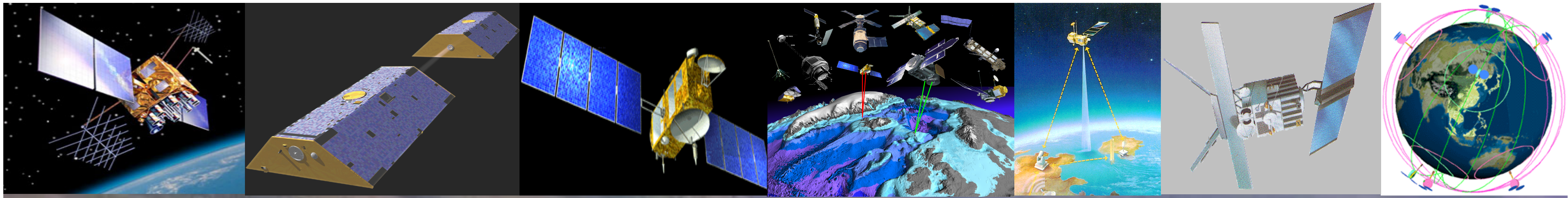

Climate Change and Sea-Level

C.K. Shum 沈嗣鈞

Division of Geodetic Science, School of Earth Sciences

The Ohio State University

Summer School

Shanghai Astronomical Observatory

Shanghai, China

17–22 July 2011

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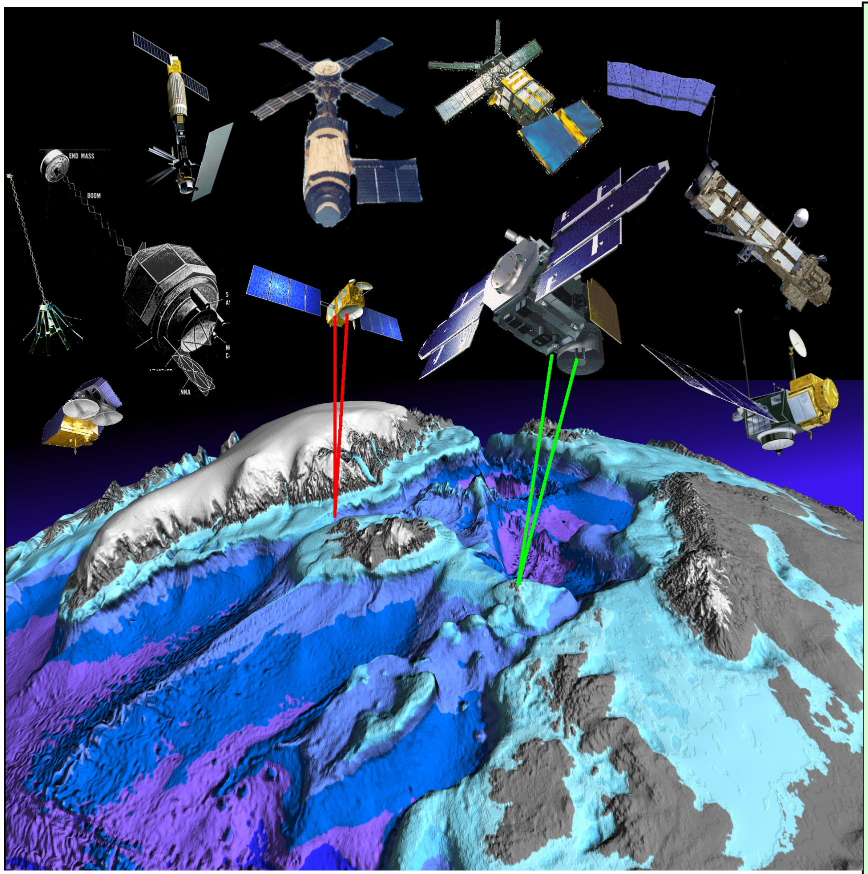
Acknowledgements: C. Kuo, H. Lee, J. Guo, J. Duan, Z. Huang, L. Wang

What Is Space Geodesy?



A science discipline to determine the size (gravity), shape (volume), and their changes of the Earth (and planets); and positions and motions of a point anywhere on the surface or in space

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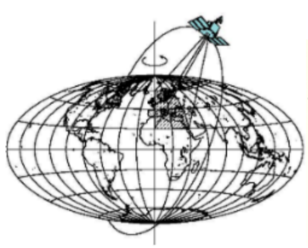
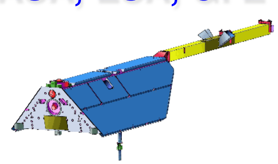
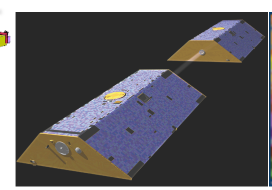
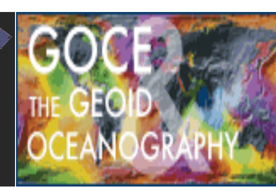
Satellite Geodesy for Interdisciplinary Earth & Planetary Science Research

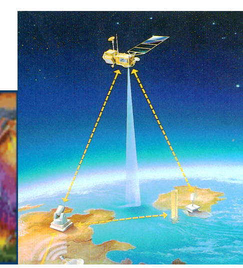
- **A Geodesist *should:***
  - **Know assumptions made in theory and data processing**
  - **Know your instrument well (*precision and accuracy*)**
  - **Science first: define your problem to solve first, then the corresponding observation requirements**
  - **Always provide *realistic* uncertainty of solutions or products**
  - **Know that the knowledge and instrument accuracy are *moving* targets that improves with time**
  - **Cross-disciplinary science: address new problems not necessarily in your field**

Progress in research is not only to *duplicate* previous results, it has to make incremental, significant or transformative advances in the field




Credit: NASA, ESA, GFZ



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Climate Change and Sea-Level

- Climate change: Natural or human-influenced?
- Causes of anthropogenic warming: CO_2 & other greenhouse gases. Consequences: temperature rise, ice melt, less snow, more water vapor, sea-level rise
- IPCC: Intergovernmental Panel on Climate Change (www.ipcc.ch) Assessments, 1990–present
- The consequences, measurements and geophysical causes of present-day global sea-level rise
- Climate change and sea-level projection to the end of the 21st century
- Satellite altimetry methods for sea-level research and cross-disciplinary science

Climate Change and Sea-Level: Science Questions

- Can we measure the 20th and present-day sea-level accurately (to sub-mm/yr accuracy)?
- Do we have evidence of anthropogenic warming on sea-level rise?
- Has sea-level rise been accelerating? If so, when and can we detect the acceleration and their epochs?
- What are the geophysical causes and the least known contributors of present-day sea-level rise?
- Sea-Level Budget: can we fully explain the roles of each contributor of present-day sea-level rise commensurate with the observed sea-level rise?
- How accurate are the sea-level projection to the end of the 21st century?
- How could modern geodetic sensors help?

The Intergovernmental Panel on Climate Change (IPCC) Sequence of Key Findings

IPCC (1990) Broad overview of climate change science, discussion of uncertainties and evidence for warming.

IPCC (1995) "The balance of evidence suggests a discernible human influence on global climate."

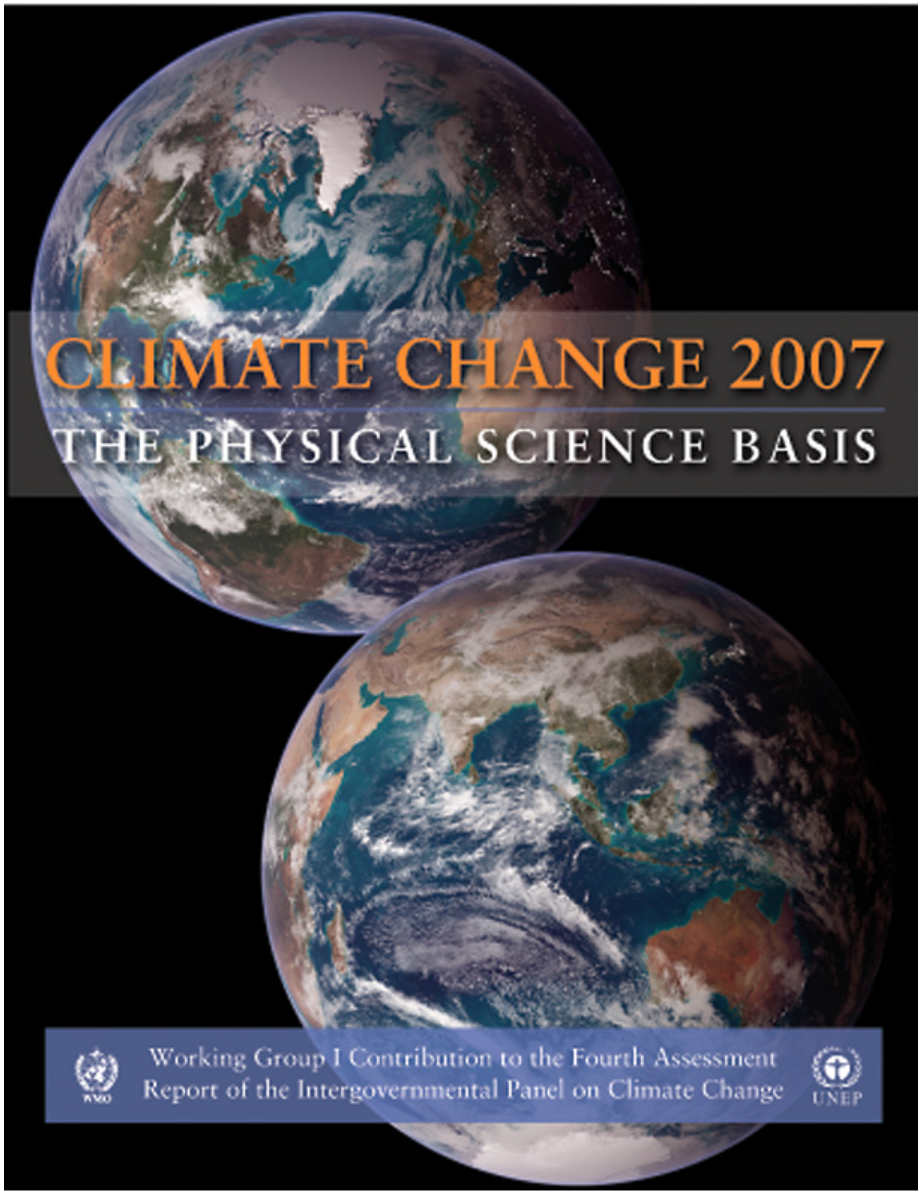
IPCC (2001) "Most of the warming of the past 50 years is likely (>66%) to be attributable to human activities."

IPCC (2007) "Warming is unequivocal, and most of the warming of the past 50 years is very likely (90%) due to increases in greenhouse gases."

IPCC (~2014) Ongoing

Modified from IPCC - WGI, *Solomon* [2007]

The IPCC Working Group I Report (2004–2007)



IPCC - WGI, Modified from *Solomon* [2007]

- **Technical Summary, 11 Chapters, 152 Authors, ~450 contributors, ~600 expert reviewers, FAQ**

Nobelprize.org

The Nobel Peace Prize 2007

"for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change"

Photo: Scanpix/Tom Hevezi

Intergovernmental Panel on Climate Change (IPCC)

1/2 of the prize

Geneva, Switzerland

Founded in 1988

Albert Arnold (Al) Gore Jr.

1/2 of the prize

USA

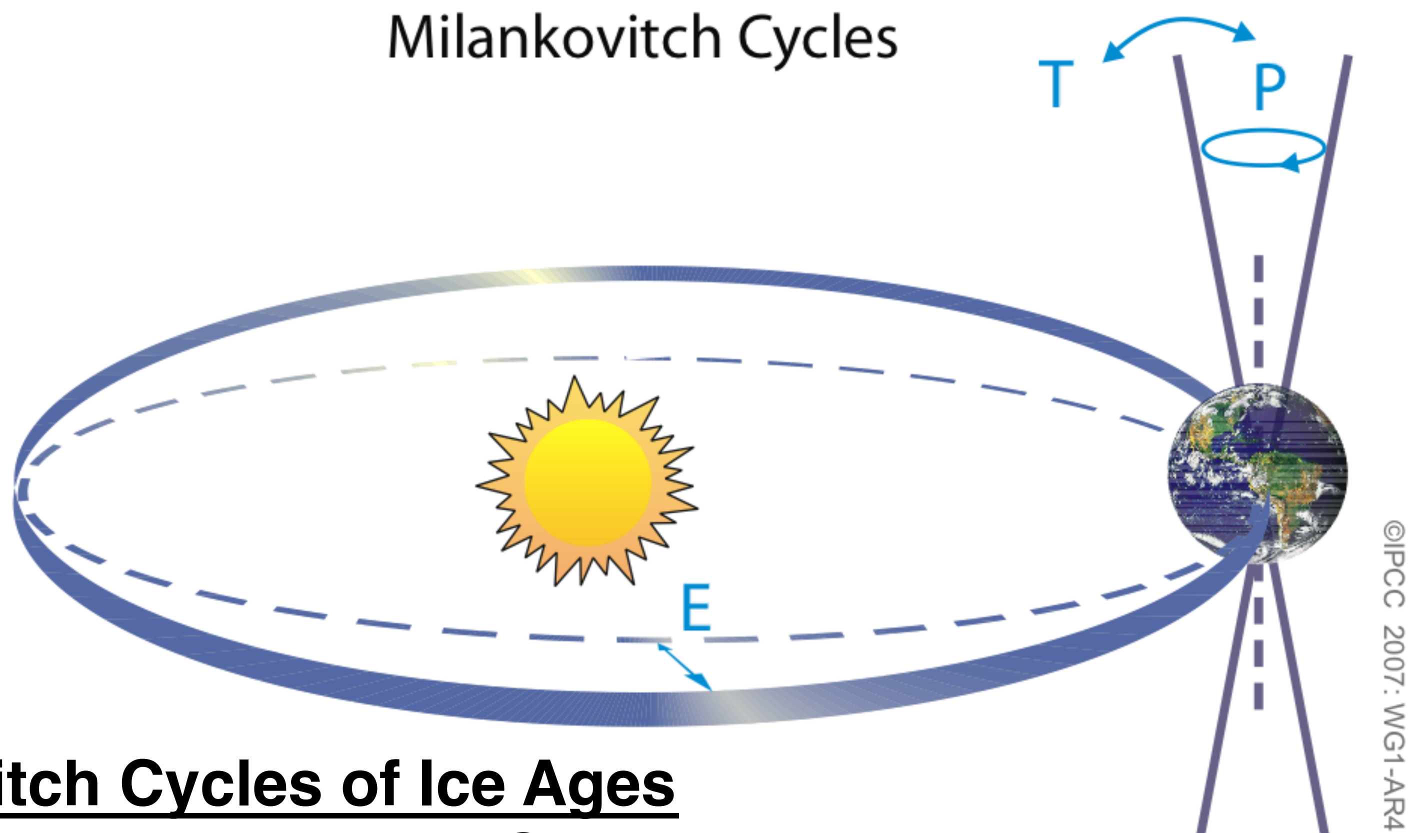
http://nobelprize.org

Ice Age Forcing and Response

Natural Climate Forcing:

Verified by analysis of deep ocean cores: *Hays, Imbrie & Shackleton*, "*Variations in the Earth's Orbit: Pacemaker of the Ice Ages*", *Science,* 1976.

E: eccentricity of Earth's orbit around the Sun
P: Precession
Obliquity (T): inclination of orbit (~22.1^0–24.5^0)

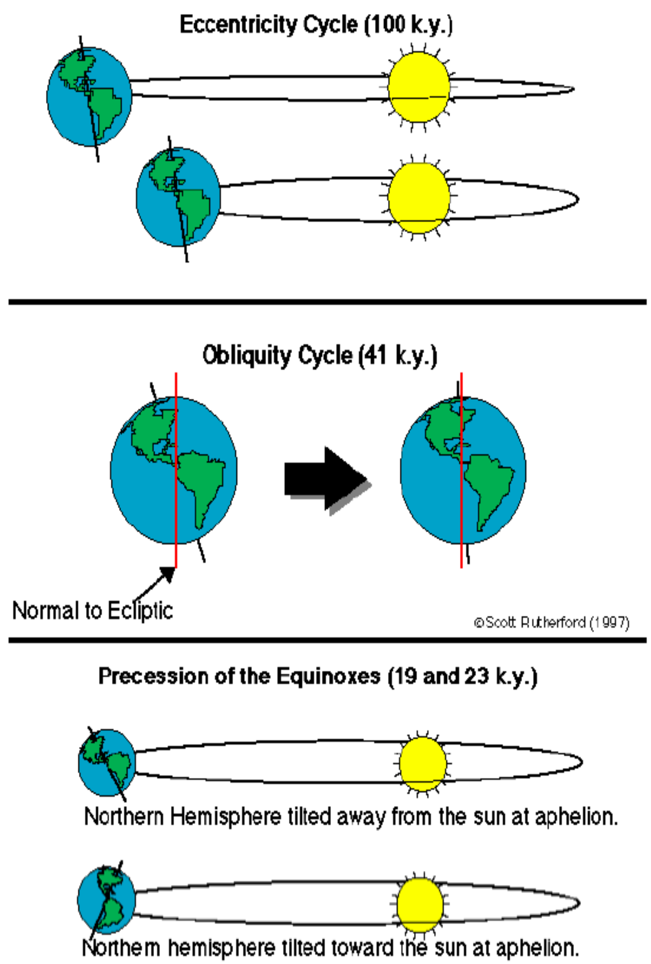


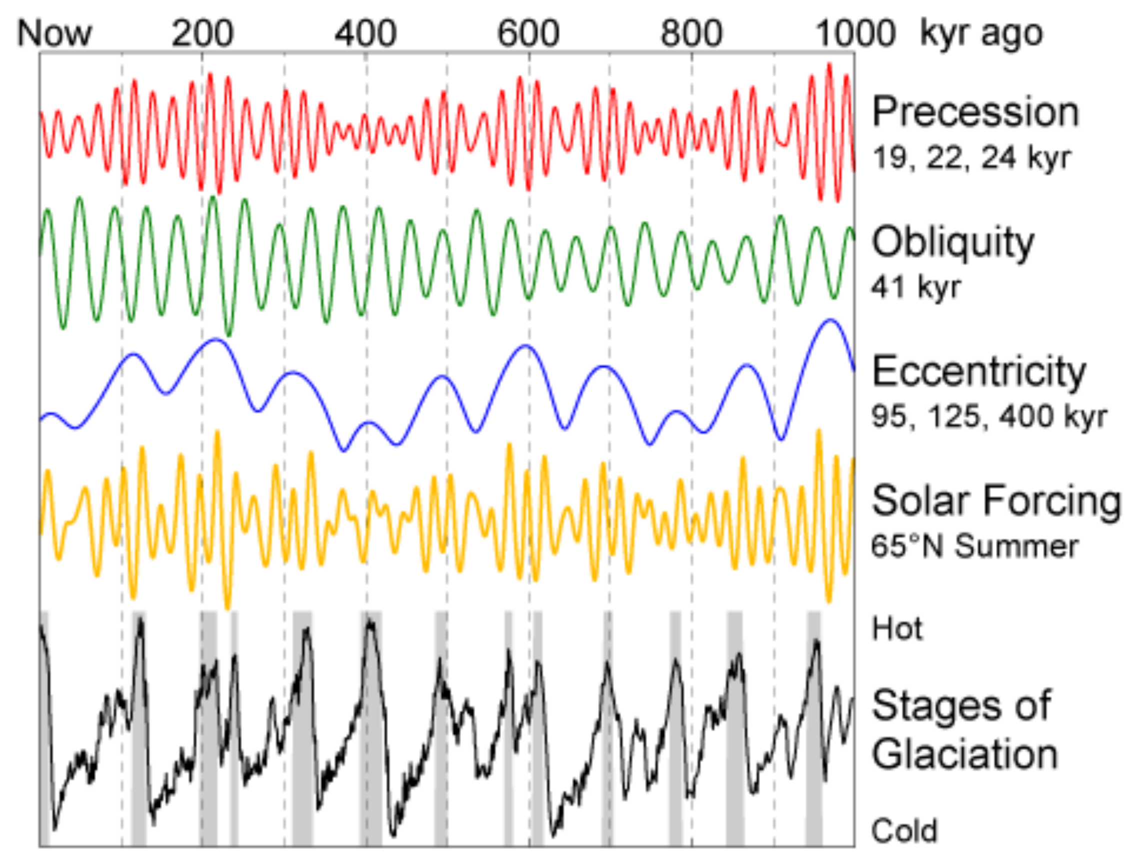
<u>Milankonvitch Cycles of Ice Ages</u> are based on the theory by Serbian mathematician Milutin Milanković

Source: IPCC WG1-AR4

Milankovitch Cycles in Paleoclimate: Ice Ages

The major cycles of the Earth's orbit



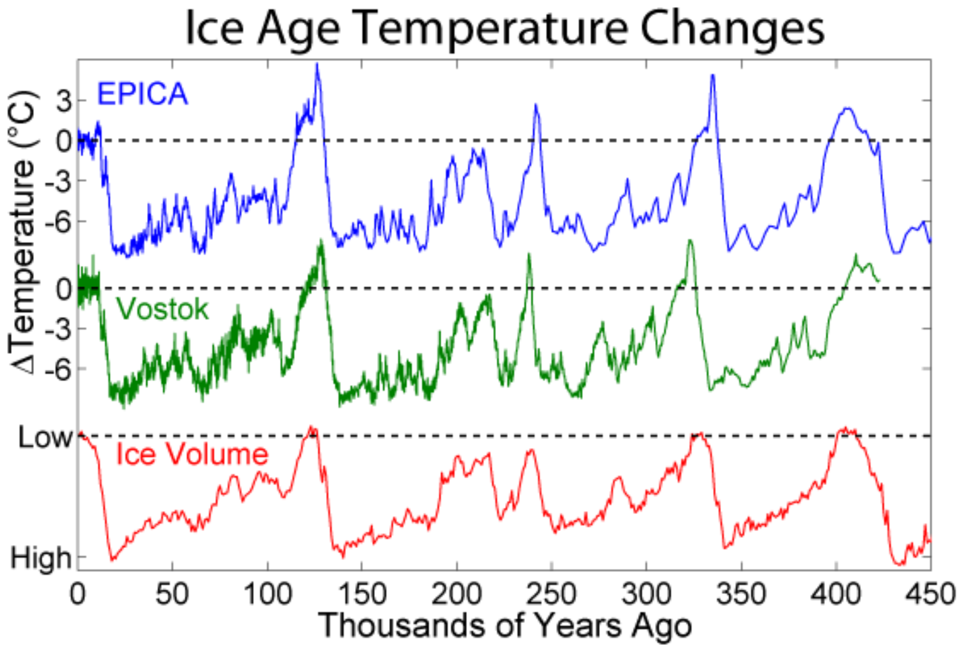


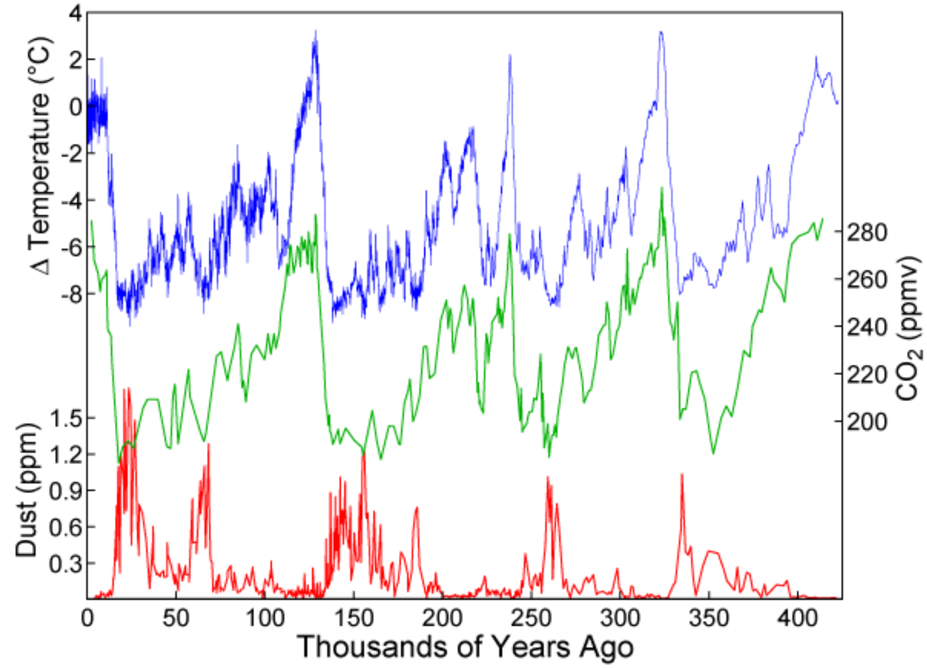
http://en.wikipedia.org

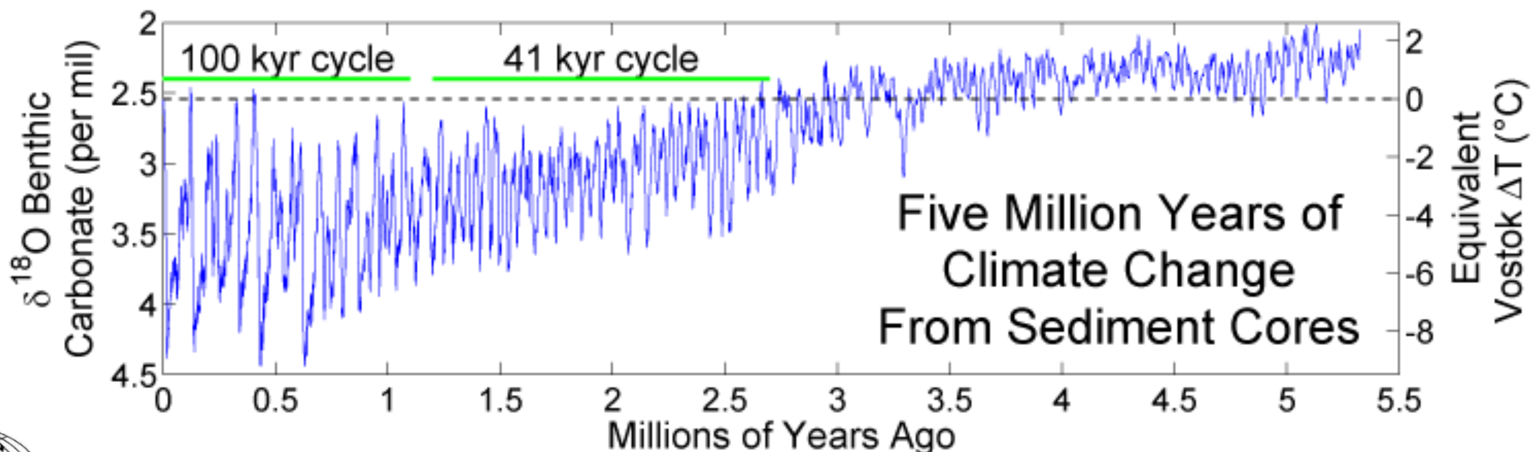
http://deschutes.gso.uri.edu/~rutherfo/milankovitch.html

Evidence of Ice Ages from Sediment/Ice Cores

EPICA: European Project for Ice Coring in Antarctica







http://en.wikipedia.org/wiki/Milankovitch_cycles

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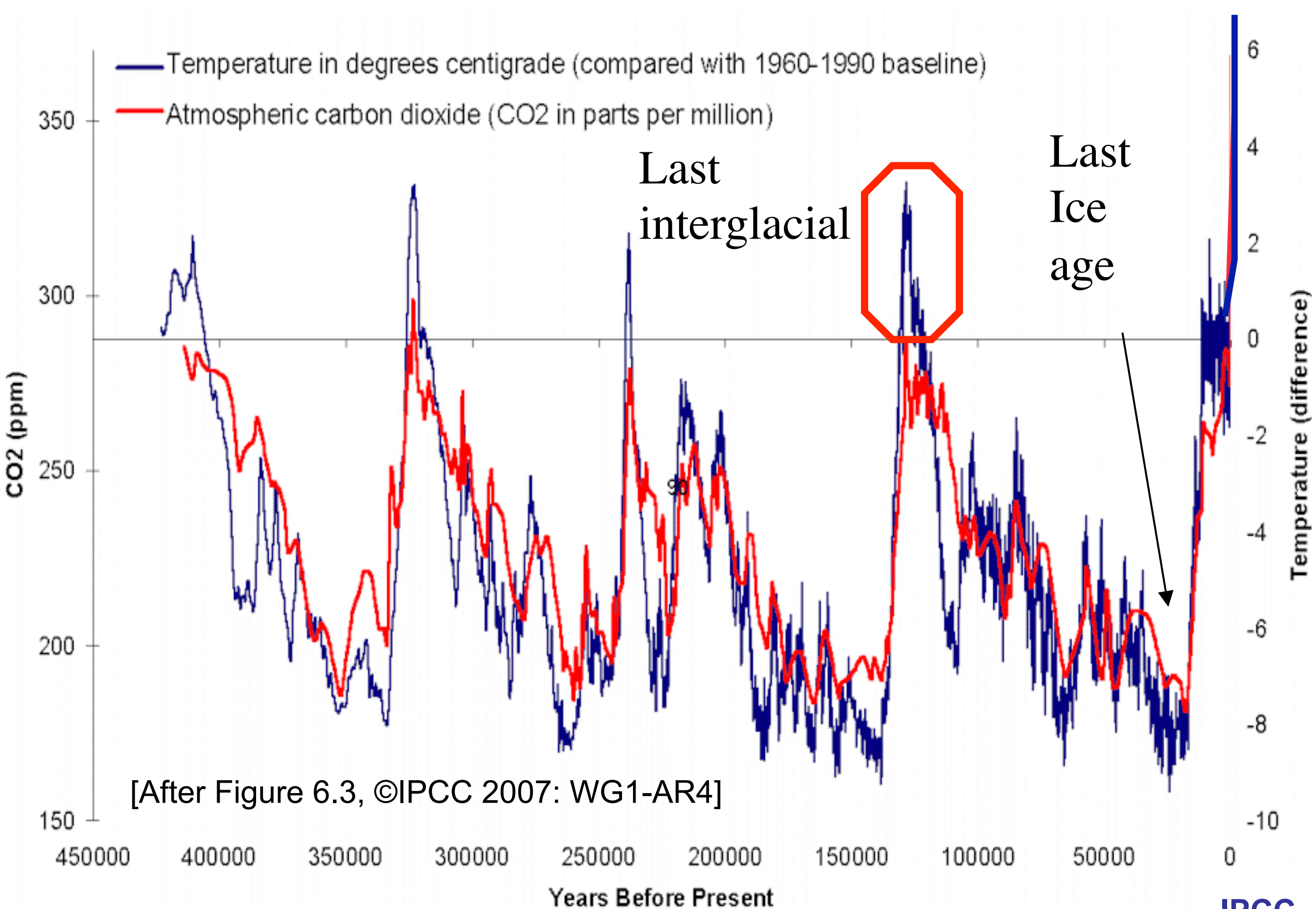
Human Causes in Global Warming?

