

Evolution of the mean sea level over the last 2000 years



Kemp et al. (2011)


60
0
-60
-120
-180
Niveau de la mer (mm)
1880
1900
1920
1940
1960
1980
2000
2020
Date

20th century sea level rise

1900-1990 (Tide gauge-based reconstructions)

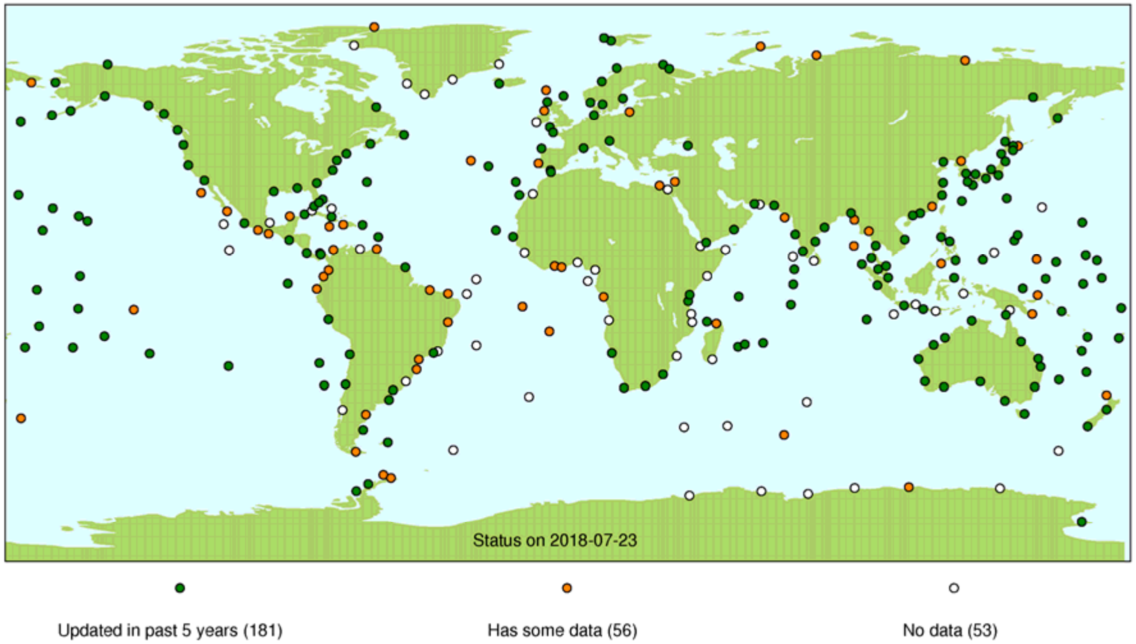
1.1 - 1.9 mm/an

Church et al. (2013) : 1.7 +/- 0.3 mm/yr

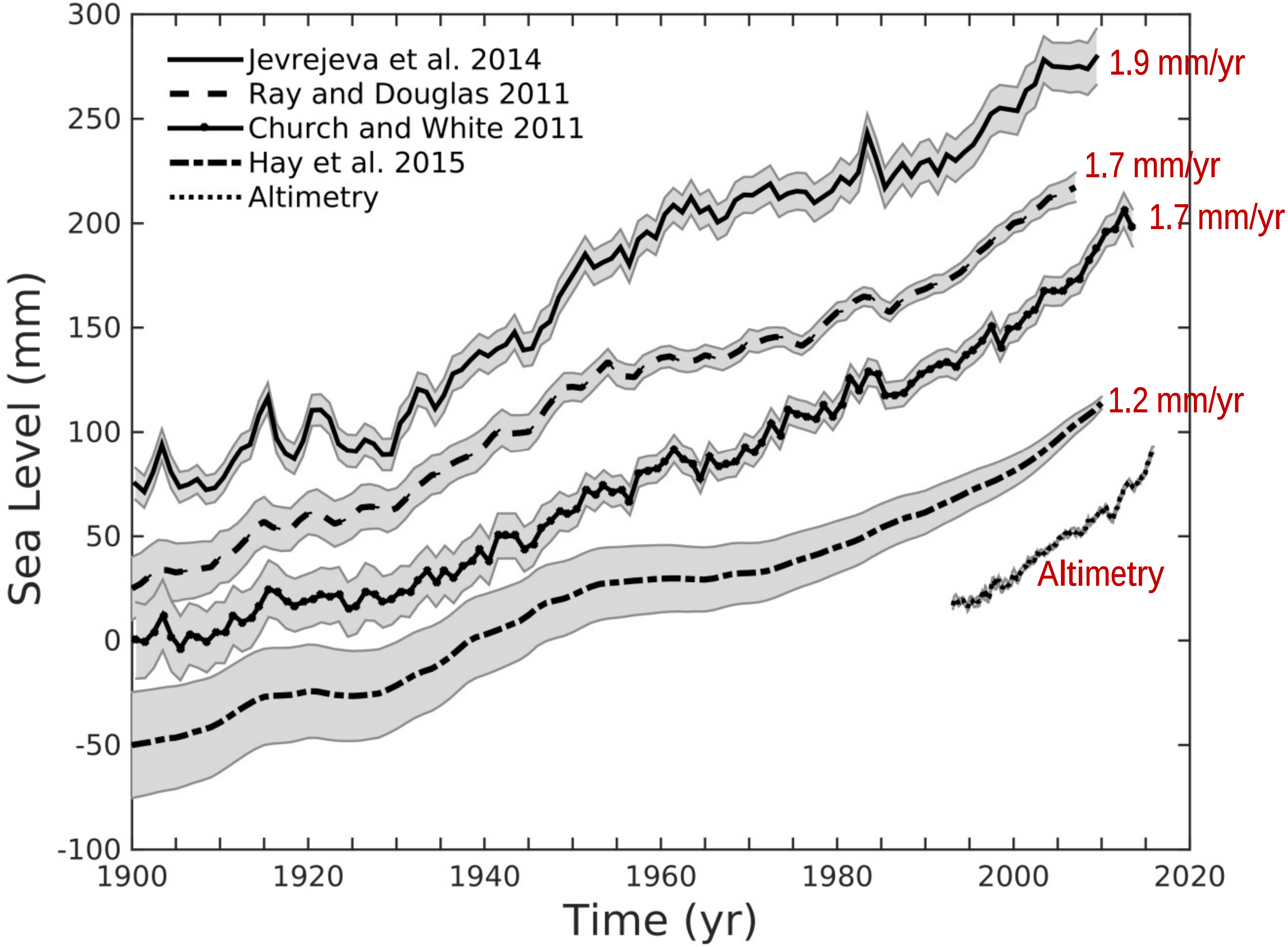
Jevrejeva et al. (2014): 1.9 +/- 0.3 mm/yr

Hay et al. (2015): 1.2 +/- 0.2 mm/yr

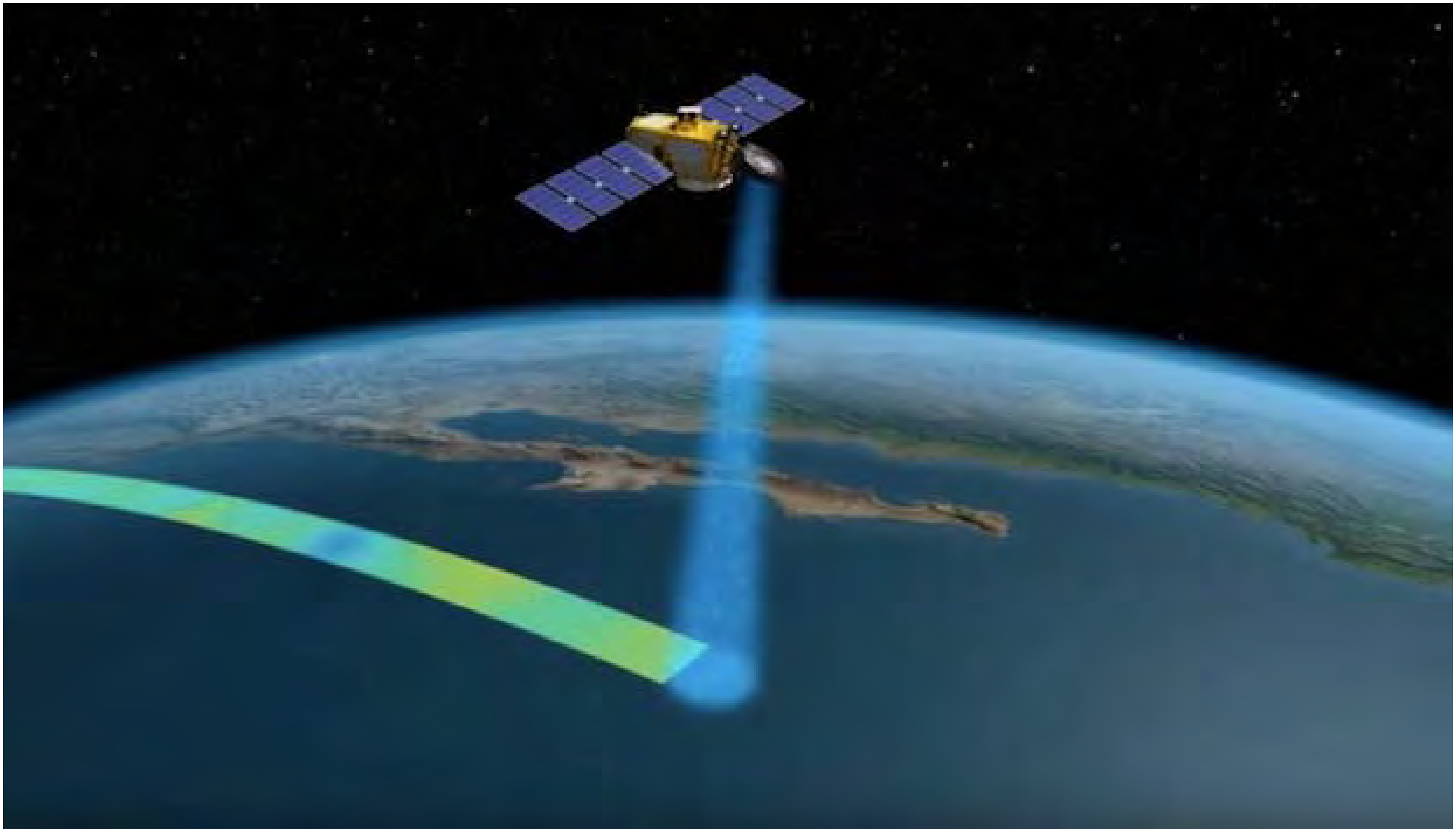
Dangendorf et al. (2017) : 1.1 +/- 0.2 mm/yr



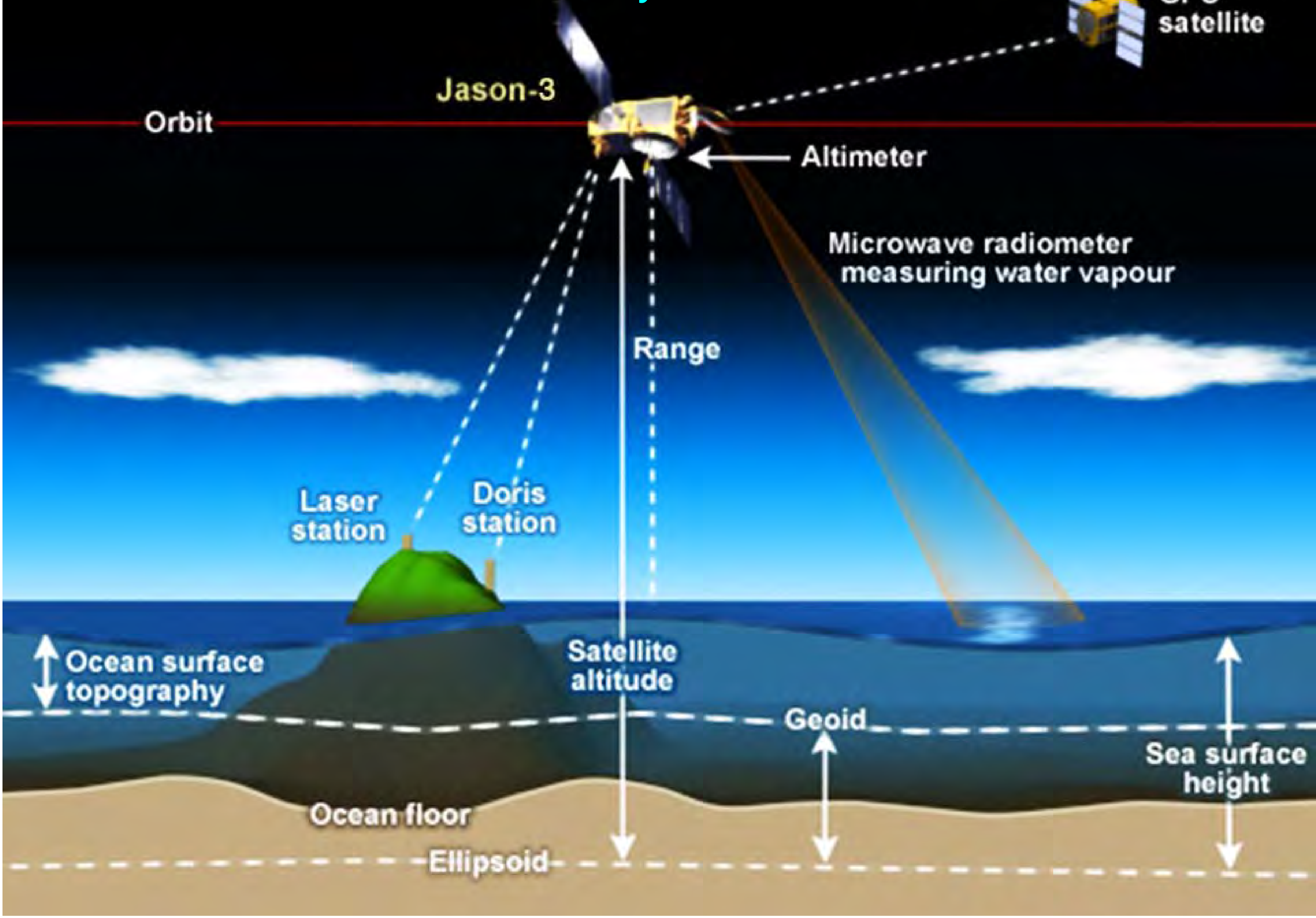
Historical sea level rise since 1900 from tide gauge-based reconstructions



Satellite Altimetry



Satellite altimetry: how it works?

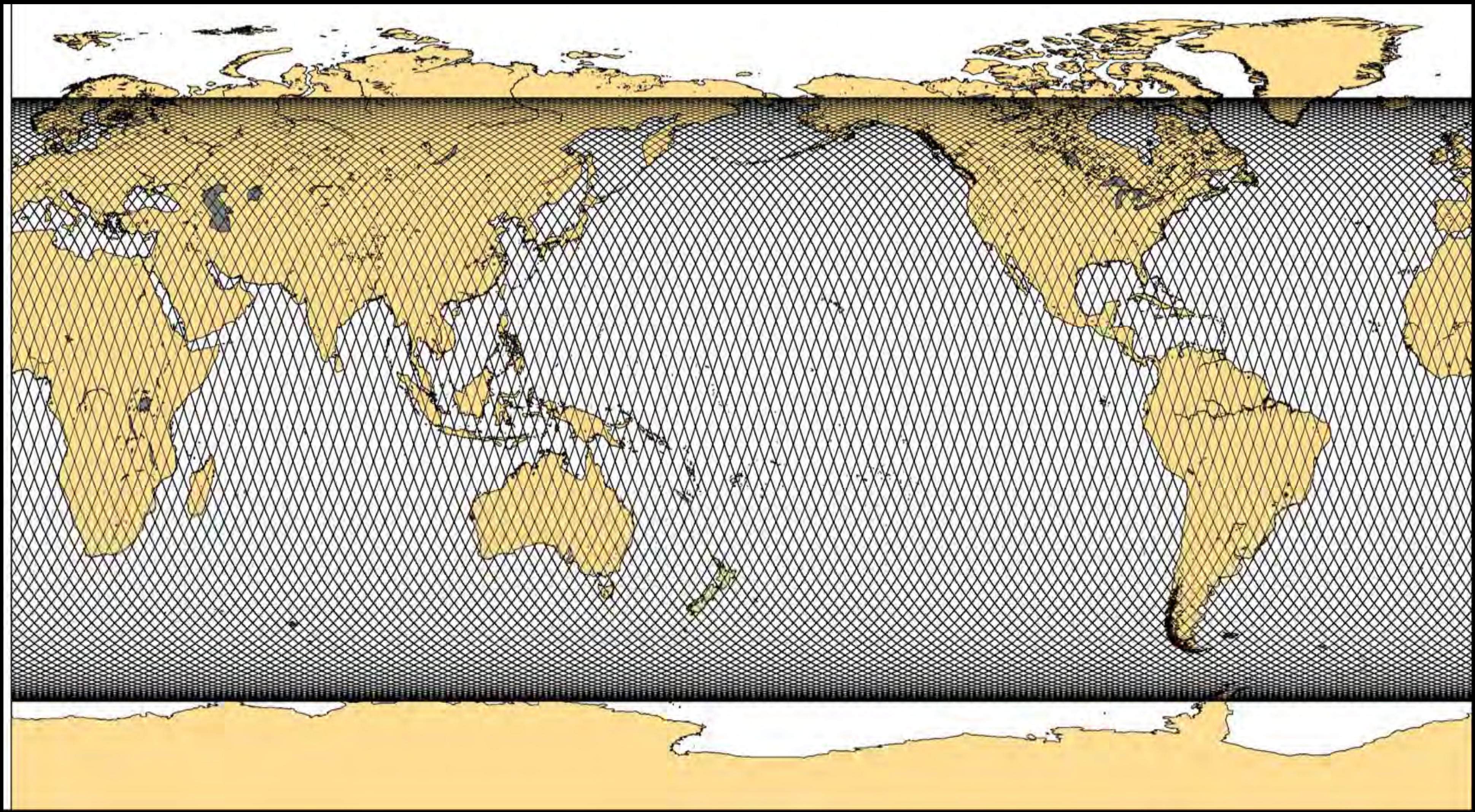


Sea Surface Height above the ellipsoid : SSH

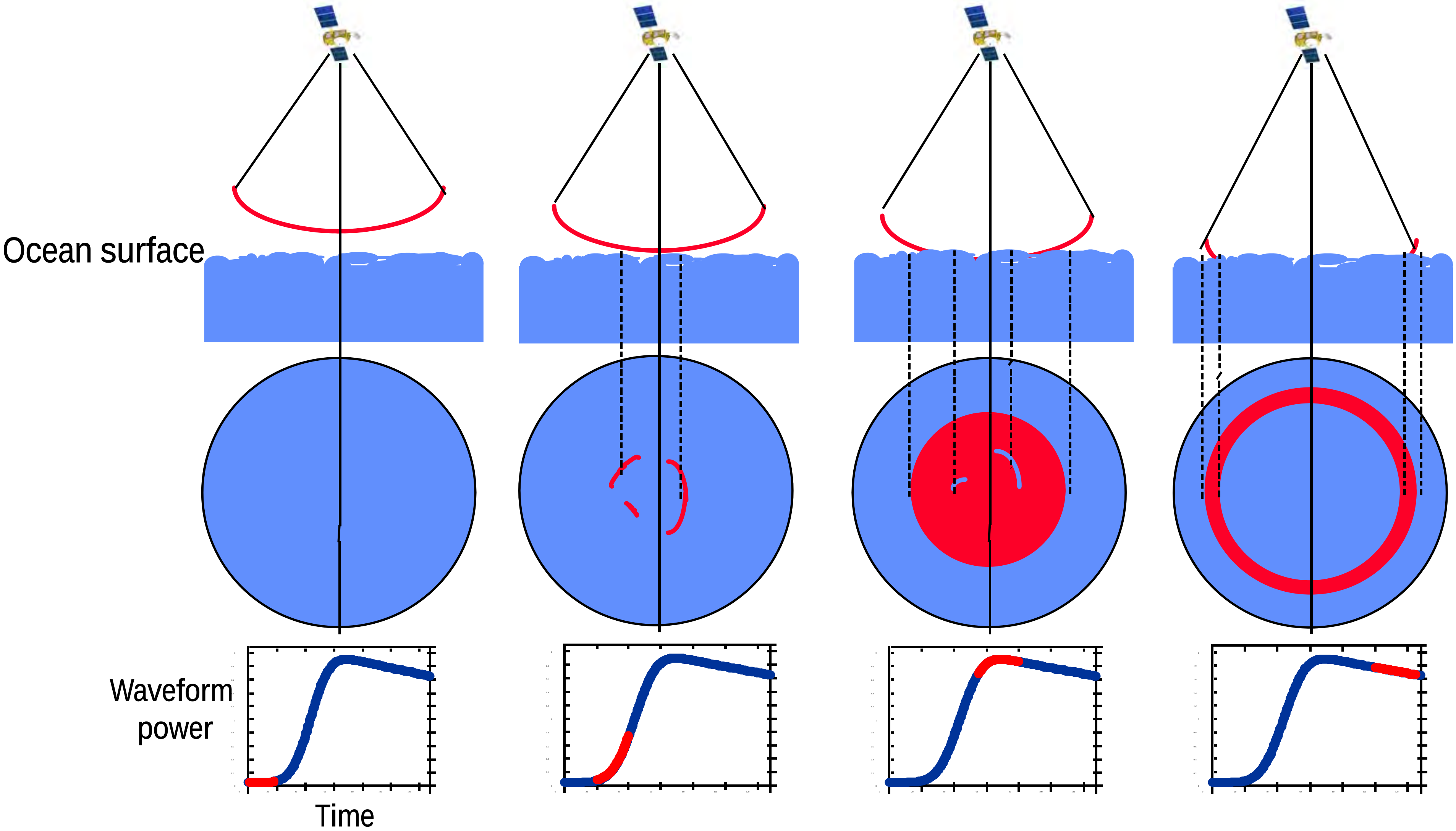
$$SSH = [h_{sat} - h_s] - [h_i + h_{iono} + h_{dry} + h_{wet} + h_{EM} + h_{otide} + h_{stide} + h_{ol} + h_{ptide} + h_{baro}] + \varepsilon$$

h_{sat} : Satellite altitude above the ellipsoid (radial orbit component)
h_s : Range (instantaneous distance between the altimeter antenna and ocean surface)
h_i : instrumental corrections
h_{iono} : ionospheric correction
h_{dry} : dry tropospheric correction
h_{wet} : wet tropospheric correction
h_{EM} : ElectroMagnetic-bias correction
h_{otide} : ocean tide correction
h_{side} : solid Earth tide correction
h_{ol} : ocean loading correction
h_{ptide} : pole tide correction
h_{baro} : inverted barometer correction
ε : random and systematic remaining errors

Global coverage in a few days or weeks → orbital cycle



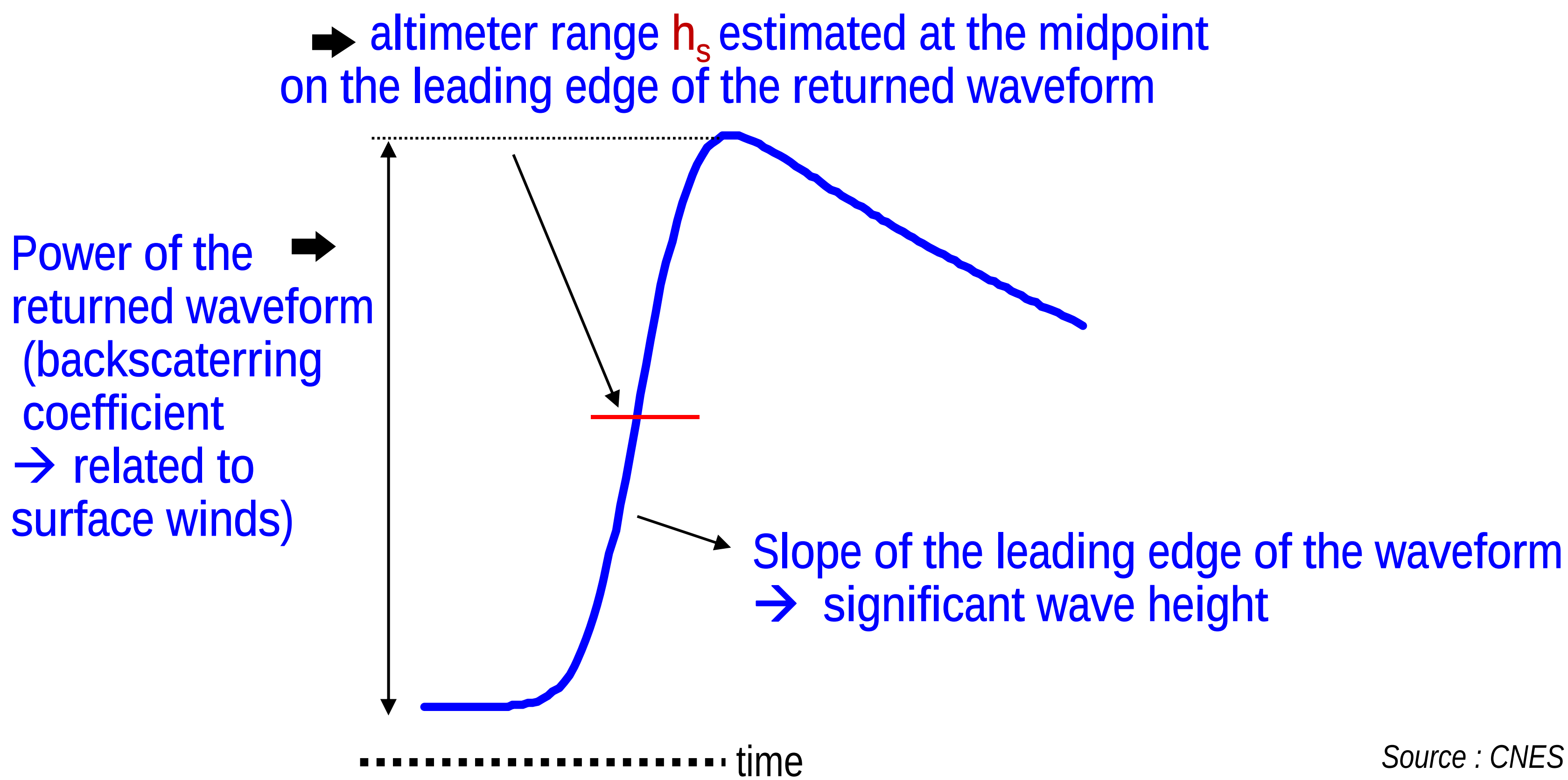
Interaction of the radar echoe (waveform) with the sea surface



