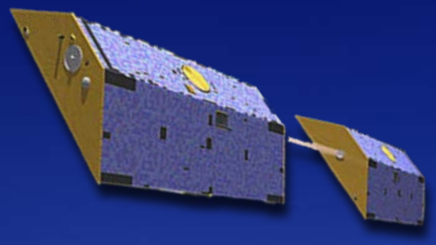


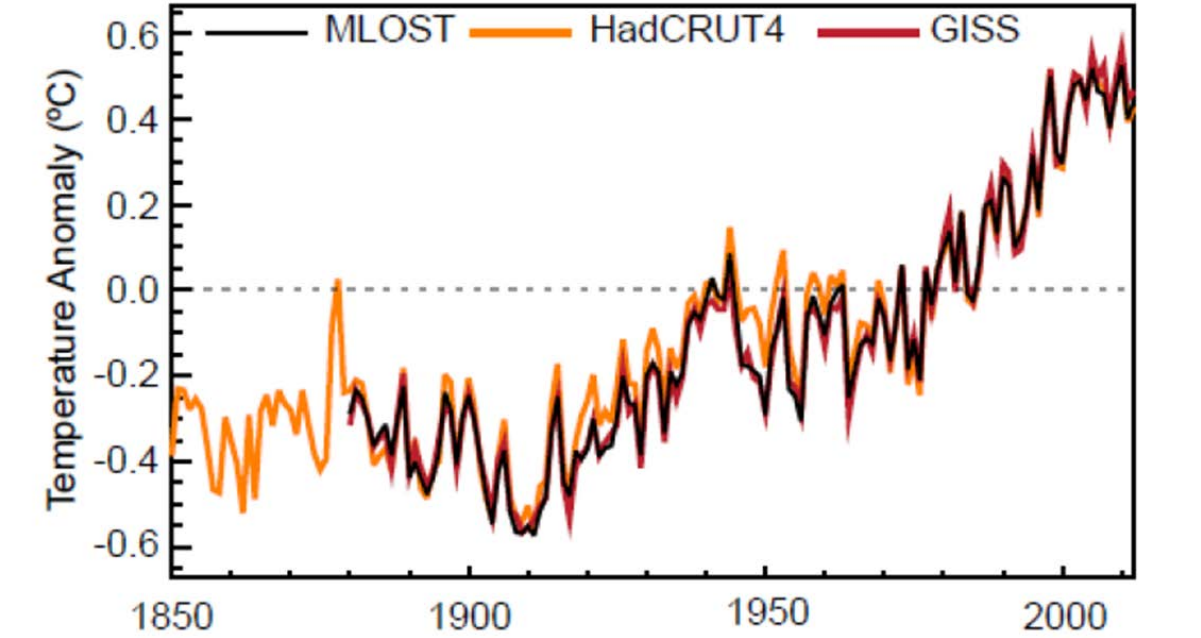
Sea level changes
recent past, present, future

Anny Cazenave
LEGOS-CNES
Toulouse, France

« Our Changing Planet » GIFT workshop, EGU 2014

IPCC 5th Assessment Report (2013): main message

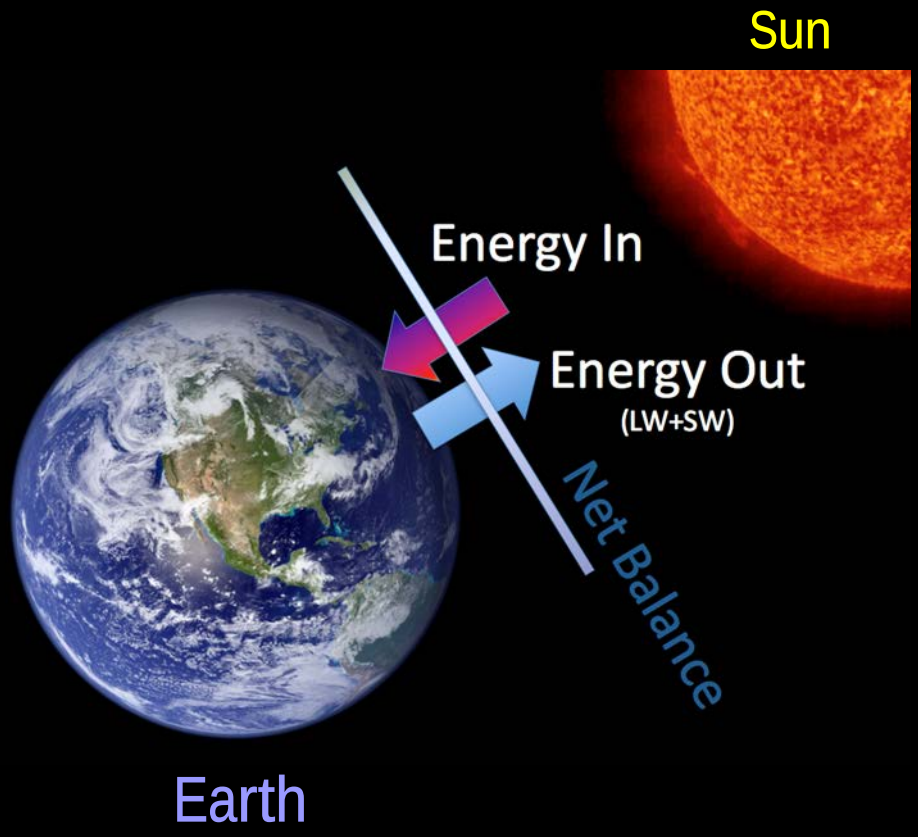
→ Global warming & dominant role of human activities confirmed



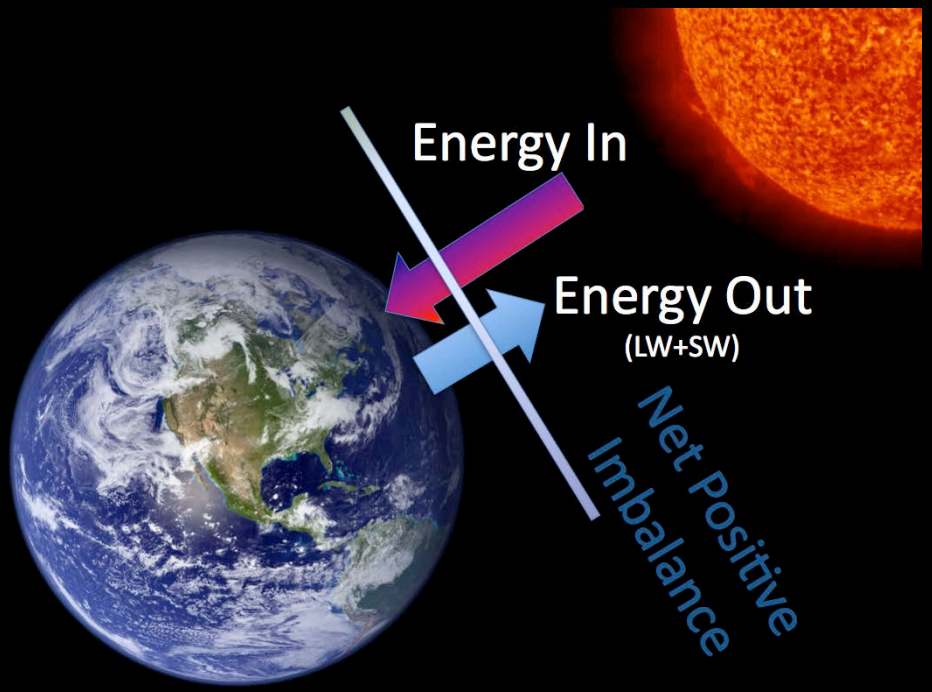
Earth's global mean surface temperature since 1850

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

Earth's Energy Budget

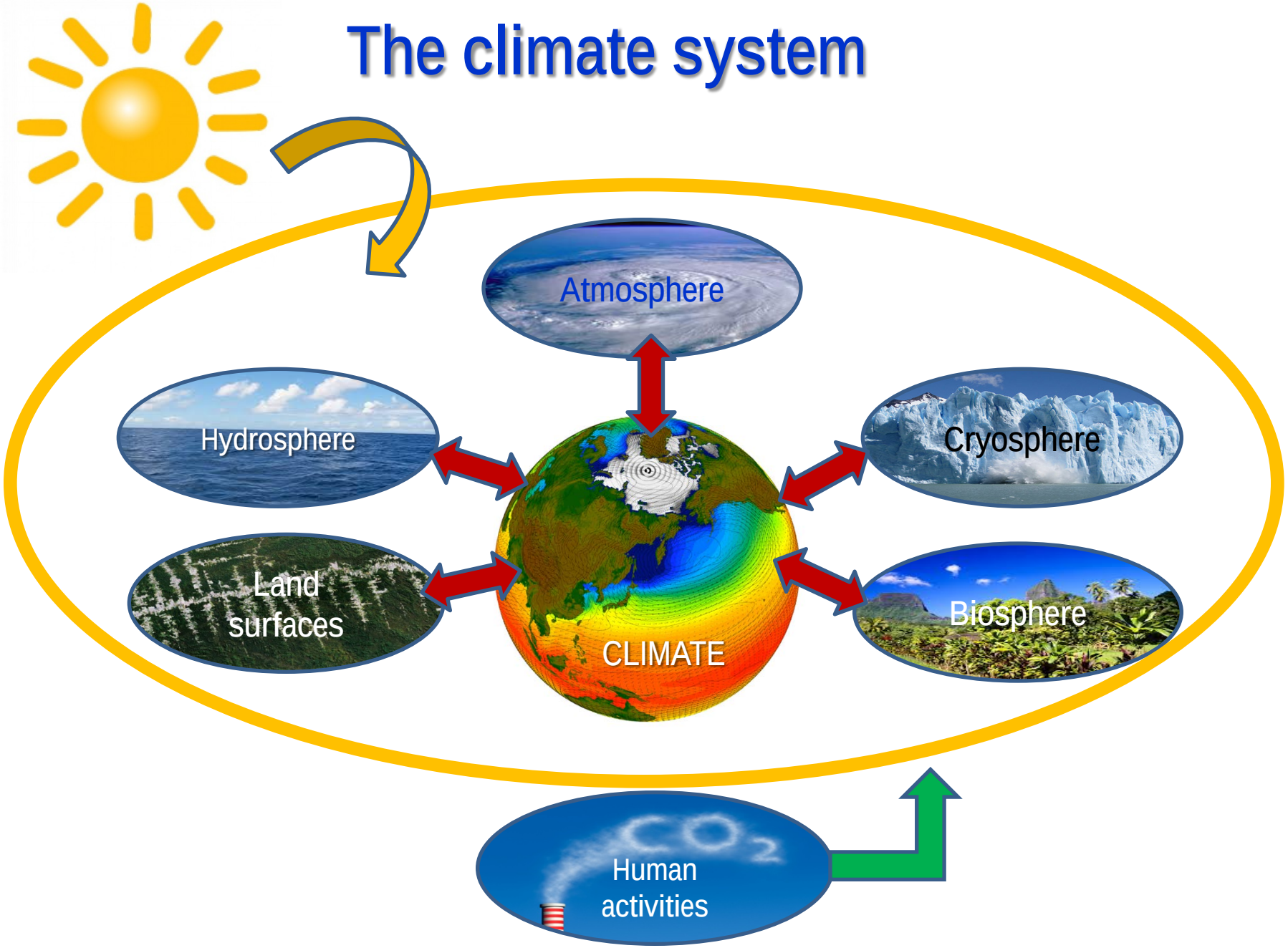


Equilibrium state

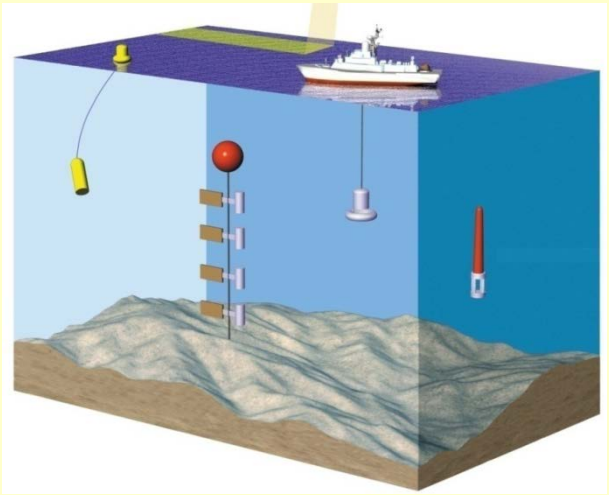


Today →Energy imbalance

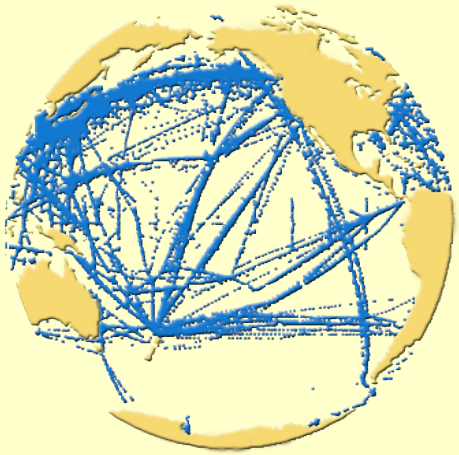
The climate system



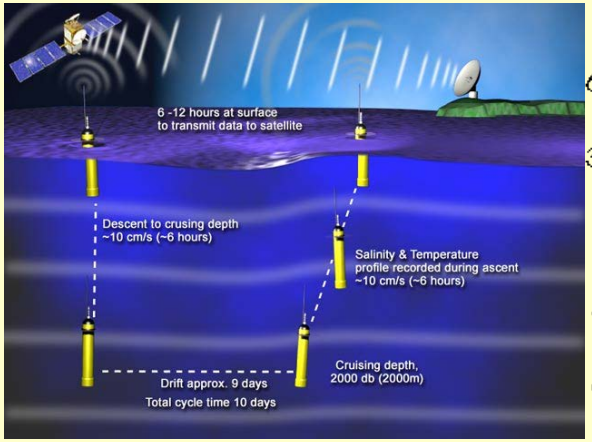
Ocean temperature measurements (XBT, Argo)

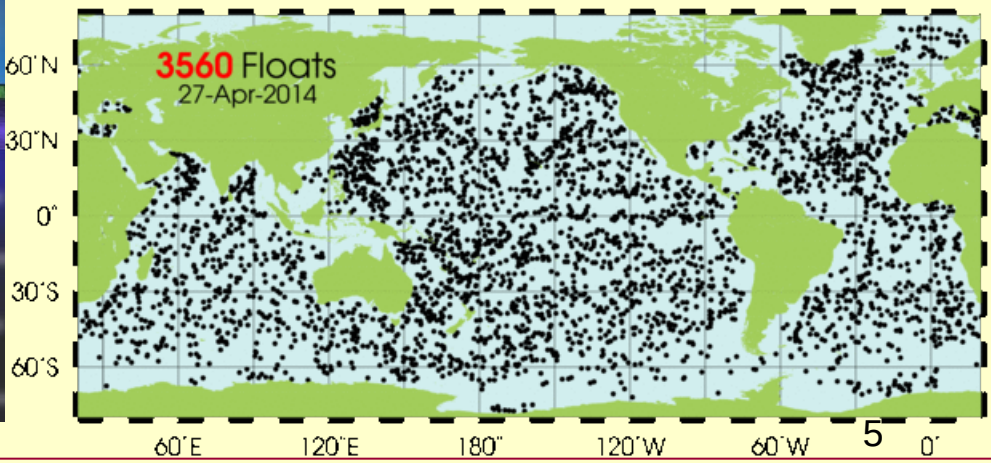


Past few decades: coverage mainly along trade roads

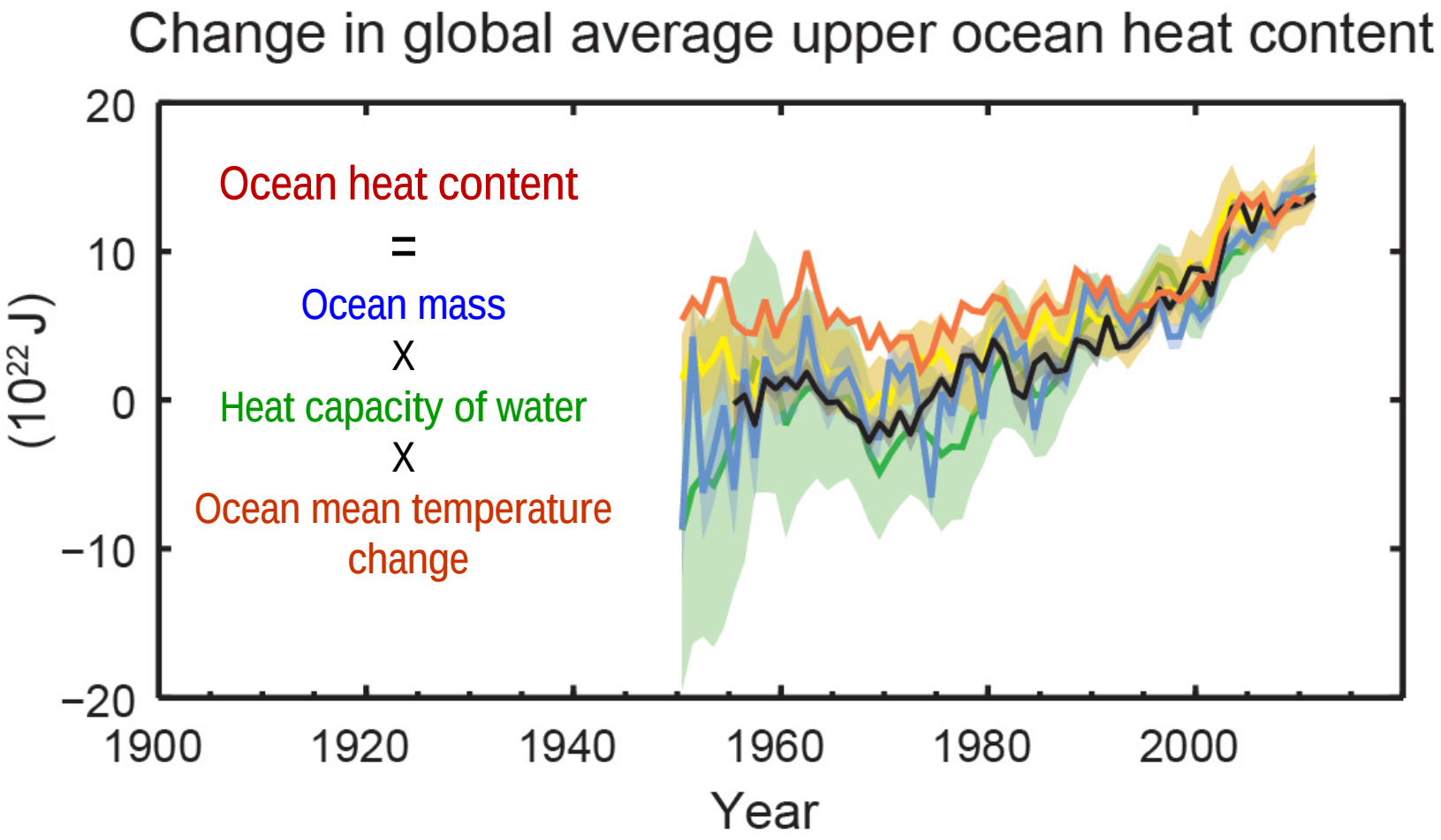


Since about 2003 → 'Argo' profiling floats





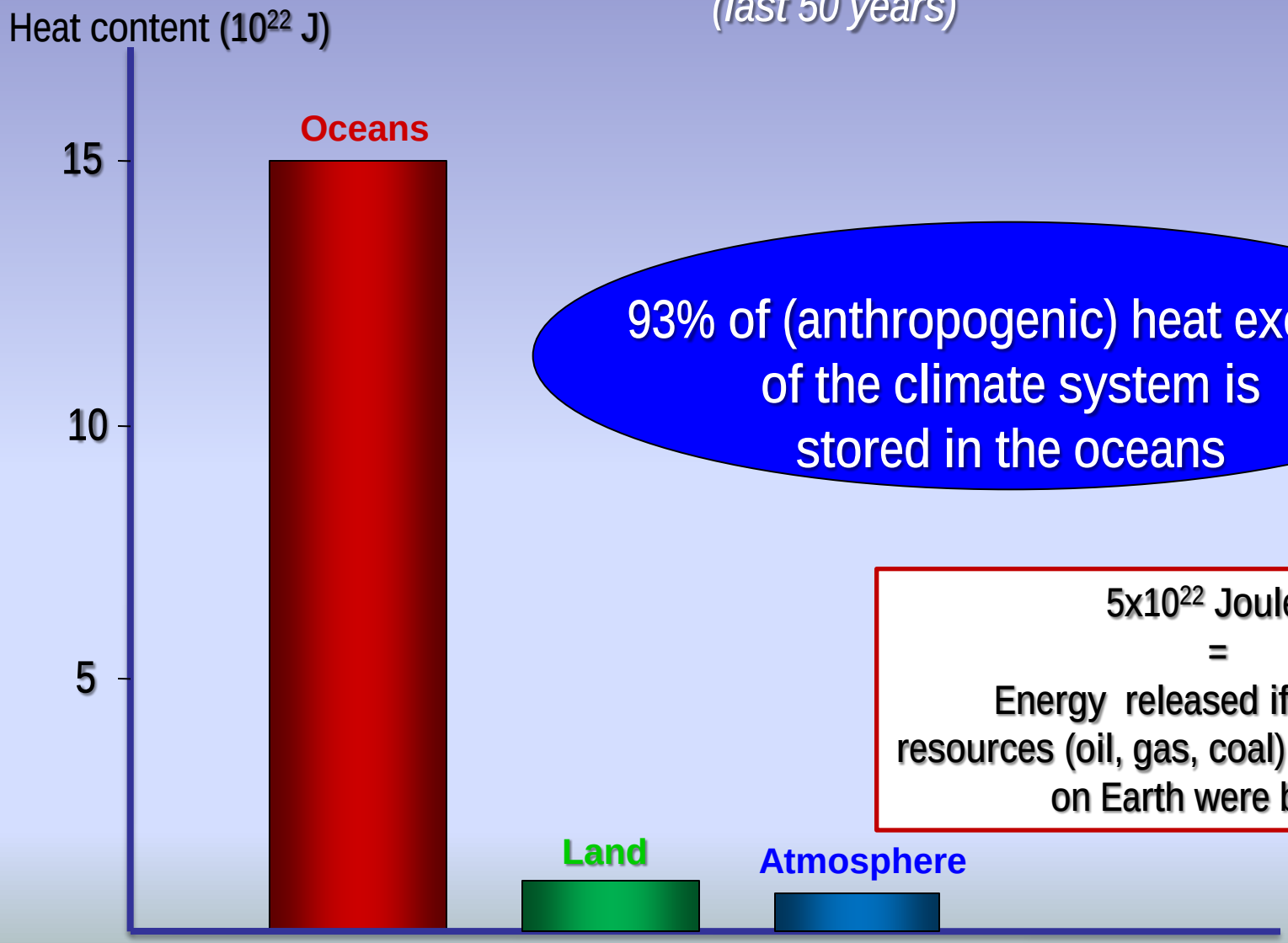
The ocean heat content is increasing



IPCC AR5

Thermal budget of the climate system

(last 50 years)



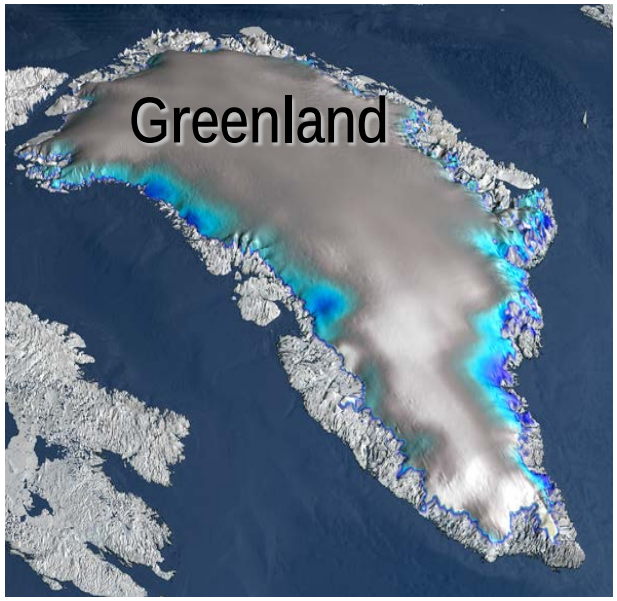
93% of (anthropogenic) heat excess of the climate system is stored in the oceans

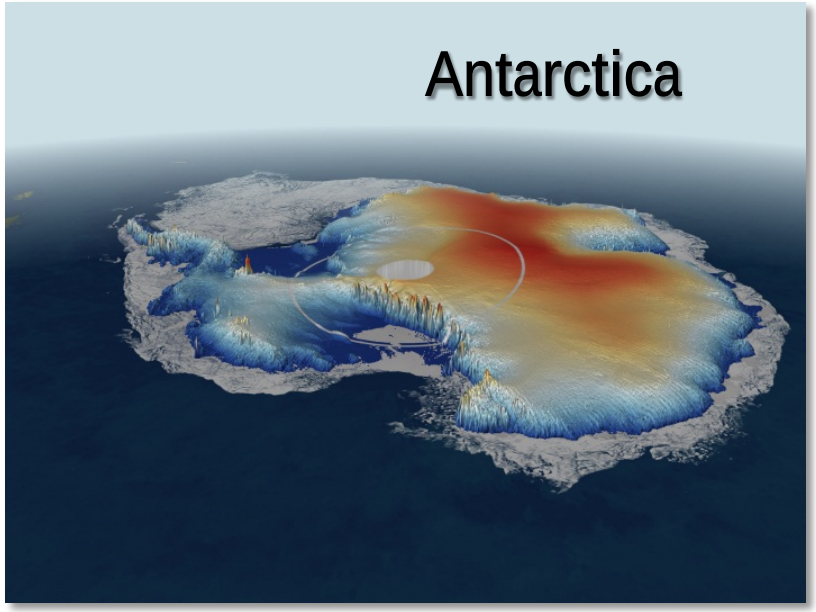
5×10^{22} Joules
=
Energy released if all fossil resources (oil, gas, coal) still remaining on Earth were burnt!

