

Lesson N°2

Sea level changes

recent past, present, future



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Shanghai, July 2014

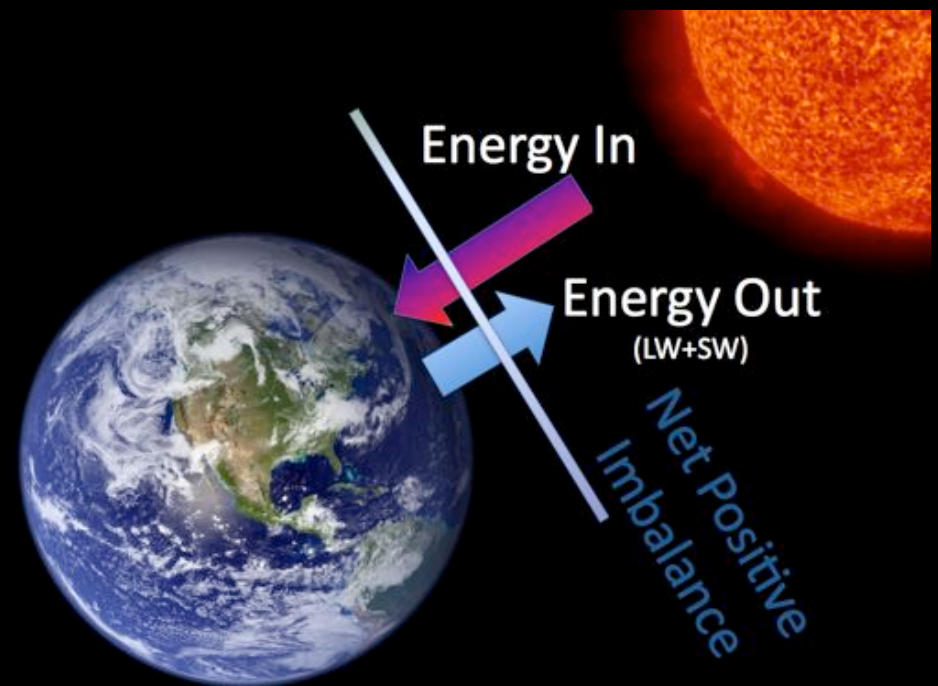
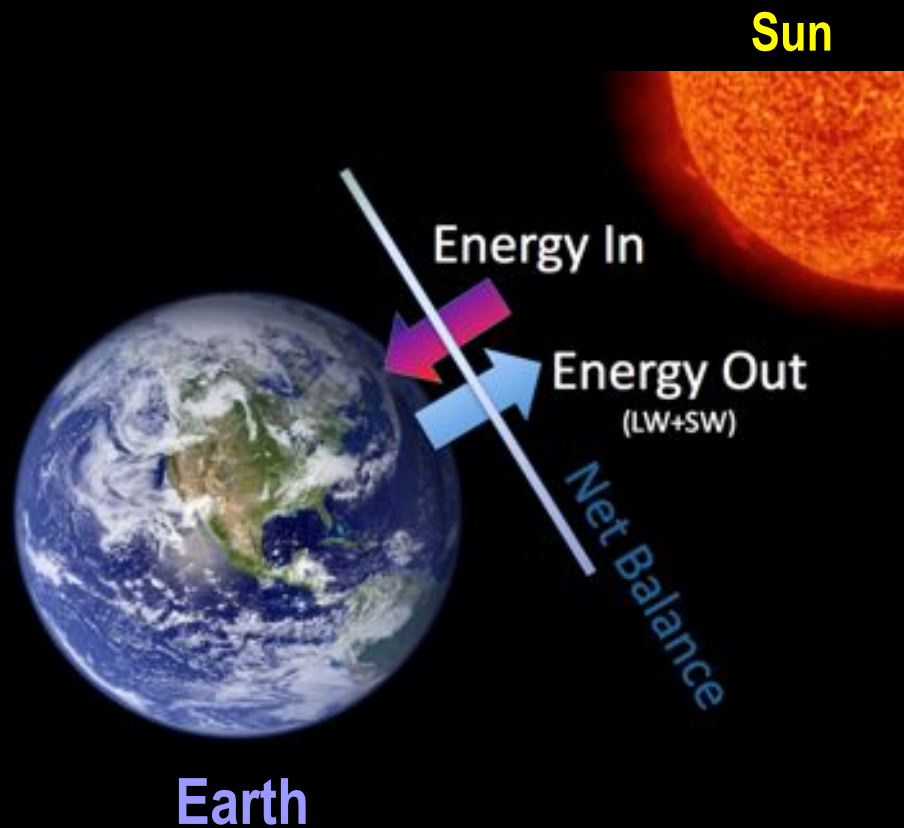
IPCC 5th Assessment Report (2013): main messages

- Global warming & dominant role of human activities confirmed
- Since IPCC 4th Assessment Report (2007)
 - longer and more accurate observations of global warming
 - refined modeling of climate change (recent past and future)



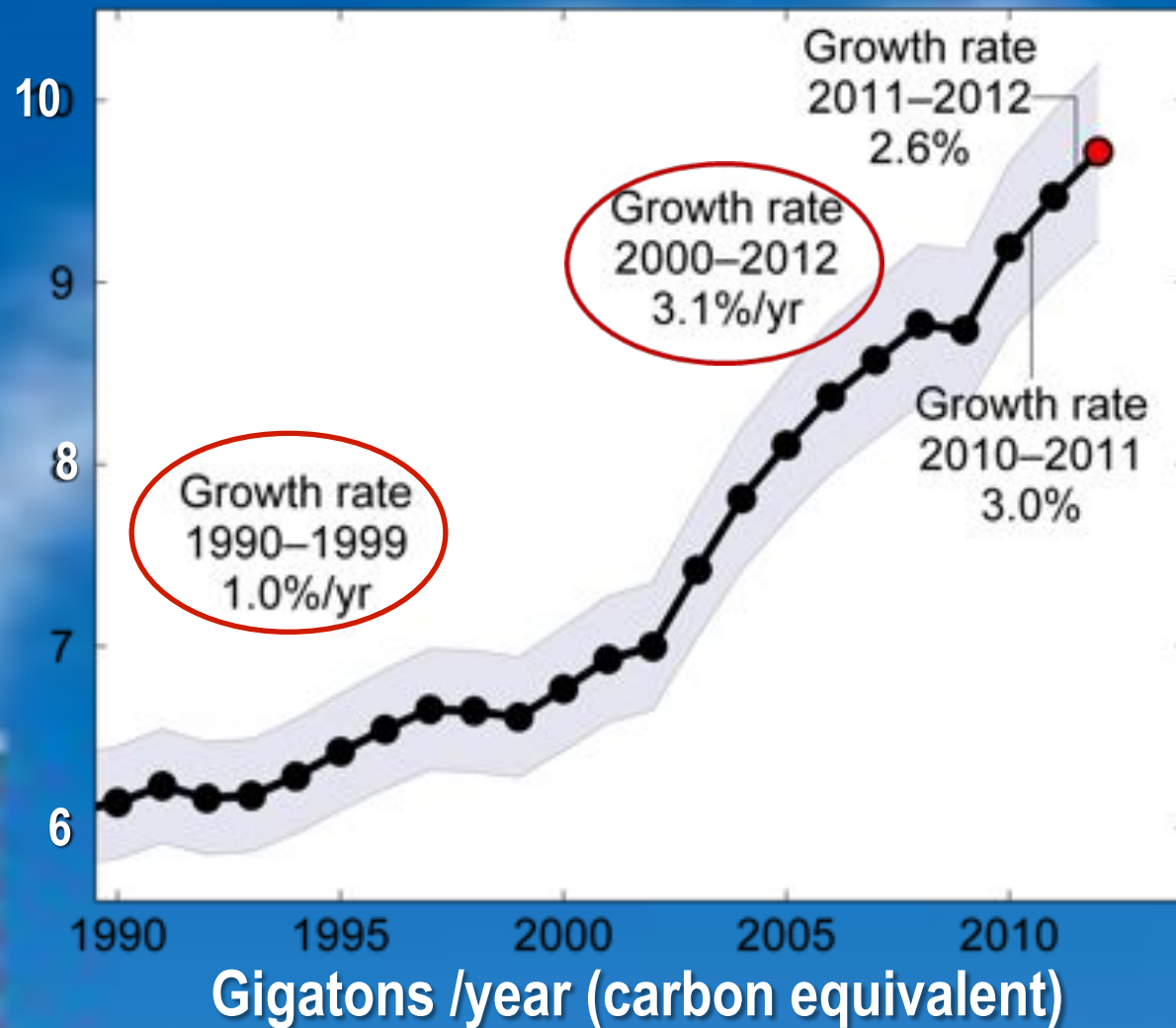
IPCC= Intergovernmental Panel on Climate Change
AR5 = 5th Assessment Report (released in September 2013)

Earth's Energy Budget



Thermal energy imbalance : $0.5-1 \text{ Wm}^{-2}$

Greenhouse Gas Emissions



The Greenhouse Effect

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.

Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

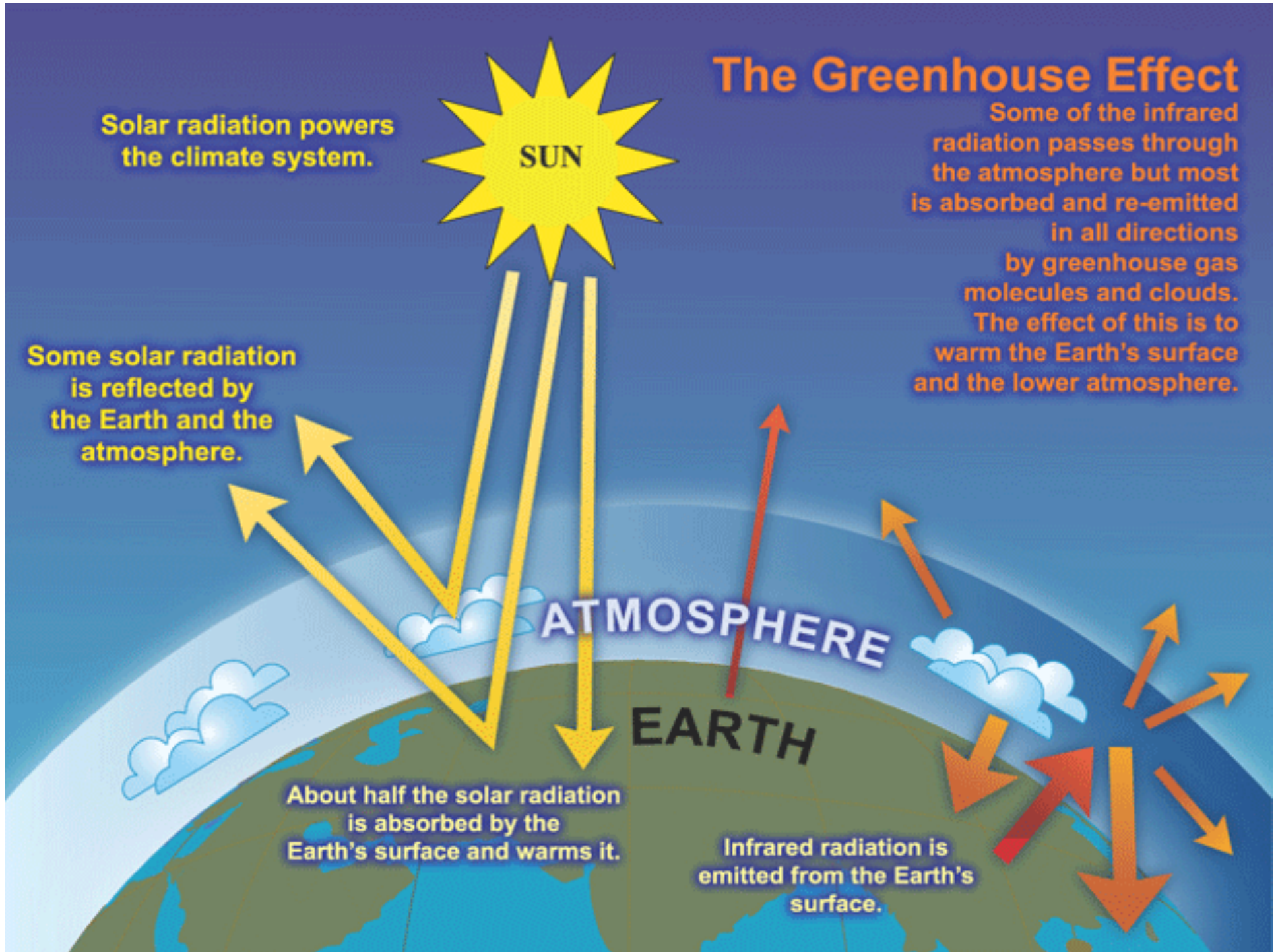
About half the solar radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

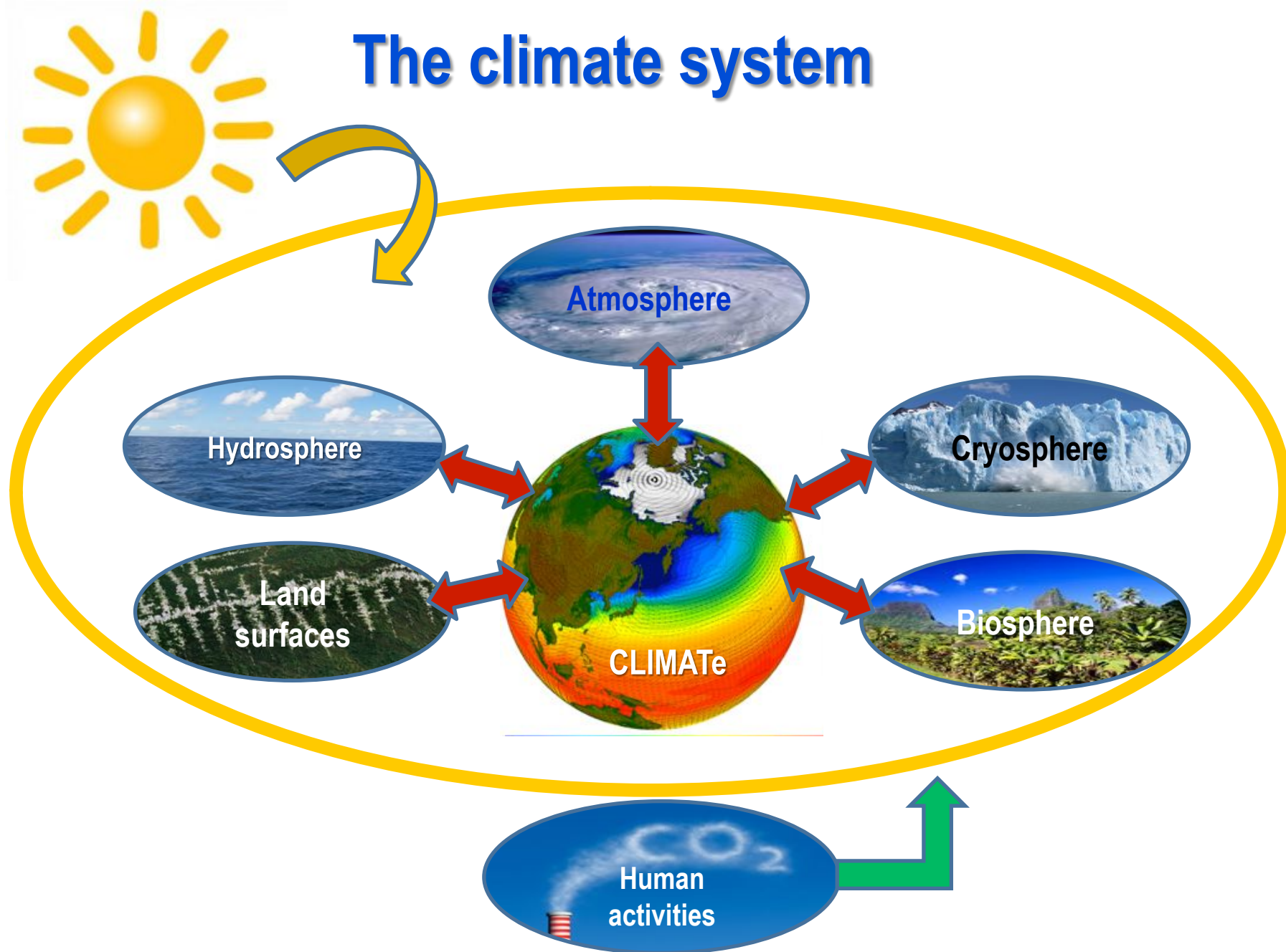
SUN

ATMOSPHERE

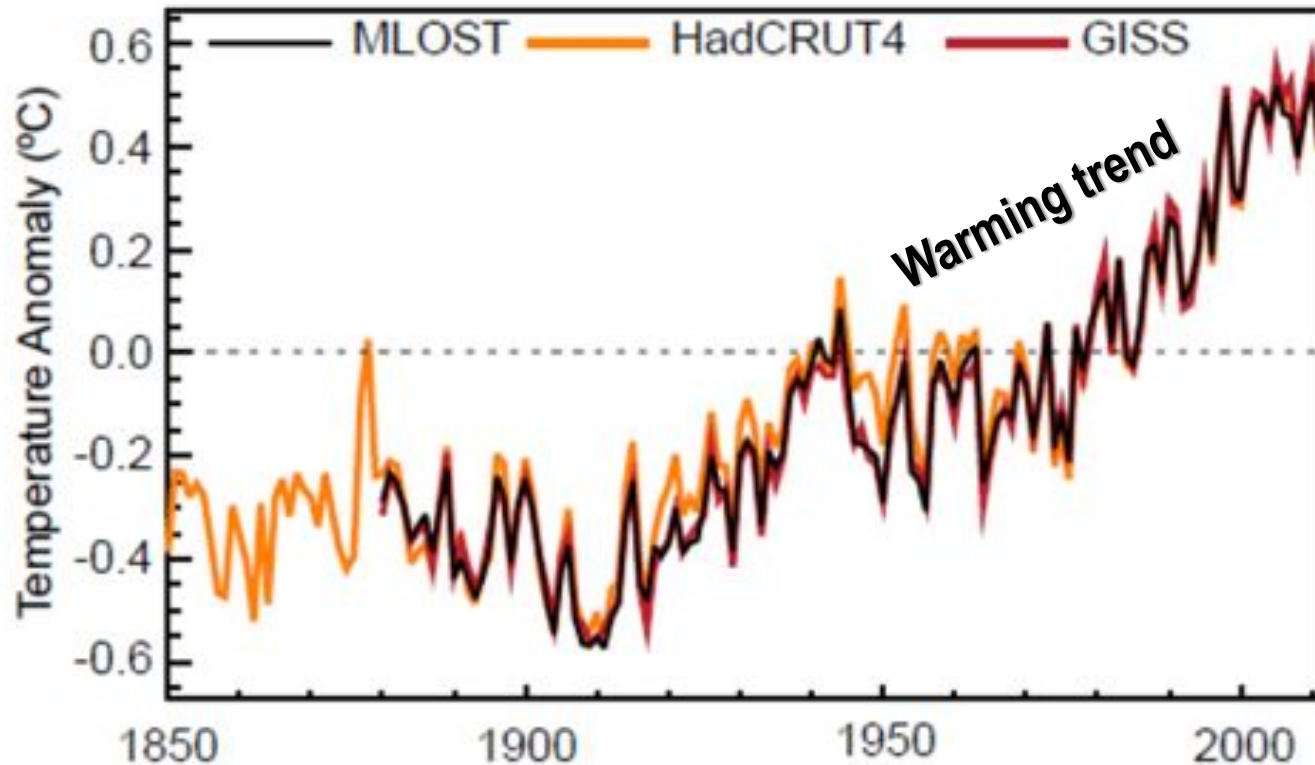
EARTH



The climate system

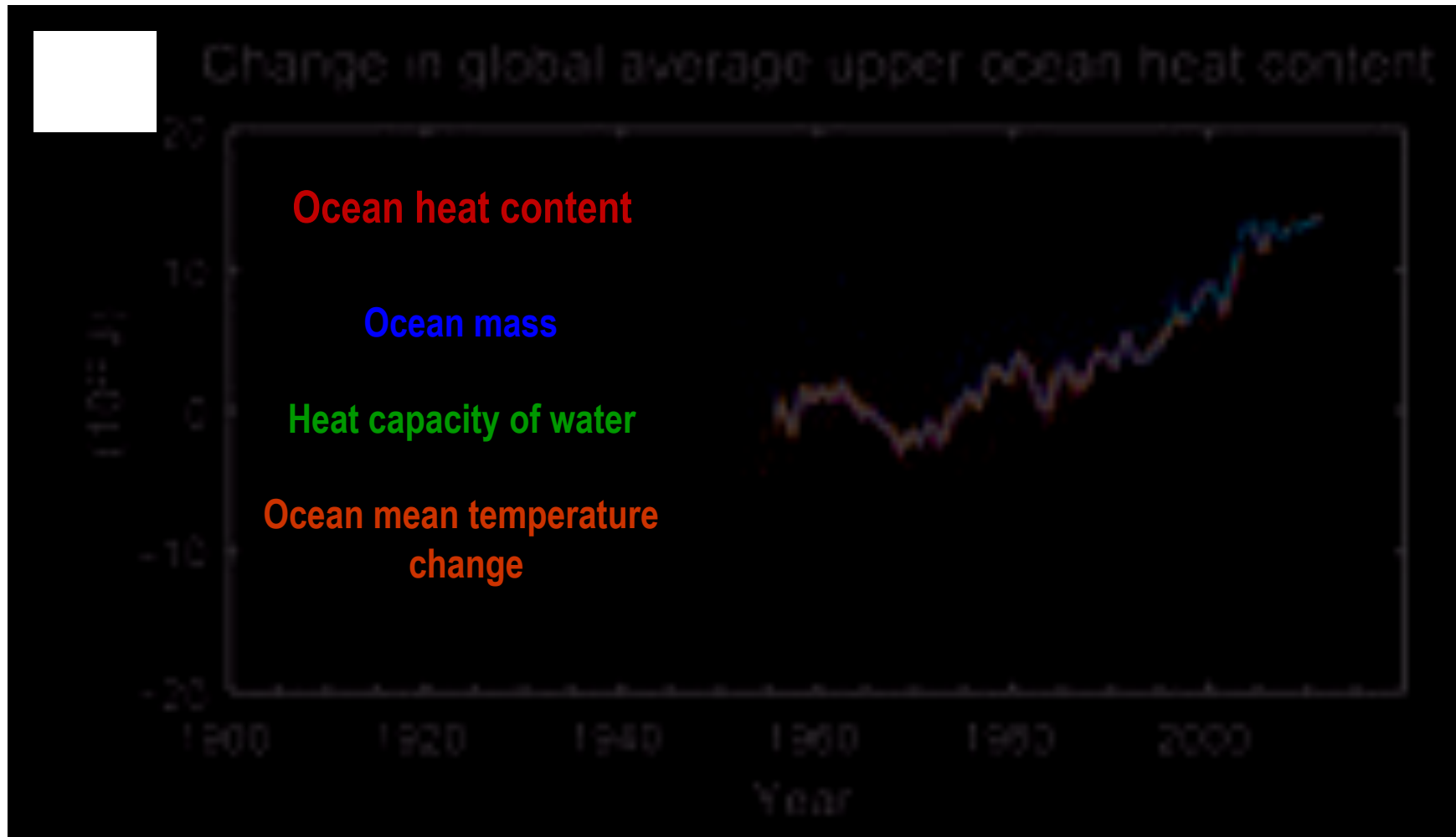


The Earth is warming



Evolution of the Earth's mean temperature since 1850
→ Increase of 0.85°C since 1900

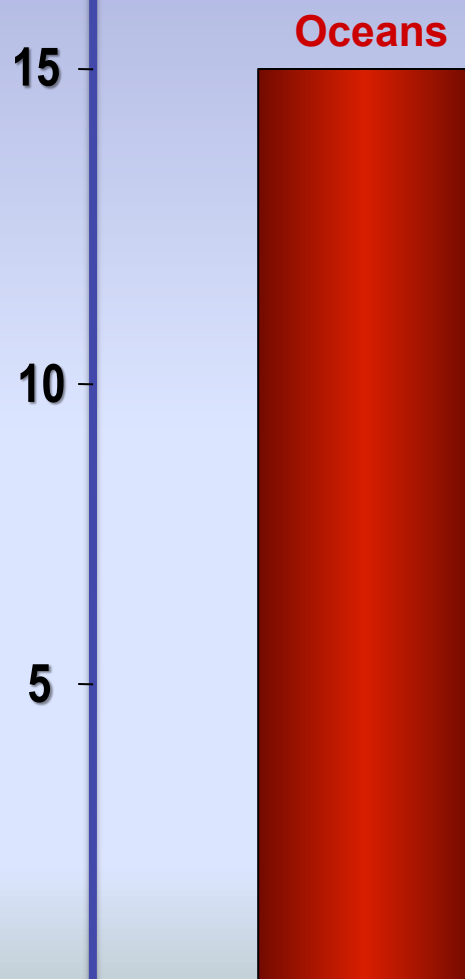
The ocean heat content is increasing



Thermal budget of the climate system

(last 50 years)

Heat content (10^{22} J)



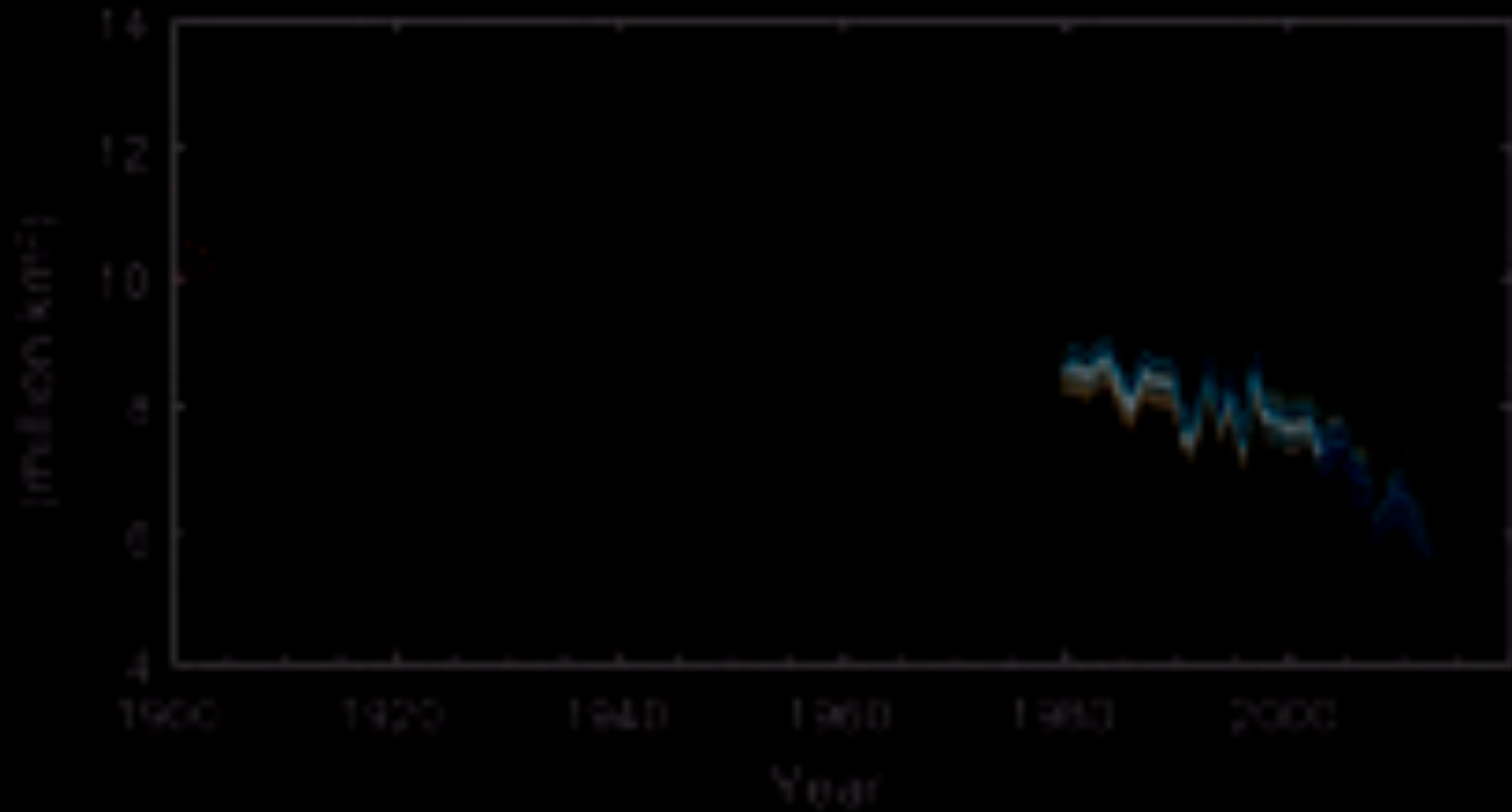
93% of (anthropogenic) heat excess
of the climate system is
stored in the oceans

5×10^{22} Joules

=

Energy released if all fossil
resources (oil, gas, coal) still remaining
on Earth were burnt!