Source: CNES

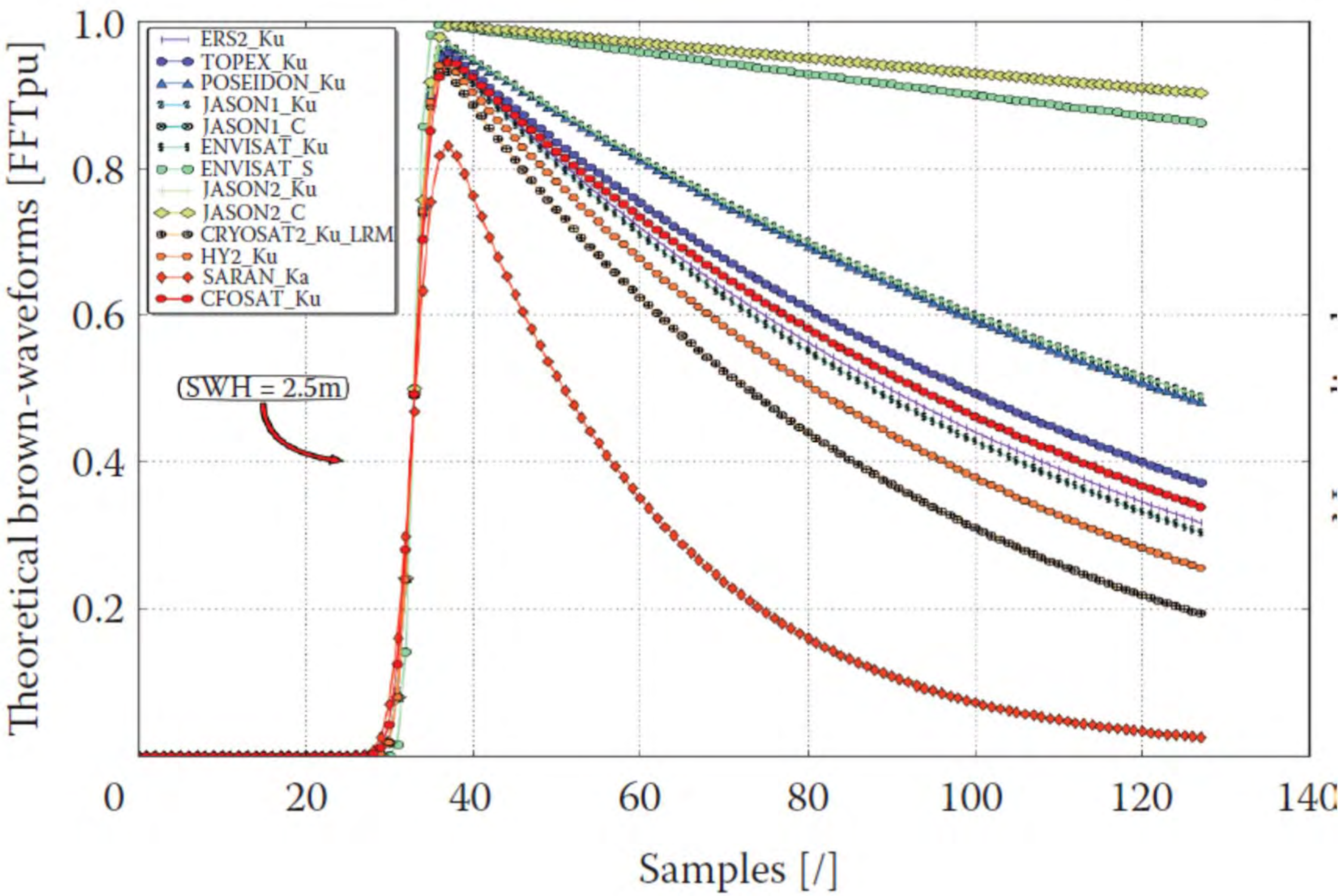
Evolution of the waveform after reflection on the sea surface (returned waveform)

In addition to the altimeter range h_s, the returned waveform informs on other parameters: wave height , surface wind speed & type of surface



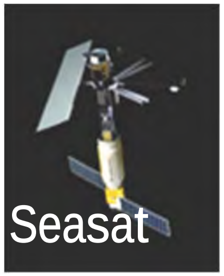
Source : CNES

Theoretical waveform shapes for classical altimetry missions



← GEOS-3 (1975)

Satellite altimetry missions



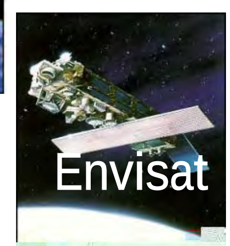
1978

1985

1991; 1995

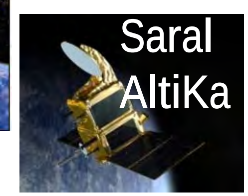
1992

2001



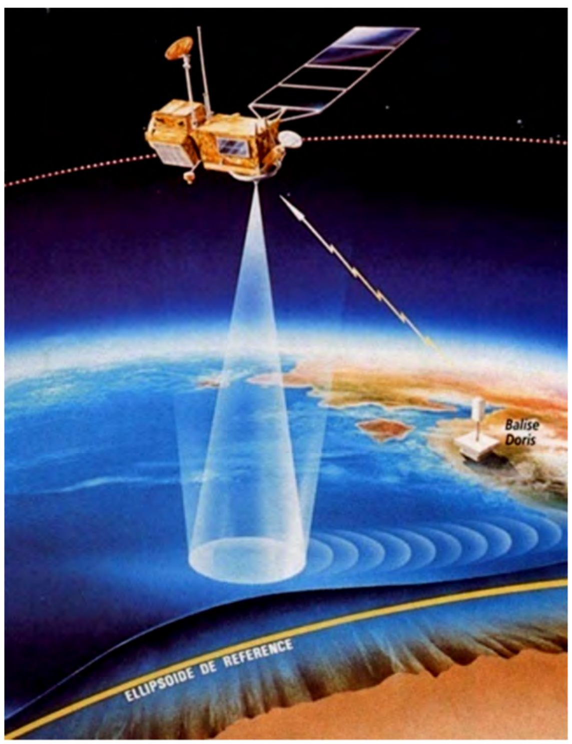
2002

2008

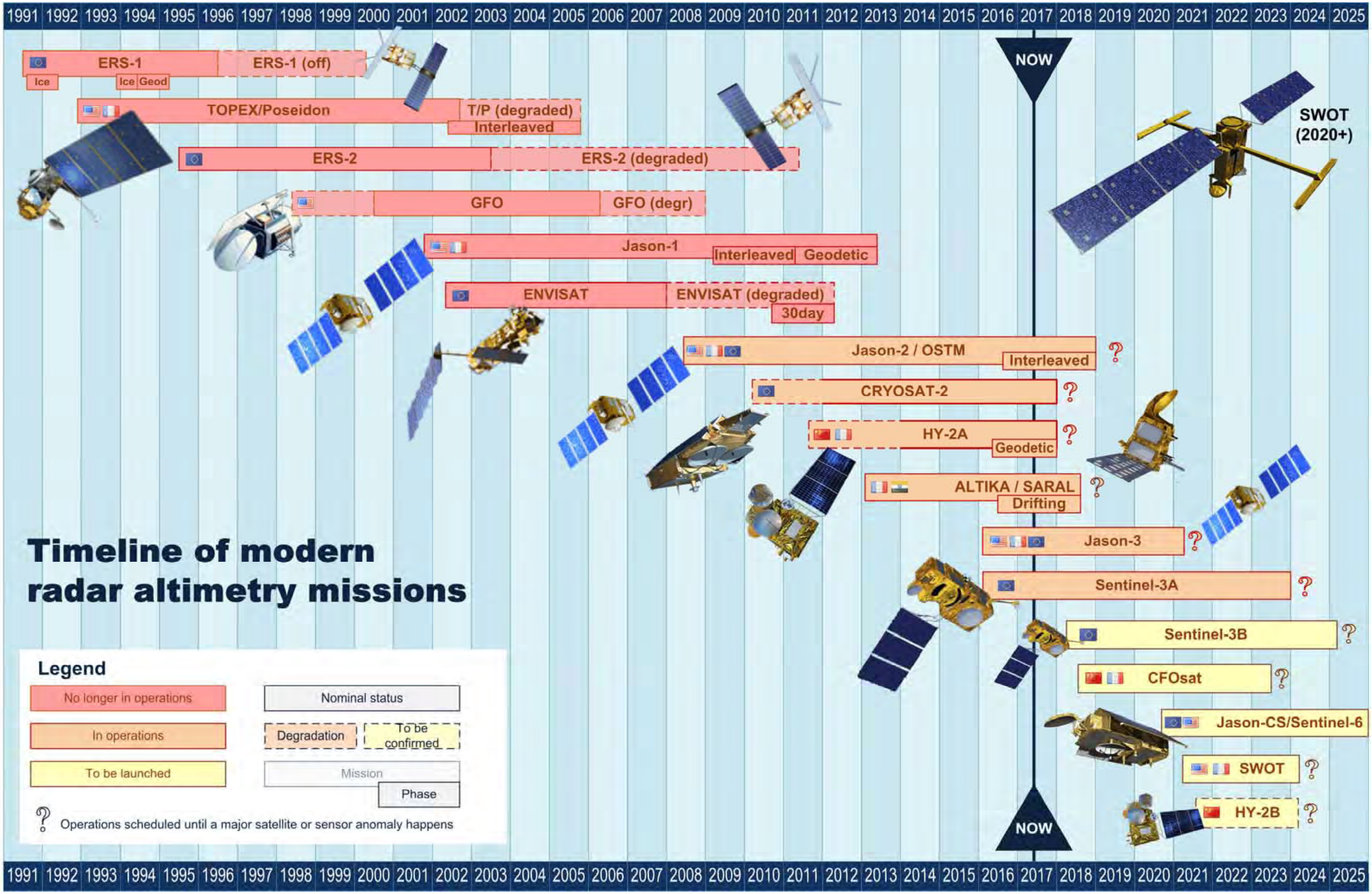


2013

…



→early 1990s : high-precision satellite altimetry



The constellation of high-precision altimeter satellites

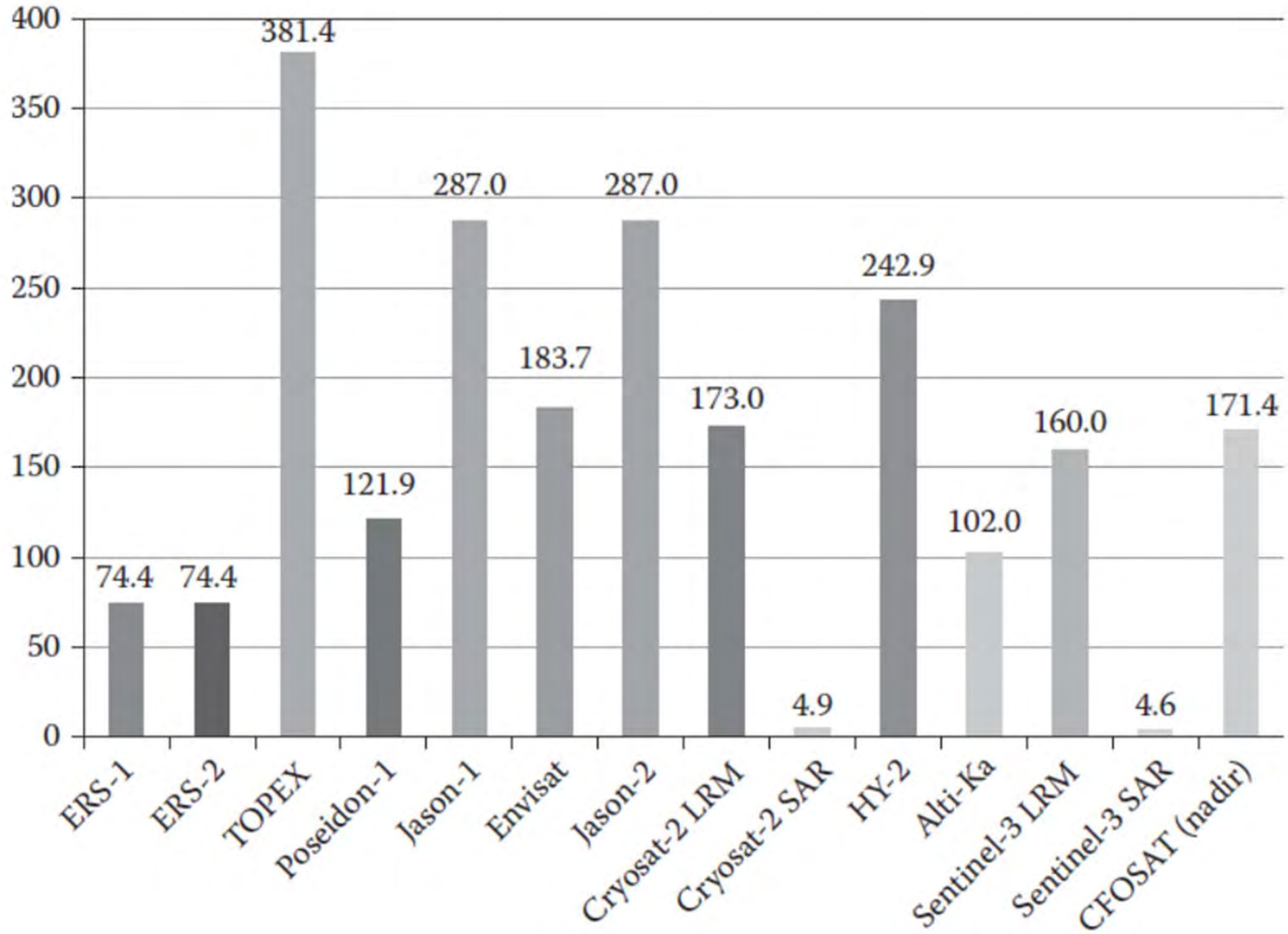
TABLE 1.3

Orbital Characteristics (geodetic phases not considered here)

	T/P, Jason	Envisat	CryoSat-2	Altika	HY-2A	Sentinel-3
Altitude (km)	1336	782	717	800	971	814
Period (s)	6746	6036	5952	6036	6267	6060
Inclination (deg.)	66	98.6	92	98.6	99.3	98.6
Sun synchronous		x		x	x	x
Cycle (days)	9.9	35	369	35	14	27

Escudier et al., 2018

WAVEFORM FOOTPRINTS (KM^2)



Escudier et al., 2018

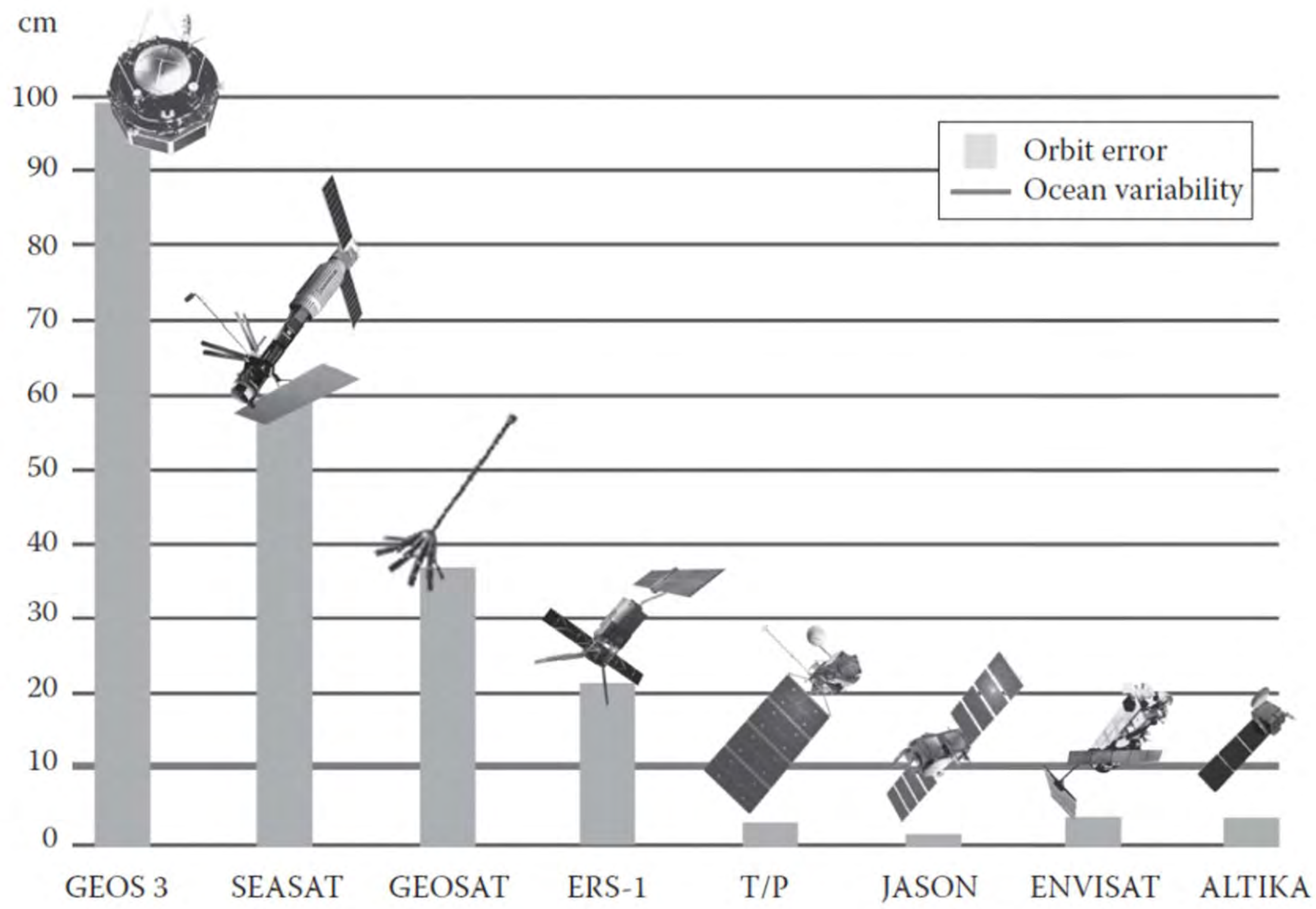
TABLE 1.12

Global Jason-2 Error Budget at Global Scale and for Short Timescales

Parameters		Altimetry Uncertainties (cm)
Parameters and correction for sea-surface height	Altimeter range	1.7 (noise)
	Filtered-out altimeter ionosphere correction	0.2
	Sea state bias	0.2
	Dry troposphere and dynamical atmospheric corrections	0.7
	Radiometer wet troposphere	0.2
	Ocean tide	1.0
	Orbit (radial component)	1.5
Sea surface height	Corrected with all the corrections	<3.5

Escudier et al., 2018

RADIAL ORBIT ERROR



Escudier et al., 2018

High-precision satellite altimetry constellation

Precision of a single sea surface height measurement
→

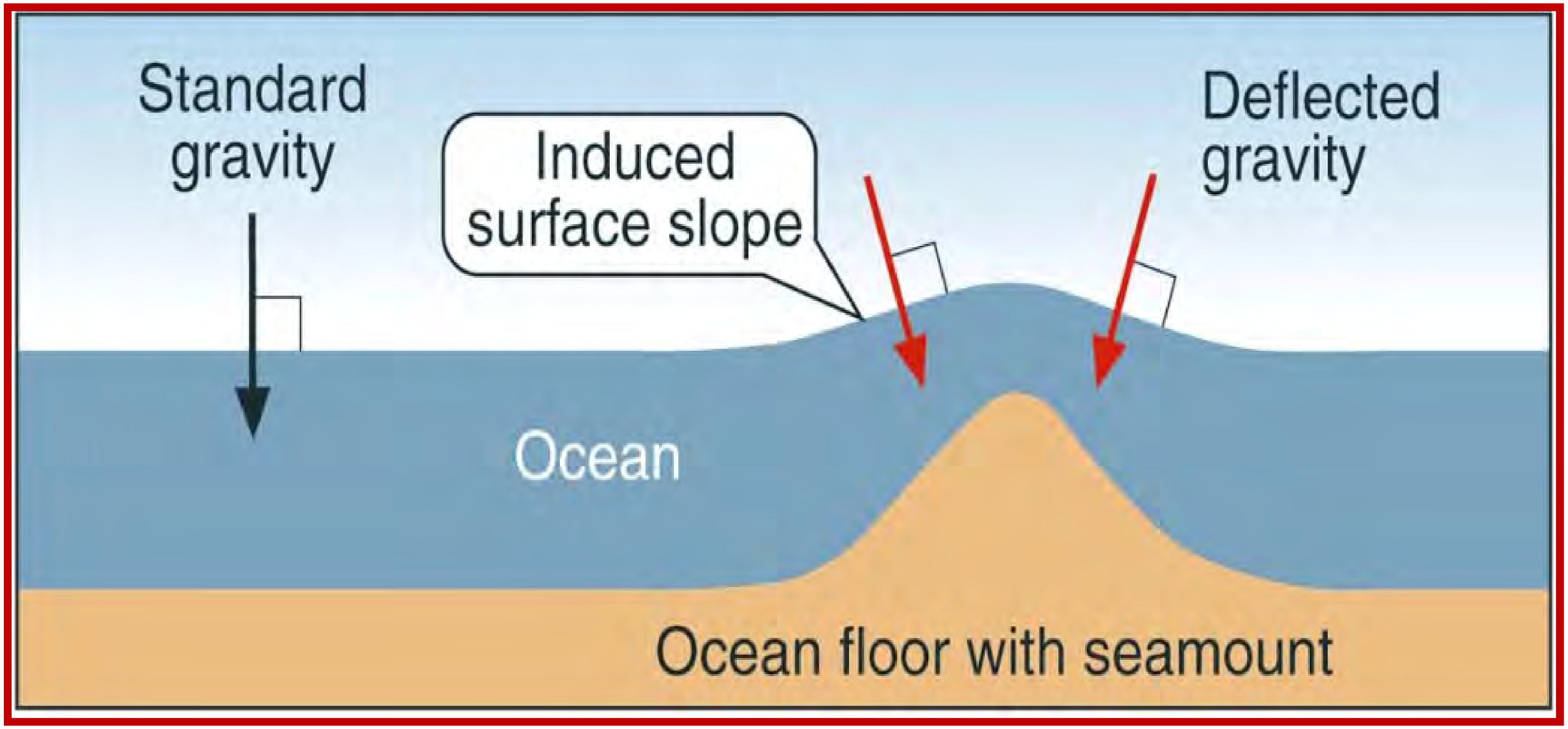
- ➢ 25 years ago: 10 cm
- ➢ Today: ~2 cm

Applications of Sea Surface Height (SSH) measurements by satellite altimetry

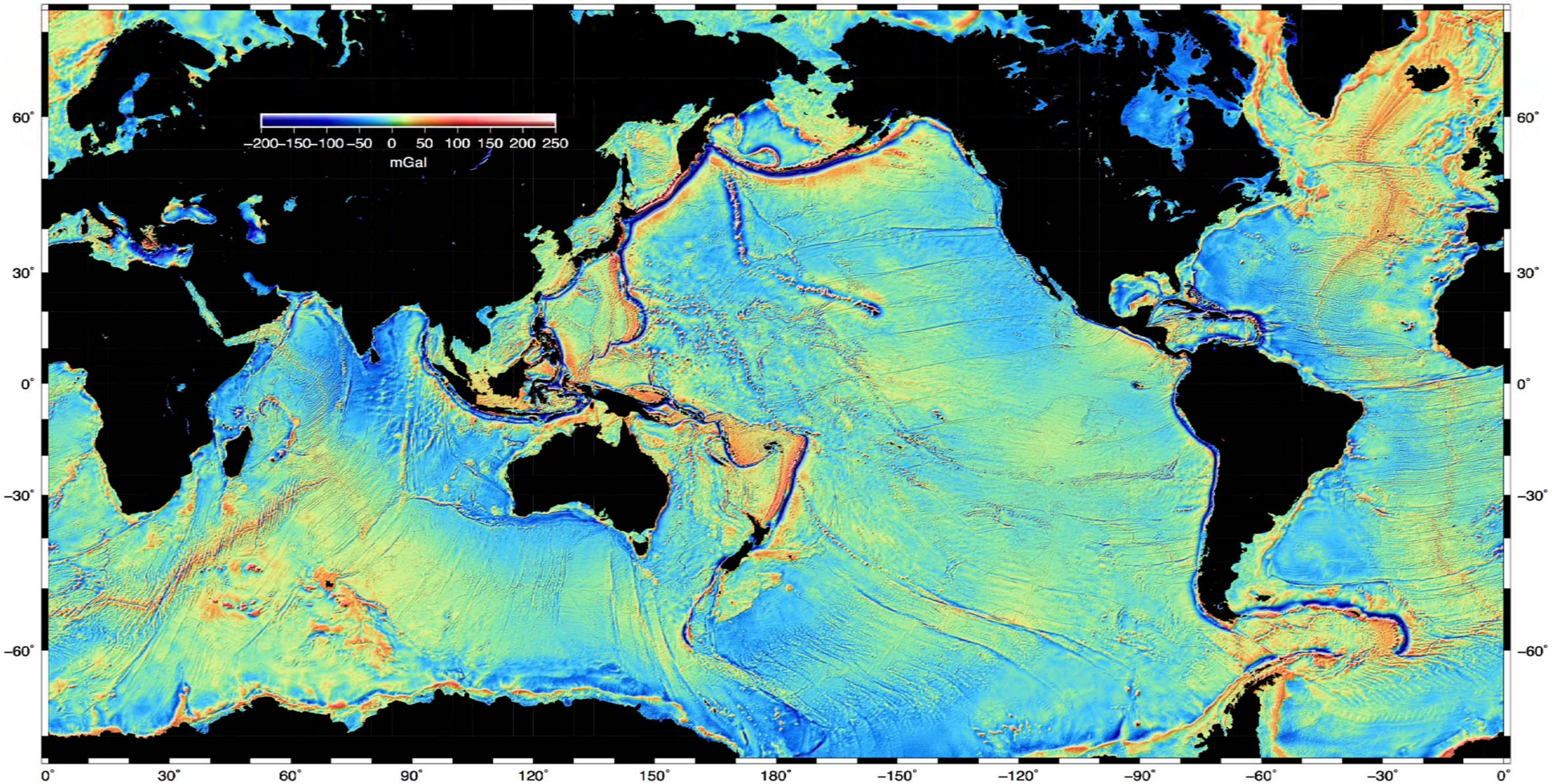
- Mean sea surface and sea floor topography → marine geophysics
- Currents → ocean circulation
- Tides
- El Nino, La Nina
- Operational oceanograhy (ocean state forecast ~2 weeks in advance)
- Sea level variations → most demanding application of satellite altimetry