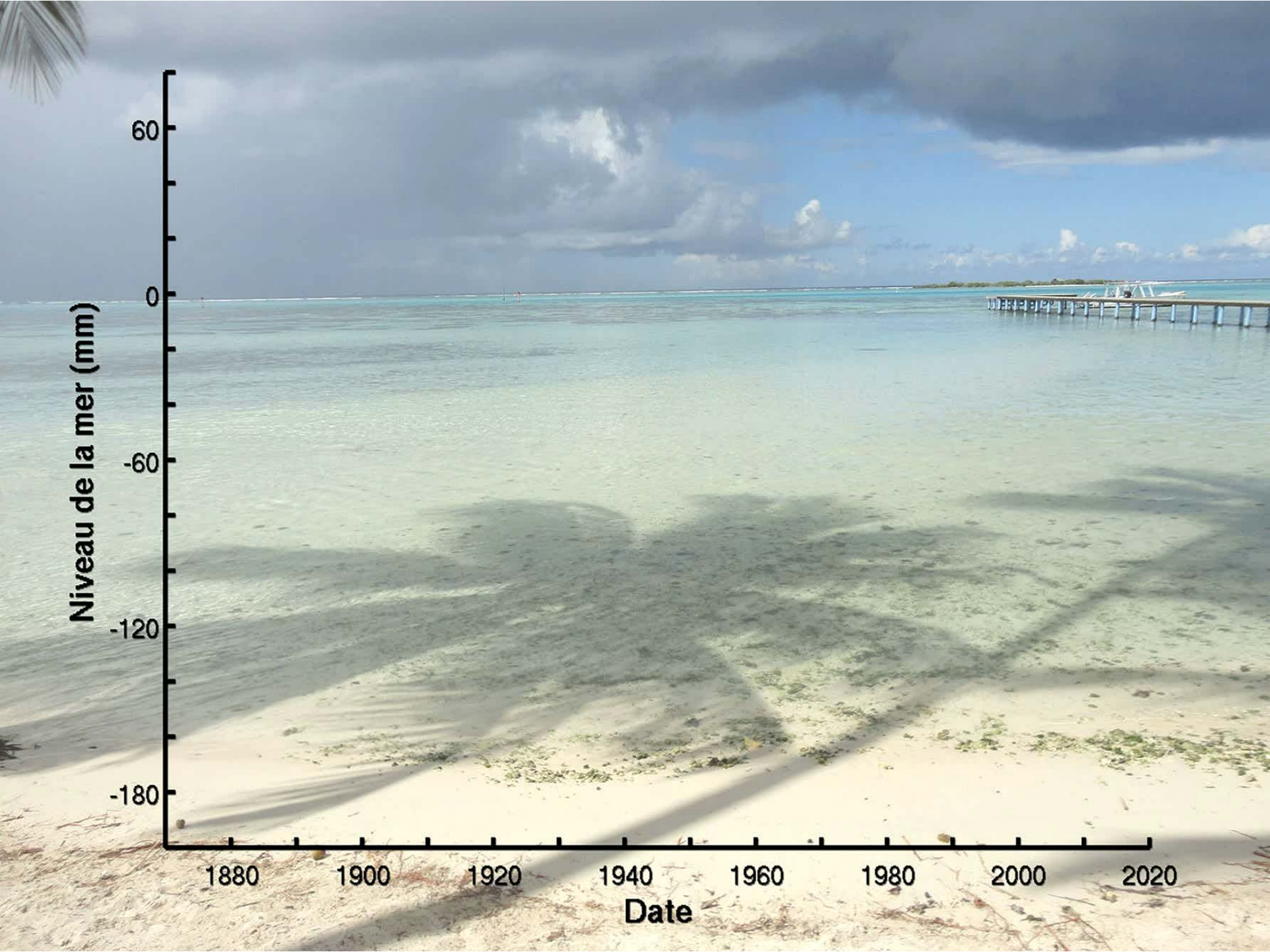
IPCC AR5

Land ice is melting….

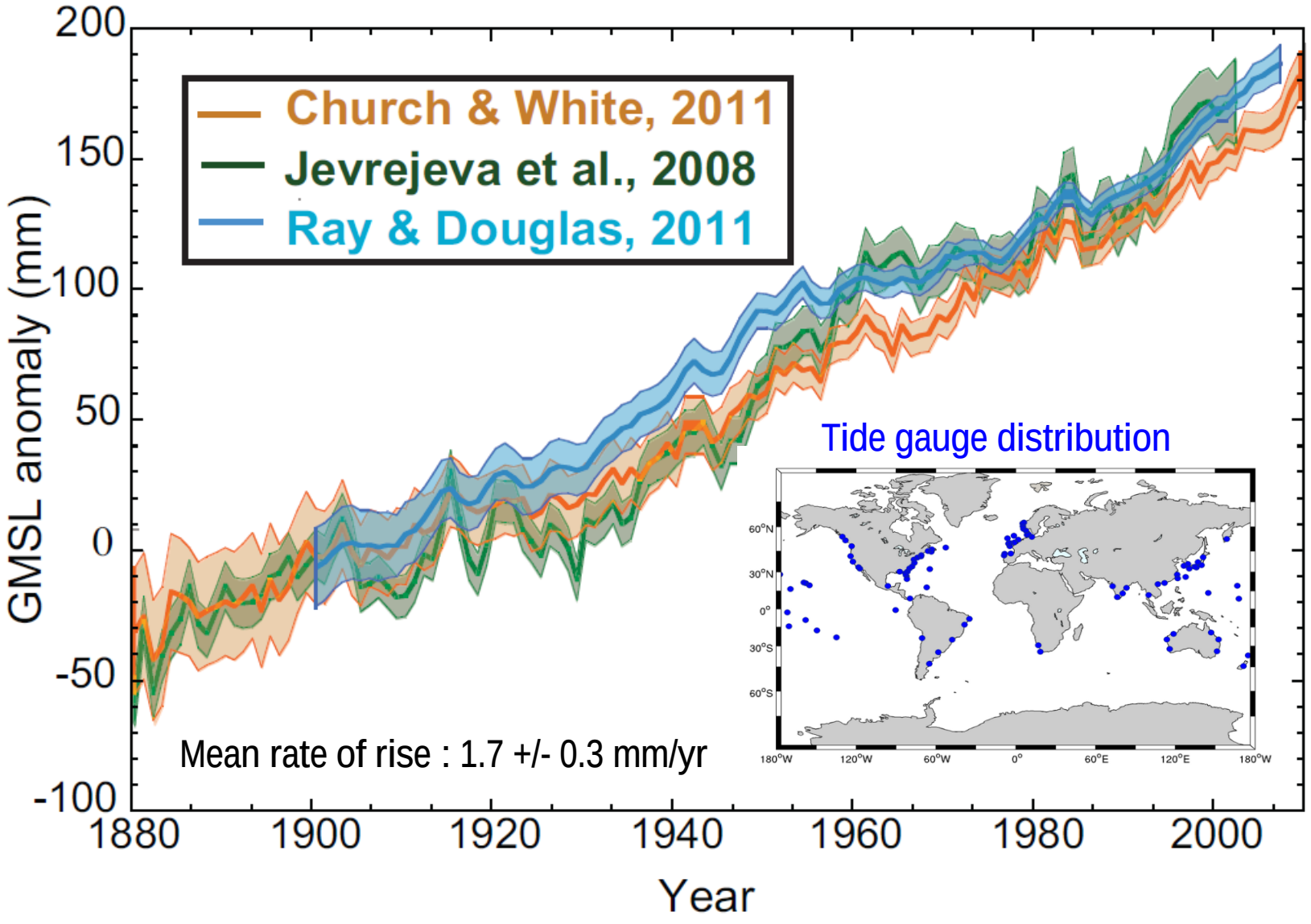
Rhone Glacier (Swiss Alps)





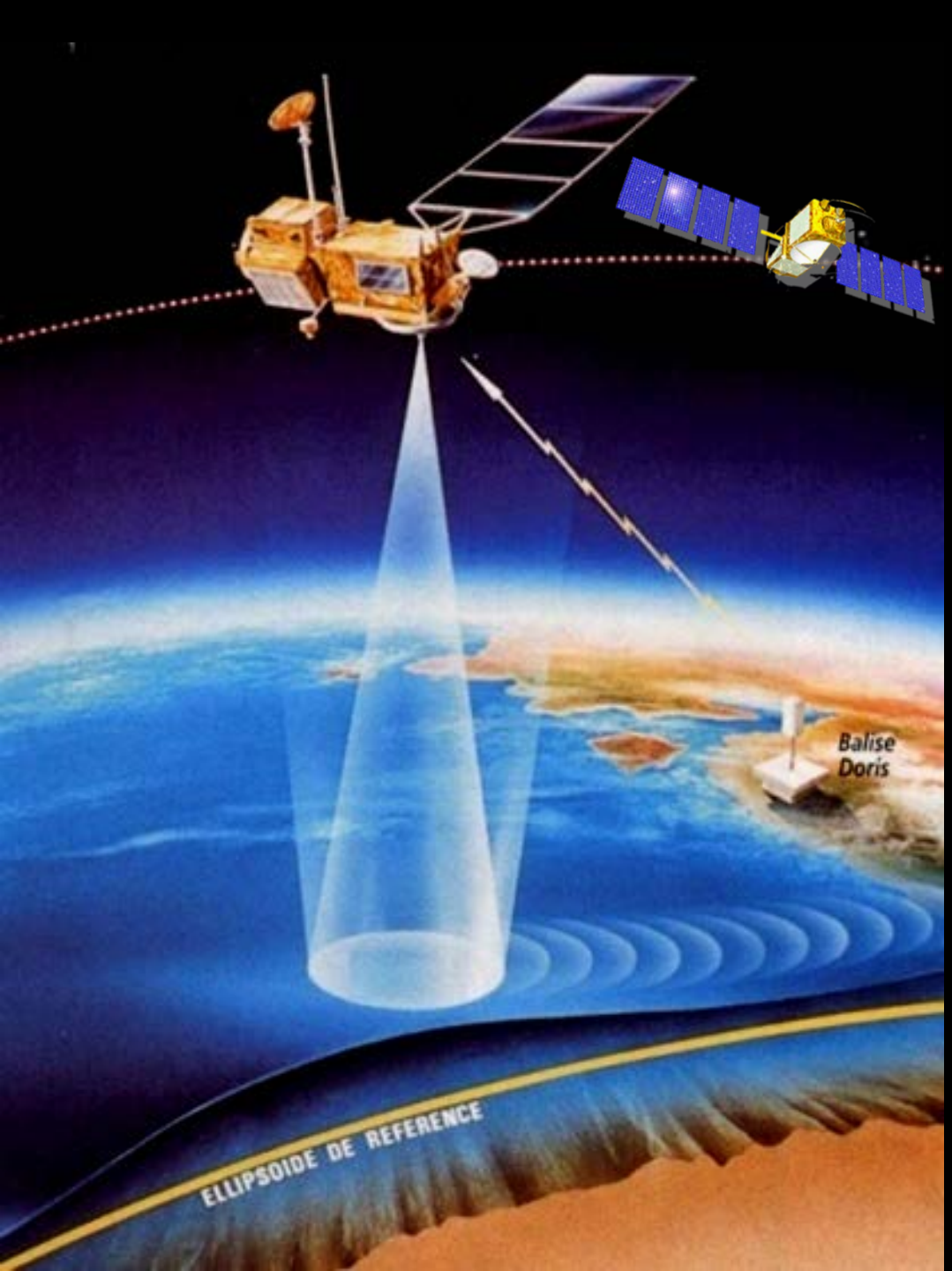

60
0
-60
-120
-180
Niveau de la mer (mm)
1880
1900
1920
1940
1960
1980
2000
2020
Date

20th century sea level rise



IPCC AR5, 2013

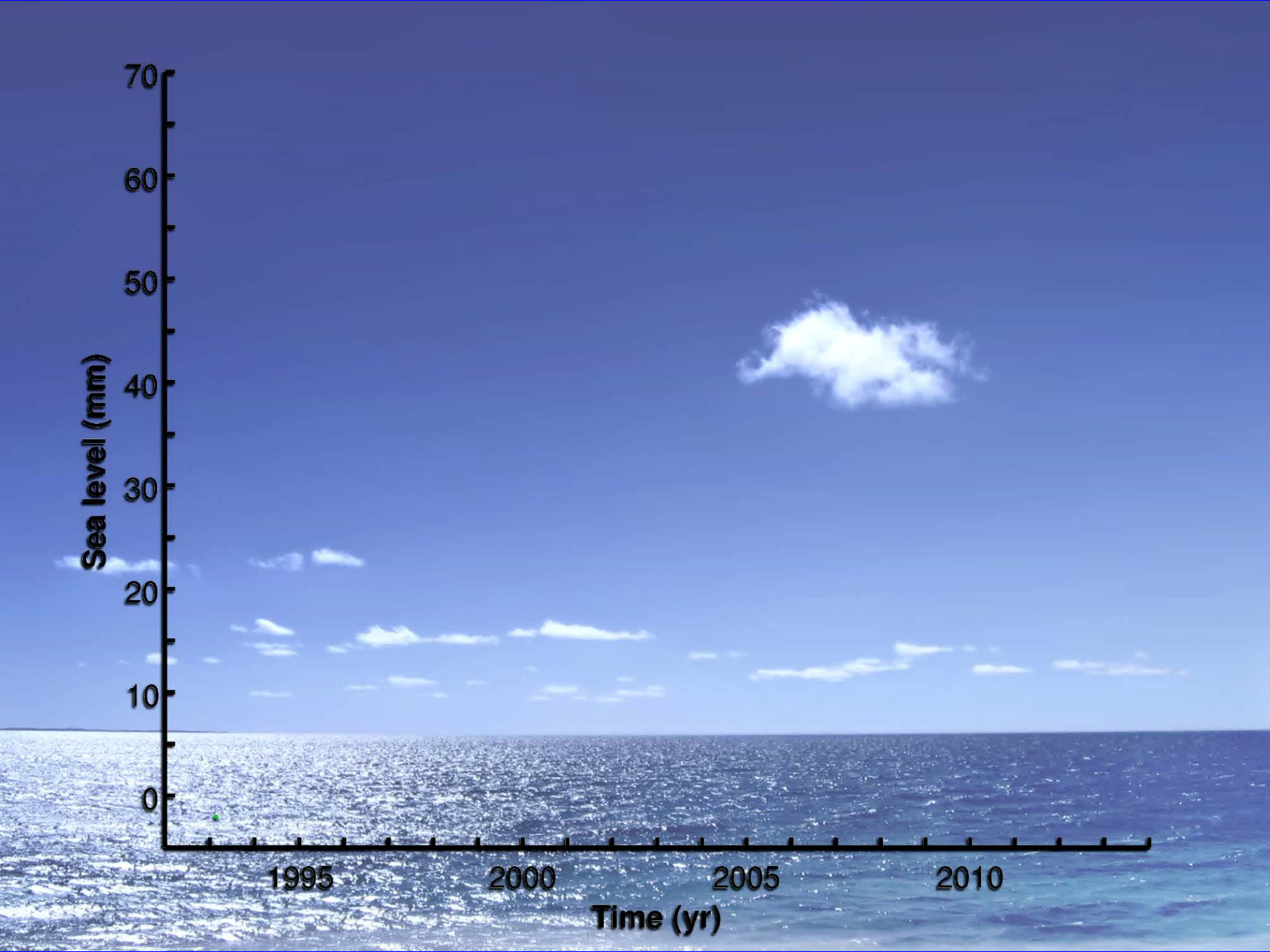
Sea level change now routinely measured by altimeter satellites

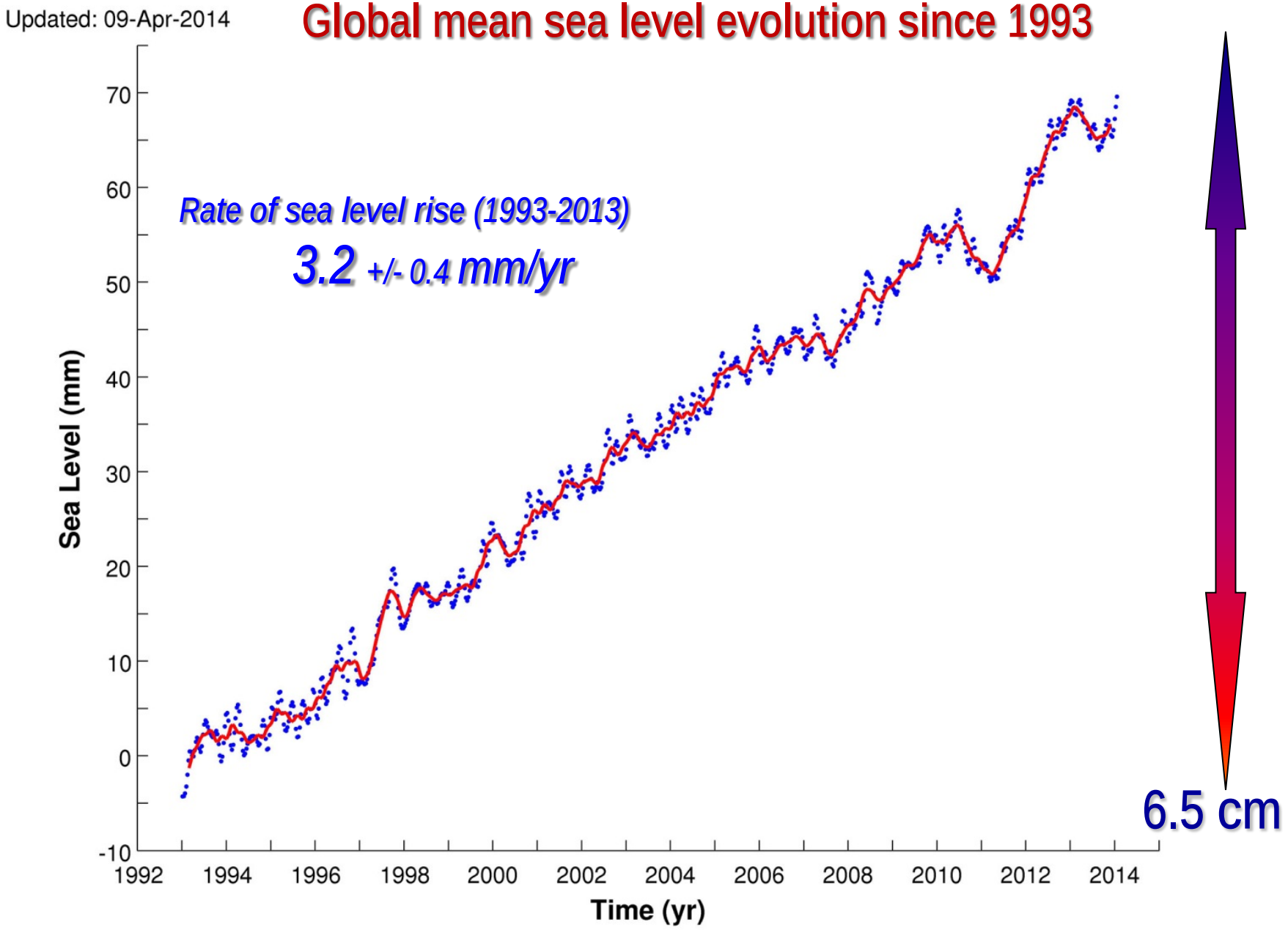


Since 1993
→ satellite altimetry

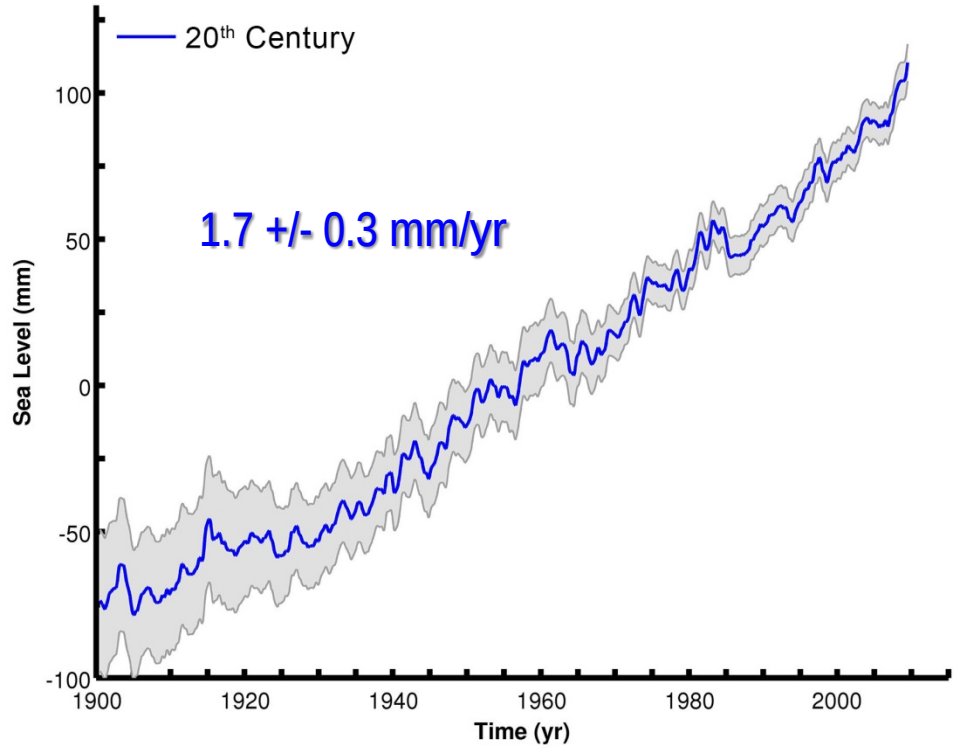
Sea surface height measurements
with 1-2 cm accuracy