Warmest years: 2005 and 2010 (tied), at 1.7^{0}F (0.62^{0}C) above the 20th century averaged temperature, since 1880 when instrument record started

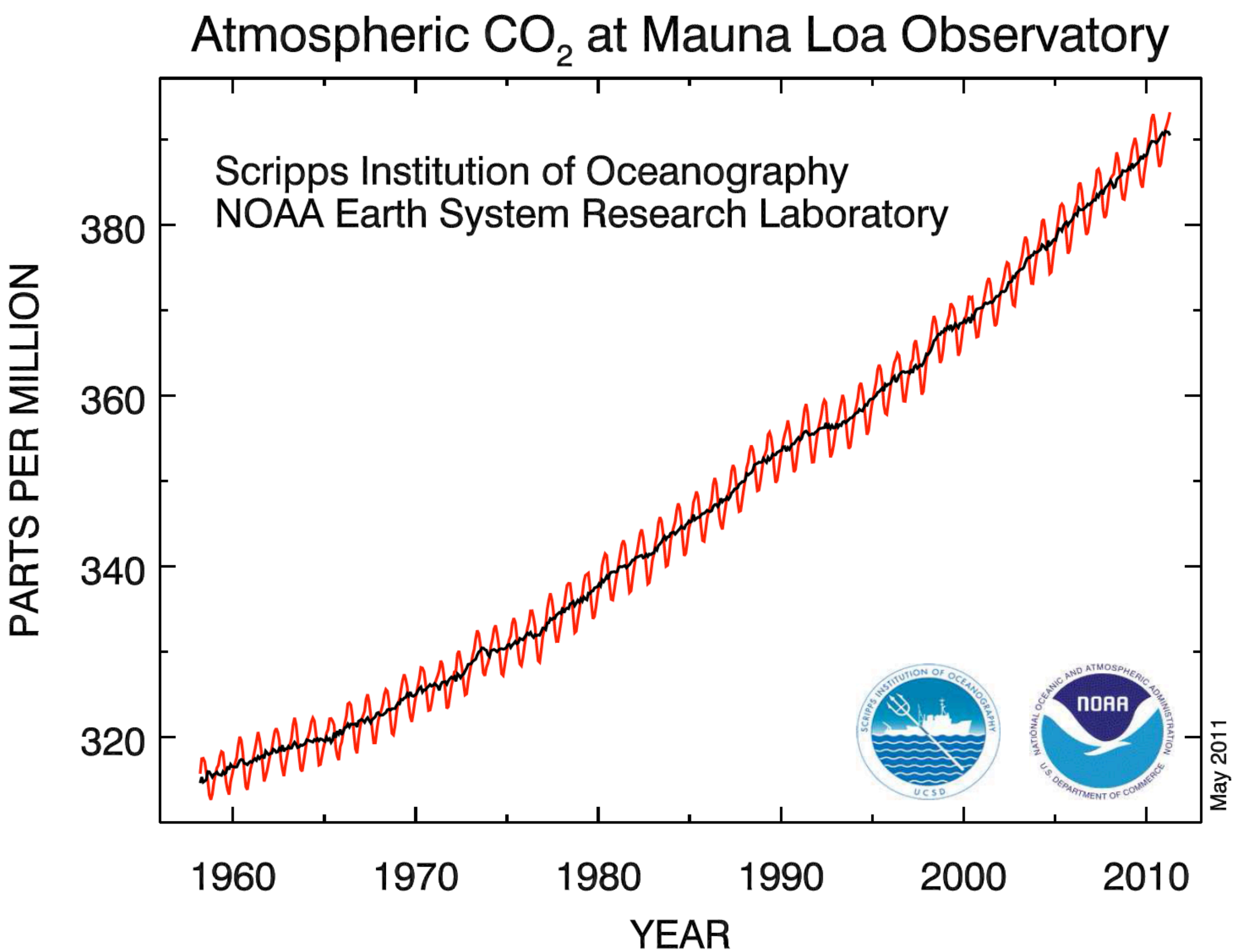


CO_2 concentration was 280 ppm for the last 400,000 years before 1900. Since 1900, CO_2 concentration has risen to 393 ppm (April, 2011), implying human activities (i.e., burning of fossil fuels, ~7 gtons/yr), causing its rise.

IPCC - WGI, Modified from *Solomon* [2007]

Observations: Carbon Dioxide Concentration

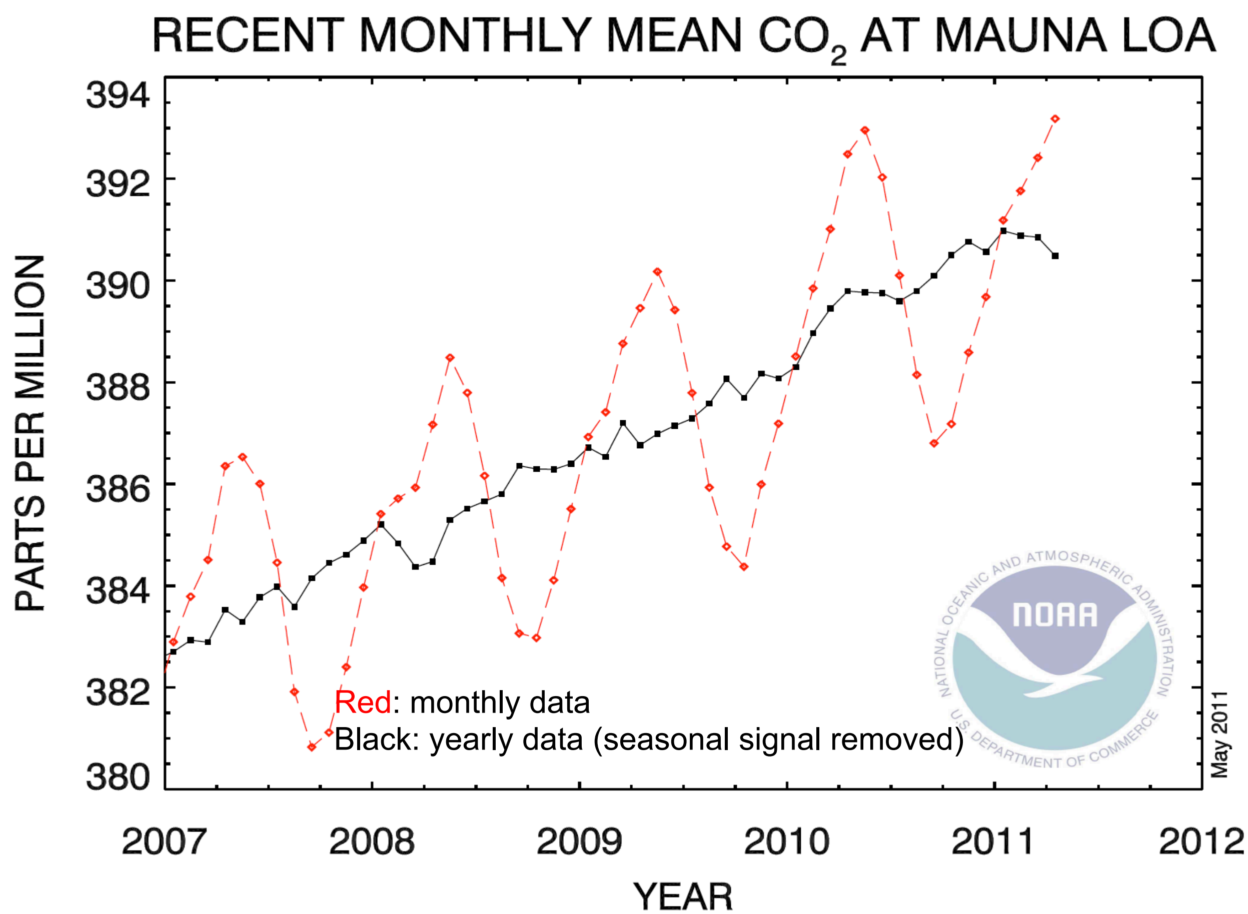
- Monthly CO_2 concentration and its trend line at Mauna Loa, Hawaii (red), up to 2010, from Scripps in collaboration with NOAA. ppm, parts per million.
- Global mean CO_2 is slightly lower than Hawaii because continents are mostly in the northern hemisphere.
- Predictions from models are dashed lines. "CO_2 concentration follows the projections almost exactly"



http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html

Observed Carbon Dioxide Concentration: April 2011

- Monthly CO_2 concentration and its trend line at Mauna Loa, Hawaii (red), up to April, 2011, from Scripps in collaboration with NOAA. ppm, parts per million.

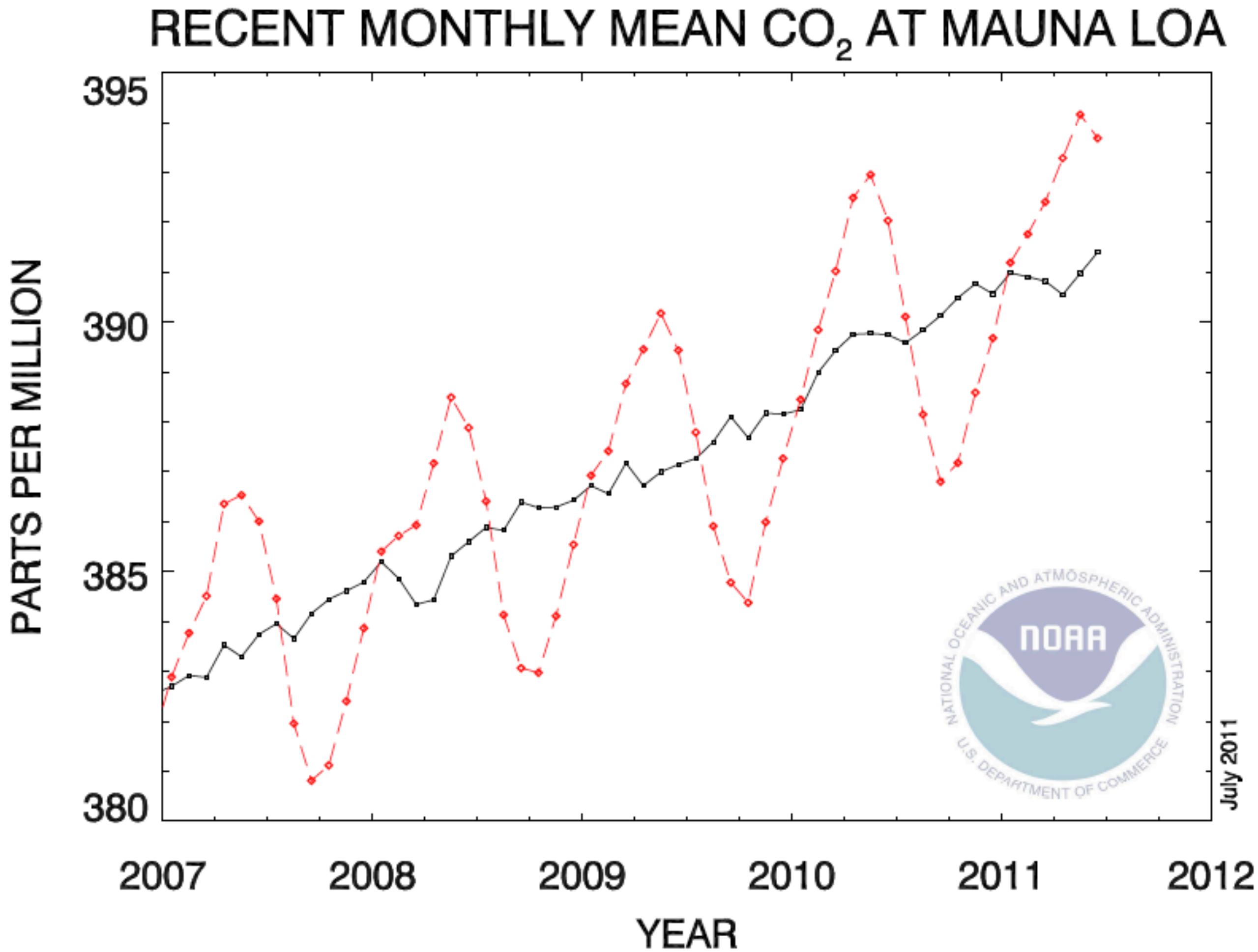


April 2011: 393.18 ppm

http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html

Observed Carbon Dioxide Concentration "Today"

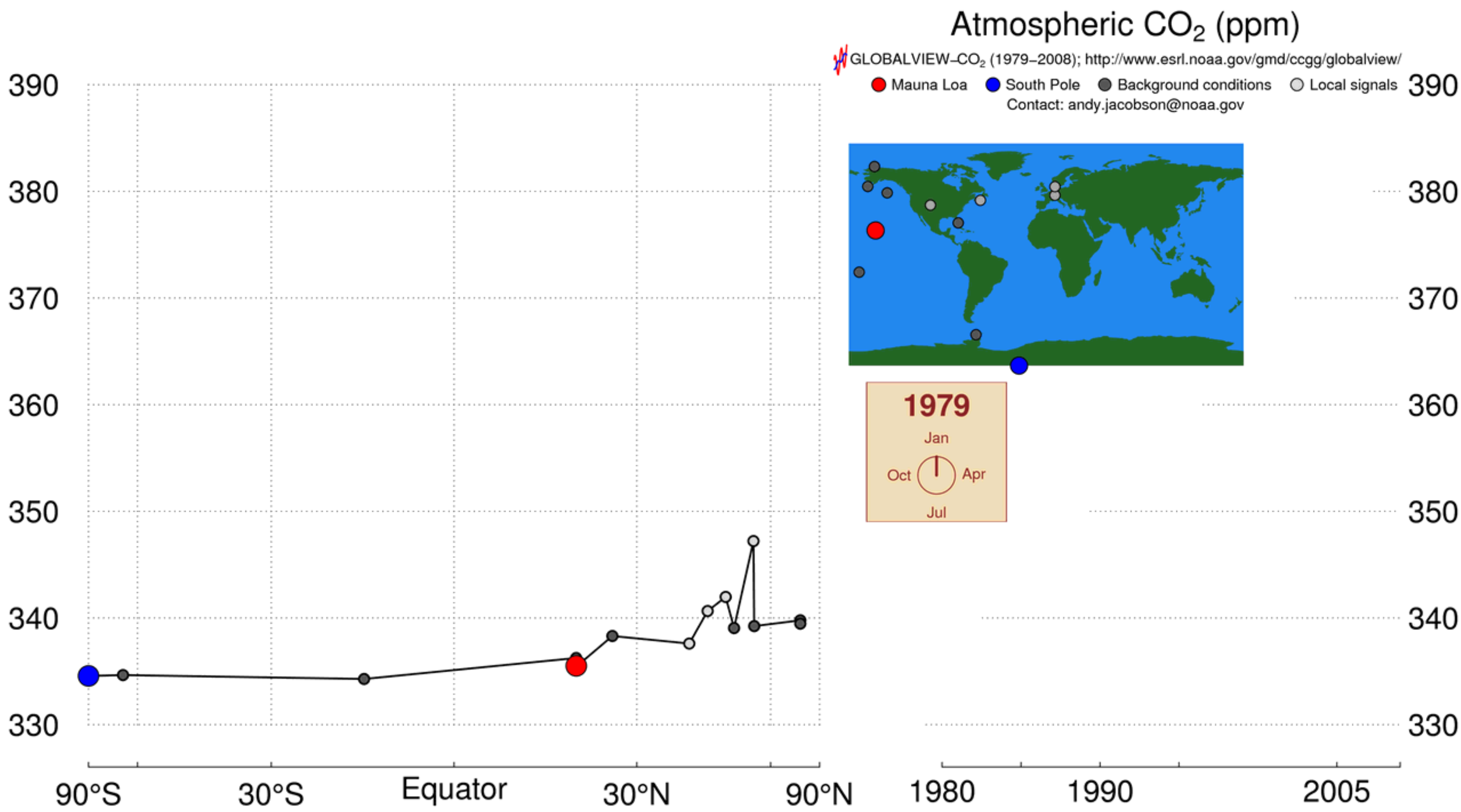
- Monthly CO_2 concentration and its trend line at Mauna Loa, Hawaii (red), up to June, 2011, from Scripps in collaboration with NOAA. ppm, parts per million.



June 2011: 393.69 ppm

http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html

Evolution of Atmospheric CO_2 Concentration



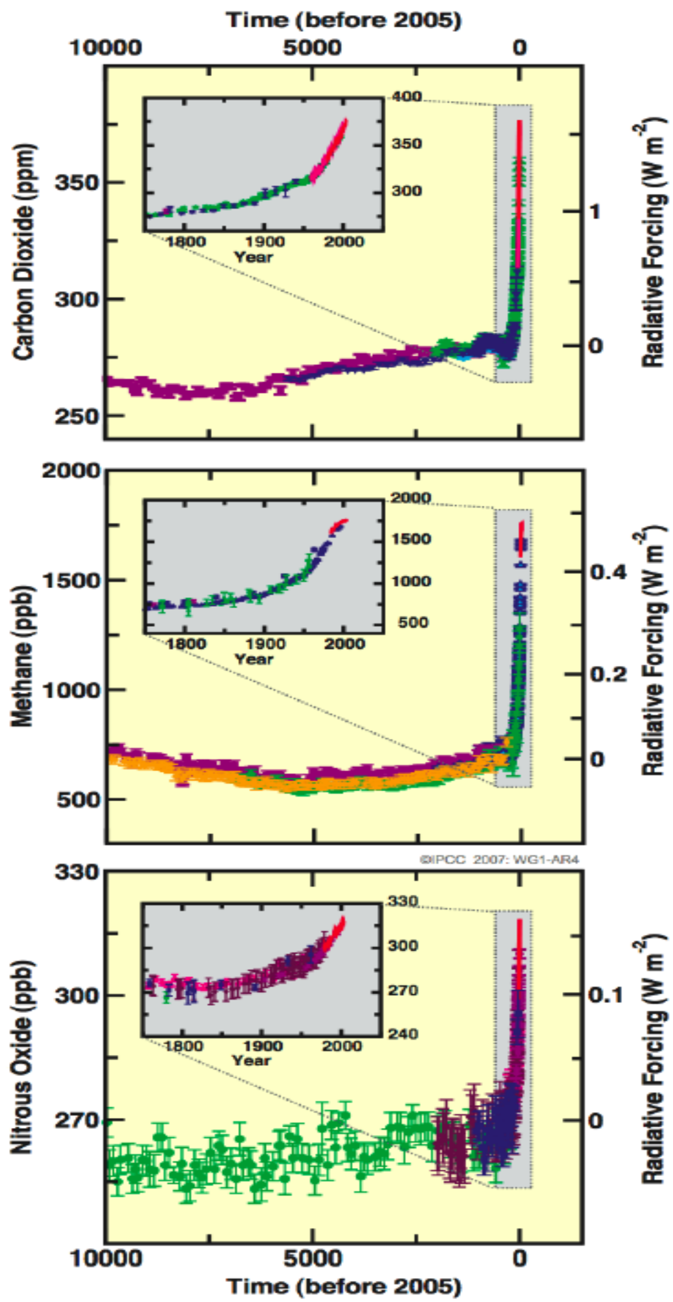
Andy Jacobson, NOAA

Changes in Greenhouse Gases
from ice-Core and Modern Data

CO_2

CH_4

N_2O



Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years

The global increases in CO_2 (carbon dioxide) concentration are due primarily to fossil fuel use and land-use change, while CH_4 (methane) and N_2O (nitrous oxide) are primarily due to agriculture

IPCC AR4 Findings (Summary for Policy Makers, 2007)

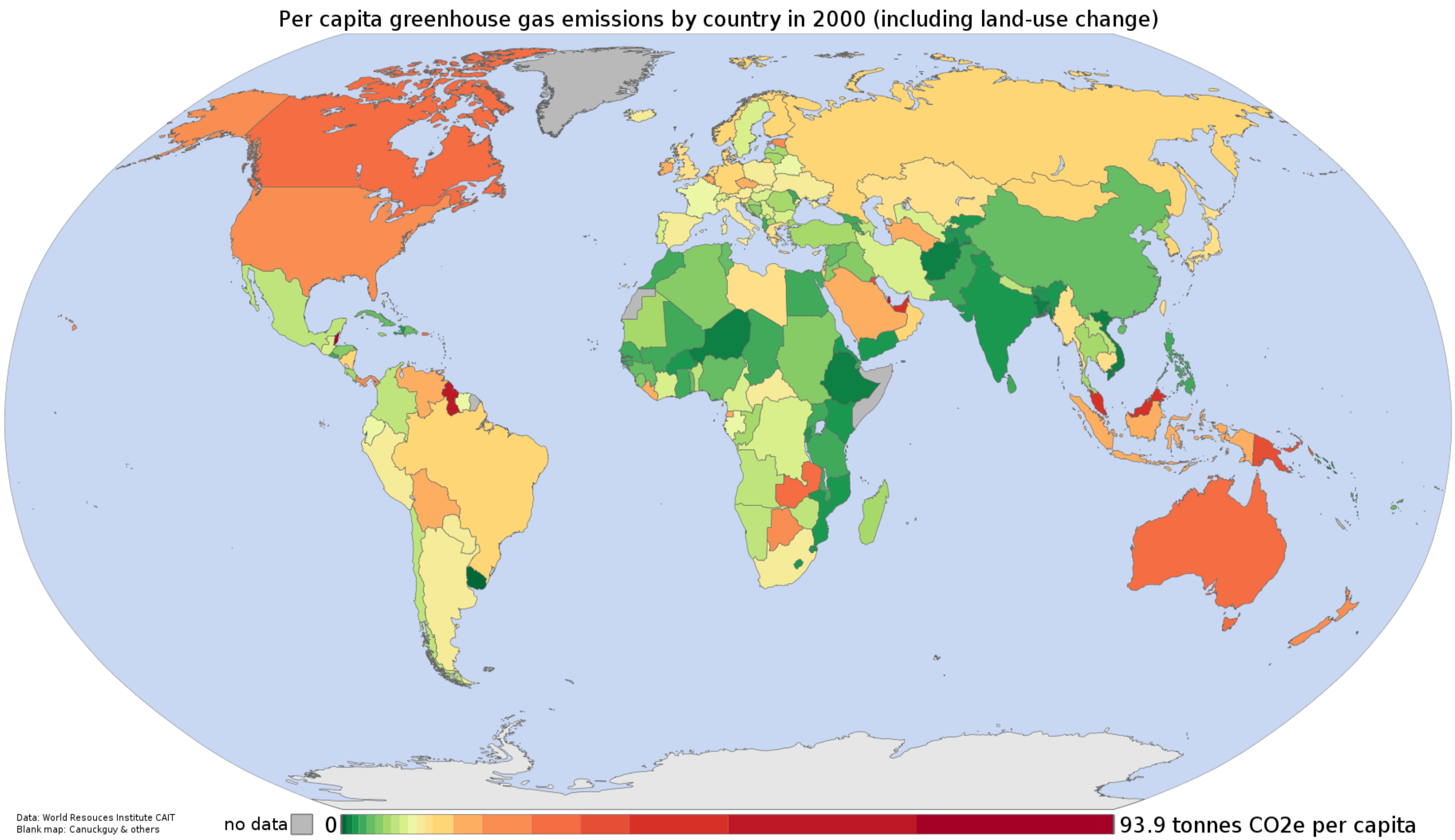
Most Abundant Greenhouse Gases in Earth's Atmosphere

- water vapor
- carbon dioxide
- methane
- nitrous oxide
- ozone
- chlorofluorocarbons

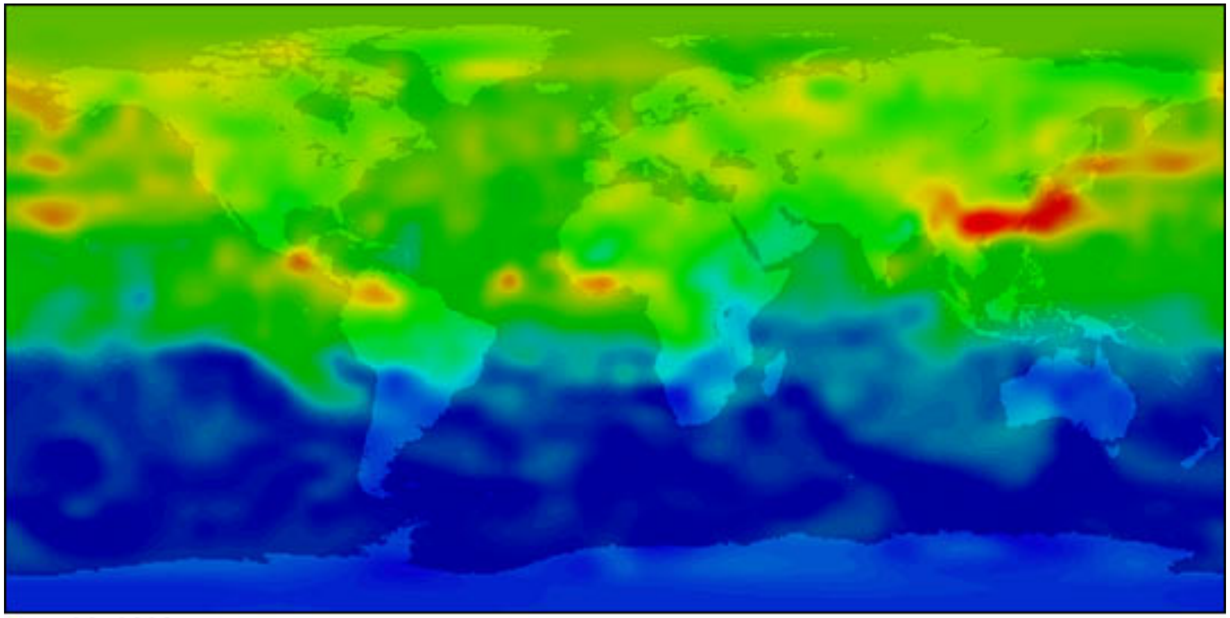
Gas	Formula	Contribution (%)
Water vapor	H_2O	36 – 72 %
Carbon dioxide	CO_2	9 – 26 %
Methane	CH_4	4 – 9 %
Ozone	O_3	3 – 7 %

Credit: http://en.wikipedia.org/wiki/Greenhouse_gas

Per Capita Greenhouse Gas Emission by Country in 2000

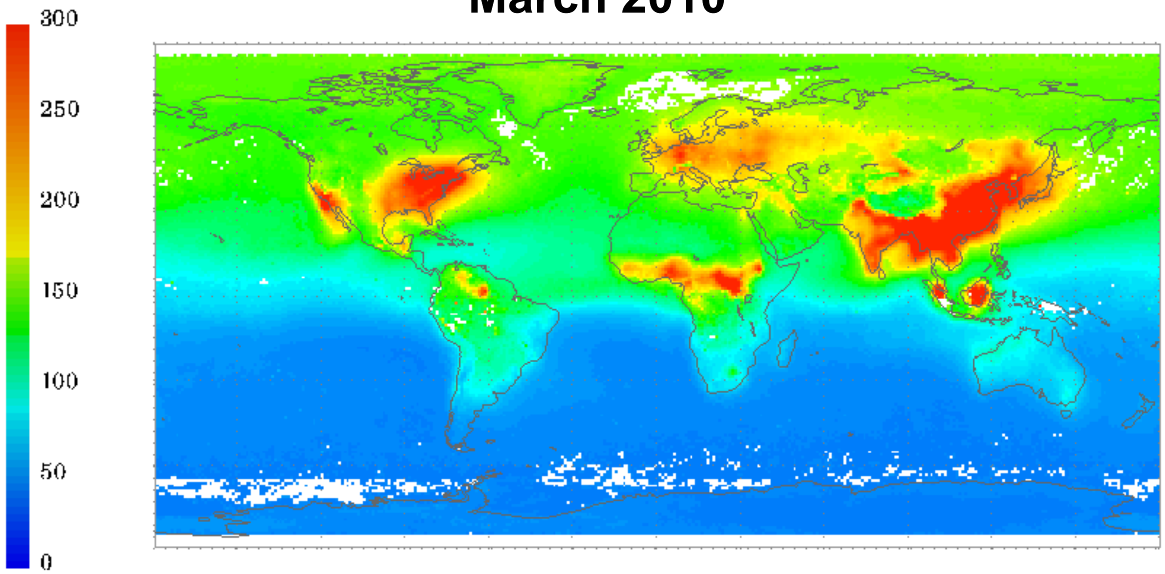


Credit: Viny Burgoo, http://en.wikipedia.org/wiki/Greenhouse_gas



April 30, 2000

March 2010



MOPITT CO Mixing Ratio at Surface (ppbv)

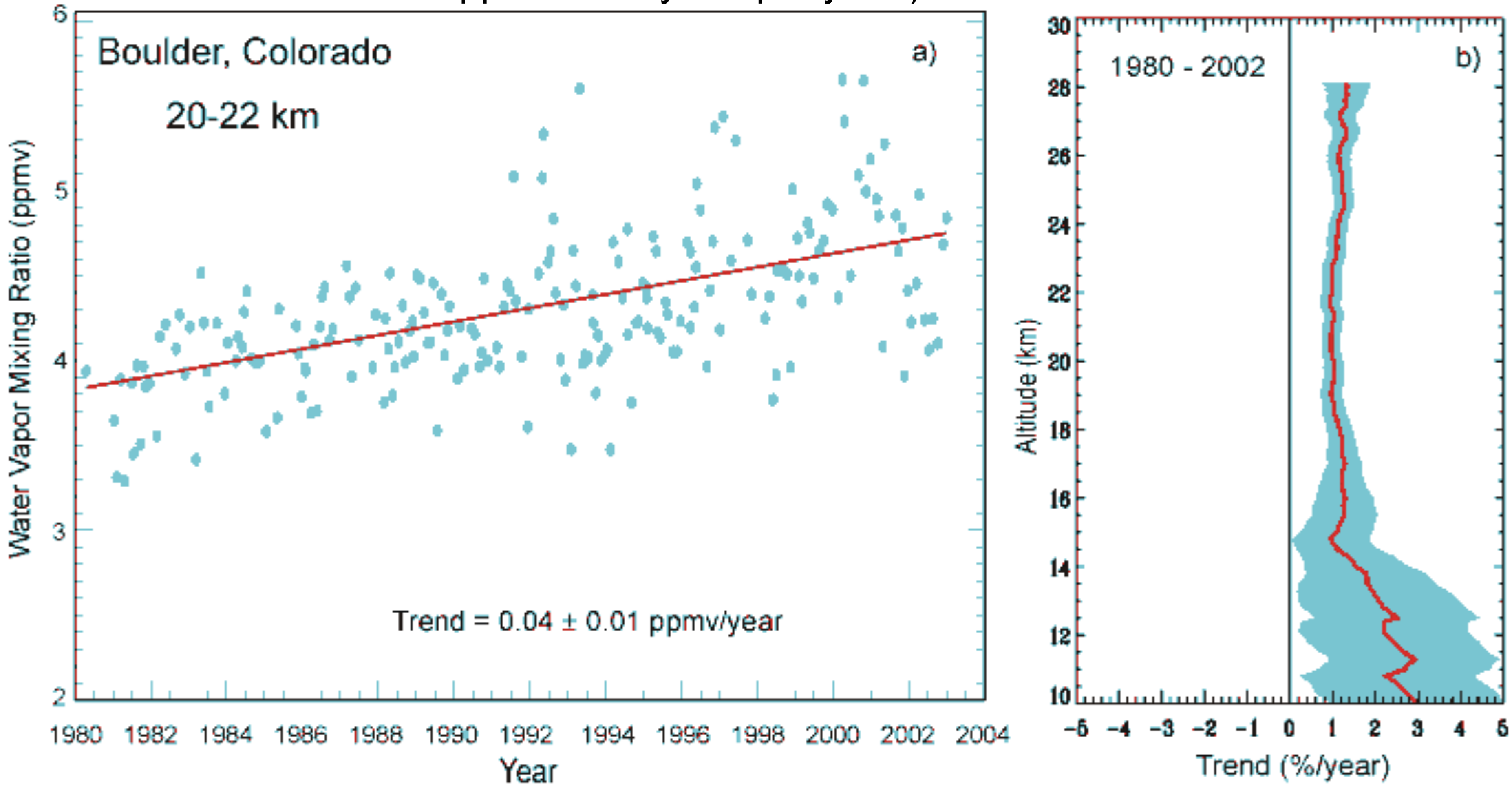
Carbon Monoxide Concentration (parts per billion)