SEA SURFACE TOPOGRAPHY

- Permanent component → geoid/marine gravity field (1m-100m)
- Time-variable component → ocean dynamics, ocean tides, …. (1cm-1m)



Altimetry-based Earth gravity map



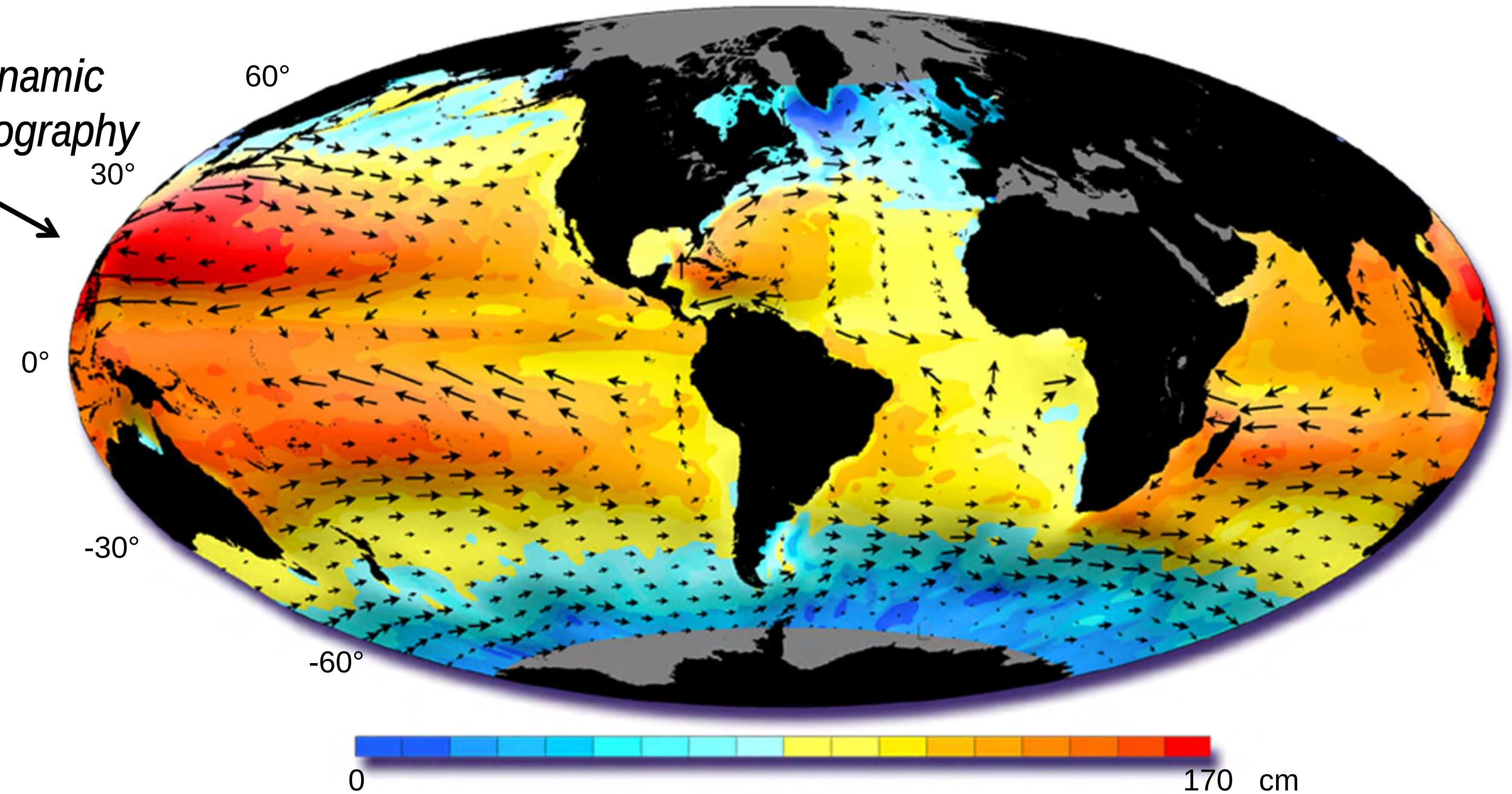
Sandwell, David T, R Dietmar Müller, Walter HF Smith, Emmanuel Garcia, and Richard Francis. 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science* 346 (6205):65-67.

The large-scale ocean circulation due to wind-driven water masses and T/S-related water density variations produces a « dynamic topography » *-above the geoid-.*

→ *signature of ocean currents*

Geostrophic equilibrium implies that the ocean current velocity is proportional to the sea surface slope

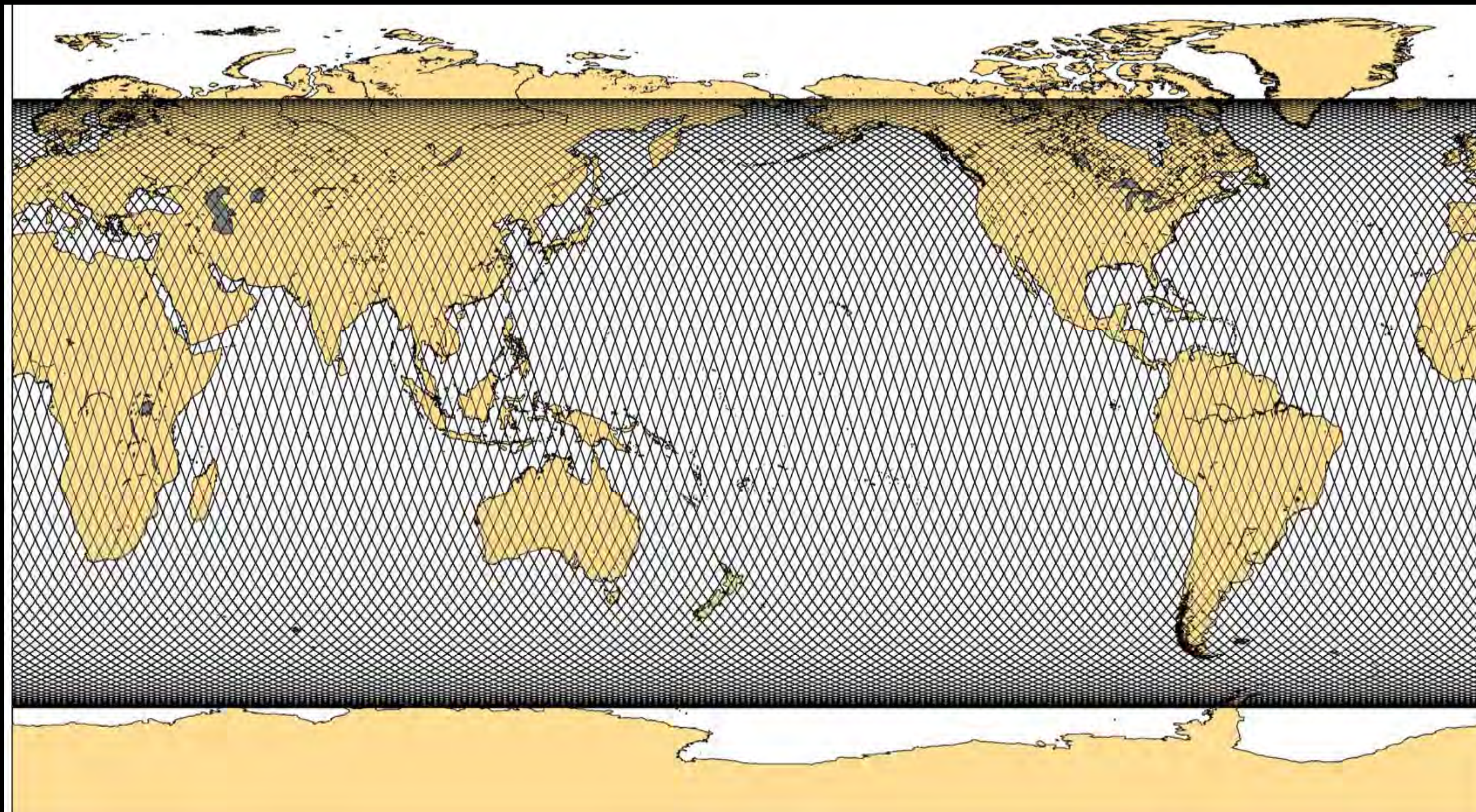
Dynamic Topography



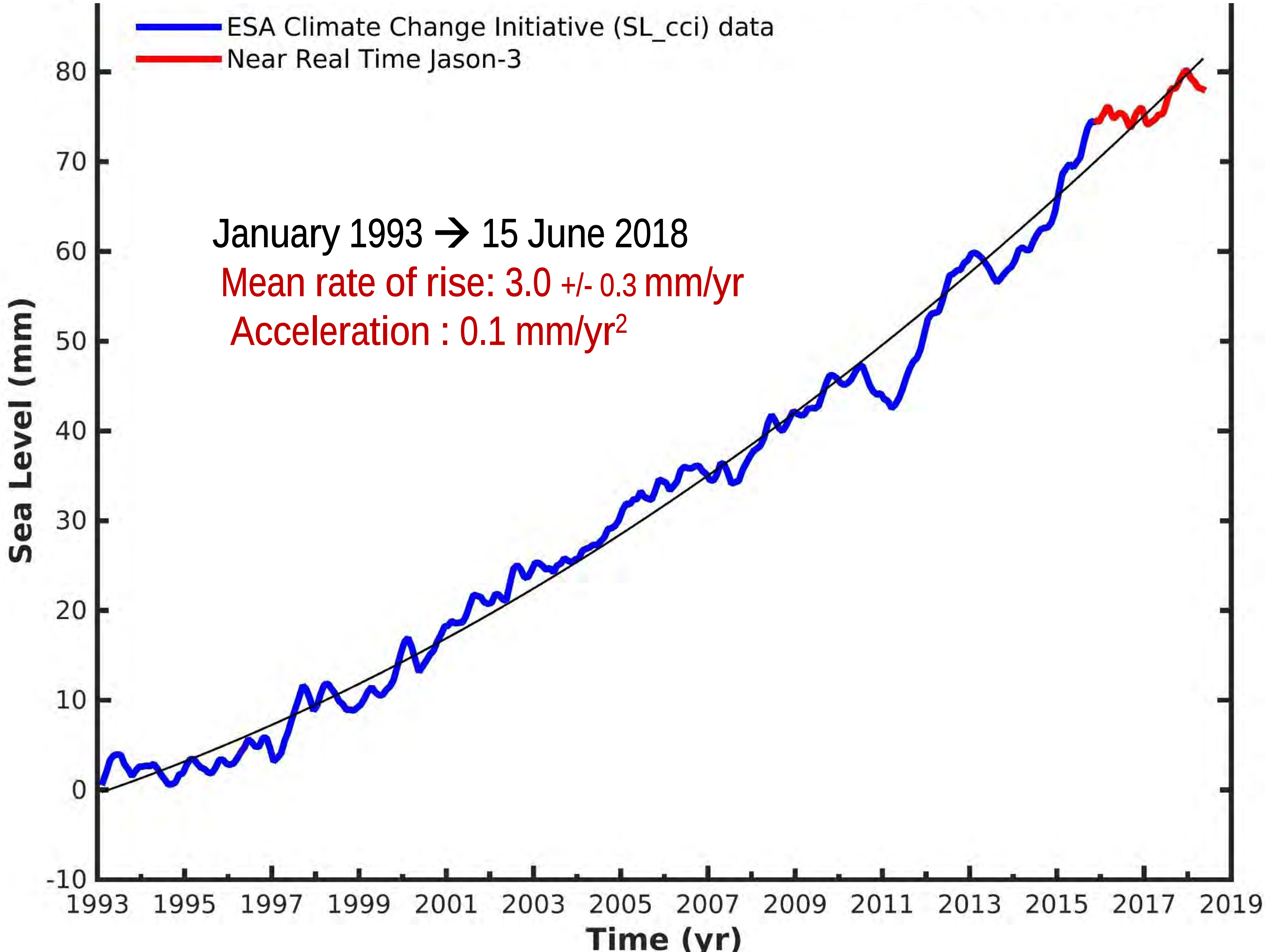
The large scale ocean circulation results from an equilibrium (geostrophic equilibrium) between horizontal pressure gradients and the Coriolis force

Source: CLS/AVISO

Averaging 1-Hz SSH measurements over an orbital cycle → mean sea level

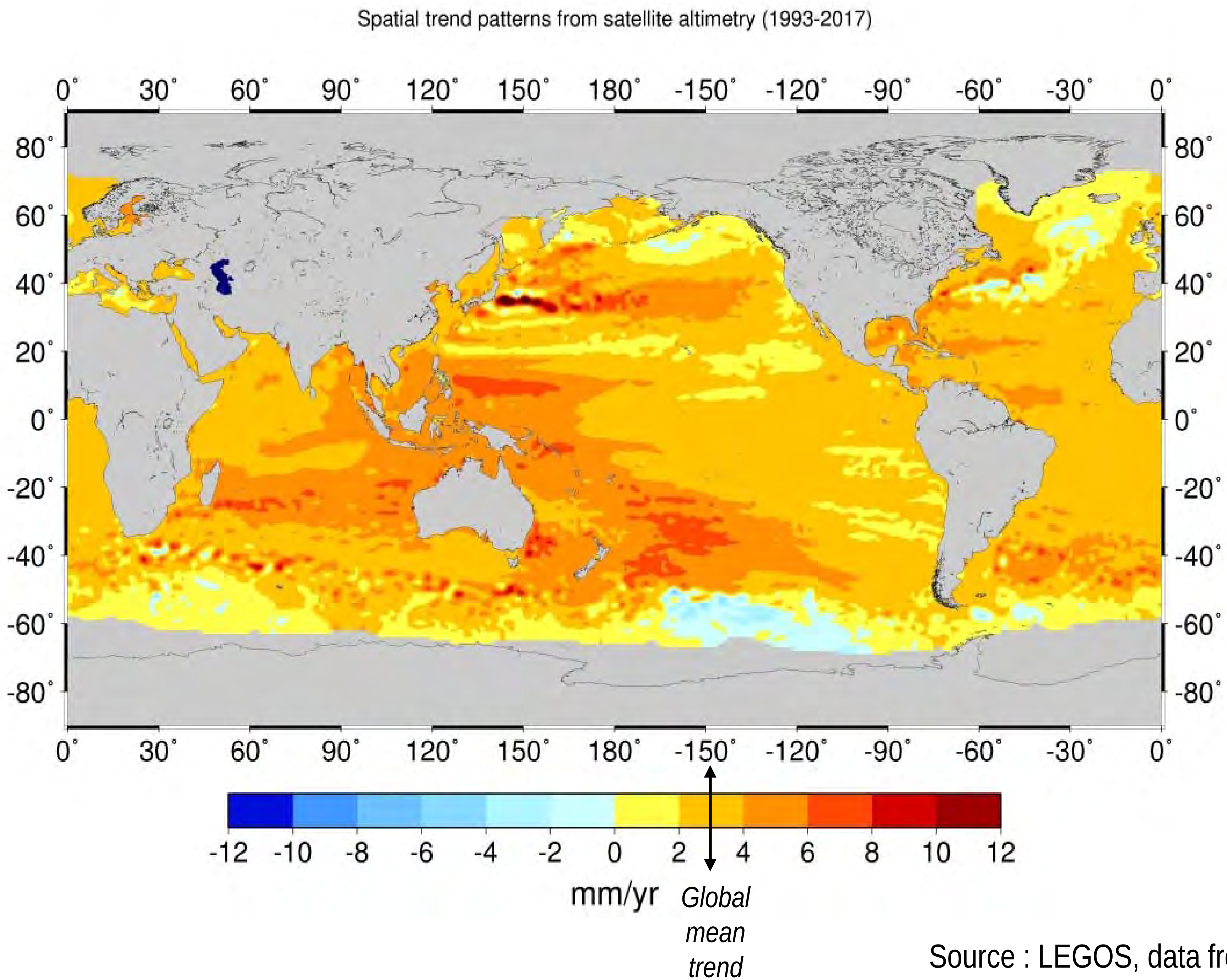


Global Mean Sea Level (GMSL) over the altimetry era



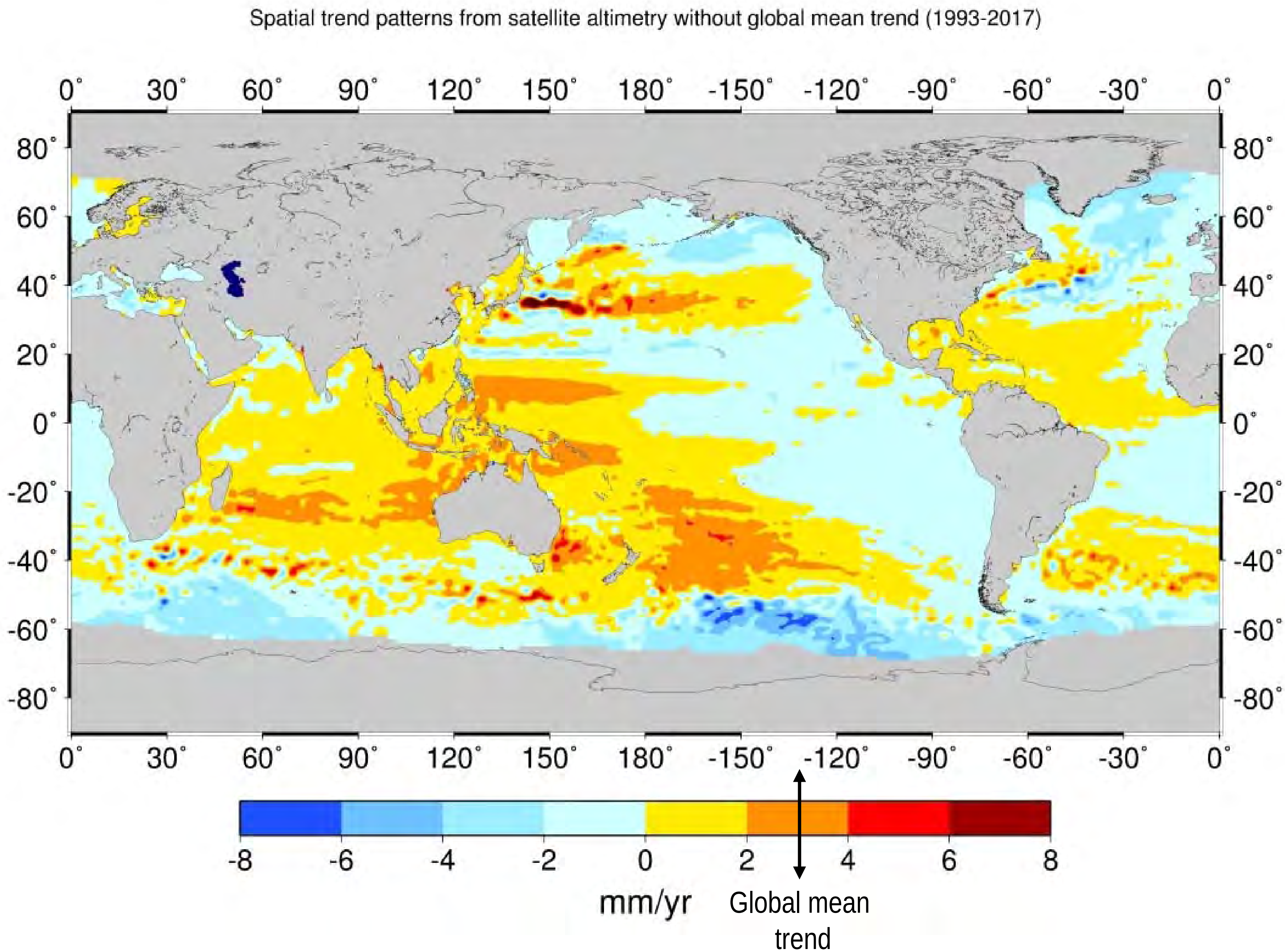
Source: LEGOS

Regional Sea Level Trends (1993-2017)



Source : LEGOS, data from Aviso

Regional sea level trends (global mean trend removed) (1993-2017)



RECENT IMPROVEMENTS

Mean Sea-Level Error Budget for the Main Climate Scales

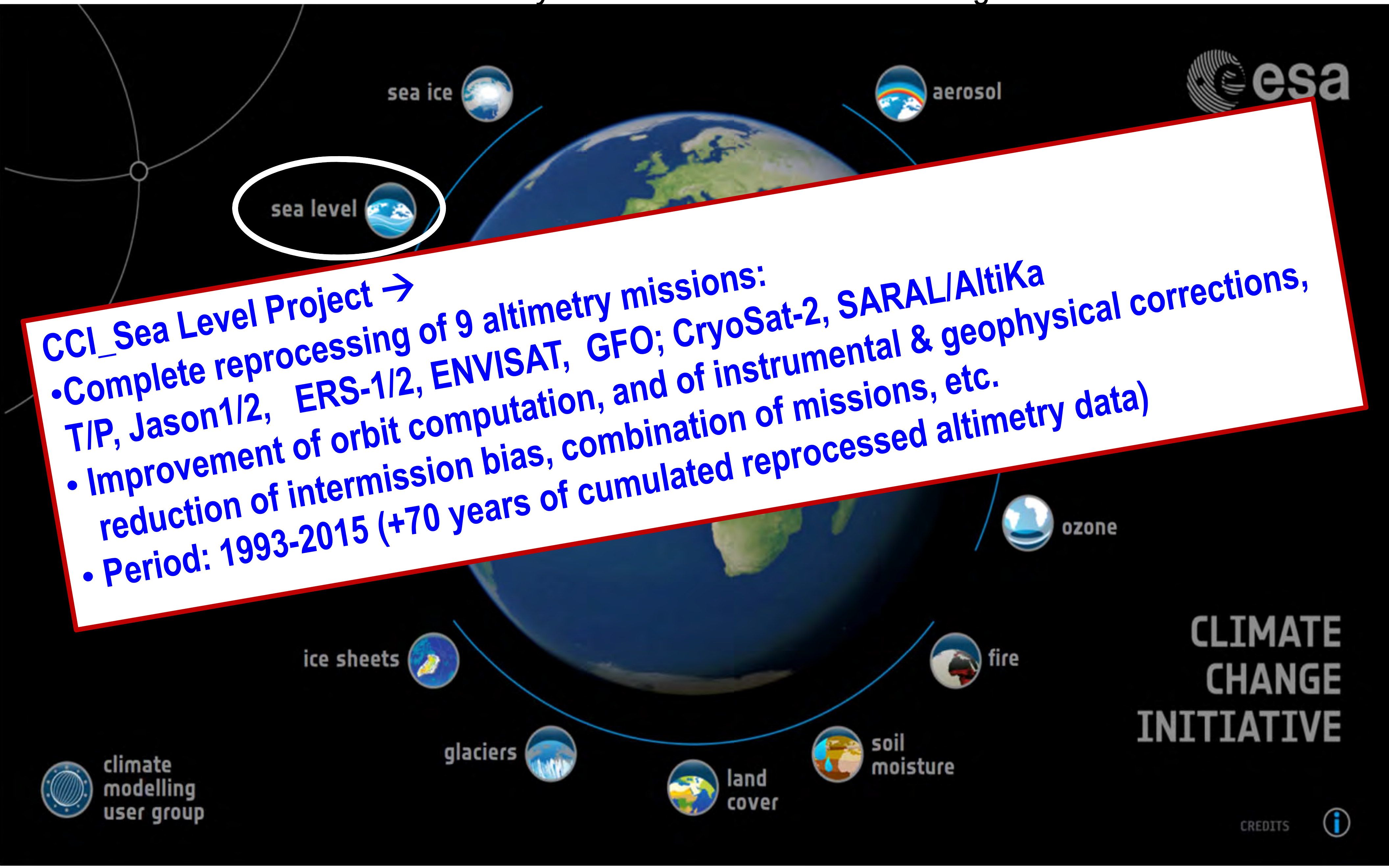
Spatial Scales	Temporal Scales	Altimetry Uncertainties	User Requirements
GMSL	Long-term evolution (>10 years)	<0.5 mm/year	0.3 mm/year
	Interannual signals (<5 years)	<2 mm over 1 year	0.5 mm over 1 year
	Annual signals	<1 mm	Not defined
Regional sea-level	Long-term evolution (>10 years)	<3 mm/year	1 mm/year
	Annual signals	<1 cm	Not defined

Source: Ablain, M., et al., *Ocean Sci.*, 11, 67–82, 2015.