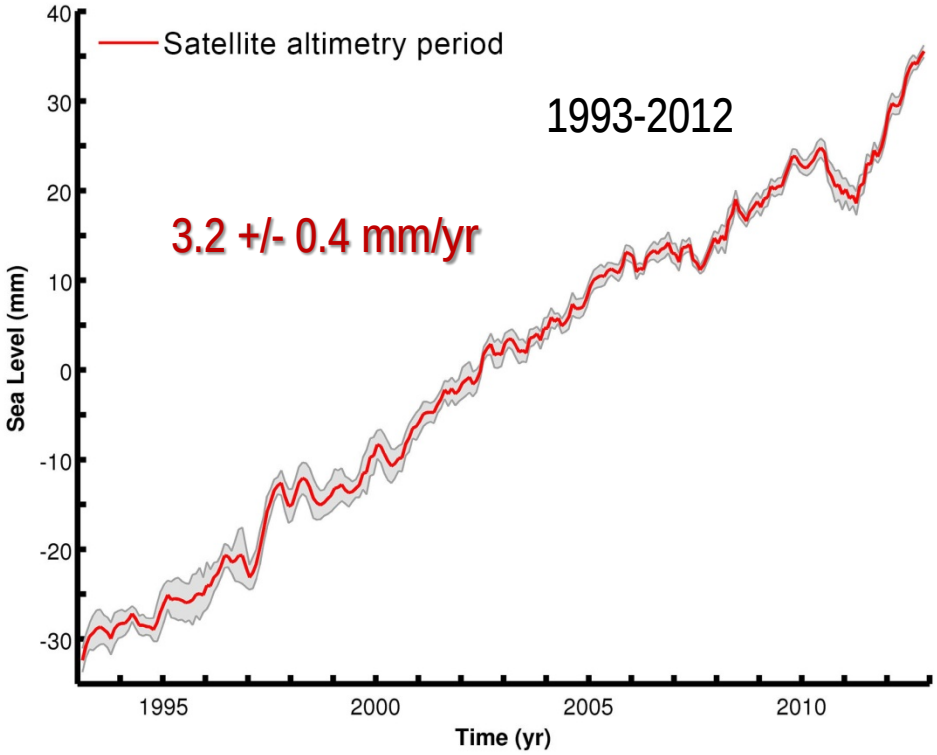
Global coverage of the oceans
in ~10 days

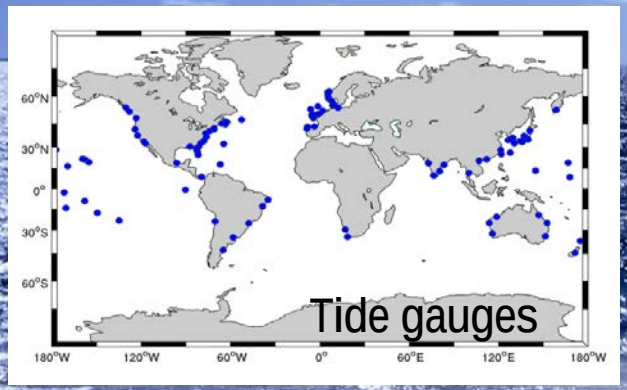

70
60
50
40
30
20
10
0
Sea level (mm)
1995
2000
2005
2010
Time (yr)

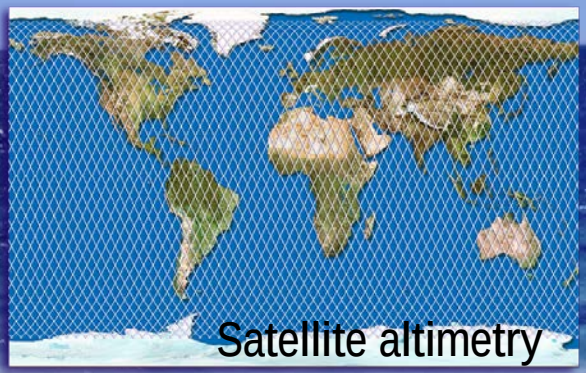

Updated: 09-Apr-2014
Global mean sea level evolution since 1993
Rate of sea level rise (1993-2013)
3.2 +/- 0.4 mm/yr
Sea Level (mm)
70
60
50
40
30
20
10
0
-10
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Time (yr)
6.5 cm

Sea level rise : 20th century and past 2 decades









Questions

- **Is sea level rise accelerating?**

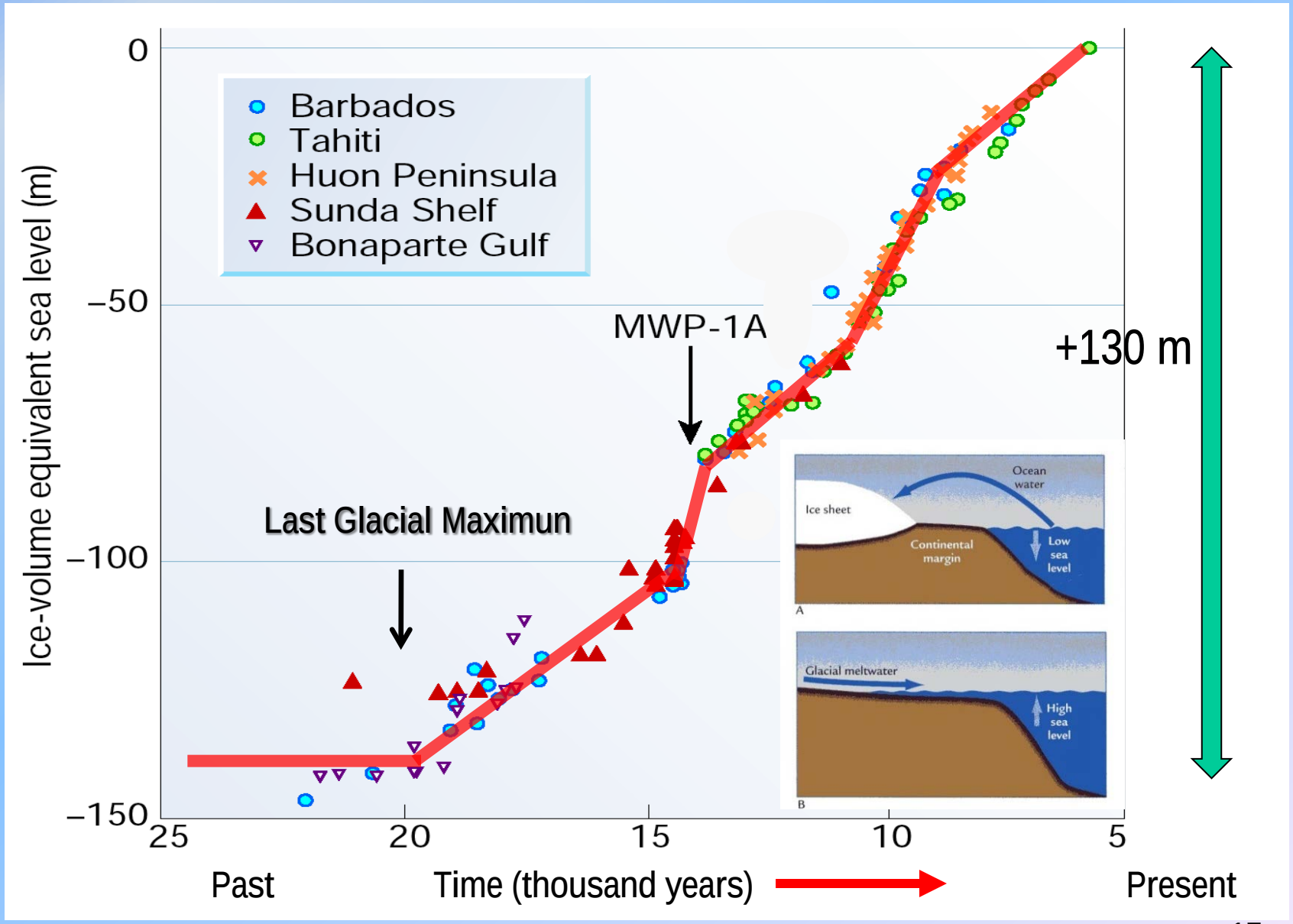
  Yes!

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?**

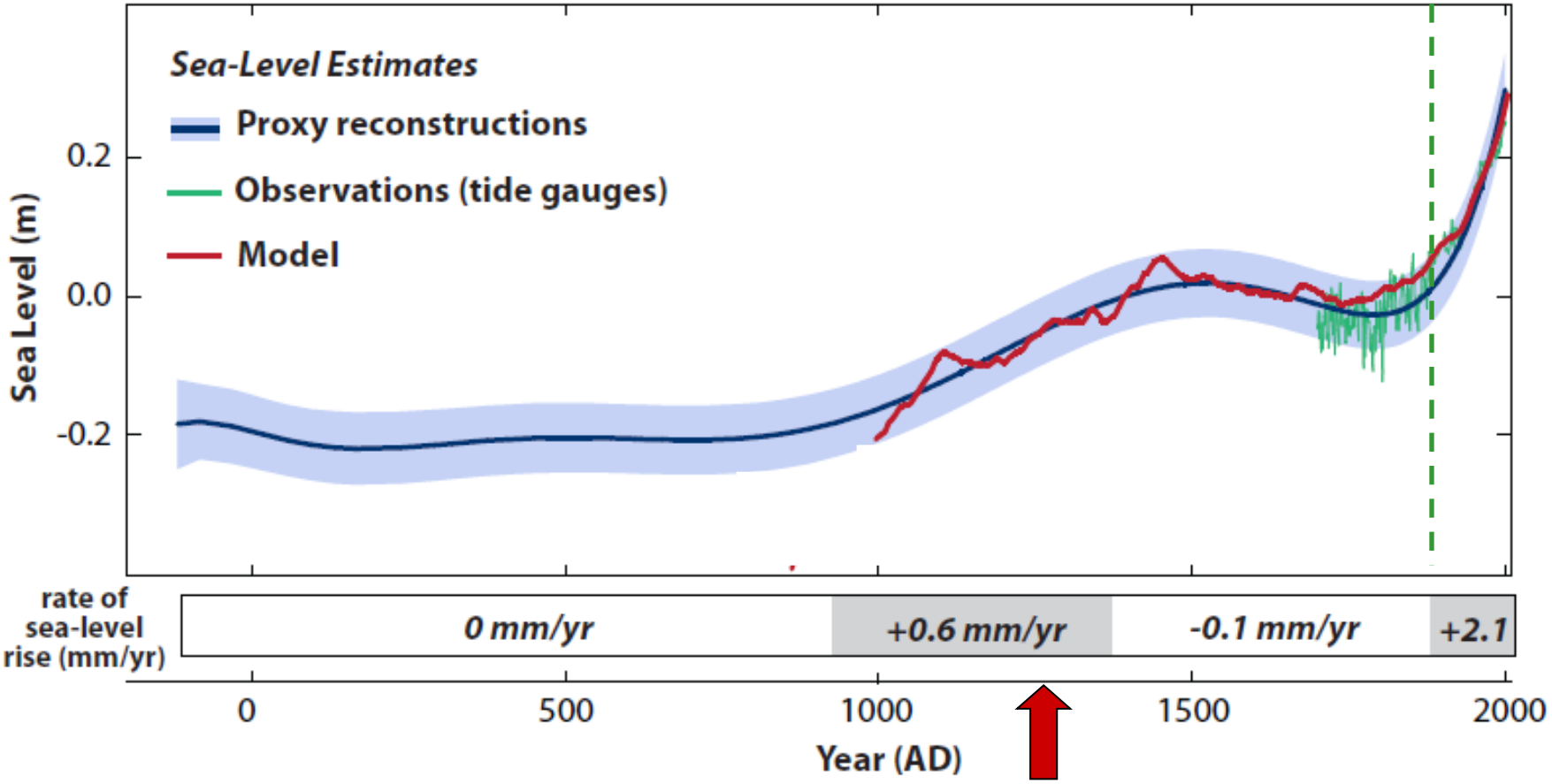
  Yes and no!

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

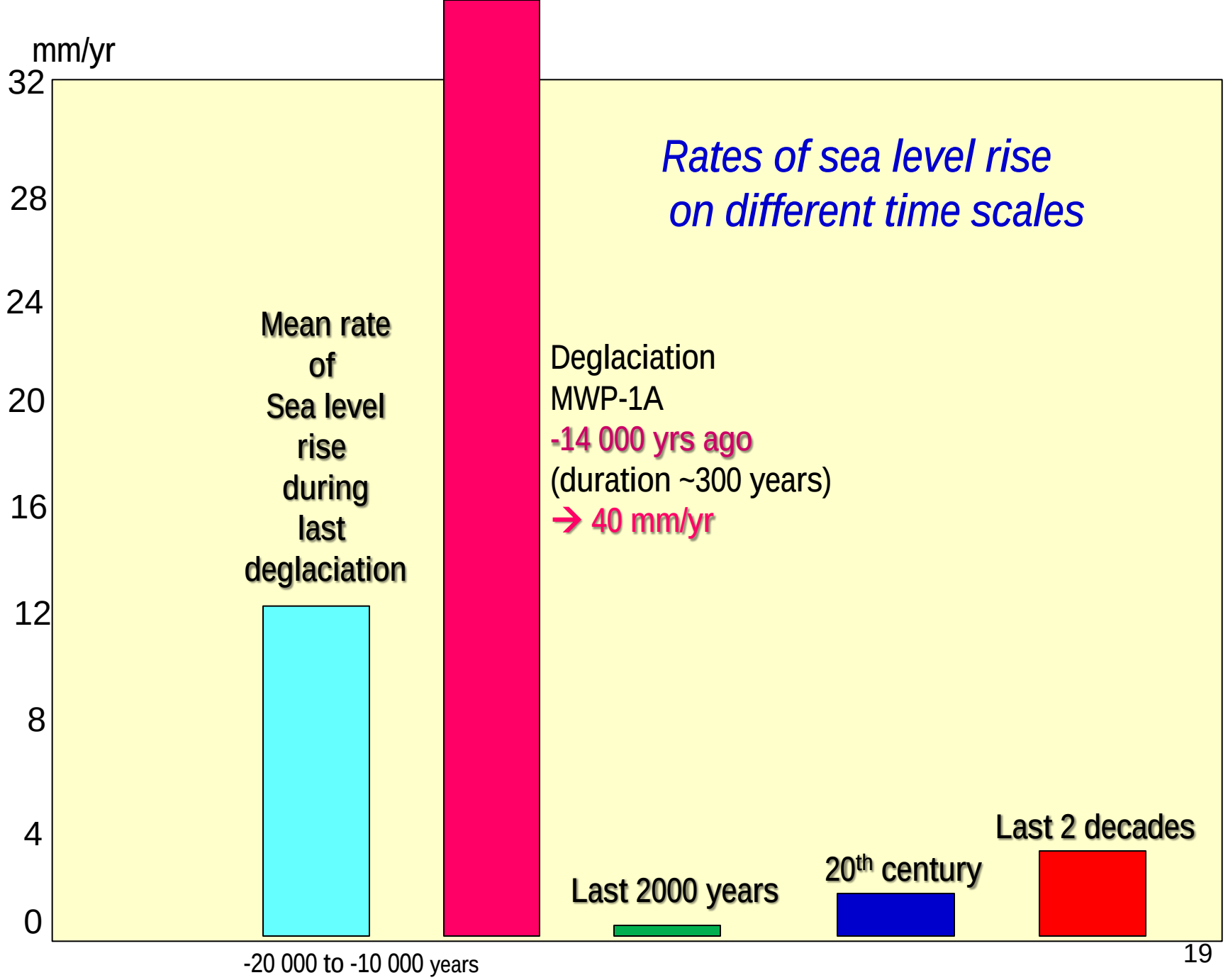


From Lambeck et al., 2002

Evolution of the mean sea level over the last 2000 years



Kemp et al. (2011)

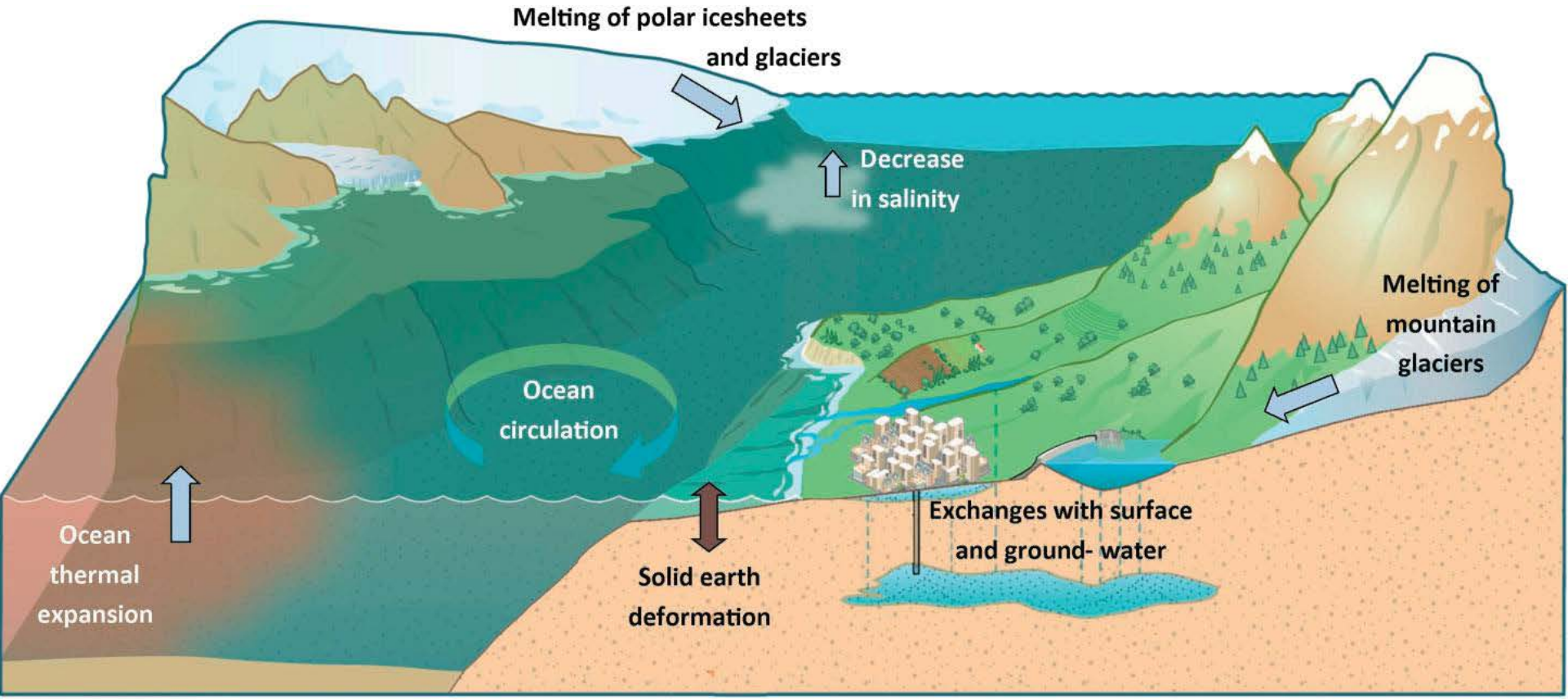

mm/yr
32
28
24
20
16
12
8
4
0
Rates of sea level rise
on different time scales
Mean rate
of
Sea level
rise
during
last
deglaciation
Deglaciation
MWP-1A
-14 000 yrs ago
(duration ~300 years)
→ 40 mm/yr
Last 2000 years
20th century
Last 2 decades
-20 000 to -10 000 years

Question

Can we close the sea level budget?