MOPITT
(Measurements of Pollution in the Troposphere, onboard NASA's Terra satellite) observed global carbon monoxide

Credit: http://en.wikipedia.org/wiki

Stratospheric Water Vapor Increase at Boulder, CO

* Observations using balloon-borne frost-point hygrometers, have detected an approximately 1% per year)



Water vapor is the most abundant GHG, contributing to 36–72% of the total GHG. Warming causes increase in humidity, which causes *additional* warming – the "Water Vapor Feedback" process

Credit: NOAA, http://www.esrl.noaa.gov/gmd/publications/annrpt24/416.htm

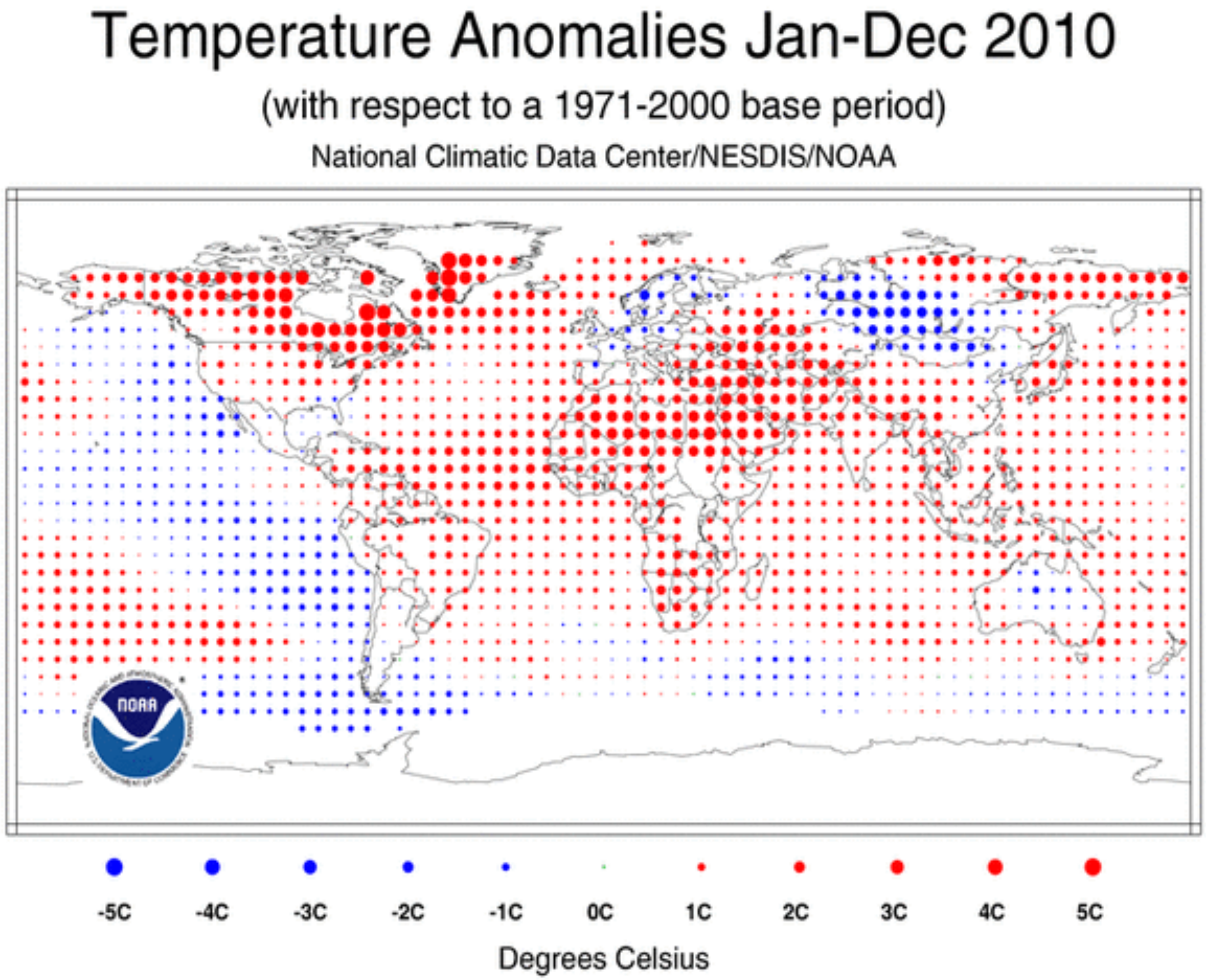
Increased Methane Release from Arctic Permafrost Degradation

Permafrost in Siberia. Methane emissions from the mid-latitude and Arctic wetland region increased by 31% from 2003-07, Photograph: Francis Latreille/Corbis

Bloom et al., *Science,* 2010

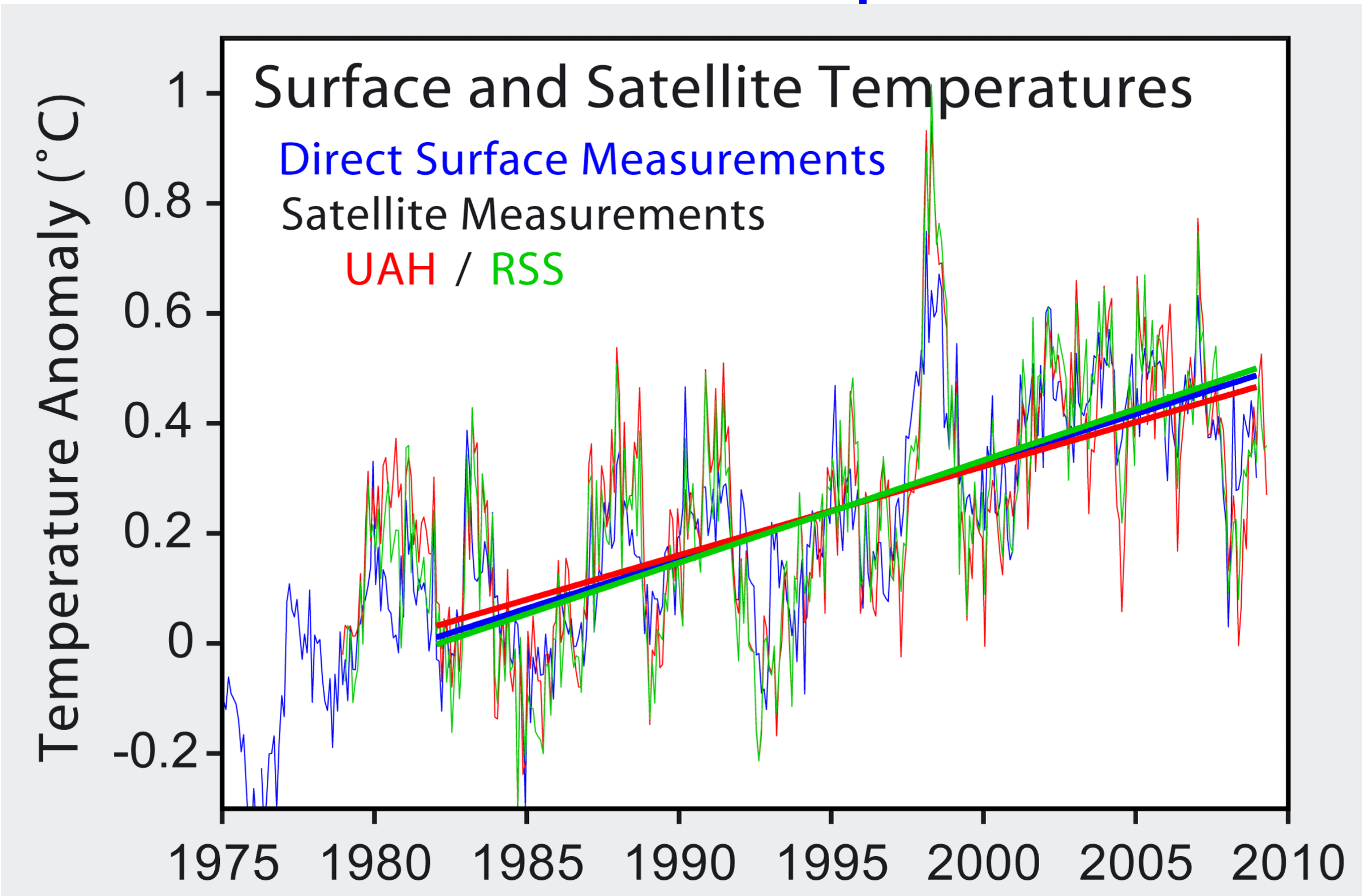
Temperature Anomalies for 2010 – Tied with 2008 as the Warmest Year on Record, beginning 1880

1.12^{0}F (0.62^{0}C) above the 20th century average



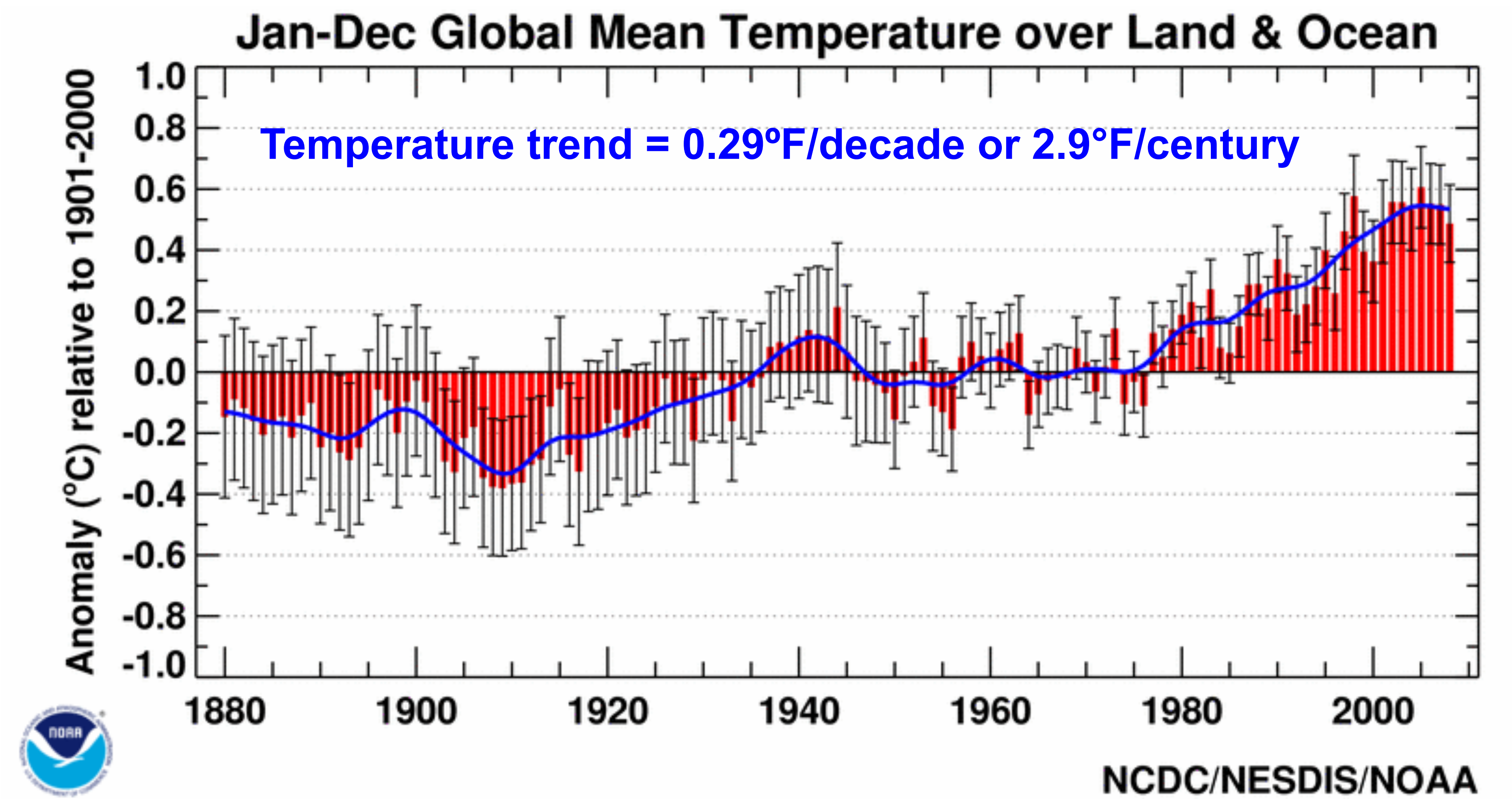
Credit: NOAA, http://www.ncdc.noaa.gov/cmb-faq/anomalies.php

Global Surface and Satellite Temperature Anomalies



Credit: NOAA

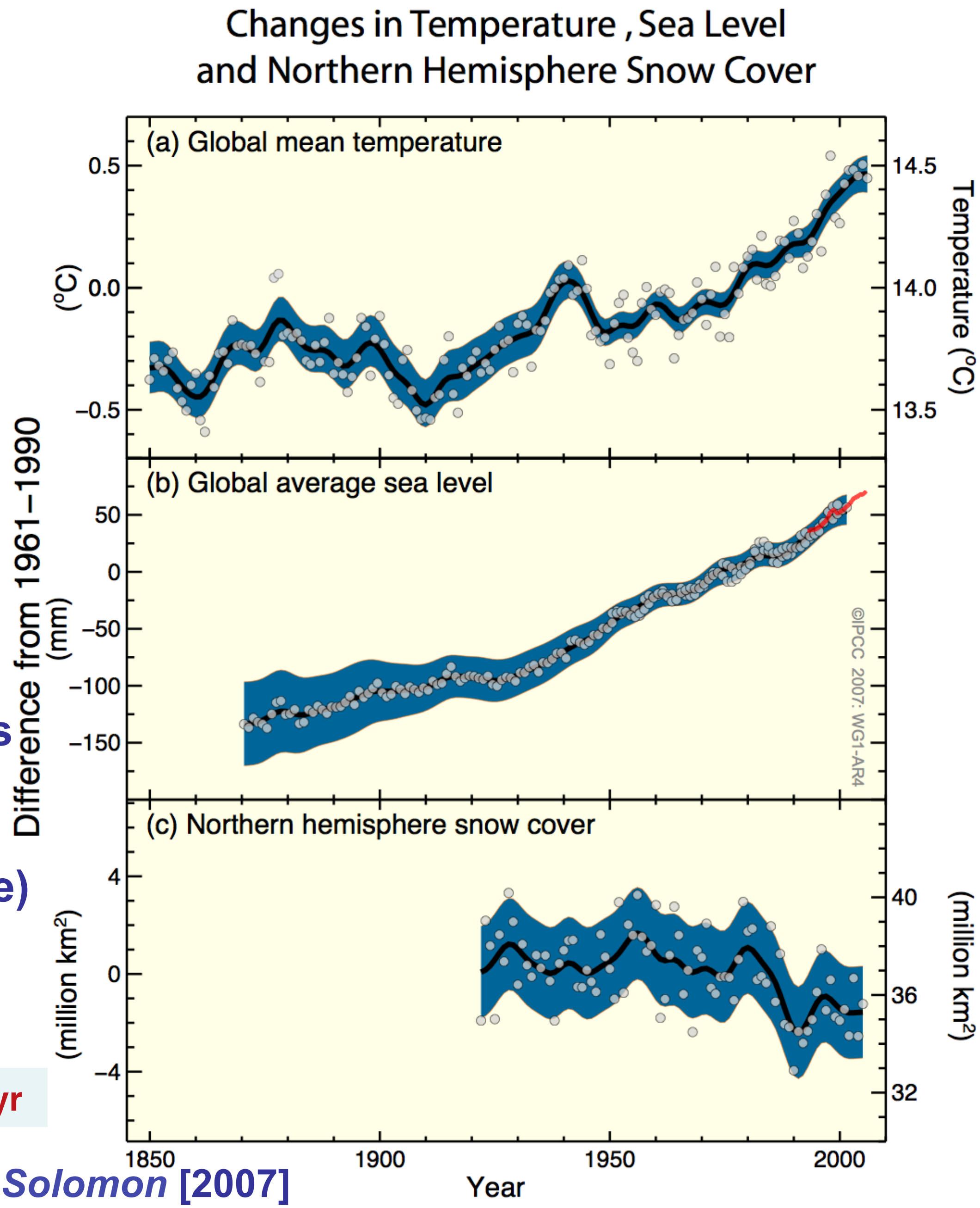
Global Surface (Ocean and Land) Temperature Trend



Credit: NOAA

Summary of Findings: IPCC WGI AR4 Report (2007)

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level



- **Snow cover, March–April changes with respect to 1961–1990 average**
- **Uncertainty (blue), 10-yr average (black curve), yearly average (circle)**
- **Satellite observed sea level (red)**

20th century observed sea-level rise: ~2 mm/yr

IPCC - WGI, Modified from *Solomon* [2007]

Sea Level Since the Last Glacial Maximum Between 20,000 to 25,000 Years Ago

Lambeck et al., *Nature*, 2002

Sea level (based on isostatically adjusted sea-level data from various sediment cores) is ~150 m lower than present during the last Ice Age (~25,000 yr ago).

The dominant contributor to sea level rise is the melting of the ice sheet

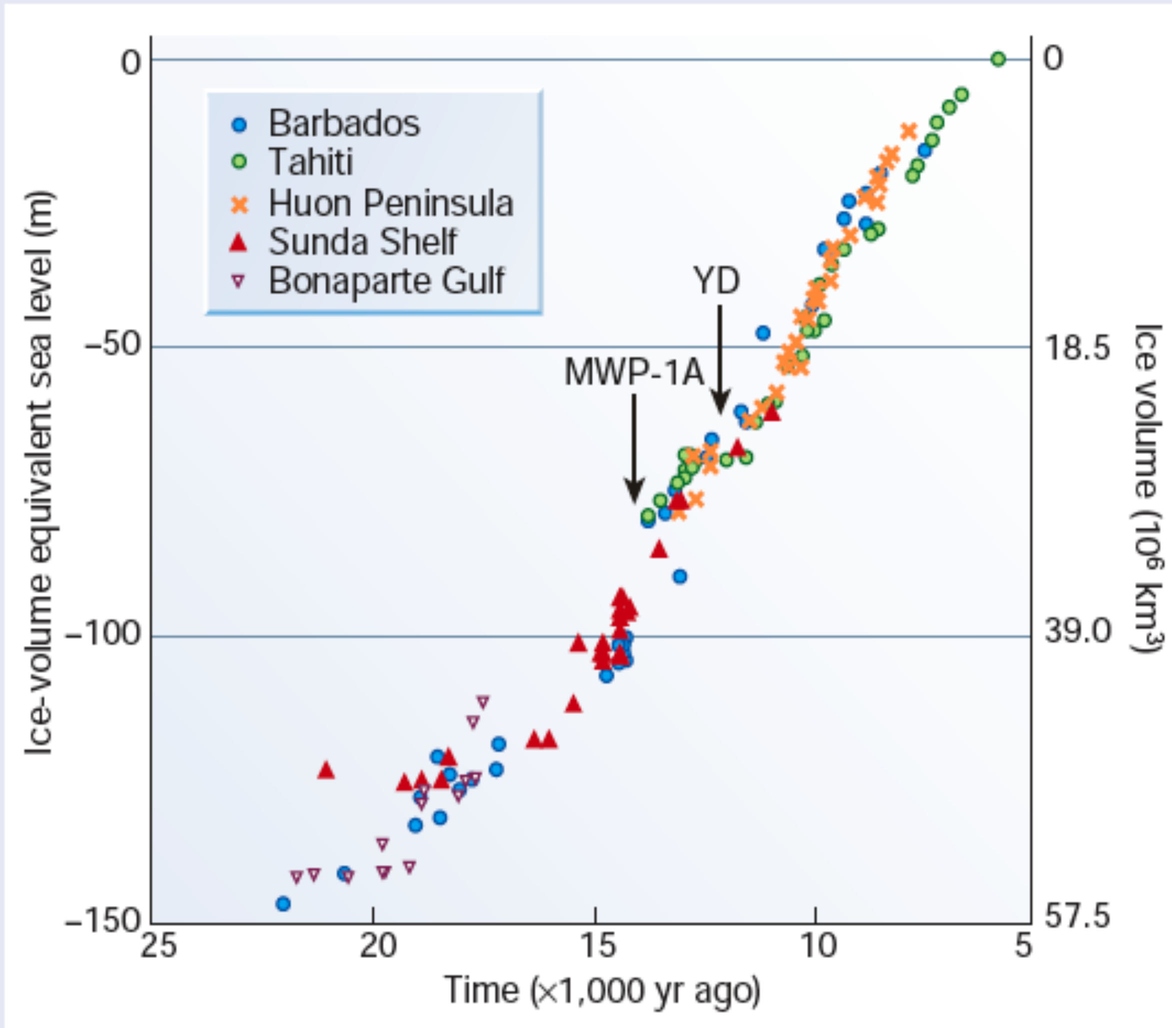
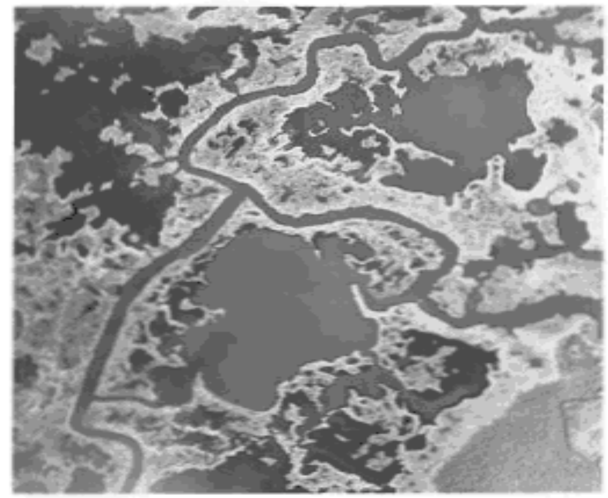


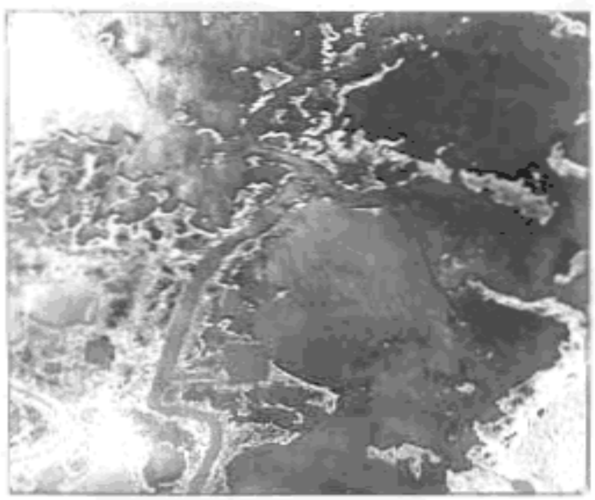
Figure 5 Changes in global ice volume from the time of the LGM to the present.

Marsh Destruction at Blackwater, Maryland, Due to Sea Level Rise

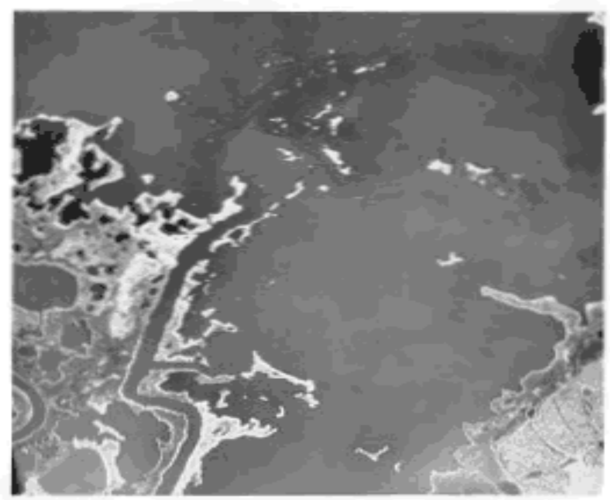
1938



1957



1972

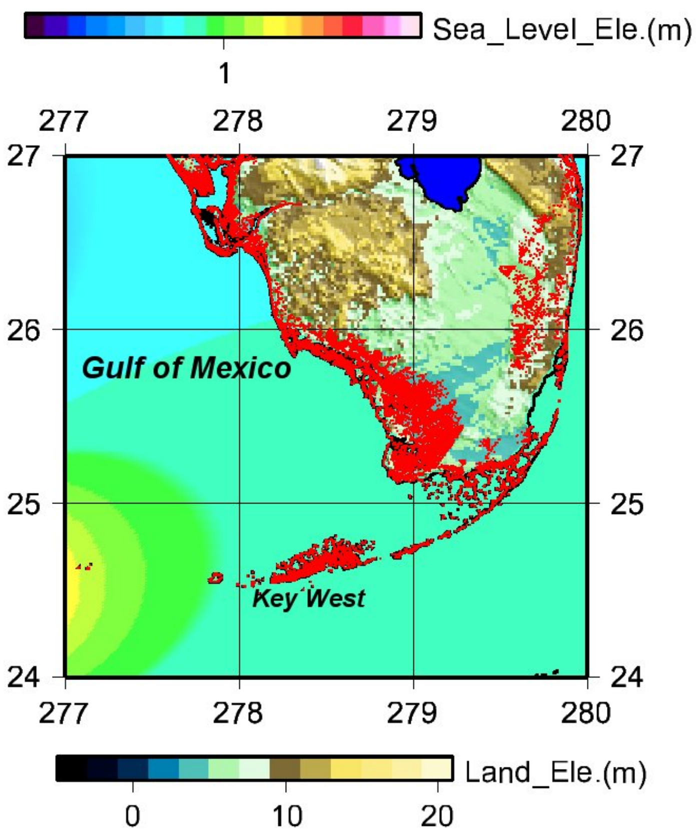


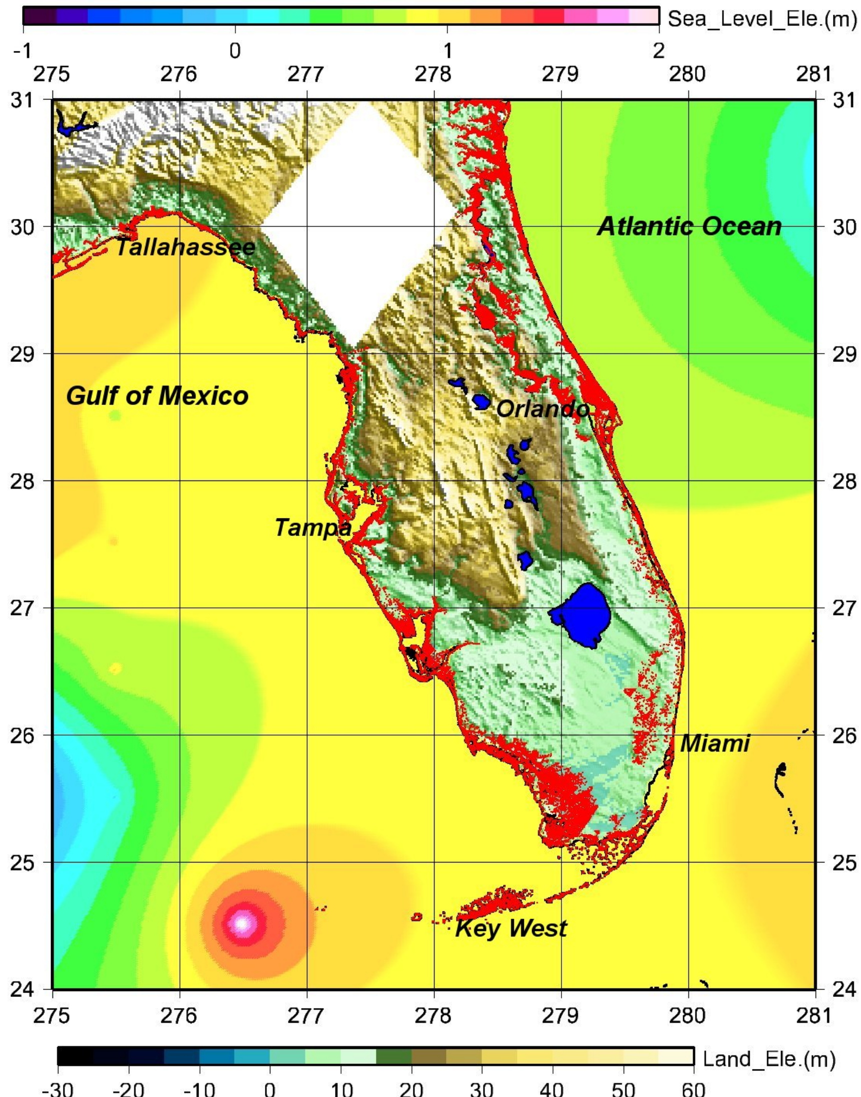
1988

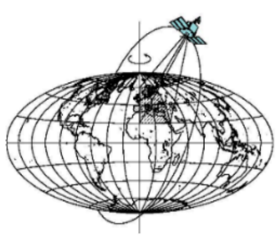
Leatherman [2001]