Escudier et al., 2018

"Climate Change Initiative" Project from ESA (2011-2017)

→ Reprocessing of a first set of Essential Climate Variables identified by GCOS to monitor climate change



CCI_Sea Level Project →

- Complete reprocessing of 9 altimetry missions: T/P, Jason1/2, ERS-1/2, ENVISAT, GFO; CryoSat-2, SARAL/AltiKa
- Improvement of orbit computation, and of instrumental & geophysical corrections, reduction of intermission bias, combination of missions, etc.
- Period: 1993-2015 (+70 years of cumulated reprocessed altimetry data)

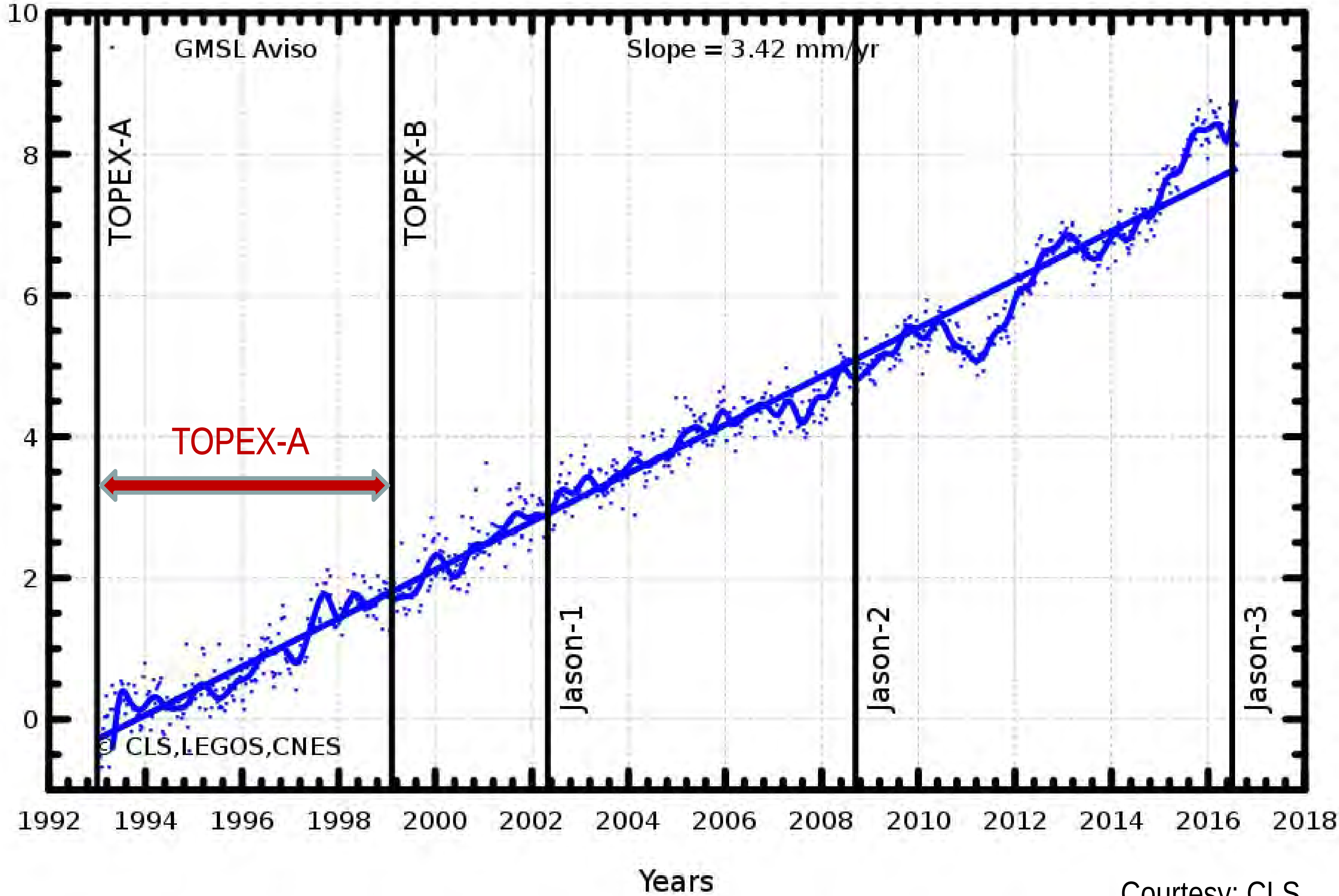
Sea Level: *current uncertainty of «ESA Climate Change Initiative/CCI» products*

Spatial Scales	Temporal Scales	GCOS Requirements	Errors of CCI products
Global Mean Sea Level	Long-term trend	<0.3 mm/yr	0.3 mm/yr
	Interannual signals	0.5 mm over 1 year	< 2 mm over 1 year
Regional Sea Level	Long-term trend	<1 mm/yr	<3 mm/yr

GCOS: Global Climate Observing System

Ablain et al., 2015, 2017, Quartly et al., 2017, Legeais et al., 2018

Global mean sea level and altimetry missions



Courtesy: CLS

Account of the TOPEX-A instrumental drift in the global mean sea level record (1993-1998)

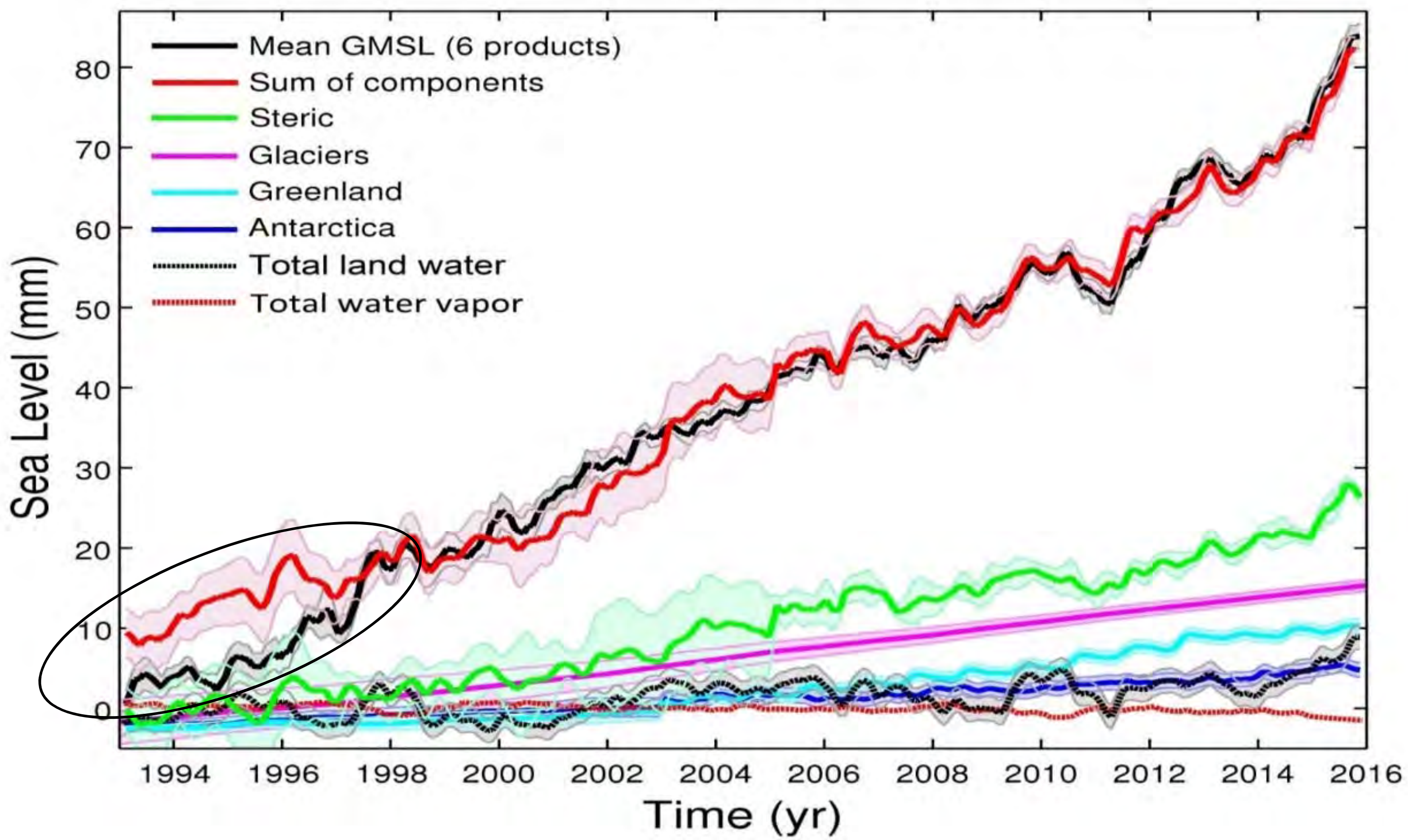
- Watson et al., 2015 → comparison with tide gauges
  → 1.5 +/- 0.5 mm/yr for the 1993-1998 time span

- Dieng et al., 2017 → comparison with sum of contributions
  → 1.5 +/- 0.5 mm/yr for the 1993-1998 time span

- Beckley et al., 2017 & Nerem et al., 2018 → removal of the « internal calibration mode » range correction included in the TOPEX 'net instrument' correction

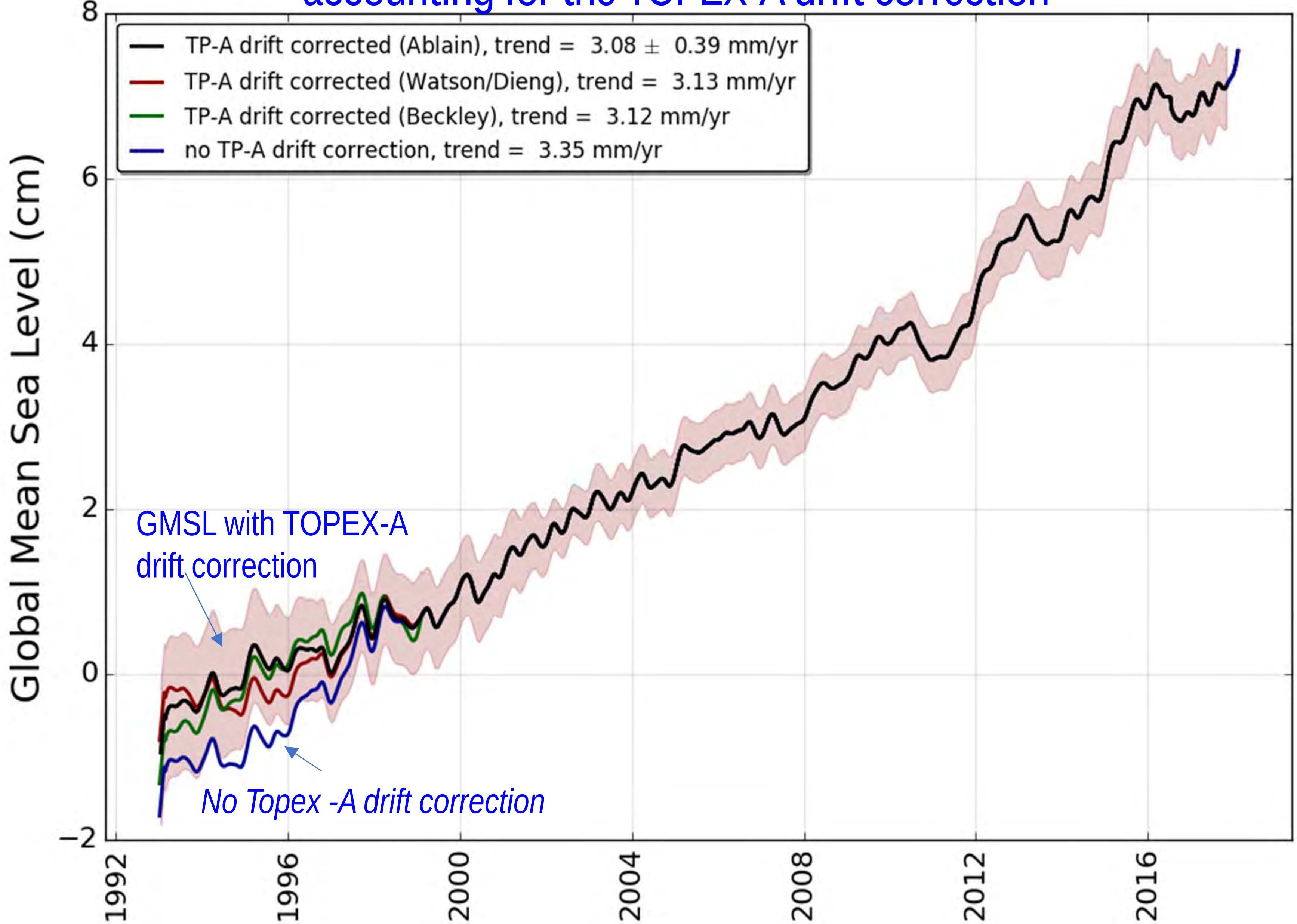
- Ablain et al., 2017 → comparison with tide gauges →
  -1.0 +/- 1.0 mm/yr over Jan 1993-July 1995
  +3 .0 +/- 1.0 mm/yr over Aug 1995-Feb 1999

Sea Level Budget 1993-2015



Dieng et al., 2017

Global Mean Sea Level (average of 6 products) accounting for the TOPEX-A drift correction



WCRP Global Sea Level Budget Group, 2018

CAUSES OF PRESENT-DAY SEA LEVEL RISE

Global Mean Sea Level Budget

Sea Level Budget

Observed Global Mean Sea Level
=
Ocean Thermal Expansion + Ocean Mass

$$\Delta M_{ocean} = -\Delta M_{LI} - \Delta M_{LW} - \Delta M_{WV} - \Delta M_{Snow} - \ldots\ldots$$

Ocean mass · *Land ice* · *Land waters* · *Atmospheric water vapor* · *Snow*

Δ = Time variation
M = Mass components
LI = Land Ice (glaciers + ice sheets)
LW = Land Waters
WV = Water Vapour

Mass Budget

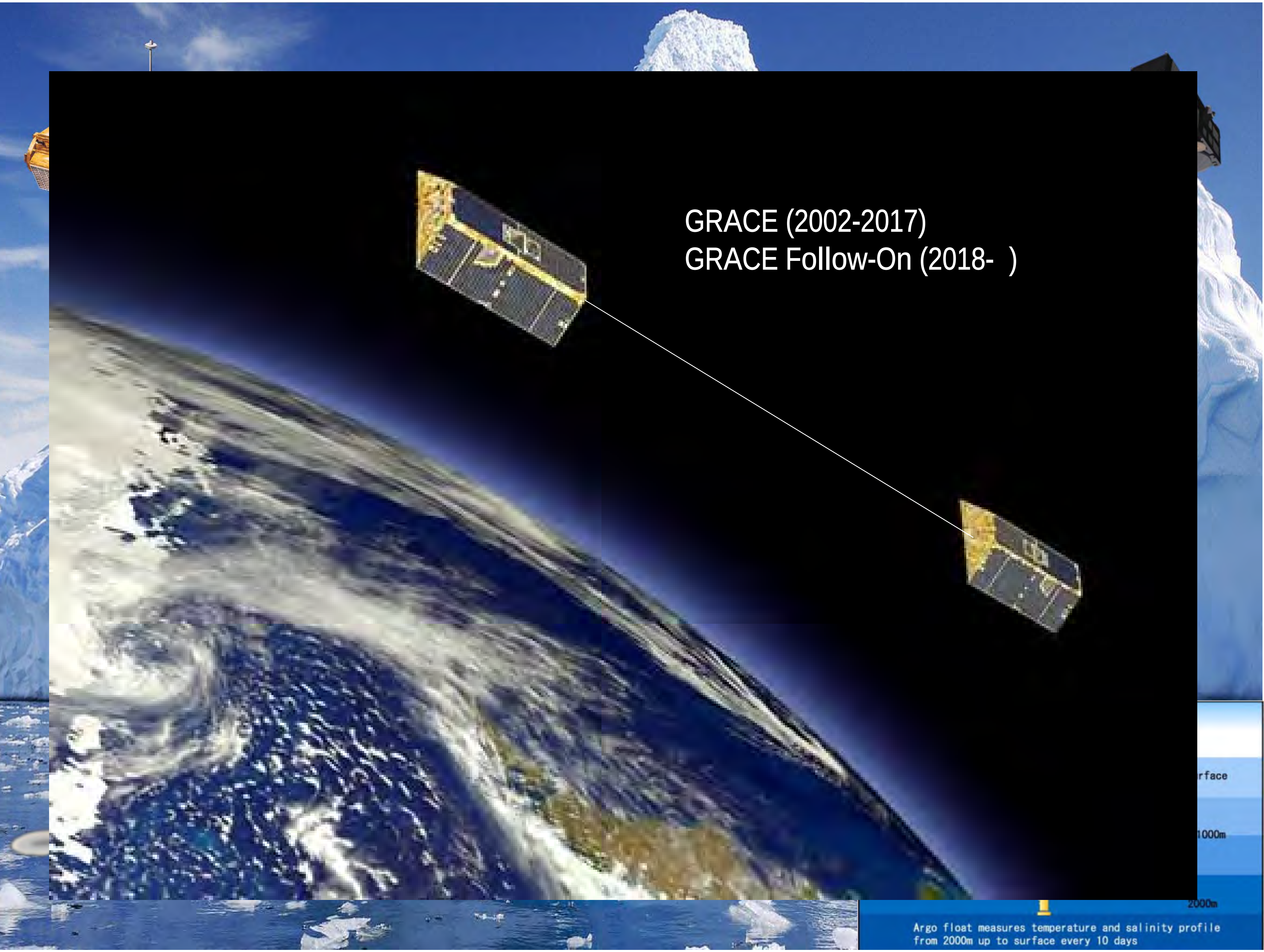
Steric Sea Level= thermal expansion of ocean waters + change in salinity

- Steric sea level variations result from temperature and salinity-related density changes of water between two depth levels Z_1 and Z_2.
- The total steric effect H can be separated into two terms: a (temperature-related) thermosteric component H_T, and a (salinity-related) halosteric component H_S, so that:

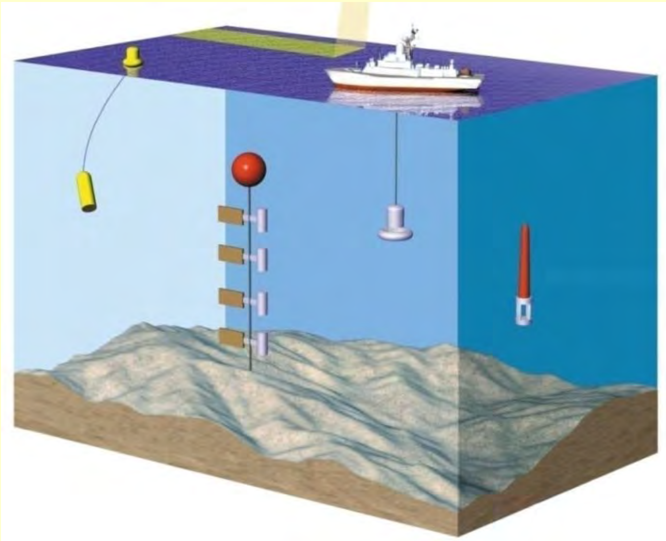
$$H = H_T + H_S = \int \alpha\,(T-T_0)\,dz \;+\; \int \beta(S-S_0)\,dz$$

- where z is depth (integration between Z_1 and Z_2). α and β are coefficients of thermal and haline expansion (note that a temperature/salinity increase causes increase/decrease in steric sea level).

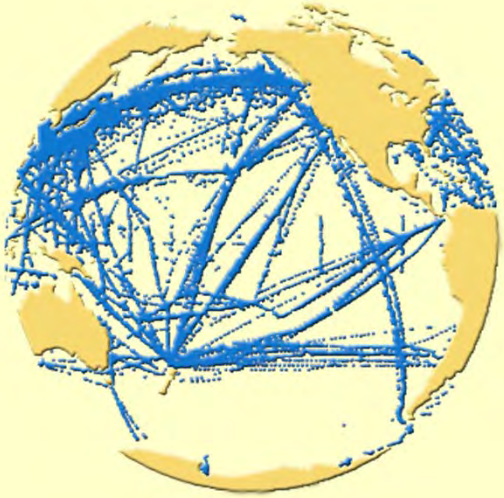
- H_T also called thermal expansion


GRACE (2002-2017)
GRACE Follow-On (2018-)
Argo float measures temperature and salinity profile
from 2000m up to surface every 10 days

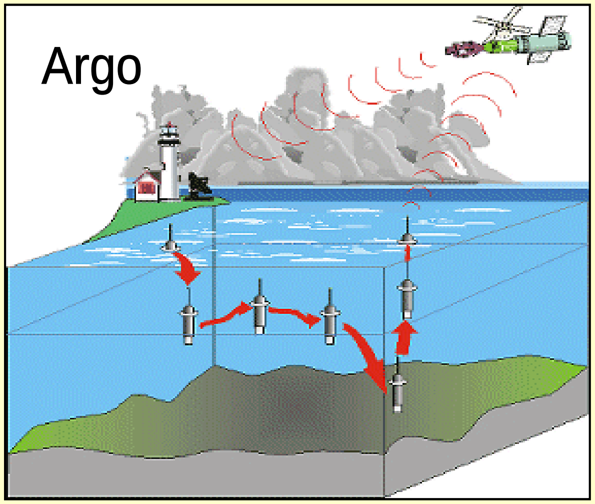
Ocean temperature measurements (XBT, Argo)

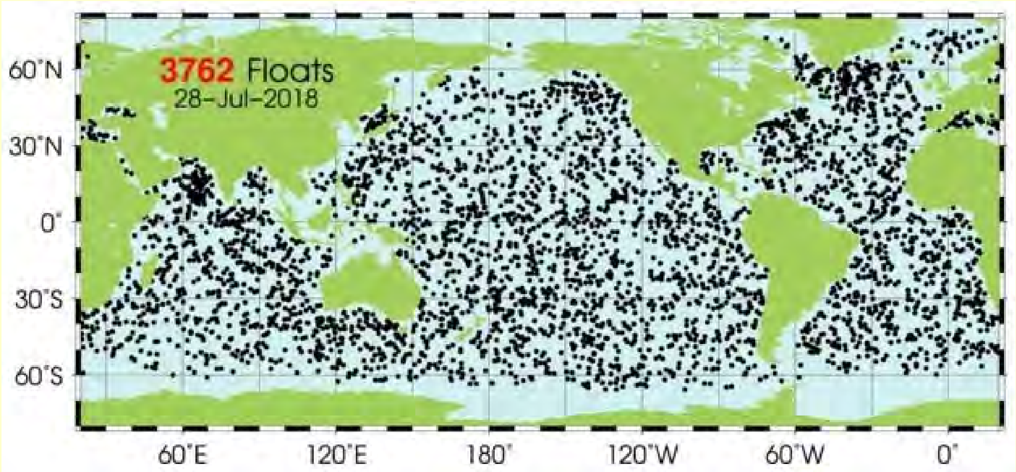


Past few decades: coverage mainly along trade roads



Since about 2003/2005 → 'Argo' profiling floats





Recent studies on the global mean sea level budget

IPCC 5th Assessment Report, 2013

Dieng et al., 2017

Chen et al., 2017

Nerem et al., 2018

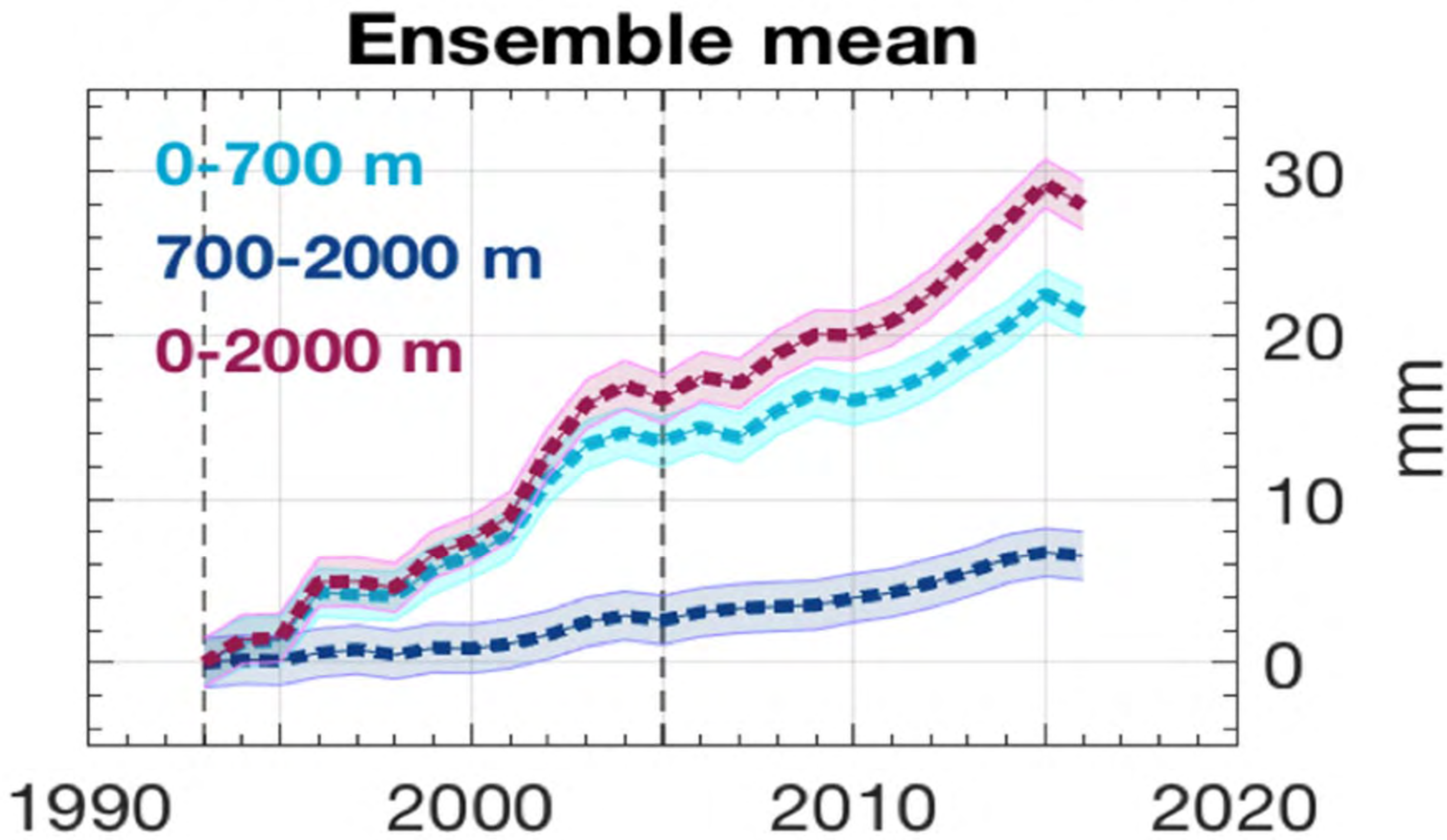
....