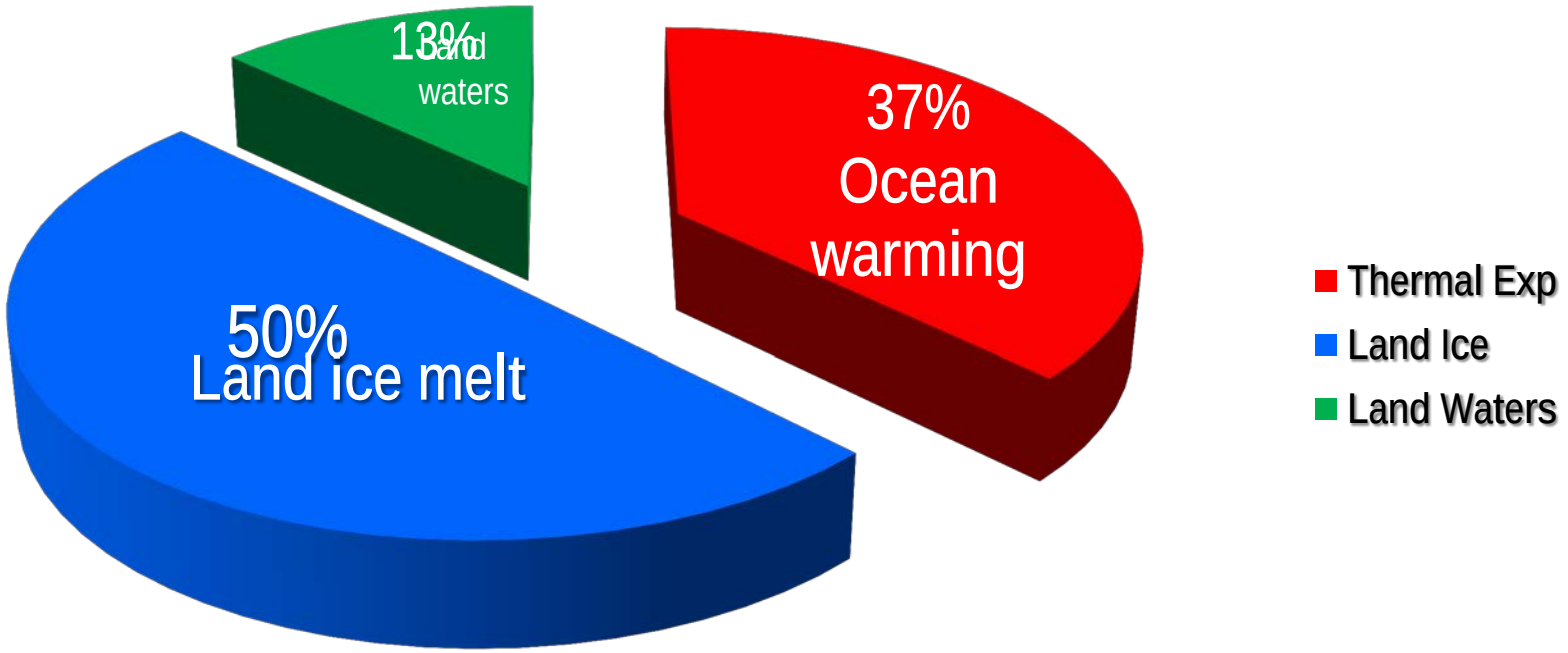
Components of the global mean sea level rise

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



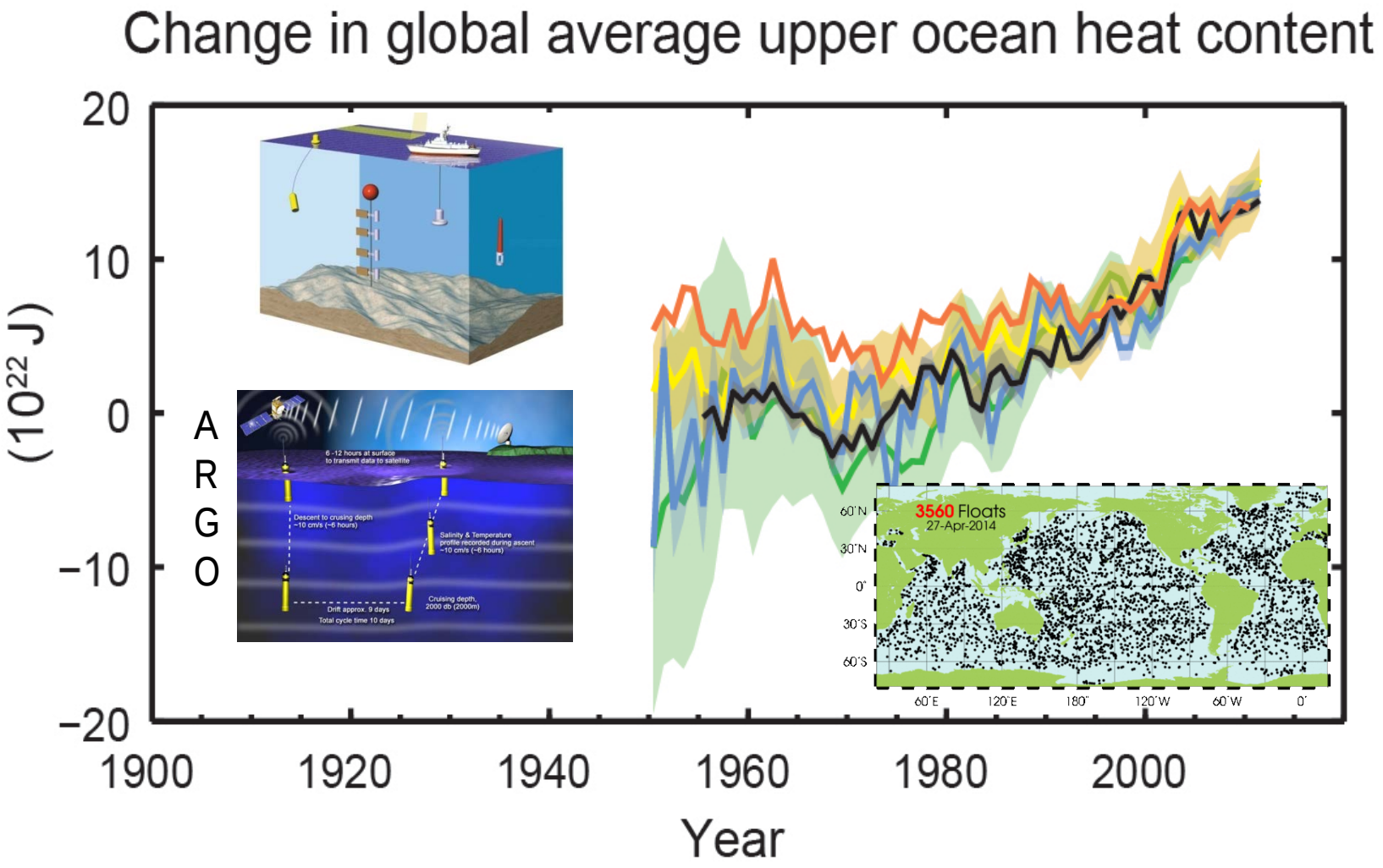
Causes of the global mean sea level rise (altimetry era: last 2 decades)

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



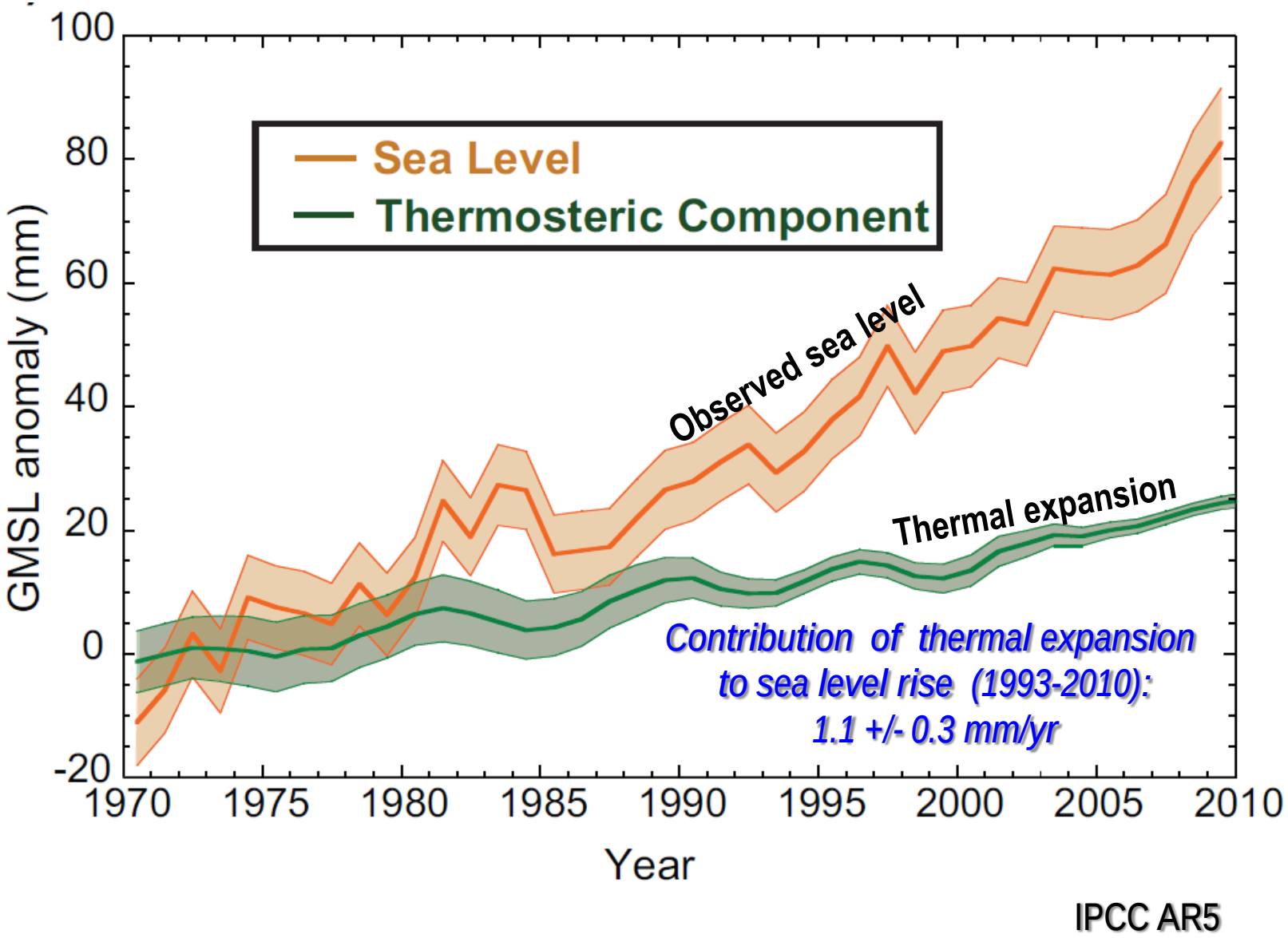
IPCC AR5

The ocean is warming

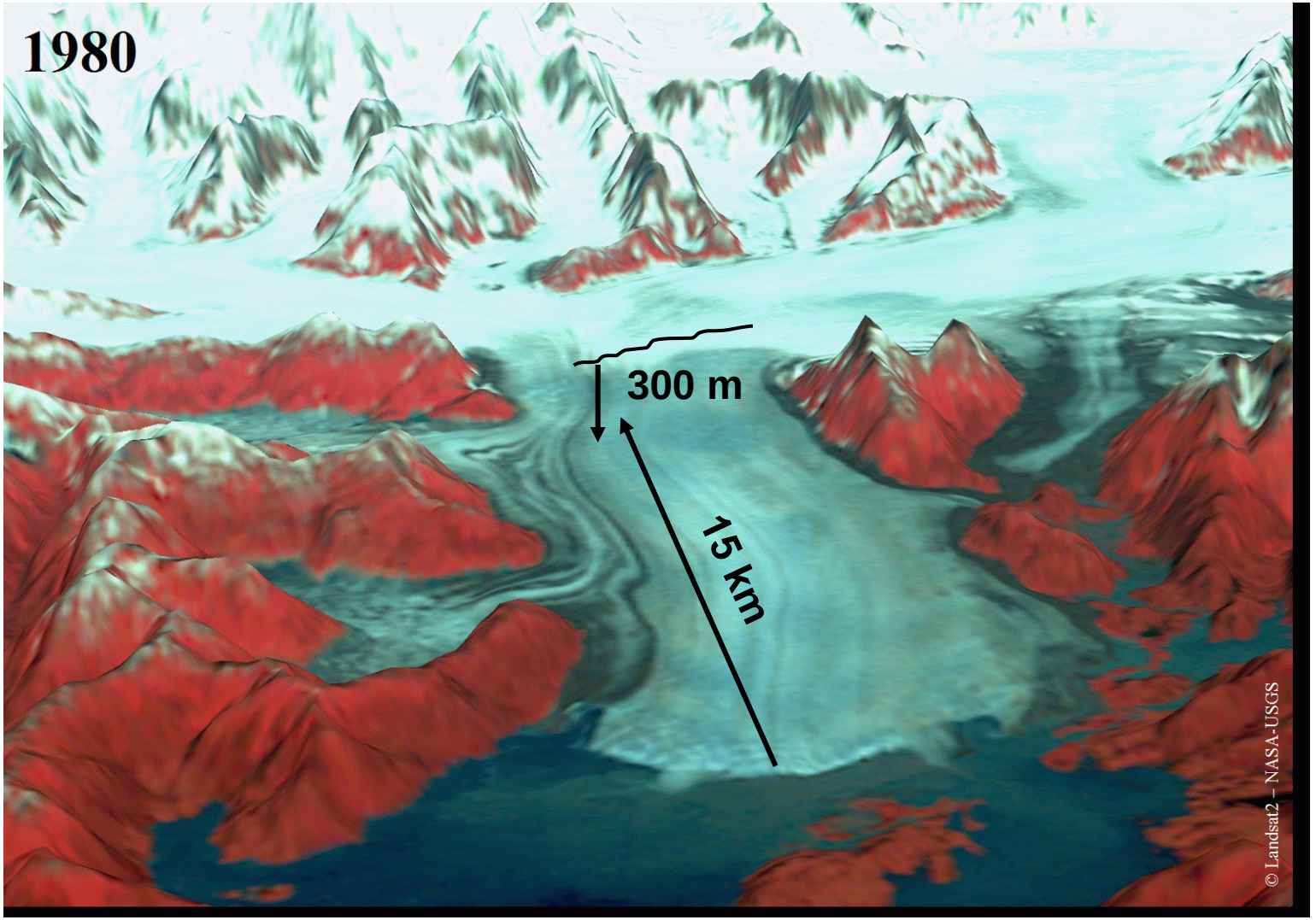


IPCC AR5

Thermal expansion contribution to sea level rise



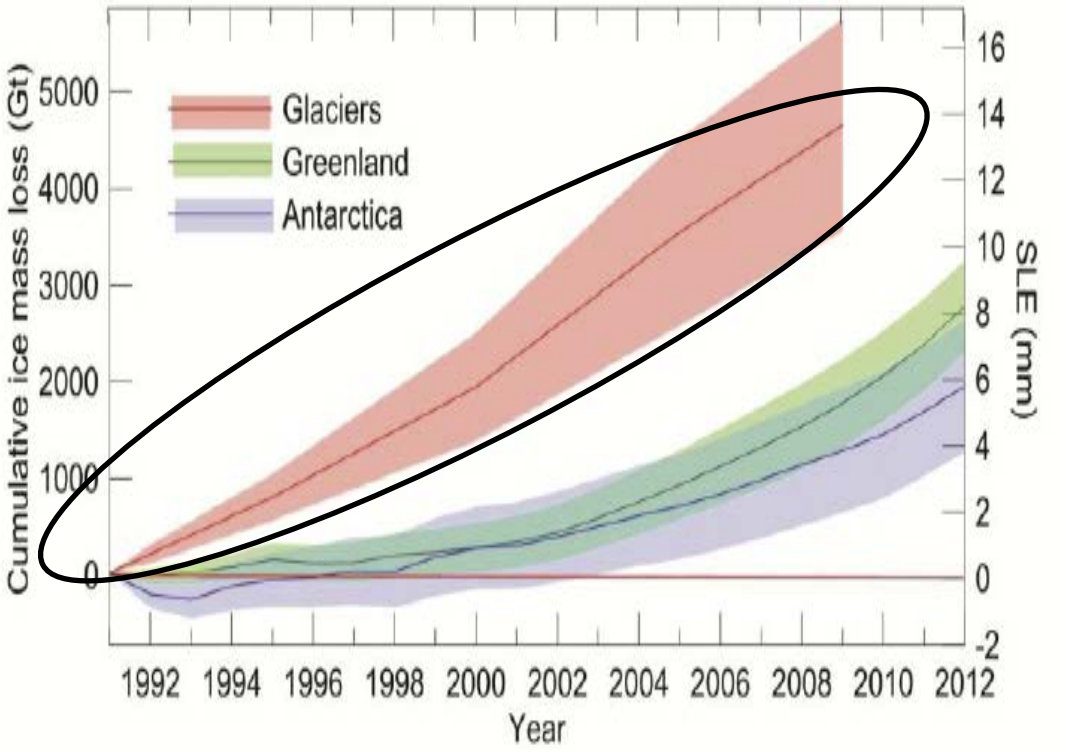
Retreat and thinning of mountain glaciers observed by satellite imagery



Columbia glacier (Alaska) 1980 and 2007

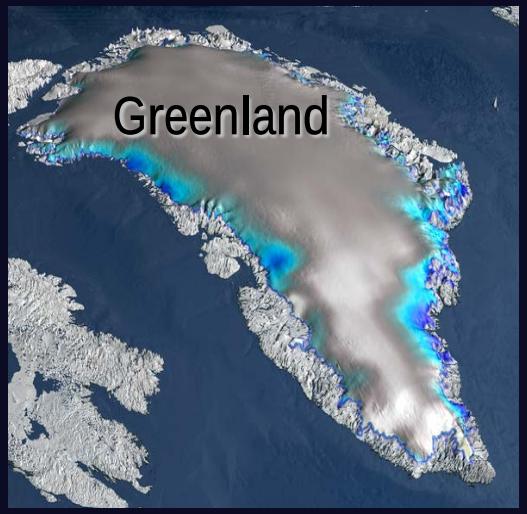
Berthier et al. 2010

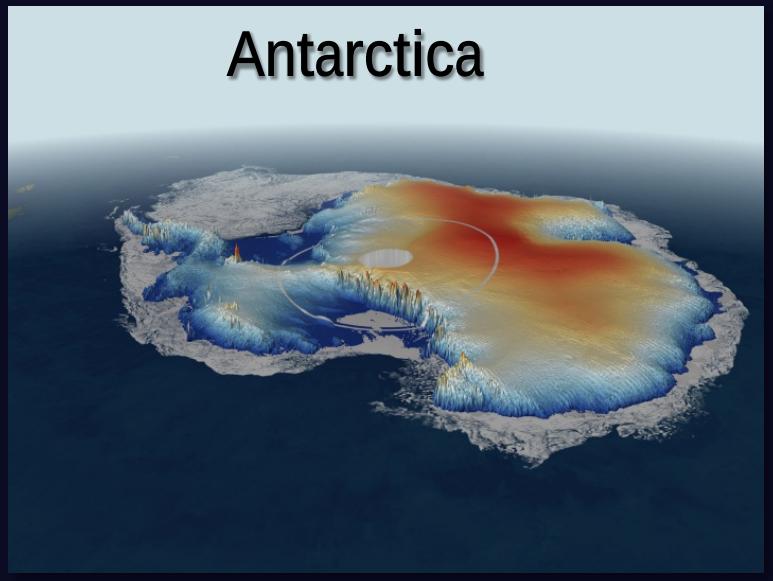
Contribution of glaciers to sea level rise (1993-2010) → ~0.9 mm/yr (IPCC AR5)



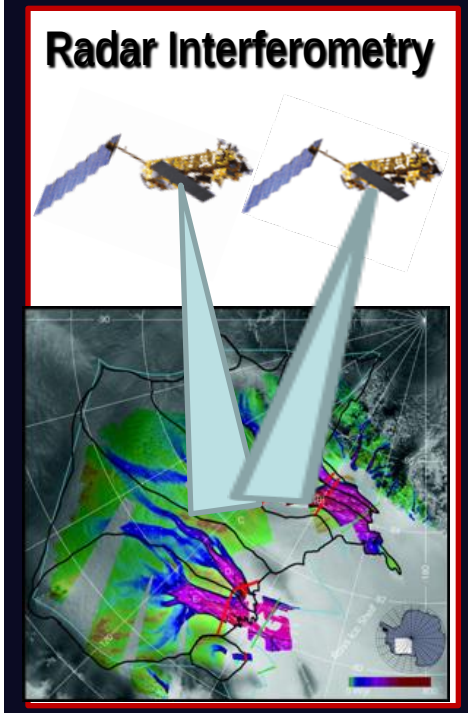
IPCC AR5

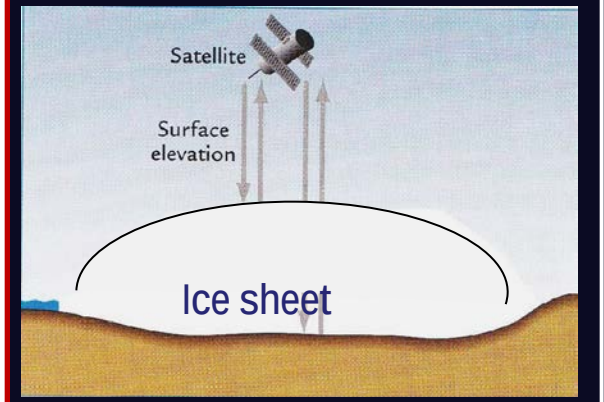
Since the early 1990s, ice sheet mass changes measured from space





« GRACE »
space gravimetry





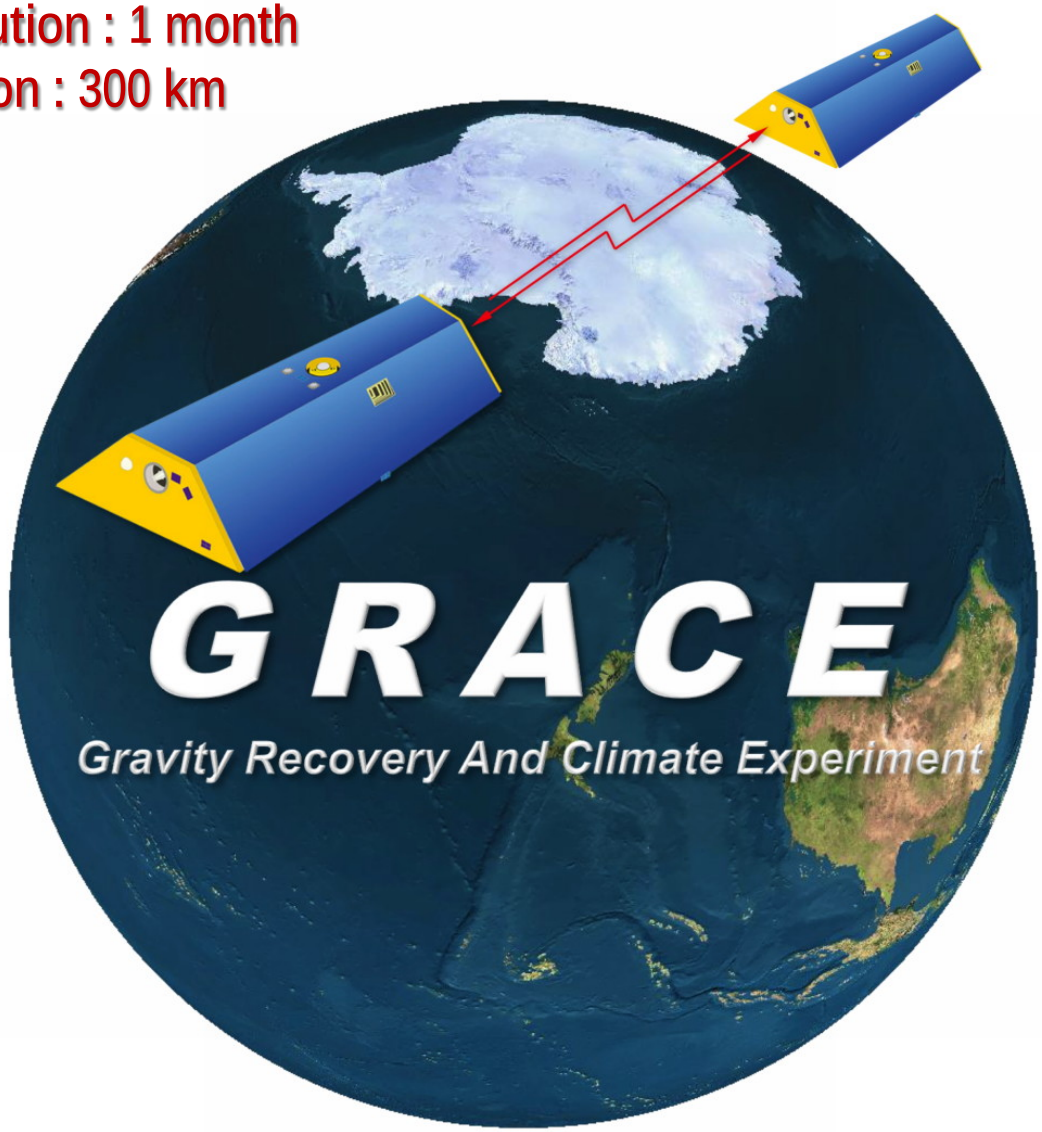
Radar & laser altimetry

GRACE space gravimetry mission (launched in 2002)