Summer sea ice extent evolution



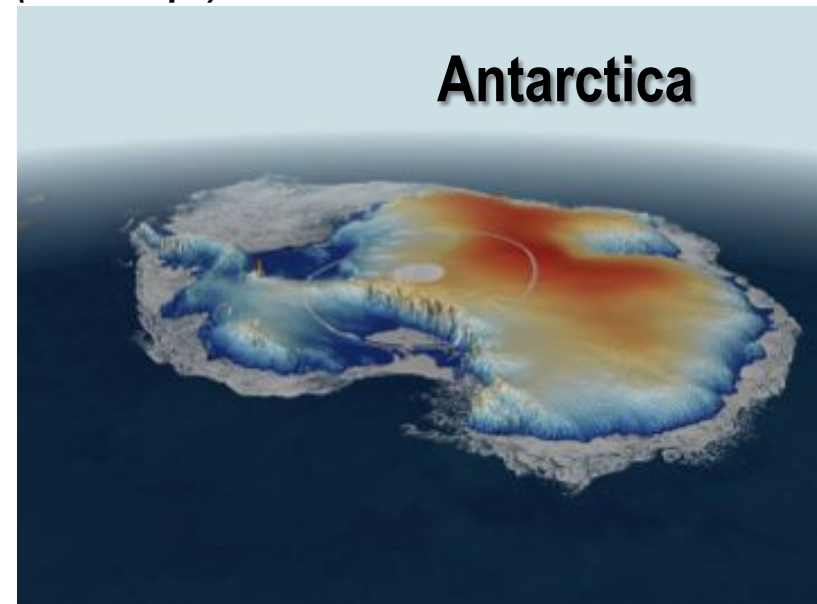
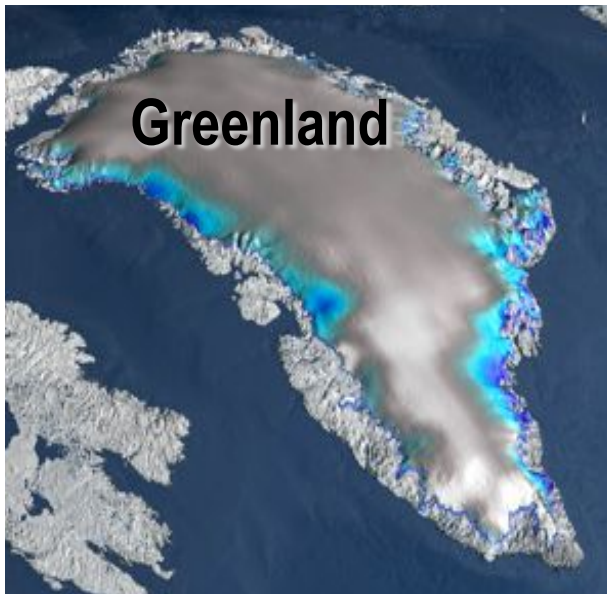
Summer sea ice extent is decreasing



Land ice is melting....

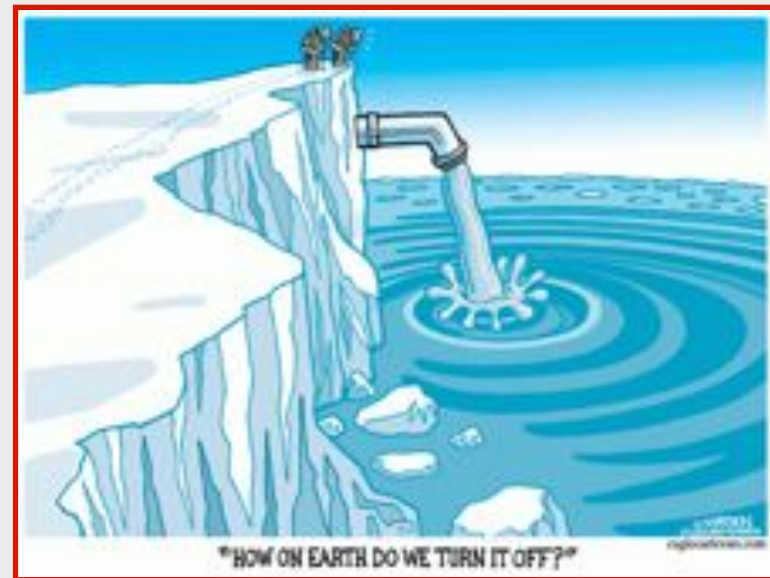


Rhone Glacier (Swiss Alps)

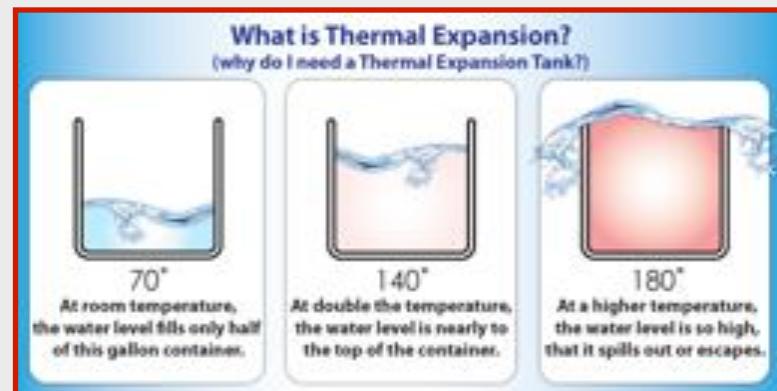


Sea level rise: a direct consequence of global warming

- Water mass addition to the oceans from land ice melt (glaciers & ice sheets)

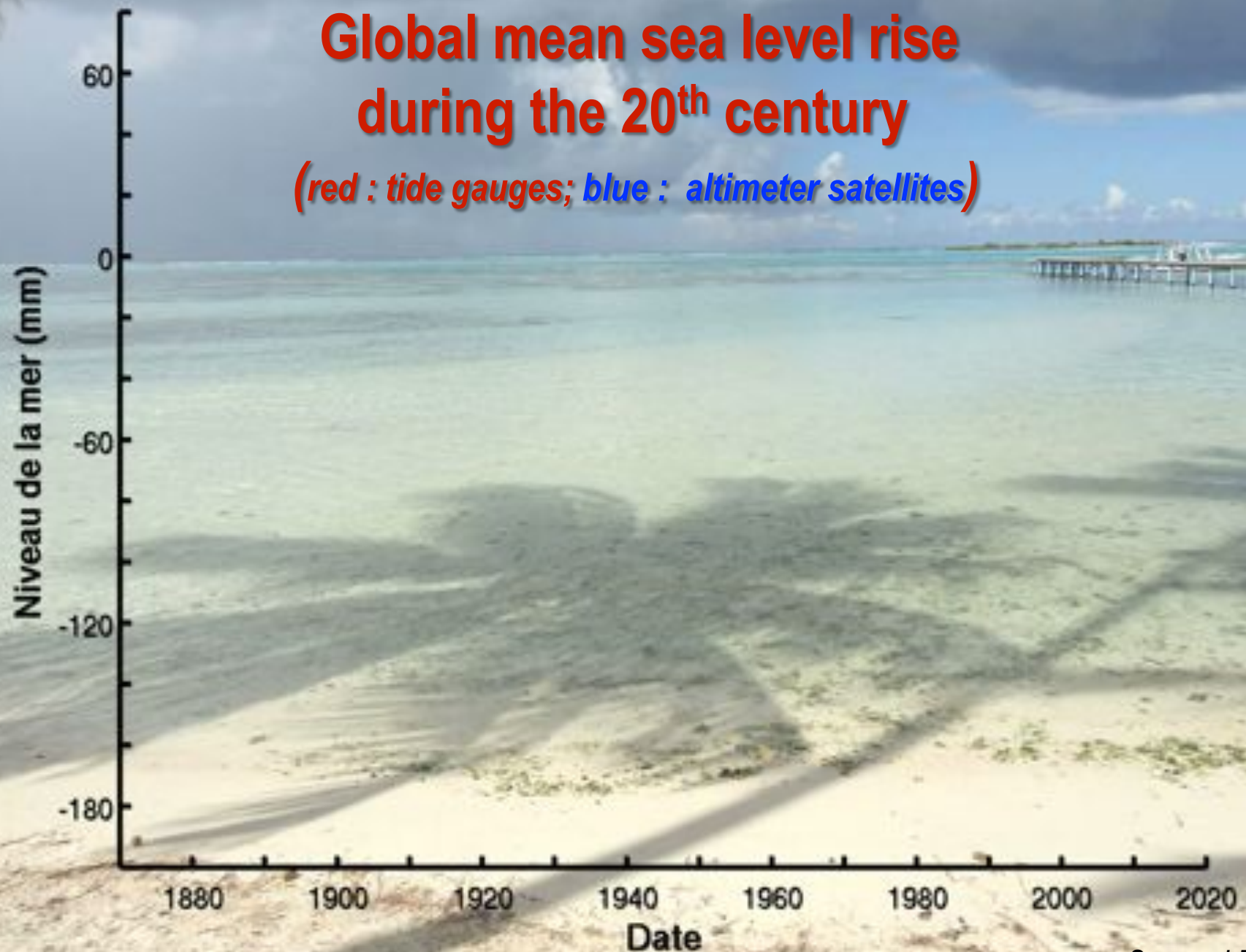


- Thermal expansion of sea waters



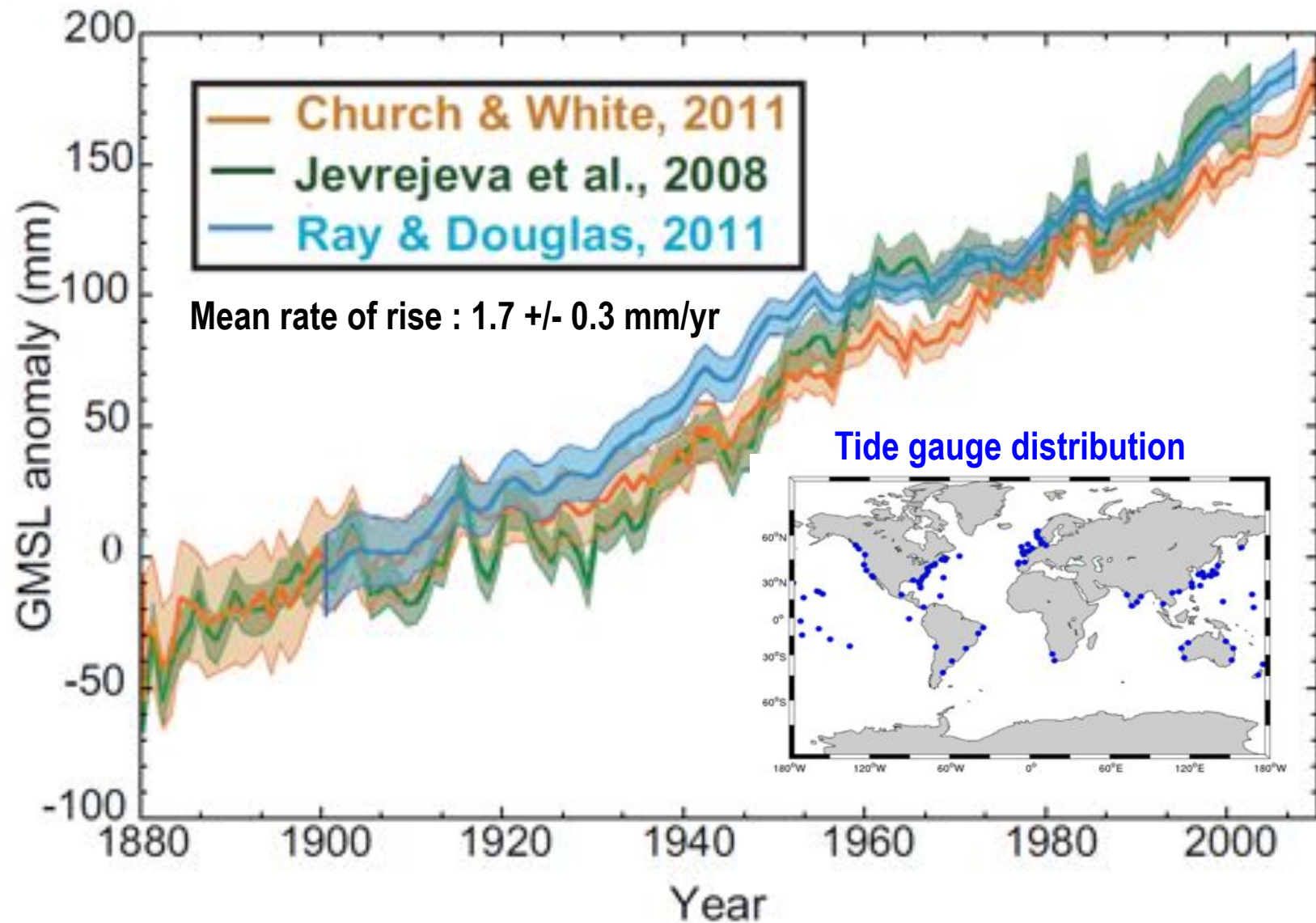
Global mean sea level rise during the 20th century

(red : tide gauges; blue : altimeter satellites)



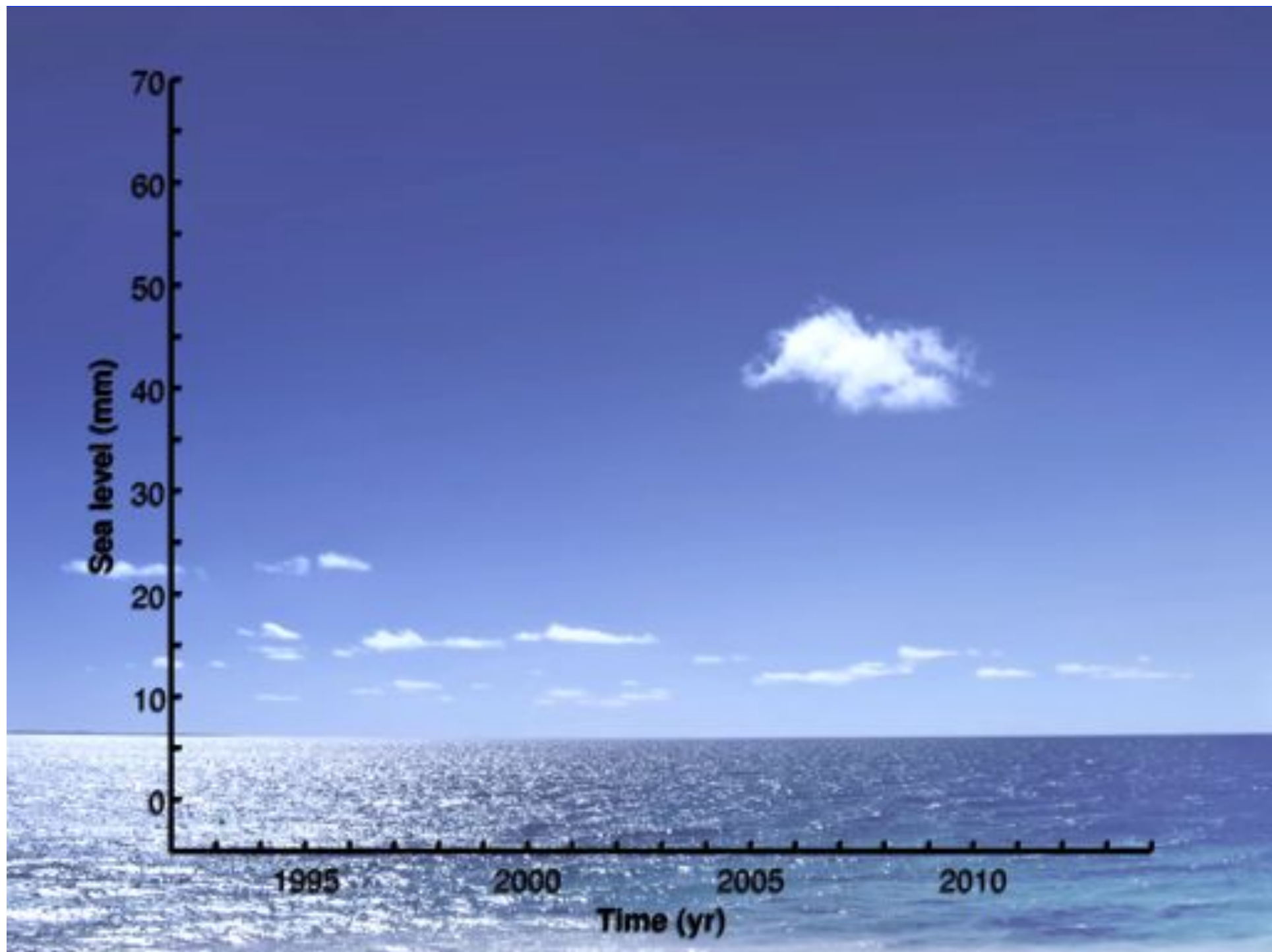
Source :LEGOS

20th century sea level rise



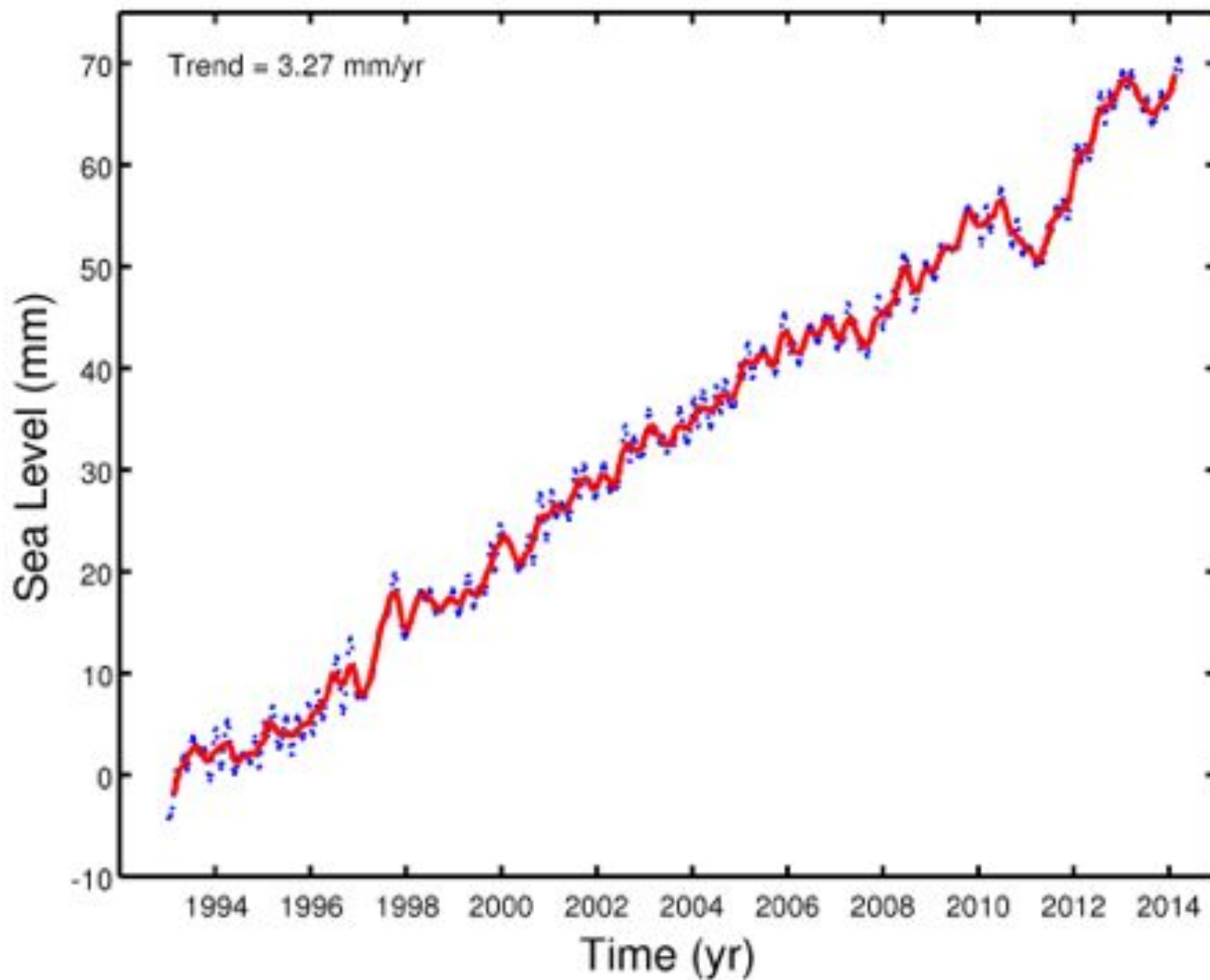
Sea level change now routinely measured by altimeter satellites





23 June 2014

Global Mean Sea Level from satellite altimetry



Questions

•Is sea level rise accelerating?

Yes!

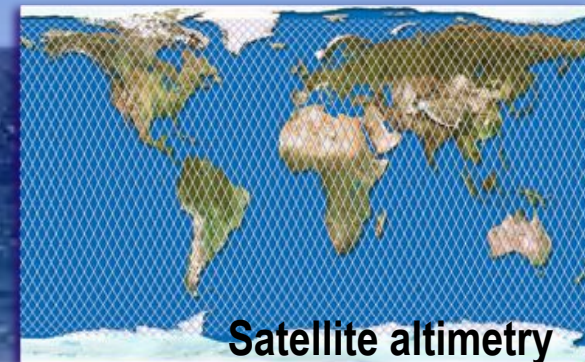
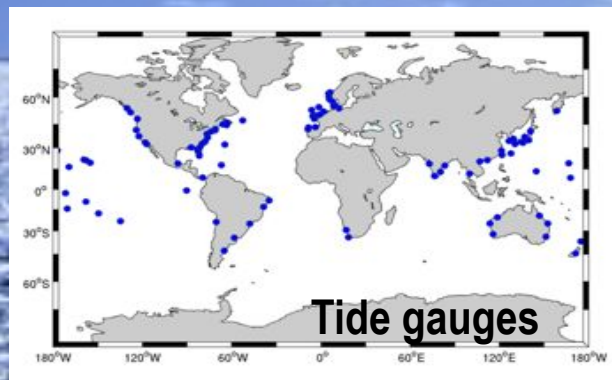
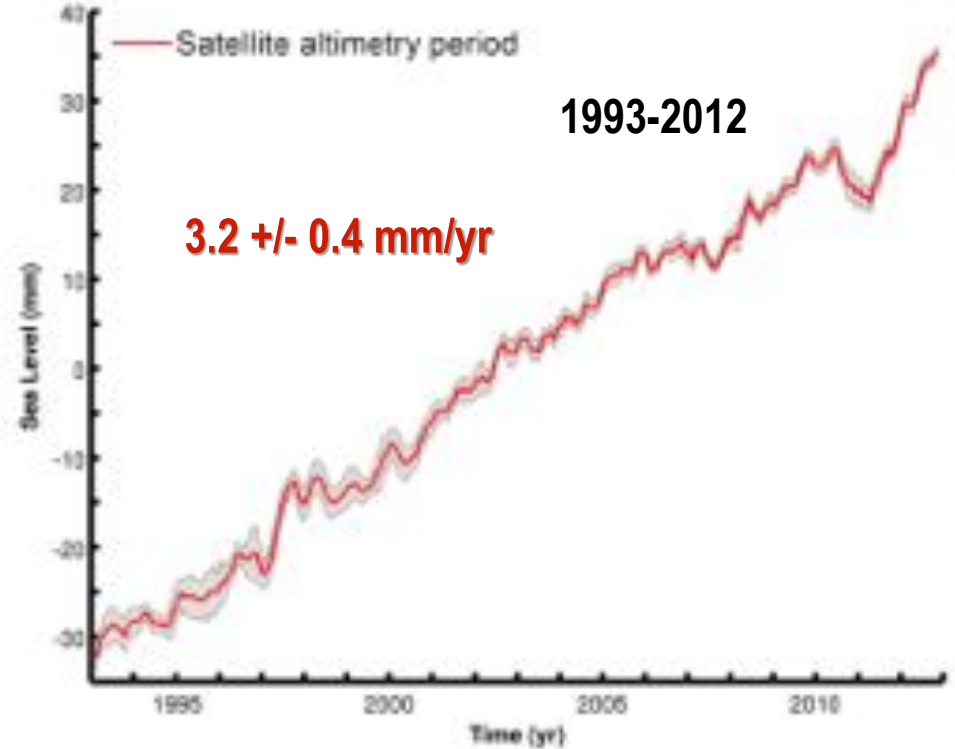
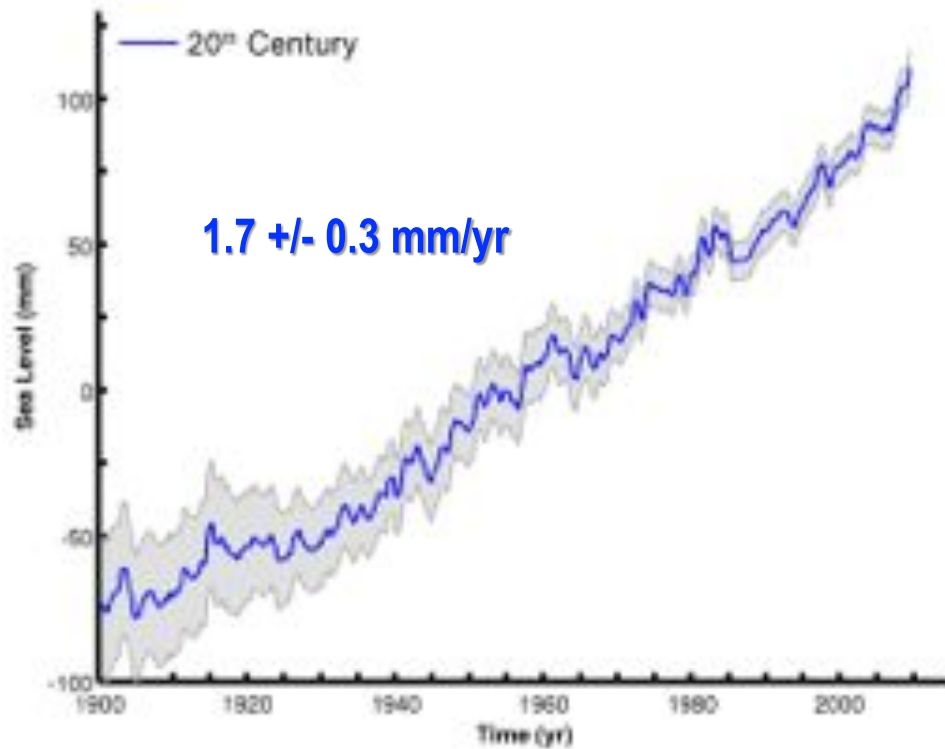
Church et al. (2013) concludes that « the increased rate of sea level rise since 1990 is not part of a natural cycle but a direct response to increased radiative forcing on the climate system »

•Is the current rate of rise unusual?