IPCC/SROCC

On-going international initiatives:

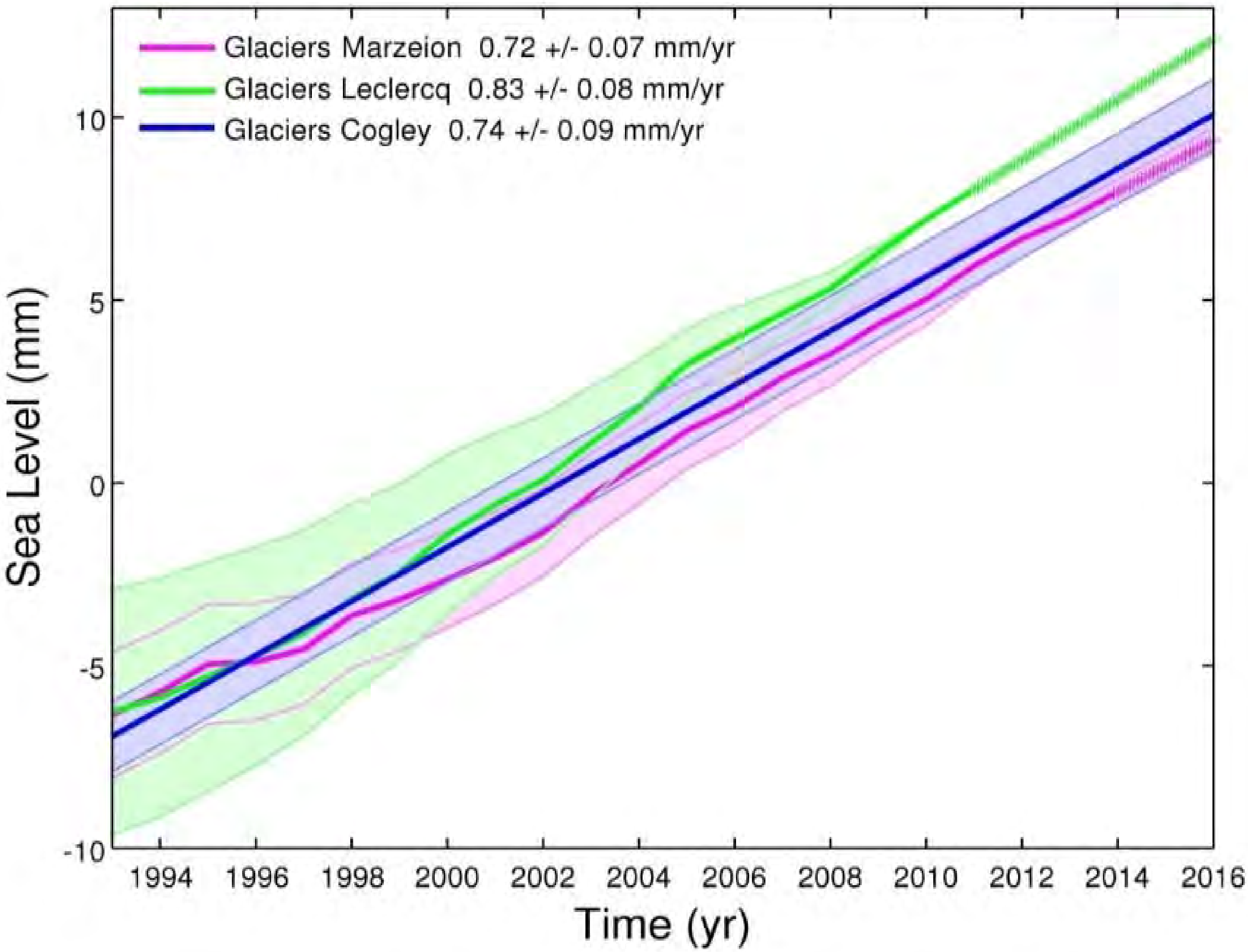
1. ESA Sea Level Budget Project → closure of the sea level budget using CCI products for the components (work in progress)
2. International assessment in the context of the World Climate Research Programme (WCRP) → Assess closure of the global mean sea level budget using all available data sets for sea level and components over the altimetry era (use of *ensemble means*); ~90 participants from 50 institutions worldwide

Global Mean Thermal Expansion (1993-2016)



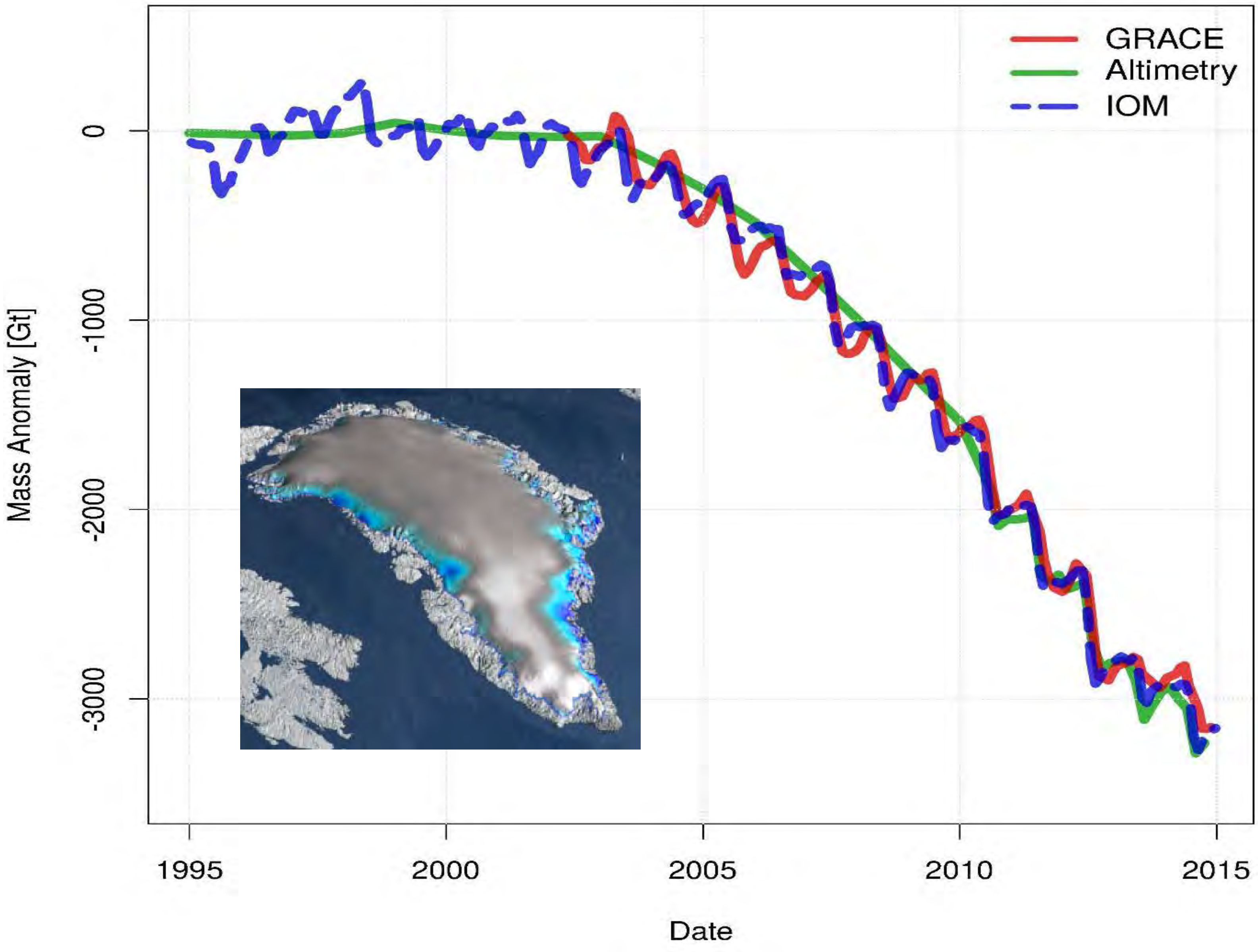
The WCRP Global Sea Level Budget Group, ESSD, 2018

Glacier Contribution to the Global Mean Sea Level



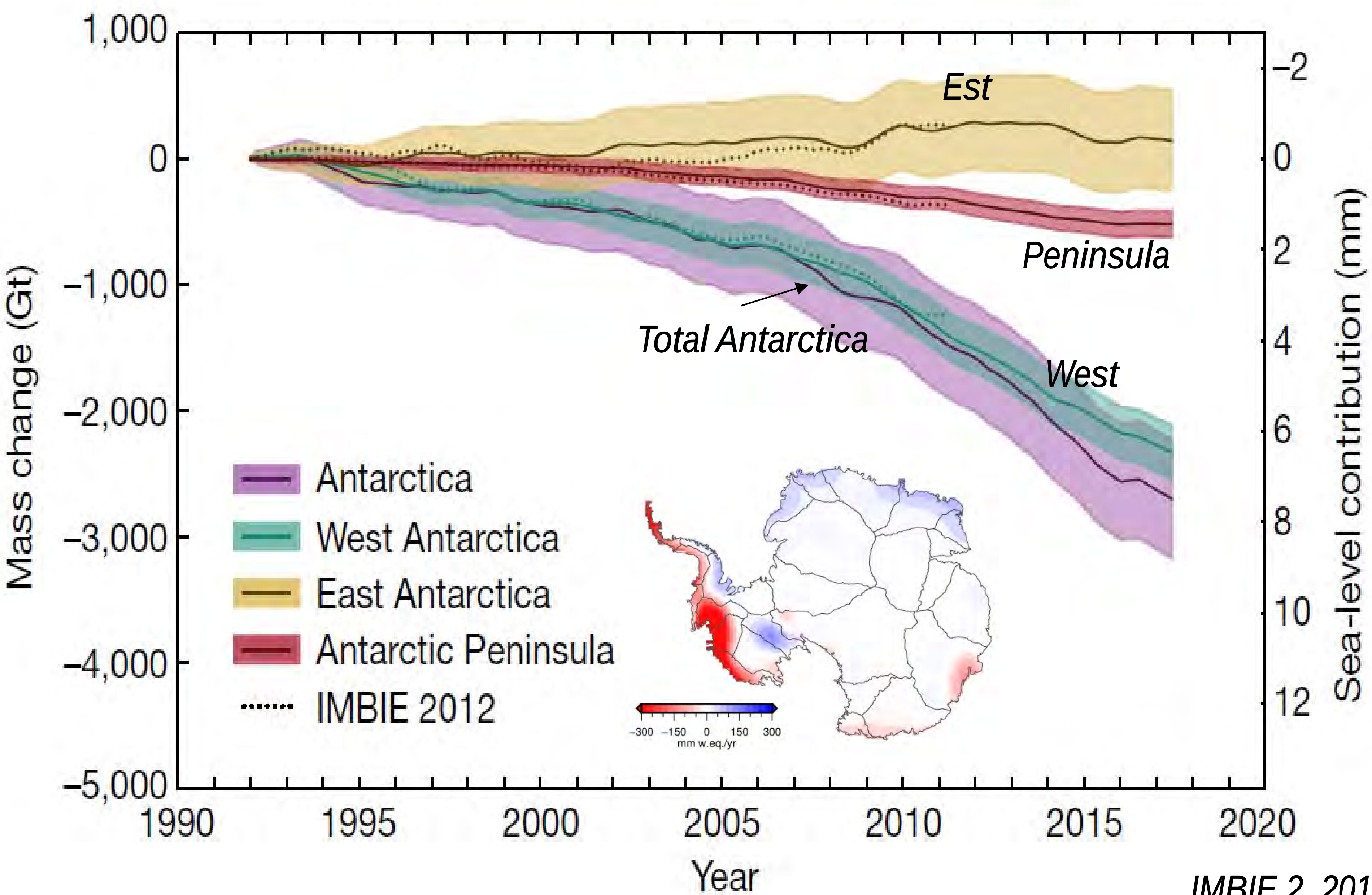
The WCRP Global Sea Level Budget Group, ESSD, 2018

Ice mass loss from the Greenland ice sheet (1993-2015)



Bamber et al., ERL, 2018

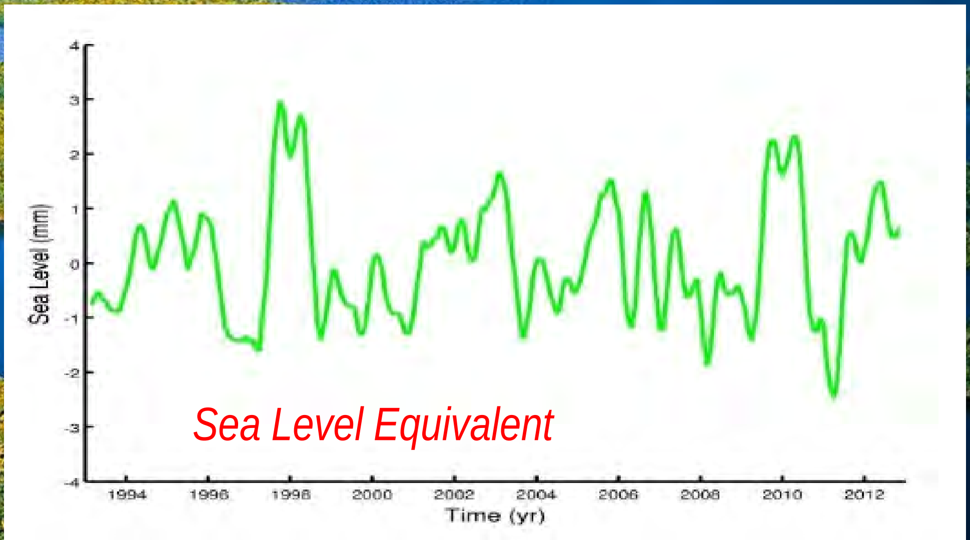
Ice mass loss from the Antarctica ice sheet (1993-present)



IMBIE 2, 2018

Land water storage variations

- Climate variability →



- Human activities

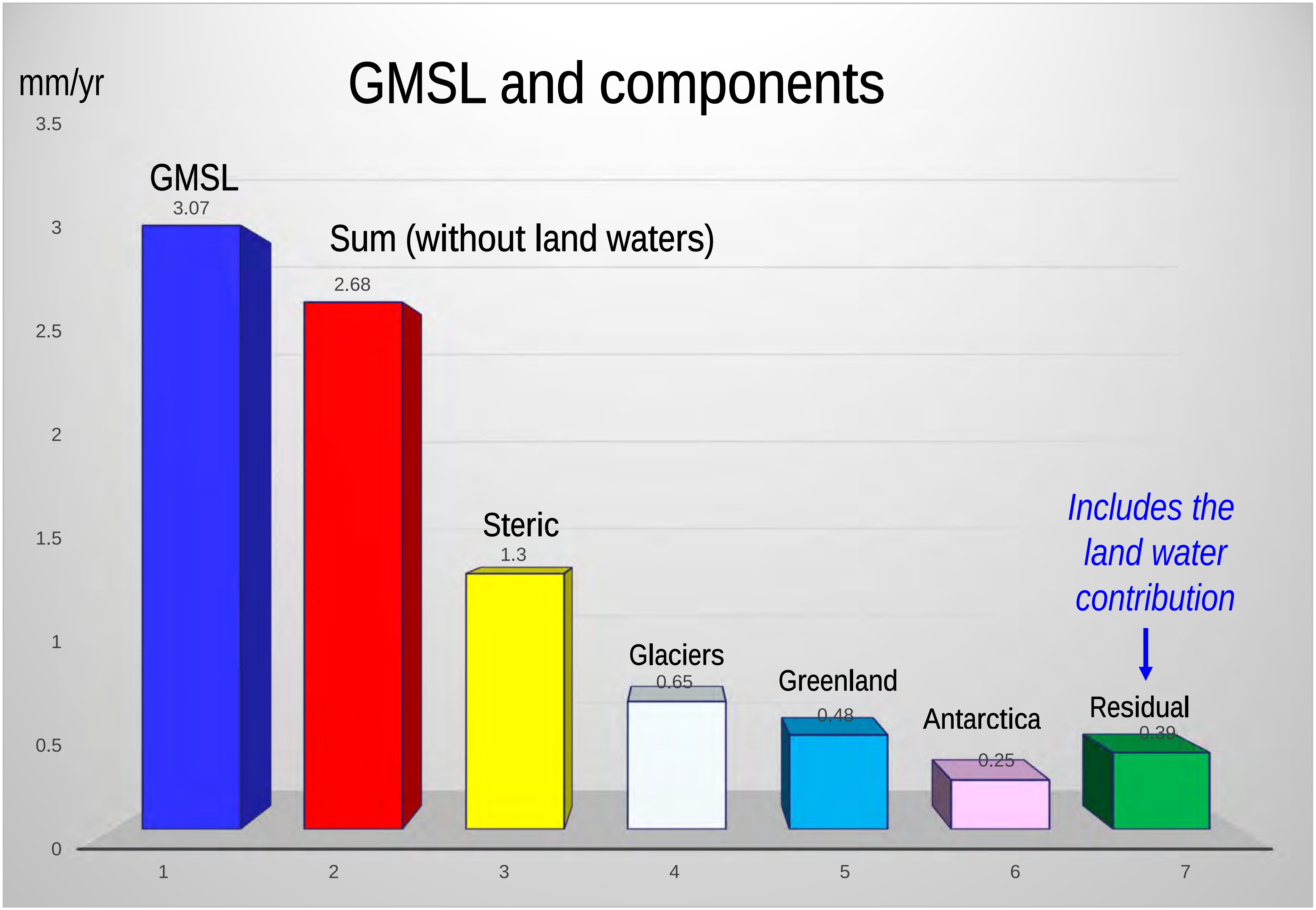
(building of dams on rivers and ground water extraction in aquifers)

↓ ↓

Sea level drop

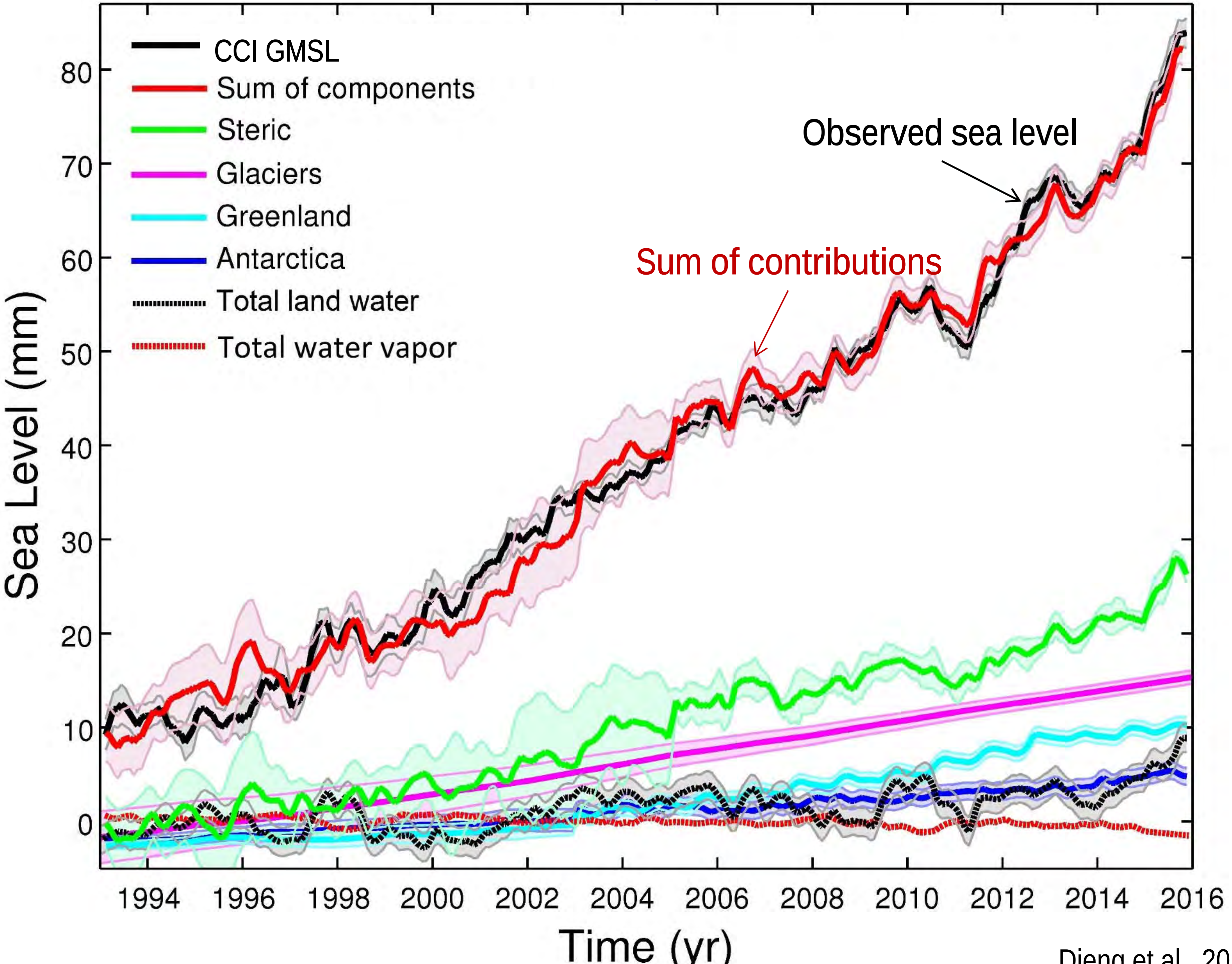
Sea level rise

Global Mean Sea Level Budget: trends (1993-2015)