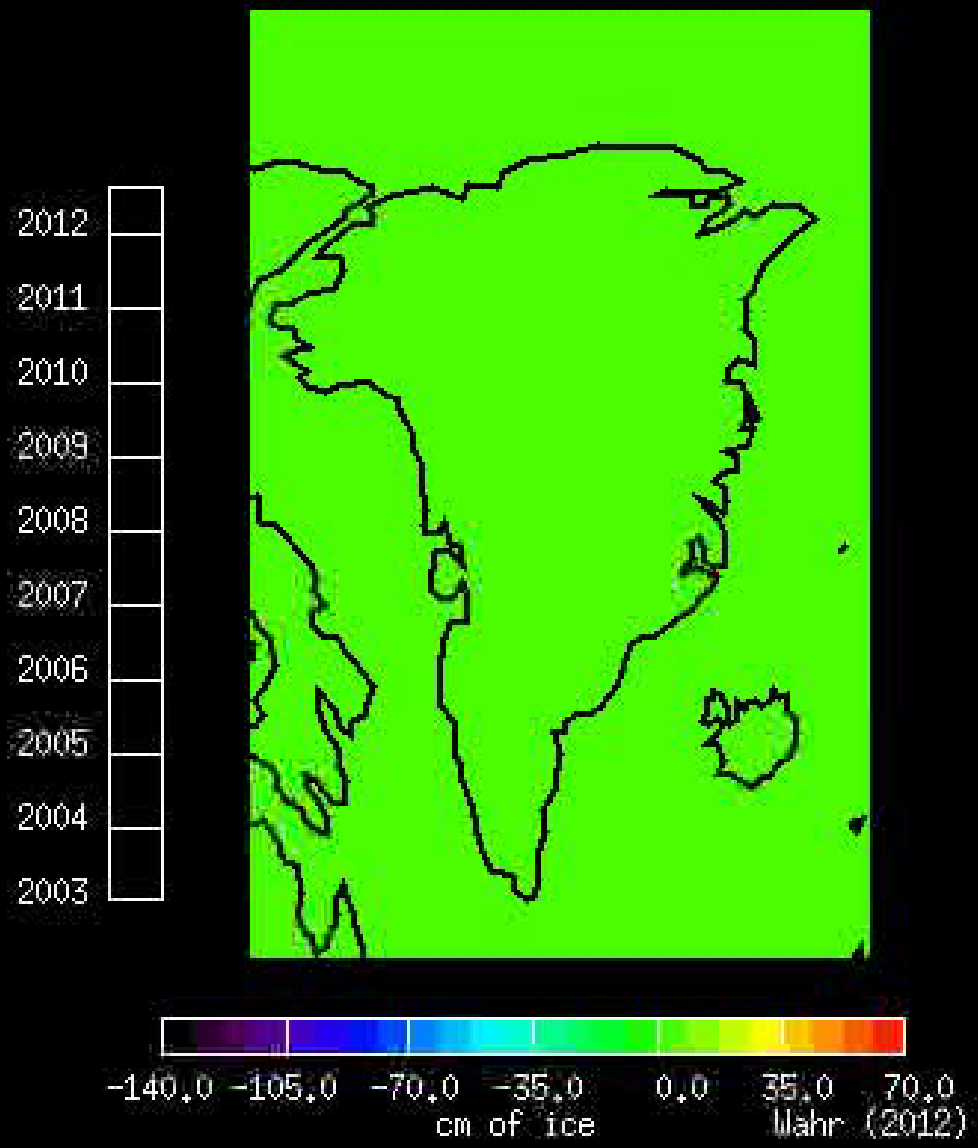
Measurement of temporal variations of the Earth's gravity field

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

- Temporal resolution : 1 month
- Spatial resolution : 300 km

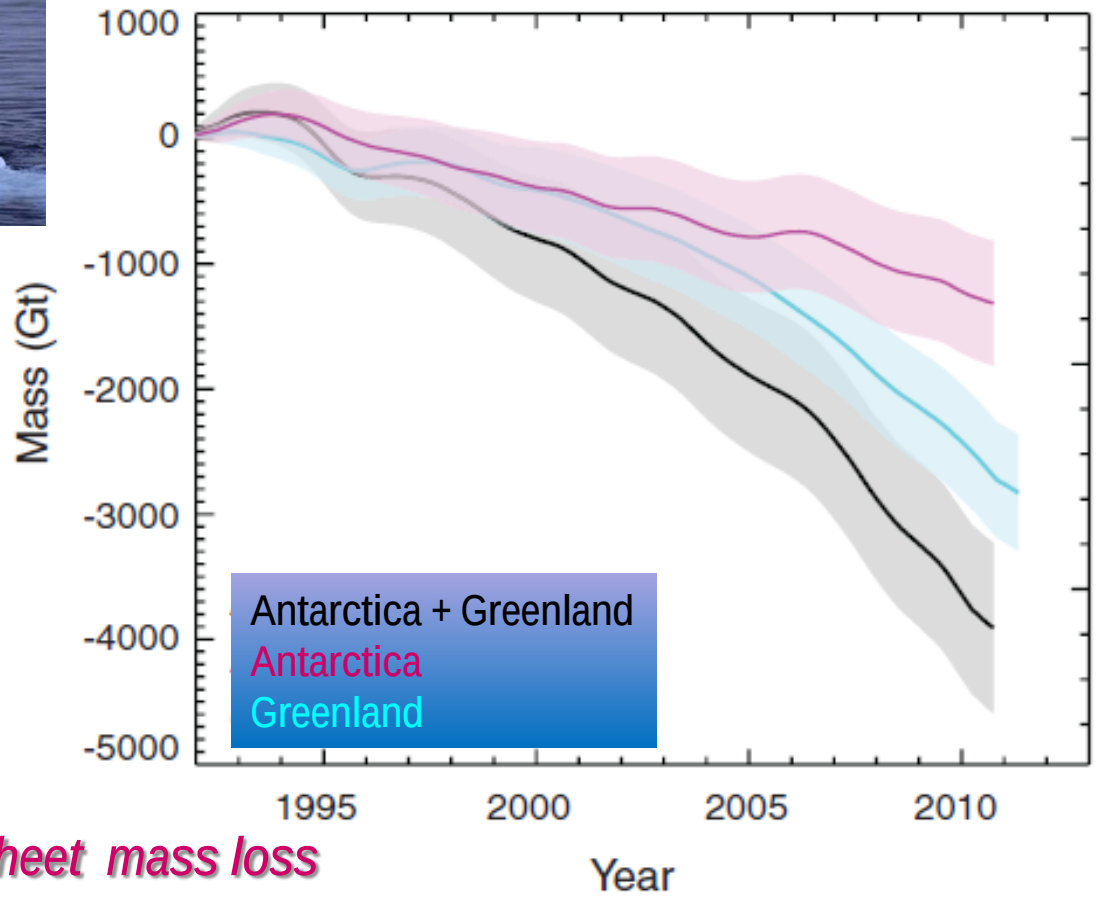


Ice mass loss of the Greenland ice sheet (blue-violet-black) between 2003 and 2012 observed by GRACE



Courtesy: 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)

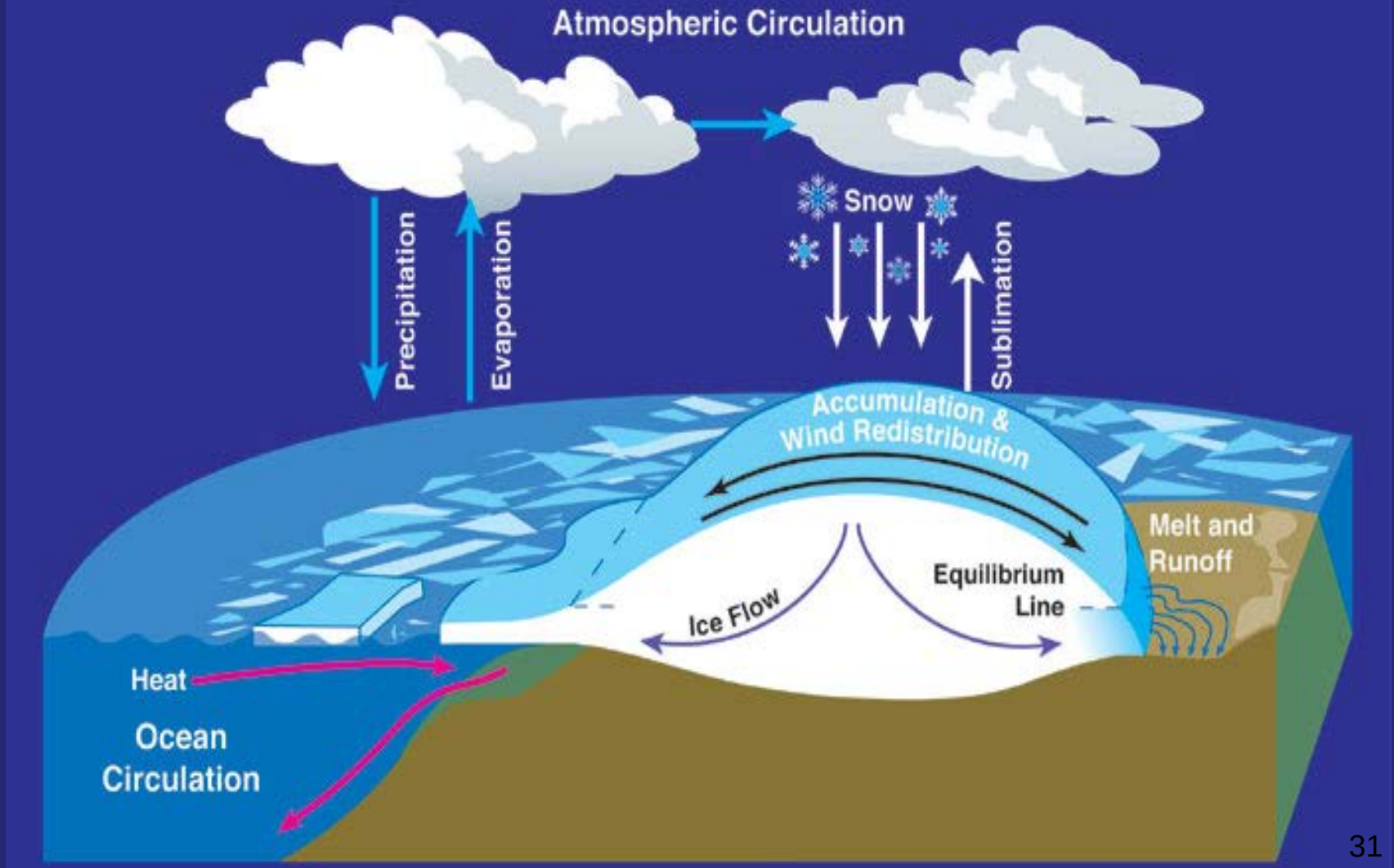
Antarctica : 30 +/- 67 Gt/yr (1992-2001); 147 (+/- 74) Gt/yr (2002-2011)

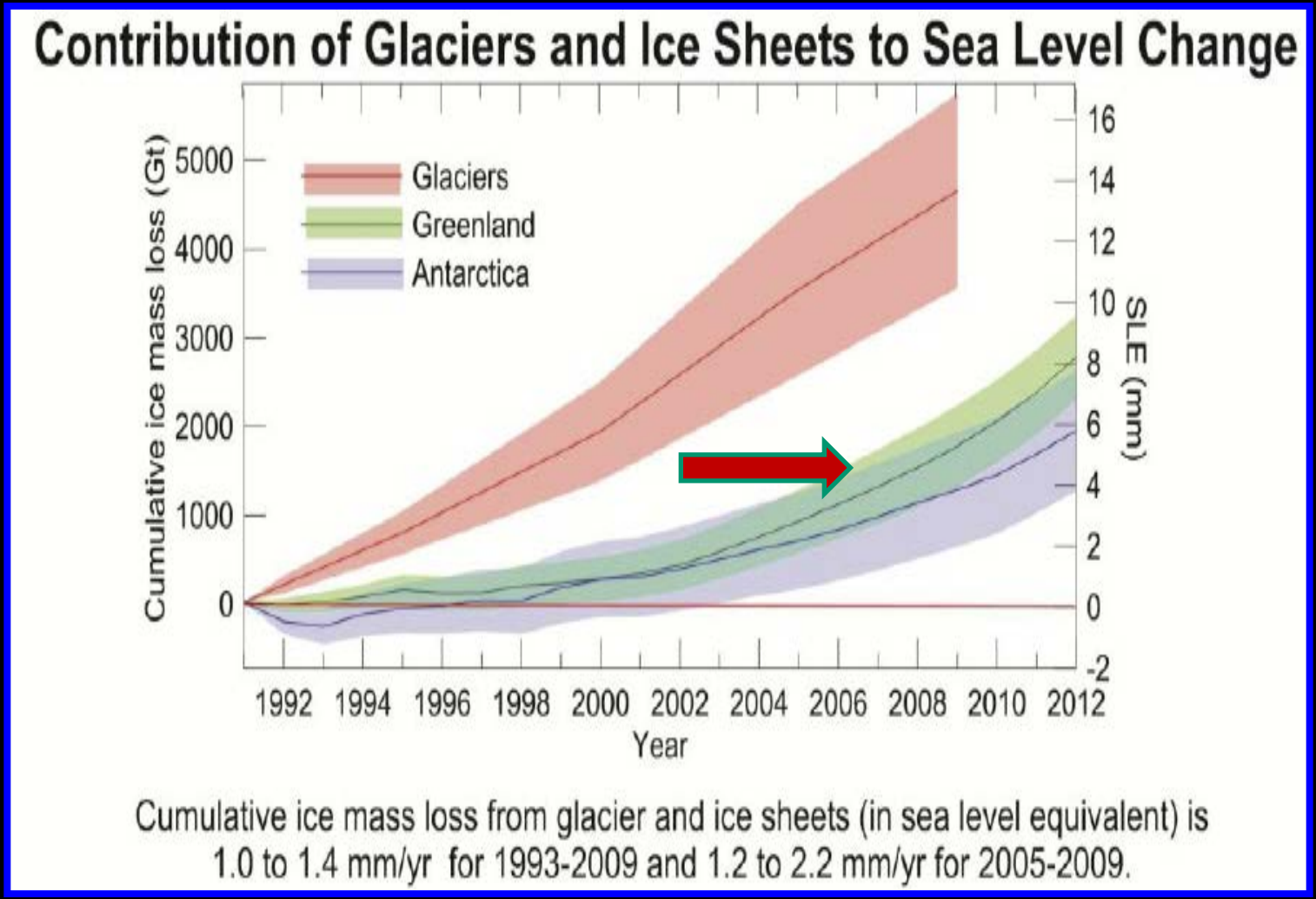
Shepherd et al., 2012
IPCC AR5

Ice sheet mass balance =

surface mass balance (accumulation/ablation)

+ ice loss through calving of icebergs (dynamical change)