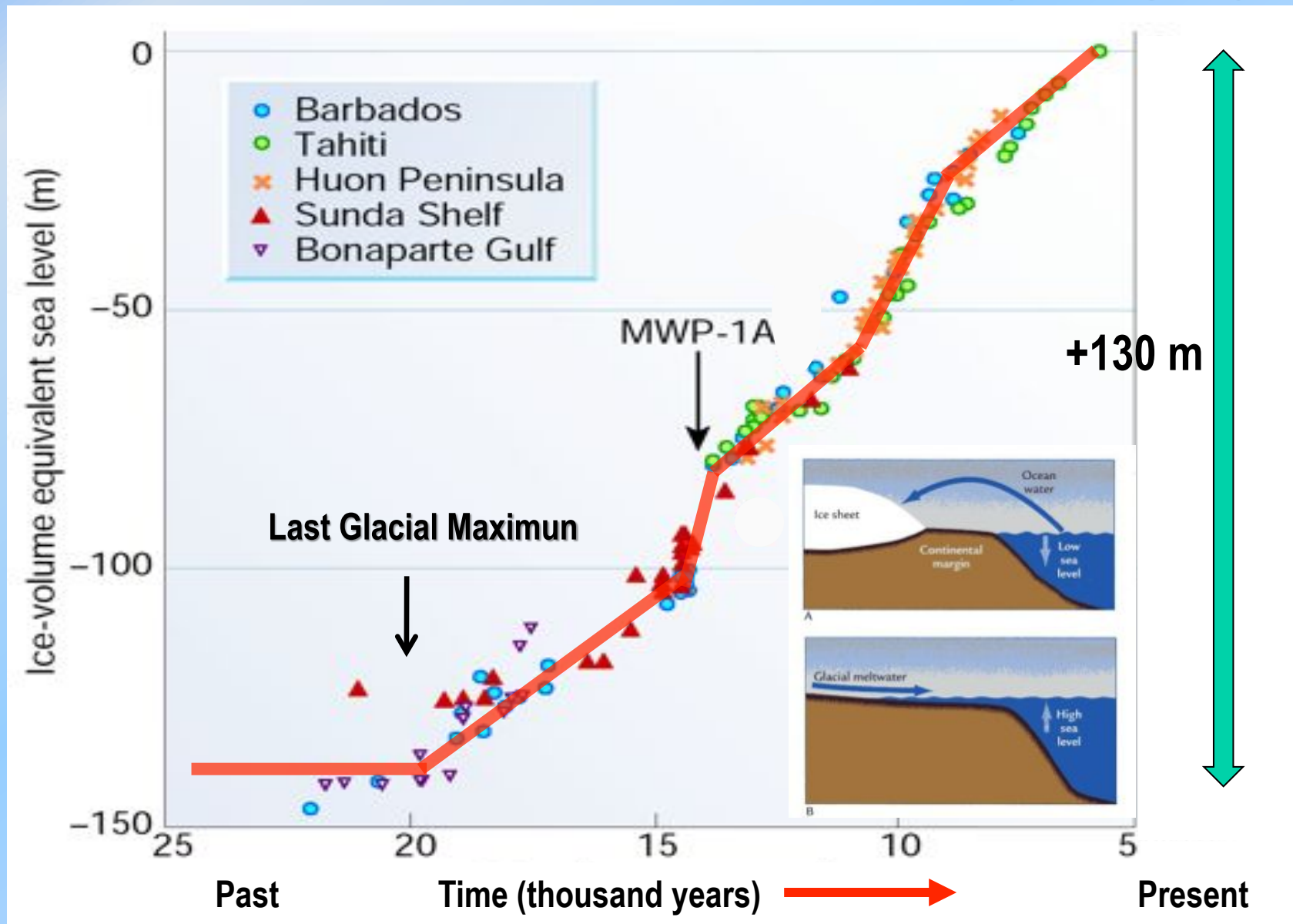
Yes and no!



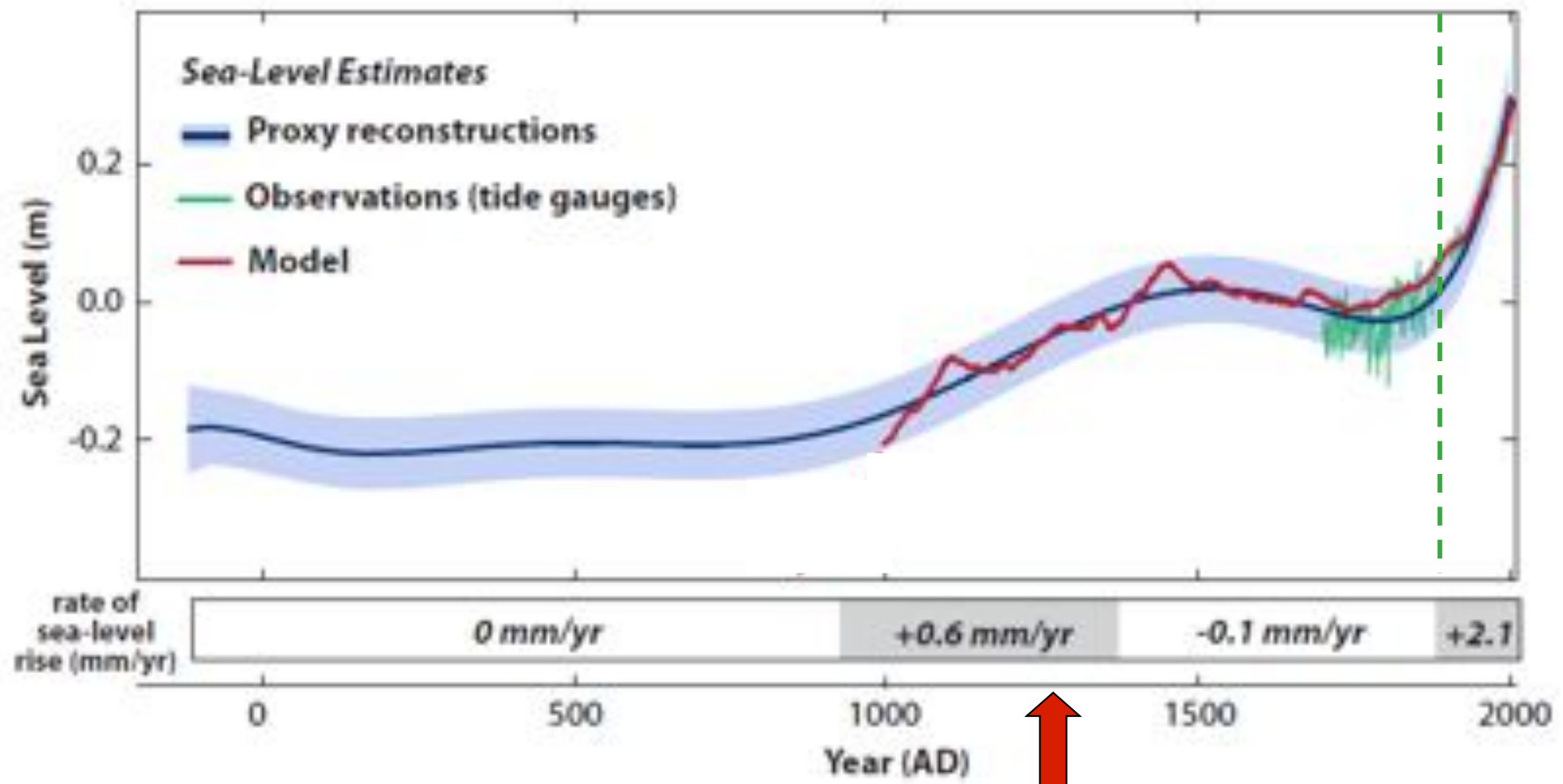
Sea level rise : 20th century and past 2 decades

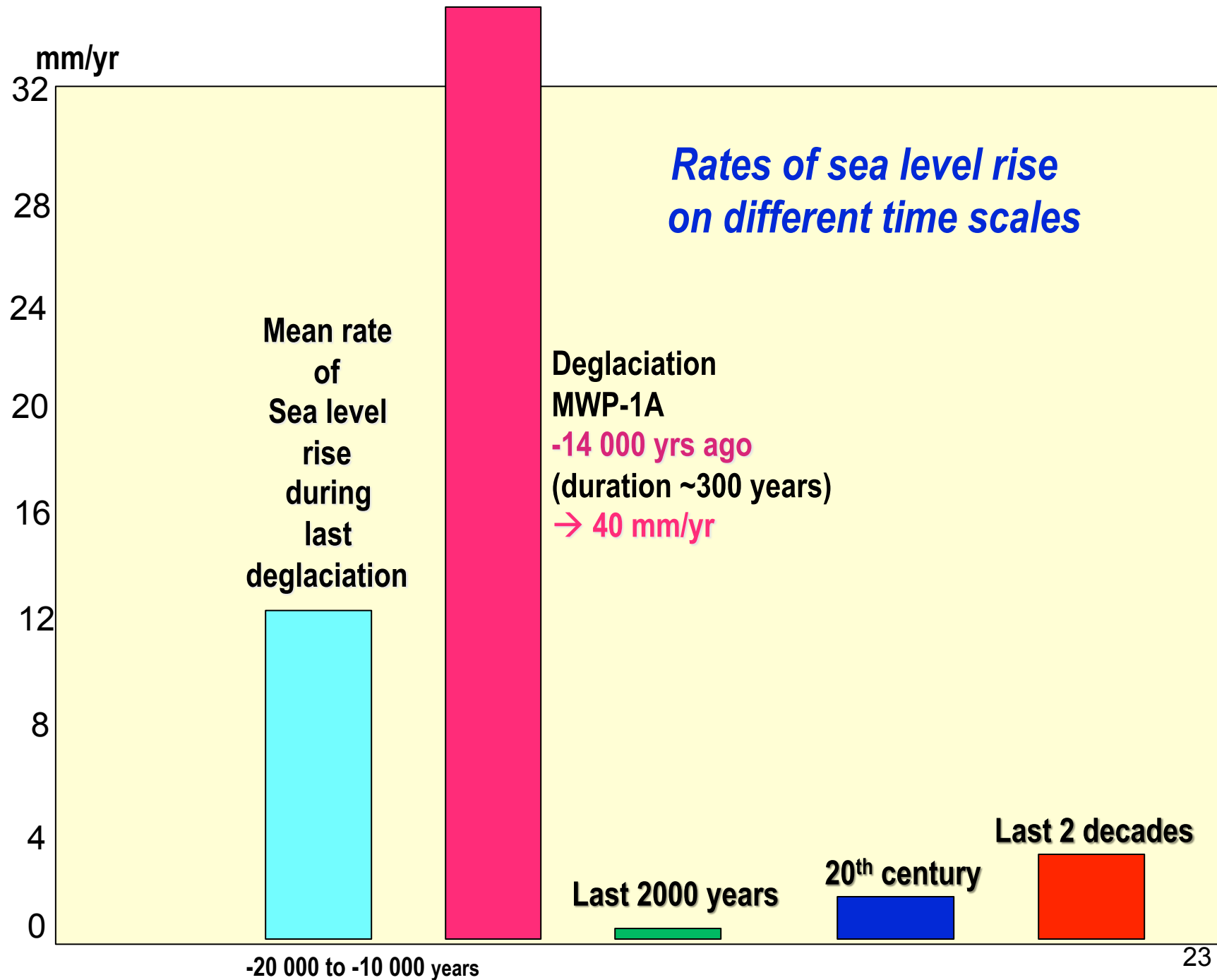


Global mean sea level rise since the Last Glacial Maximum (- 20 000 years)



Evolution of the mean sea level over the last 2000 years

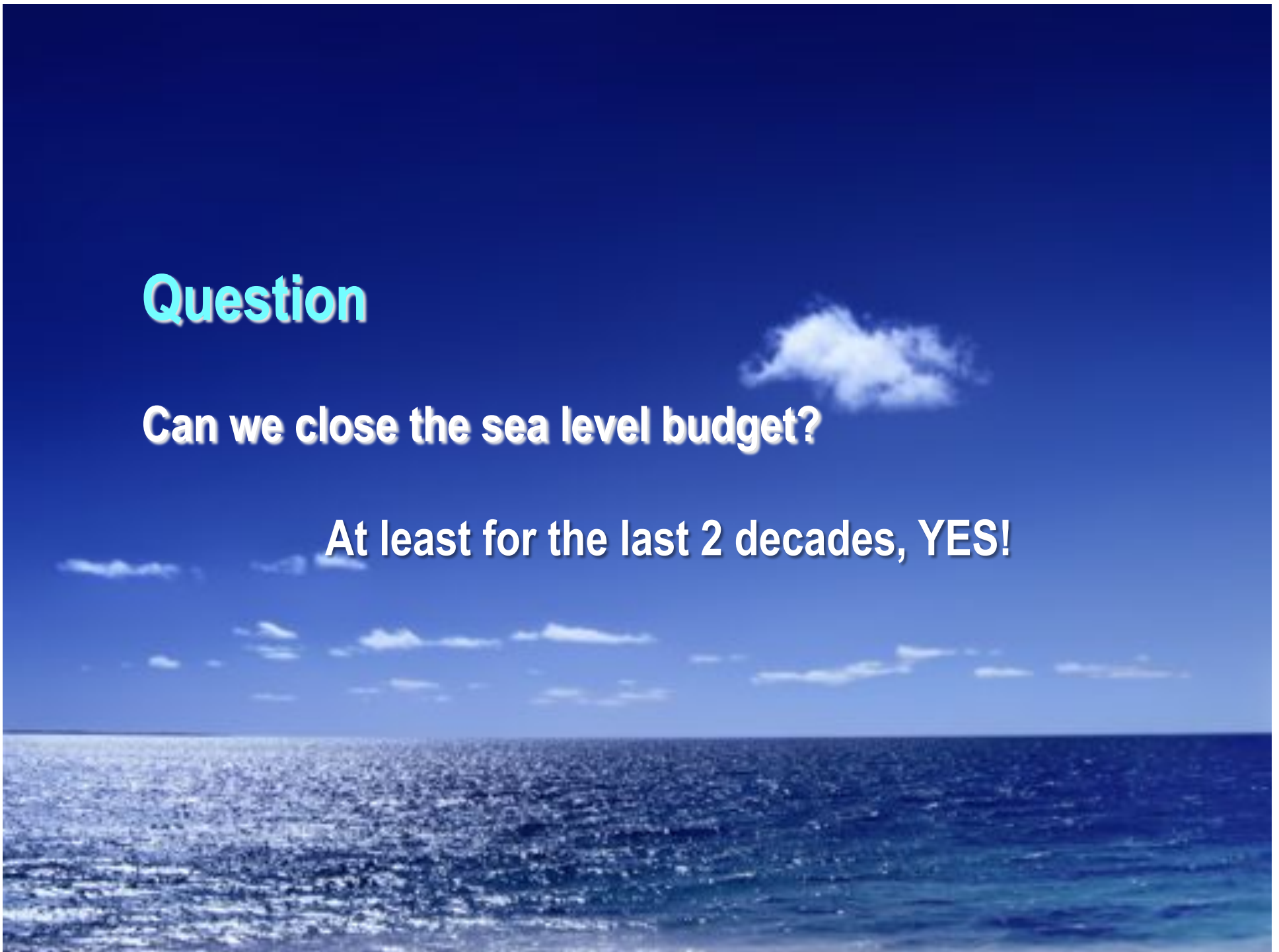




Question

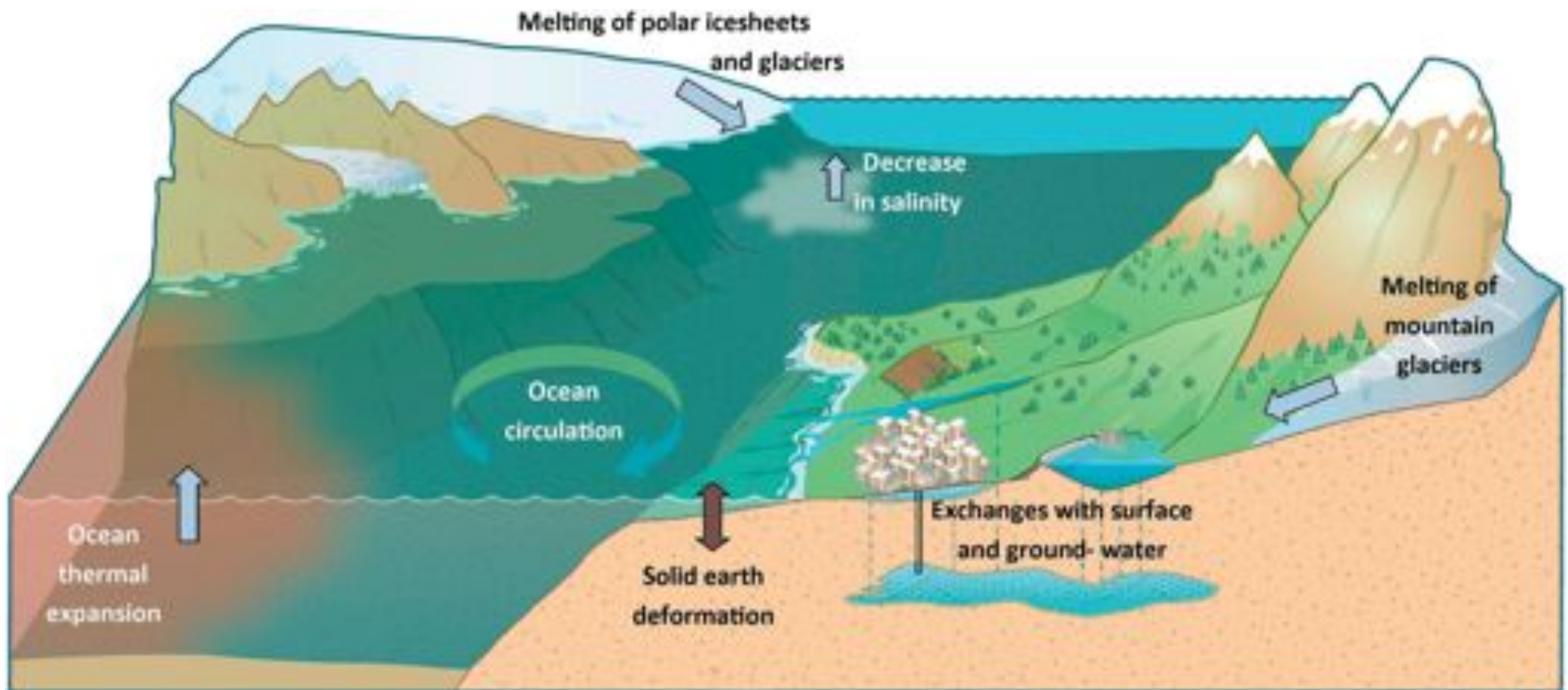
Can we close the sea level budget?

At least for the last 2 decades, YES!

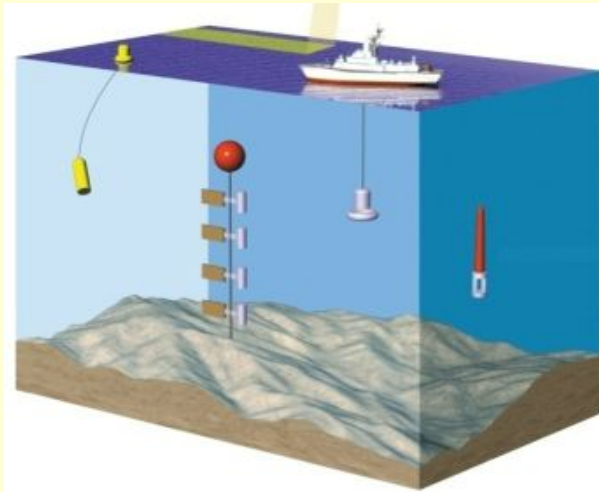


Components of the global mean sea level rise

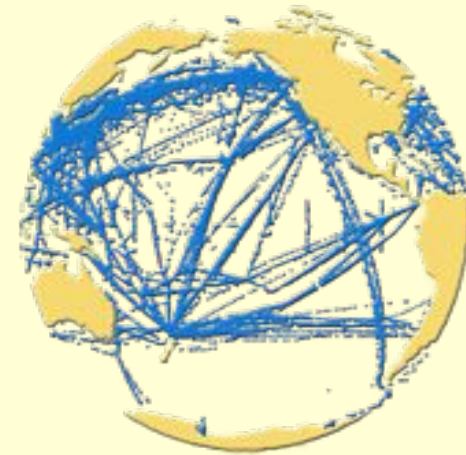
- Ocean warming (thermal expansion)
- Land ice melt
- Exchange of water with continental reservoirs



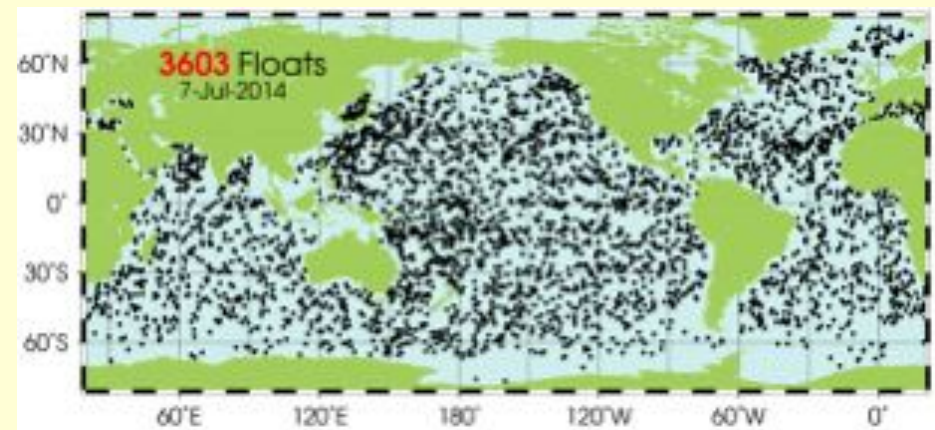
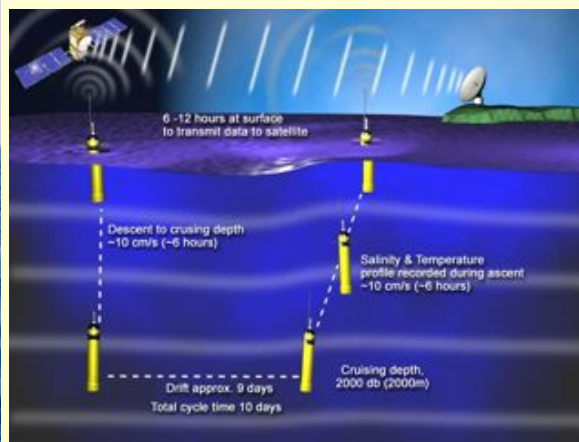
Ocean temperature measurements (XBT, Argo)



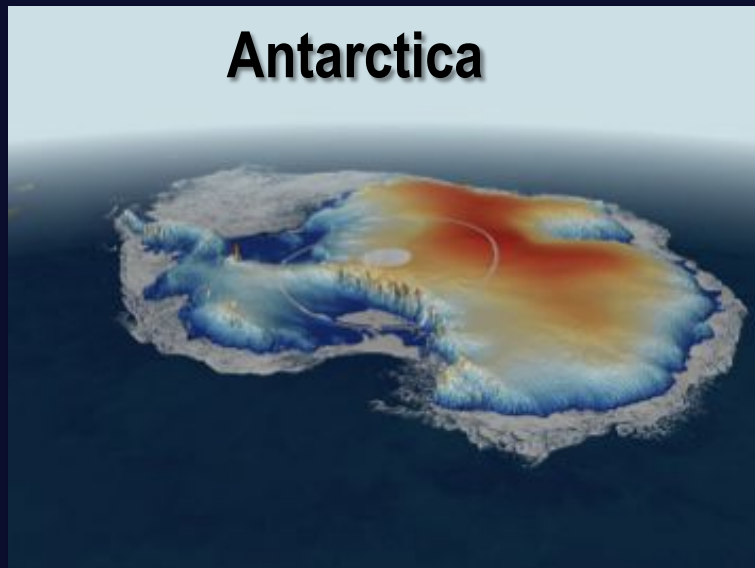
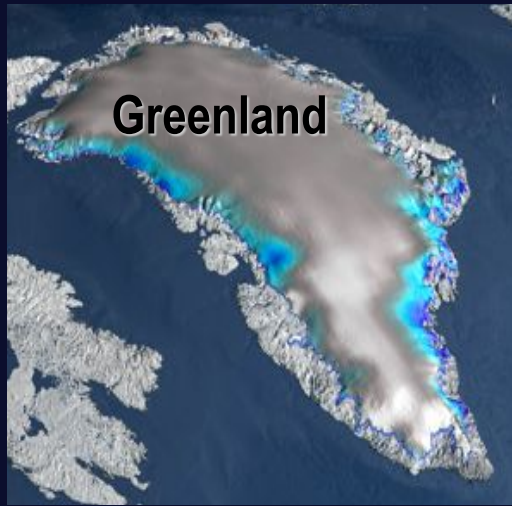
Past few decades:
coverage mainly
along trade roads



Since about 2003 → 'Argo' profiling floats

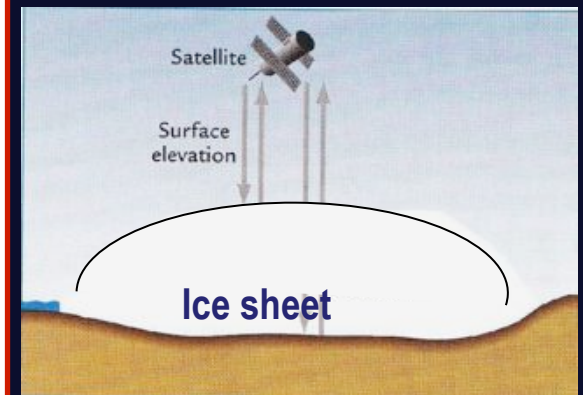
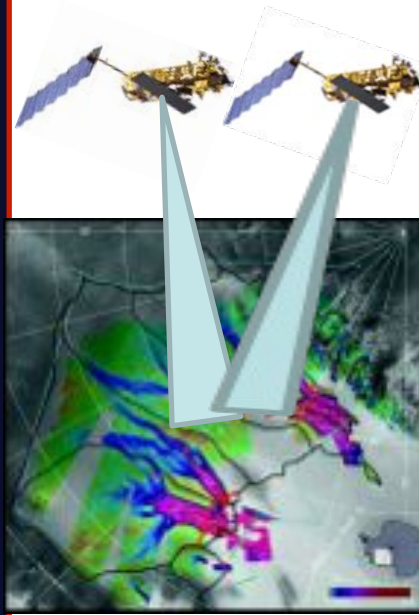


Since the early 1990s, ice sheet mass change measured from space



« GRACE »
space gravimetry

Radar Interferometry



Radar & laser altimetry

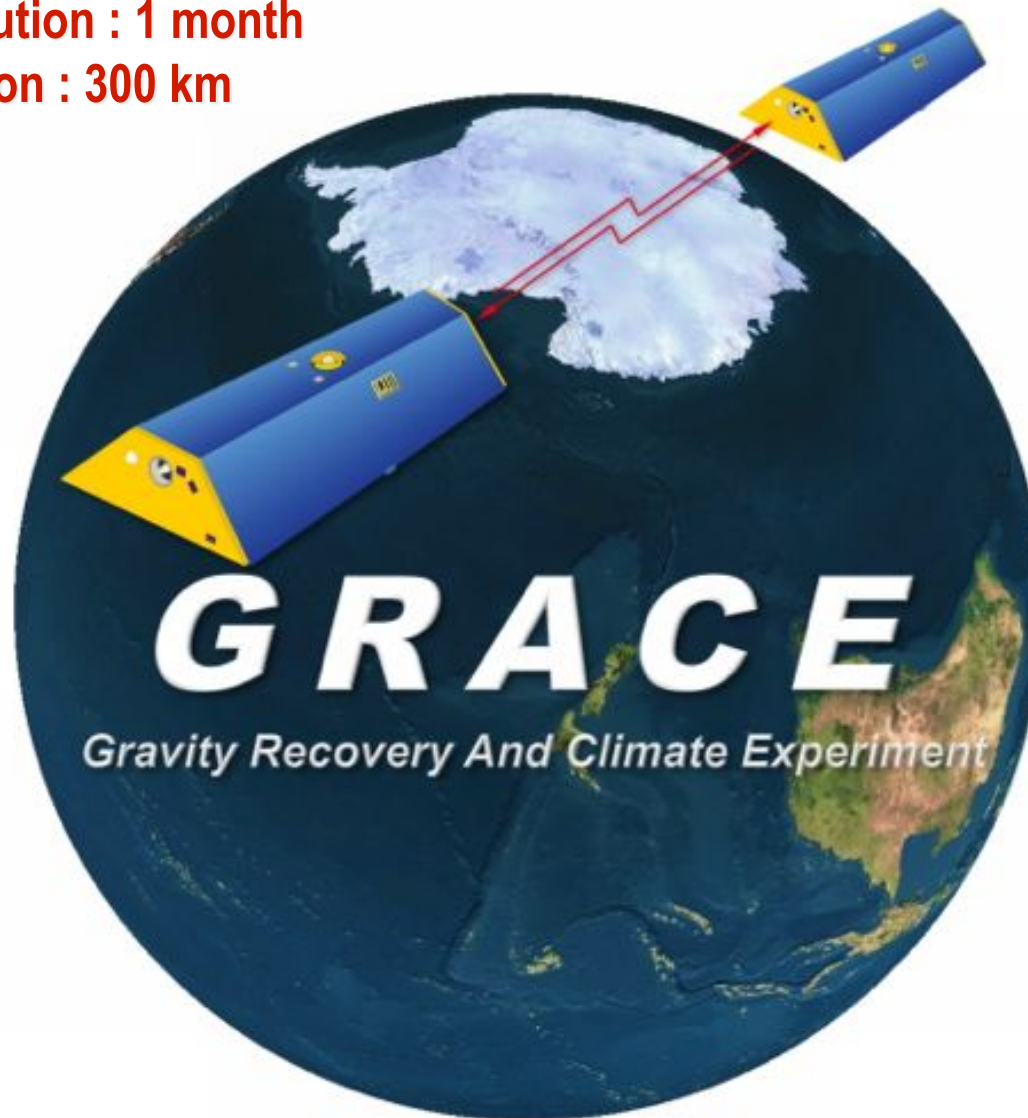
GRACE space gravimetry mission (launched in 2002)