LAND LOSS DUE TO 1 METER SEA LEVEL RISE

Land Elevation Modeled Using SRTM 30-m DEM







Sea Level Modeled Based on Altimetry Determined Secular Trend

C. Shum, 1/07

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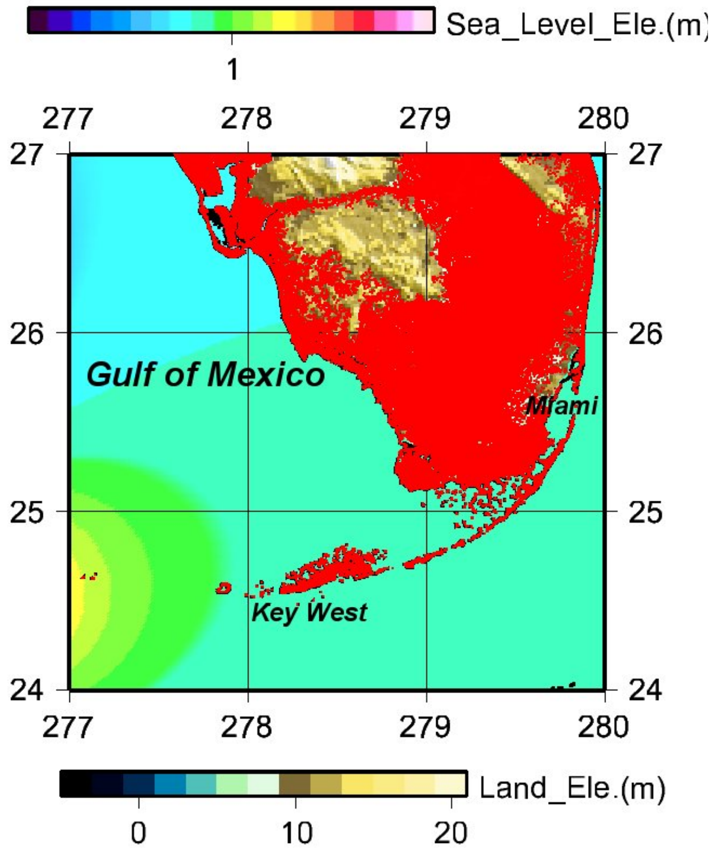
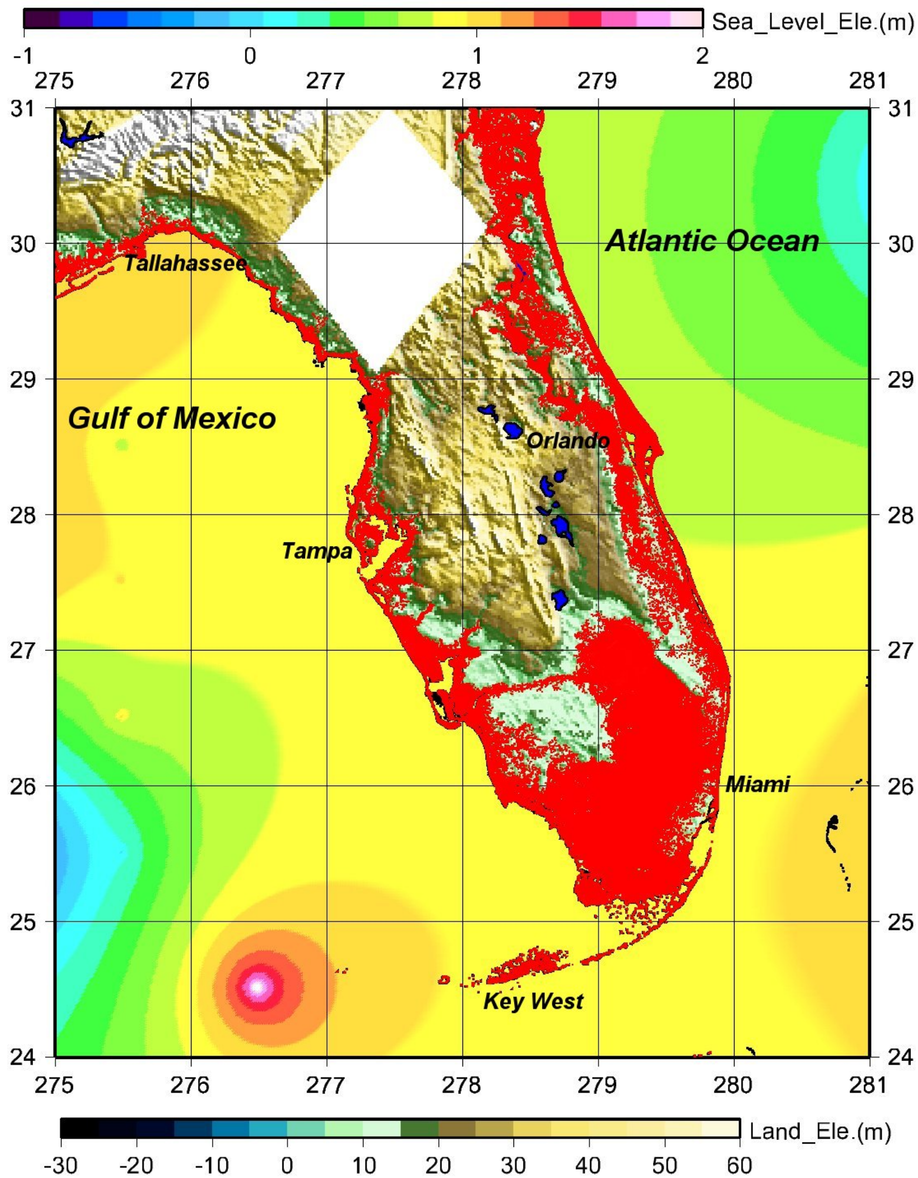
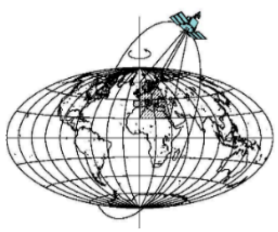
LAND LOSS DUE TO 5 METER SEA LEVEL RISE

Land Elevation Modeled Using SRTM 50-m DEM







Sea Level Modeled Based on Altimetry Determined Trend

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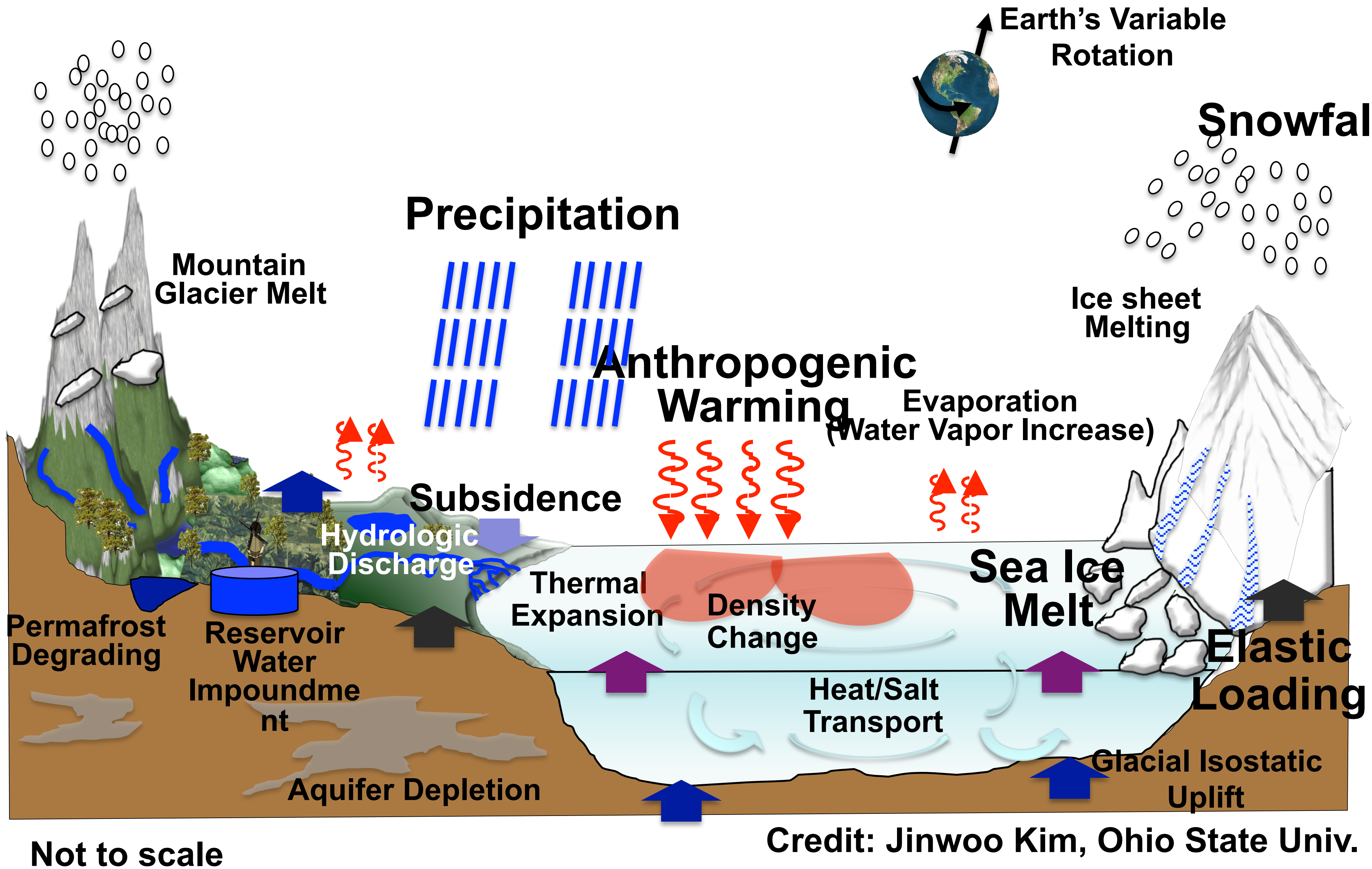
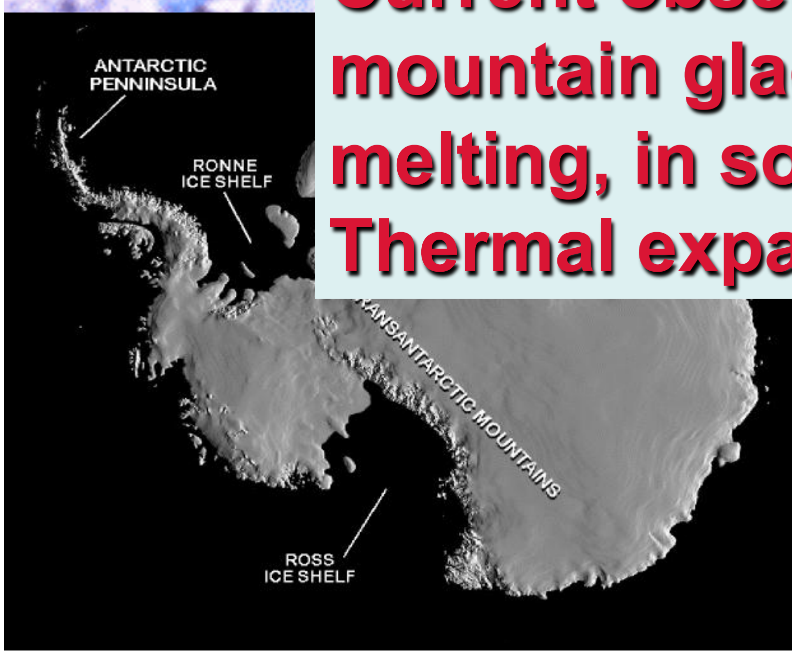


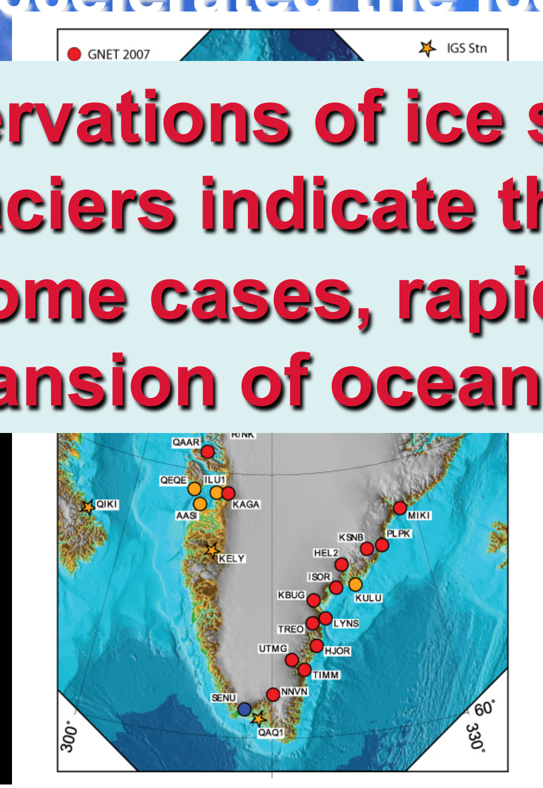
Schematic for Processes Contributing to Present-Day Sea-Level Rise

Ice-Sheets and Glaciers

Sea level rise during the last 5 million years and since the Pleistocene (the last Ice Age) are driven mostly driven by melting of ice sheets, human-induced warming appeared to have accelerated the ice sheet melt.

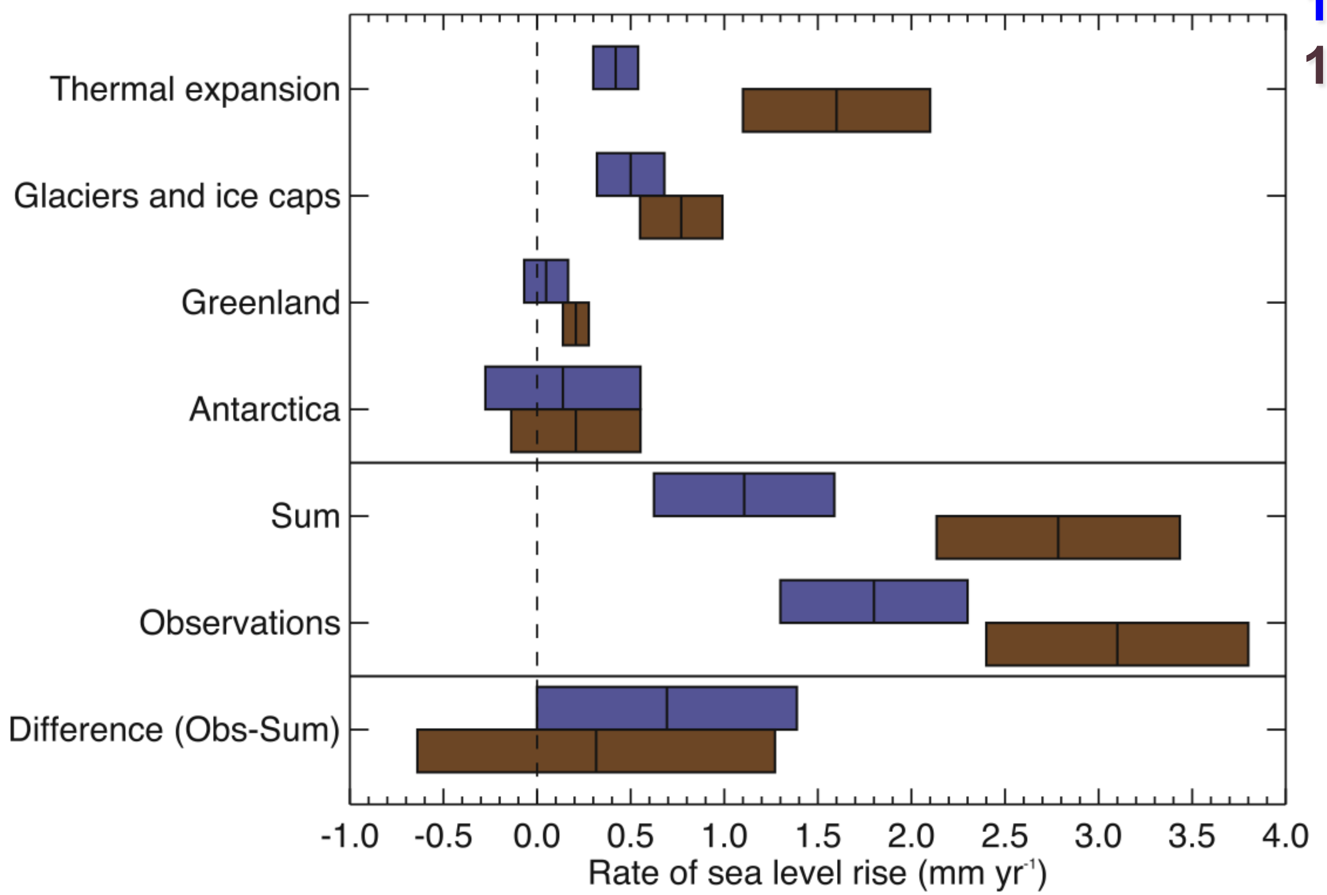
Current observations of ice sheets & mountain glaciers indicate that they are melting, in some cases, rapidly.
Thermal expansion of ocean is increasing.





2007 IPCC Sea Level Budget (Observed vs Explanation)

IPCC - WGI, Chapter 5, Fig. 5.21 [*Bindoff et al.*, 2007]



1961–2003 (blue)
1993–2003 (brown)

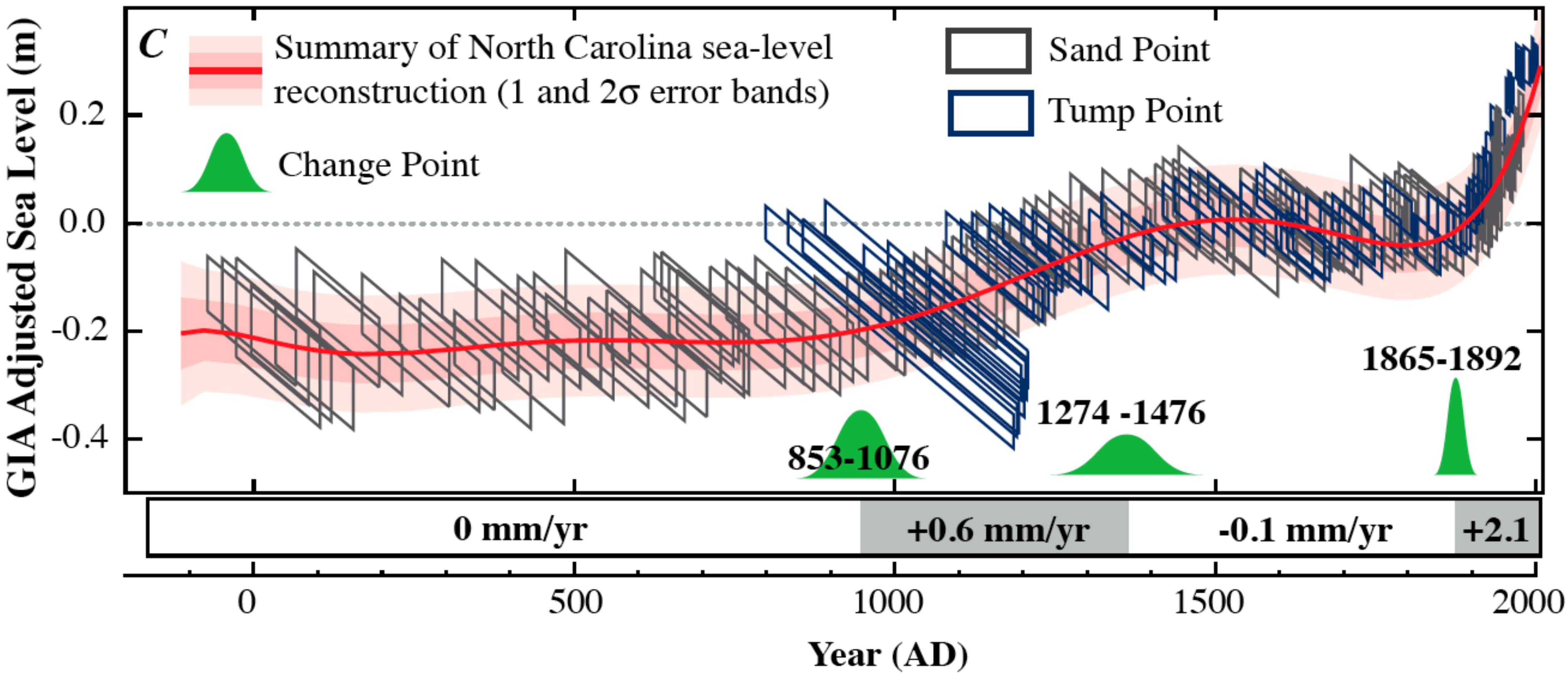
1.1 mm/yr
2.8 mm/yr
1.8 mm/yr
3.1 mm/yr
0.7± 0.7 mm/yr
0.3 ±1.0 mm/yr

Current estimate of ice sheet mass balance (equivalent sea level):

Antarctica: –0.03 to 0.57 mm/yr (1992–2005)
Greenland: –0.12 to 0.17 mm/yr (1992–2006)

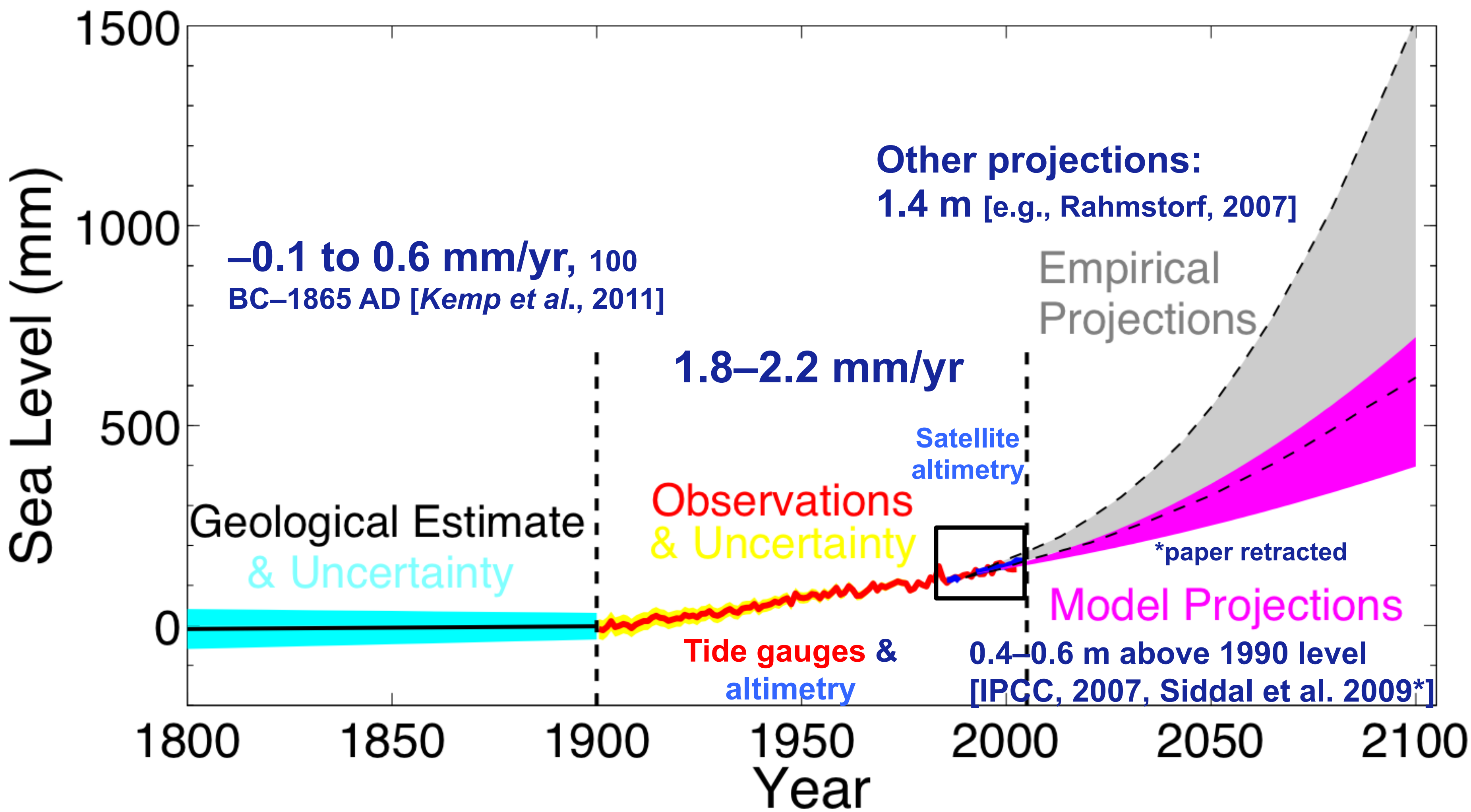
GIA-Corrected Sea-Level Reconstruction North Carolina Site, 100 BC – 2000 AD

–0.1 to 0.6 mm/yr, 100 BC – 1870 AD

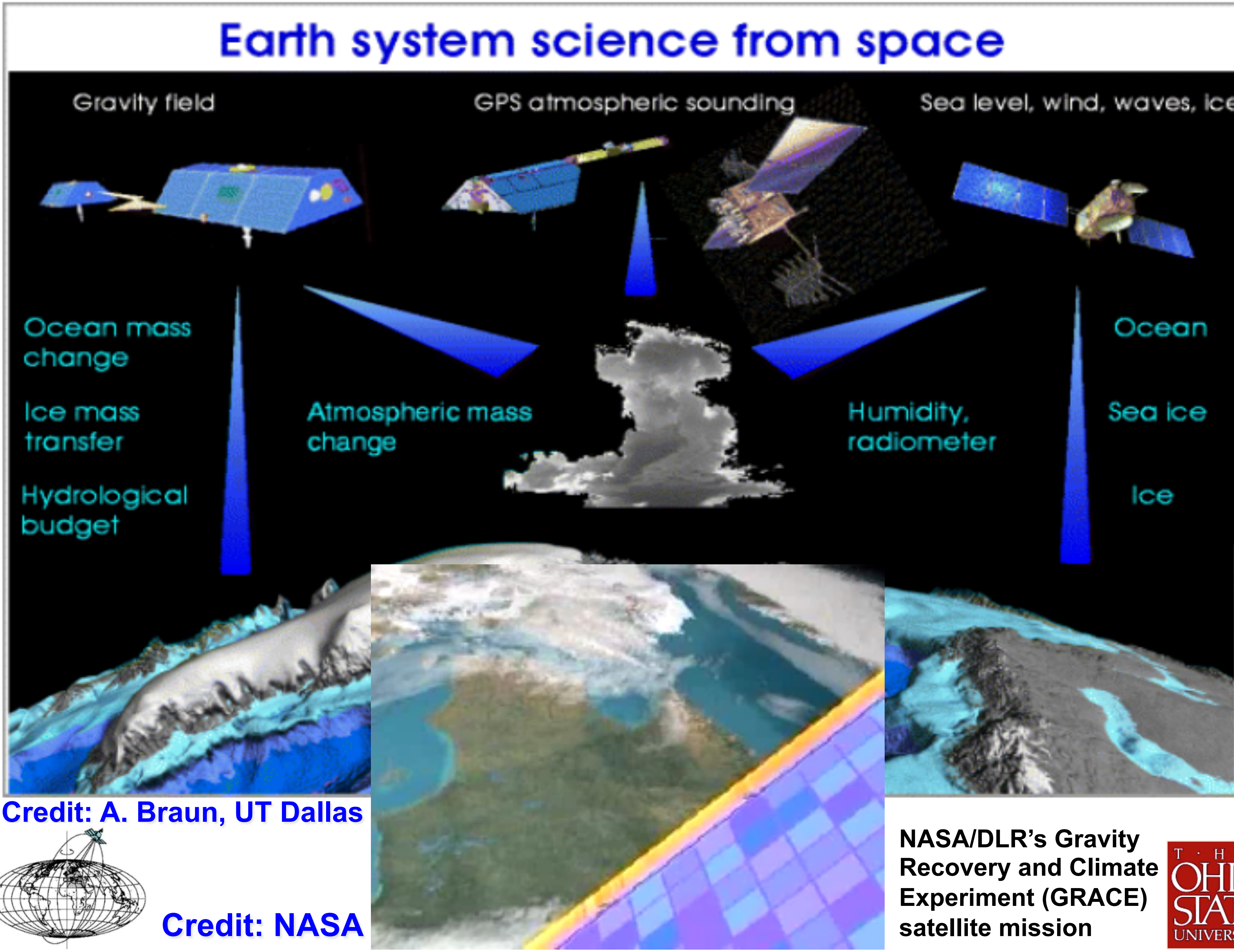


Kemp et al. [2011]

Global Sea Level Rise: Estimation & Prediction (1800-2100)



Updated from [*Shum* & Kuo, 2011]