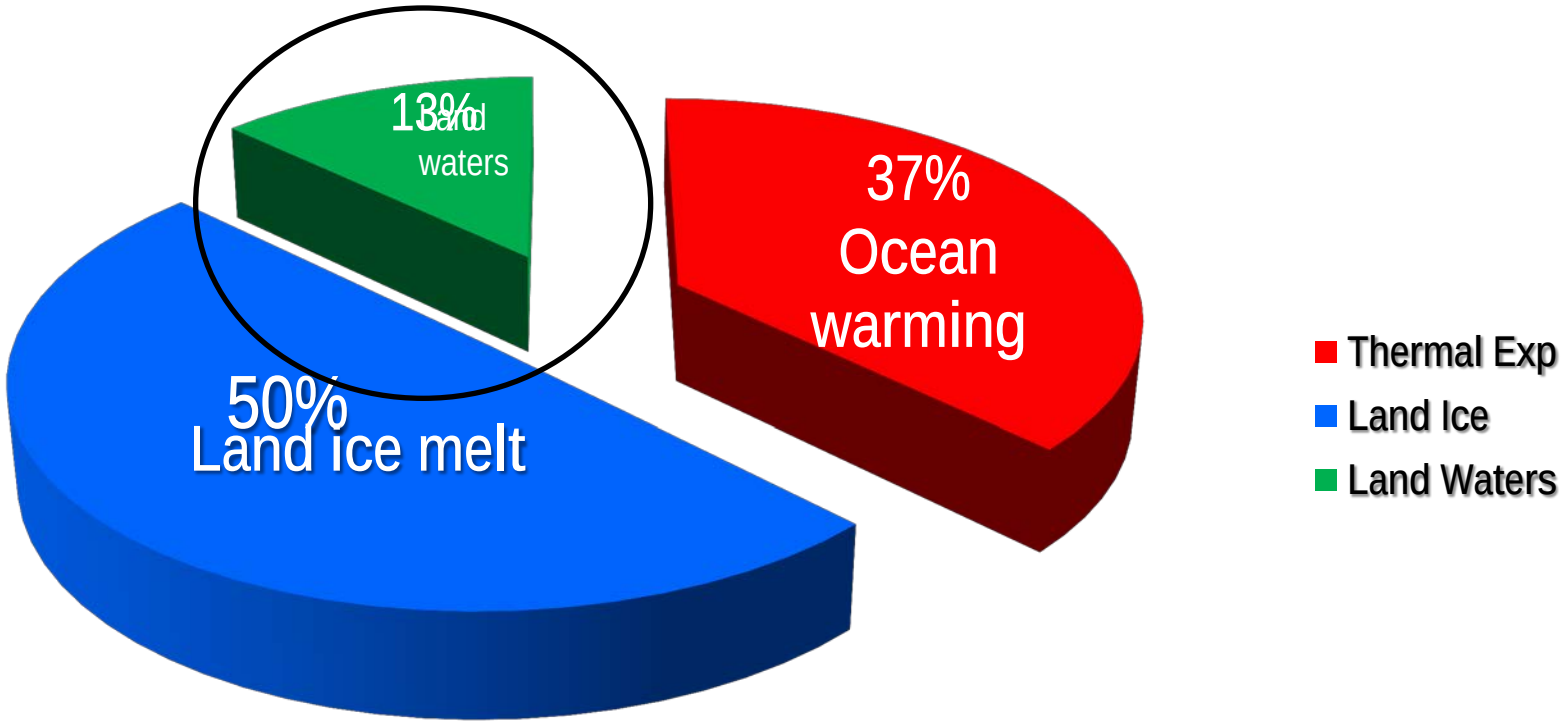


Ice sheet contribution (1993-2010) : 0.6 +/- 0.2 mm/yr

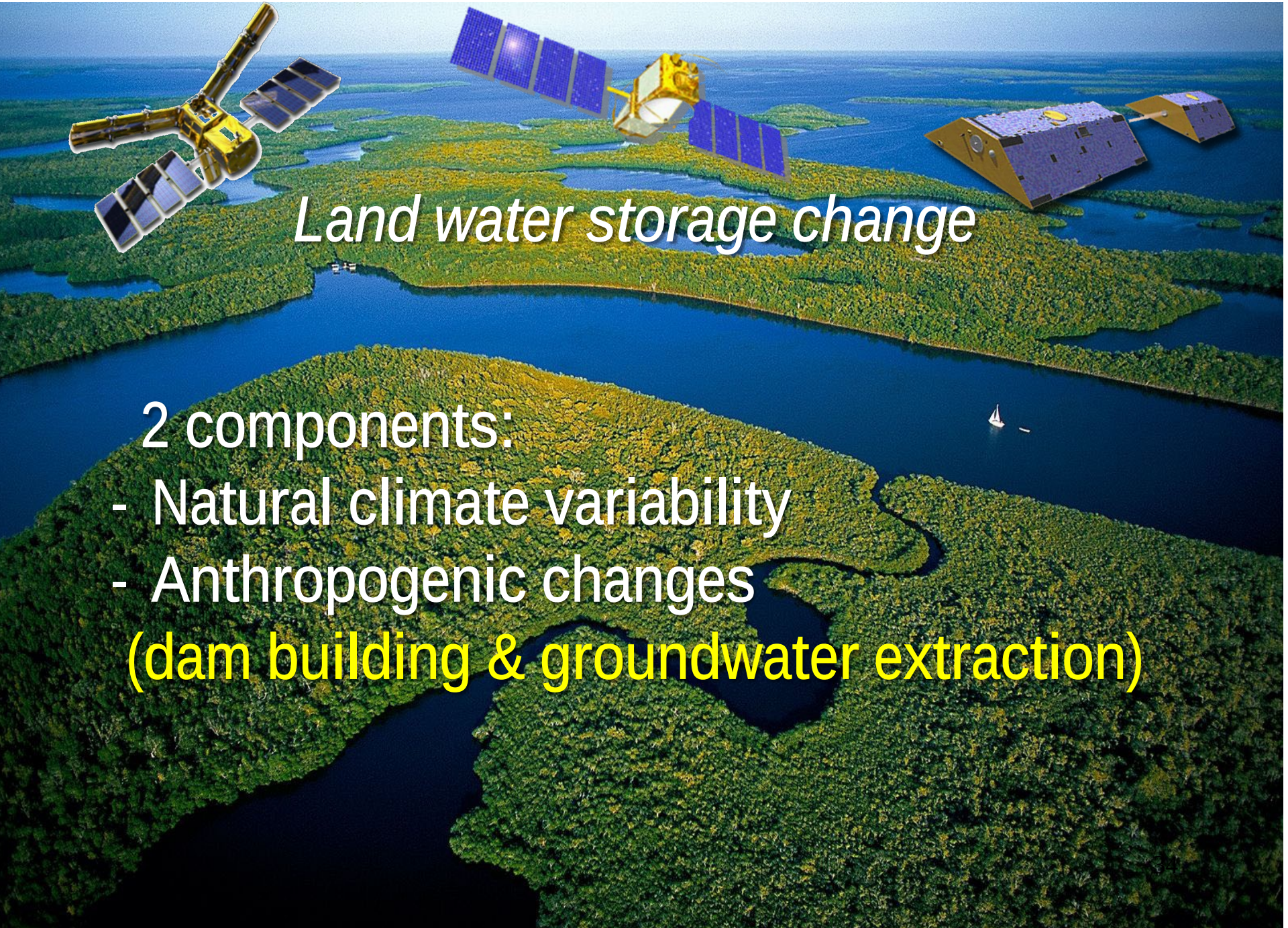
IPCC AR5

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

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



IPCC AR5



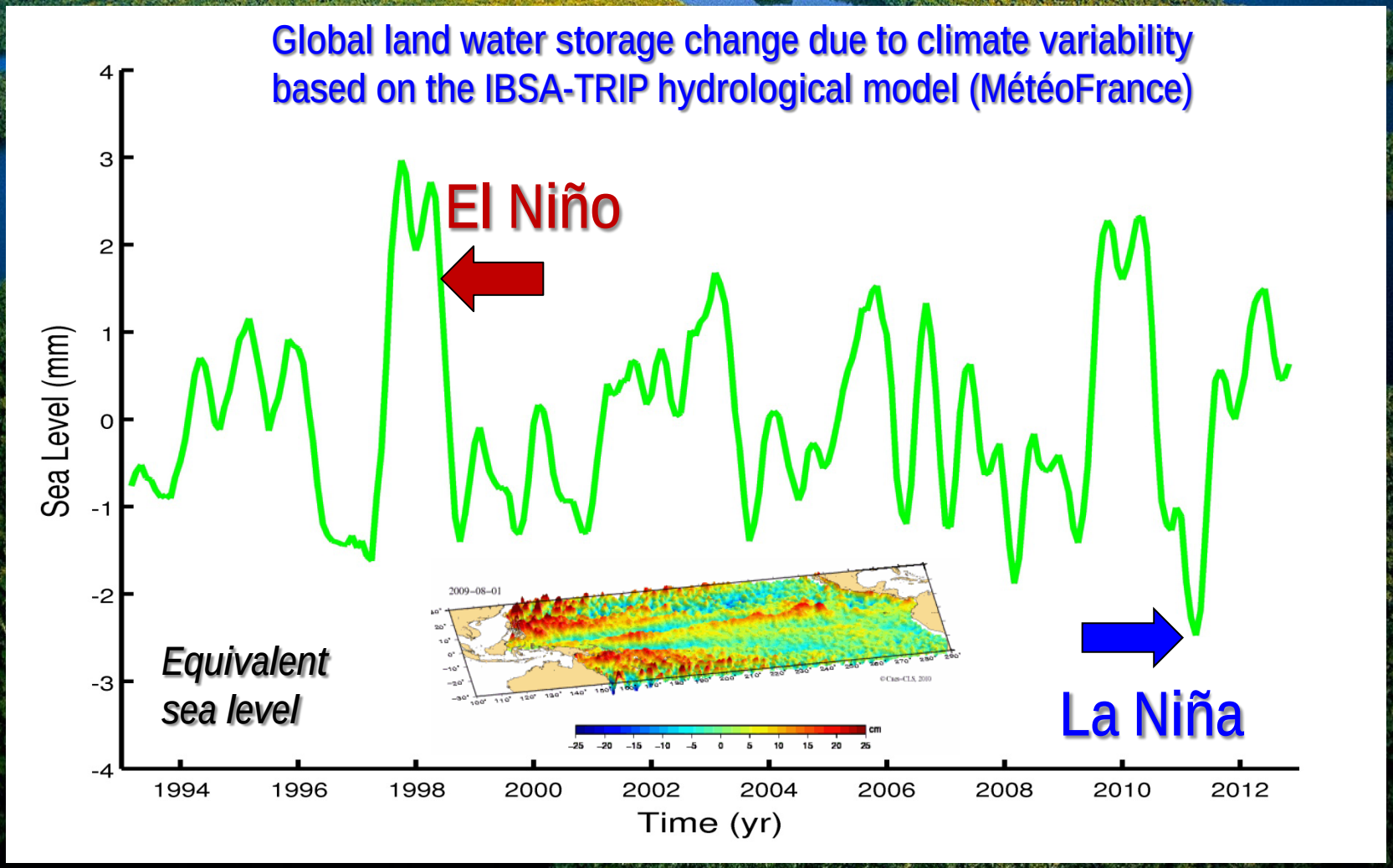
Land water storage change

2 components:

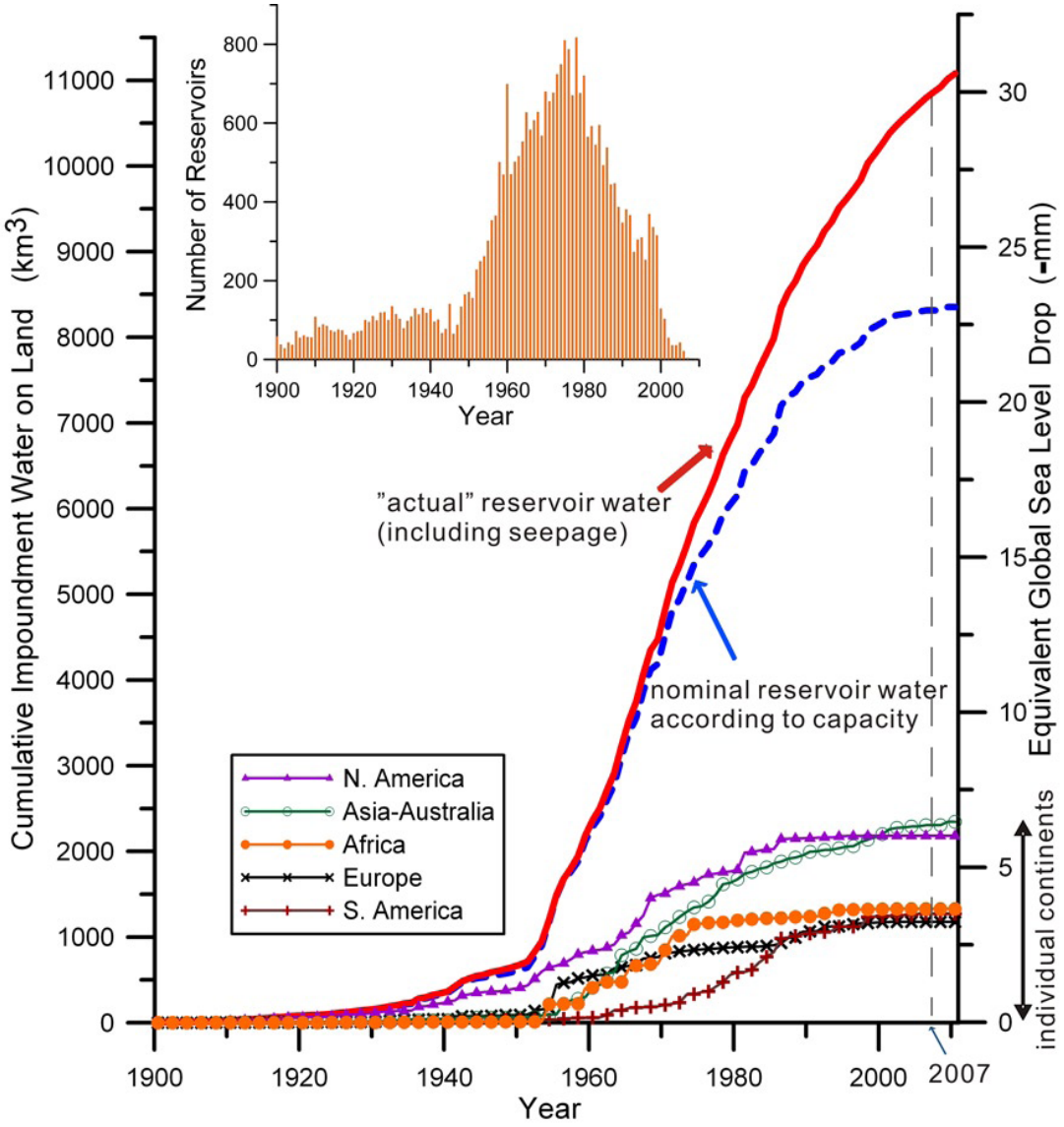
- Natural climate variability
- Anthropogenic changes

(dam building & groundwater extraction)

Land water storage change due to natural sources



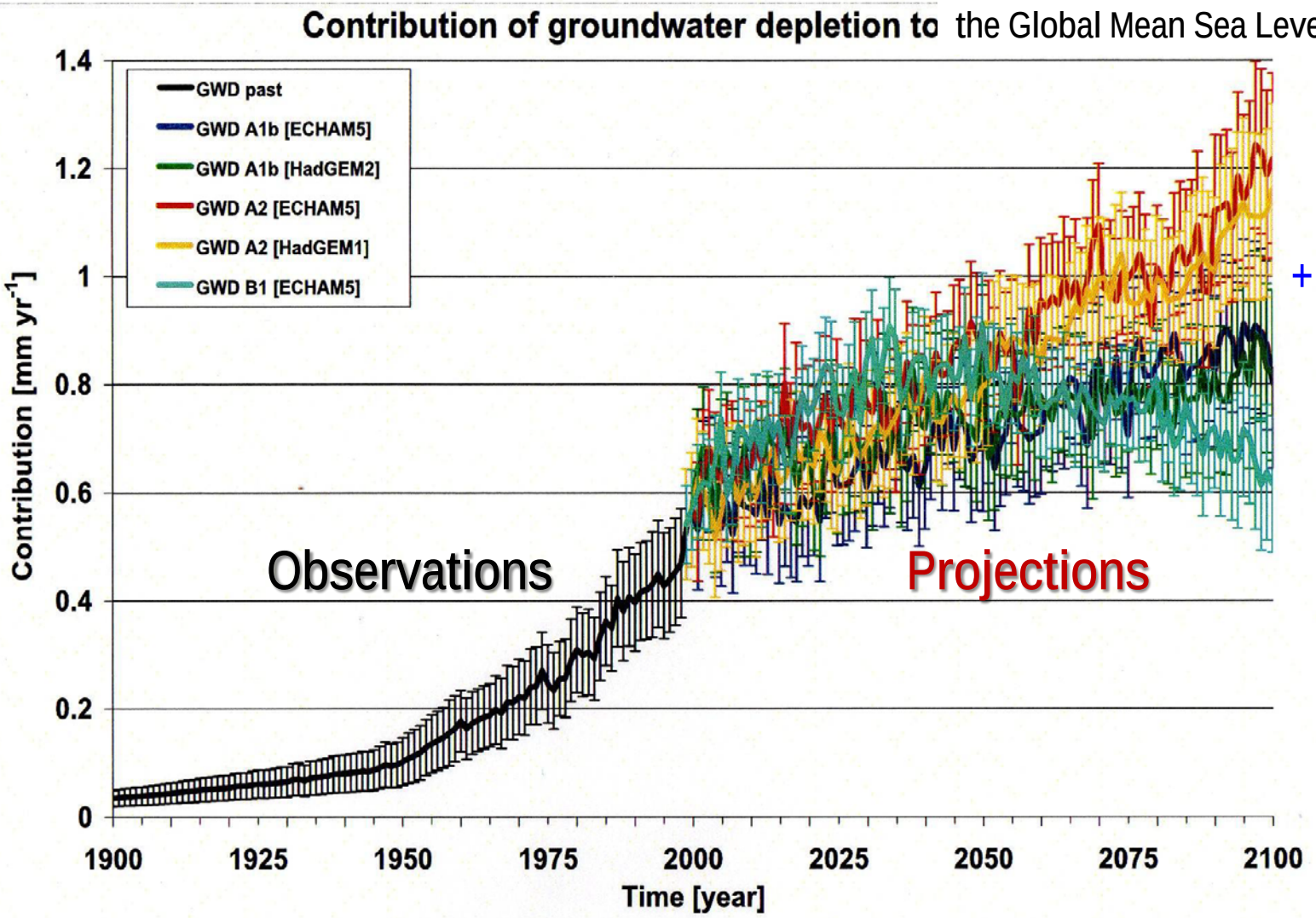
Dam building along rivers → Sea level drop



1993-2012
→ -0.3 mm/yr

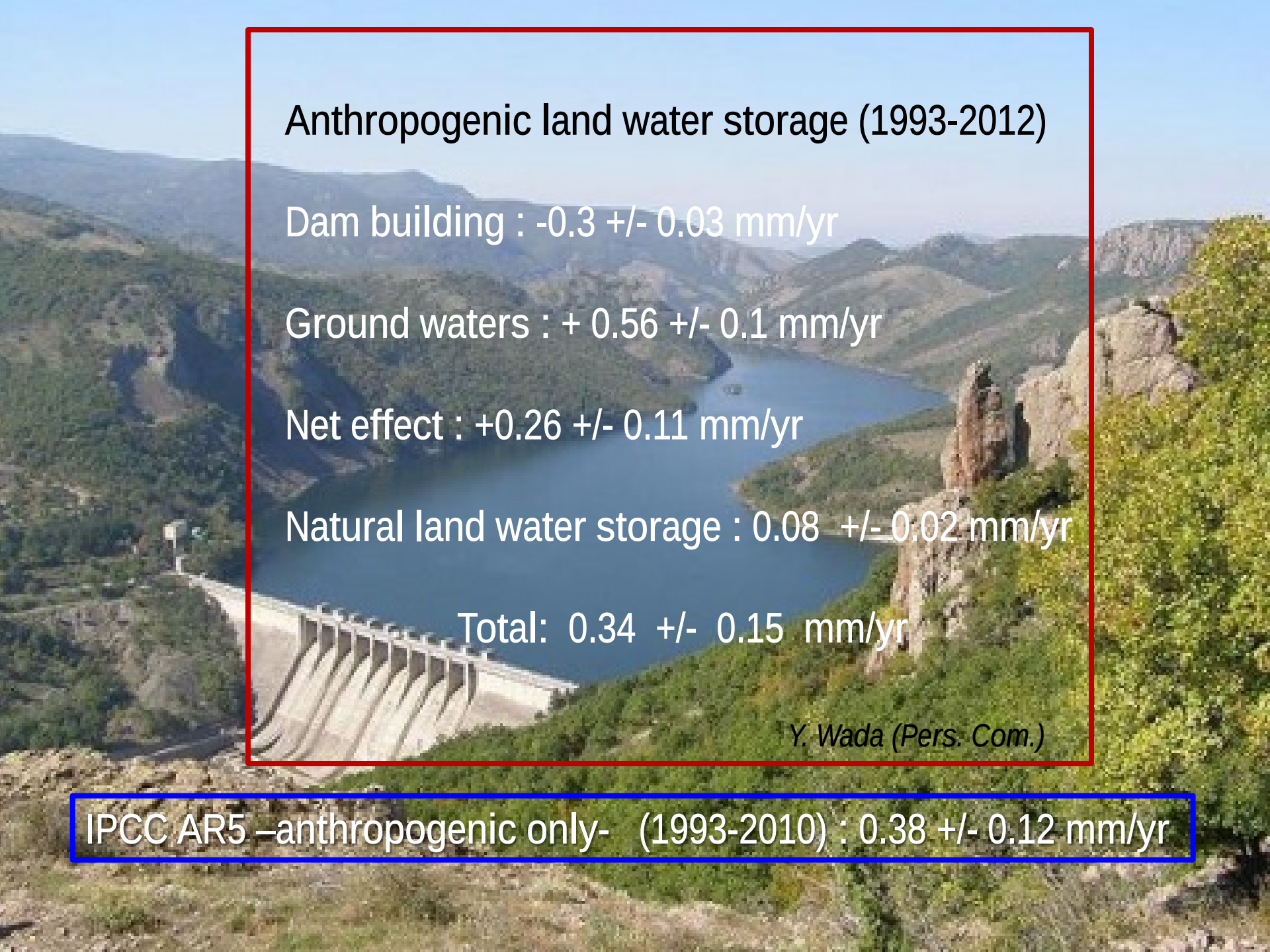
Chao et al., 2008

Ground water depletion → Sea level rise



1993-2012
→
+ 0.56 mm/yr

Wada et al., 2012



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

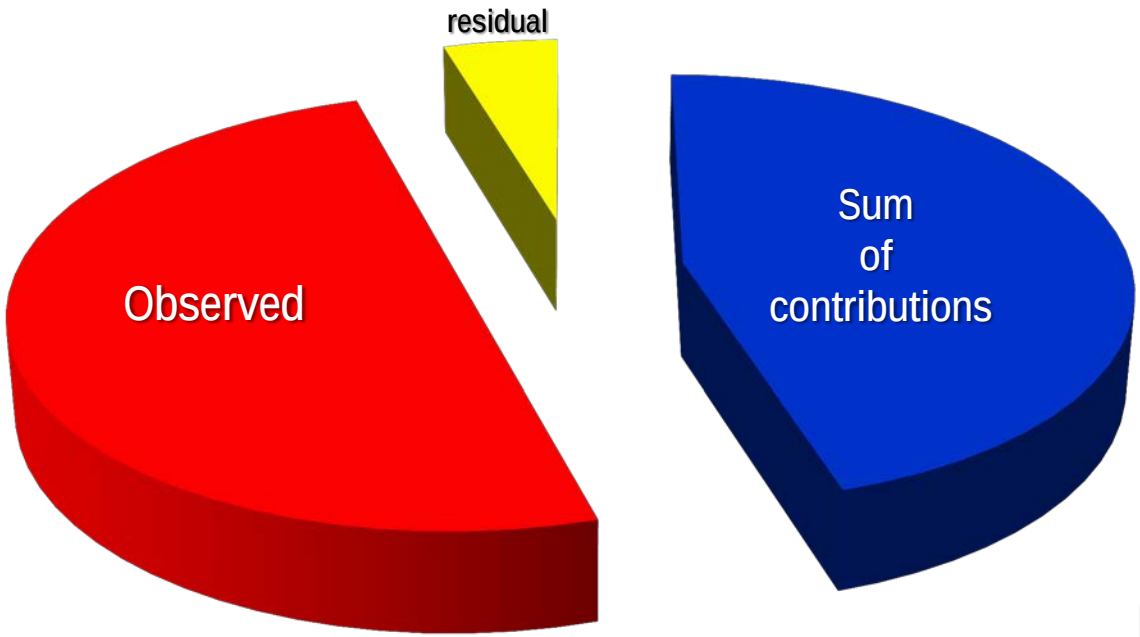
Natural land water storage : 0.08 +/- 0.02 mm/yr

Total: 0.34 +/- 0.15 mm/yr

Y. Wada (Pers. Com.)

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

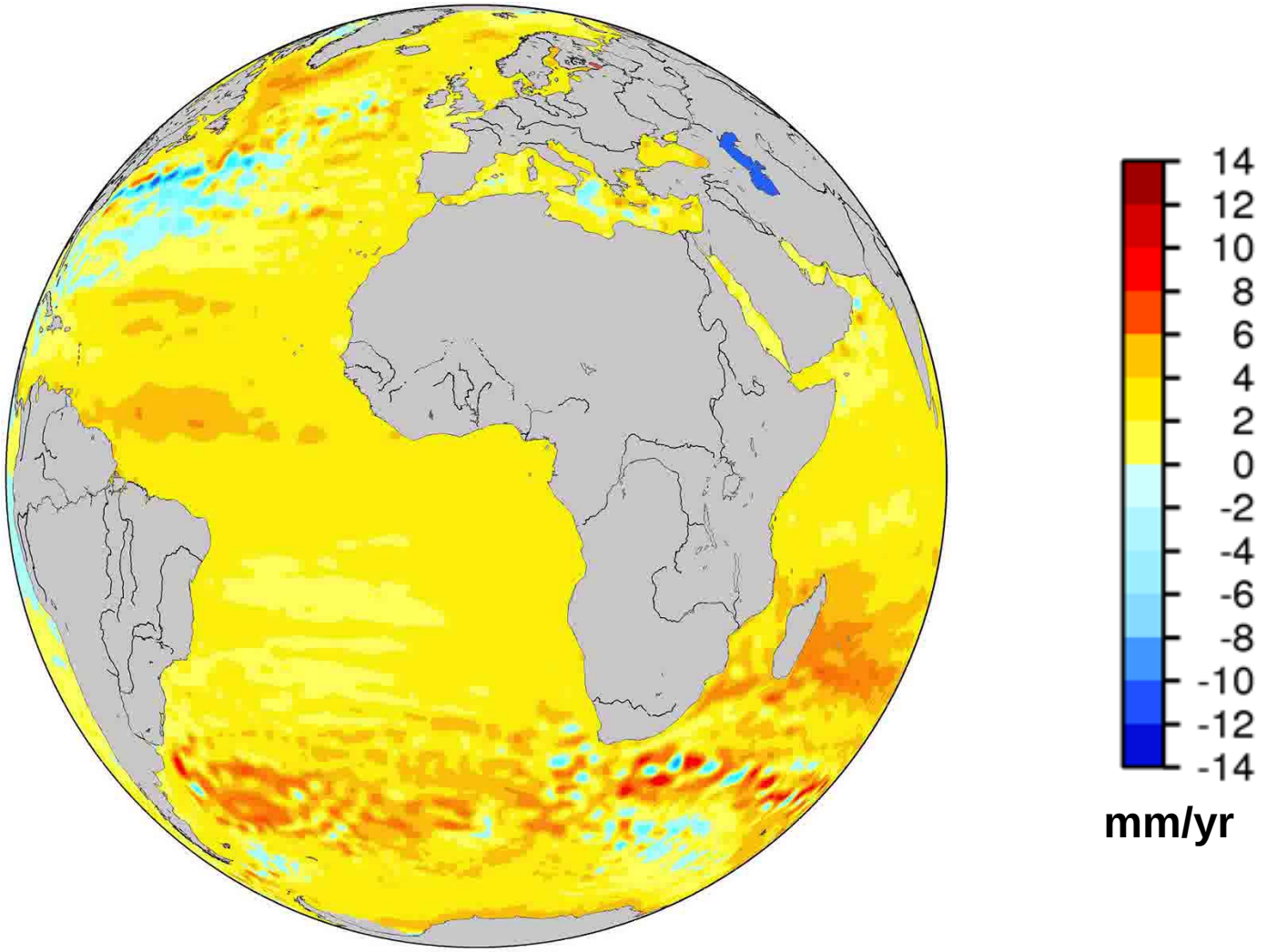
Observed sea level budget during the altimetry era (1993-2010)
IPCC AR5



	Rate of rise
Sum Contrib.	2.8 +/- 0.5 mm/yr
Observed	3.2 +/- 0.4 mm/yr
Residual	0.4 mm/yr

Regional variability

Sea level rise is not uniform!