WCRP Global Sea Level Budget Group, ESSD, 2018

Sea Level Budget 1993-2015



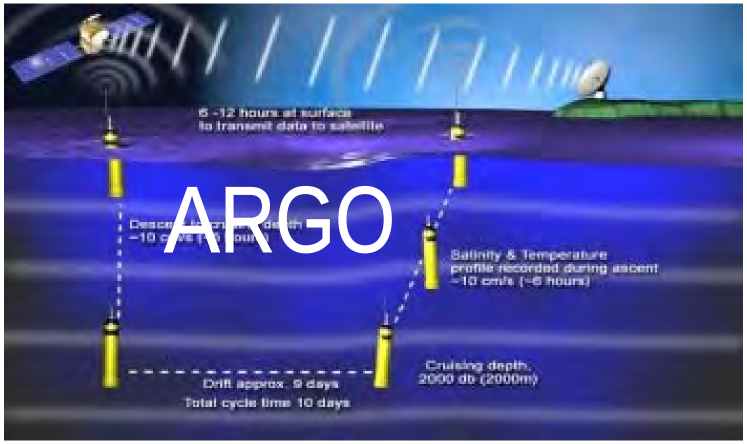
Dieng et al., 2017

As of ~ 2005, global mean sea level budget using GRACE and Argo data

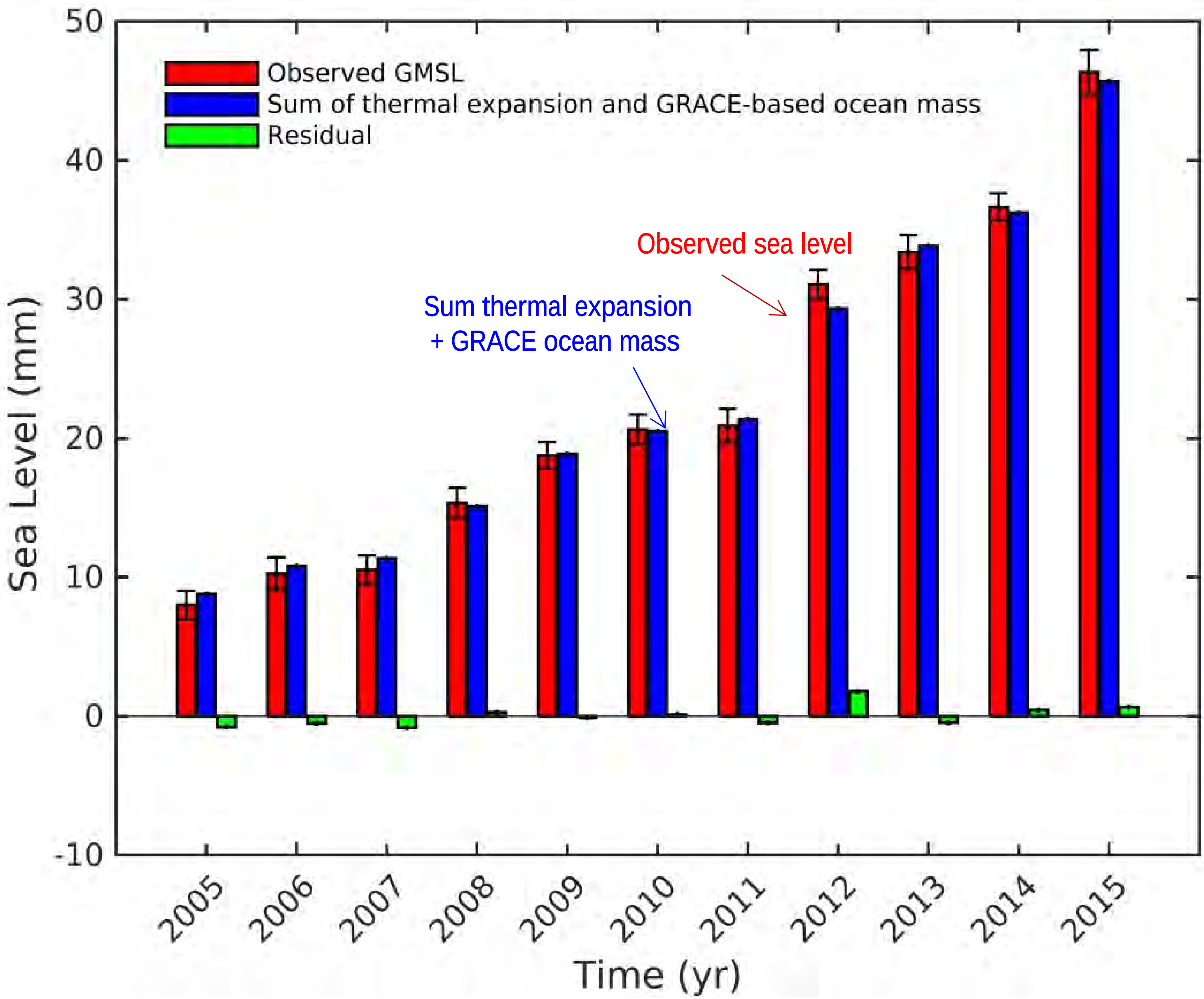
Observed Global Mean Sea Level

=

Ocean Thermal Expansion + Ocean Mass

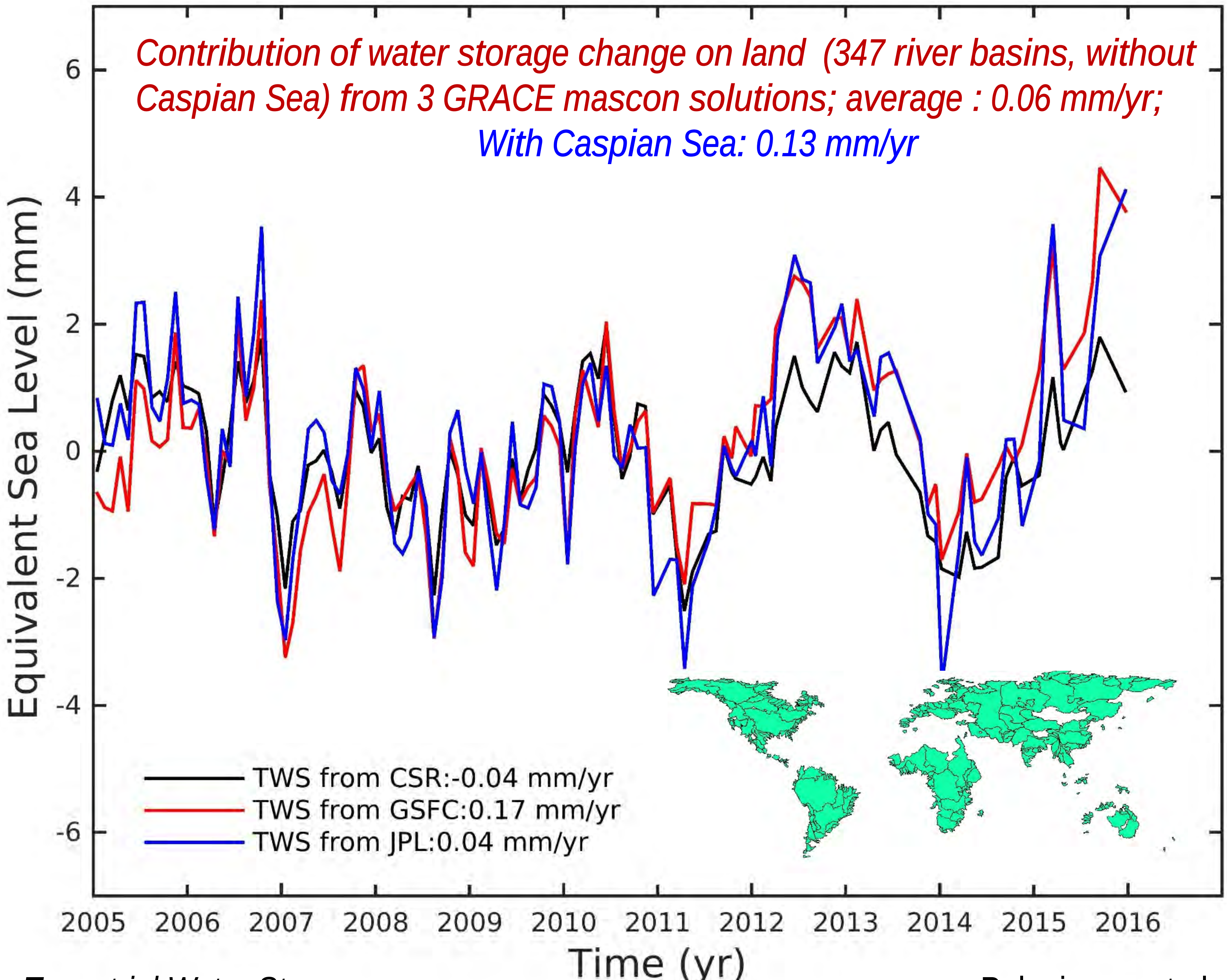


Annual Sea Level Budget (2005-2015)



The WCRP Global Sea Level Budget Group, ESSD, 2018

Land water contribution from GRACE (2005-2015)

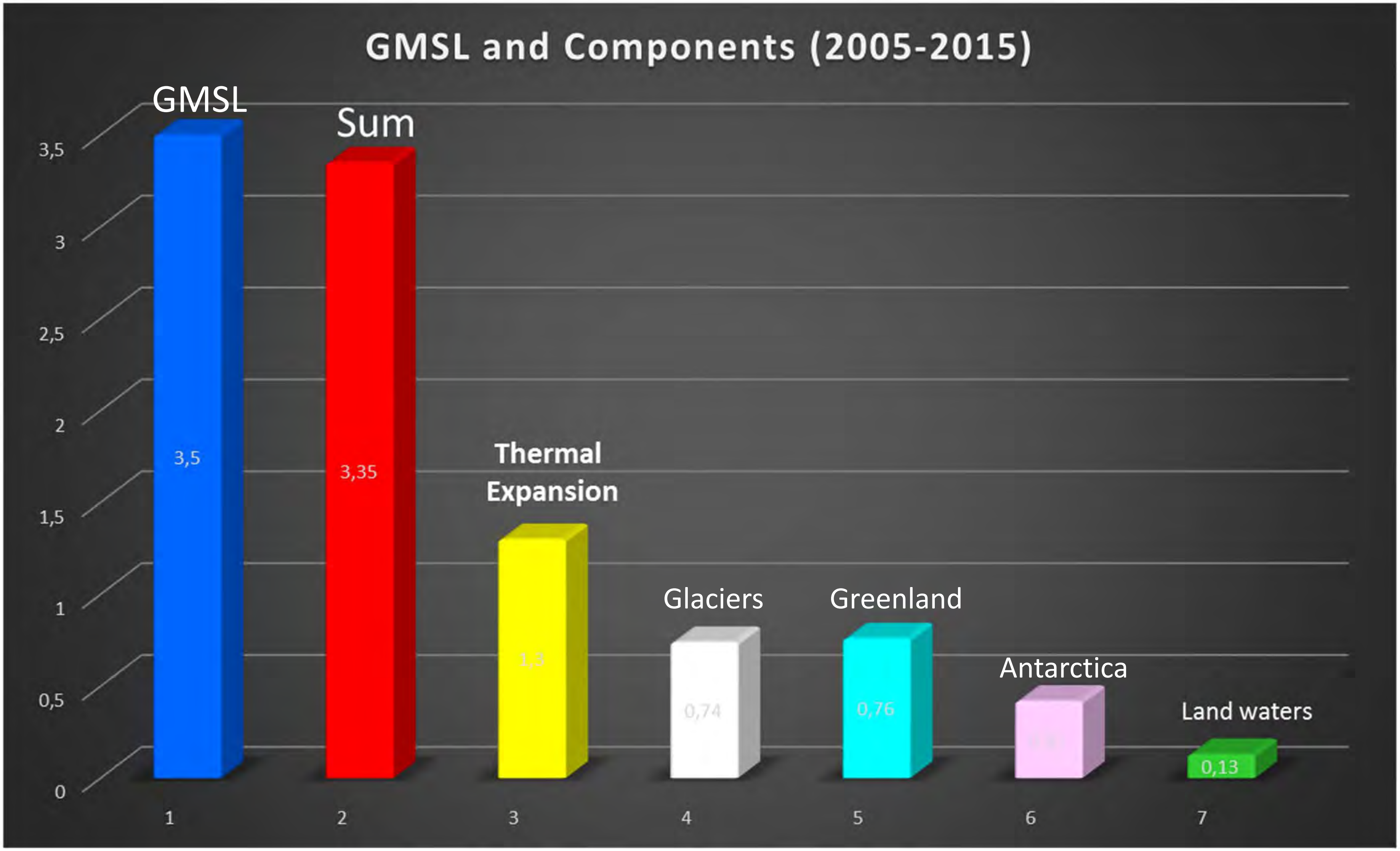


TWS = Terrestrial Water Storage

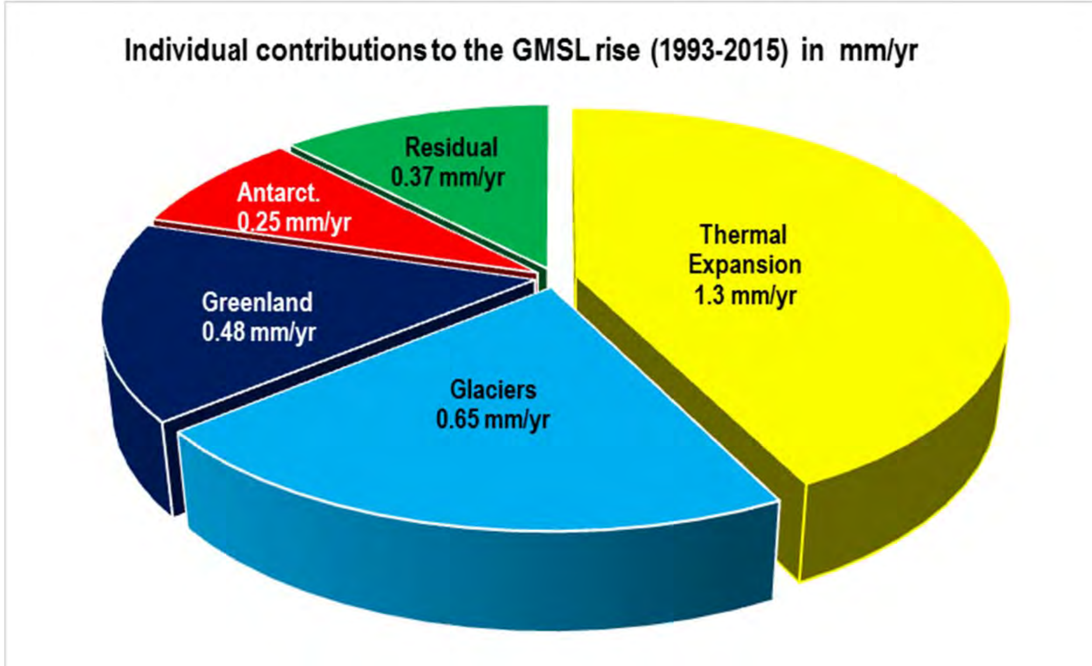
Palanisamy et al., 2018

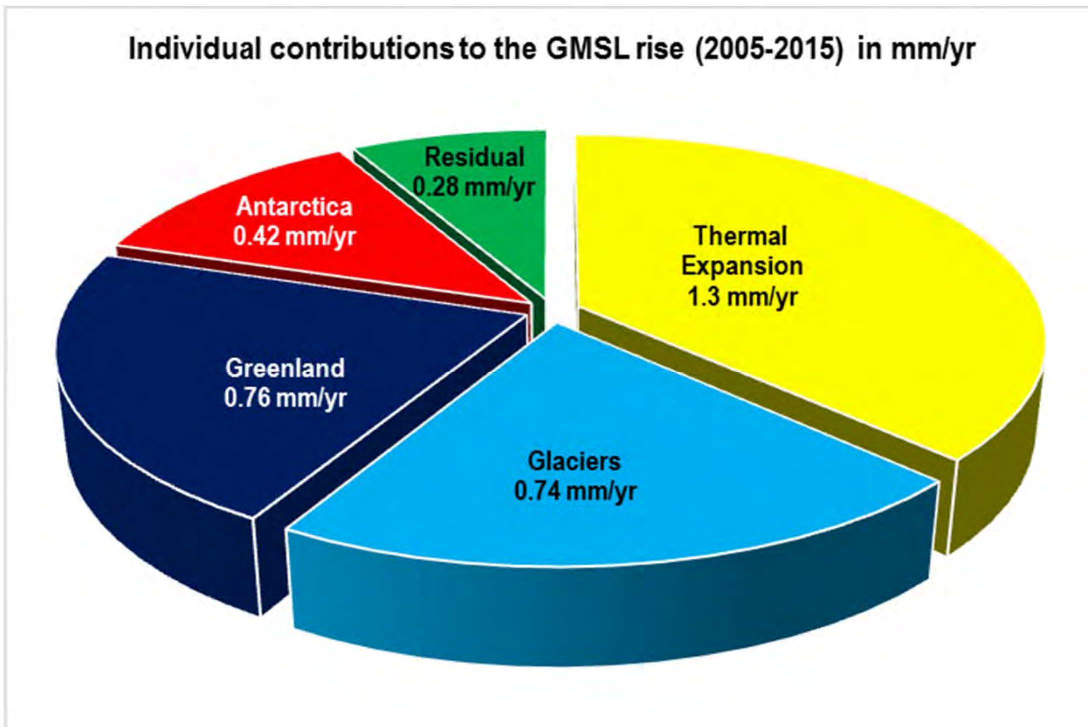
Global Mean Sea Level Budget: trends (2005-2015)

mm/yr



WCRP Global Sea Level Budget Group, ESSD, 2018 & ESA Sea Level Budget Project

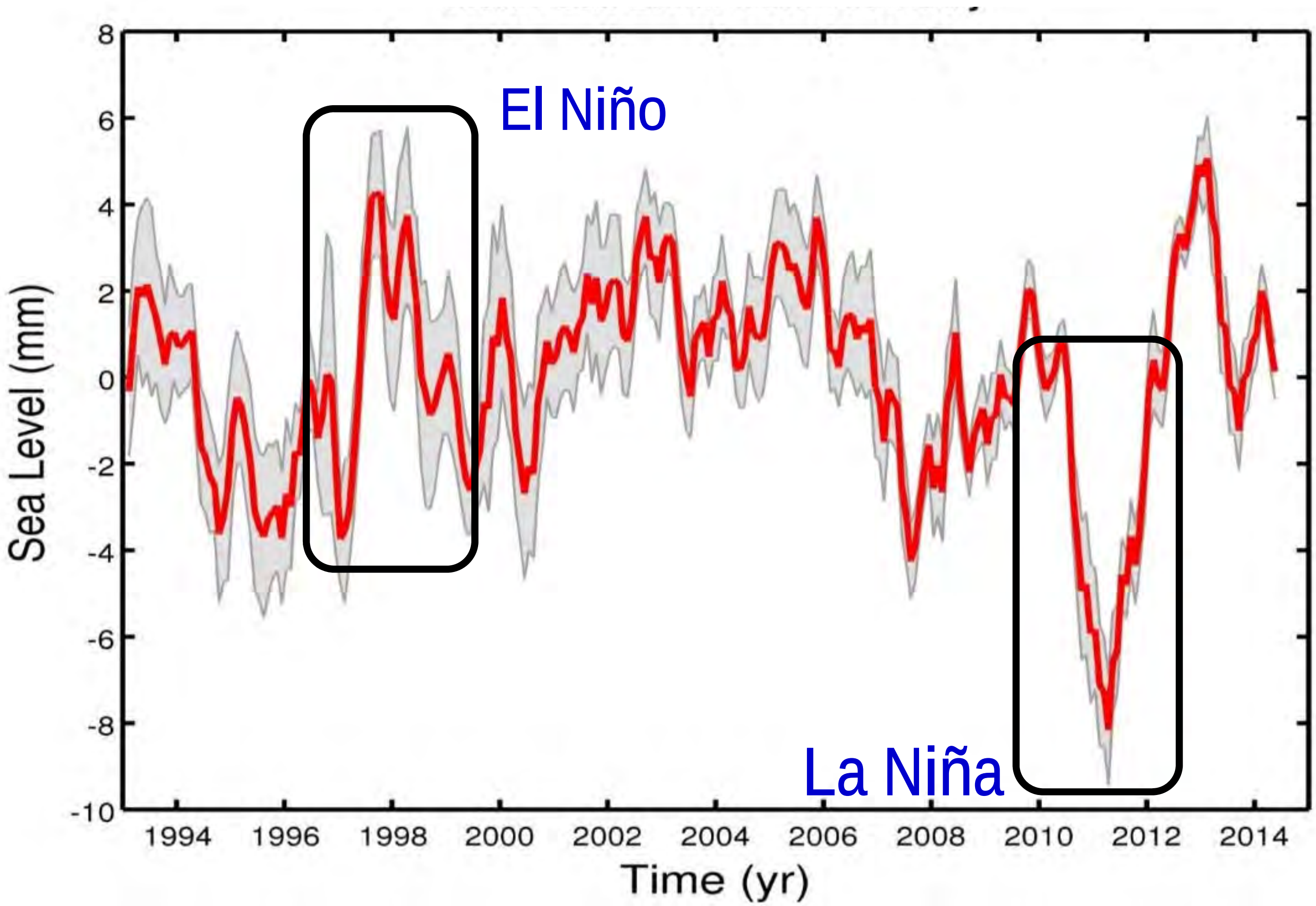


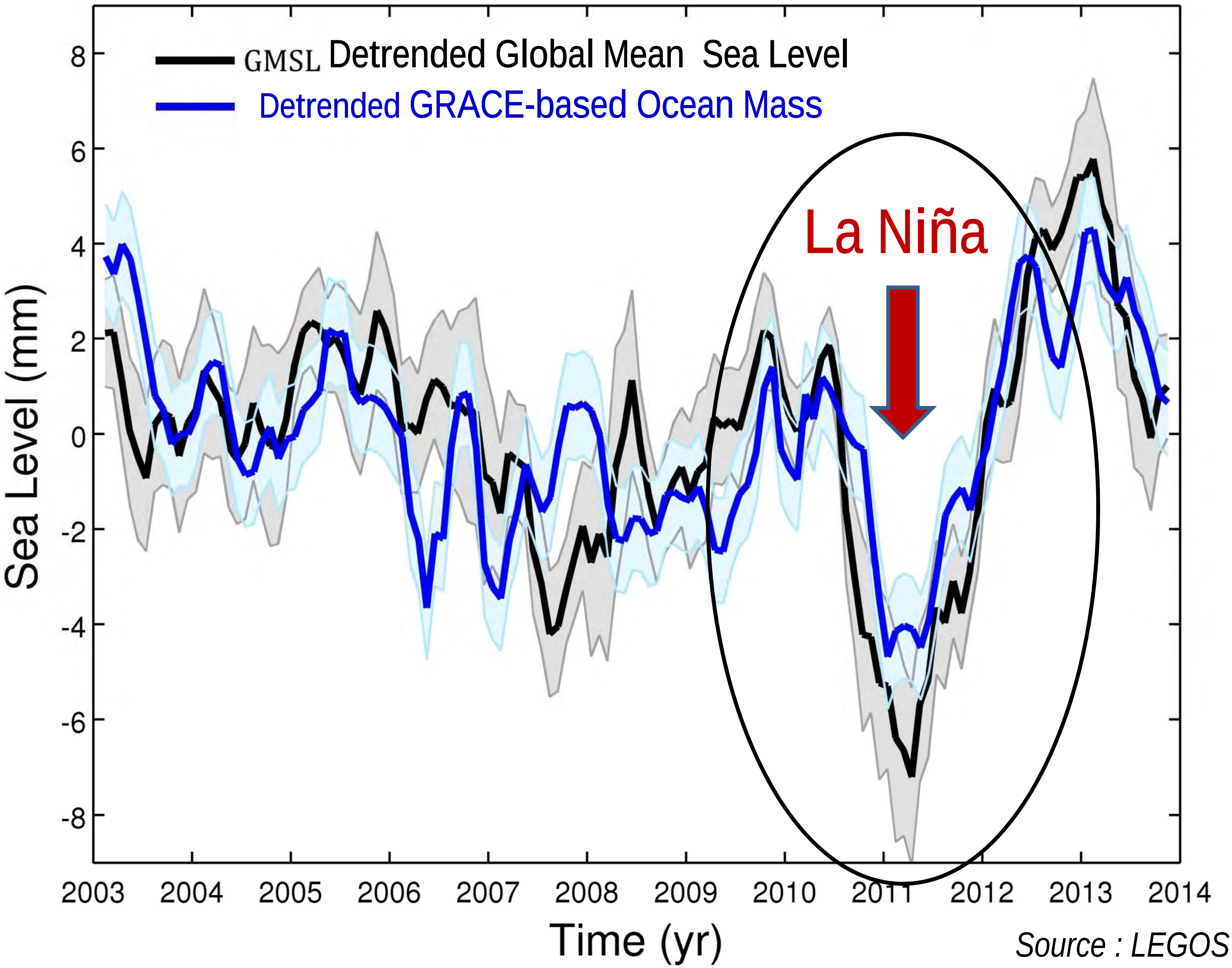


Cazenave et al., 2018

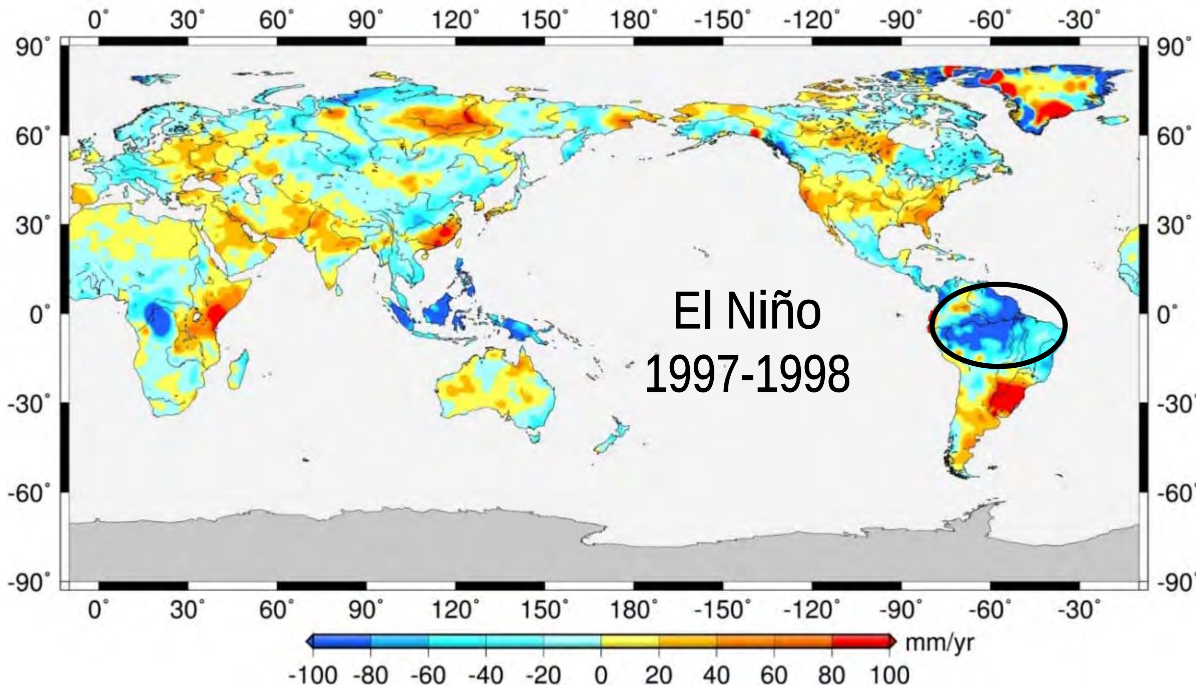
INTERANNUAL VARIABILITY

Detrended Global Mean Sea Level



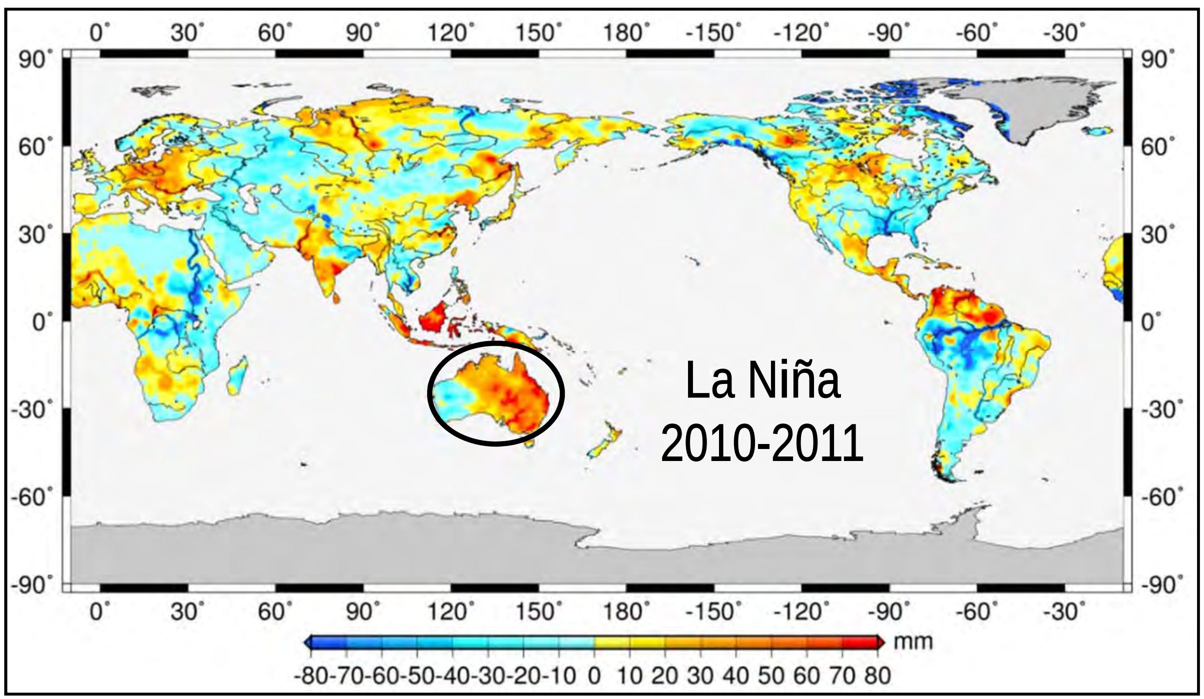

GMSL Detrended Global Mean Sea Level
Detrended GRACE-based Ocean Mass
La Niña
Sea Level (mm)
8
6
4
2
0
-2
-4
-6
-8
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Time (yr)
Source : LEGOS