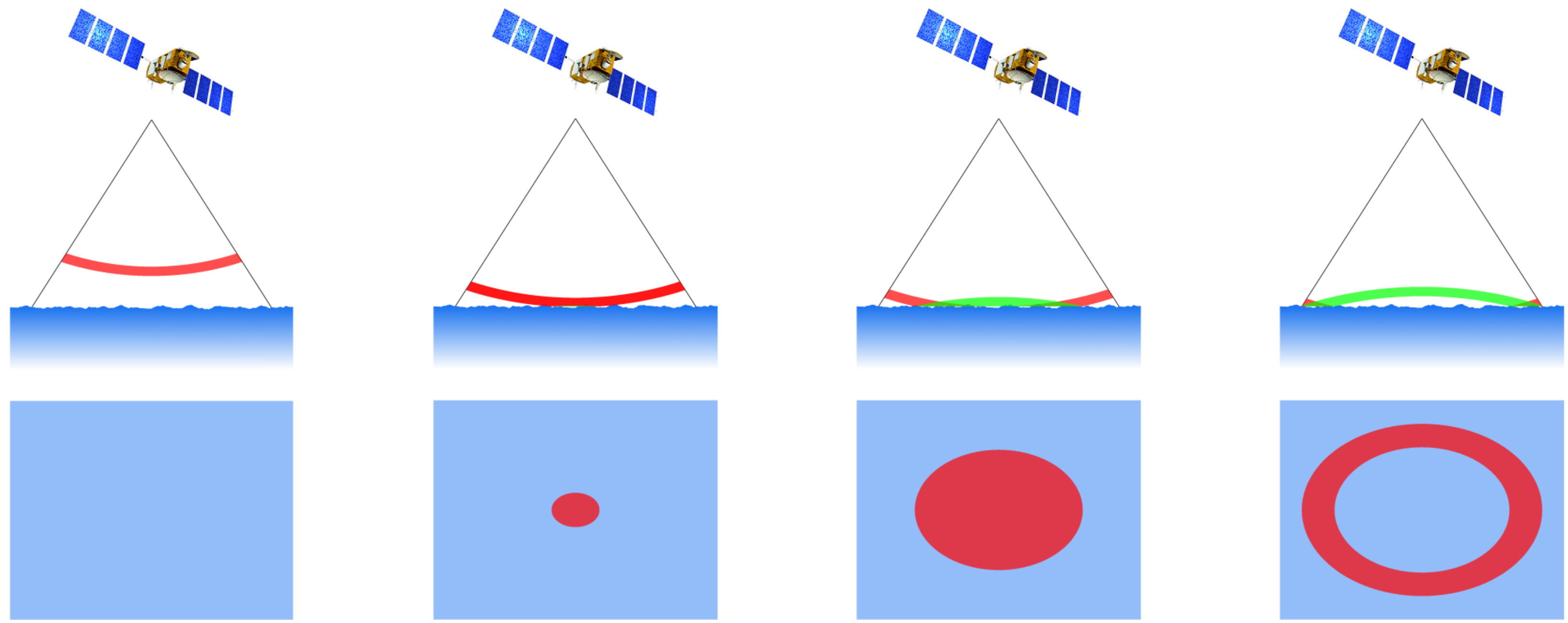


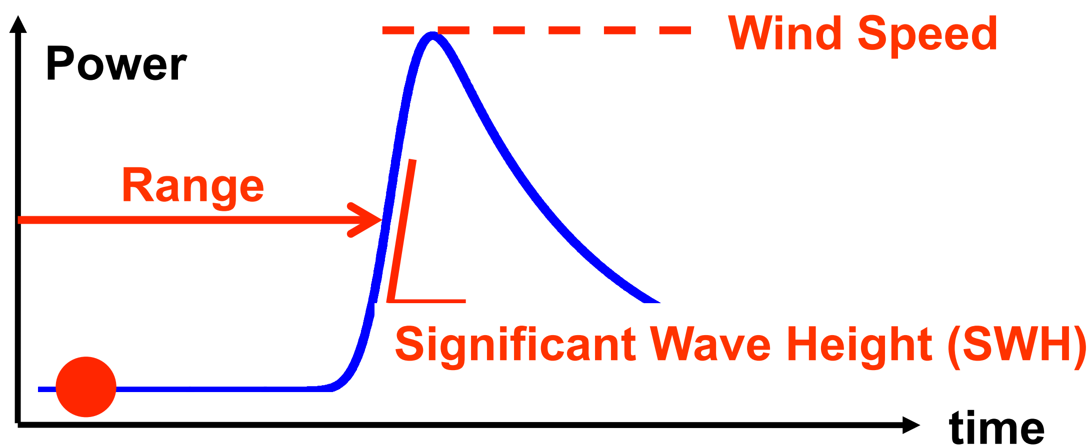
Credit: A. Braun, UT Dallas

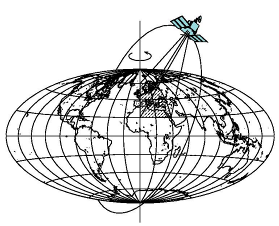
Credit: NASA

NASA/DLR's Gravity Recovery and Climate Experiment (GRACE) satellite mission

Pulse-Limited Radar Altimeter Principle

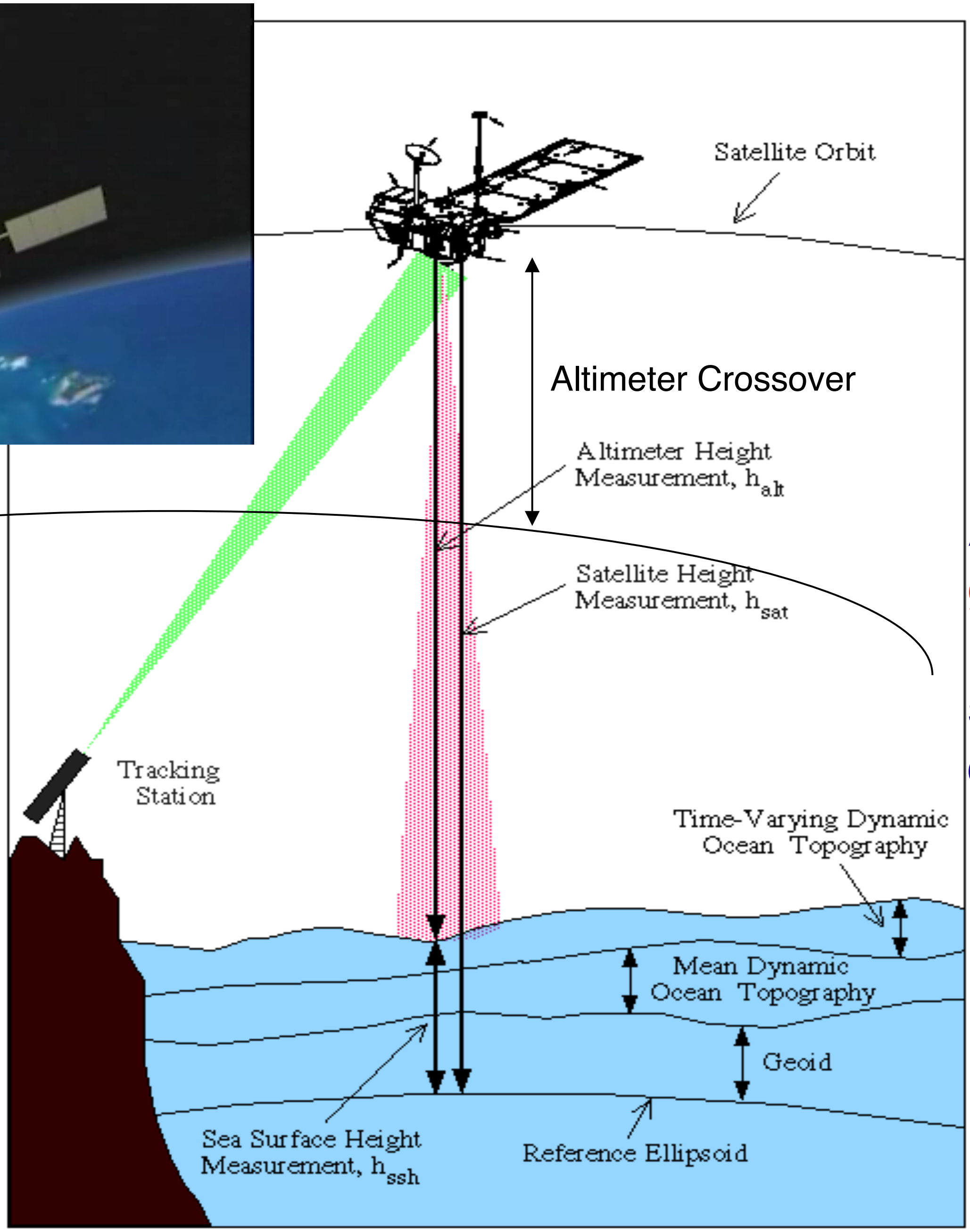






Credit: Praphun Naenna, OSU

JASON-1
(Credit: JPL)



Altimeter measures geocentric sea level, lake/river, ice sheet, and land elevation change

C.K. Shum, 2/07

Radar Altimeter Geometry

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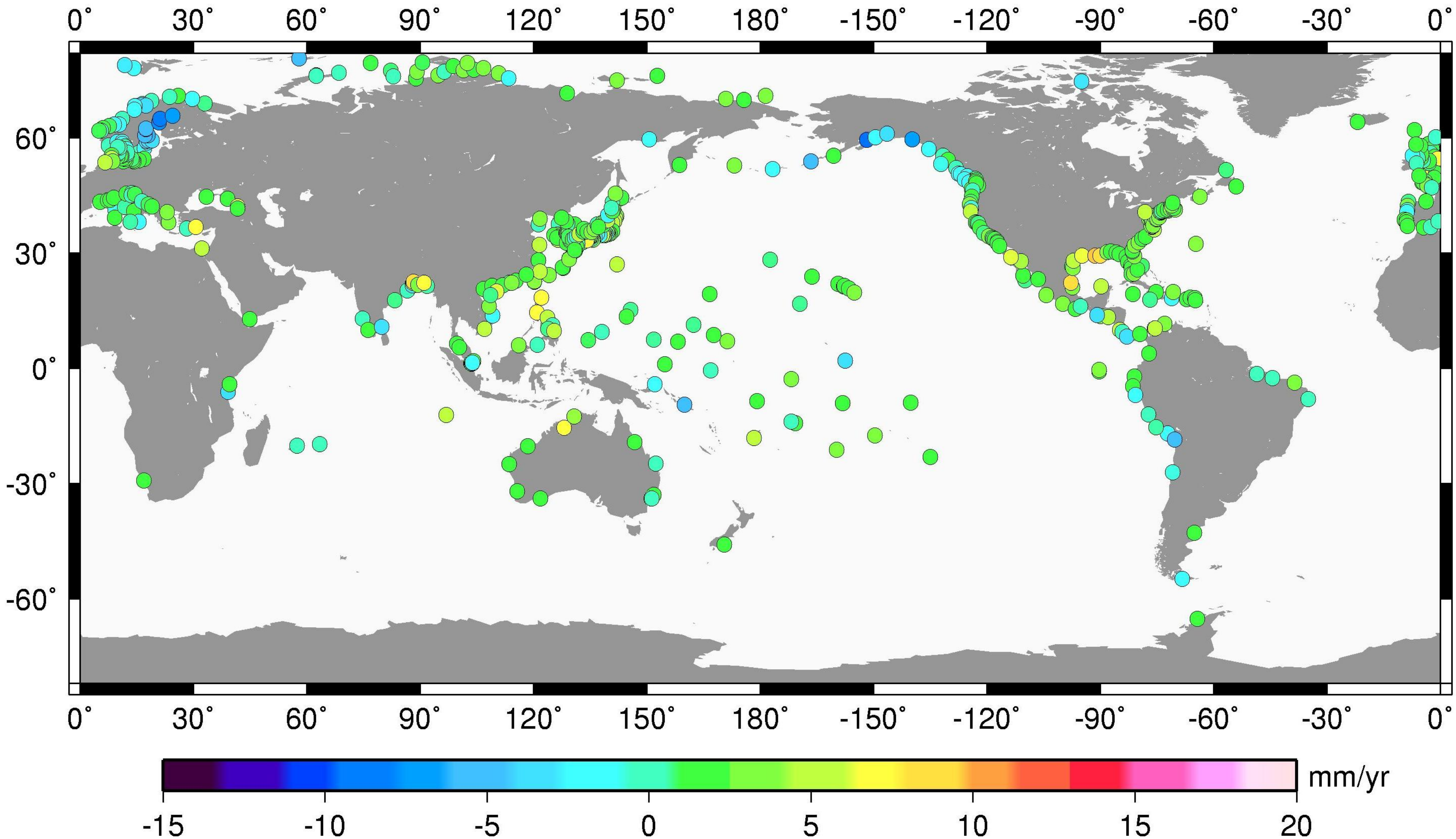
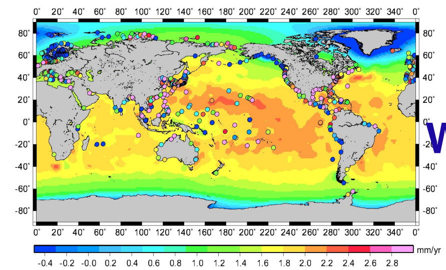
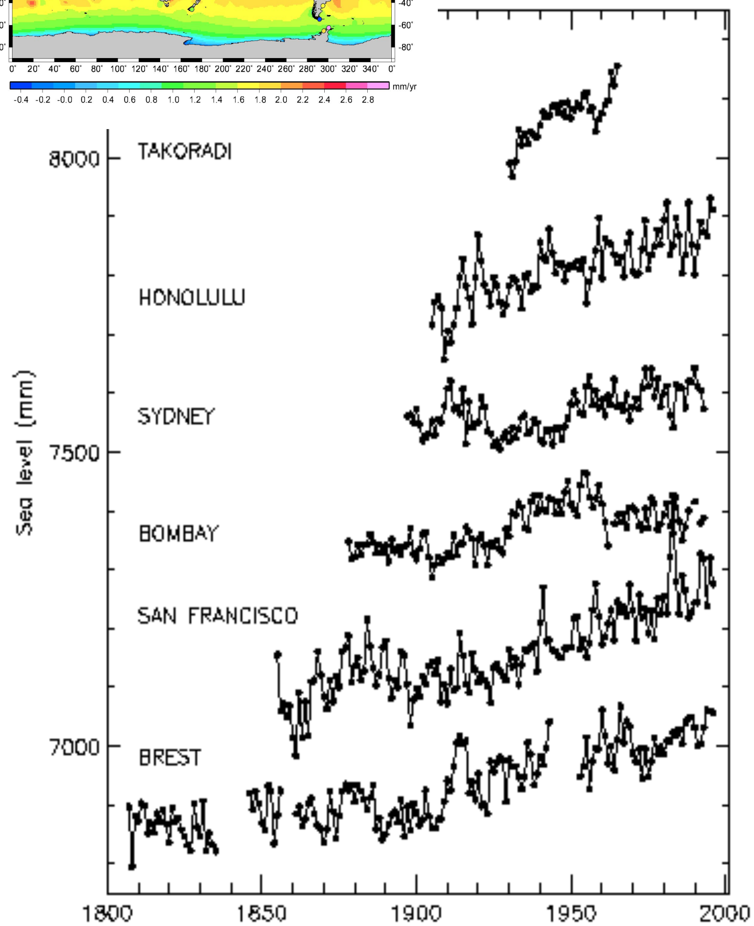


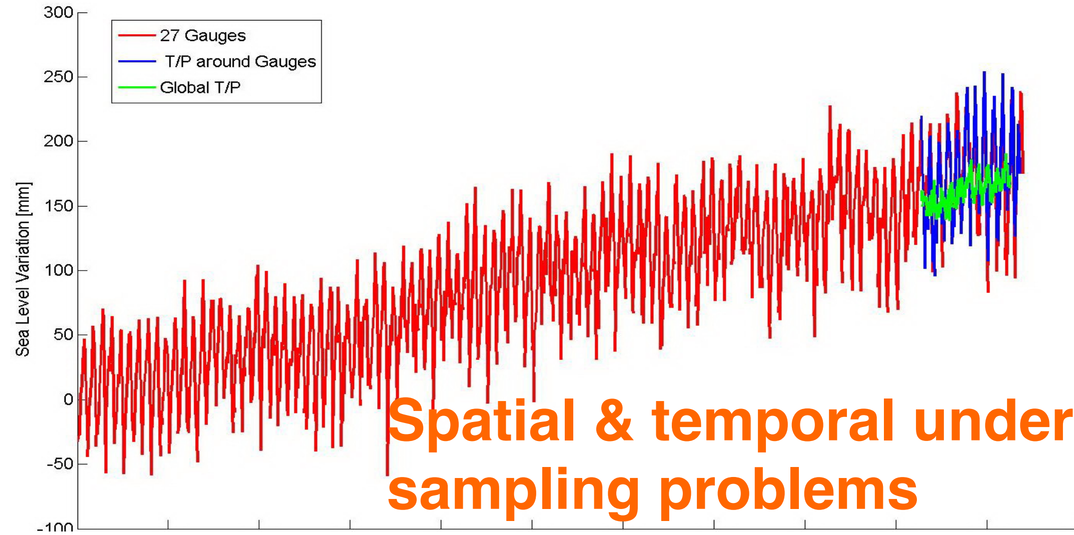
Estimated Global Sea Level Trend:
Tide gauges (1900–2007, 704 sites, color-coded) = 1.65±0.4 mm/yr

Sea Level Observations (Tide Gauge & Altimetry)

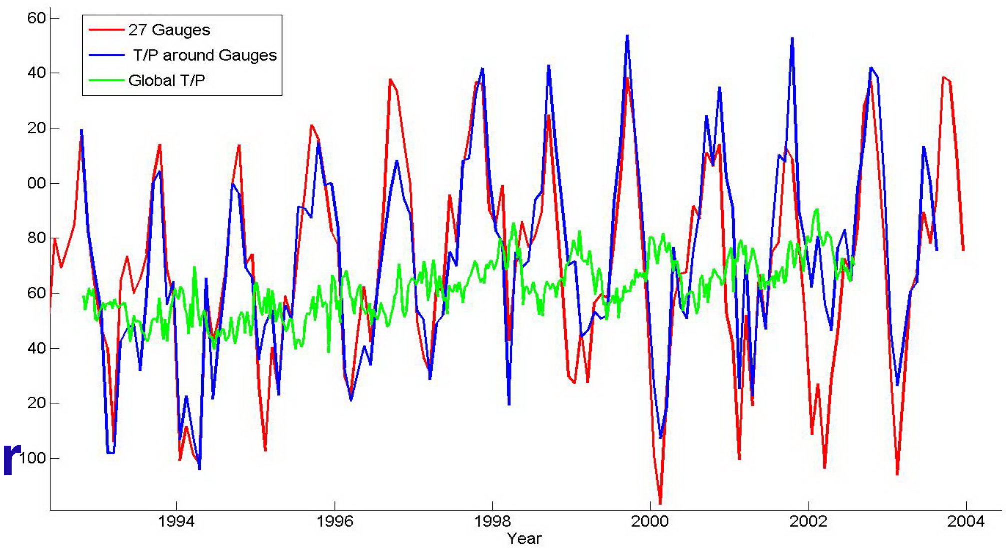


Woodworth [2000]





Spatial & temporal under-sampling problems



Sea level rise: ~1.8–2.0 mm/yr
100–200 year records

Douglas, 2001; Church et al., 2004, 2006; Cazenave & Nerem [2004]; Holgate & Woodworth [2004]

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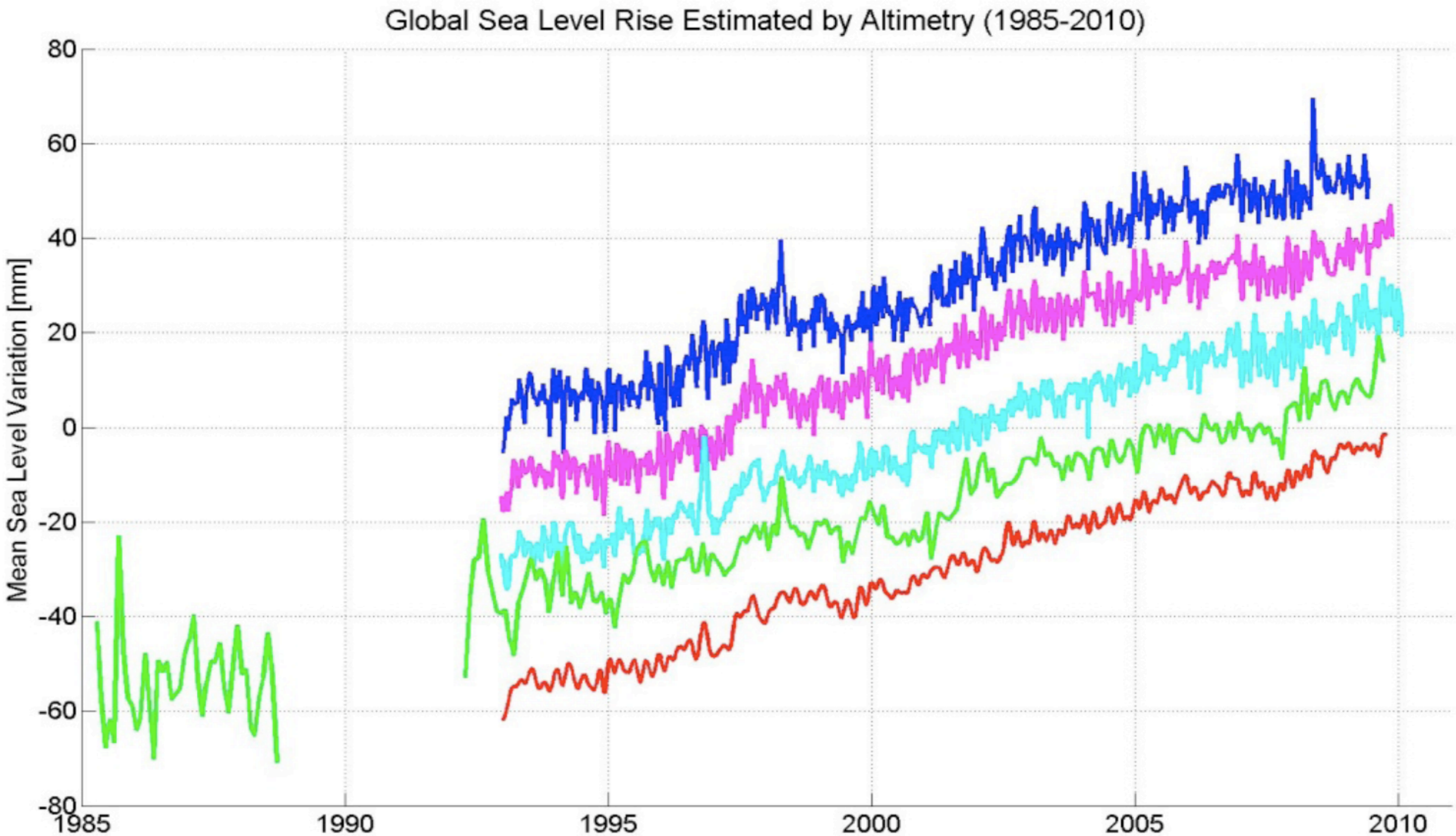
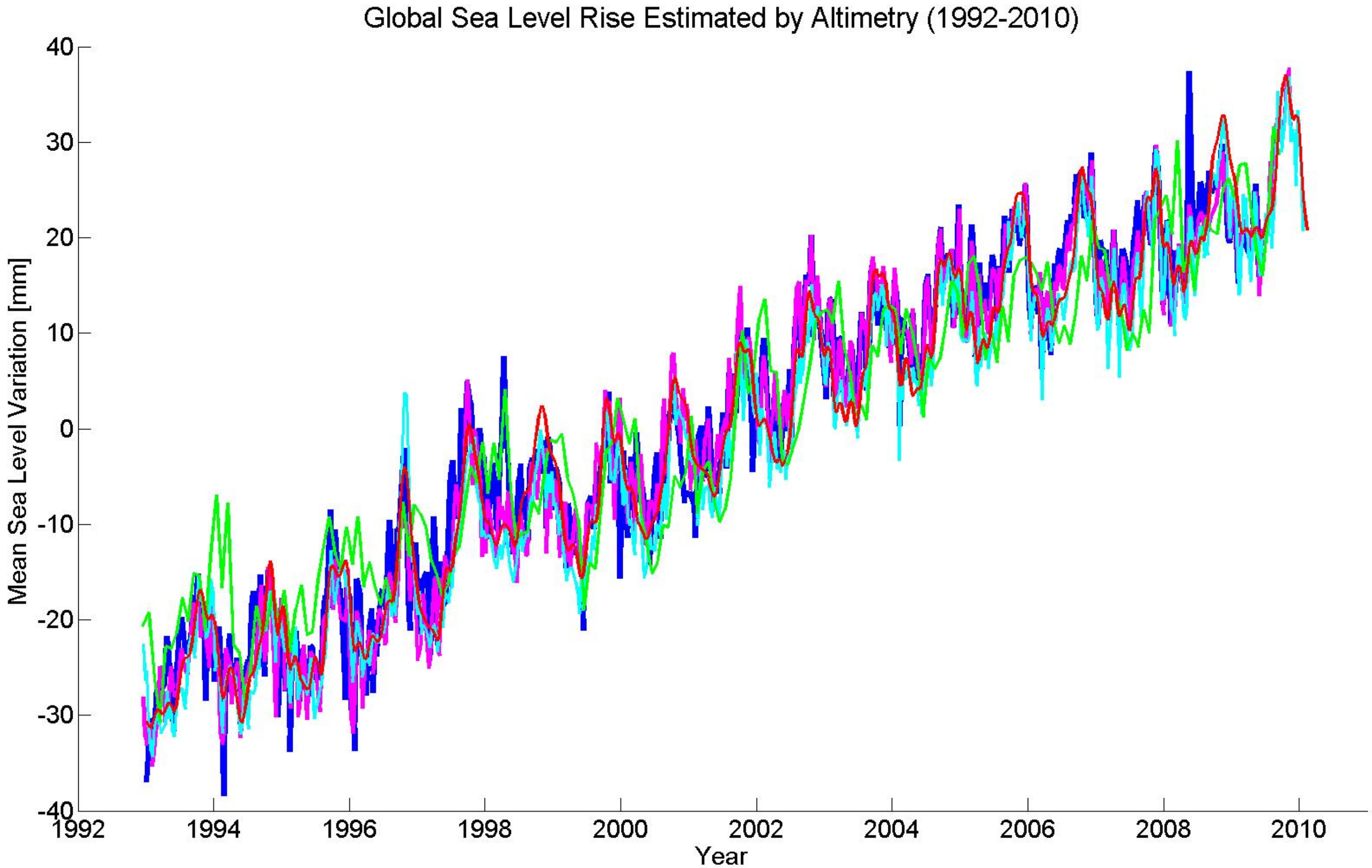


Global Sea Level Observed by Radar Altimetry (seasonal signal removed), TOPEX & Jason-1/2, except Kuo & Shum [2010] who used multiple altimetry, IB & GIA Corrected

Blue: Chambers [2010], 3.3±0.05 mm/yr
Magenta: Nerem et al. [2010], 3.3±0.05 mm/yr
Cyan: Leuliette & Miller [2010], 3.2±0.03 mm/yr
Green: Kuo & Shum [2010], 2.9±0.05 mm/yr (Geosat, ERS, TP, GFO, Envisat, Jason)
Red: Cazenave & Llovel [2010], 3.3±0.02 mm/yr



Global Sea Level Observed by Radar Altimetry (seasonal signal removed), TOPEX & Jason-1/2, except Kuo & Shum [2010] who used multiple altimetry, IB & GIA Corrected

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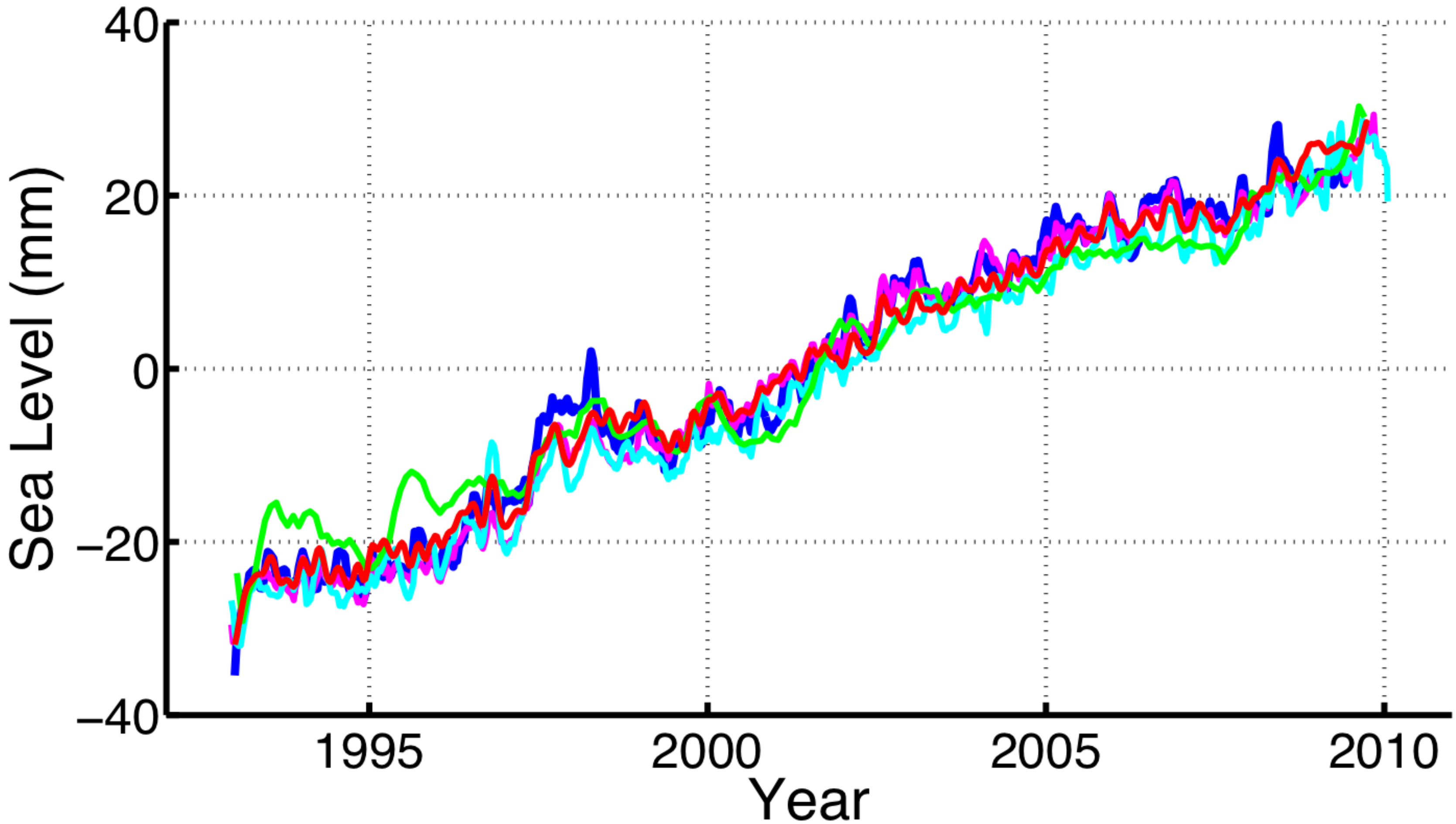

Global Sea Level Observed by Radar Altimetry (seasonal signal removed), TOPEX & Jason-1/2, except Kuo & Shum [2010] who used multiple altimetry, IB & GIA Corrected