Measurement of temporal variations of the Earth's gravity field

→ mass redistribution at the surface of (and within) the Earth

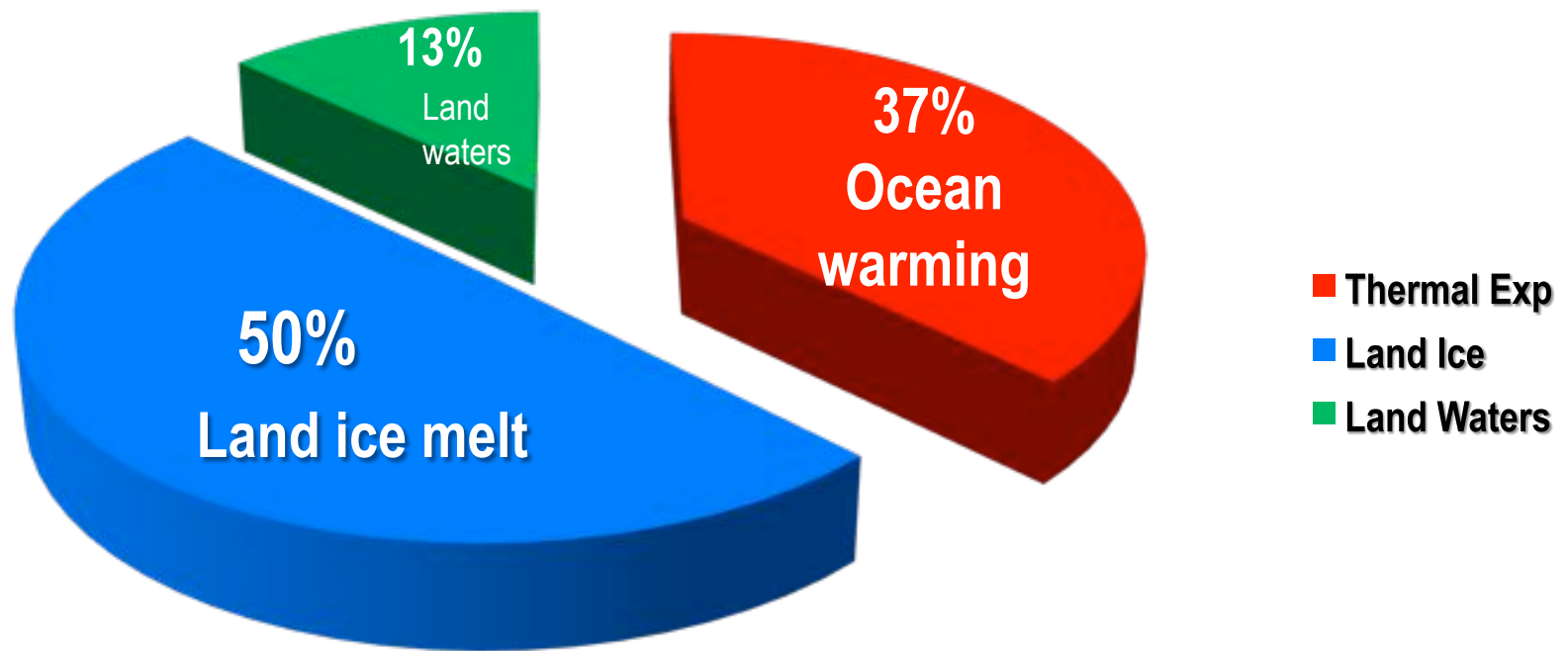
- Temporal resolution : 1 month

- Spatial resolution : 300 km

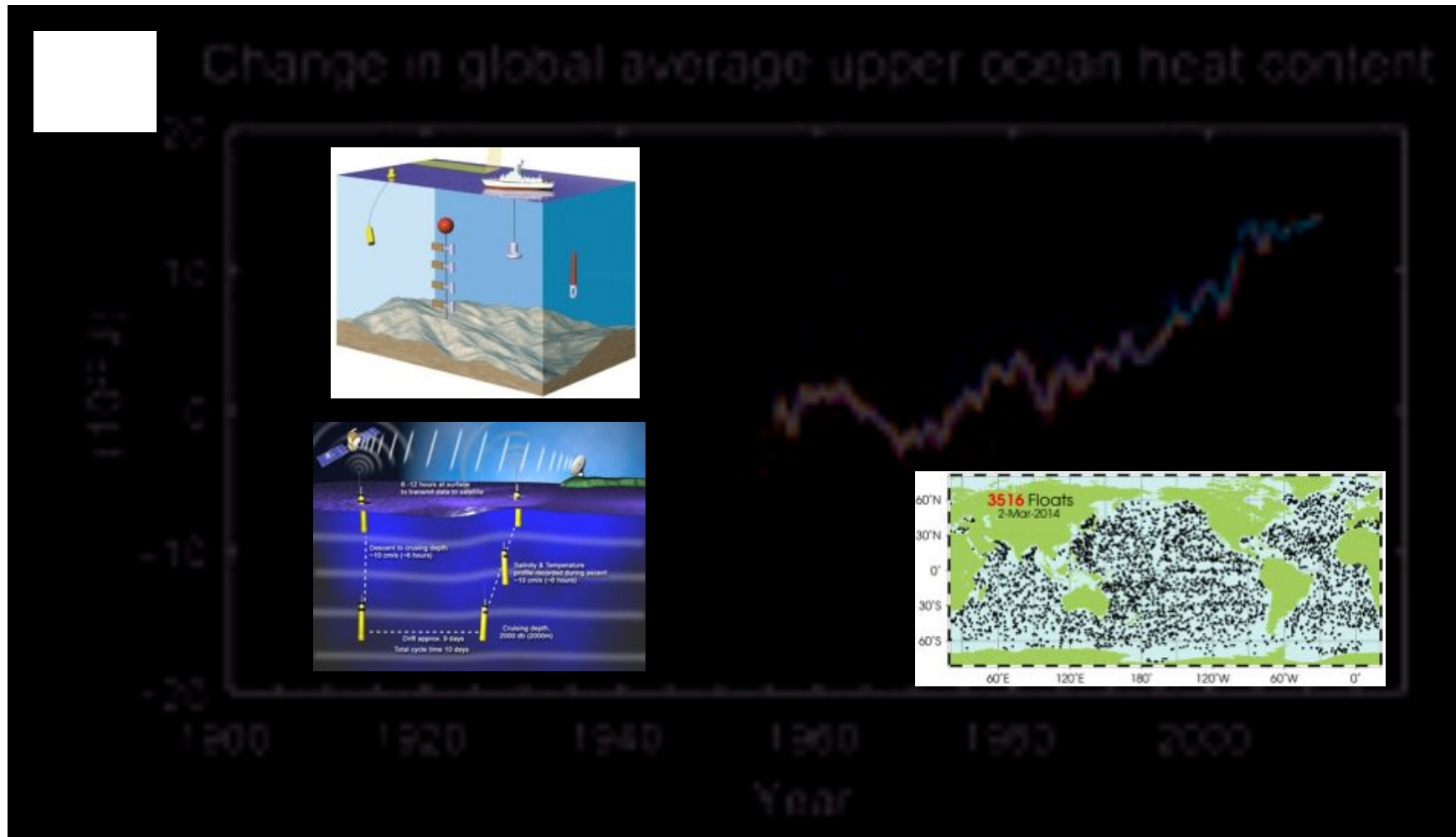


Causes of sea level rise (altimetry era: last 2 decades)

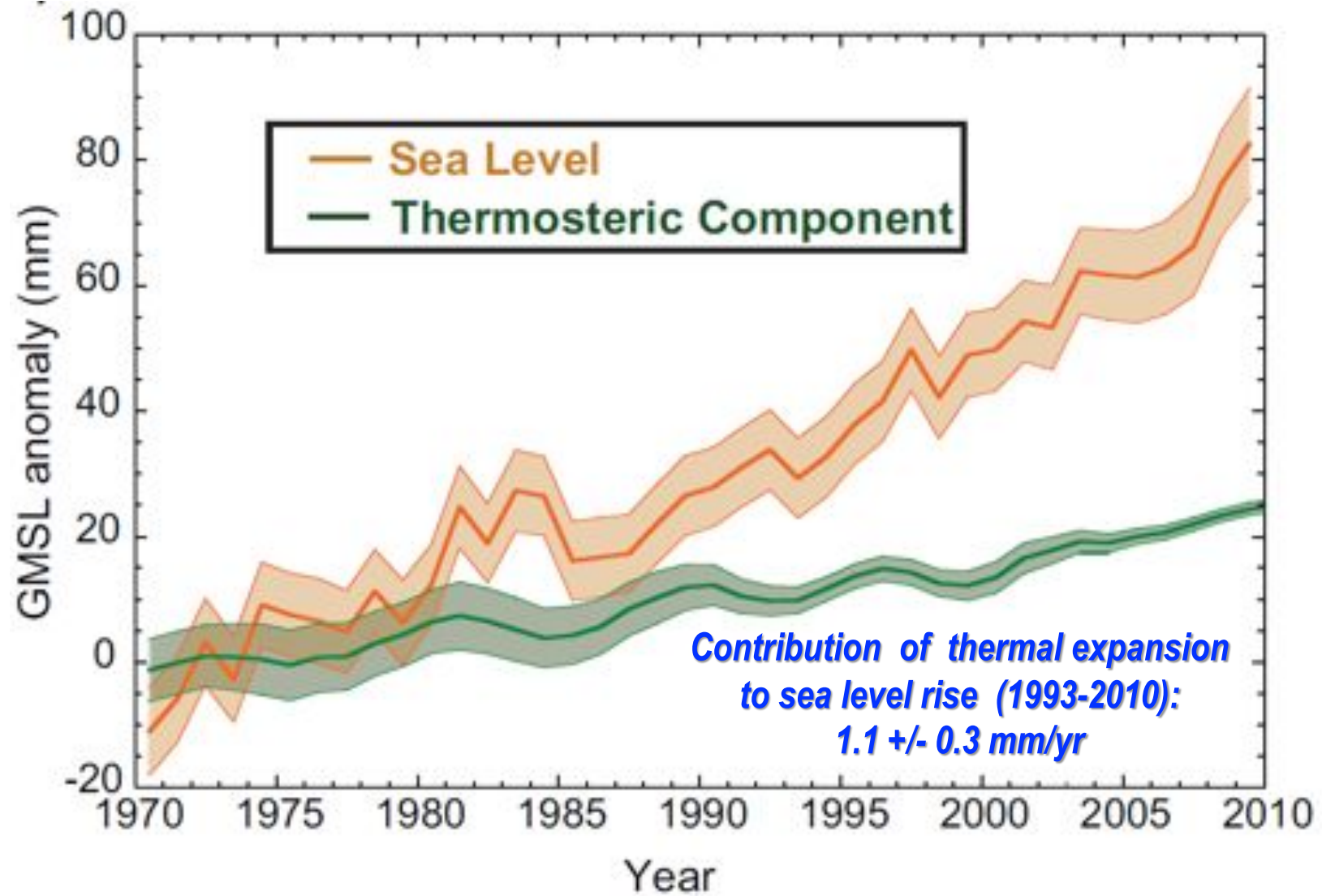
Individual contributions (in % of the observed rate of rise)



The ocean is warming



Thermosteric contribution to sea level rise

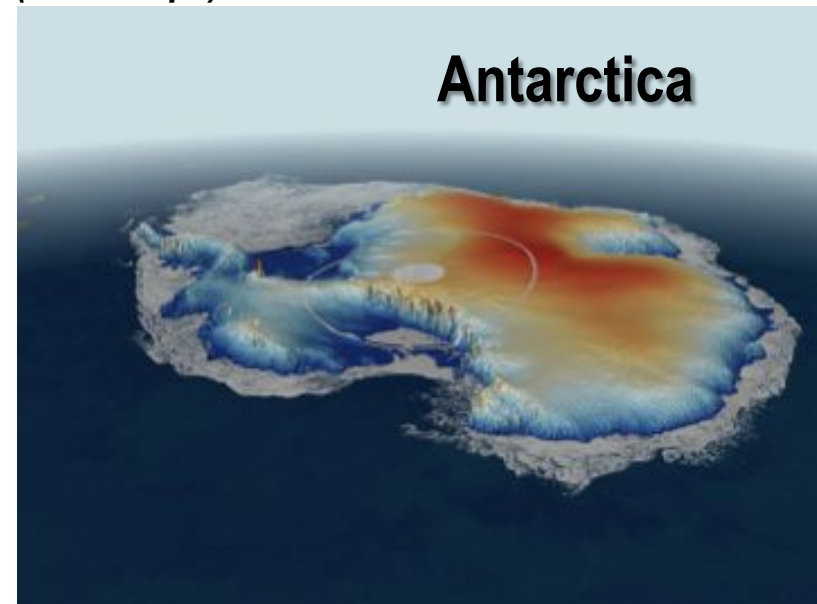
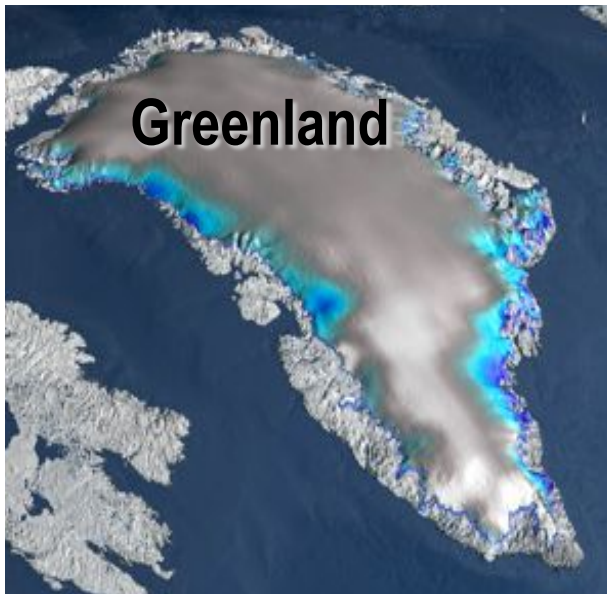


IPCC AR5

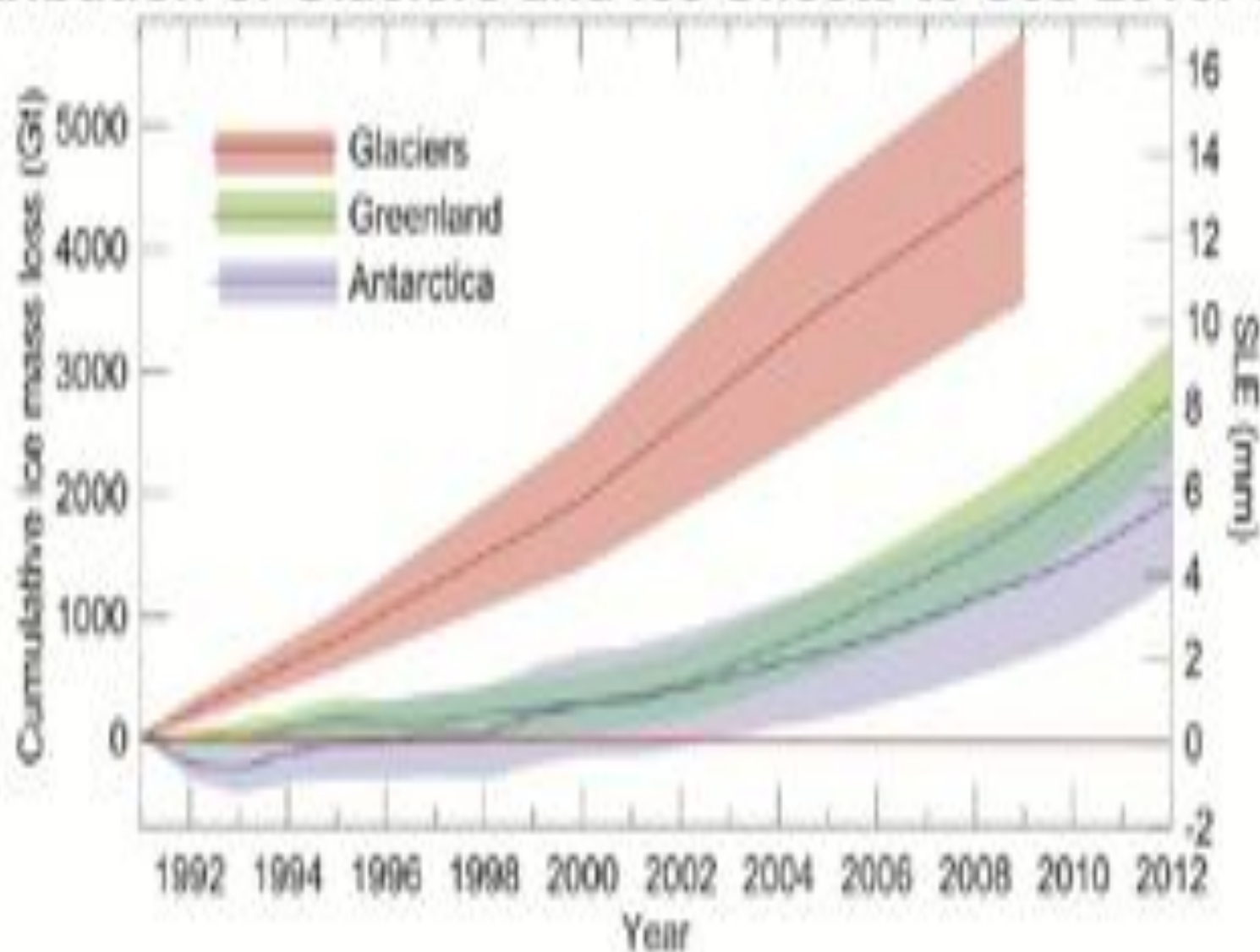
Land ice contribution to sea level rise



Rhone Glacier (Swiss Alps)

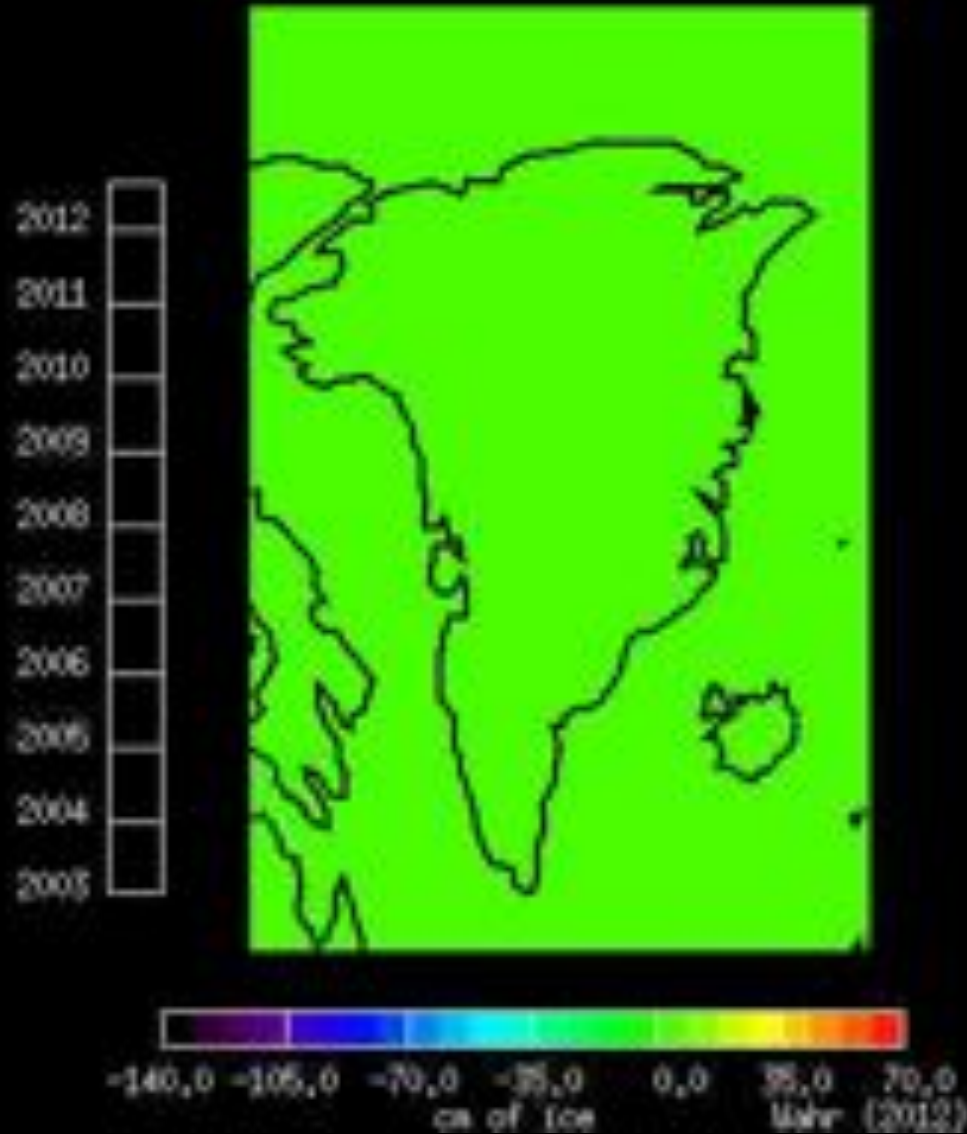


Contribution of Glaciers and Ice Sheets to Sea Level Change



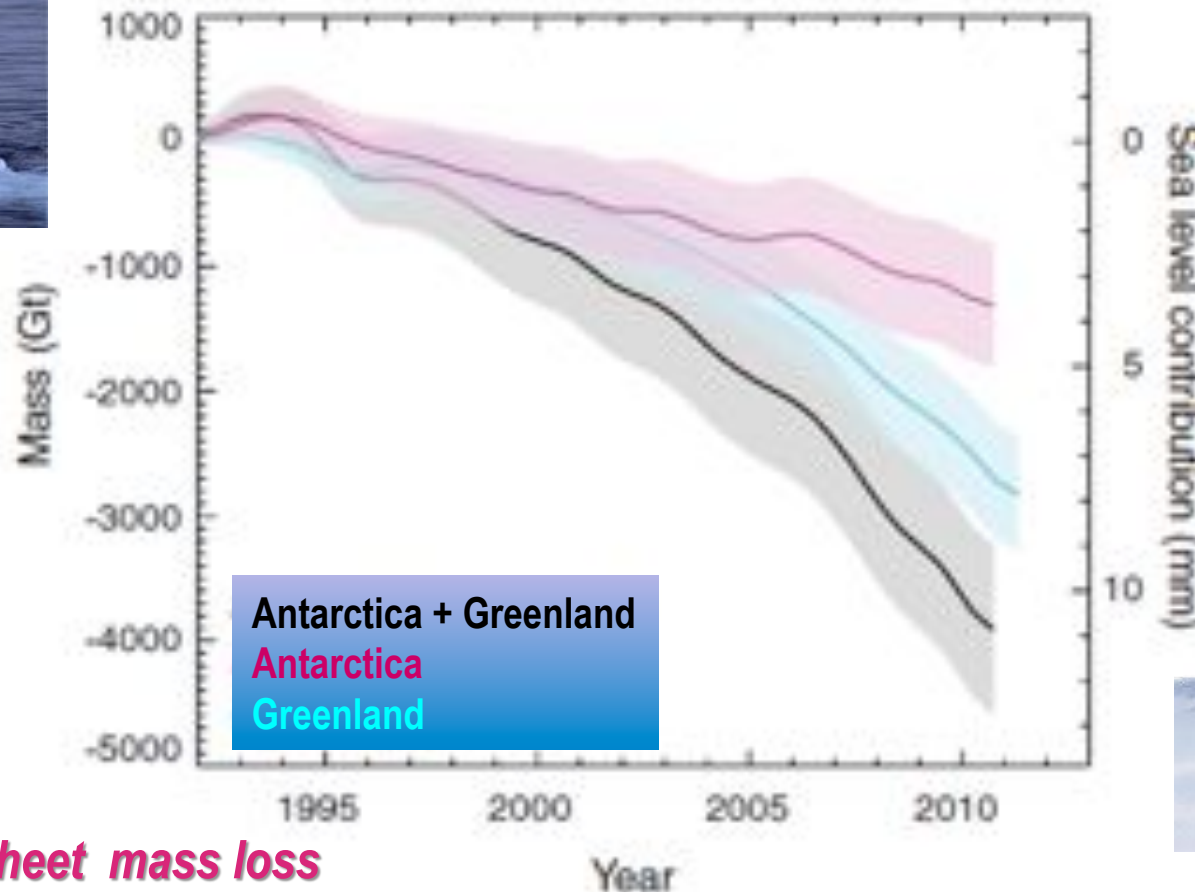
Cumulative ice mass loss from glacier and ice sheets (in sea level equivalent) is 1.0 to 1.4 mm/yr for 1993-2009 and 1.2 to 2.2 mm/yr for 2005-2009.