Land water storage from GRACE during ENSO events



During El Niño → more rain over the tropical Pacific; less water over tropical land

Blue = water deficit
Red = water excess



During La Niña → less rain over the tropical Pacific; more water over tropical land

Source: LEGOS

REGIONAL VARIABILITY

Main causes:

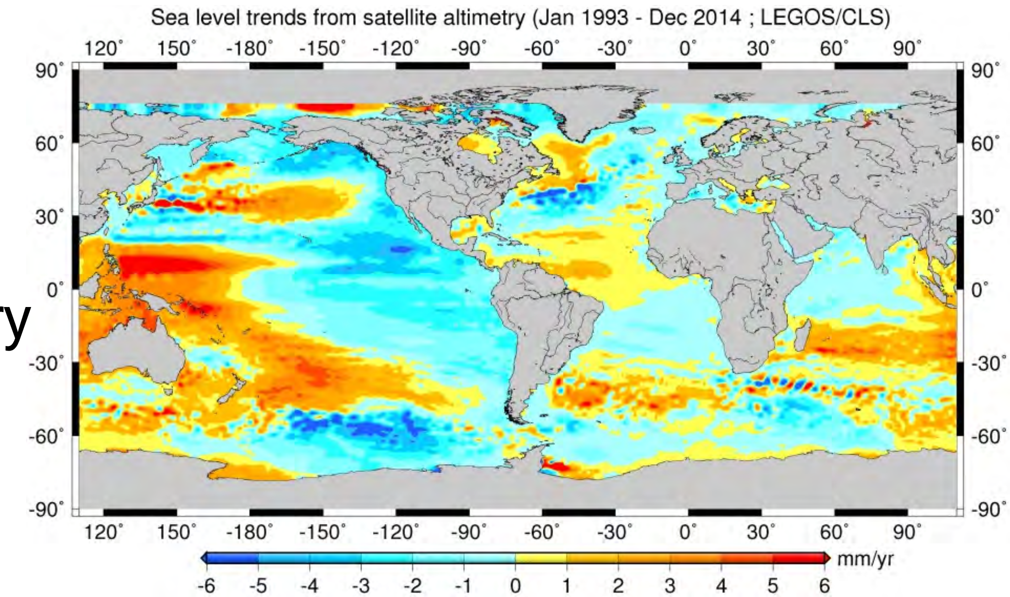
1. Steric effects (ocean thermal expansion + salinity effects)

2. Solid Earth’s response to past and on-going mass redistributions

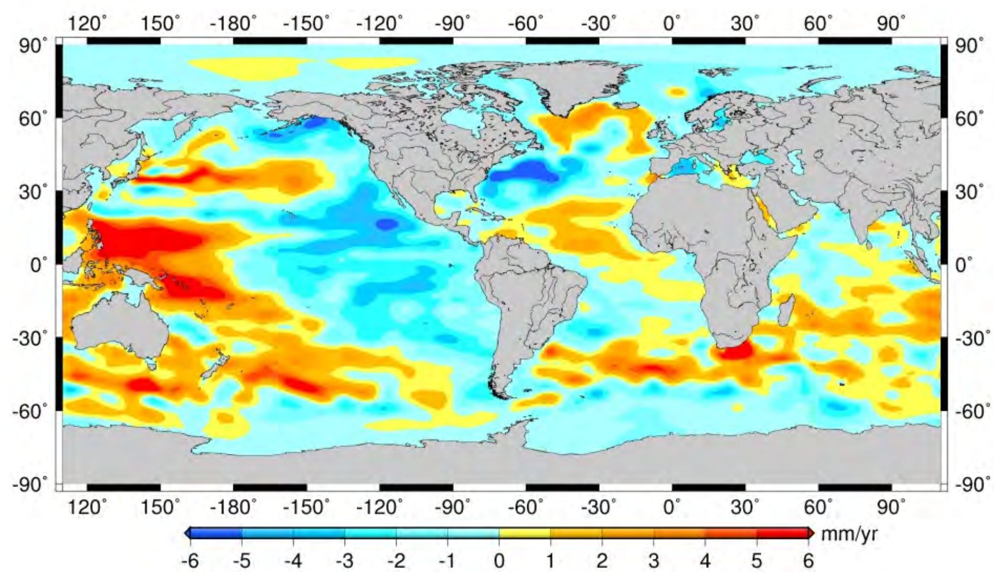
3. Atmospheric loading

Spatial trend patterns in sea level (1993-2014) (*global mean trend removed*)

Observed sea level trends from altimetry

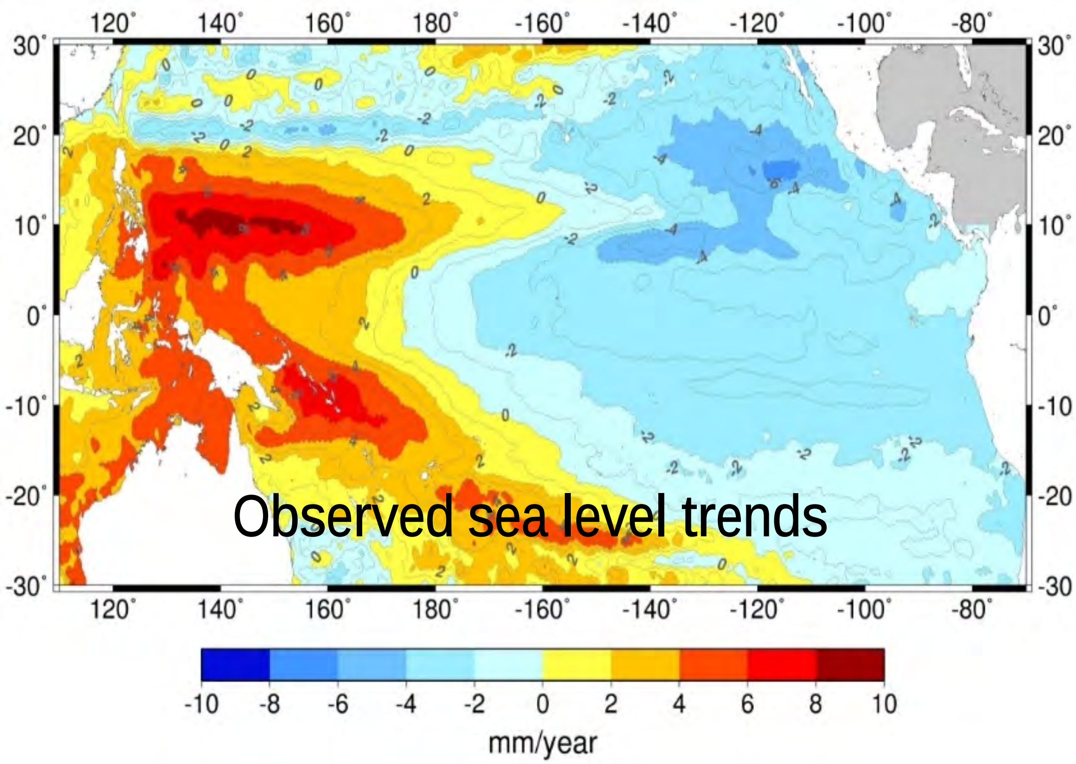


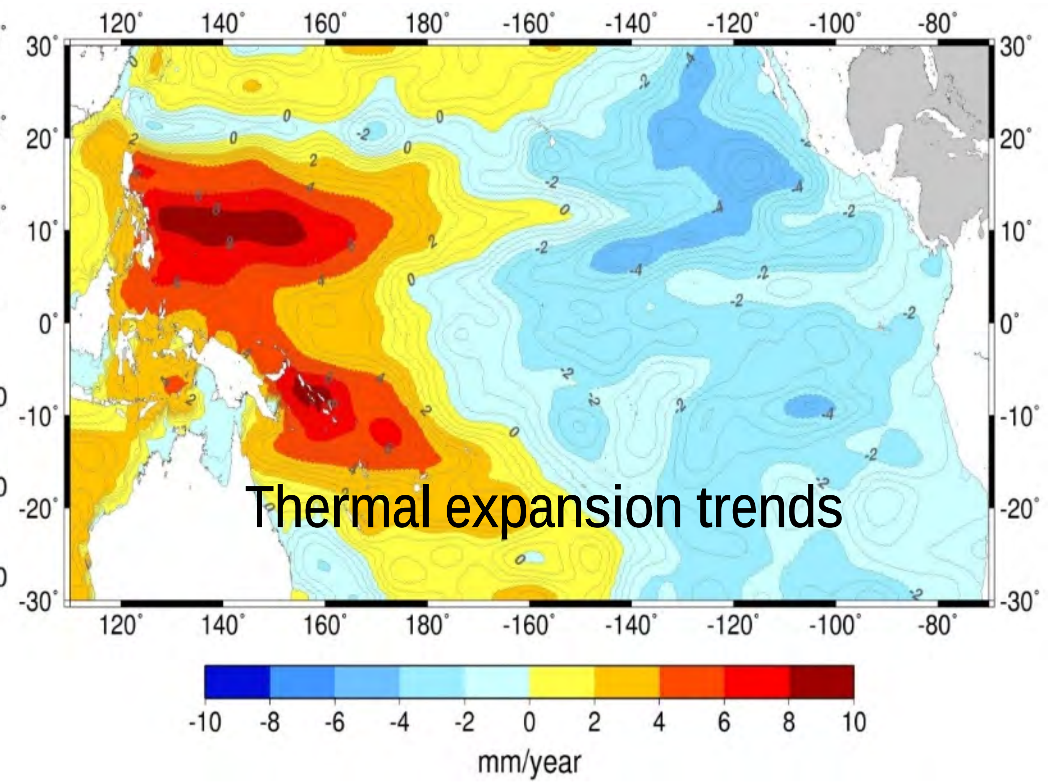
Steric trends



Church et al., 2013 (AR5)
Stammer et al., 2013
and many other references

Regional trends in sea level in the western tropical Pacific (1993-2015)





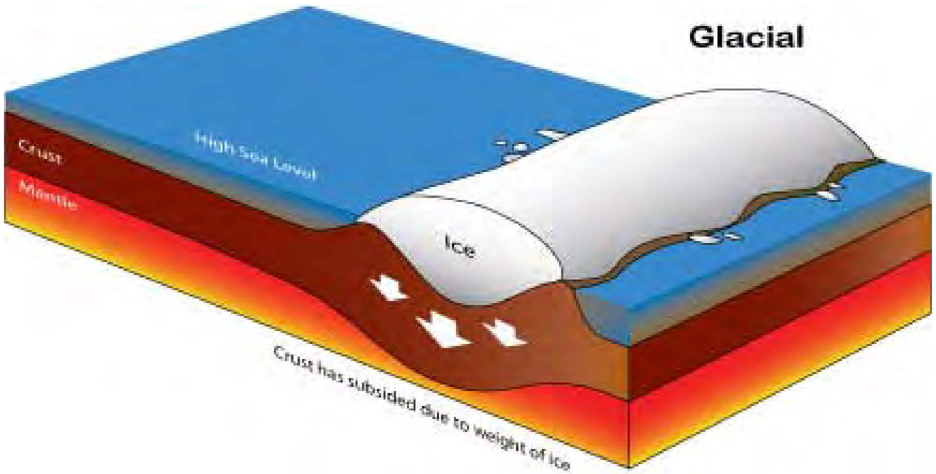
Cause : Increase in trade winds intensity → the thermocline deepens

Timmermann et al.2010, Merrifield et al, 2012, McGregor et al., 2012, England et al., 2014, Palanisamy et al., 2015……

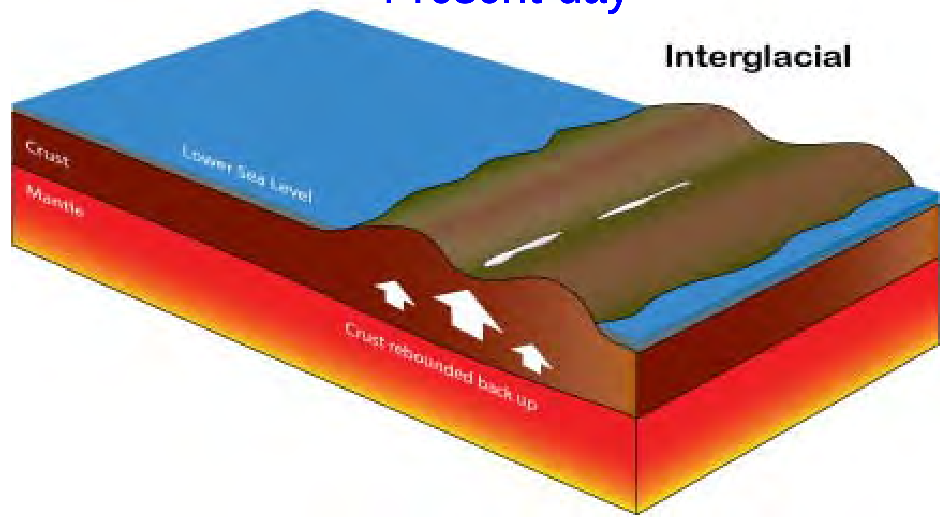
Non-uniform thermal expansion & salinity changes are not the only cause of regional variability: Large-scale water mass redistributions due to past and present land ice melt deform the ocean basins (because the Earth's mantle is viscous and the crust is elastic), and change the mutual gravitational attraction of water & ice masses → *regional changes in sea level*

Past ice mass redistribtions → Post Glacial Rebound

Last Glacial Maximum



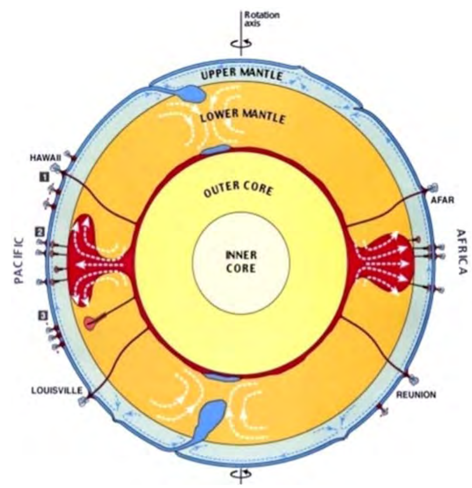
Present-day



Models of
Post Glacial Rebound
(also called
Glacial Isostatic Adjustment
or GIA)

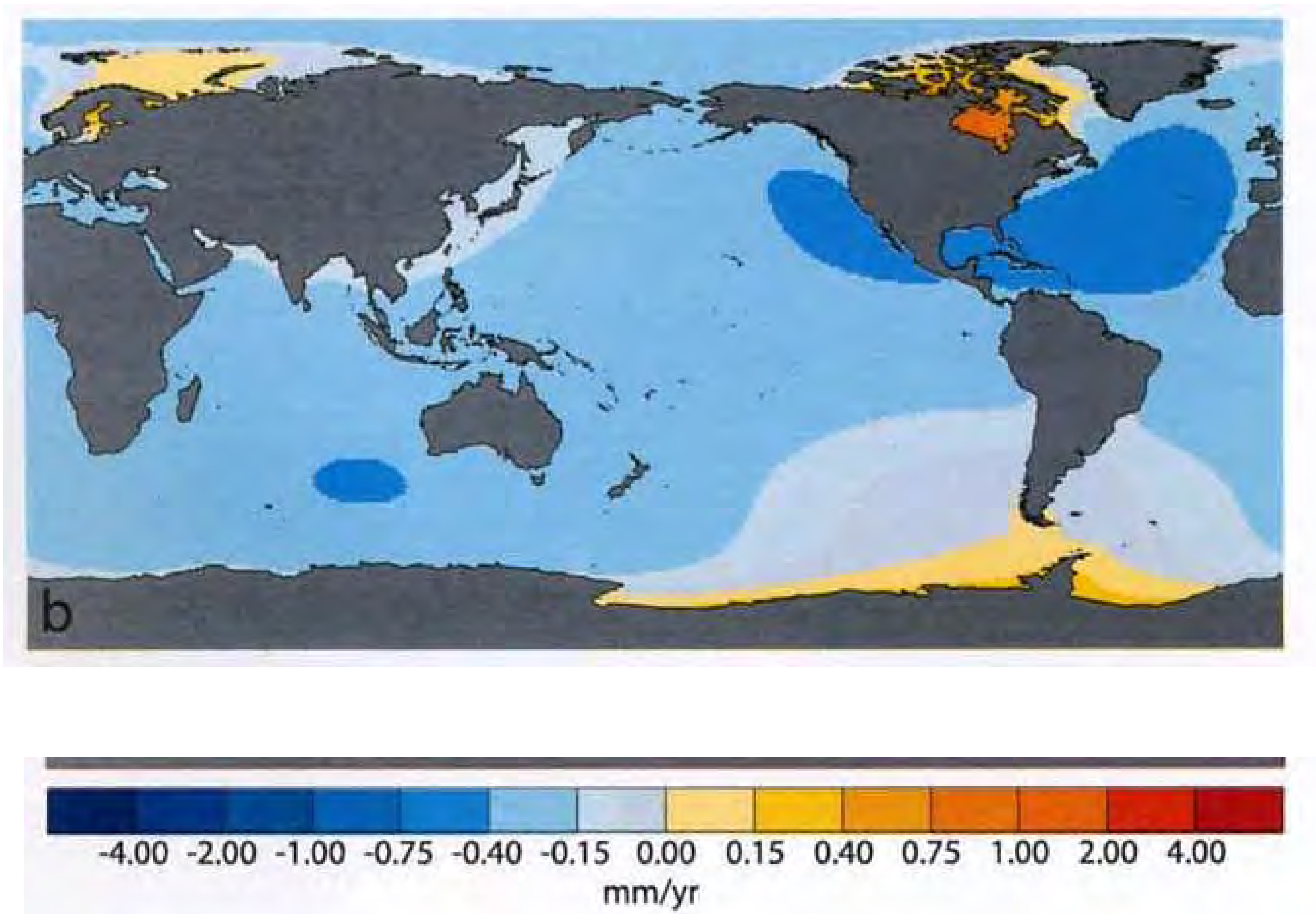
Deglaciation history

\+



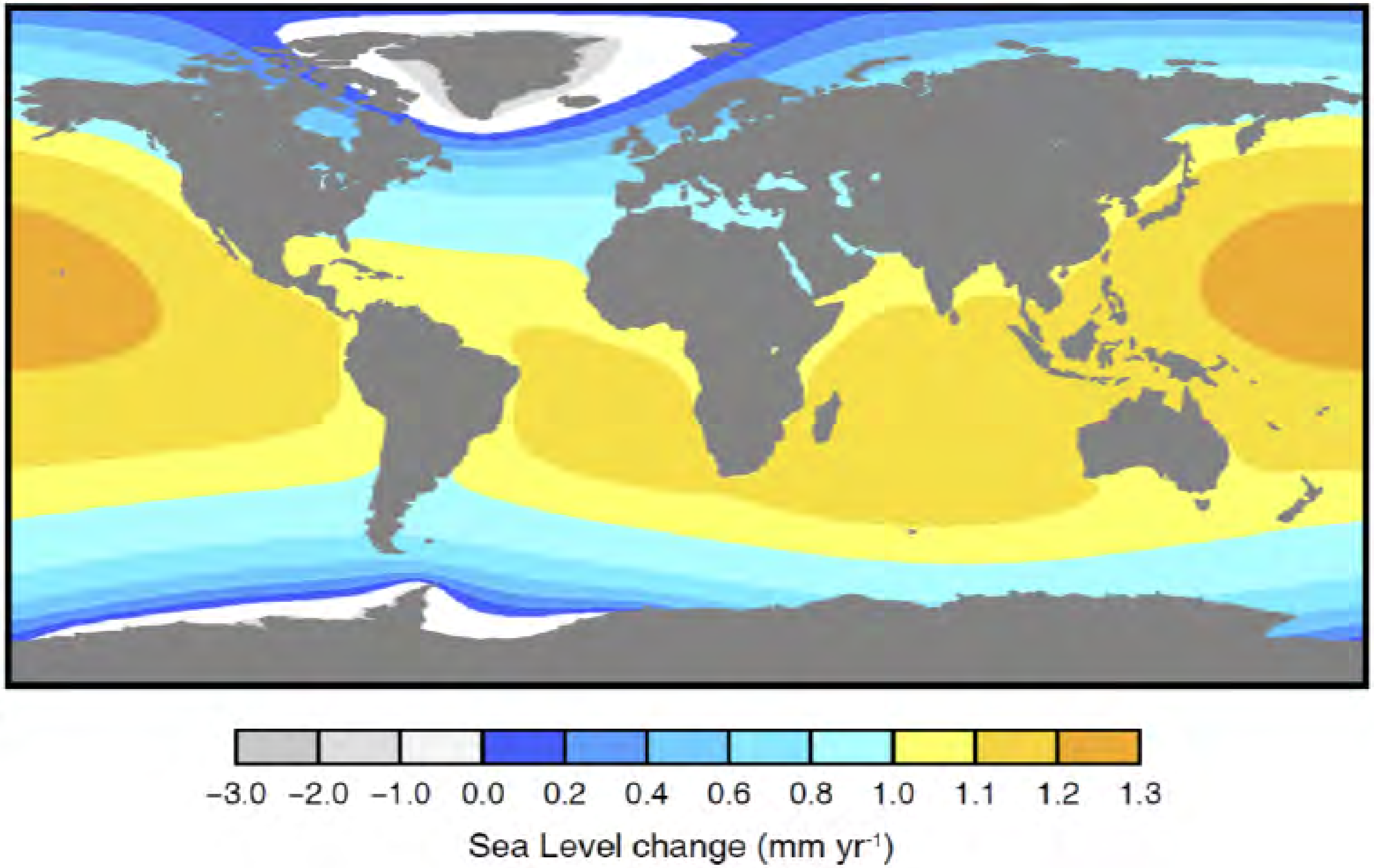
Models of
Earth's viscosity structure

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



Tamisiea (2010)

Effects ongoing & future ice sheet melting on regional sea level (Greenland : 0.5 mm/yr; west Antarctica : 0.5 mm/yr)



Amplification of the rate of sea level rise in the tropics by 20%-30%

IPCC AR5

COASTAL SEA LEVEL

- 600 million people live close to the sea (*Altitude < 10 m)*
- 1.4 billion people expected around 2060

Expected impacts of future sea level rise

-Stronger temporary flooding during extreme events*

-Permanent flooding in low coastal areas

-Shoreline erosion

-Shoreline retreat

-Salt intrusion in coastal aquifers and estuaries

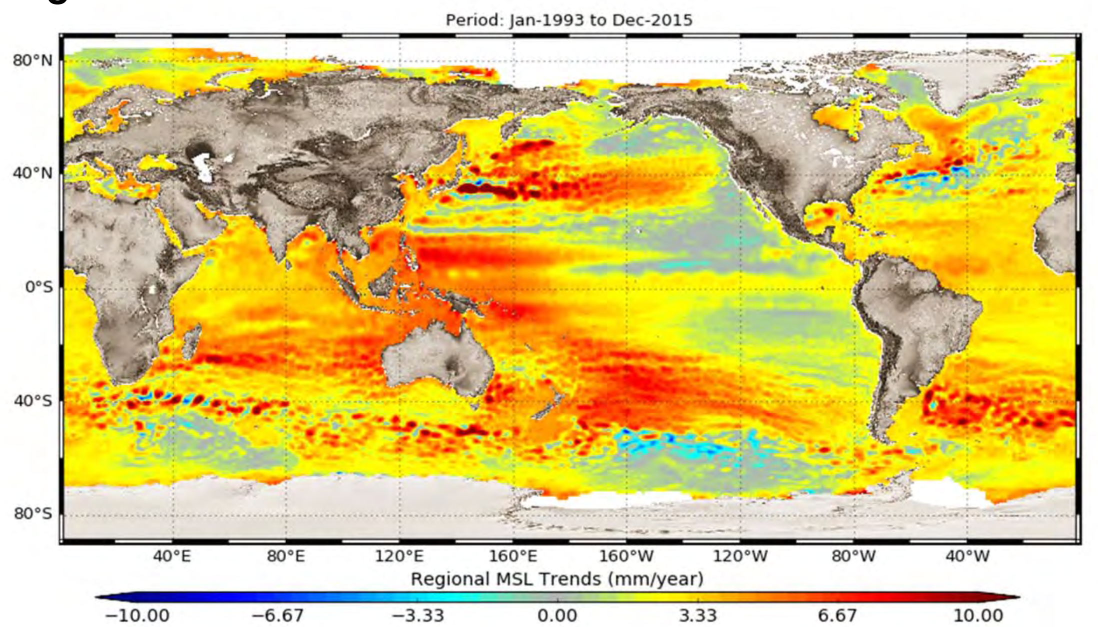
-Damages on coastal defences

-Negative impacts on coastal biodiversity

-.....