Blue: Chambers [2010], 3.3±0.05 mm/yr
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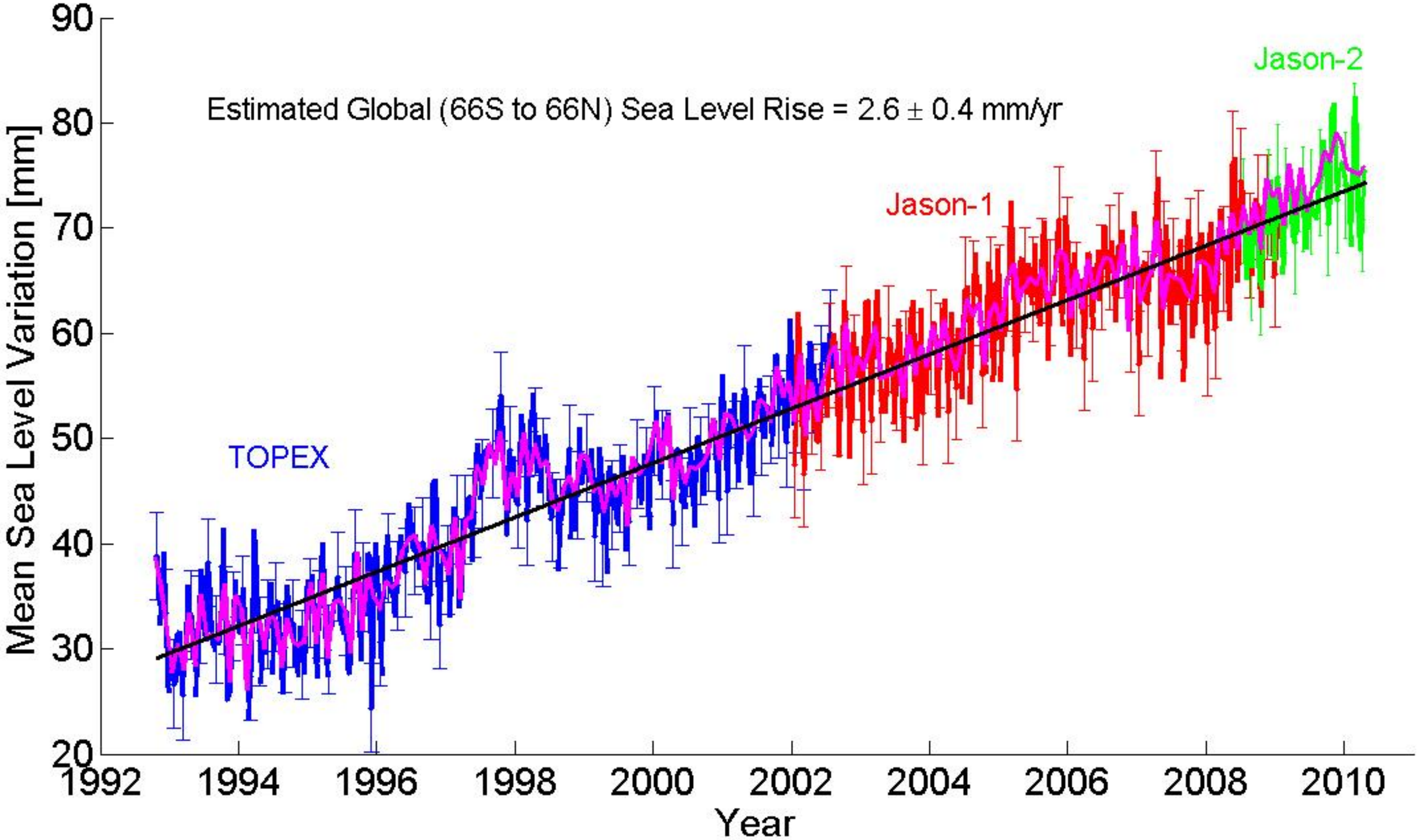
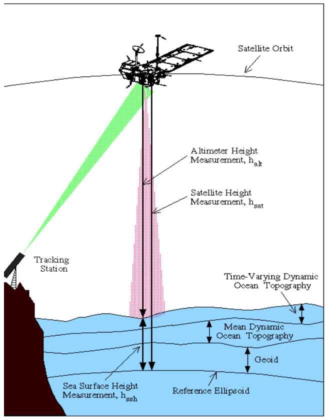
Green: Kuo & Shum [2010], 2.9±0.05 mm/yr (Geosat, ERS, TP, GFO, Envisat, Jason)
Red: Cazenave & Llovel [2010], 3.3±0.02 mm/yr

Estimated Sea Level Trend (1985–2010): 2.6±0.4 mm/yr
After Sea Floor Basin “geoid” GIA Correction (ICE5G): Trend = 2.9 mm/yr

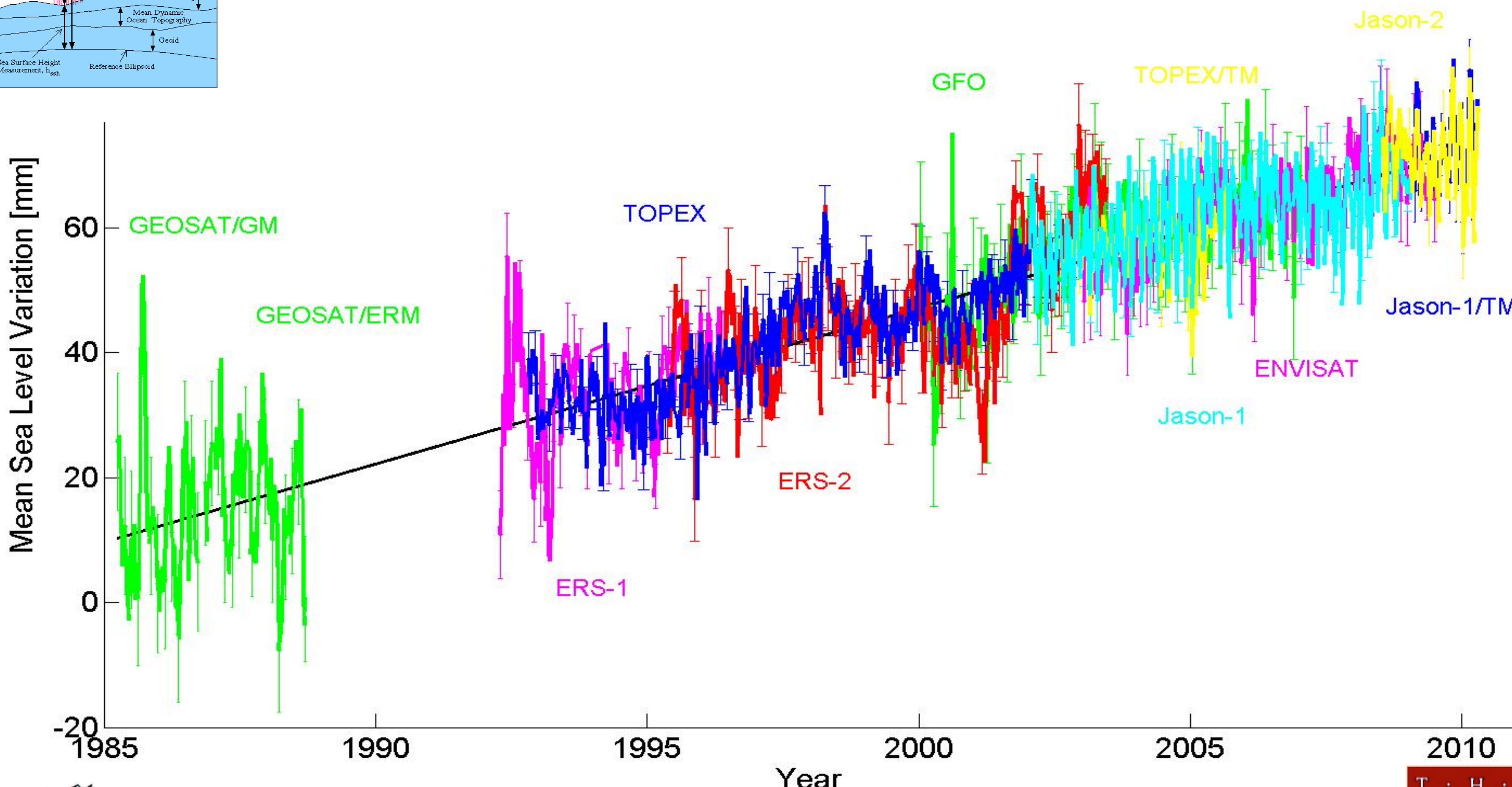


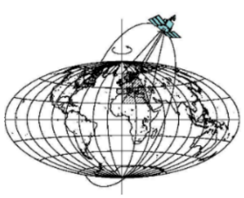
Multi-mission satellite altimetry data (T/P, Jason-1/2) used
“Dynamic” Inverted Barometer (IB) correction applied
Seasonal signal not removed



Estimated Global Sea Level Trend (1985–2010): 2.6±0.4 mm/yr
After Sea Floor GIA Correction (ICE5G): Trend = 2.9 mm/yr

Global Sea Level Rise Estimated by Altimetry (1985-2010)





Multi-mission satellite altimetry data used
Dynamic Inverted Barometer (IB) correction applied
Seasonal signal not removed

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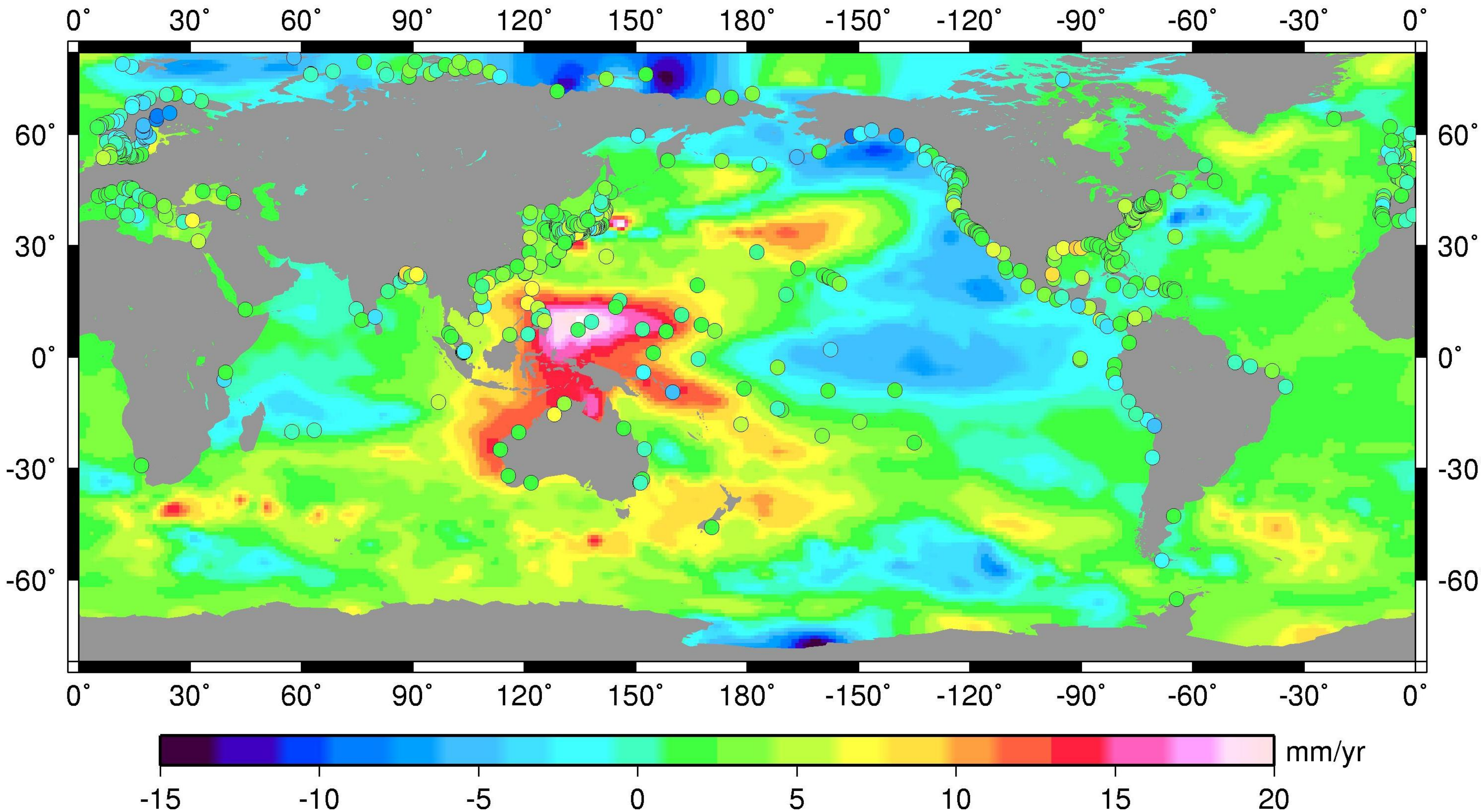
Altimetry Trend Dominated by Interannual or Longer Variations

Global Sea Level Observed by Tide Gauges (1900-2009) & Altimetry (1985-2010)

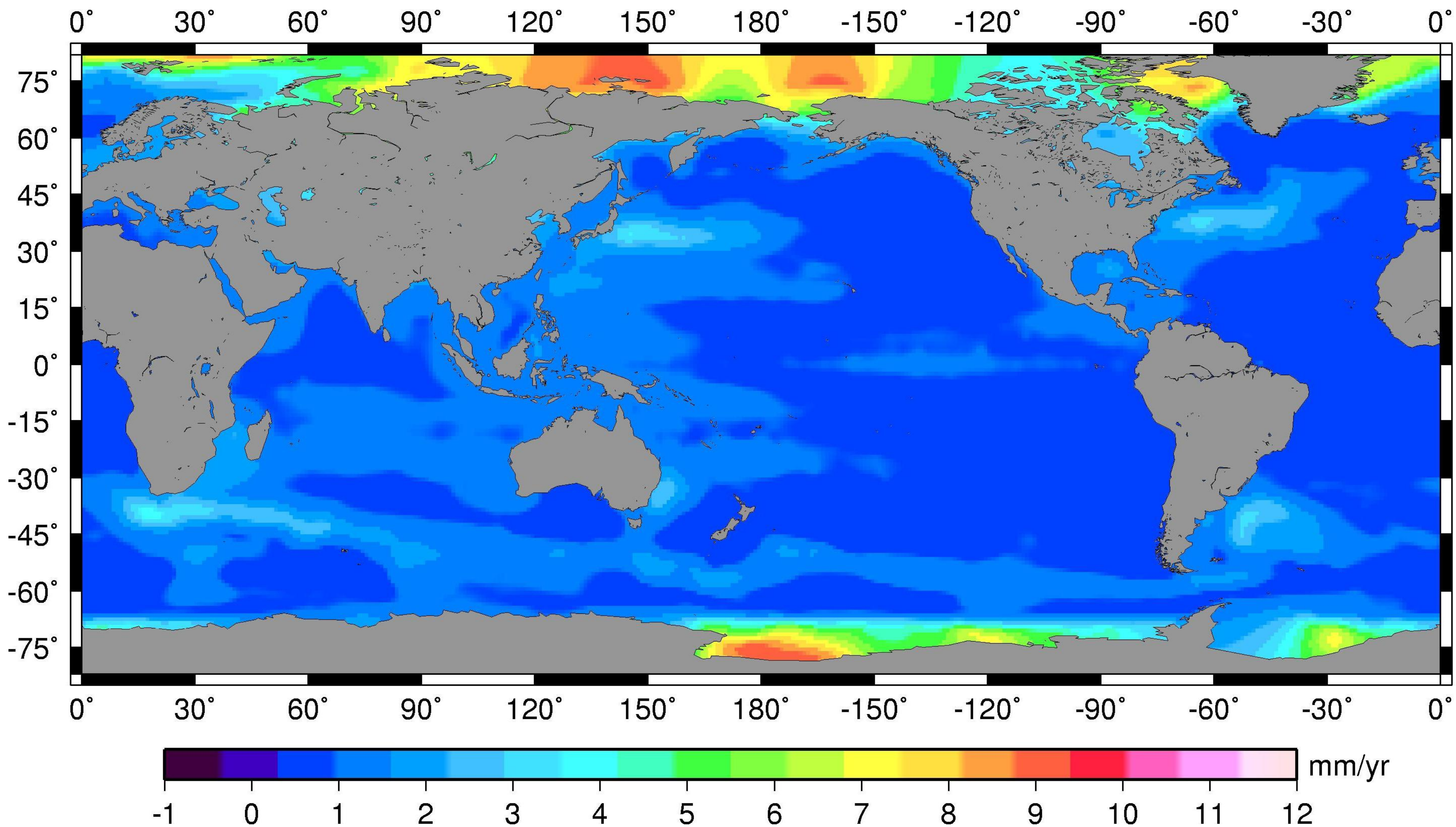


Estimated Global Sea Level Trend:

Tide gauges (1900–2007, 704 sites, color-coded) = 1.65±0.4 mm/yr

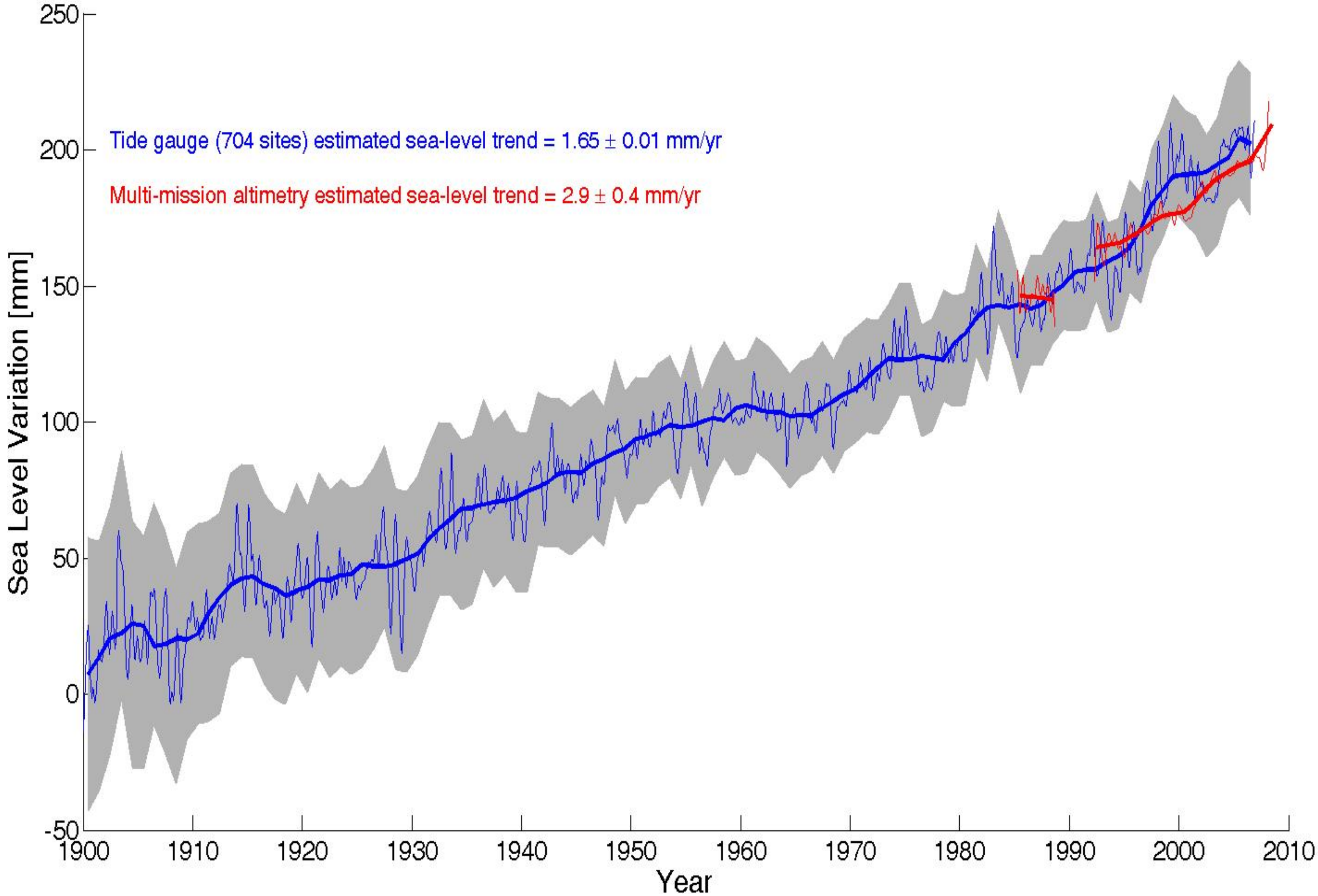
Multiple altimetry (1985–2010) = 2.9±0.4 mm/yr (GIA/IB correct. applied)

Estimated Formal Errors from Multi-Altimetry Sea-Level Trend

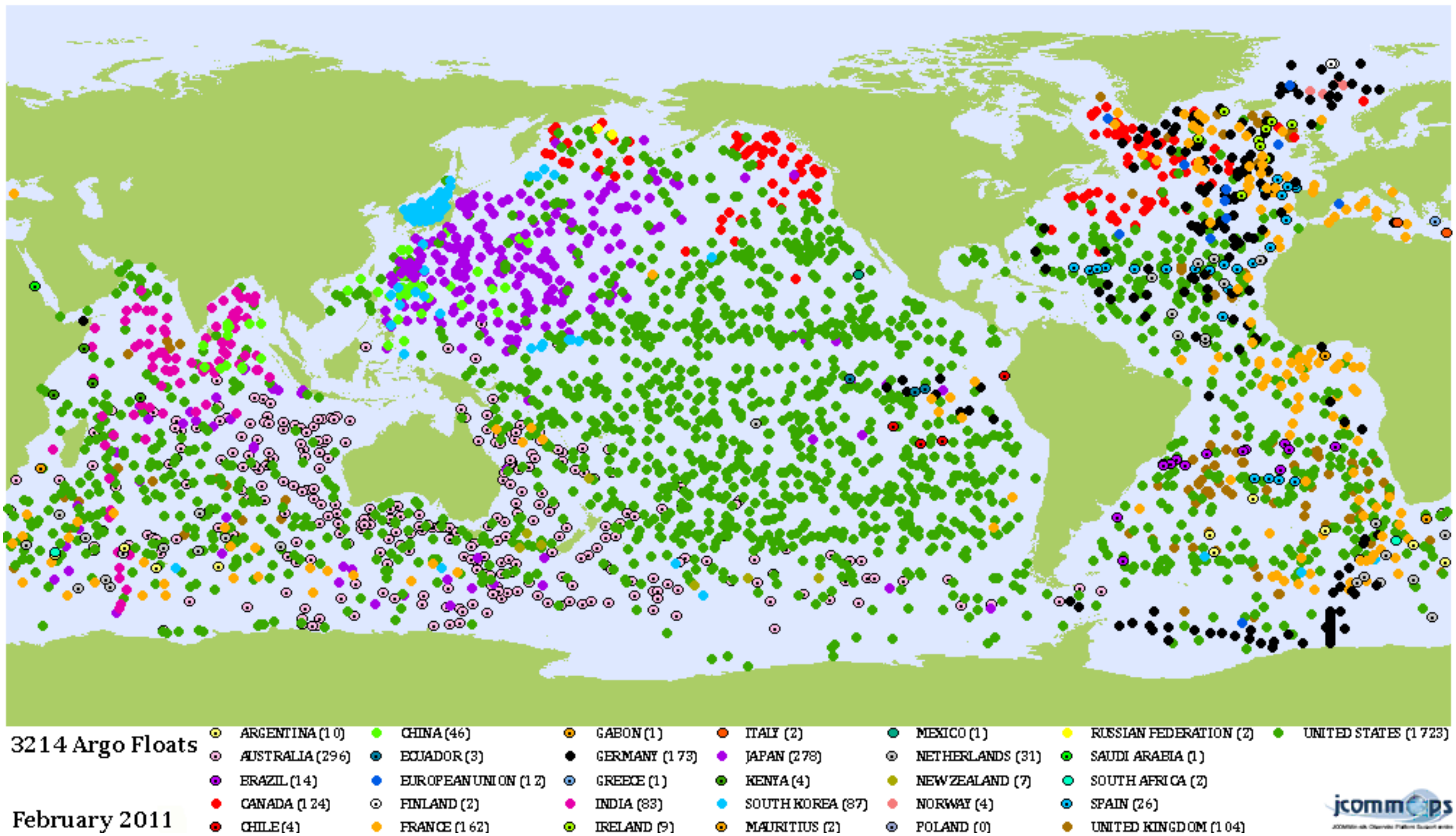


Multiple altimetry (1985–2010) = 2.9±0.4 mm/yr (GIA/IB correct. applied)

Observed 20th Century and Current Sea-Level Rise

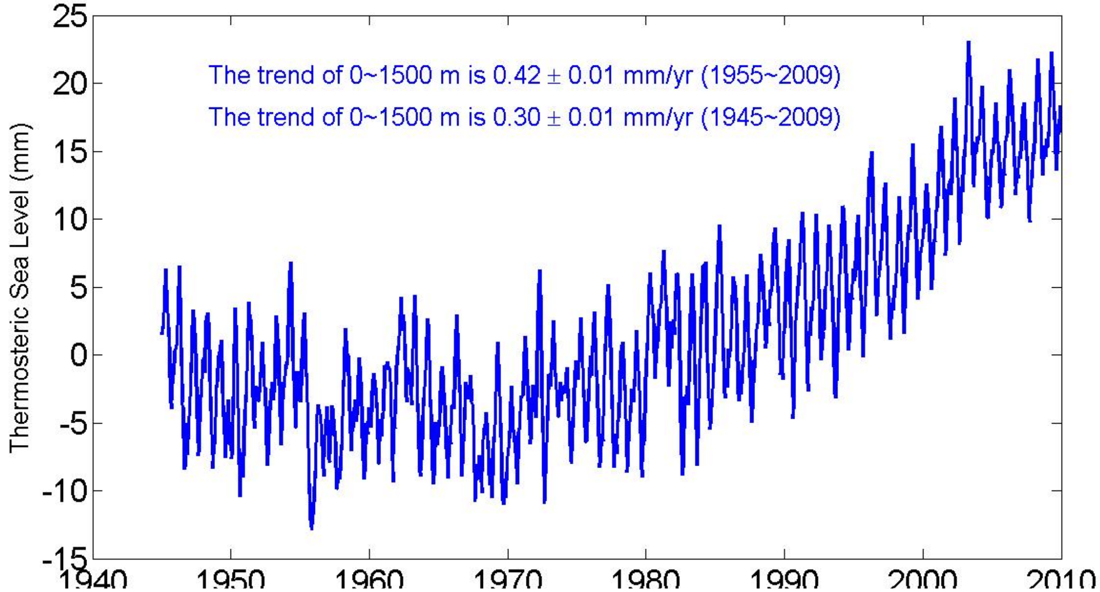


Map of ARGO Float Network as of Feb 2011



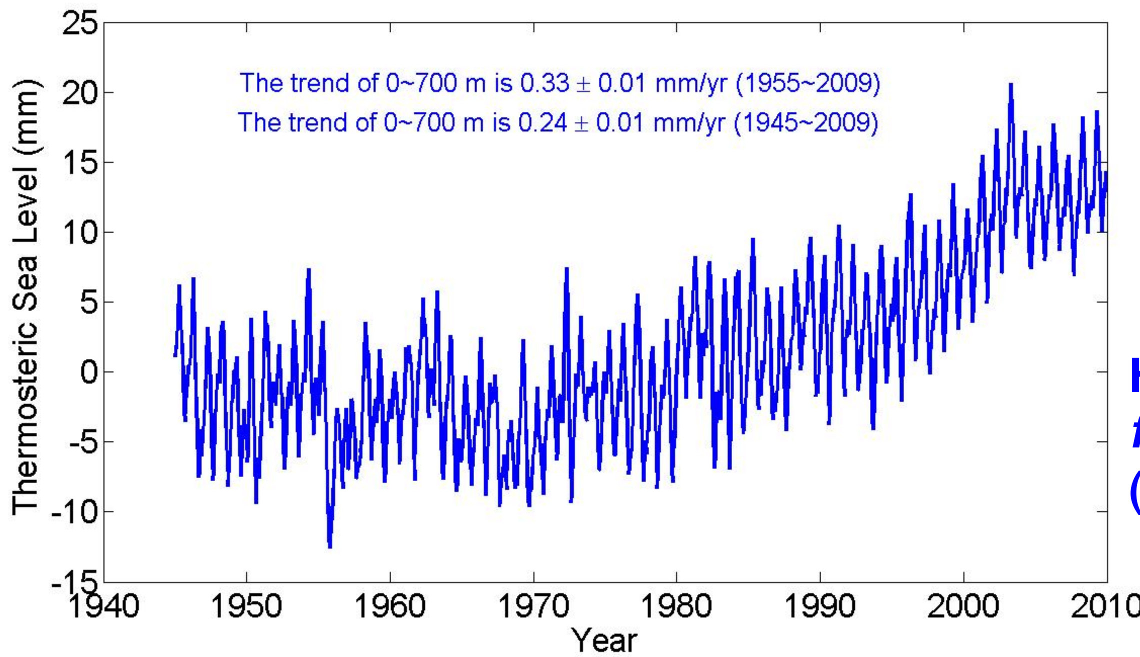
Credit: Scripps

Thermo-Sea Level, 1945–2009



Trend=0.42 mm/yr
0–1500 m

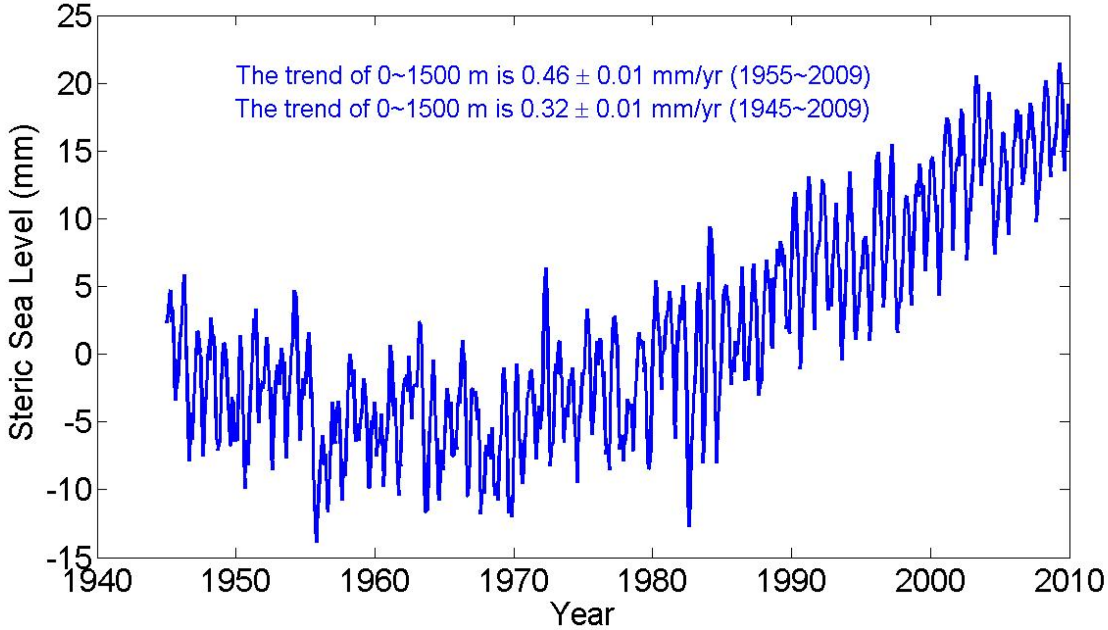
Only temperature data used



Trend=0.33 mm/yr
0–700 m

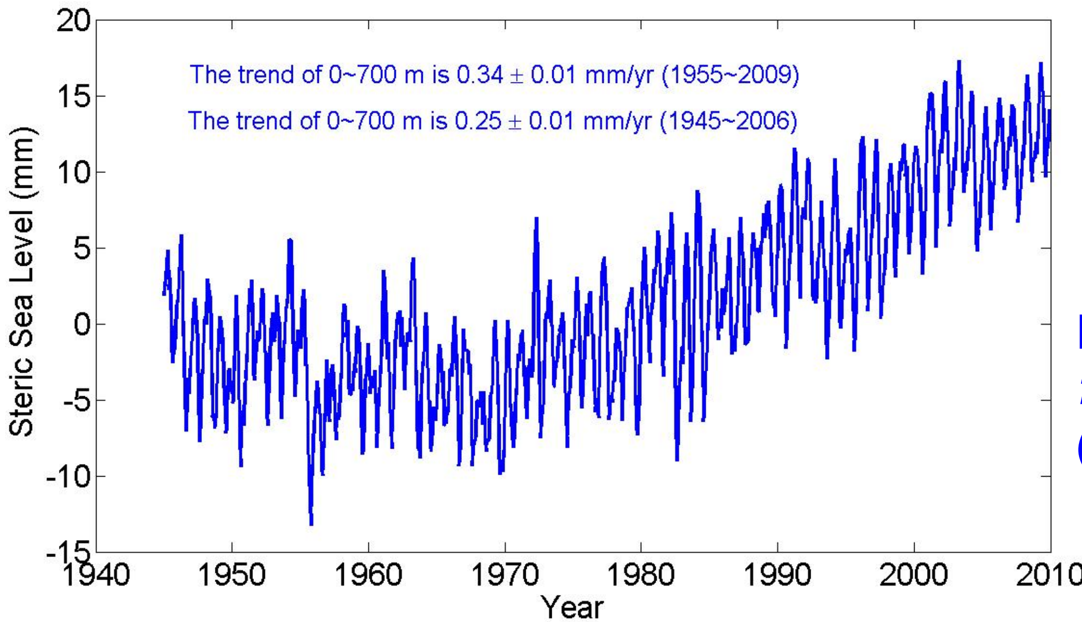
Hydrographic data update *from* [*Ishii & Kimoto*, 2009
(data courtesy, M. Ishii)