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



Source: J. Wahr

**Ice mass loss from Greenland and Antarctica
measured by space techniques
since 1990 (in Gt) → mass loss acceleration since 10-15 years**



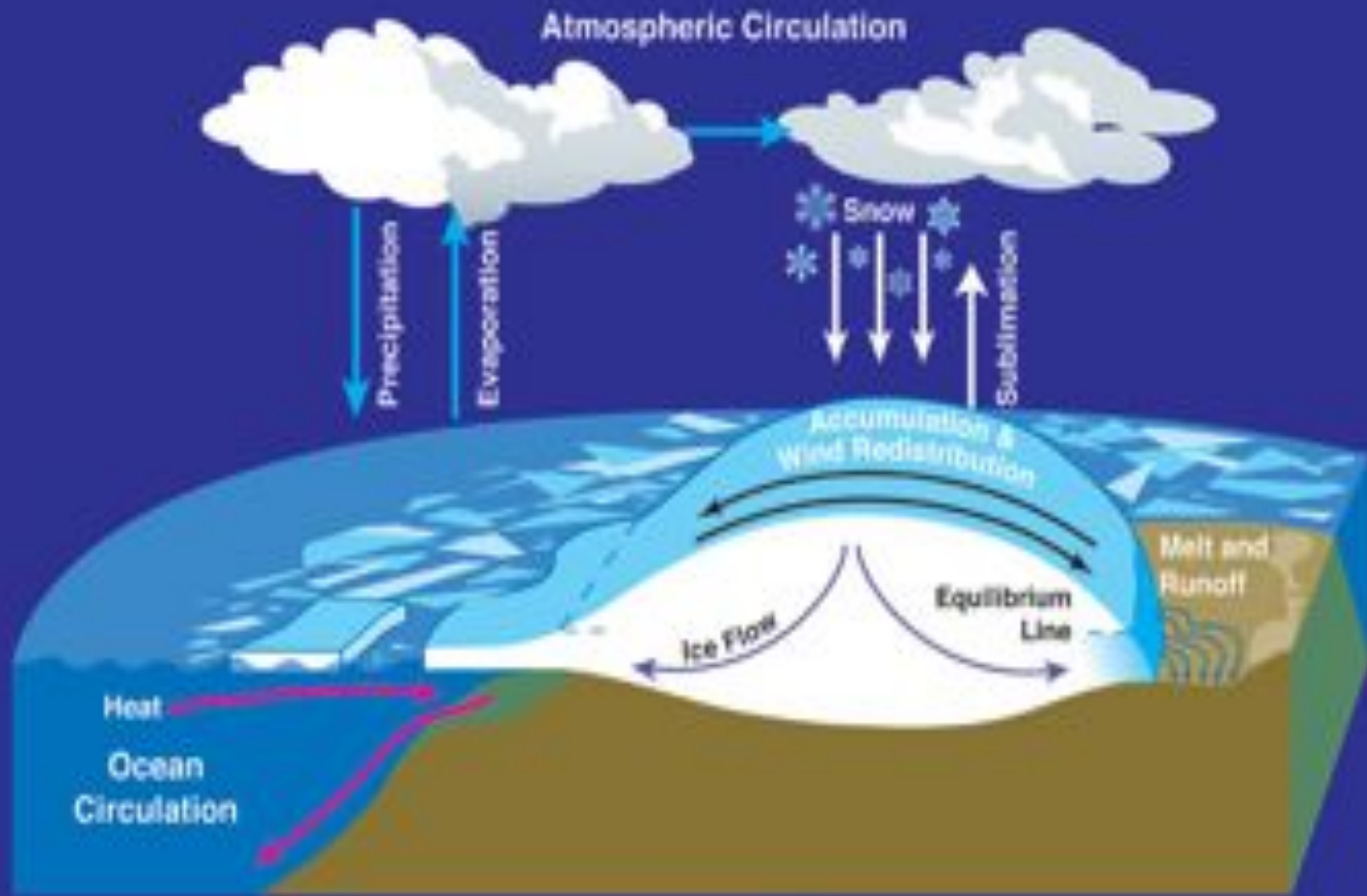
Rate of ice sheet mass loss

Greenland : 34 +/- 40 Gt/yr (1992-2001); 215 (+/- 60) Gt/yr (2002-2011)

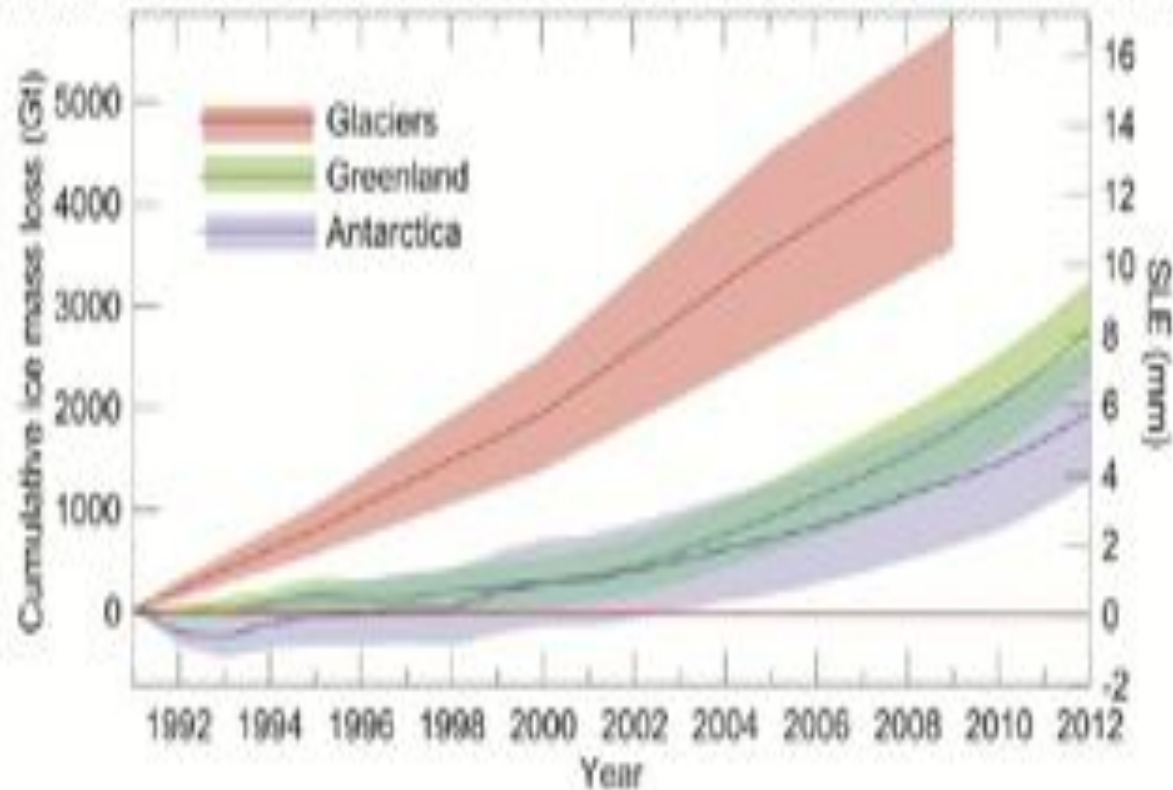
Antarctica : 30 +/- 67 Gt/yr (1992-2001); 147 (+/- 74) Gt/yr (2002-2011)

Shepherd et al., 2012
IPCC AR5

Ice sheet mass balance =
surface mass balance (accumulation/ablation)
+ ice loss through calving of icebergs (dynamical change)



Contribution of Glaciers and Ice Sheets to Sea Level Change



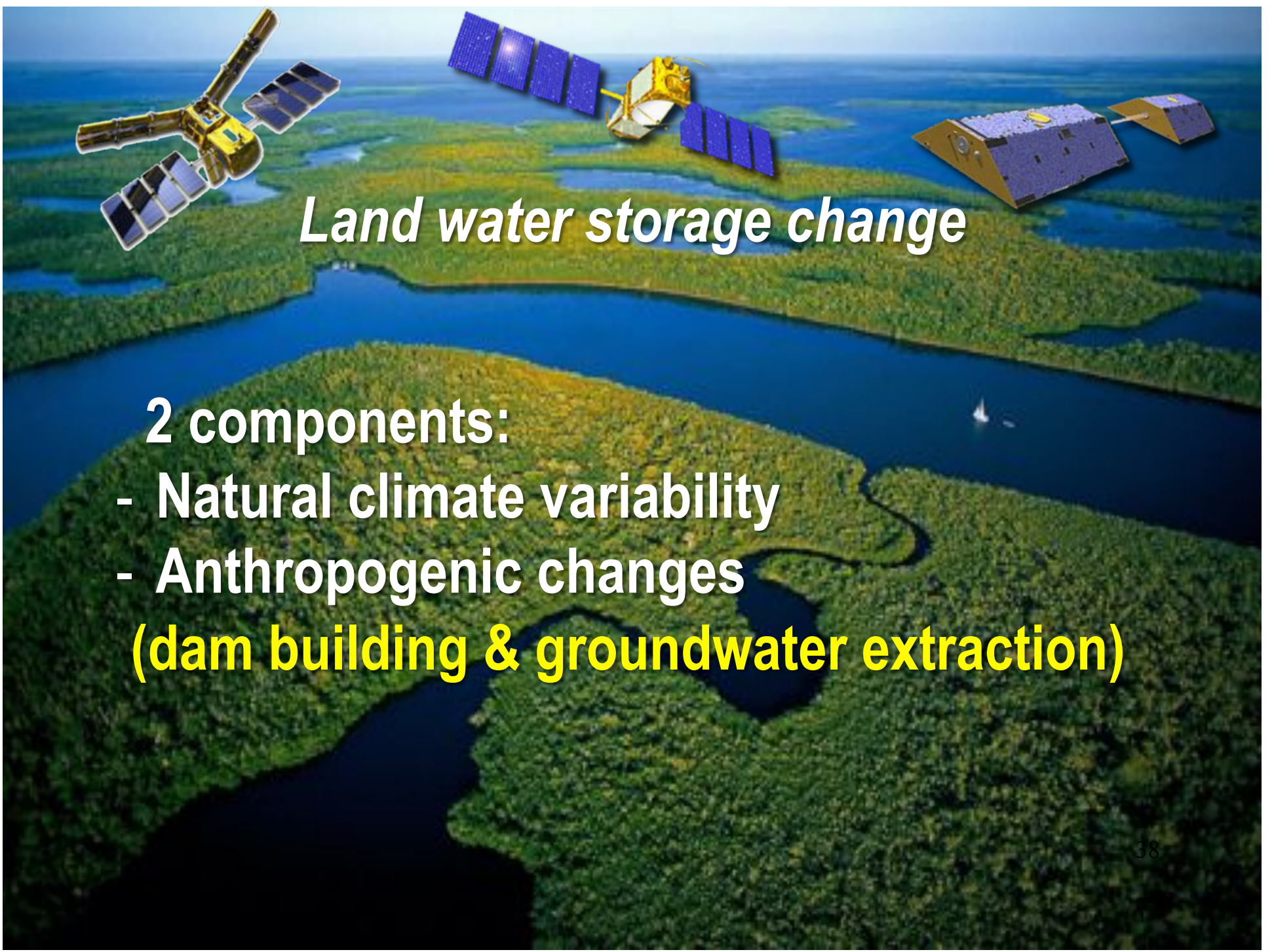
Cumulative ice mass loss from glacier and ice sheets (in sea level equivalent) is



1.0 to 1.4 mm/yr for 1993-2009 and 1.2 to 2.2 mm/yr for 2005-2009.

Ice sheet contribution (1993-2010) : 0.6 +/- 0.2 mm/yr

IPCC AR5

The background of the slide is a composite image. It features three satellites in orbit above a lush green landscape with a winding river. The satellites are depicted with gold-colored bodies and large blue solar panel arrays. The landscape below is a dense green forest with a prominent blue river that meanders through it. The sky is a clear, light blue.

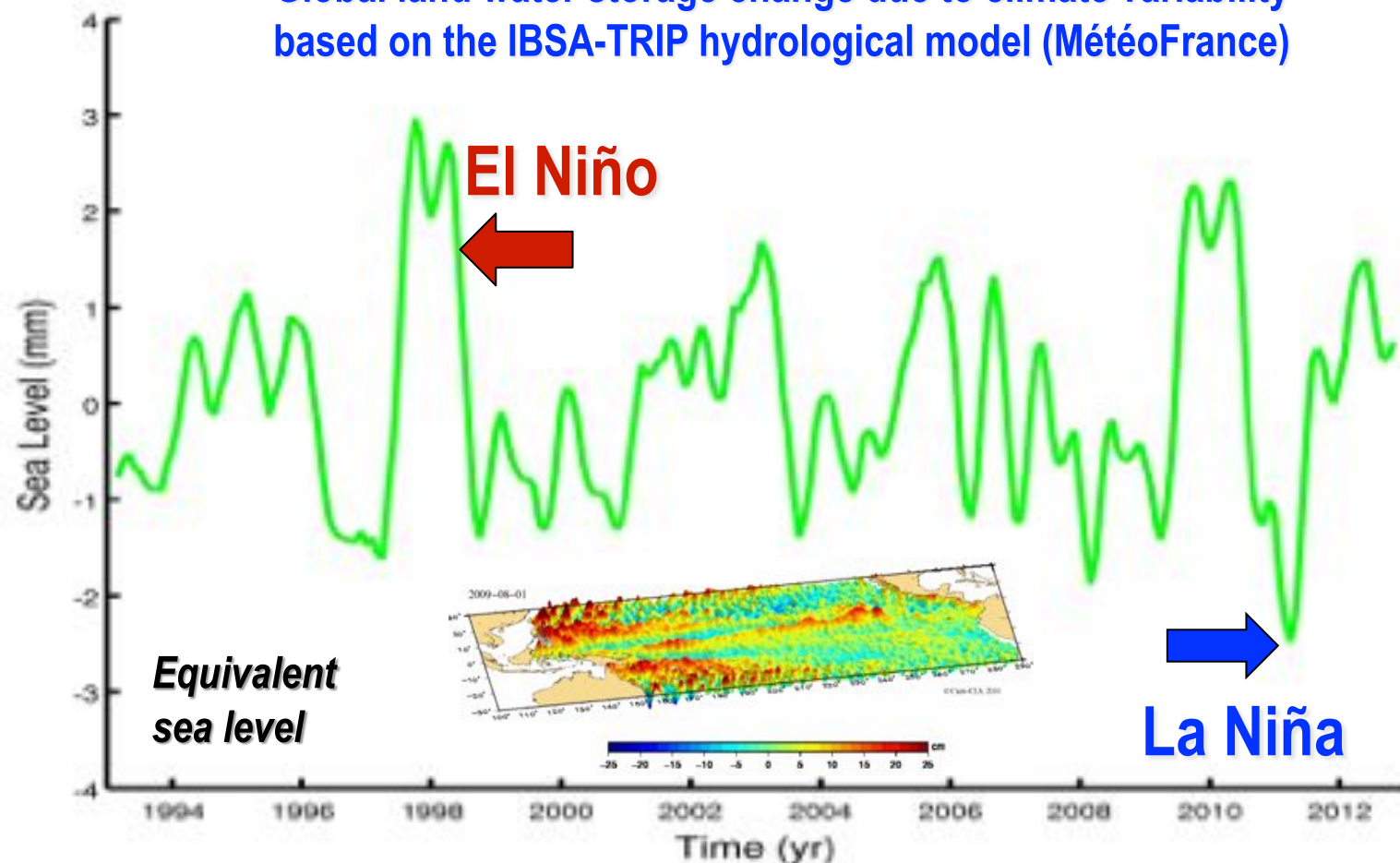
Land water storage change

2 components:

- Natural climate variability
- Anthropogenic changes
(dam building & groundwater extraction)

Land water storage change due to natural sources

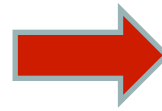
Global land water storage change due to climate variability
based on the IBSA-TRIP hydrological model (MétéoFrance)



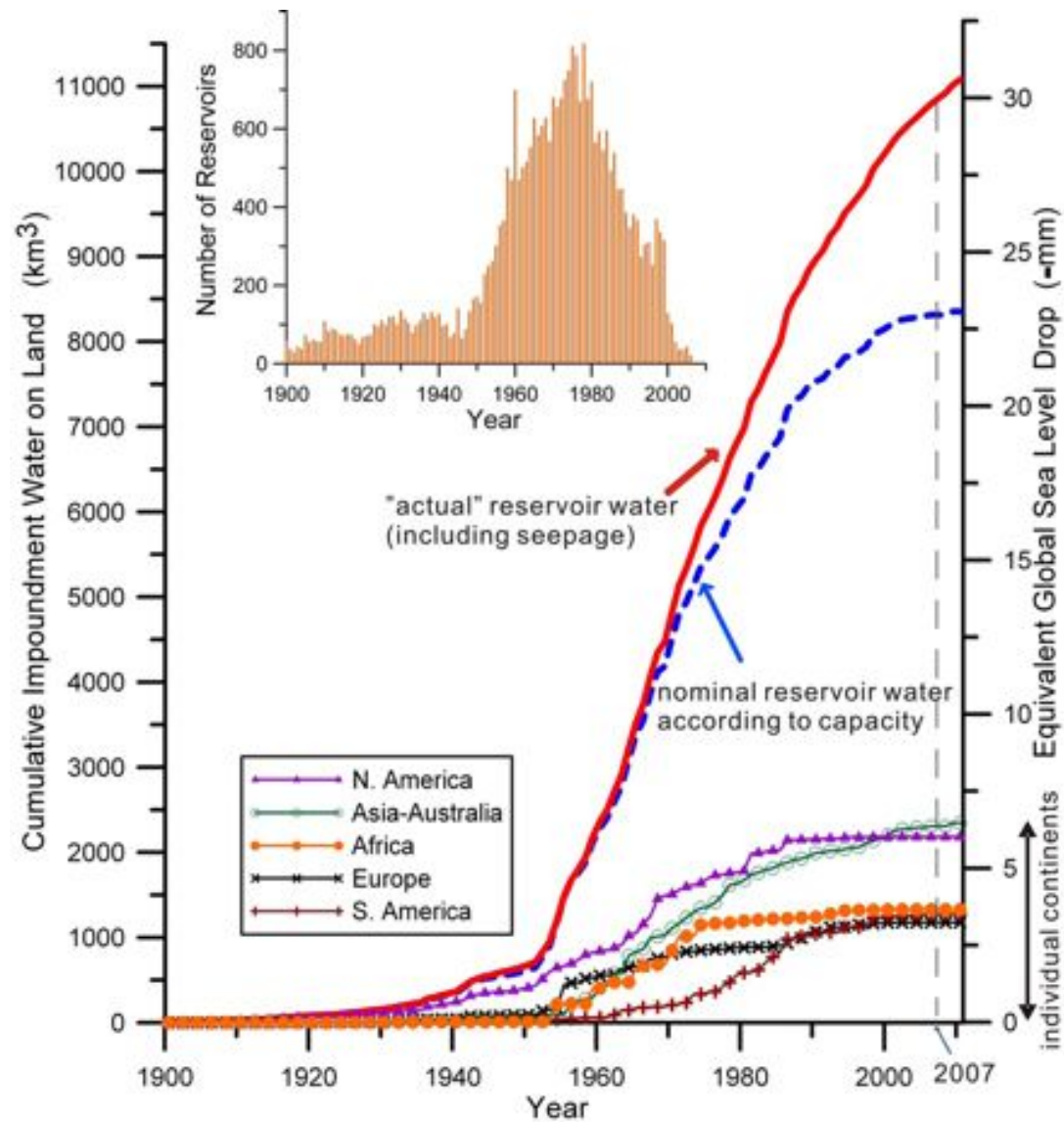
Building of dams on river → sea level drop



Building of dams on rivers



Sea level drop

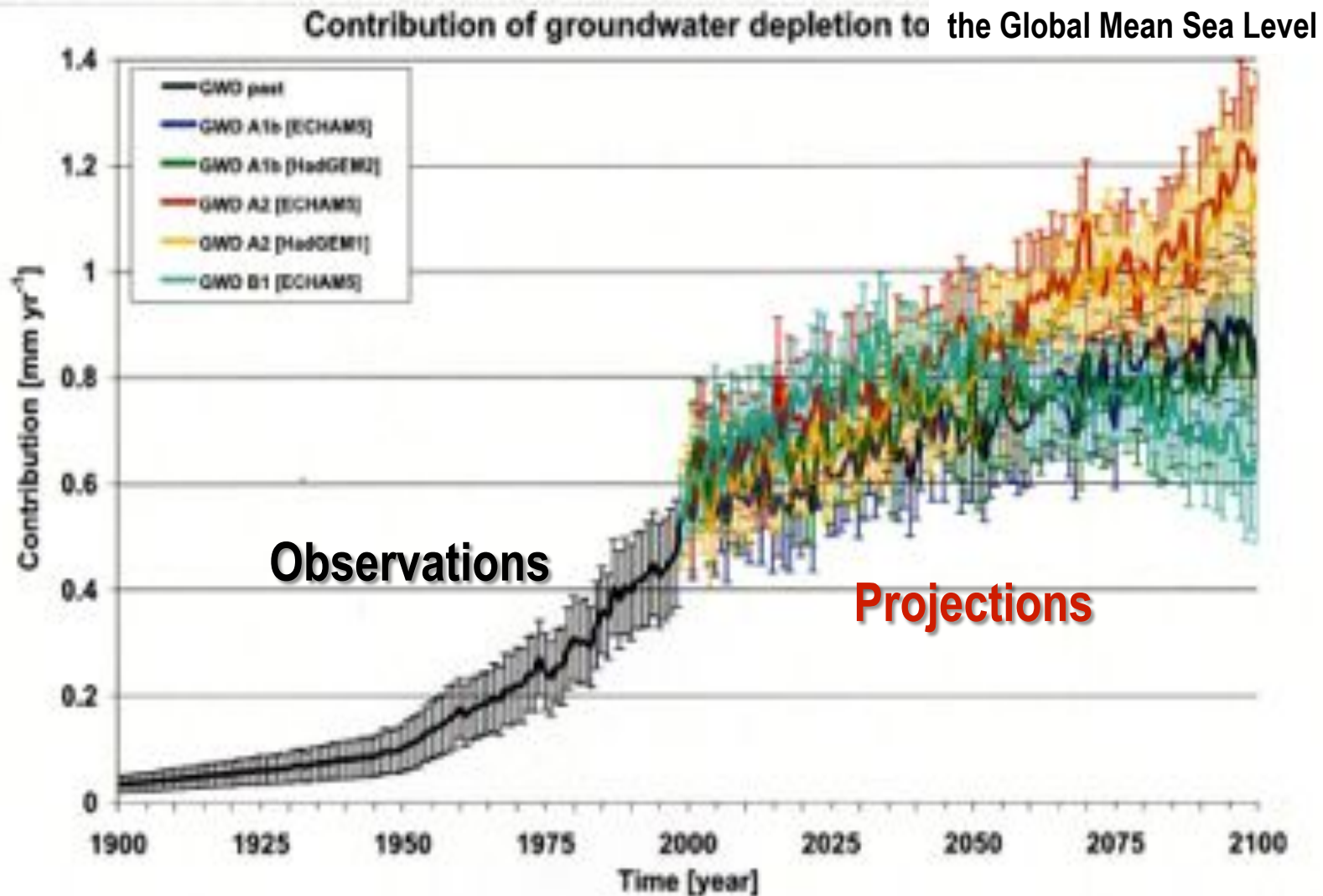


Chao et al., 2008

Ground water depletion



Sea level rise



Wada et al., 2012



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

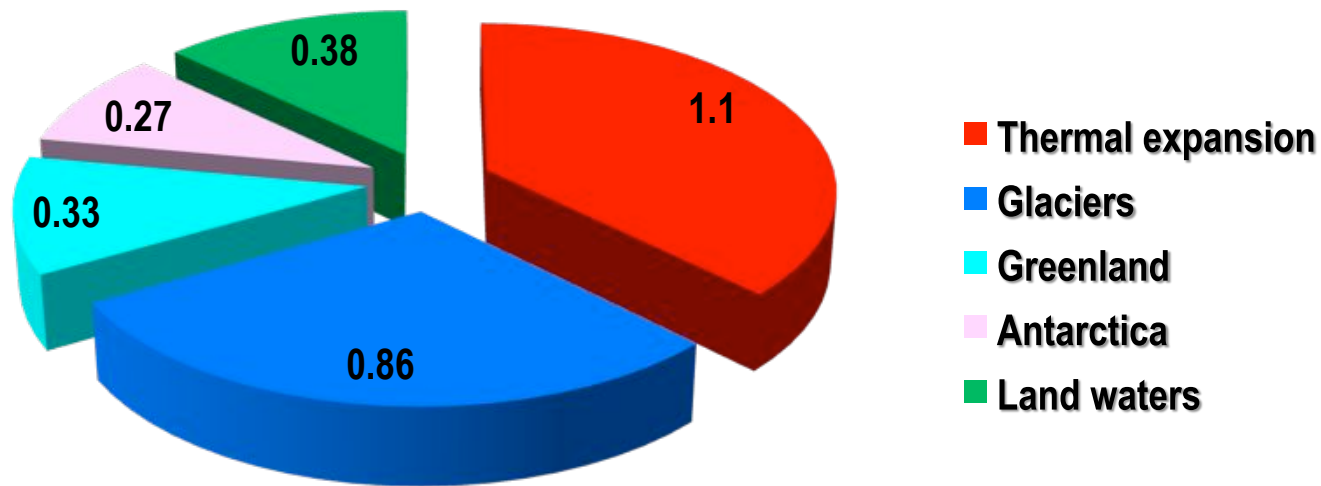
Natural land water storage : 0.08 +/- 0.02 mm/yr

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)

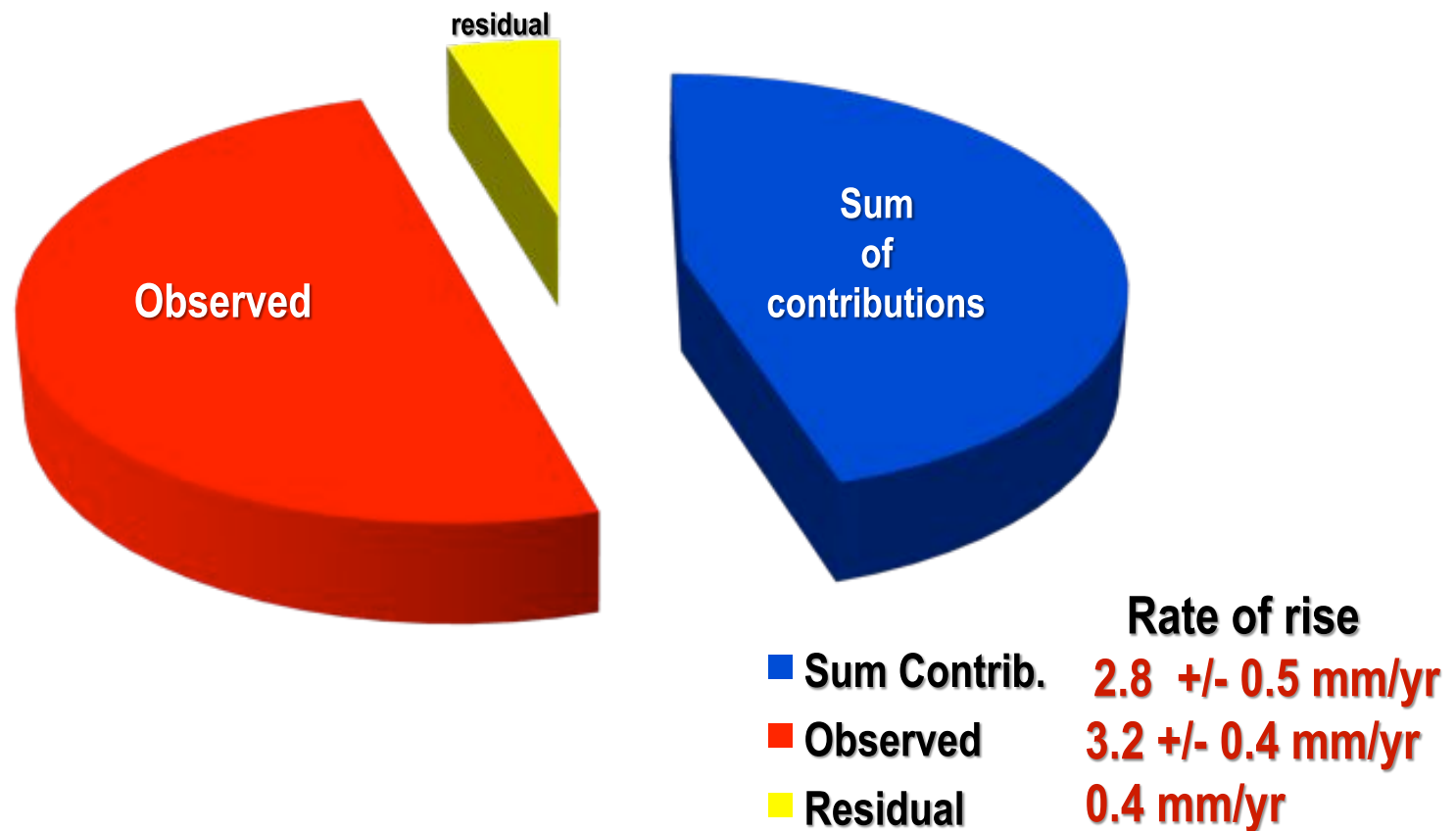
Individual contributions (mm/yr)