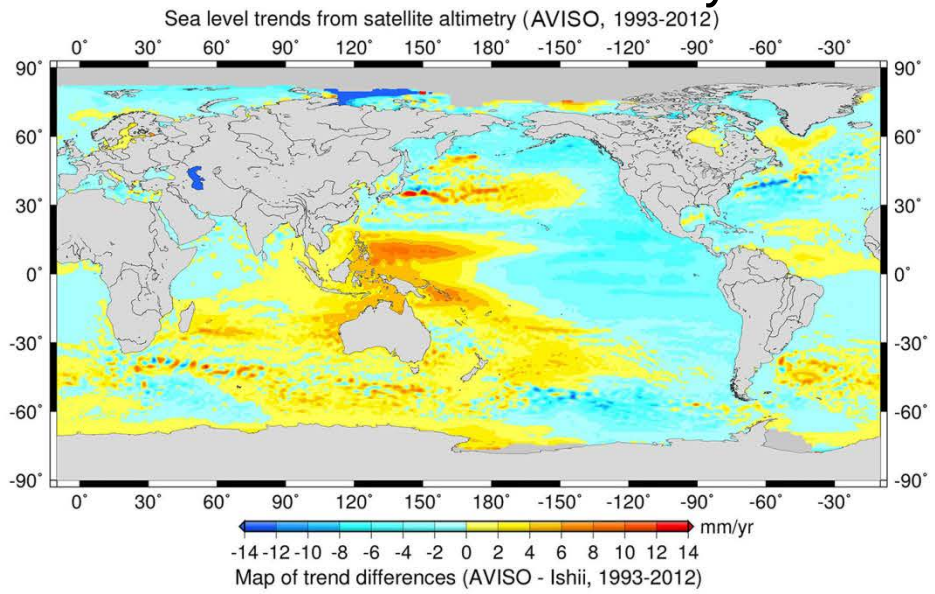


Rates of sea level rise observed by satellite altimetry (1993-2013)

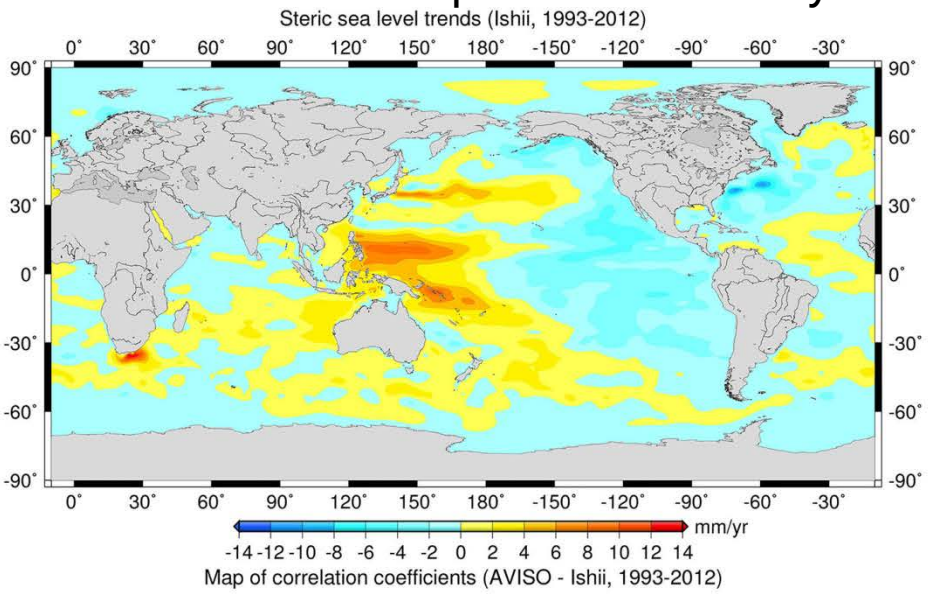
Regional variability in sea level change over 1993-2012 →

Spatial trend patterns mainly caused by non uniform thermal expansion (& to a lesser extent to salinity variations)

Observed spatial trend patterns from satellite altimetry



Spatial trend patterns from thermal expansion and salinity

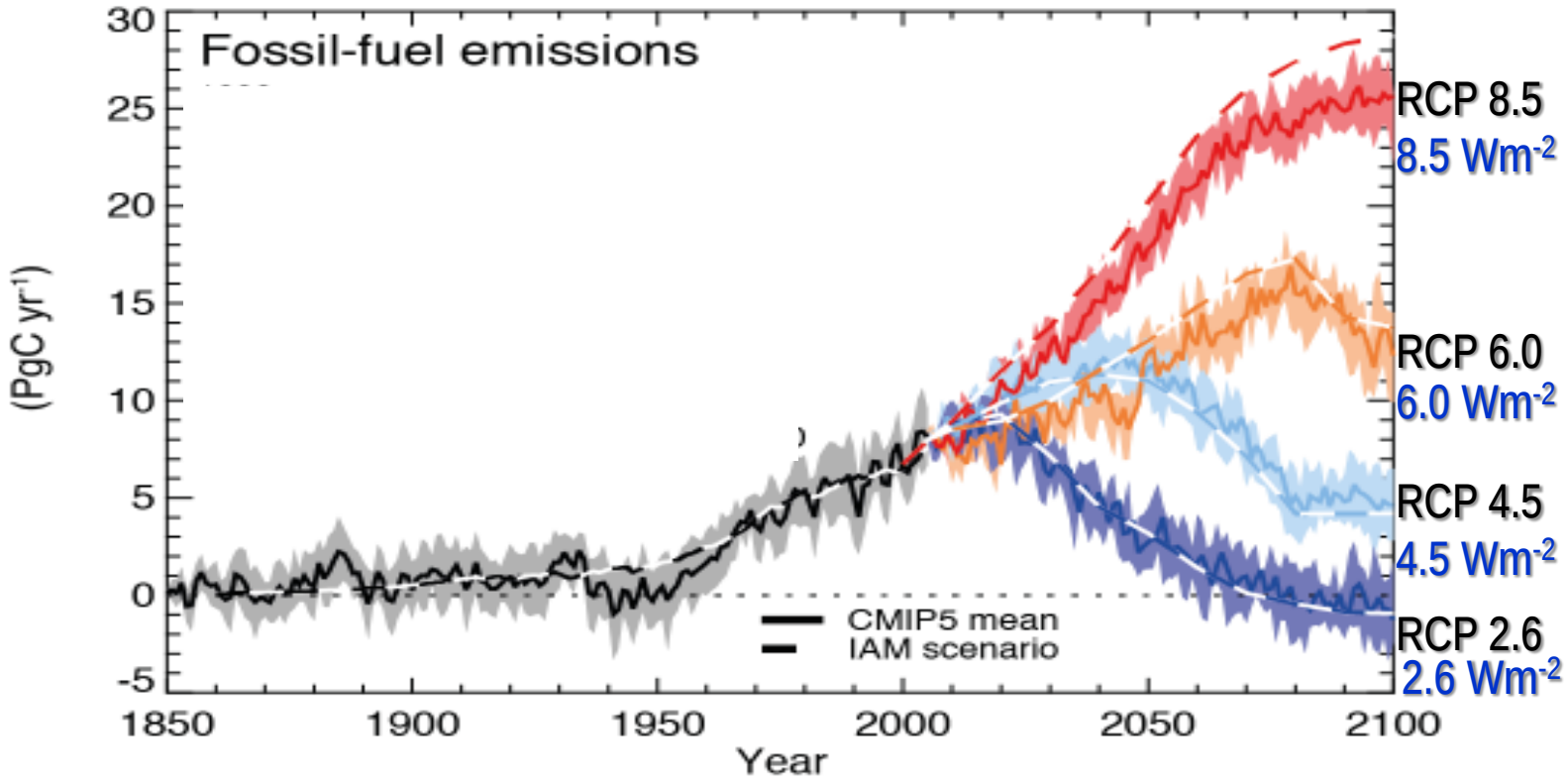


Global mean trend removed

Source: LEGOS

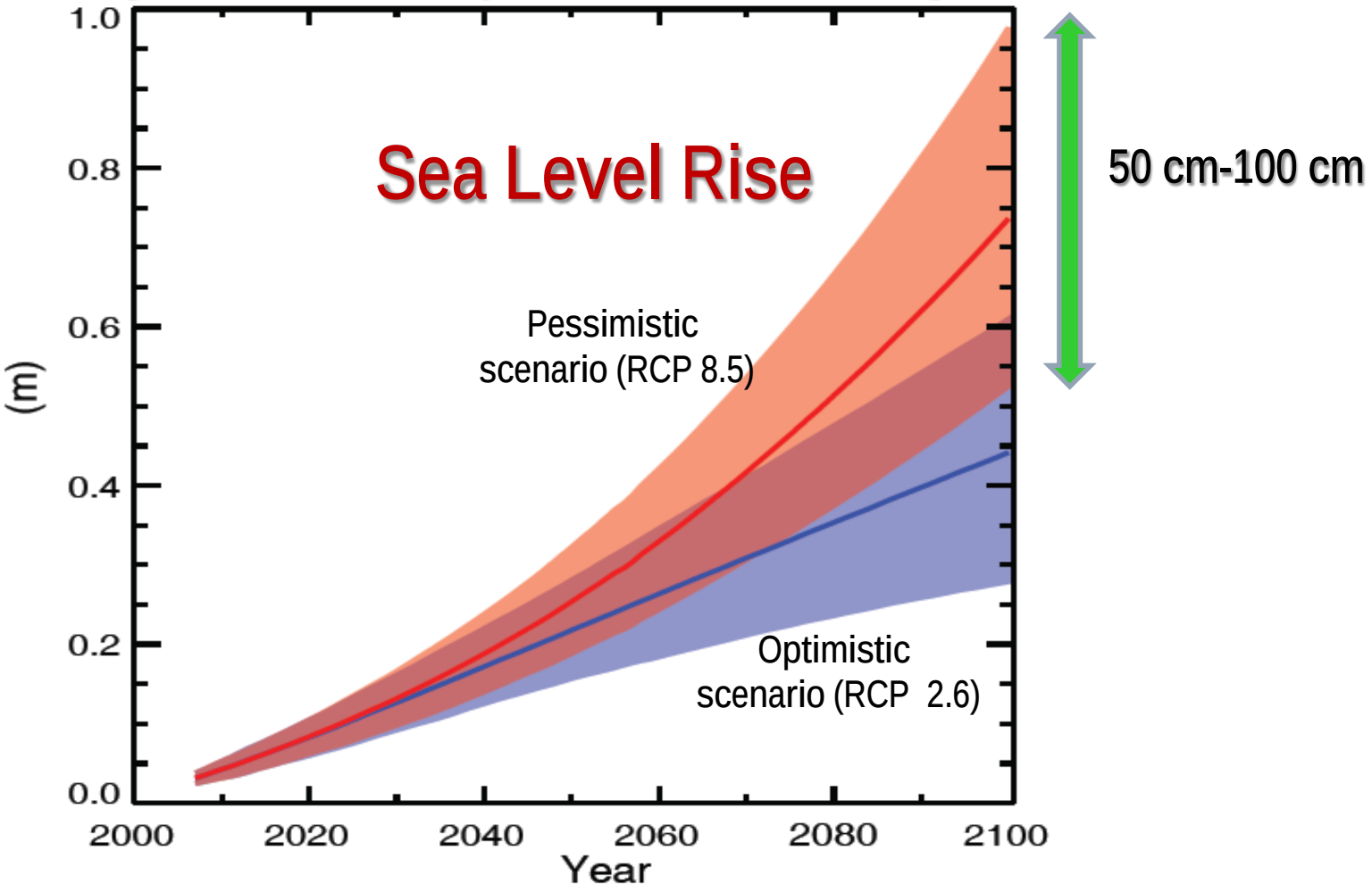
Future sea level rise

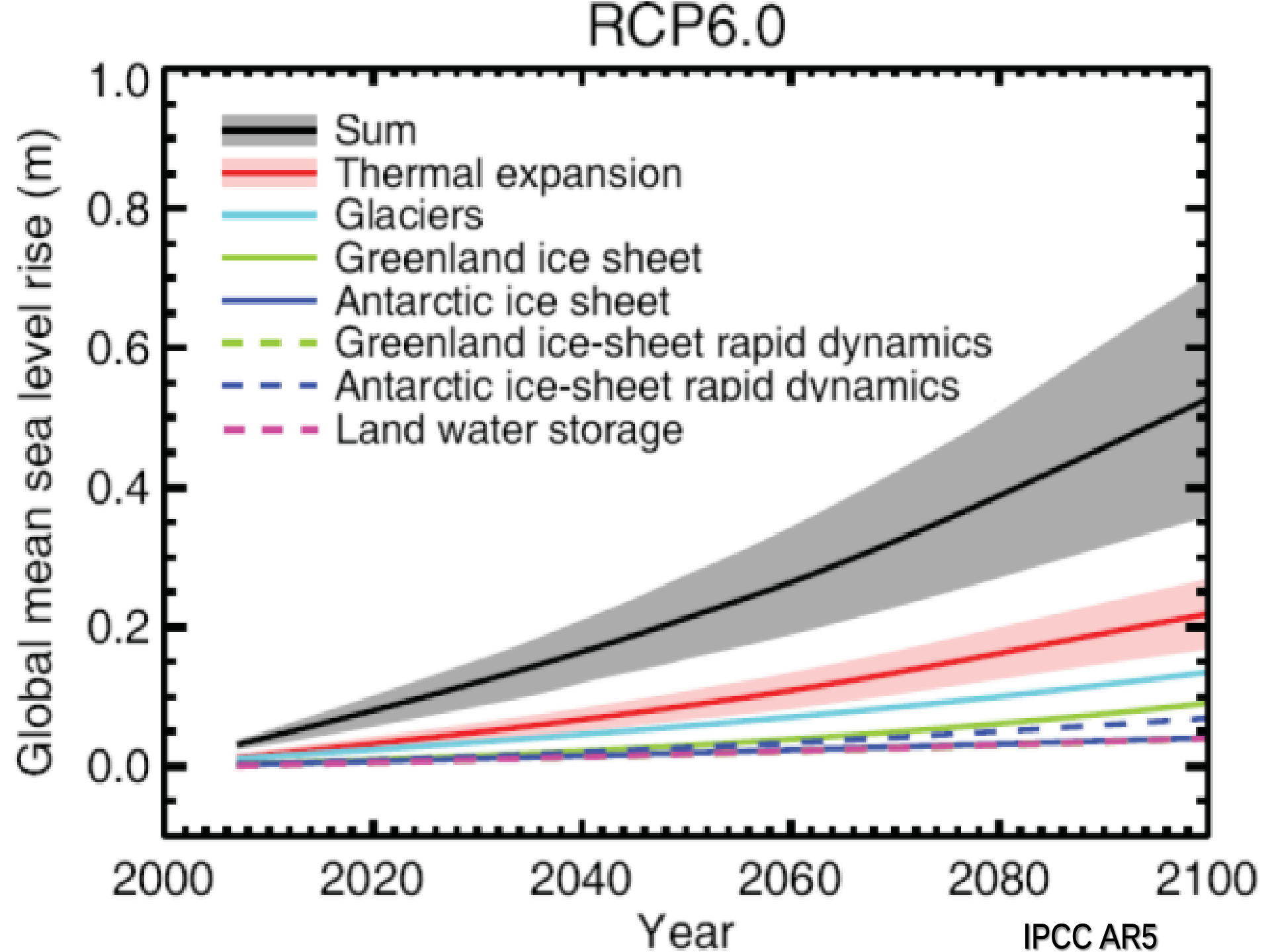
4 scenarios for future greenhouse gas emissions considered by IPCC AR5 for the 21st century



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})*

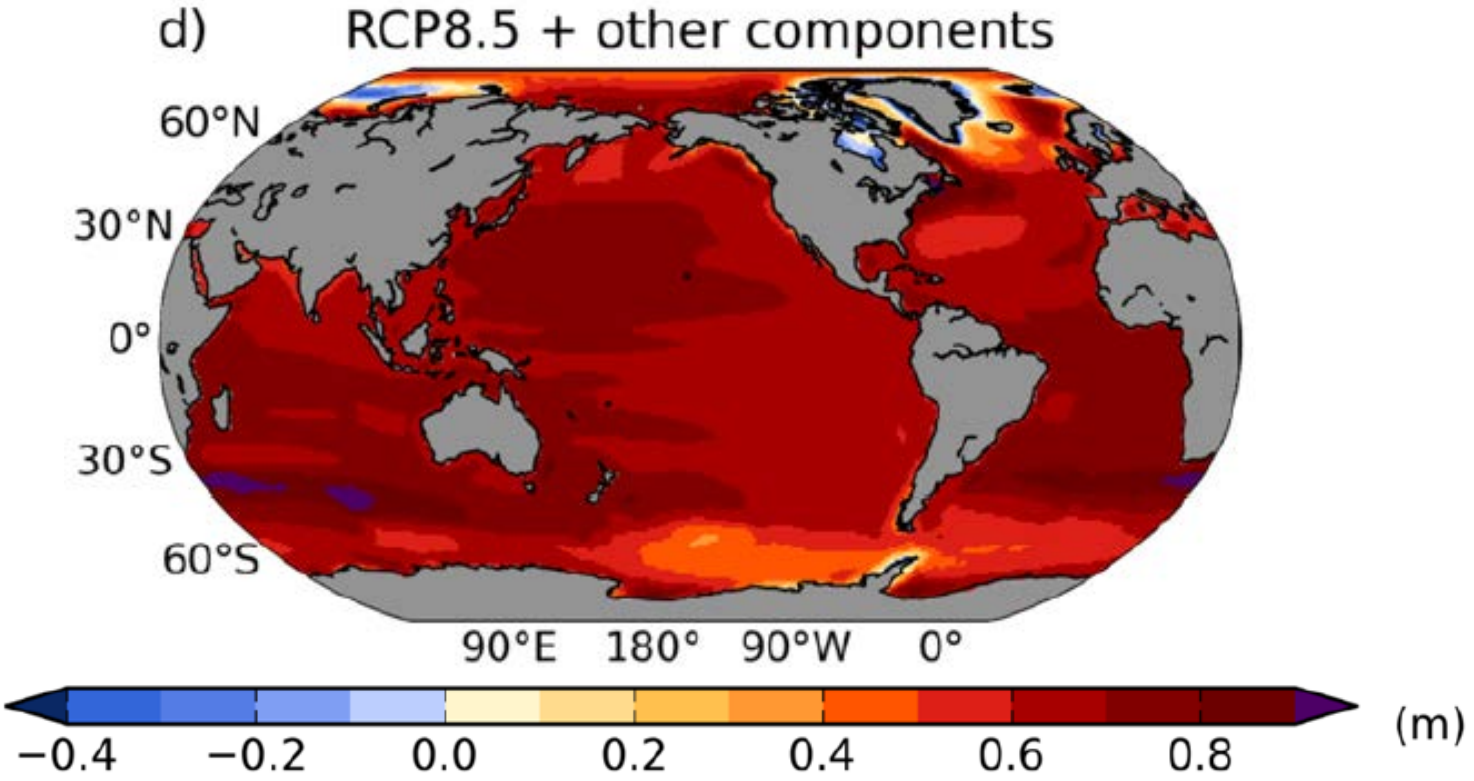
IPCC-AR5 projections of Global Mean Sea Level Rise during the 21st century under two warming scenarios




RCP6.0
Sum
Thermal expansion
Glaciers
Greenland ice sheet
Antarctic ice sheet
Greenland ice-sheet rapid dynamics
Antarctic ice-sheet rapid dynamics
Land water storage
Global mean sea level rise (m)
1.0
0.8
0.6
0.4
0.2
0.0
2000
2020
2040
2060
2080
2100
Year
IPCC AR5

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)



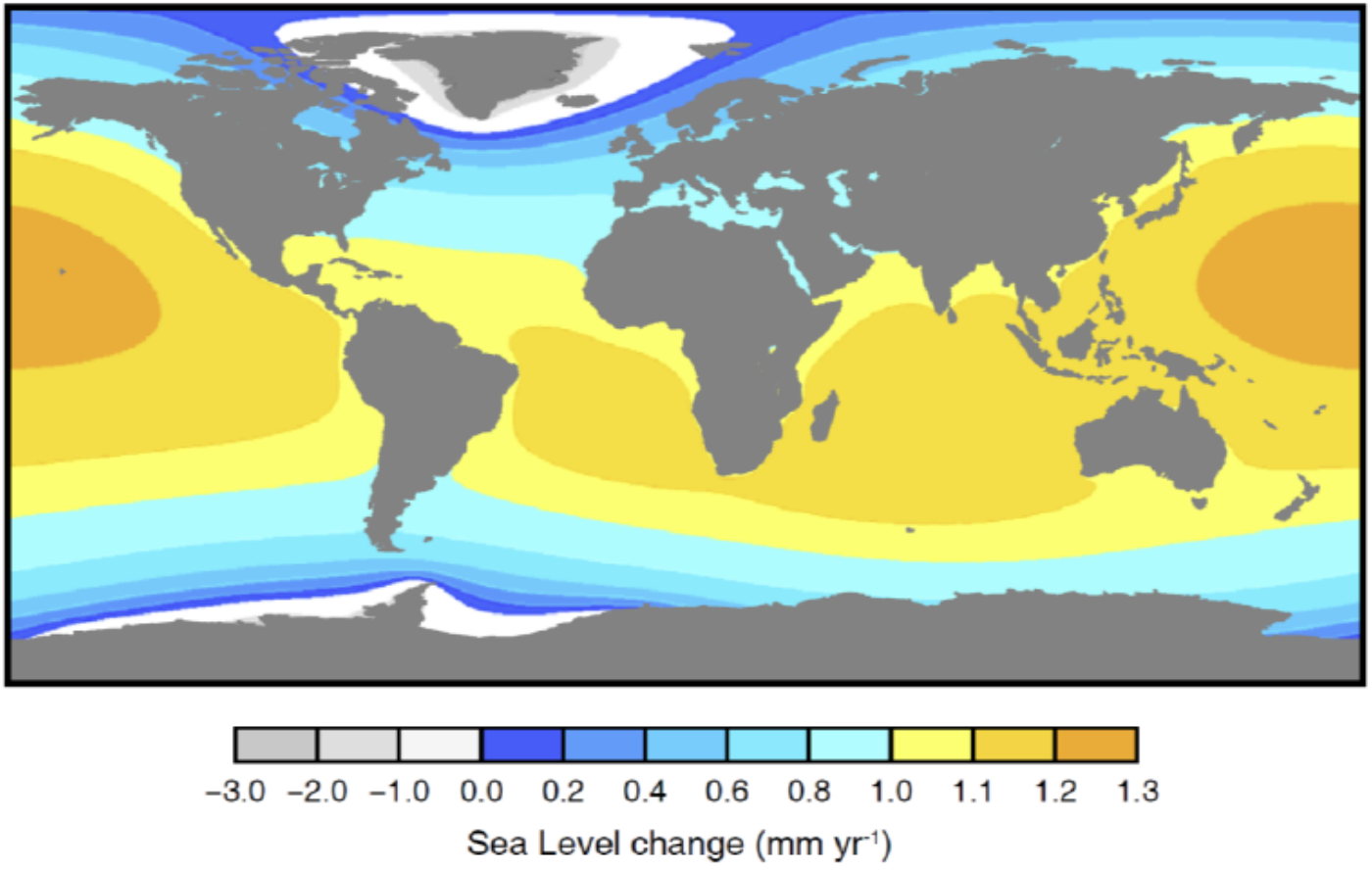
Global mean sea level rise of 75 cm

(high warming scenario)

Non-uniform thermal expansion is not the only cause of regional variability :

Large-scale water mass redistributions due to past, present and future 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*