Steric Sea-Level, 1945–2009



Trend=0.46 mm/yr
0–1500 m

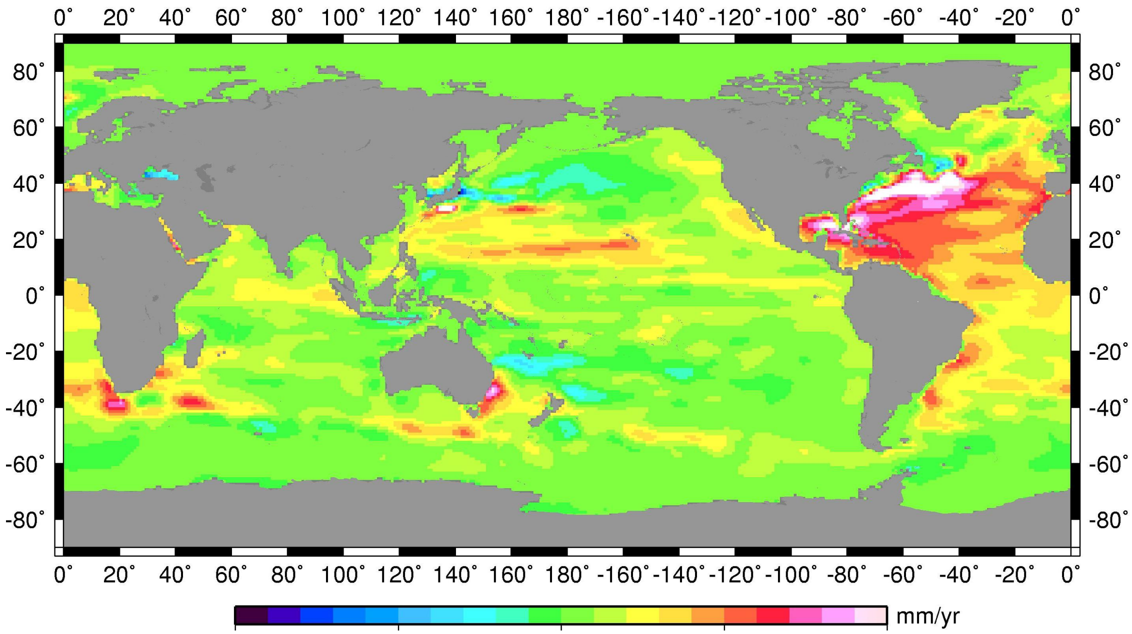
Both temperature & salinity used



Trend=0.34 mm/yr
0–700 m

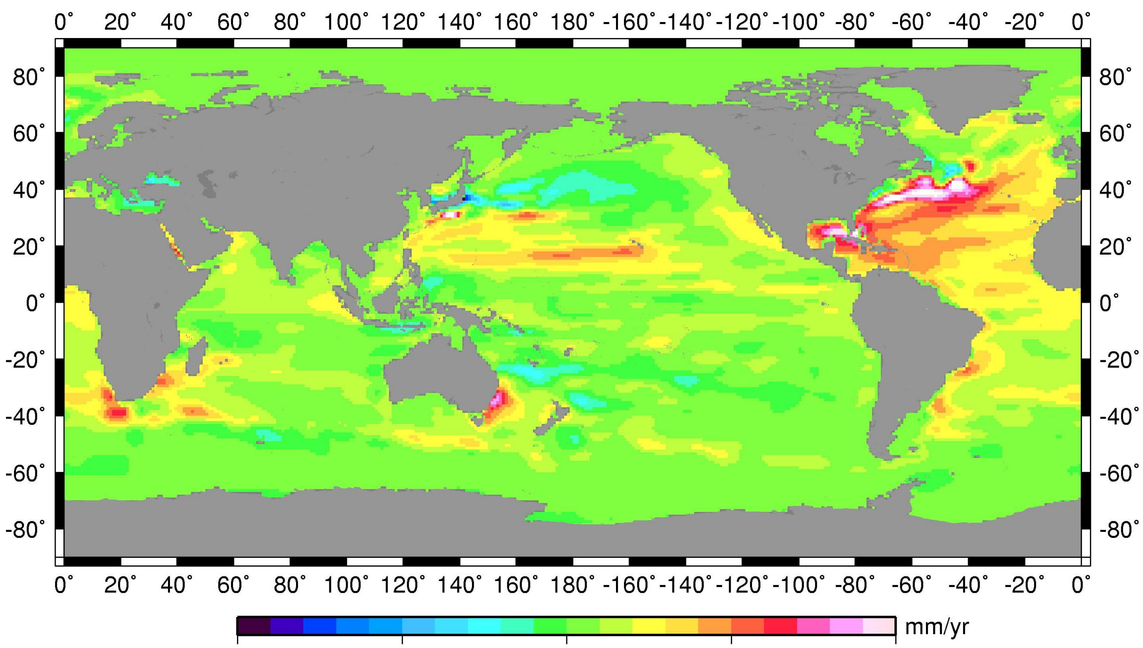
Hydrographic data updated *from* [*Ishii & Kimoto*, 2009], (data courtesy, M. Ishii)

Thermosteric Sea Level Trend, 1945–2009



0–1500 m
Trend=0.33±0.01 mm/yr

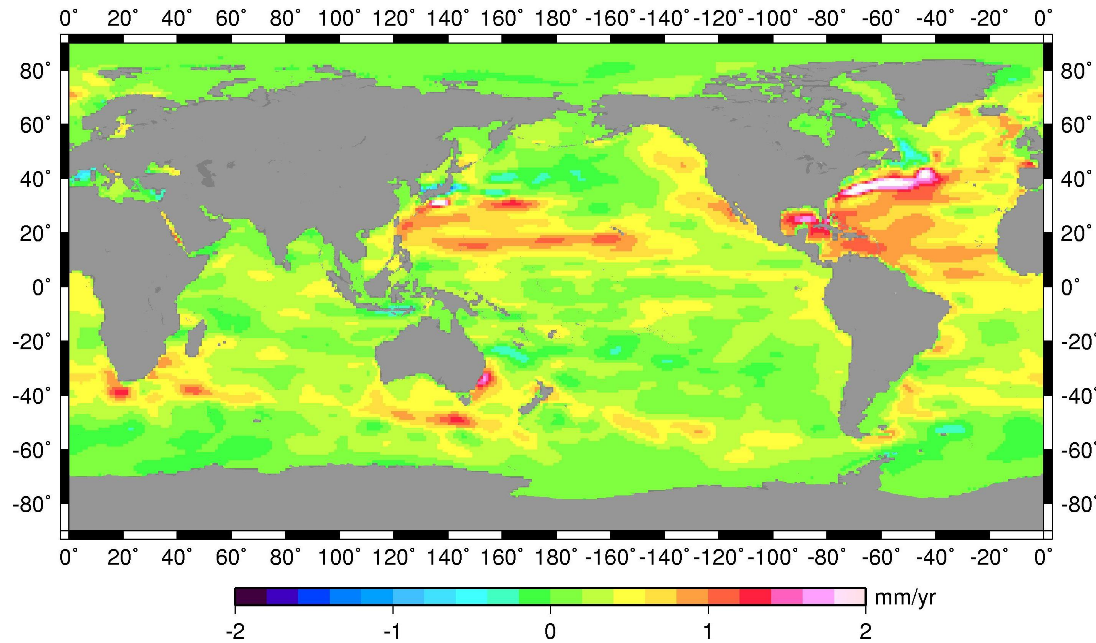
Both temperature & salinity data used



0–700 m
Trend=0.24±0.01 mm/yr

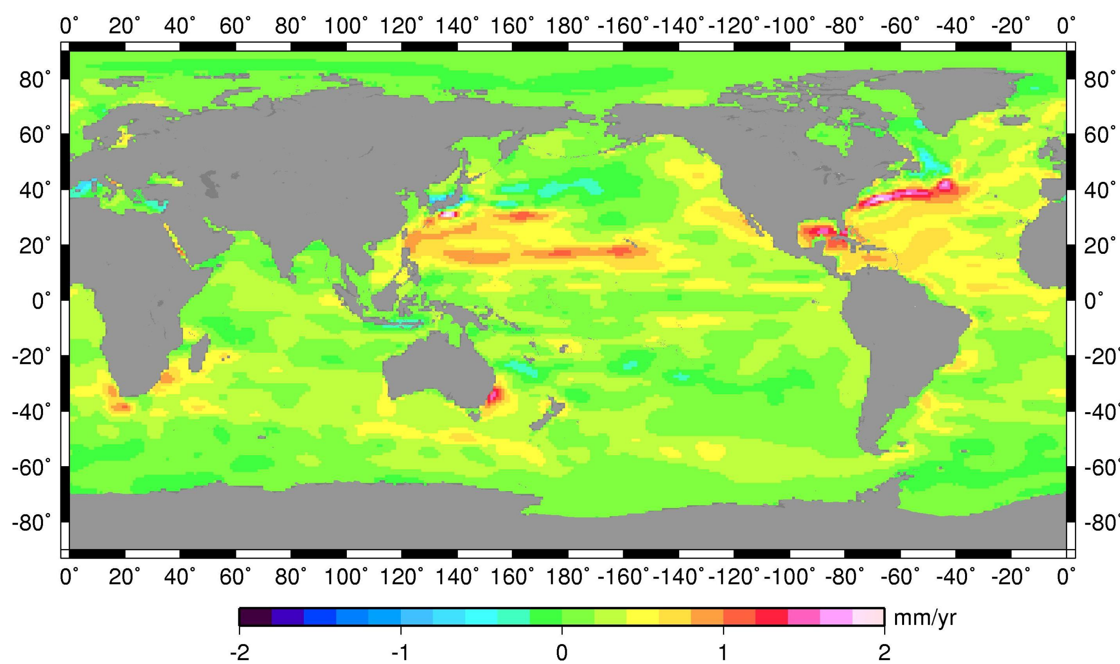
Hydrographic data updated *from* [*Ishii & Kimoto*, 2009]
(data courtesy, M. Ishii)

Steric Sea Level Trend, 1945–2009



Trend=0.32±0.01 mm/yr
0–1500 m

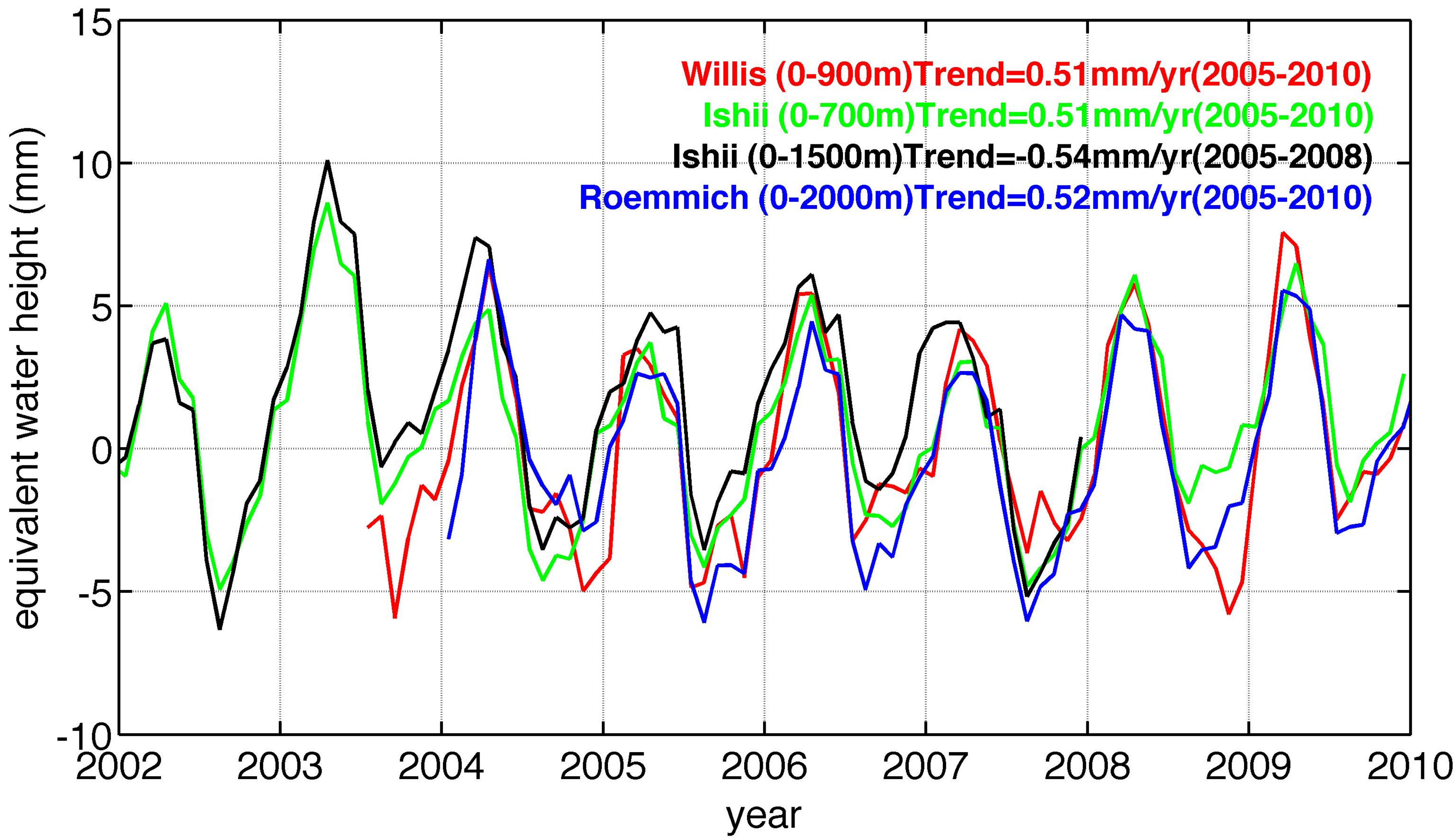
Both temperature & salinity data used

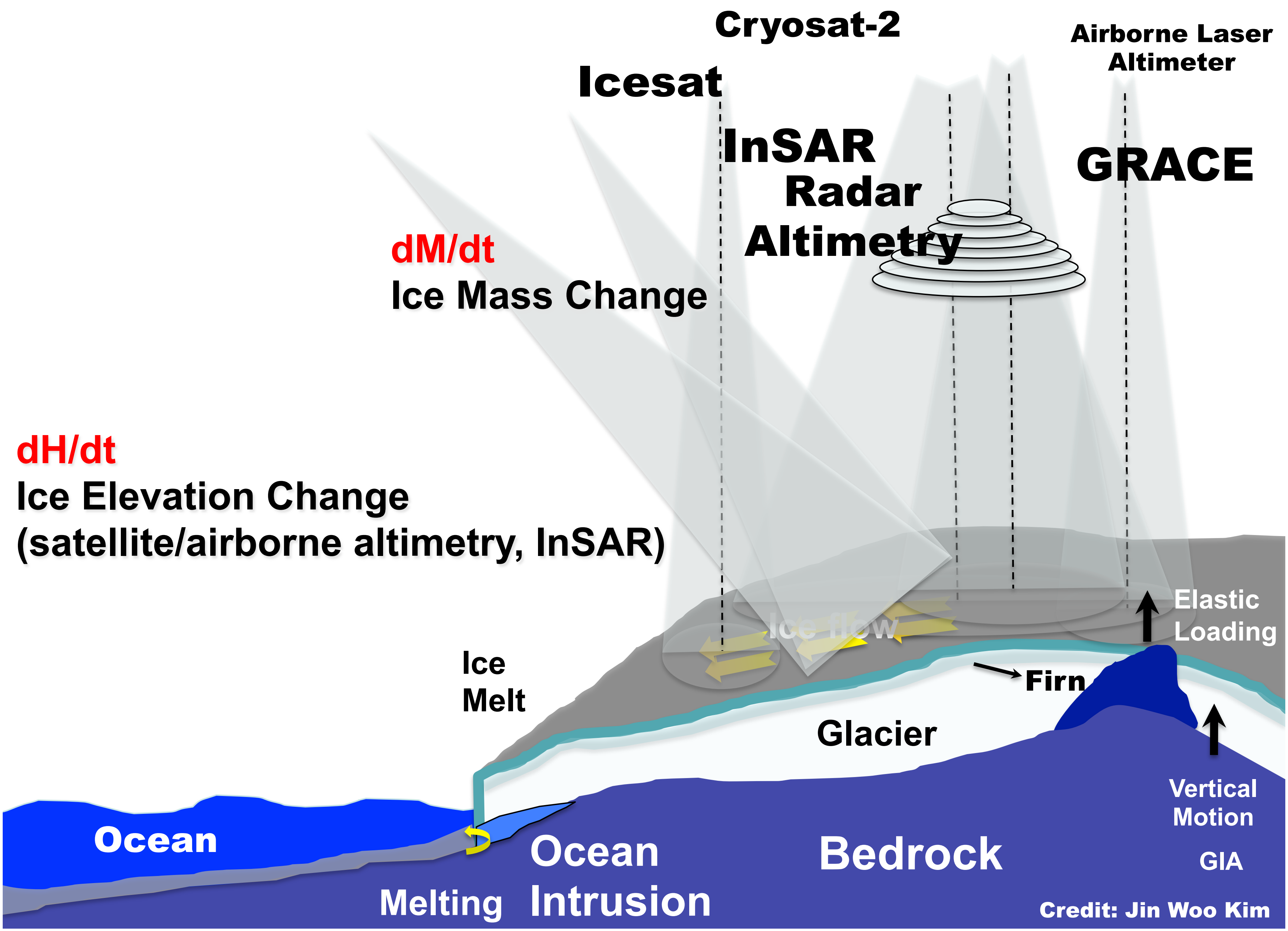


Trend=0.25±0.01 mm/yr
0–700 m

Hydrographic data updated *from* [*Ishii & Kimoto*, 2009] (data courtesy, M. Ishii)

Comparison of Globally Averaged Thermal Sea-Level Variations from Argo/XBT, 2002–2010





Cryosat-2
Airborne Laser Altimeter
Icesat
InSAR
Radar Altimetry
GRACE
dM/dt
Ice Mass Change
dH/dt
Ice Elevation Change
(satellite/airborne altimetry, InSAR)
Ice flow
Elastic Loading
Ice Melt
Firn
Glacier
Vertical Motion
GIA
Ocean
Ocean Intrusion
Bedrock
Melting
Credit: Jin Woo Kim

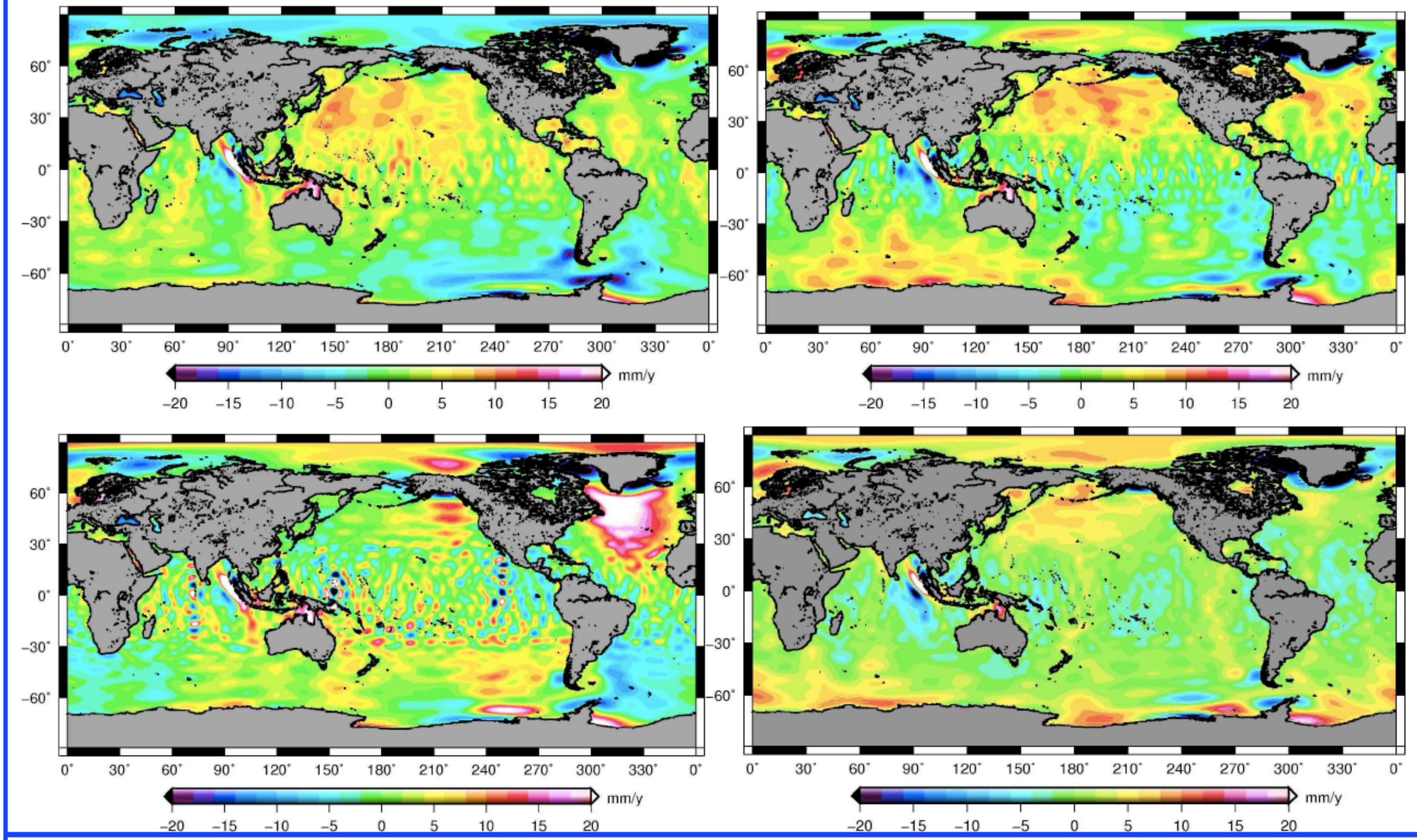
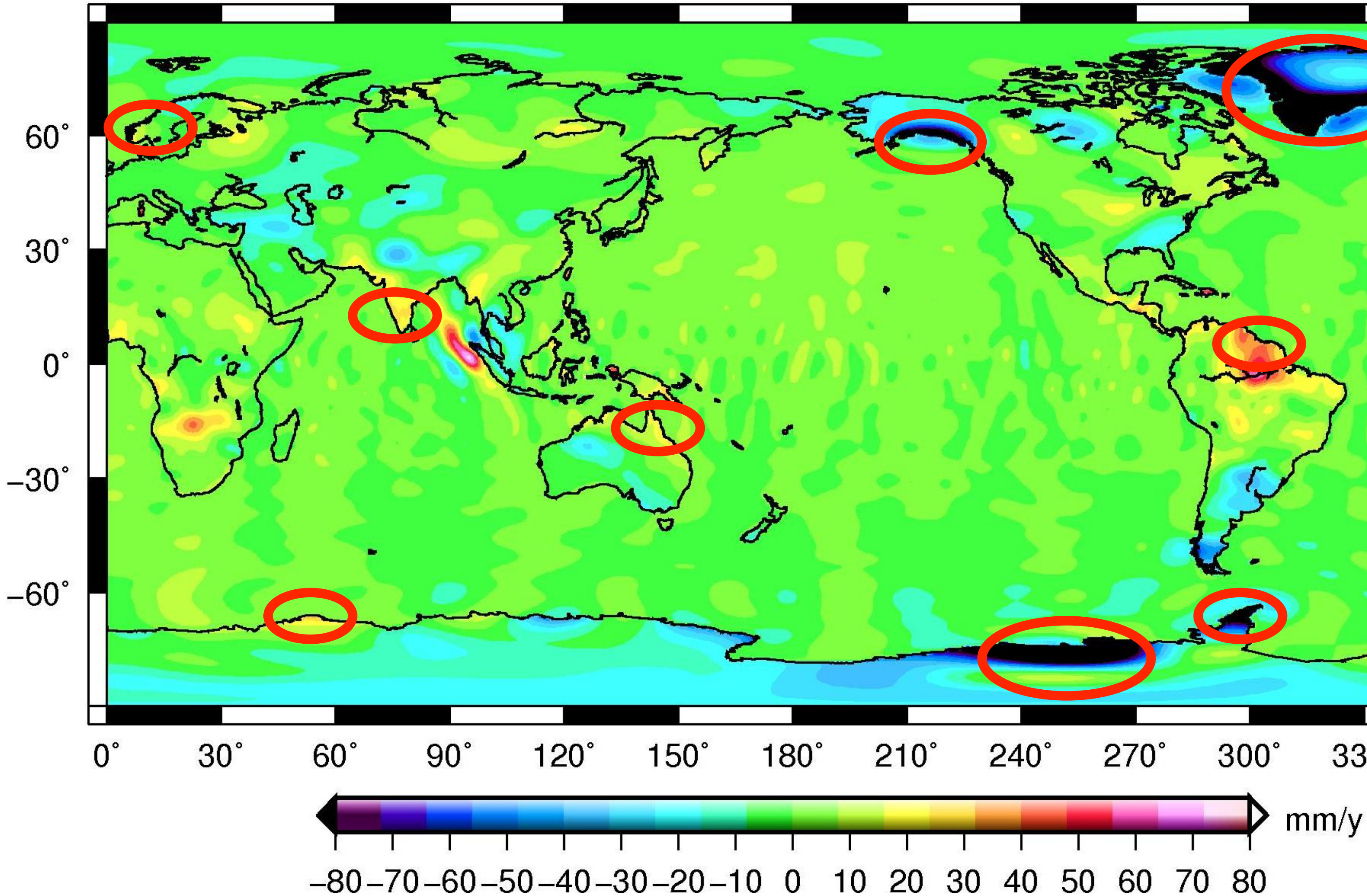


Fig. 2. GRACE estimated OBP trends from CSR, GFZ, JPL & ITG (Top to bottom, left to right), 2003–2010. Decorrelated, 300 km filtering, and leakage reduction [*Duan et al*. 2009; *Guo & Shum*, 2009; *Guo et al*. 2010] applied to both GSM and GAD [*Flechtner*, 2007] and GRACE data. Paulson GIA model [*Paulson et al*. 2007] used.