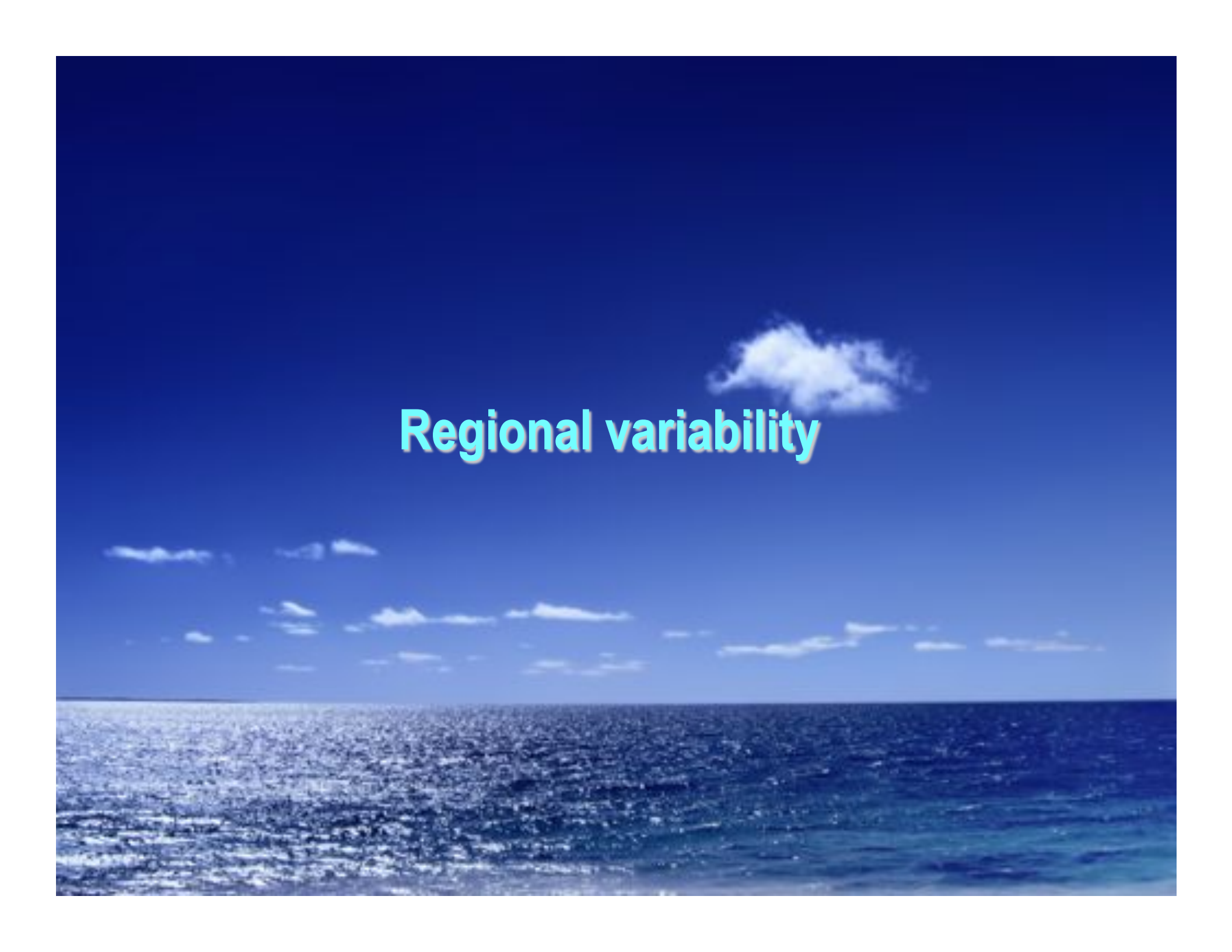


Sum of contributions : 2.8 +/- 0.5 mm/yr

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

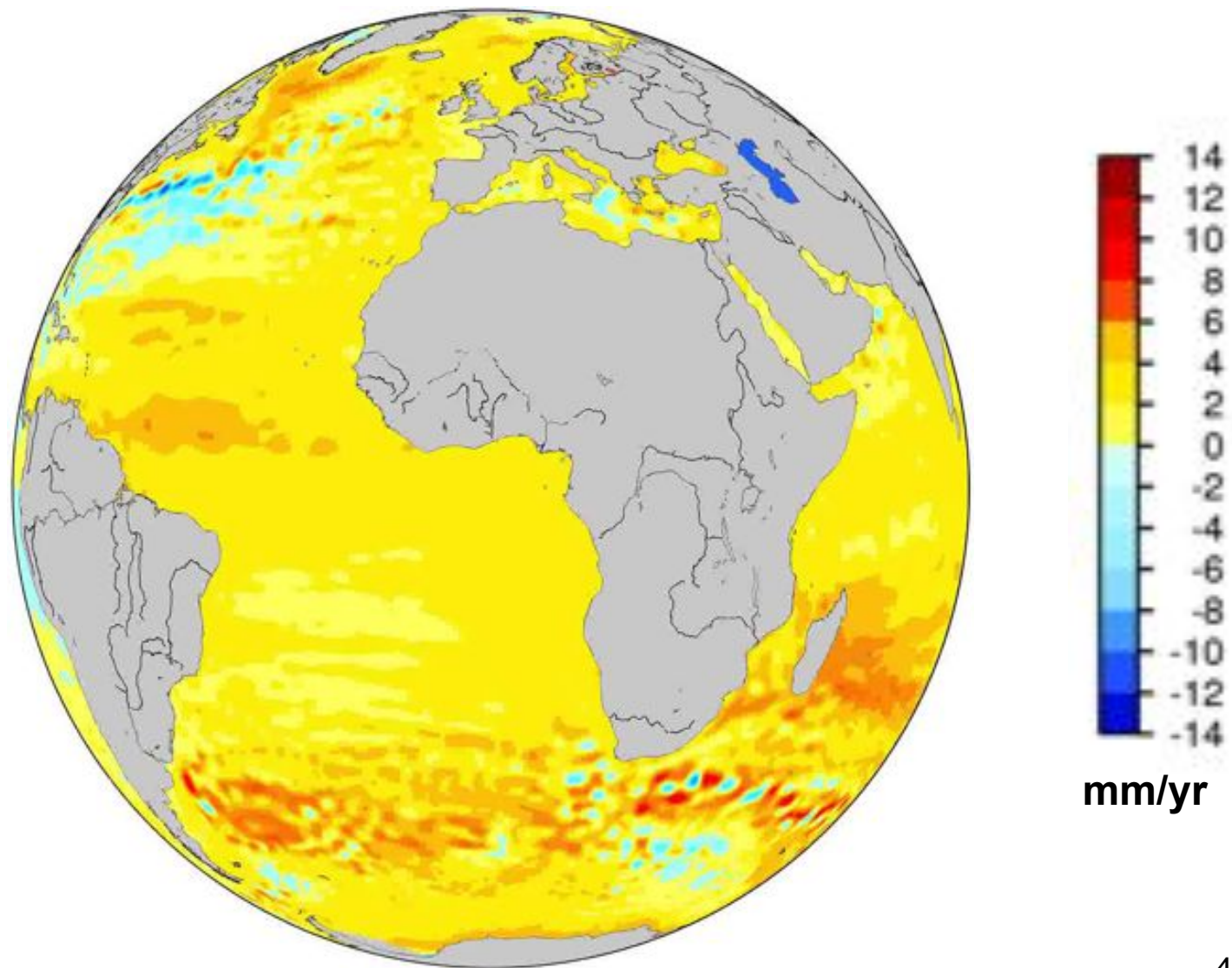
Observed sea level budget during the altimetry era (1993-2010) IPCC AR5





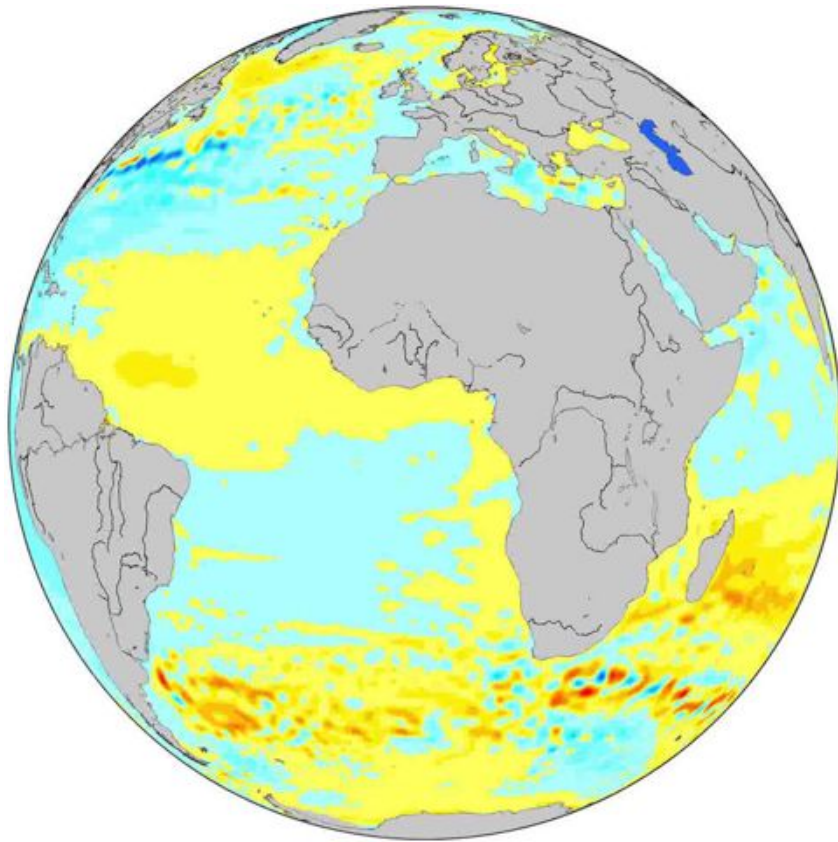
Regional variability

Sea level rise is not uniform!

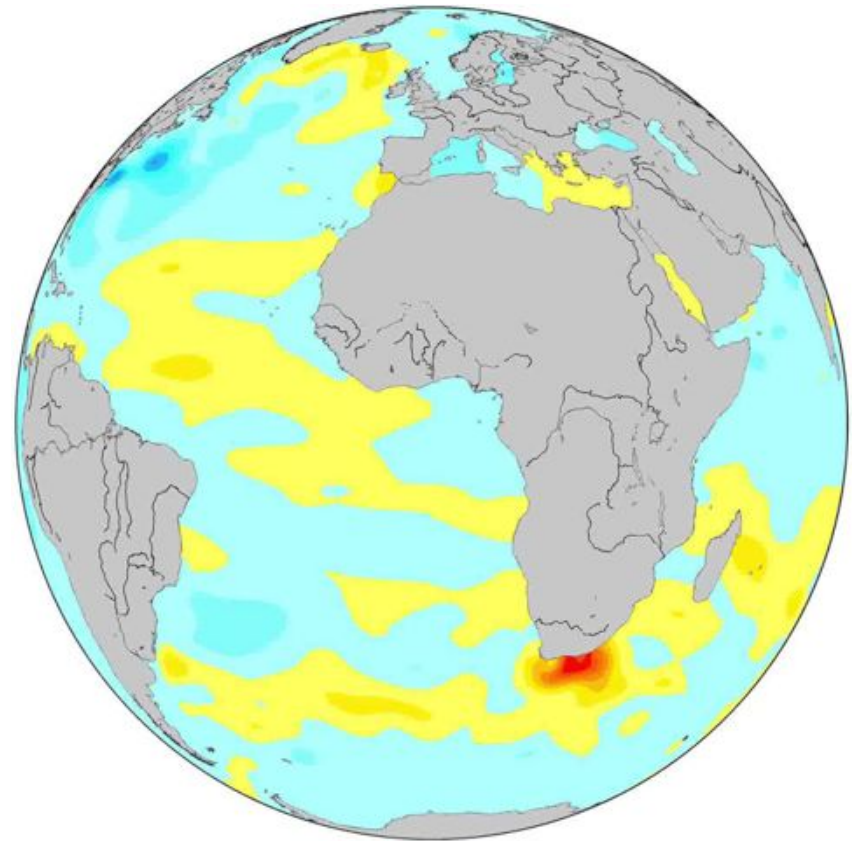


Sea level trend patterns from satellite altimetry (1993-2012)

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



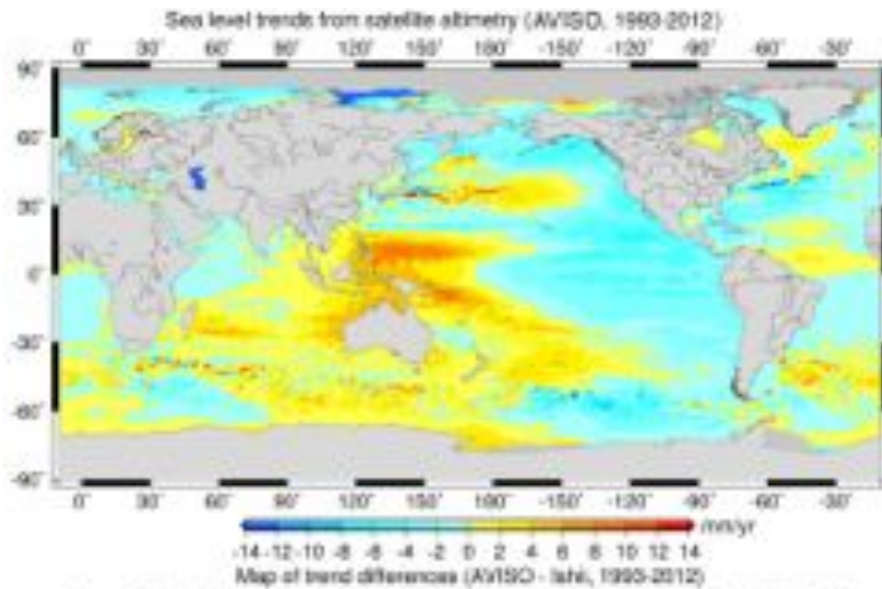
**Observed sea level
by satellite altimetry**



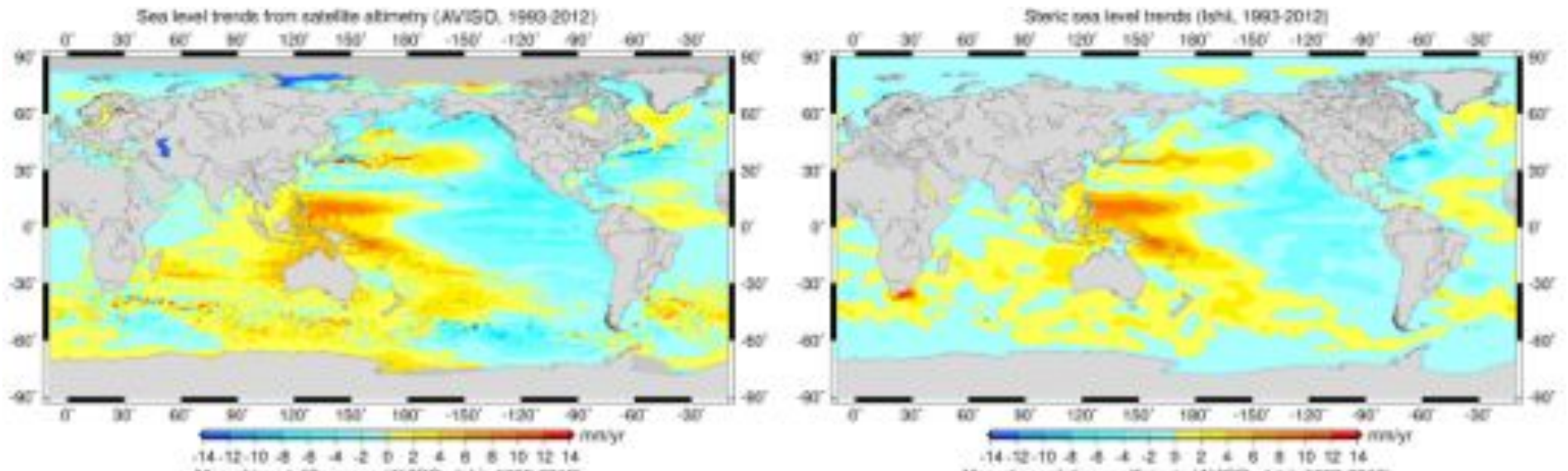
**Observed thermal expansion
+ salinity changes**

Regional variability in sea level trends

Satellite altimetry



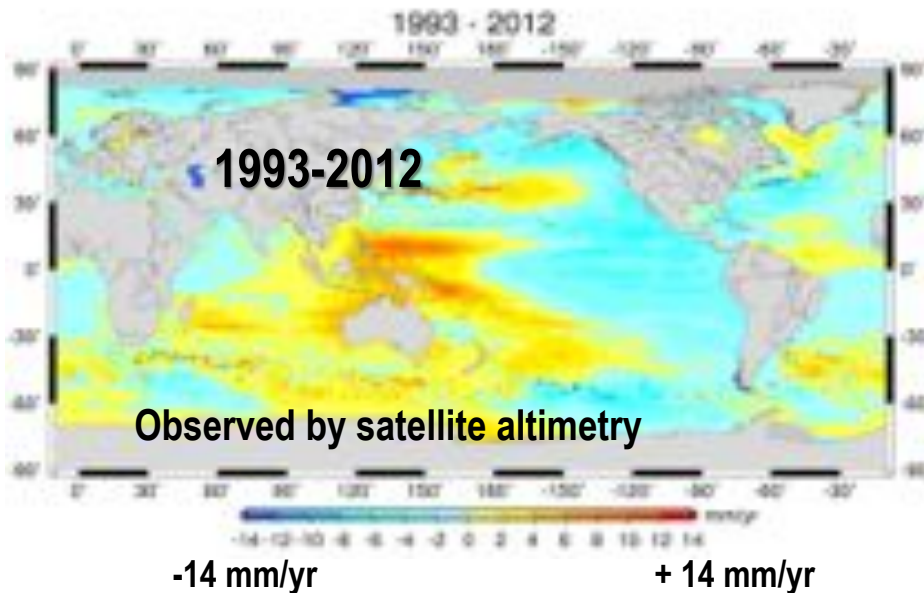
Steric sea level trends



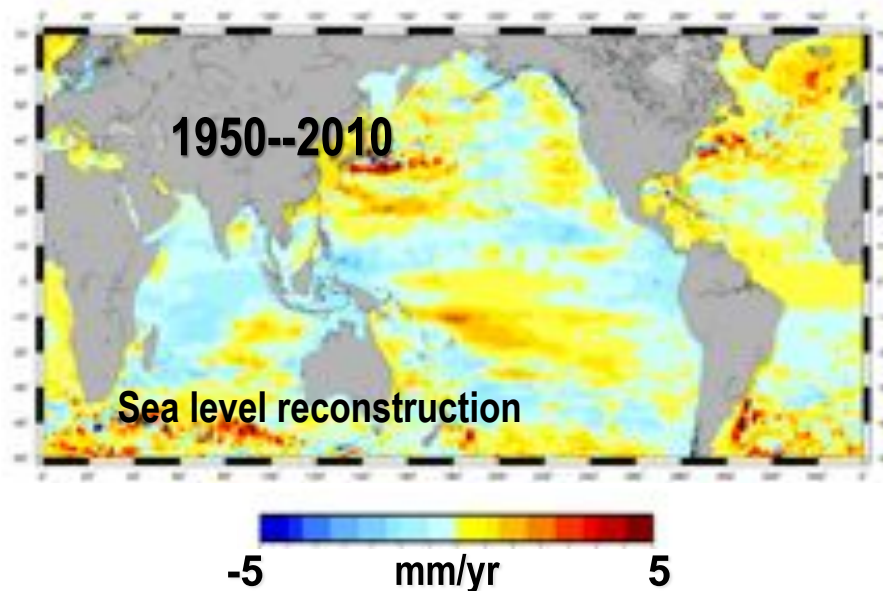
**Spatial patterns
(1993-2012)**

Source: LEGOS

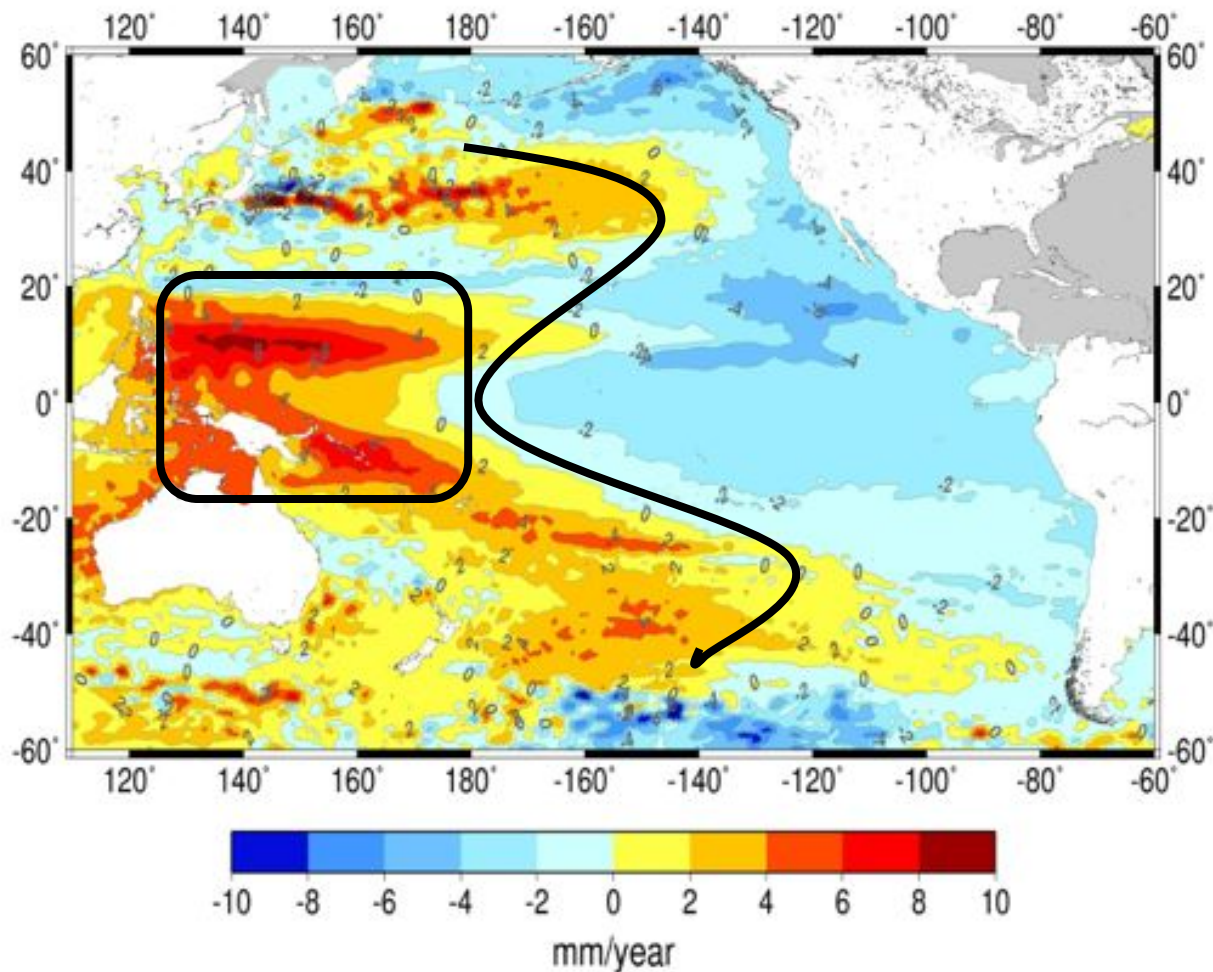
Altimetry-based spatial trend patterns are NOT stationary features



The spatial trend patterns oscillate in space and time in response to natural (internal) climate modes (El Nino-Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation)



Altimetry based sea level trend pattern (global mean removed)



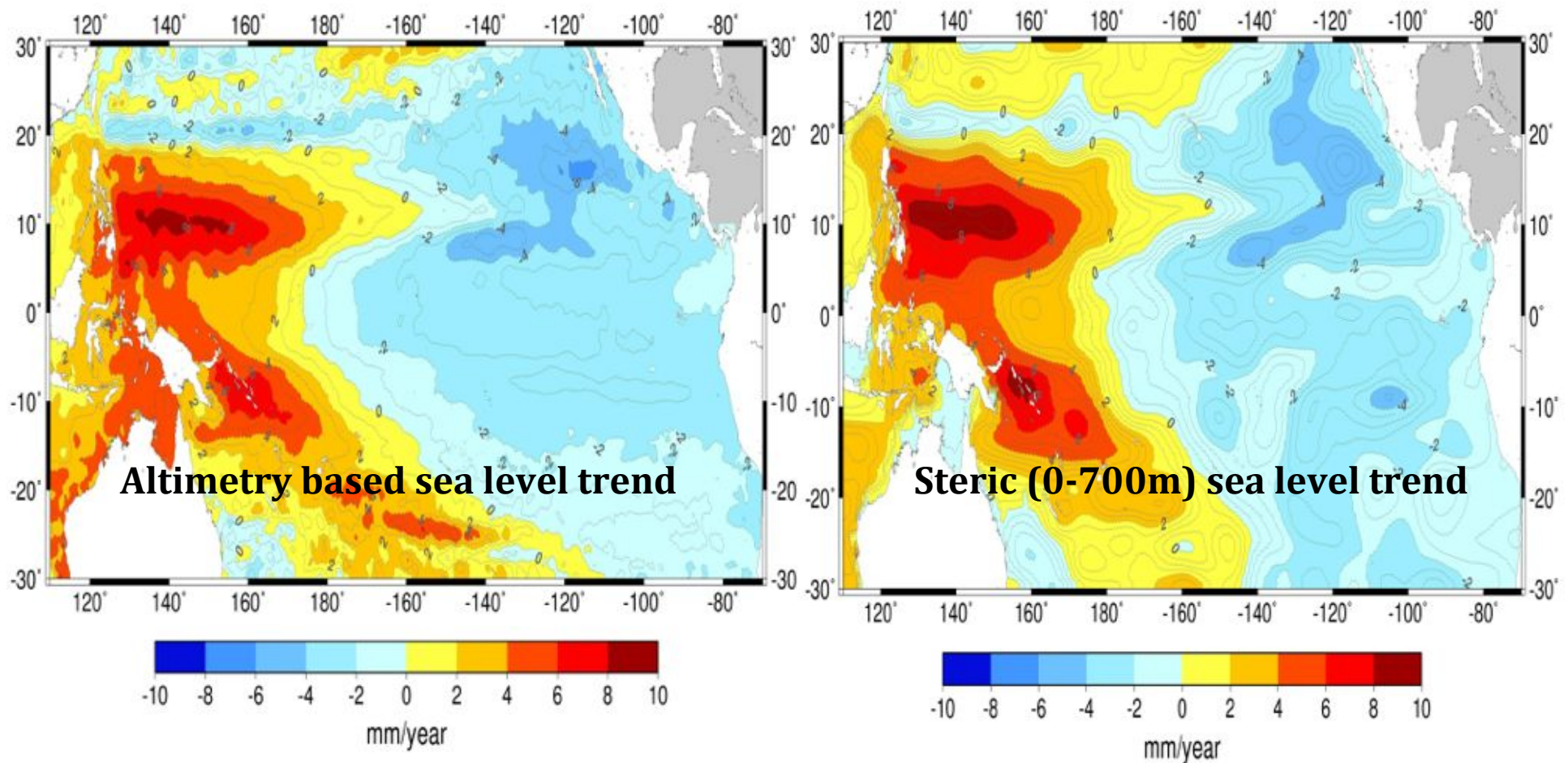
→ *PDO*

- *Zhang and Church, 2012*
- *Han et al., 2013,*
- *Hamlington et al., 2013*
- *England et al., 2014*

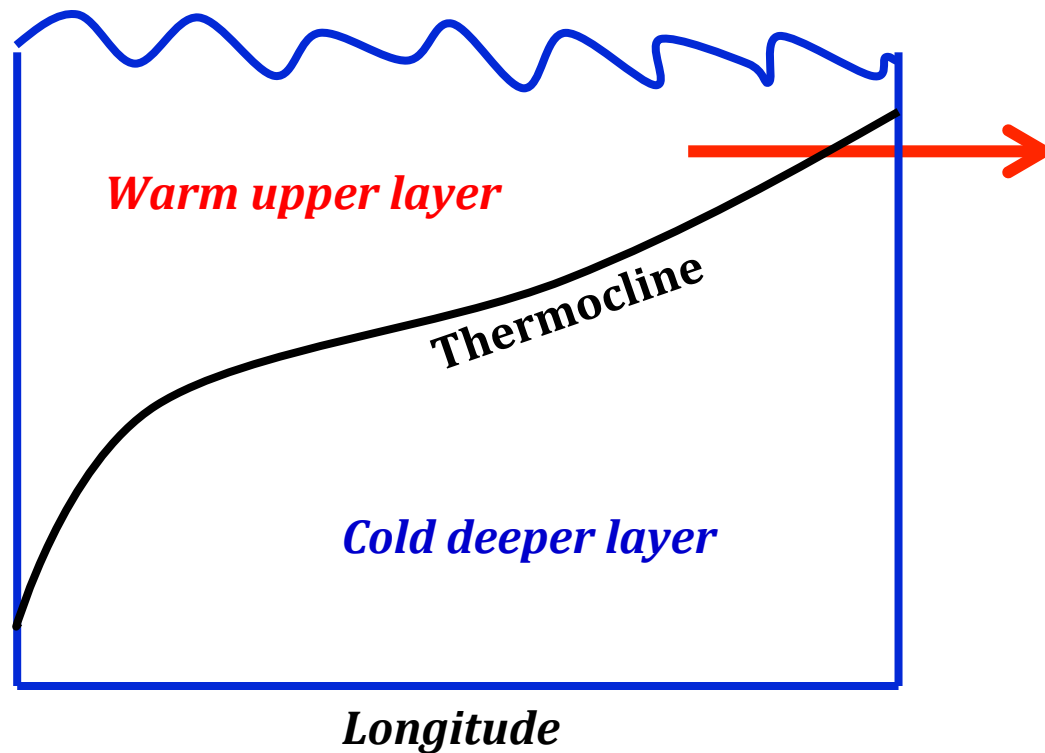
→ *ENSO*

- *Stammer et al., 2013*
- *Timmermann et al., 2010*
- *Merrifield, 2011,2012*
- *McGregor et al., 2012*
- *Nidheesh et al., 2013*

Altimetry based and steric sea level trend 1993-2012



Mechanism causing sea level variations in tropical Pacific : the role of thermocline