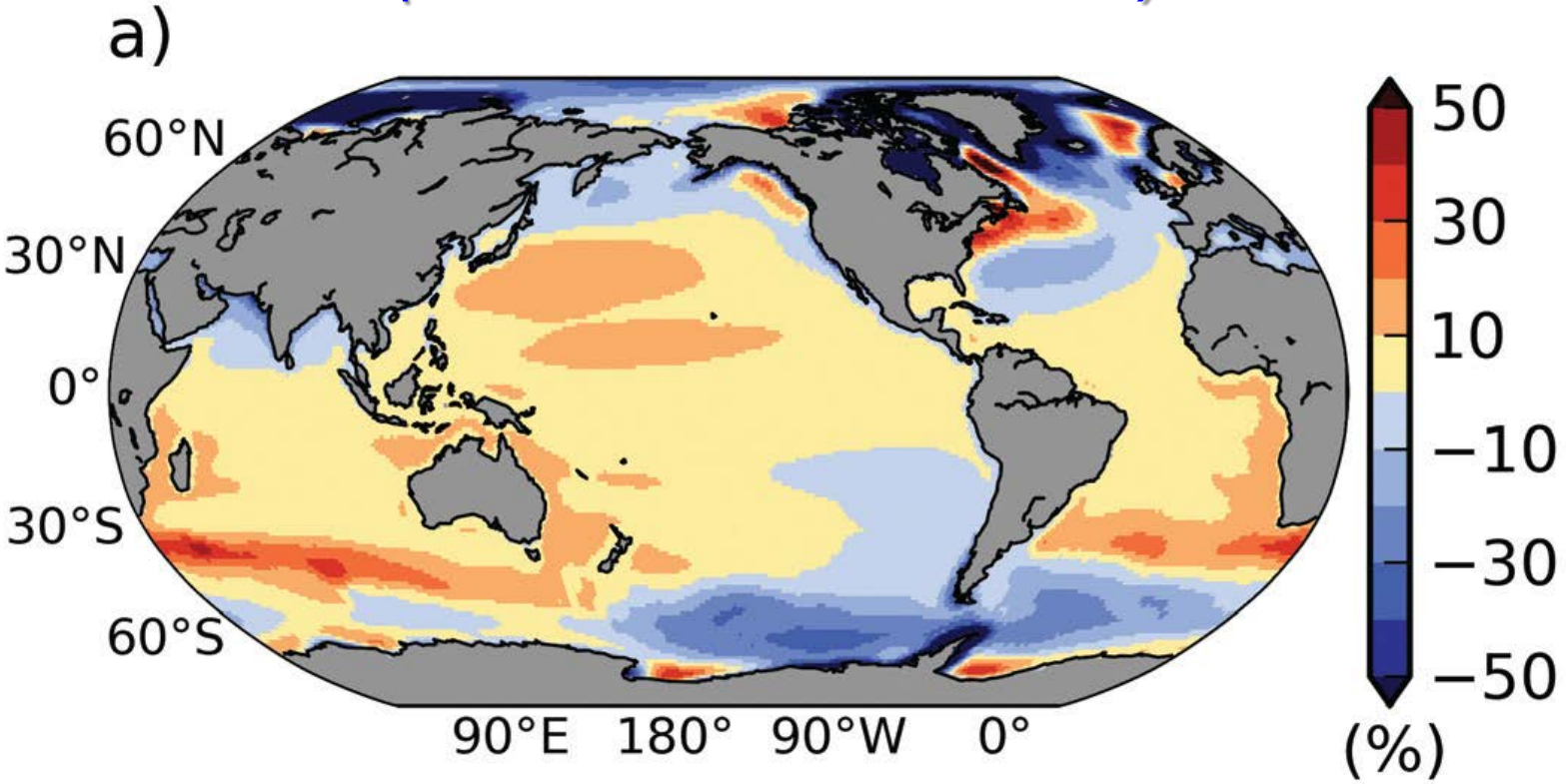
Effects on regional 'relative' sea level due to solid Earth's deformations in response to ongoing & future ice sheet melting (Greenland : 0.5 mm/yr; west Antarctica : 0.5 mm/yr)



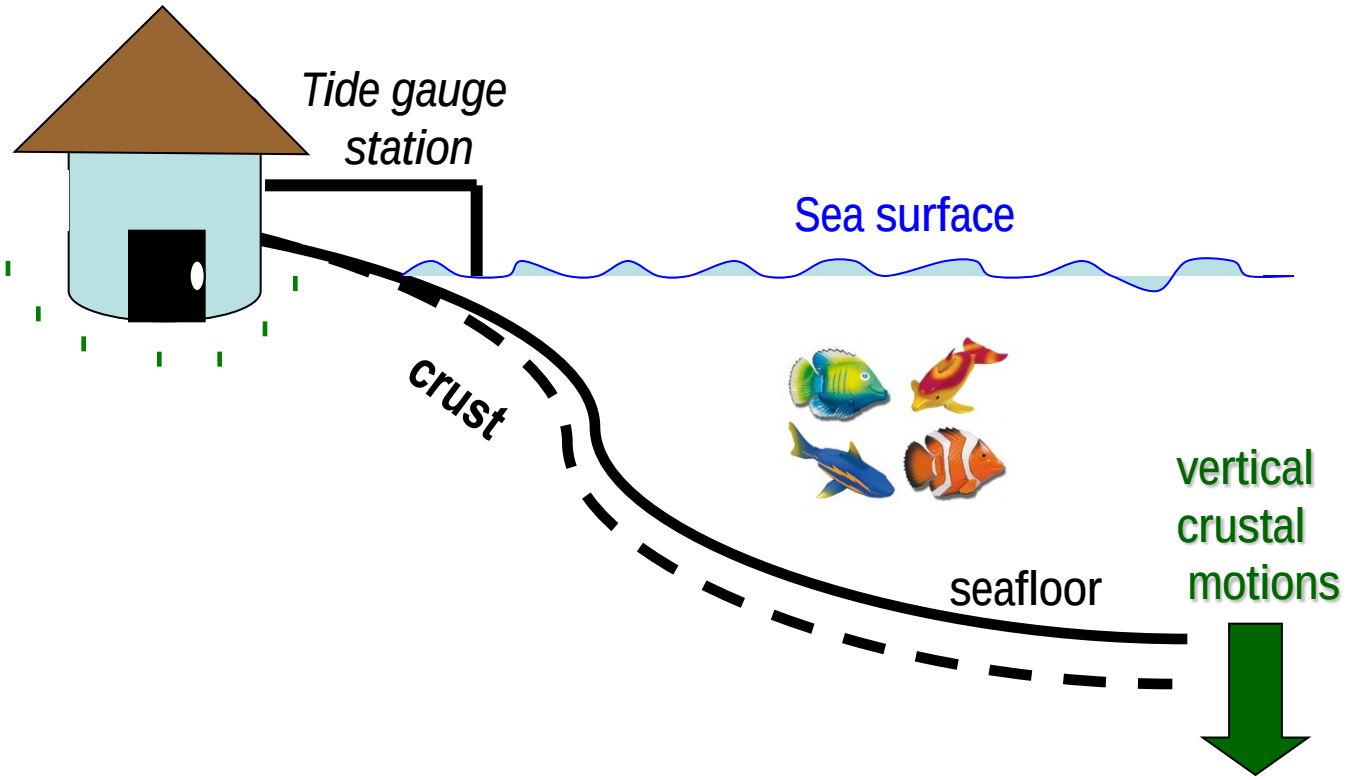
Amplification of the rate of sea level rise in the tropics by 20%-30%

IPCC AR5

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



Vertical crustal motions can amplify the climate-related sea level rise (if the ground is subsiding)



What counts is the TOTAL 'relative' sea level !!!

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 CO_2 will remain in the atmosphere more than 1000 years

- Sea level will continue to rise for mainy centuries in response to deep ocean warming and associated thermal expansion

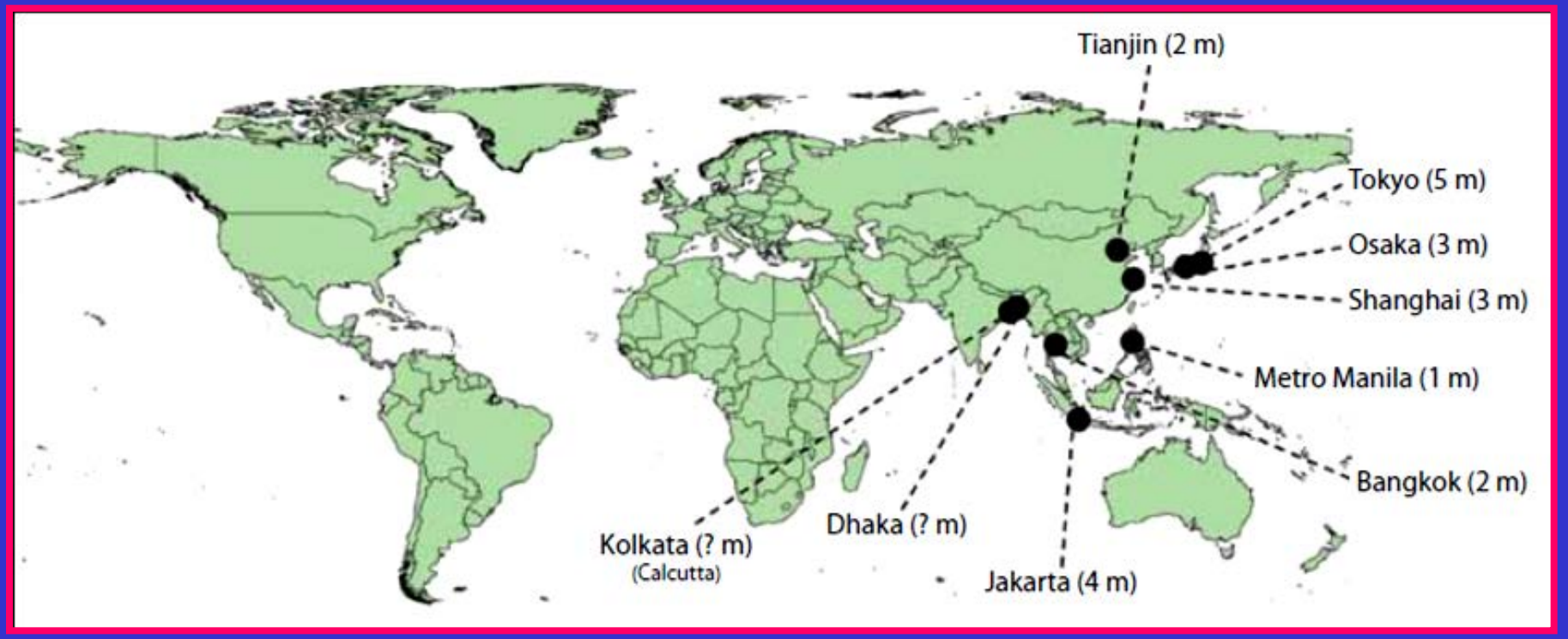
- Ice sheet mass loss may become irreversible (Greenland) → sustained warming above a certain threshold (1°C-4°C) may lead to near-complete loss of the Greenland ice sheet over a time scale of 1000 years (→ 7 m of sea level rise)

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

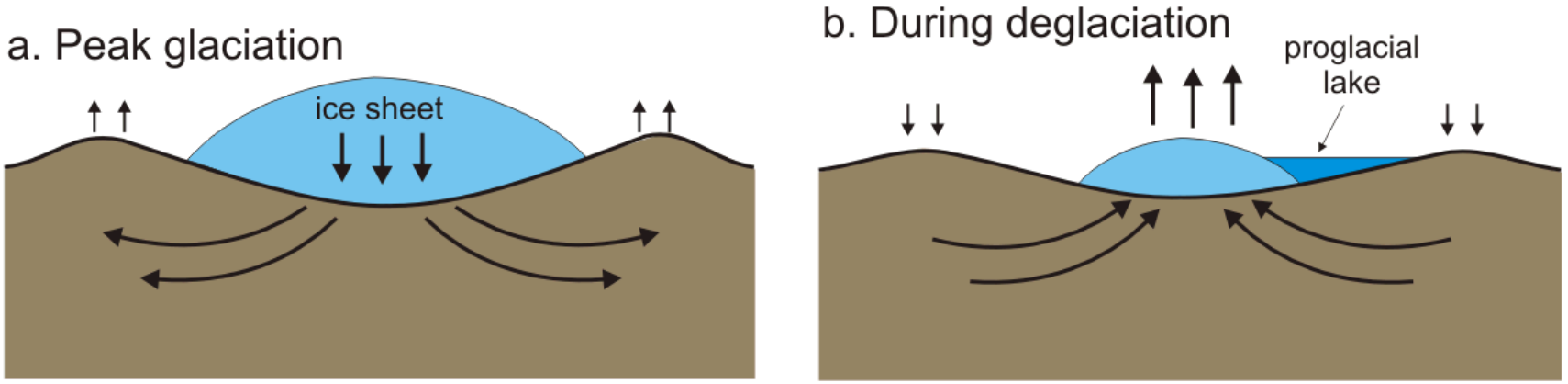

Thanks for your attention

Subsidence of coastal megacities during the past few decades

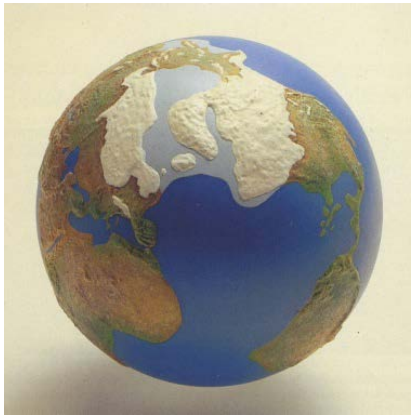


From Nicholls (2011)

Post Glacial Rebound

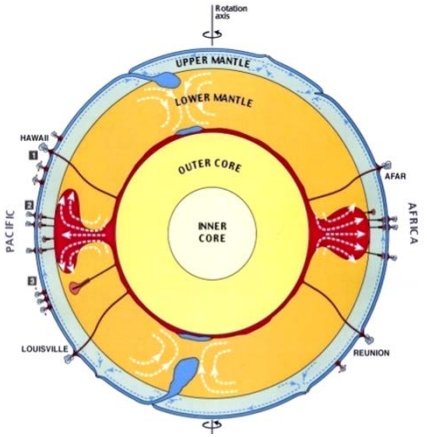


Models of
Post Glacial Rebound
(also called
Glacial Isostatic Adjustment
or GIA)



Deglaciation history

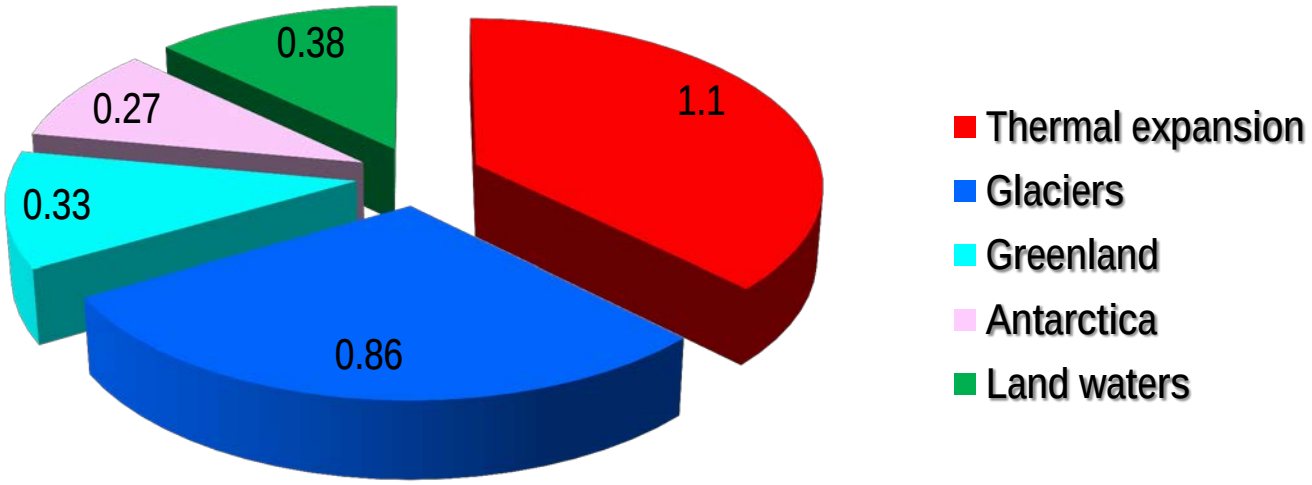
+



Models of
Earth's viscosity structure

Observed sea level budget 1993-2010 (IPCC AR5)

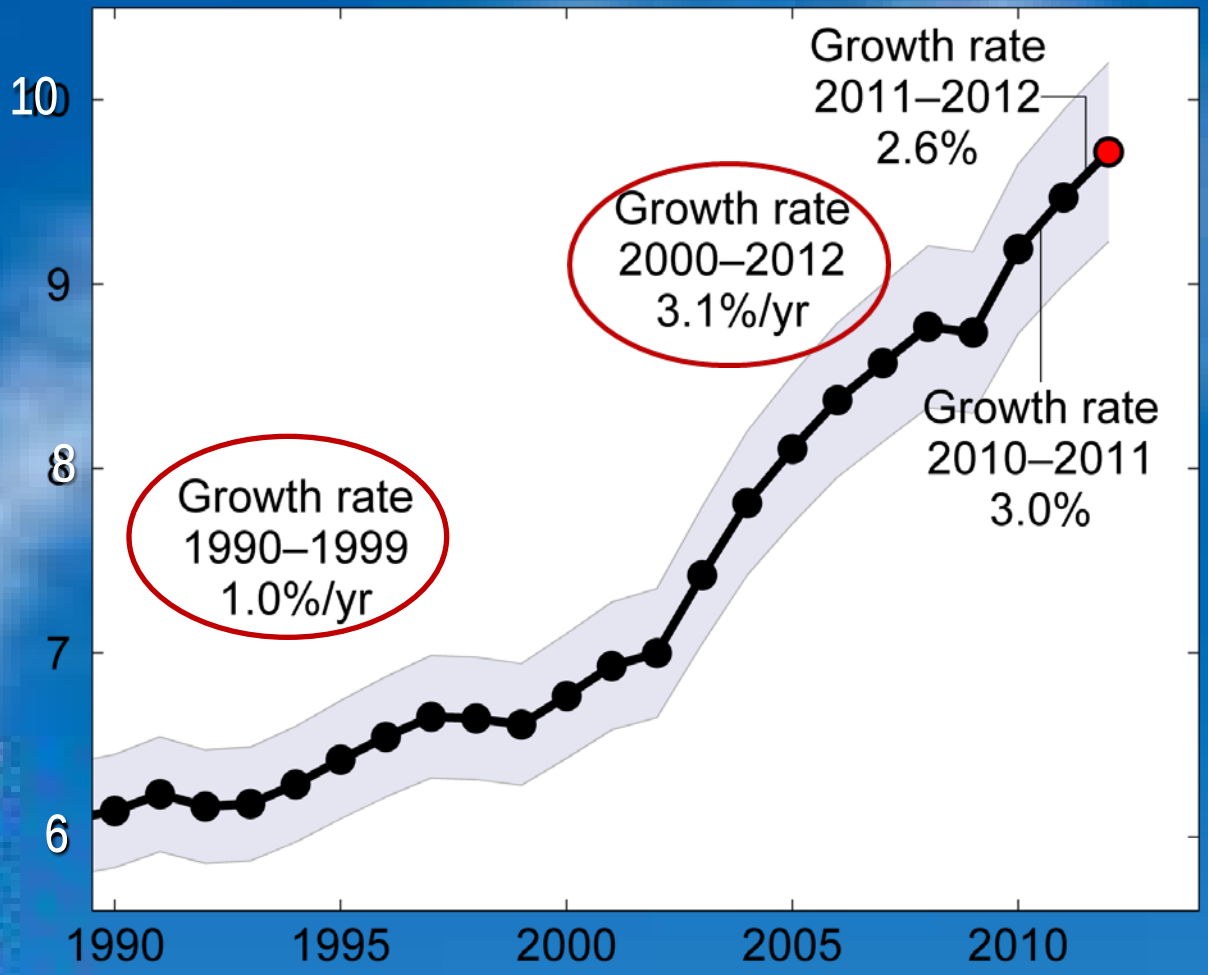
Individual contributions (mm/yr)



Sum of contributions : 2.8 +/- 0.5 mm/yr
Observed rate of rise: 3.2 +/- 0.4 mm/yr

IPCC AR5

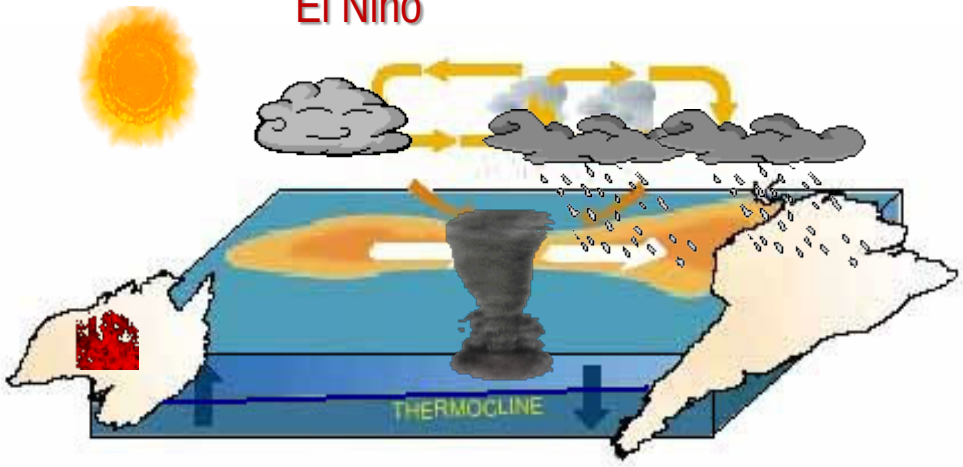
Greenhouse Gas Emissions



Le Quéré et al., 2012

EL Nino-Southern Oscillation (ENSO) → a major natural/internal perturbation of the climate system

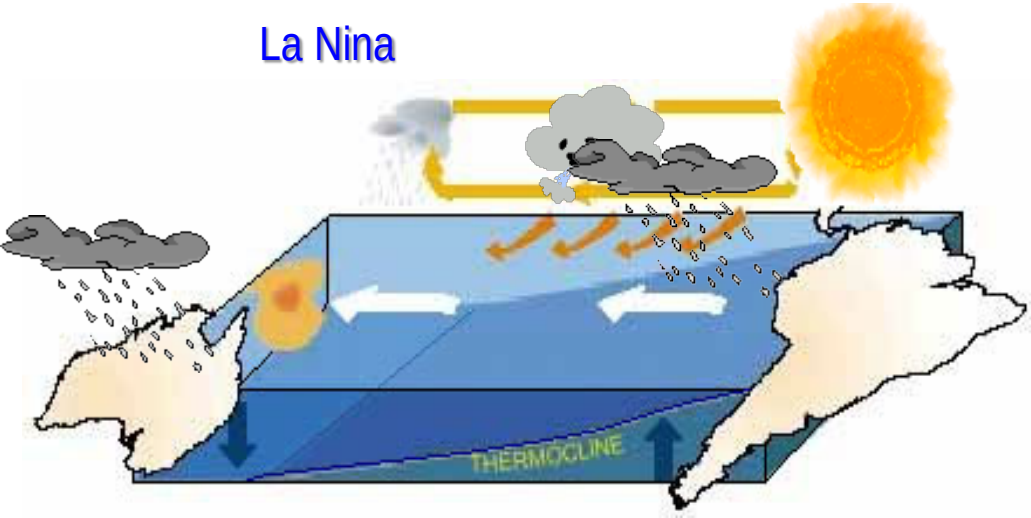
El Nino



El Niño

Warm water and more rain over the central and eastern tropical Pacific

La Nina



La Niña

Cold phase of ENSO

Source: C. Cassou