**most immediate impact*

Regional trends in sea level over the 1993-2015 time span



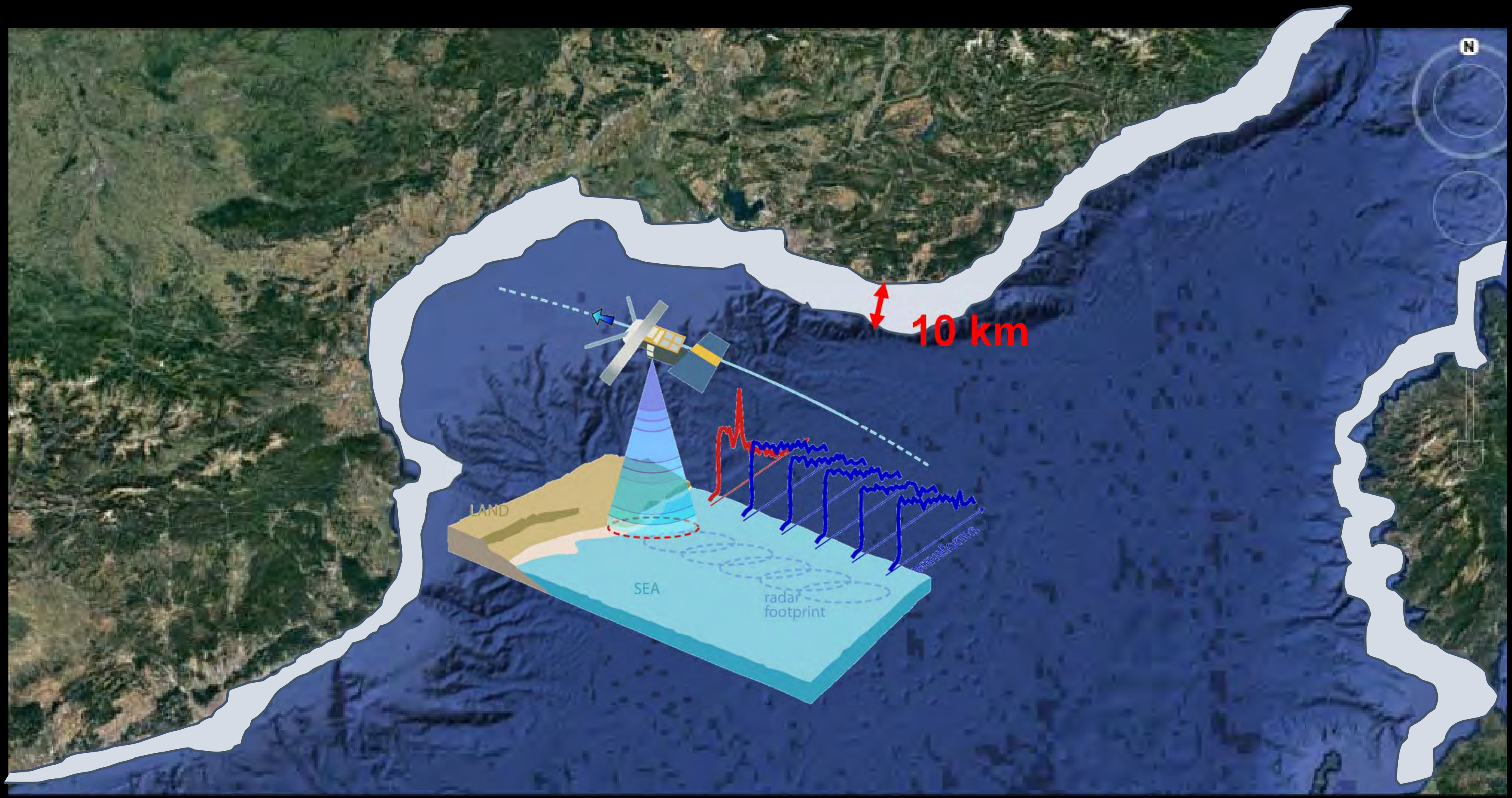
ESA Climate Change Initiative
Legeais et al., 2017

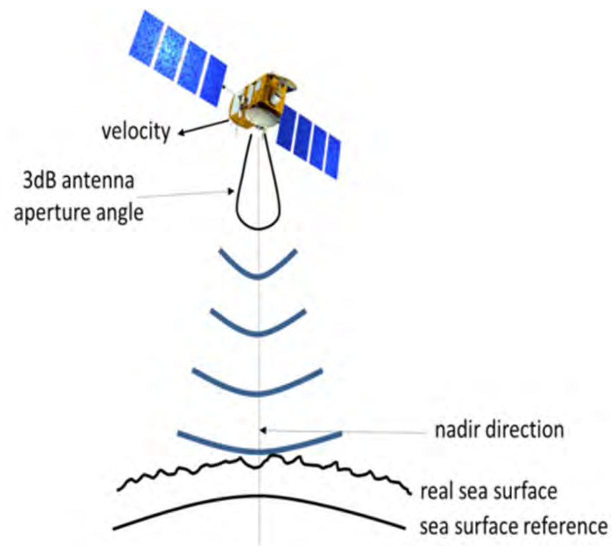
There are reasons to suspect that coastal sea level change is not just an extension of open ocean sea level change but may differ at the coast →

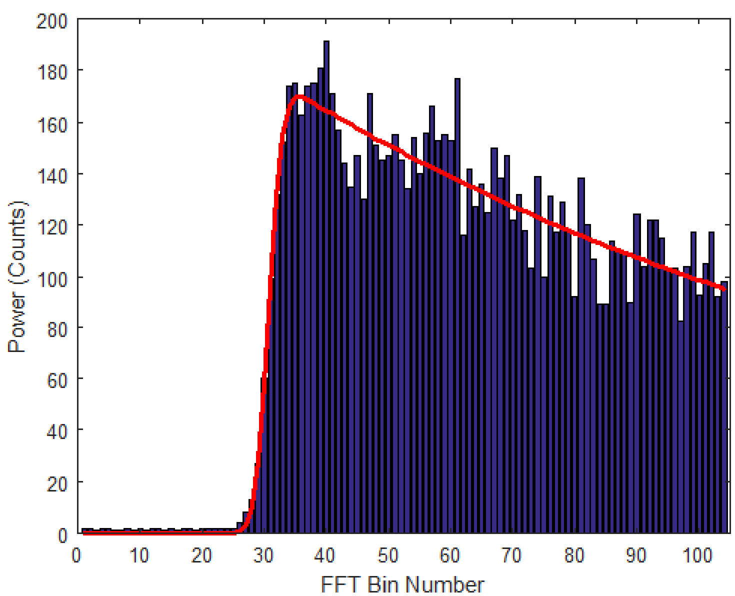
- *High-resolution ocean circulation models show that sea level observed by satellite altimetry in open ocean is different in the coastal zone (consequence of trapped Kelvin waves, shelf currents, baroclinic instabilities, etc.)*

- *Some processes (e.g., waves, river runoff in deltas and estuaries) only occur at the coast, and can also impact coastal sea level*

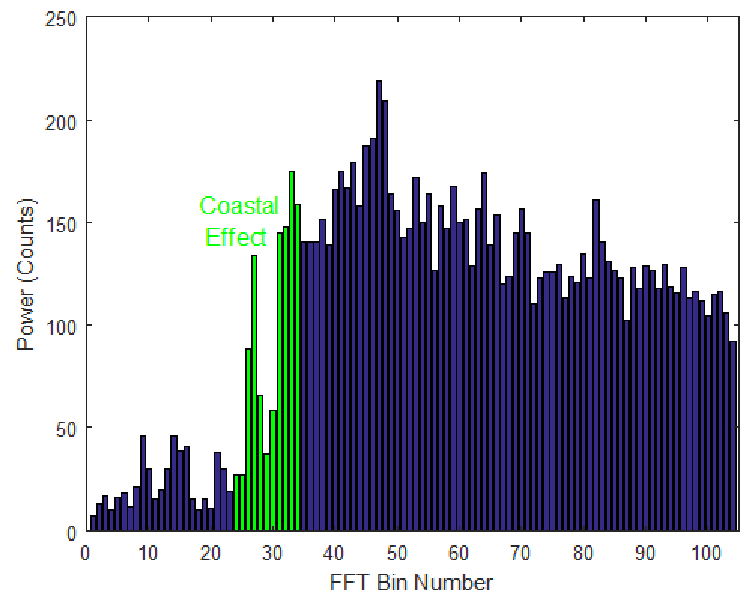
- *Coastal sea level rise only known from tide gauges but poor spatio-temporal coverage*
- *Not yet global information from satellite altimetry*





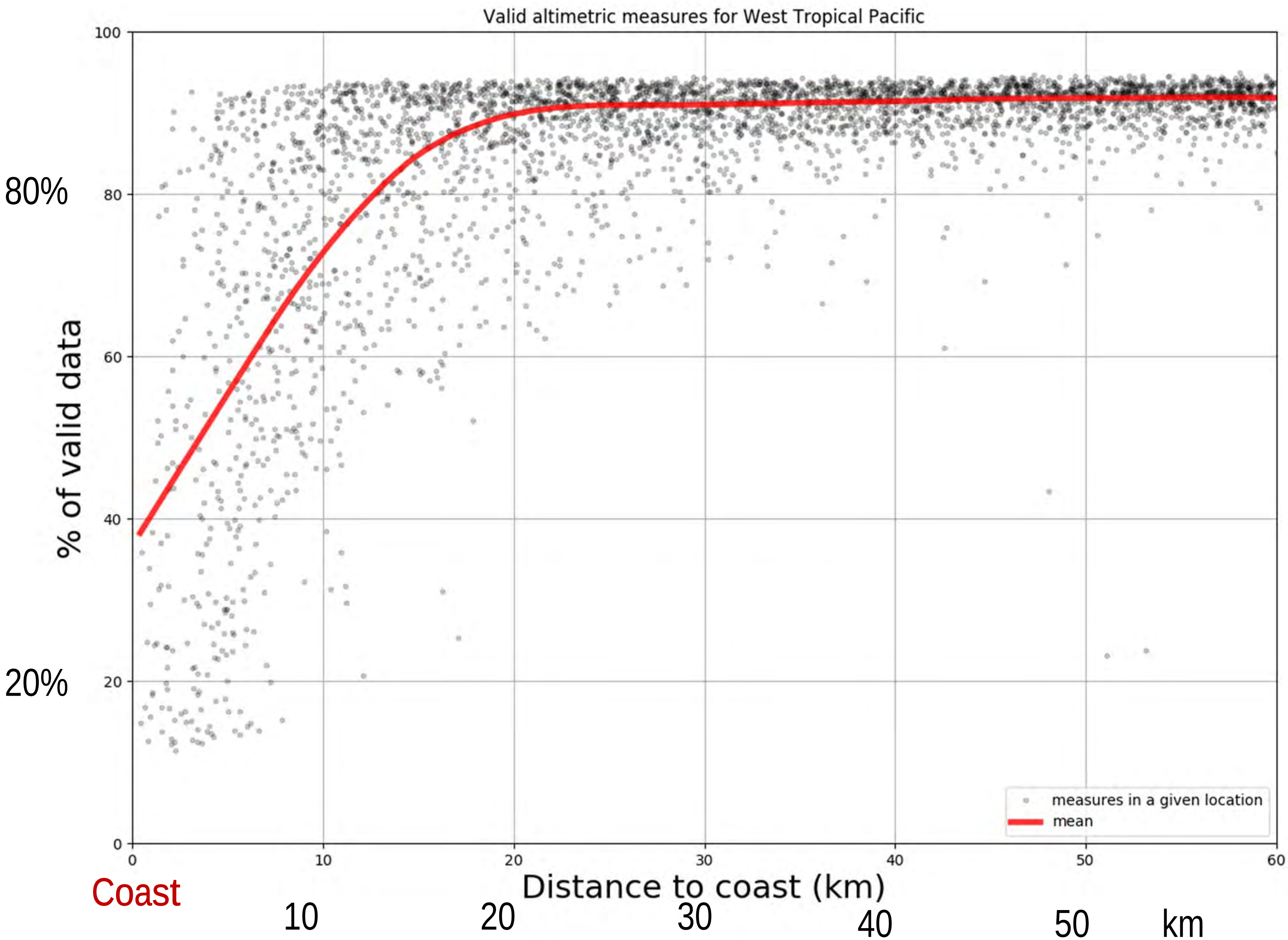


Typical open ocean radar waveform (Brown model)



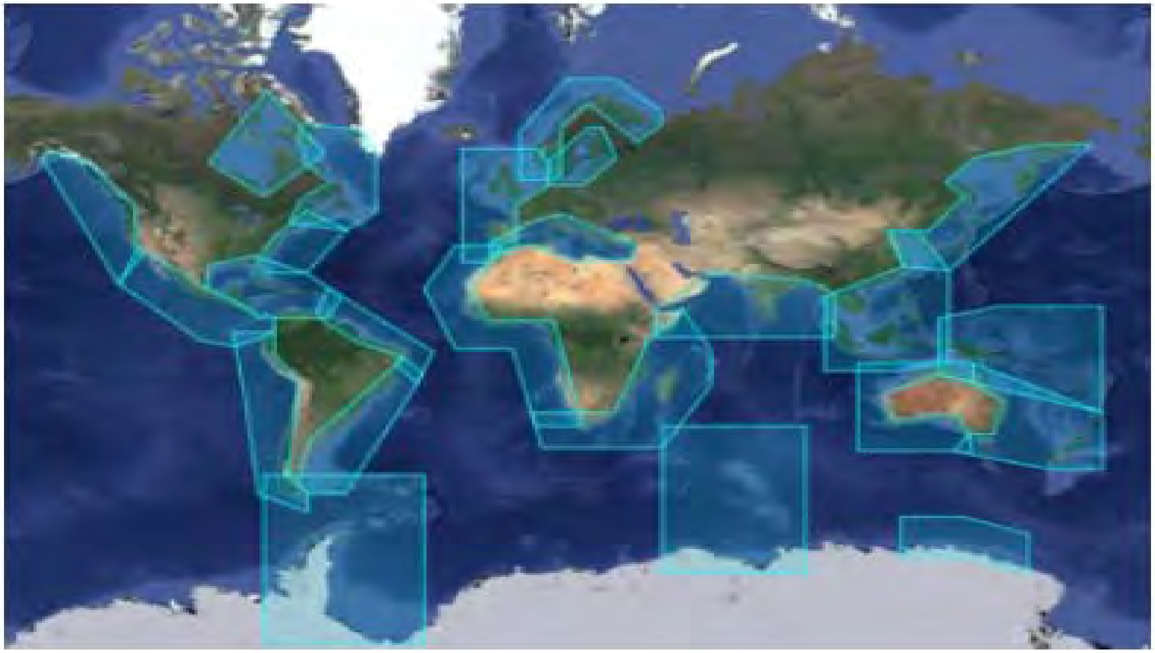
Example of radar waveform in the coastal zone

Percentage of valid altimetry measurements as a function of distance to the coast



To answer to the question: "is sea level at the coast rising at the same rate as in the open ocean?", we need for a global, altimetry-based, coastal sea level data set (*with reprocessing of radar echoes, improved corrections, gridded multi mission products, link with open ocean sea level, …*)

→ important for assessing coastal impacts of climate change and develop adaptation strategies



Another important process….vertical land motions

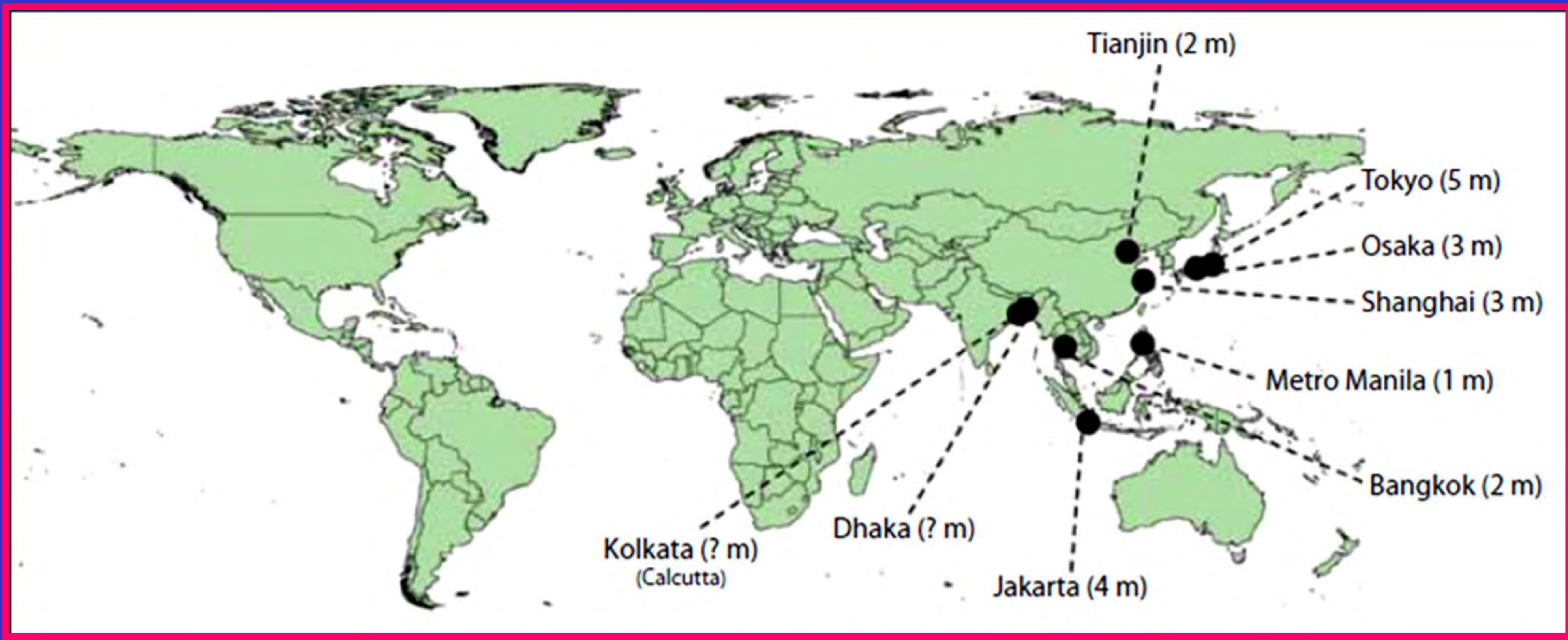
What counts at the coast

→TOTAL 'relative' sea level rise

⇩

∑ (global mean rise + regional trends +
local oceanic processes)+ local land motions

Subsidence of coastal megacities during the past few decades



From Nicholls (2011)

Conclusions

- Current global mean sea level rise is accelerating
- The sea level budget (Argo and GRACE period since 2005) almost closed
- Global mean sea level rise: very likely a consequence of anthropogenic global warming
- Regional variability (spatial trend patterns) change with time and space as the redistribution of heat is modulated by internal (natural) climate modes (e.g., ENSO)
- The global mean sea level will continue to rise during the 21st century in response to global warming (values by 2100 between 1-2m NOT unlikely)
- The regional variability will amplify the global mean rise by 20-30% in the tropics and some other regions
- Even if GHG emissions stop tomorrow, sea level will continue to rise during several centuries

Future prospects: What do we need for science?

- A long and accurate global and regional sea level record for climate studies → sustained altimetry missions + continuing R&D activities to feed operational production of sea level by the Copernicus Climate Change Service

- Sustained/improved observations of all contributions (Argo, GRACE, …)

- Regular assessments of closure of the sea level budget at global and regional scales → process understanding, constraints on missing contributions and Earth's Energy Imbalance, detection & attribution studies, validation of climate models…

- A global, multi-mission Coastal Altimetry data set + vertical land motions; important for studying COASTAL IMPACTS of climate change and human interventions

A few relevant publications

Ablain M., A. Cazenave, G. Larnicol et al. , "Improved Sea Level Record over the Satellite Altimetry Era (1993–2010) from the Climate Change Initiative Project." *Ocean Science* 11 (1). Copernicus GmbH:67–82. https://doi.org/10.5194/os-11-67-2015, 2015.

Ablain M., J. F. Legeais, P. Prandi et al. , "Satellite Altimetry-Based Sea Level at Global and Regional Scales." *Surveys in Geophysics* 38, 1,7–31. https://doi.org/10.1007/s10712-016-9389-8, 2017

Beckley, B. D., P. S. Callahan, D. W. Hancock et al. "On the 'Cal-Mode' Correction to TOPEX Satellite Altimetry and Its Effect on the Global Mean Sea Level Time Series." *Journal of Geophysical Research, C: Oceans* 122 (11):8371–84. https://doi.org/10.1002/2017jc013090, 2017.

Cazenave, A, H.B. Dieng, B. Meyssignac et al. "The Rate of Sea-Level Rise." *Nature Climate Change* 4 (5):358–61. https://doi.org/10.1038/nclimate2159, 2014.

Cazenave A. and Le Cozannet G., Sea level rise and coastal impacts, *Earth's Future*, vol2, 2, 15-34, 2014.

Cazenave A., Palanisaly H. and Ablain M., Contemporary Sea Level Changes from Satellite Altimetry: What have we learned? What are the new challenges? ASR, in press, 2018.

Chen, X., Zhang X., Church J.A. et al., "The Increasing Rate of Global Mean Sea-Level Rise during 1993–2014." *Nature Climate Change* 7 (7):492–95. https://doi.org/10.1038/nclimate3325, 2017

Cipollini, P., F. Birol, M. J. Fernandes et al.,Satellite altimetry in coastal regions, In Satellite altimetry over oceans and land surfaces, Stammer & Cazenave edts, CRC Press, 2018.

Dieng, H.B, A.Cazenave, B.Meyssignac et al., New estimate of the current rate of sea level rise from a sea level budget approach, *Geophysical Research Letters*, 44, doi:10.1002/ 2017GL073308, 2017a

Escudier P., Couhert A., Mercier F. et al., Satellite radar altimetry: principle, accuracy and precision, in 'Satellite altimetry over oceans and land surfaces, D.L Stammer and A. Cazenave edts., 617 pages, CRC Press, Taylor and Francis Group, Boca Raton, New York, London, ISBN: 13: 978-1-4987-4345-7, 2018.

Legeais, J-F, Ablain M., Zawadzki L. et al., ., "An Accurate and Homogeneous Altimeter Sea Level Record from the ESA Climate Change Initiative." *Earth System Science Data Discussions*, 1–35. https://doi.org/10.5194/essd-2017-116, 2018.

Nerem R.S., Beckley B.D., Fasullo J. et al., Climate Change Driven Accelerated Sea Level Rise Detected In The Altimeter Era, *PNAS*, 2018a.

Quartly G.D., Legeais J.F., Ablain M. et al., A new phase in the production of quality-controlled sea level data, *Earth Syst. Sci. Data*, 9, 557–572, doi.org/10.5194/essd-9-557-2017, 2017.

Stammer D., Cazenave A., Ponte R. et al., Contemporary regional sea level changes, *Annual Review Marine Sciences*, 5, 21–46, 2013.

Stammer, D., and Cazenave A., *Satellite Altimetry Over Oceans and Land Surfaces*, 617 pp., CRC Press, Taylor and Francis Group, Boca Raton, New York, London, ISBN: 13: 978-1-4987-4345-7, 2018.

Watson, C. S., White N.J. , JChurch J.A. et al., "Unabated Global Mean Sea-Level Rise over the World Satellite Altimeter Era." *Nature Climate Change* 5 (6):565–68. https://doi.org/10.1038/nclimate2635, 2015.

WCRP (World Climate Research Programme) Sea Level Budget Group (The), Global sea level budget (1993-present), in revision, *Earth System Science Data Discussions*, https://doi.org/105194/essd-2018-53, 2018.

THANKS FOR YOUR ATTENTION