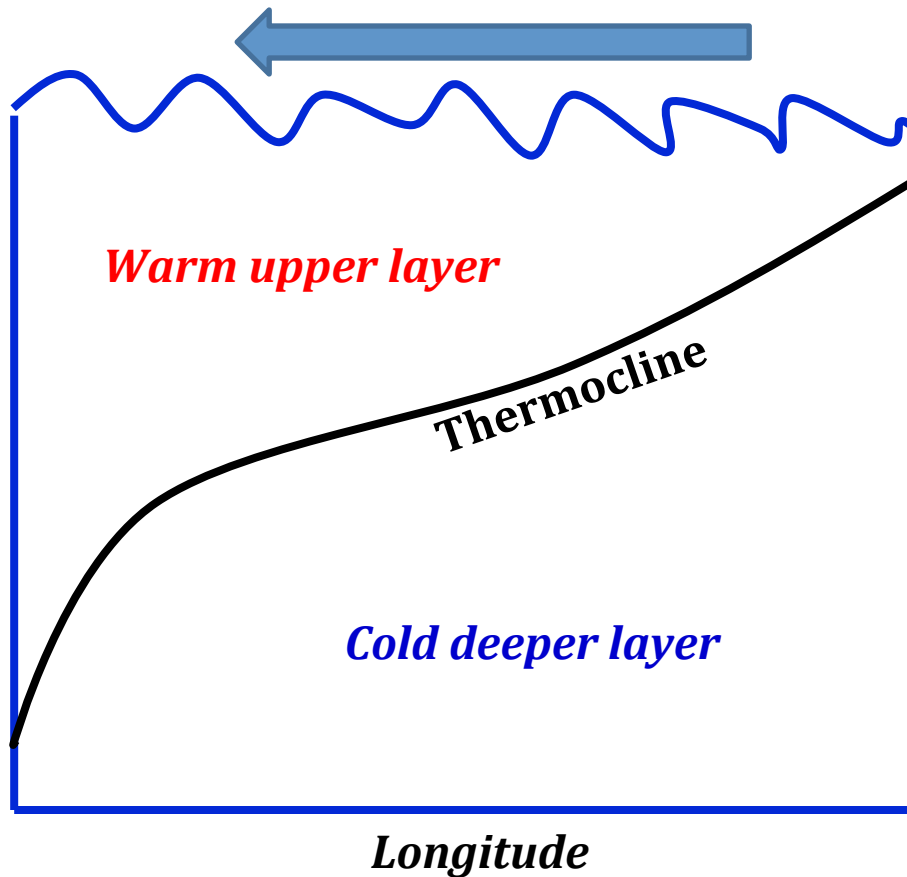


Sea level variations

- *Wyrтки and Kendall, 1967;*
- *Chaen and Wyrтки, 1981;*
- *Rebert et al., 1985;*
- *McGregor et al., 2012*
(using model data)

In our study, we use Ishii
and Kimoto, 2009
observation based
Temperature and Salinity
data

Mechanism causing vertical thermocline movement : the role of wind stress



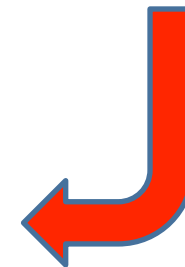
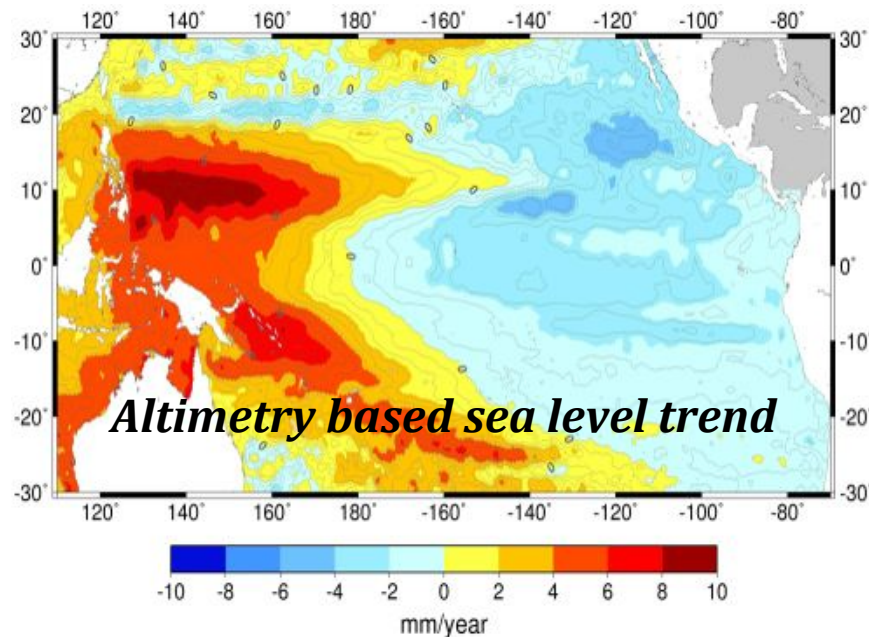
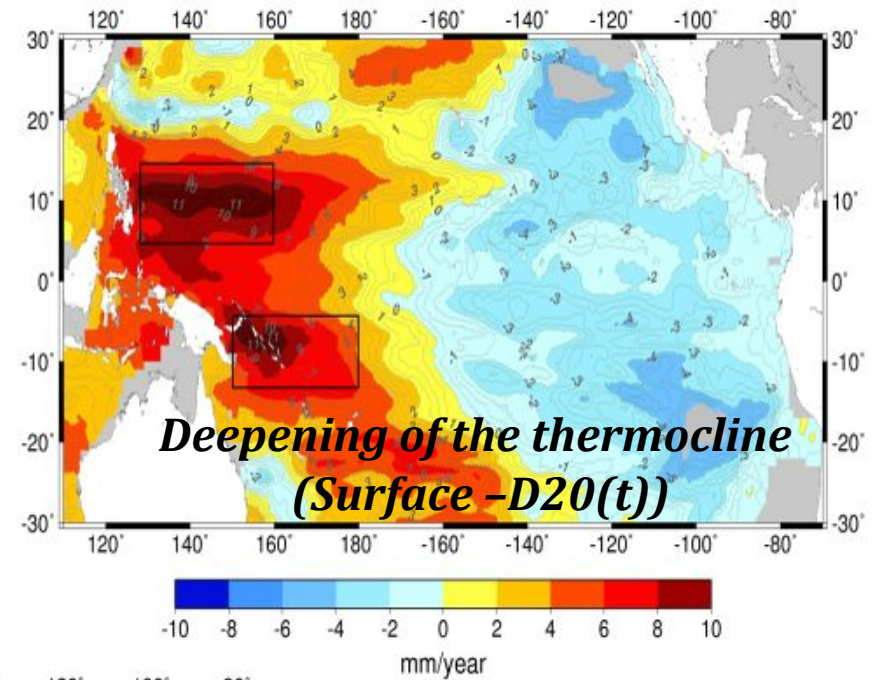
Thermocline slope , dH/dx

- In the equatorial band (5°N - 5°S),
→ zonally averaged wind stress
- 5°N - 15°N and 5°S - 15°S
→ Ekman pumping (wind stress curl, zonal wind stress)

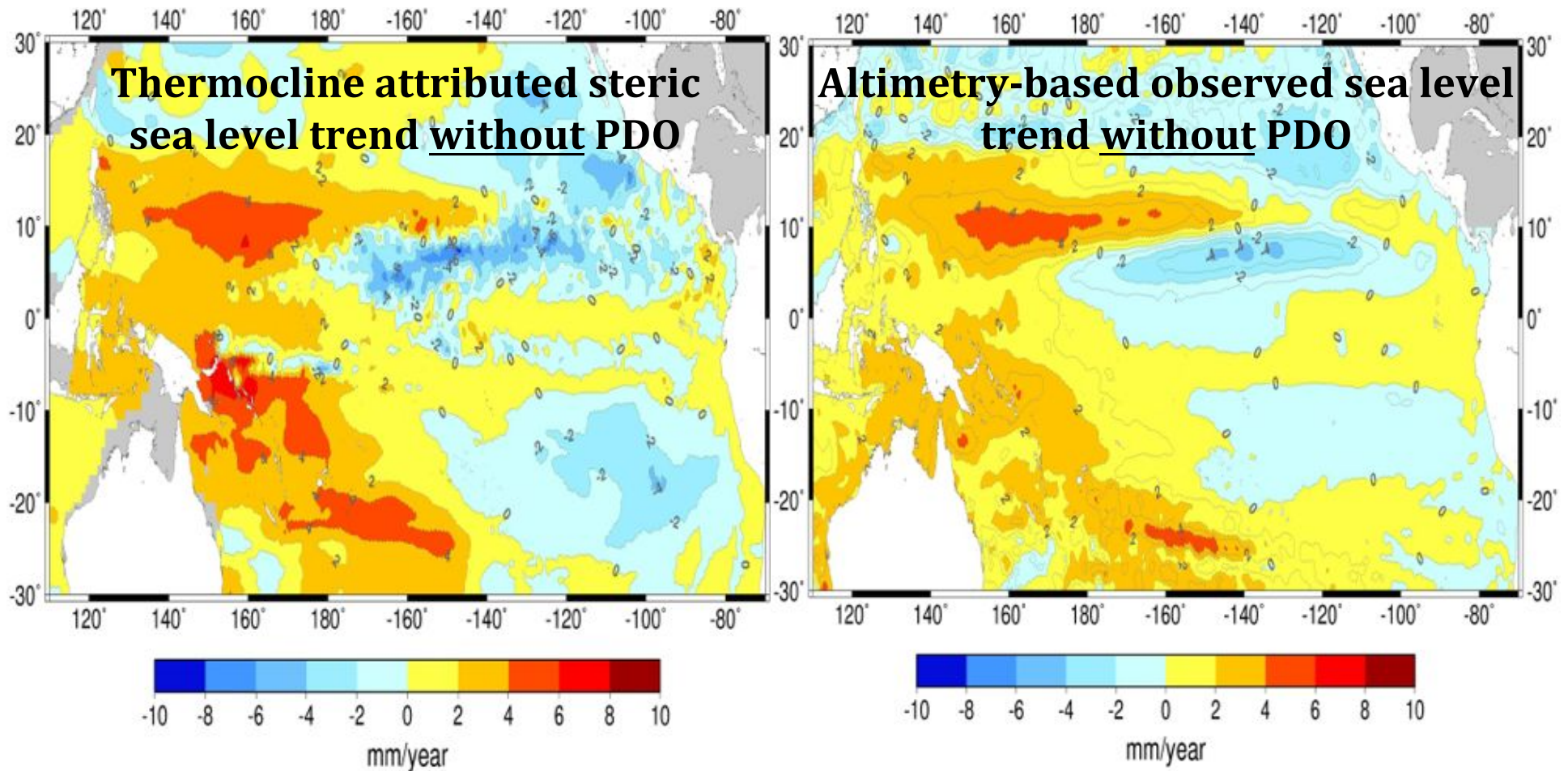
Kessler, 1990, McGregor et al., 2012

Mechanism of sea level variations in tropical Pacific

Zonal wind stress trend



Sea level trends without PDO 1993-2012



→ The mechanism causing sea level variations in the tropical Pacific cannot also be completely explained by the internal climate variability (assuming that ENSO and the PDO remain unaffected by the anthropogenic forcing during our study period)



Future sea level rise

Warming scenarios considered by IPCC AR5

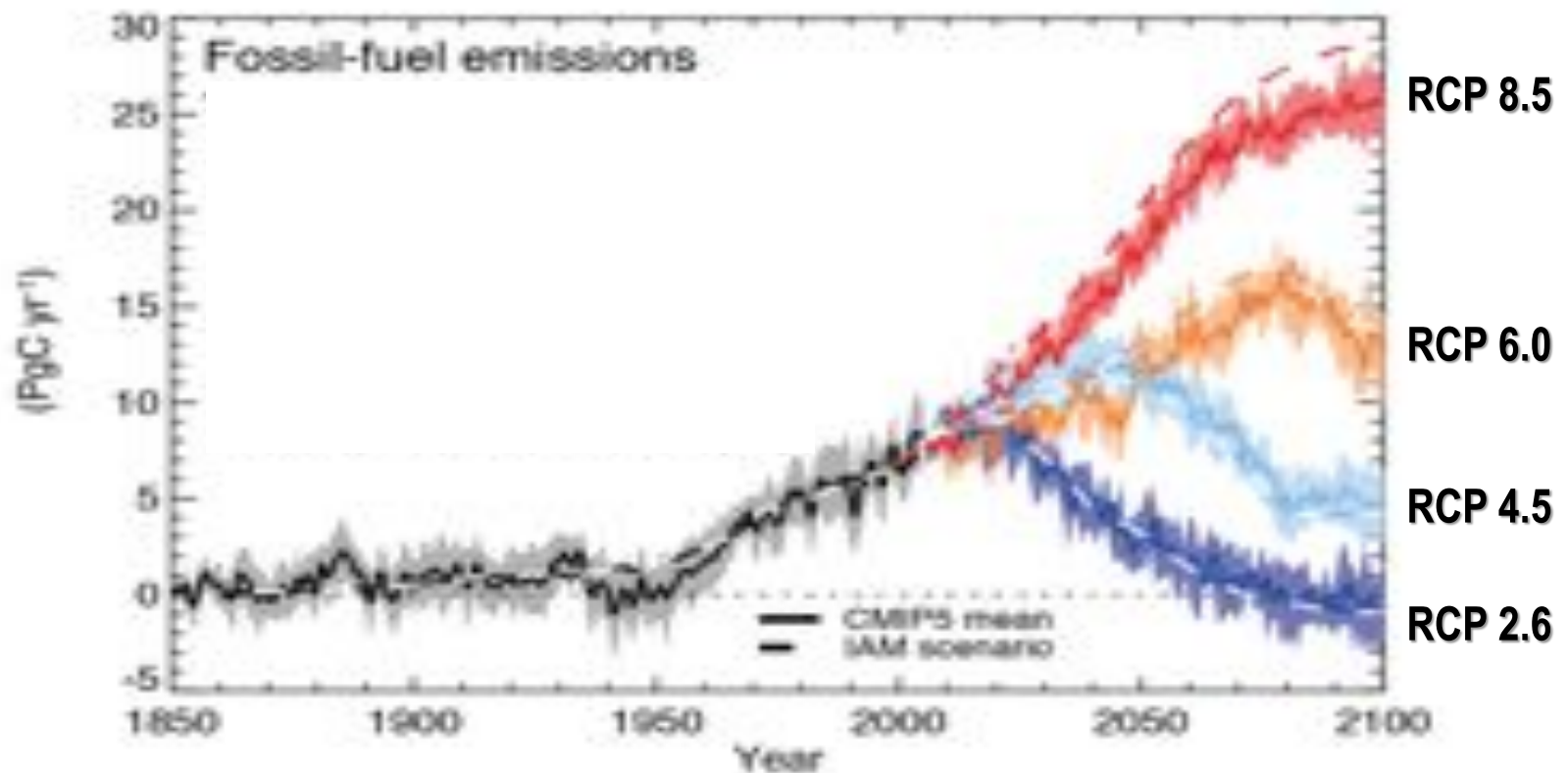
→ Representative Concentration Pathways (RCPs)

→ 4 RCP scenarios defined by their total radiative forcing by 2100:

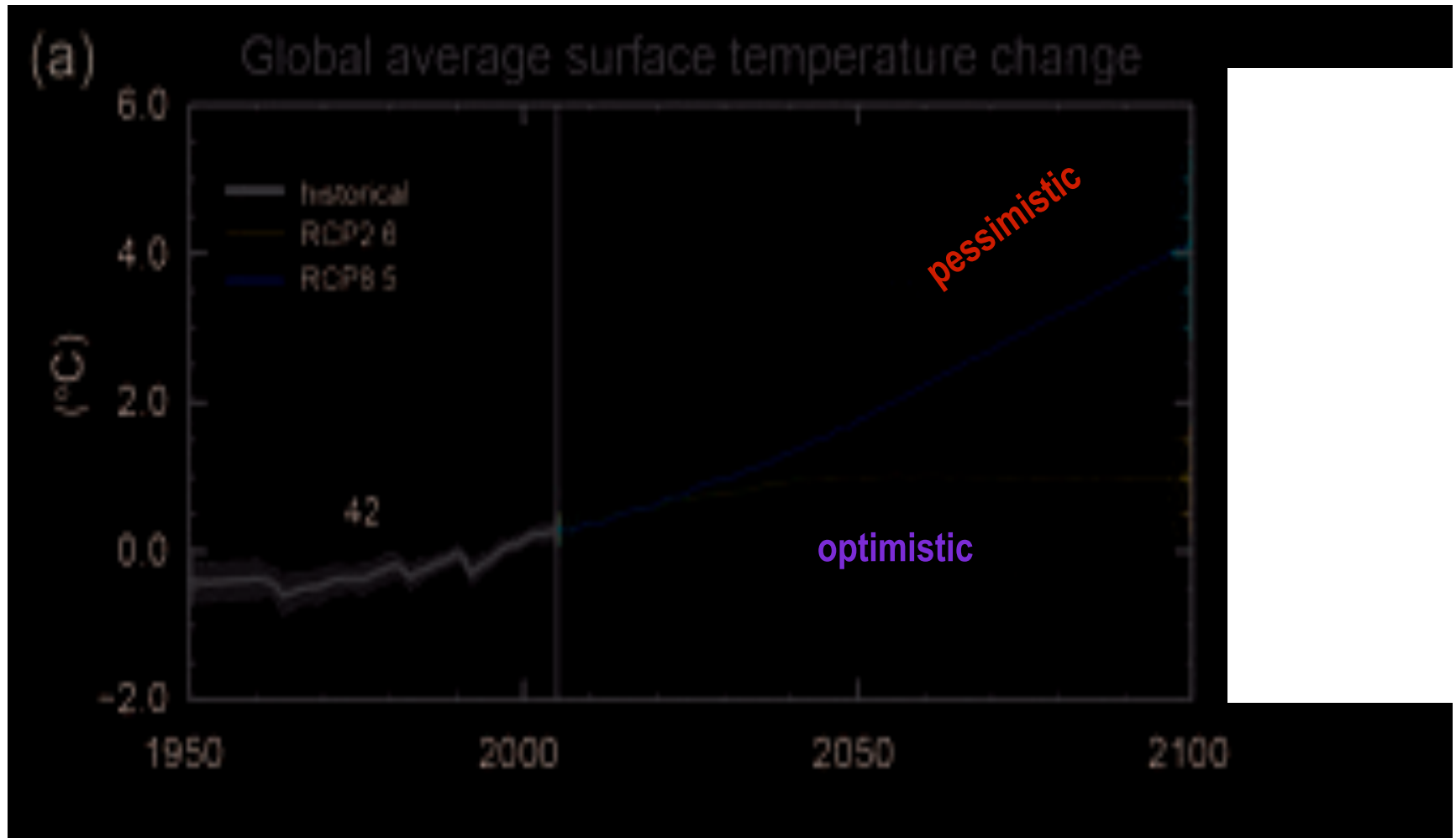
- RCP2.6 (2.6 Wm^{-2})
- RCP4.5 (4.5 Wm^{-2})
- RCP6.0 (6.0 Wm^{-2})
- RCP8.5 (8.5 Wm^{-2})

Radiative forcing : an energy imbalance imposed on the climate system either externally or by human activities; ususally reported as a change in energy flux at the top of the atmosphere and expressed in units of watts per square meters (Wm^{-2})

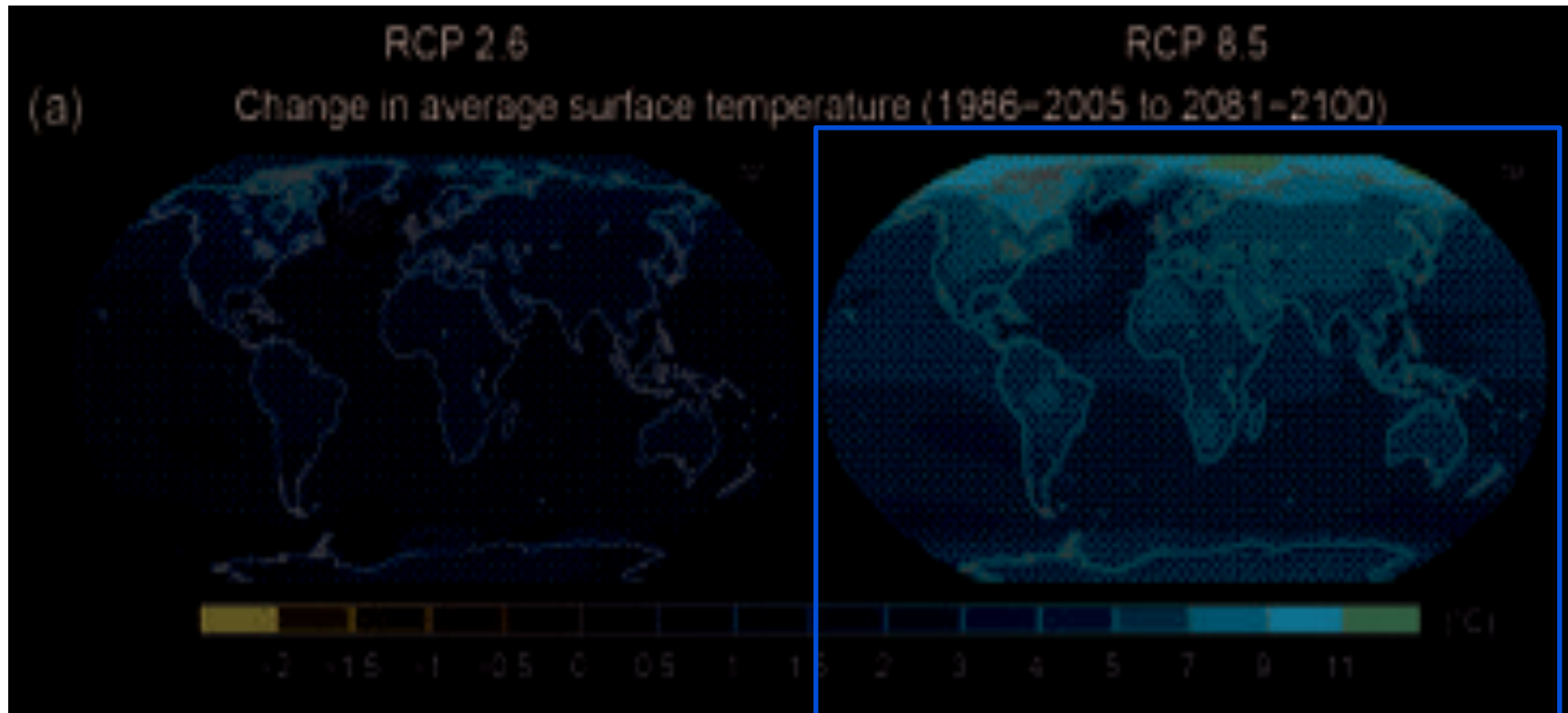
**4 scenarios for future greenhouse gas emissions considered
by IPCC AR5 for the 21st century**



Evolution of the Earth's mean temperature under two warming scenarios



Maps of surface temperature change by the end of the 21st century under 2 extreme warming scenarios

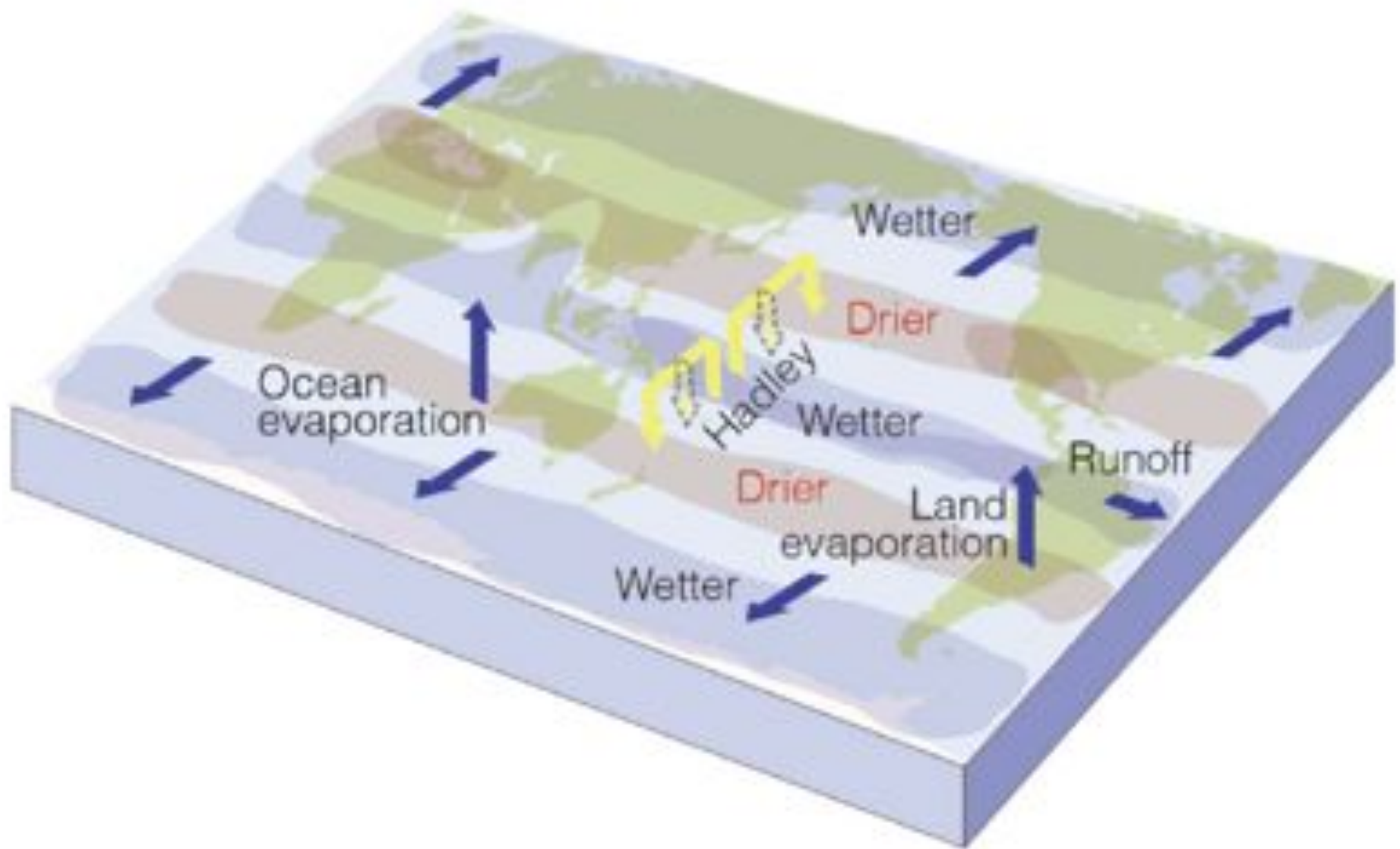


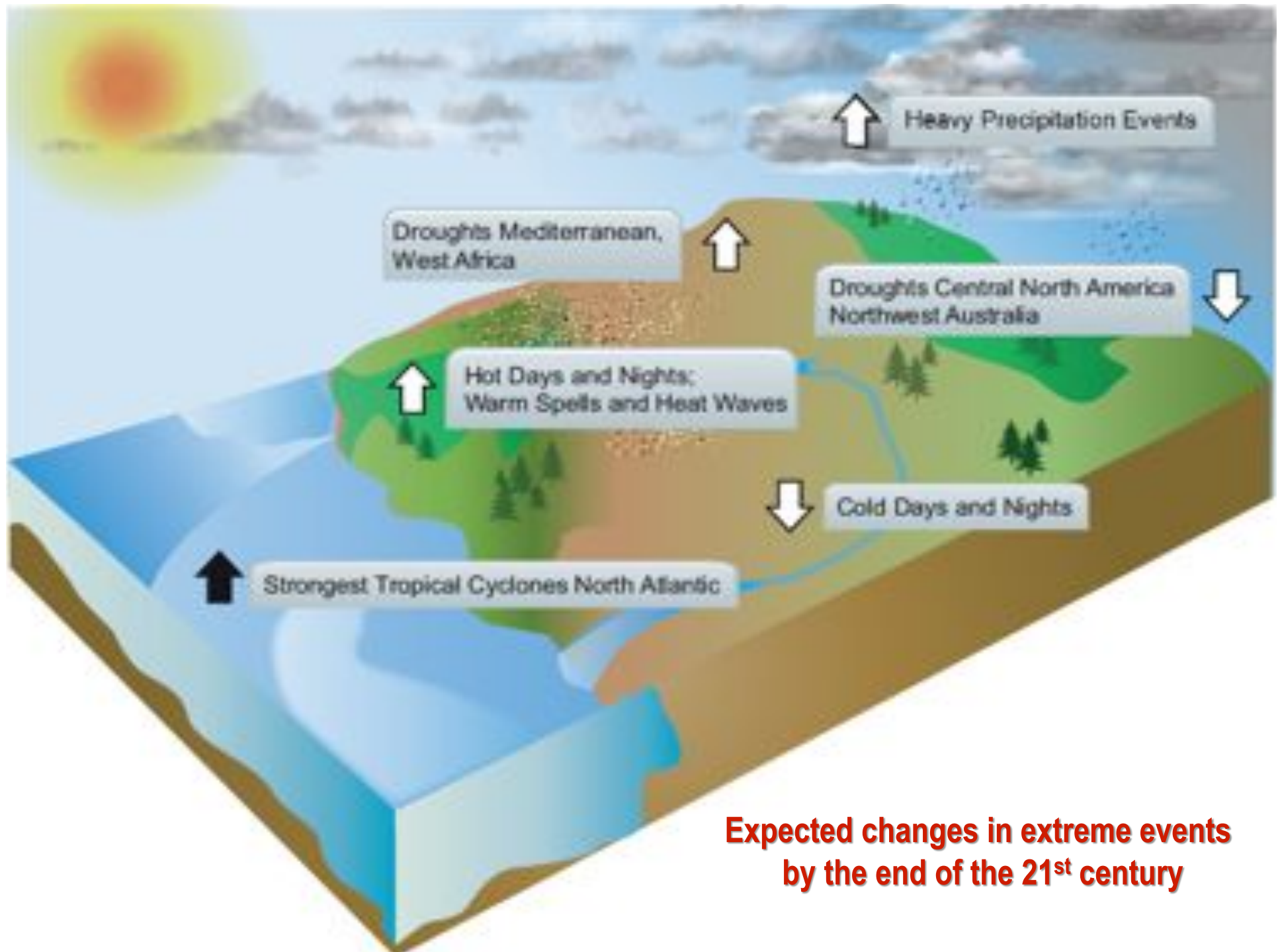
optimistic

pessimistic

Mean temperature increase : 4°C

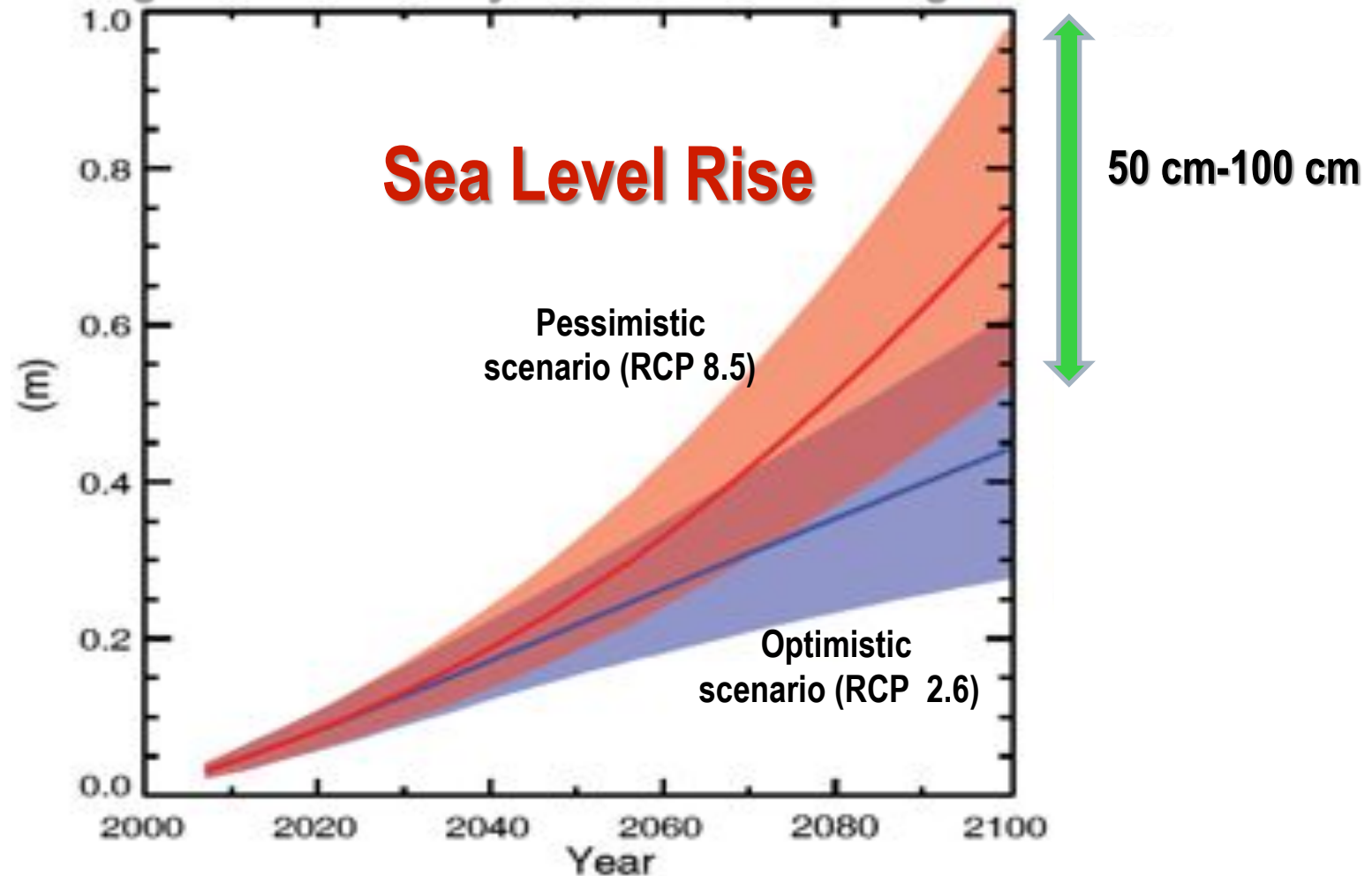
Change in hydrological conditions by the end of the 21st century



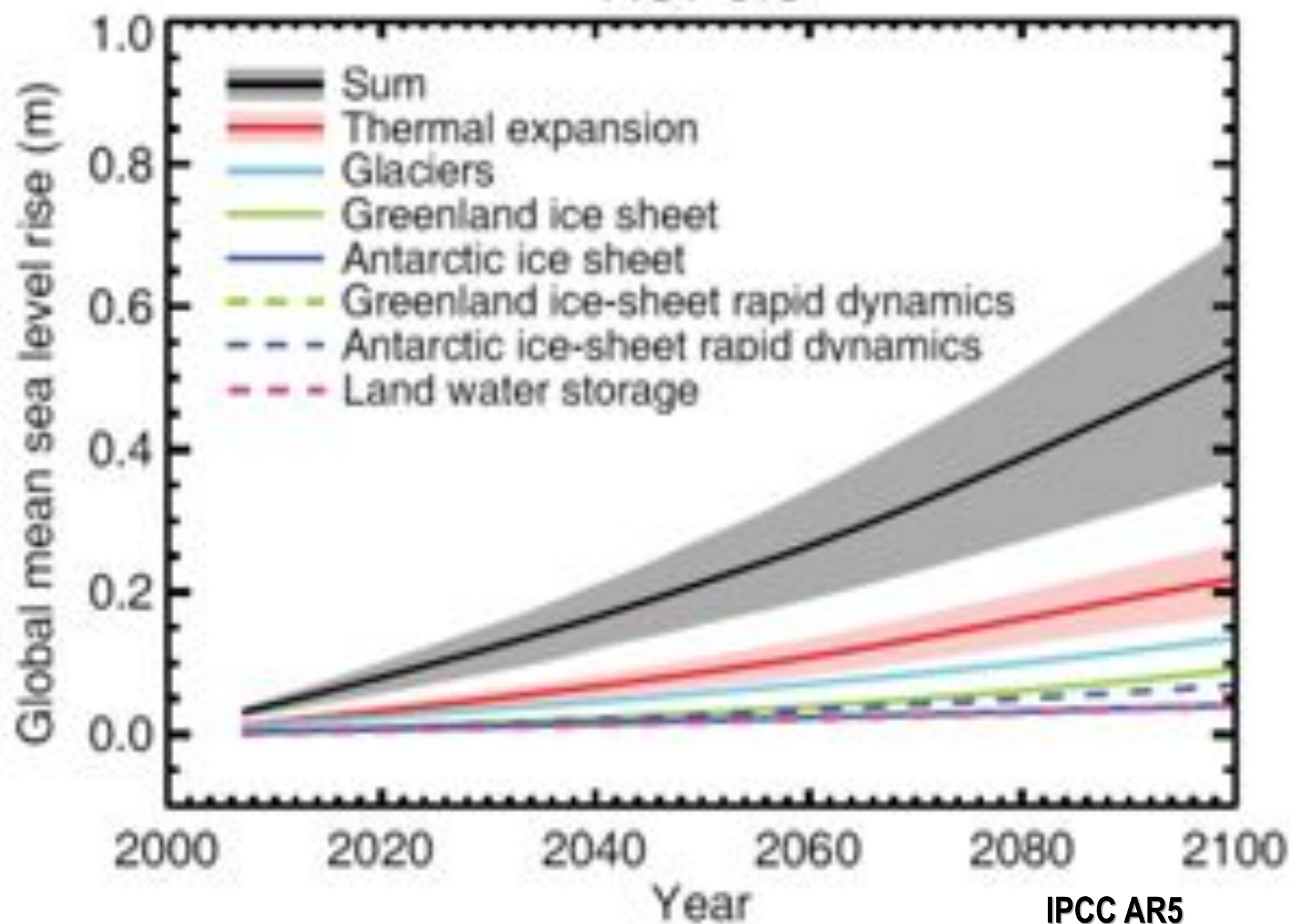


**Expected changes in extreme events
by the end of the 21st century**

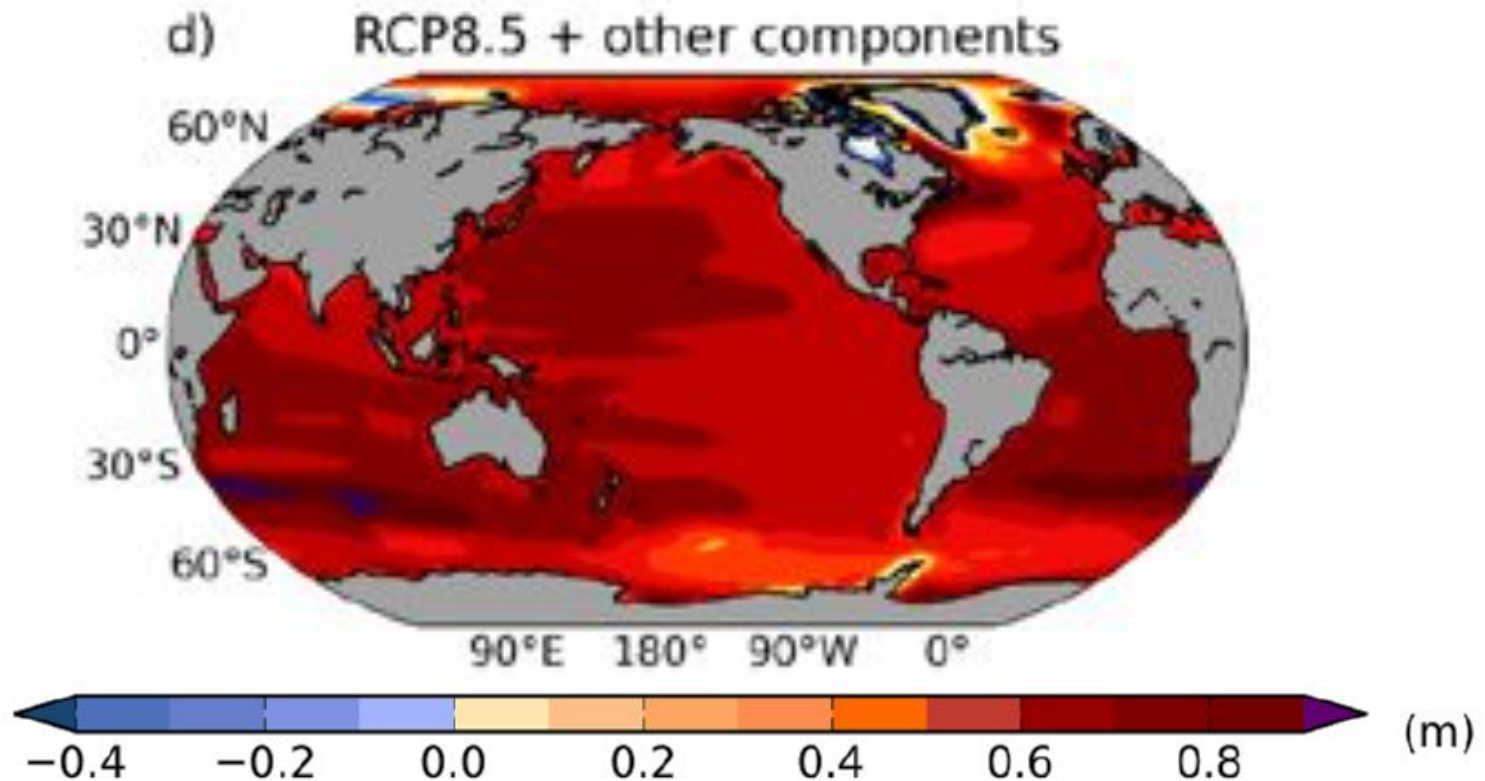
IPCC-AR5 projections of Global Mean Sea Level Rise during the 21st century under two warming scenarios



RCP6.0



Ensemble mean projections of regional sea level rise by the end of the 21st century
*(regional variability due to non uniform thermal expansion & salinity
+ solid Earth effects)*



***Global mean sea level rise
of 75 cm
(high warming scenario)***

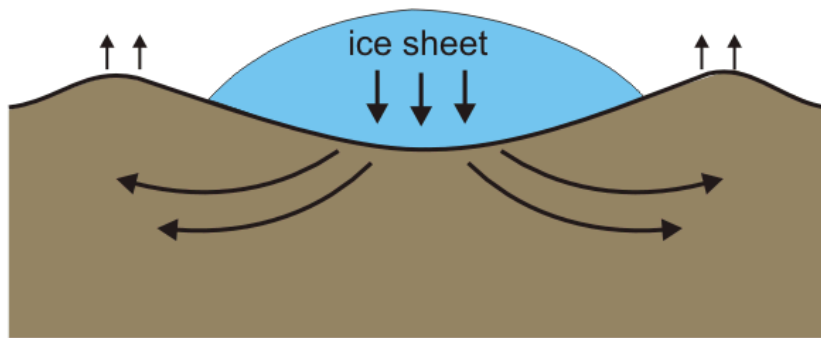
In addition to steric effects, there are other sources of regional variability

- large-scale water mass redistributions due to land ice melt
- Deformations of ocean basins (because the Earth mantle is viscous and the crust is elastic) + changes in mutual gravitational attraction of water & ice masses

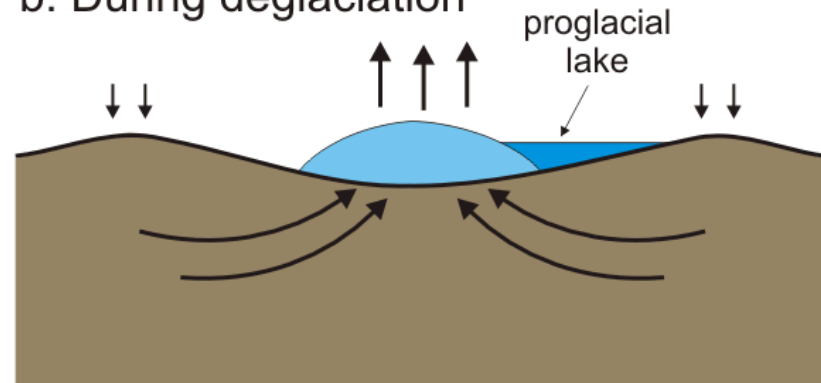


Post Glacial Rebound

a. Peak glaciation



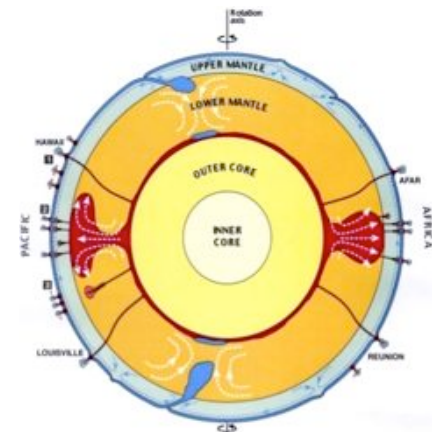
b. During deglaciation



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

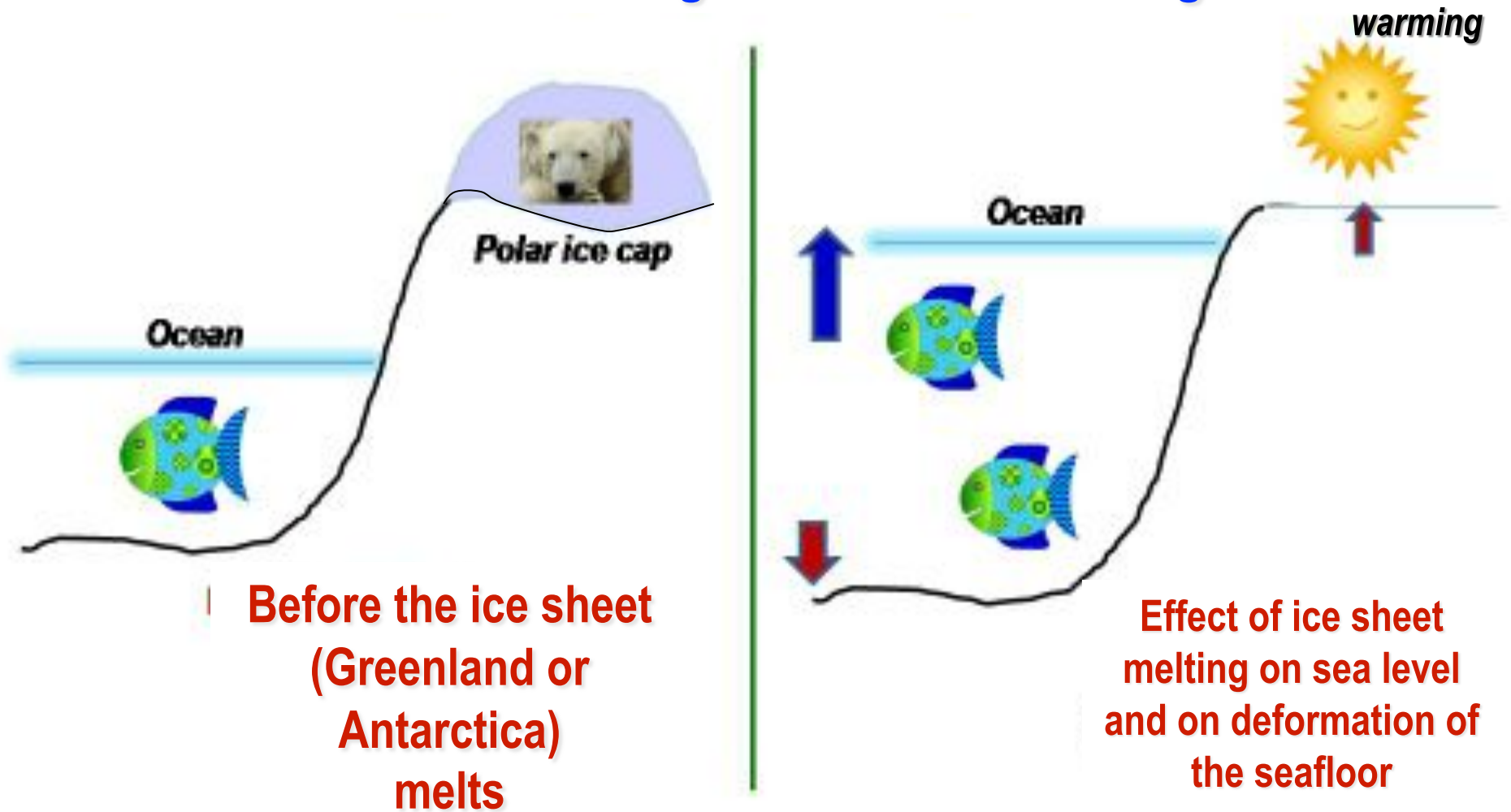


Deglaciation history

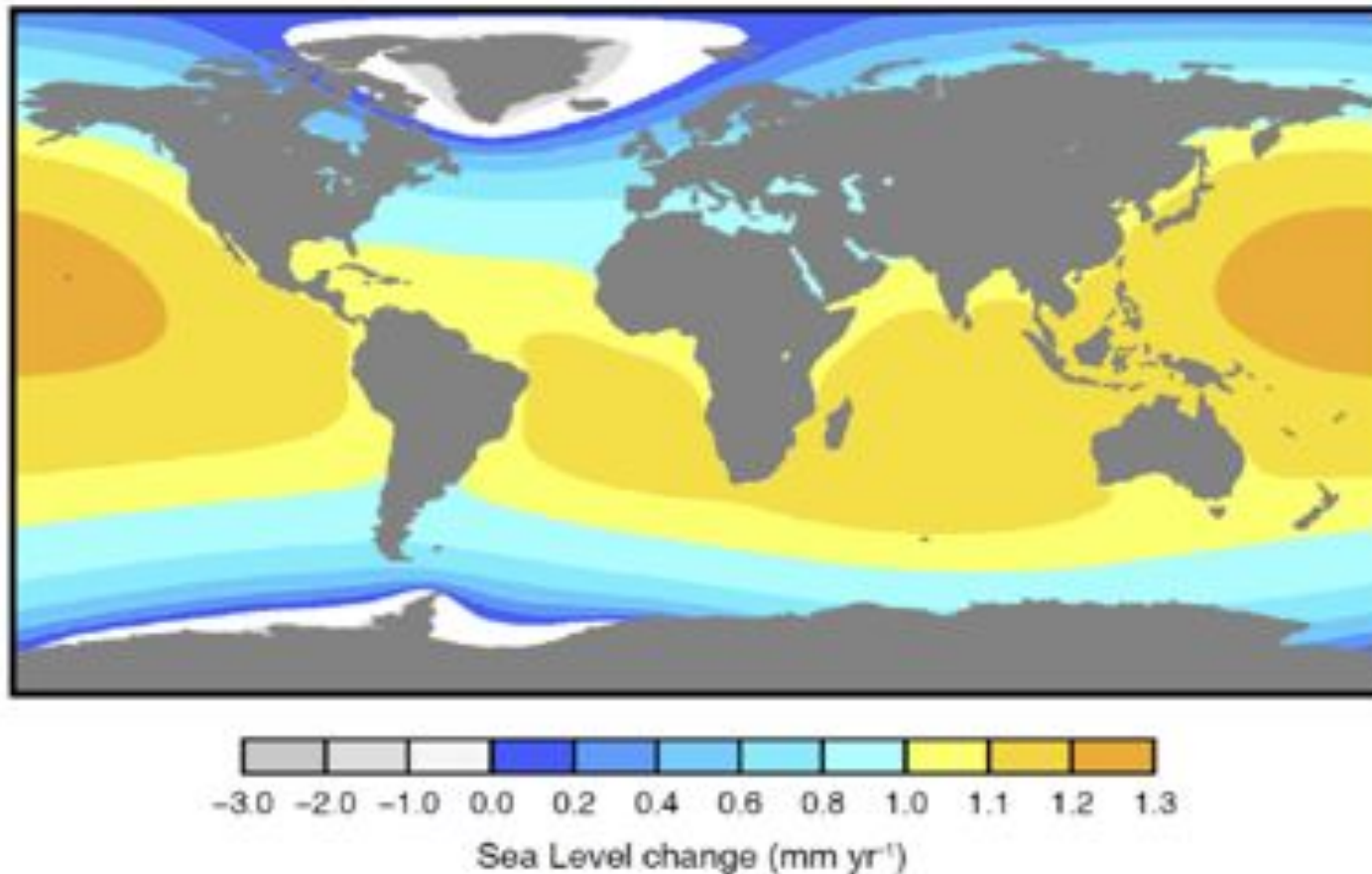


*Models of
Earth's viscosity structure*

Because the Earth is not rigid, large scale ice/water mass redistributions cause ocean basins to deform, hence cause regional sea level changes

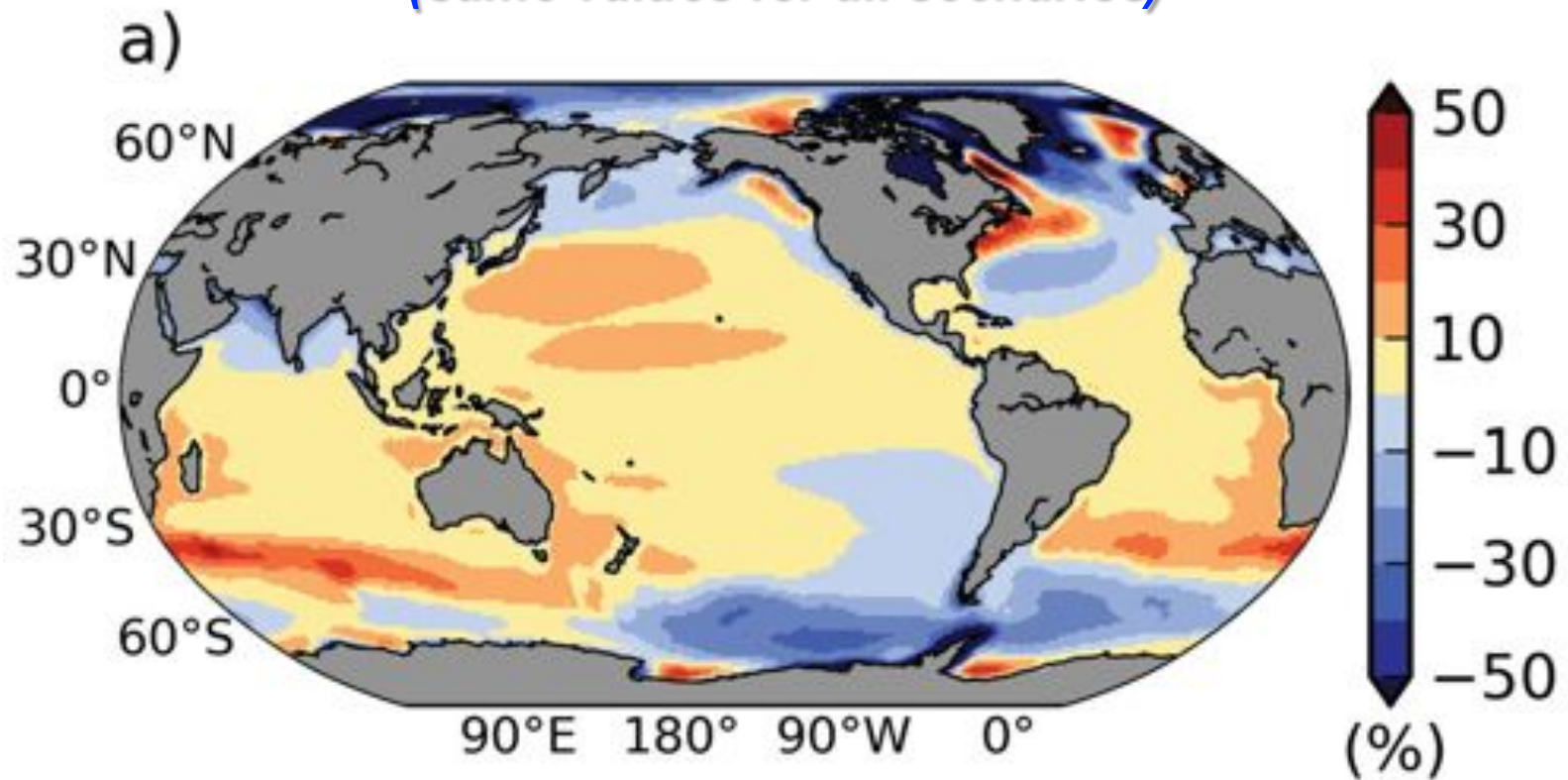


Effects on regional 'relative' sea level due to solid Earth's deformations in response to ongoing & future ice sheet melting
(Greenland : 0.5 mm/yr; west Antarctica : 0.5 mm/yr)



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

Regional variability by 2100
Percentage of deviation from the global mean rise
(same values for all scenarios)



Long-term climate change

Many aspects of climate change will persist for many centuries even if emissions of greenhouse gases are stopped!

- 20% of emitted CO₂ will remain in the atmosphere more than 1000 years
- Sea level will continue to rise for many centuries in response to deep ocean warming and associated thermal expansion
- Ice sheet mass loss may become irreversible (Greenland)
→ sustained warming above a certain threshold (1°C-4°C) may lead to near-complete loss of the Greenland ice sheet over a time scale of 1000 years (→ 7 m of sea level rise)

Conclusions

- Current global mean sea level rise is likely accelerating
- The sea level budget (altimetry era) almost closed
- Global mean sea level rise: very likely a consequence of anthropogenic global warming
- Regional variability (spatial trend patterns) : still dominated by natural (internal) modes of climate variability
- The global mean sea level will continue to rise during the 21st century in response to global warming (values by 2100 in the range 50 cm-1 m NOT unlikely)
- The regional variability will amplify the global mean rise by 30%-40% in the tropics
- Even if GHG emissions stop tomorrow, sea level will continue to rise during several centuries

Thanks for your attention