GRACE RL04 data, destriped, 250 km radius filtering, Paulson GIA model & SLR geocenter corrections, 2003–2009

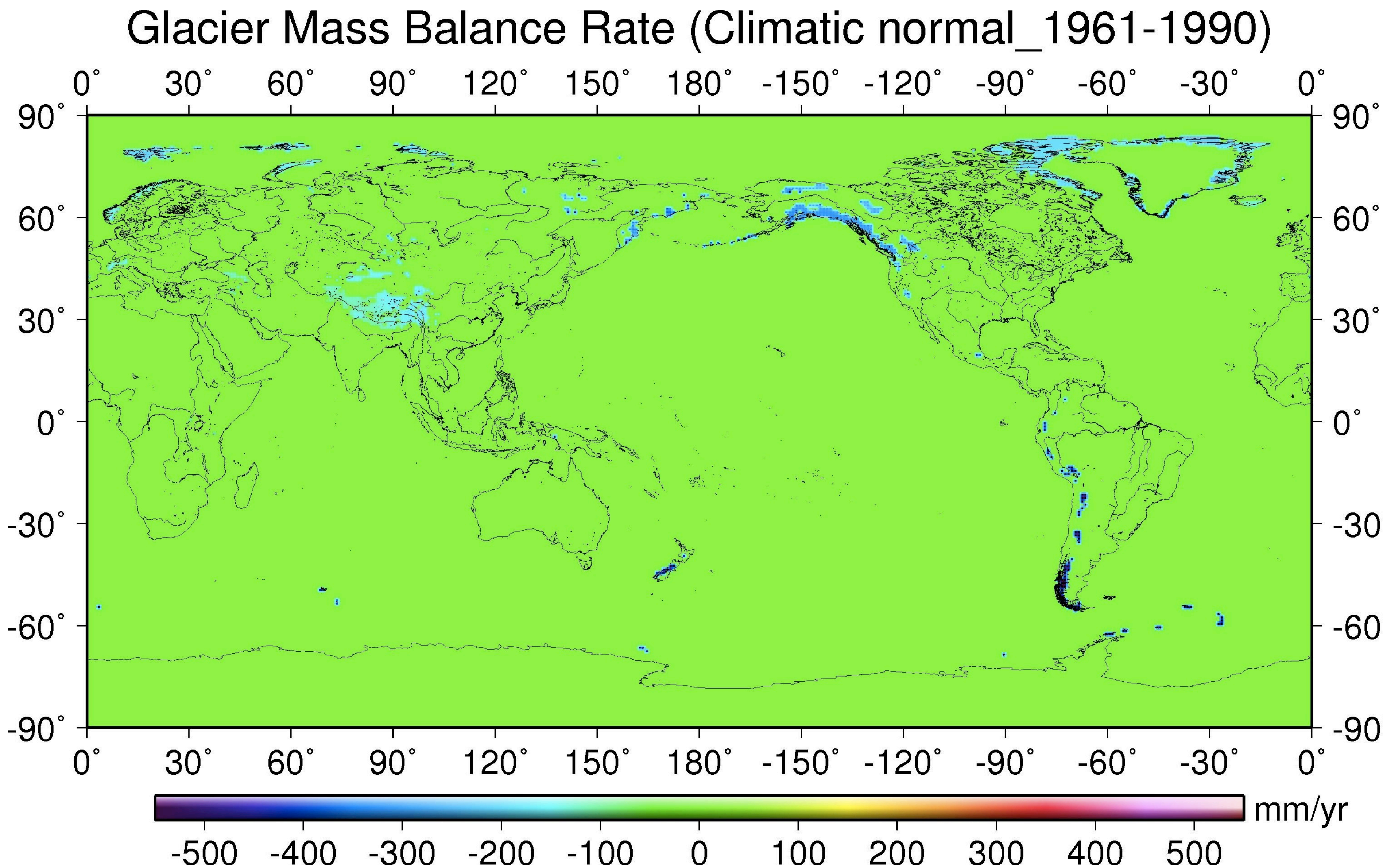
GRACE Observed Water Thickness Change



CSR RL04, destriped, 250 km radius filtering, Paulson GIA model & SLR geocenter corrections, 2003–2009

With Land Signal Leakage Reduction [*Guo et al.*, 2010]

Mass Balance Estimates for Mountain Glaciers & Ice-Caps



Data courtesy: *Cogley* [2010]

Mountain Glaciers/Ice Cap Ice Mass Balance

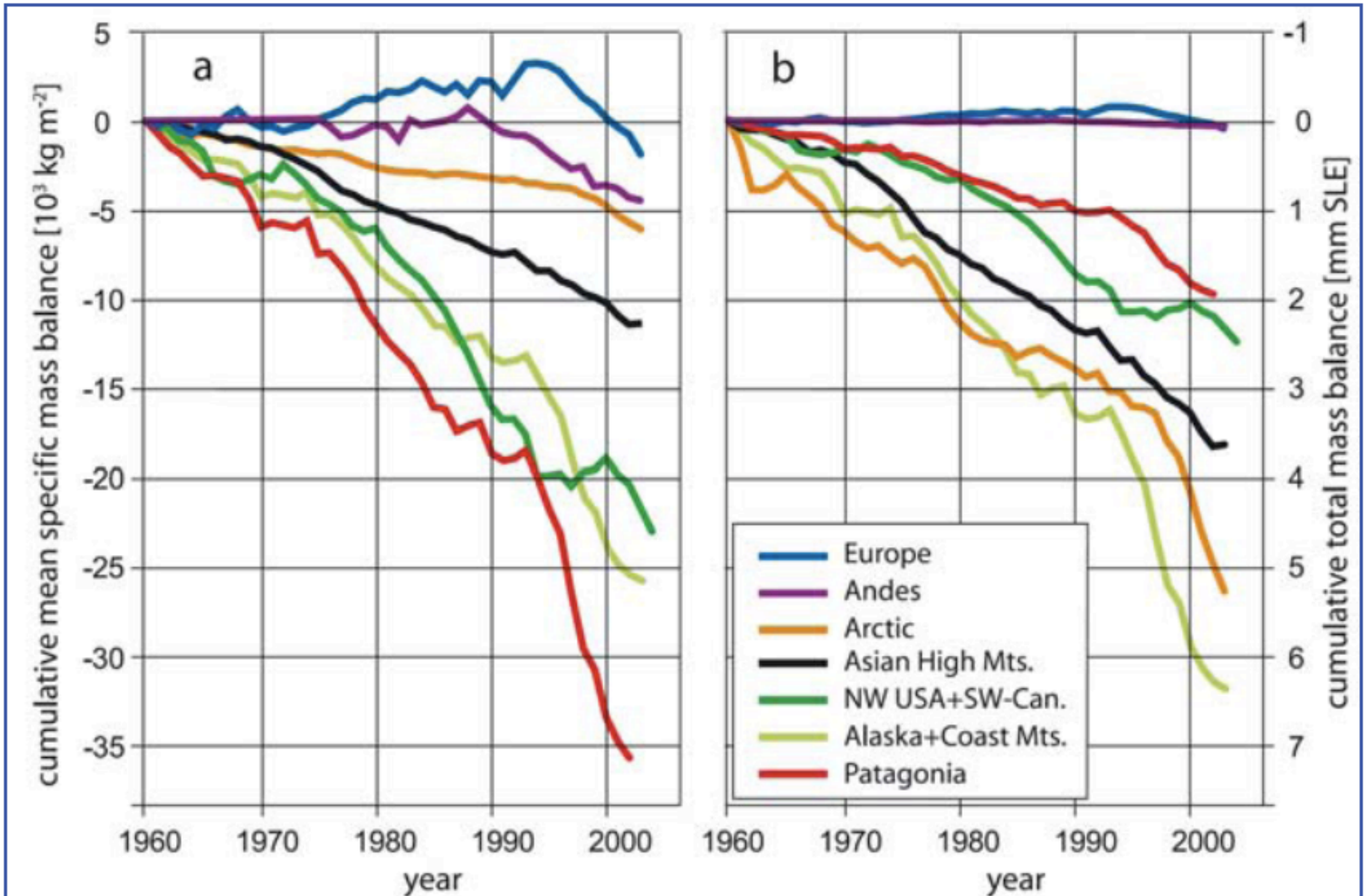
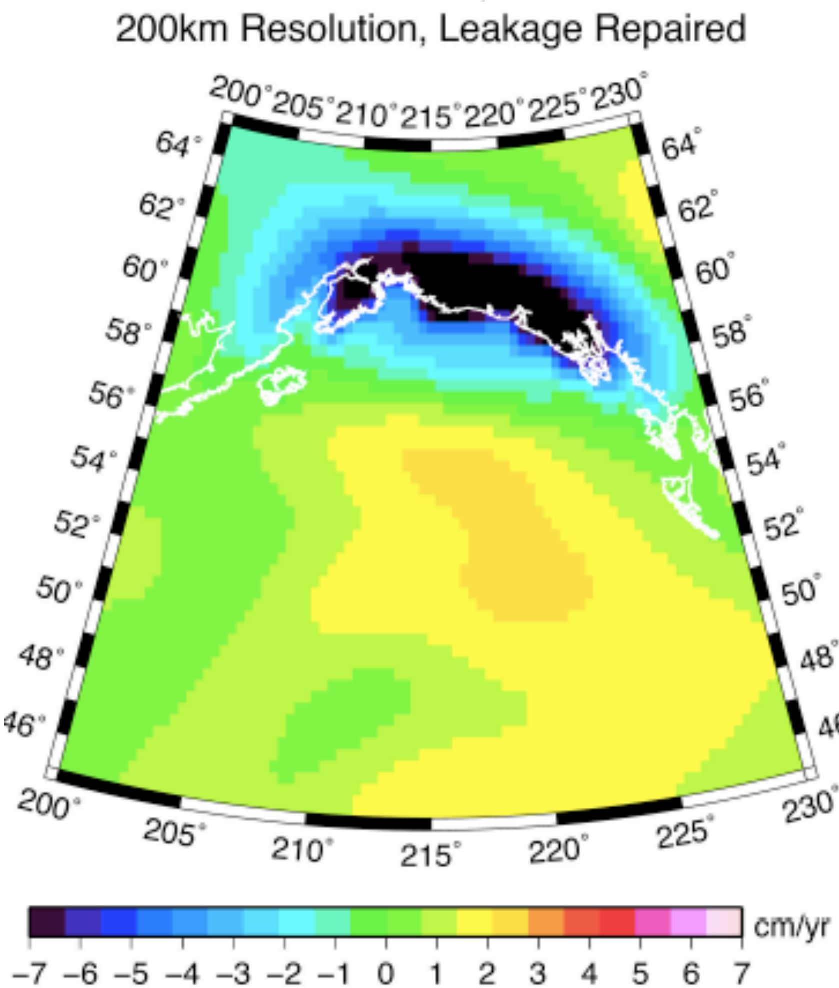
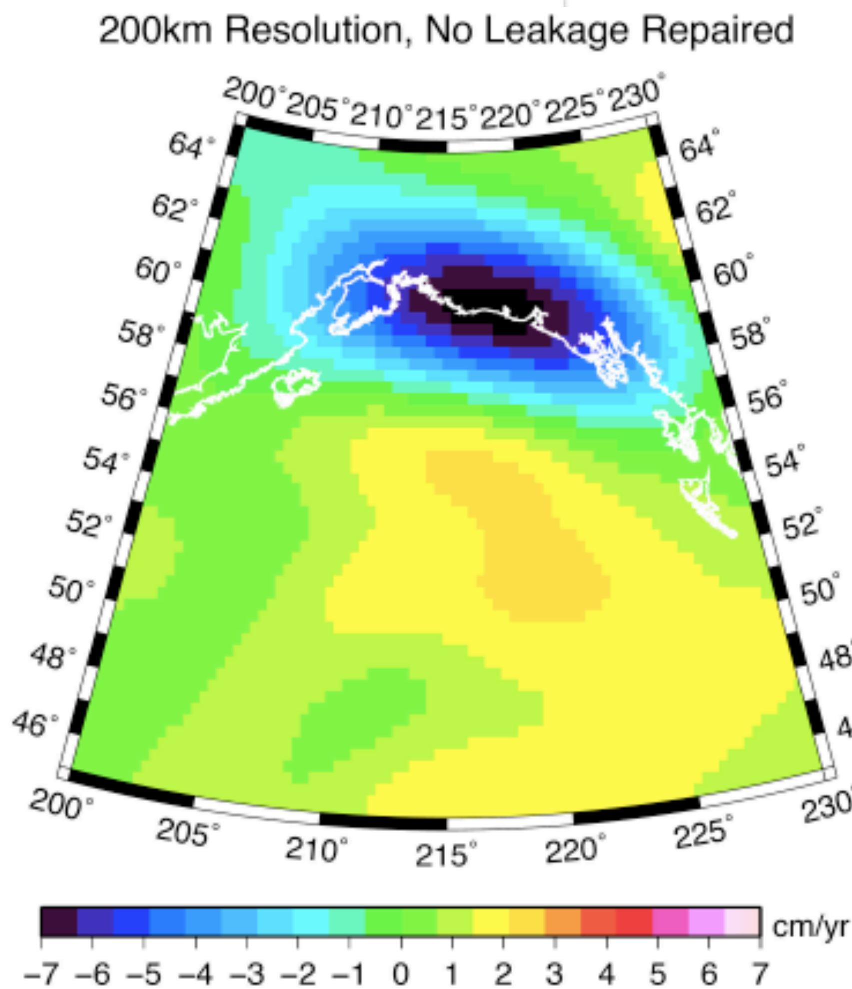


Figure 1. Cumulative (a) specific and (b) total mass balances of glaciers and ice caps, calculated using data for large regions [*Dyurgerov & Meier*, 2005]. Specific mass balances signalize the strength of the glacier response to climatic change in each region. Total mass balances indicate each region's contribution to sea level (from *Kaser et al.* [2006]).

Estimated glacier contribution to sea level: 0.52–1.10 mm/yr [*Kaser et al.*, 2006]; after accounting for tide-water glaciers, revised contribution is: 0.52–1.40 mm/yr [*Cogley*, 2010]

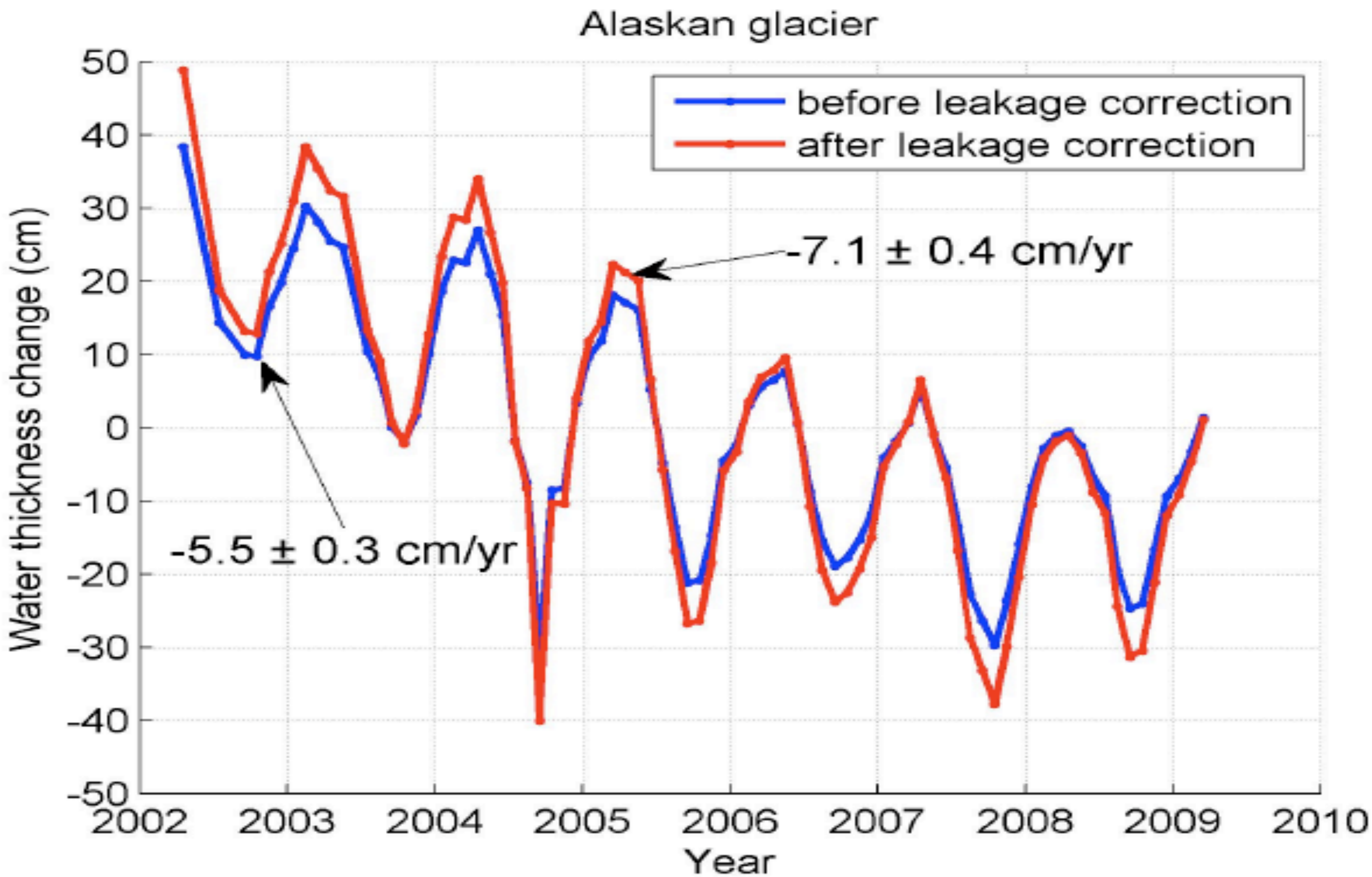
Alaskan Glacier Mass Balance Observed by GRACE: Land Signal Leakage Correction



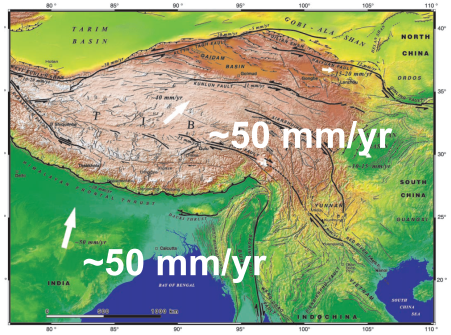


JPL RL04 data, destripping, 200 km filtering, ICE5G GIA, SLR geocenter corrections

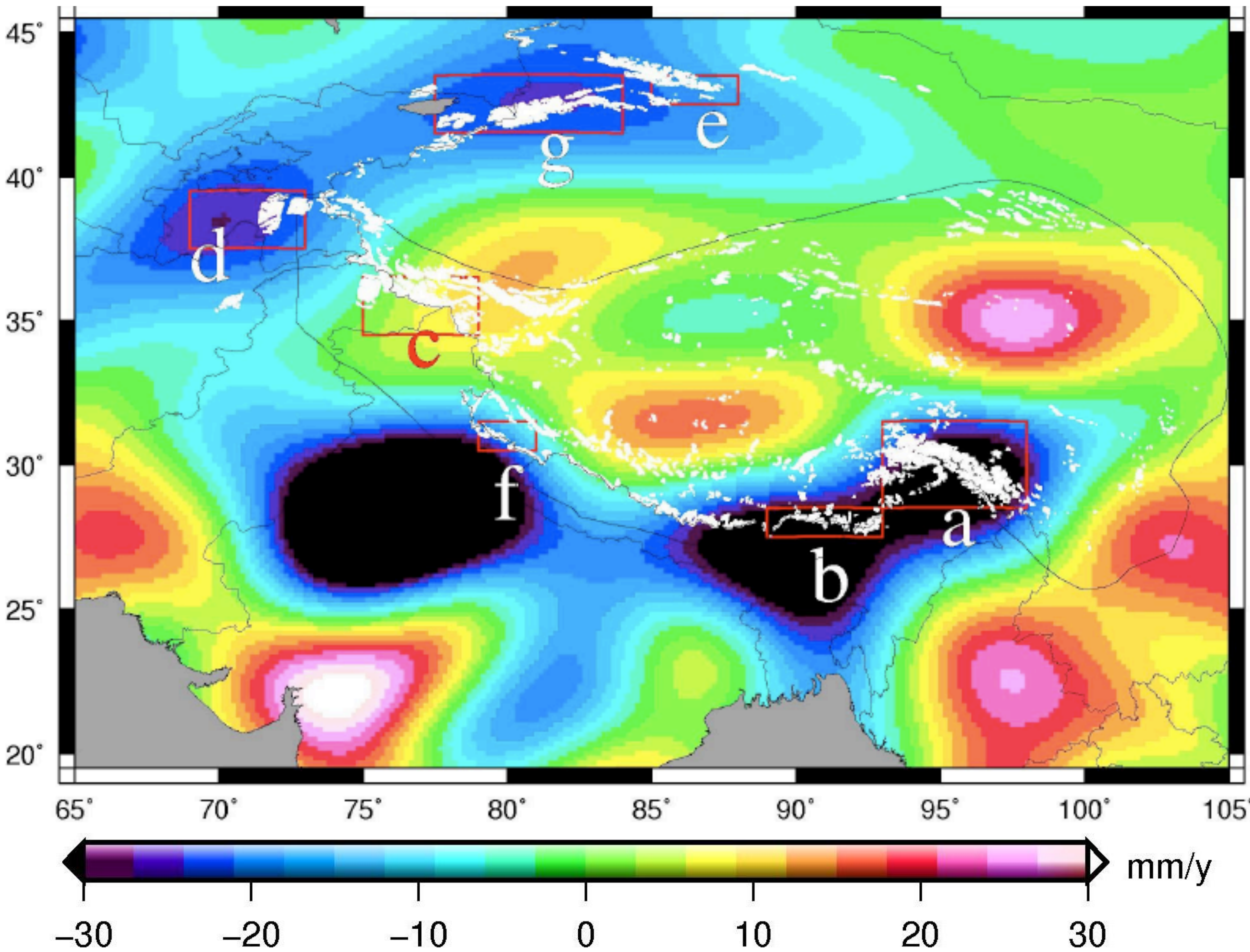
Alaskan Glacier Mass Balance Observed by GRACE: Land Signal Leakage Correction



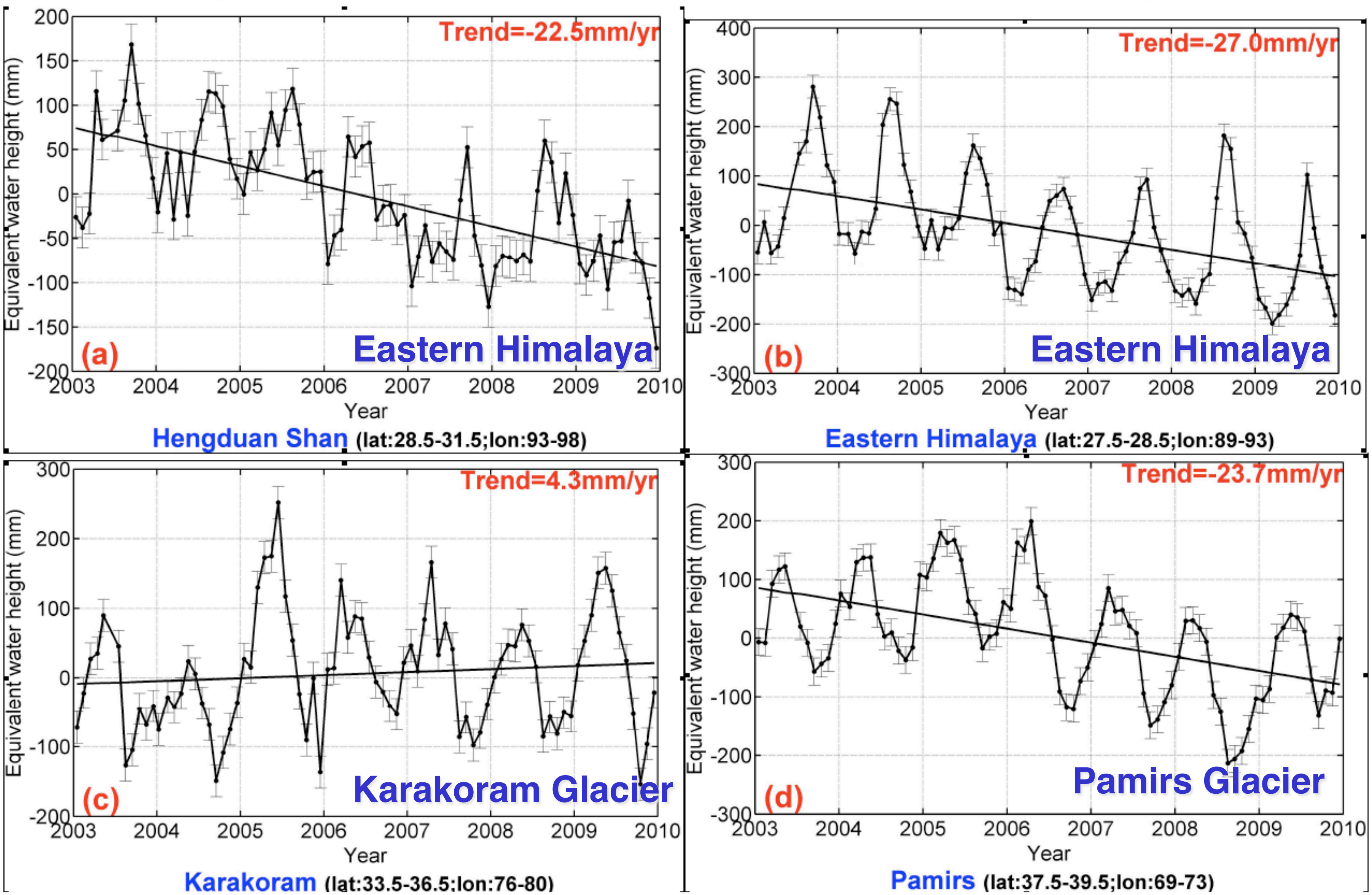
JPL RL04 data, destripping, 200 km filtering, ICE5G GIA, SLR geocenter corrections



Asian High Mountain Glacier & Groundwater Change Observed by GRACE

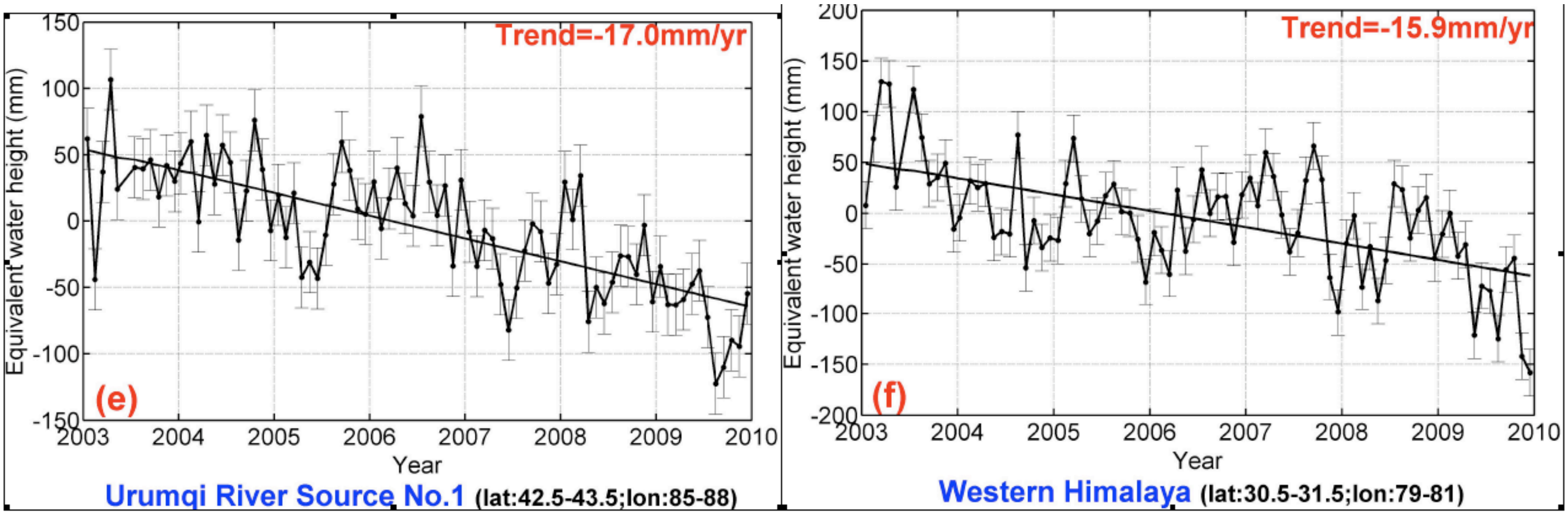


Asian High Mountain Glacier MB Observed by GRACE



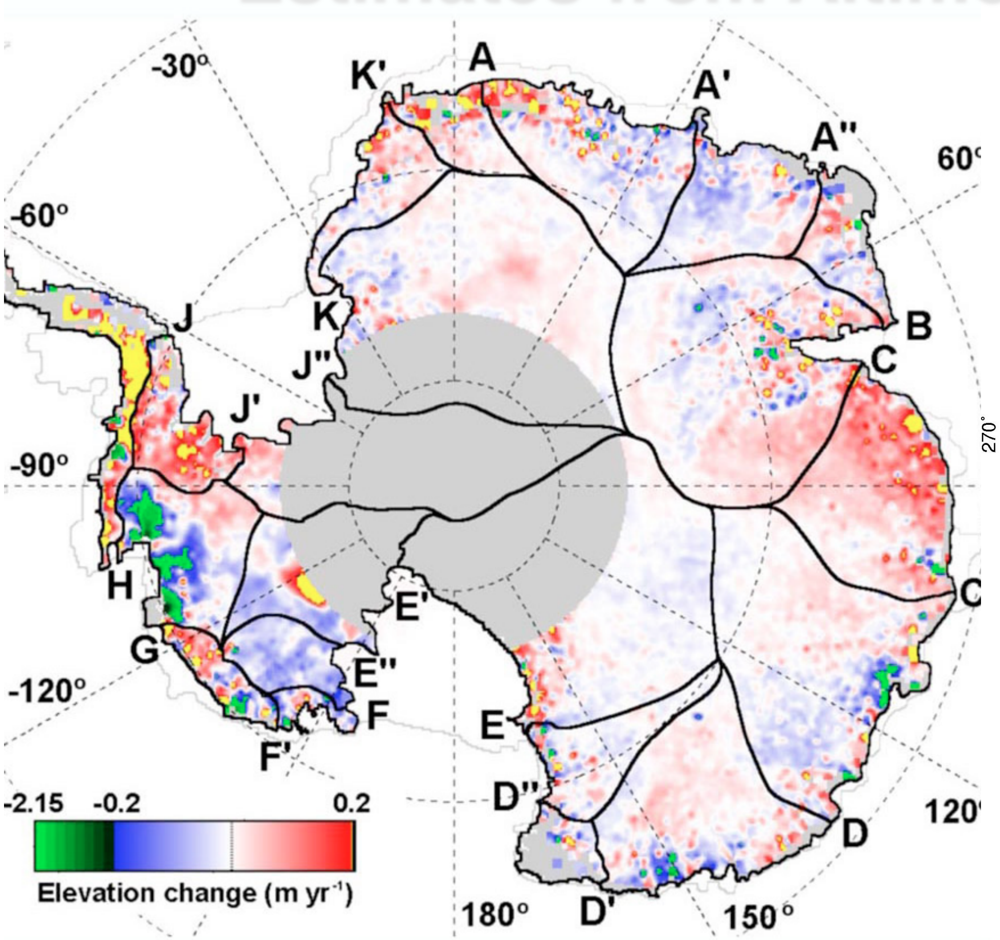
CSR RL04 data, destriping, resolution: ~330 km
Paulson GIA, SLR geocenter corrections

Asian High Mountain Glacier MB Observed by GRACE

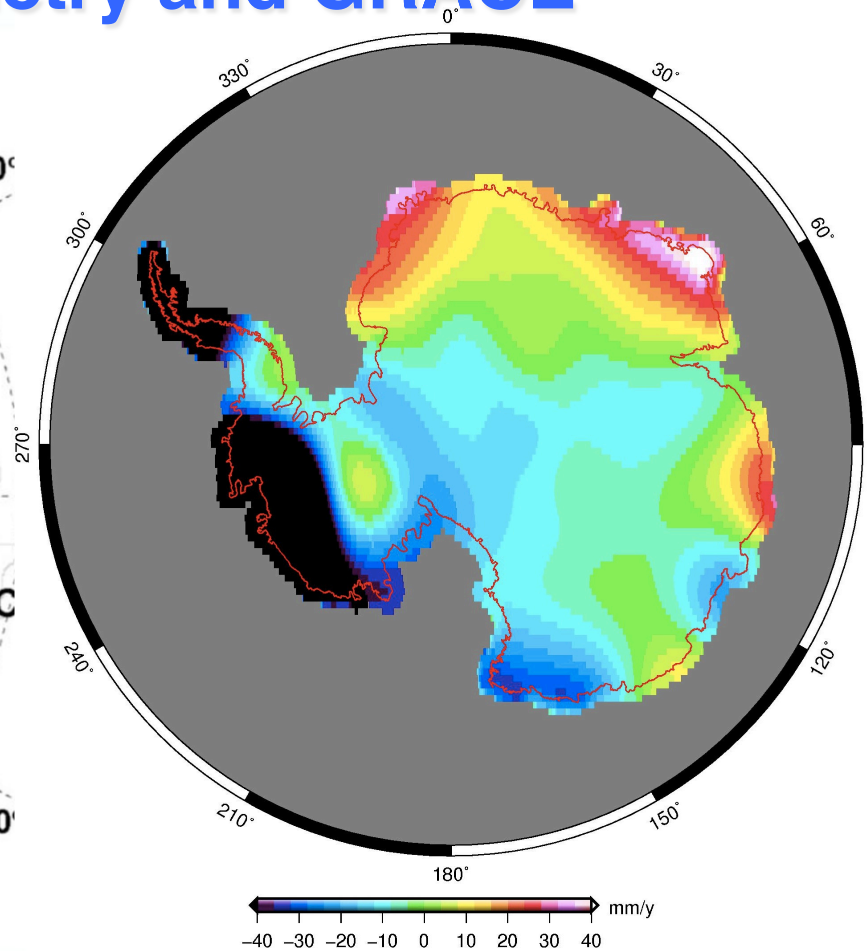


CSR RL04 data, destriping, 200 km filtering, Paulson GIA, SLR geocenter corrections

Antarctic Present-day Ice-Sheet Mass Balance Estimates from Altimetry and GRACE



ERS-1/-2 radar altimetry determined Antarctica ice elevation change (m/yr, 1992–2003) [*Wingham et al.*, 2006], +27±29 Gton/yr

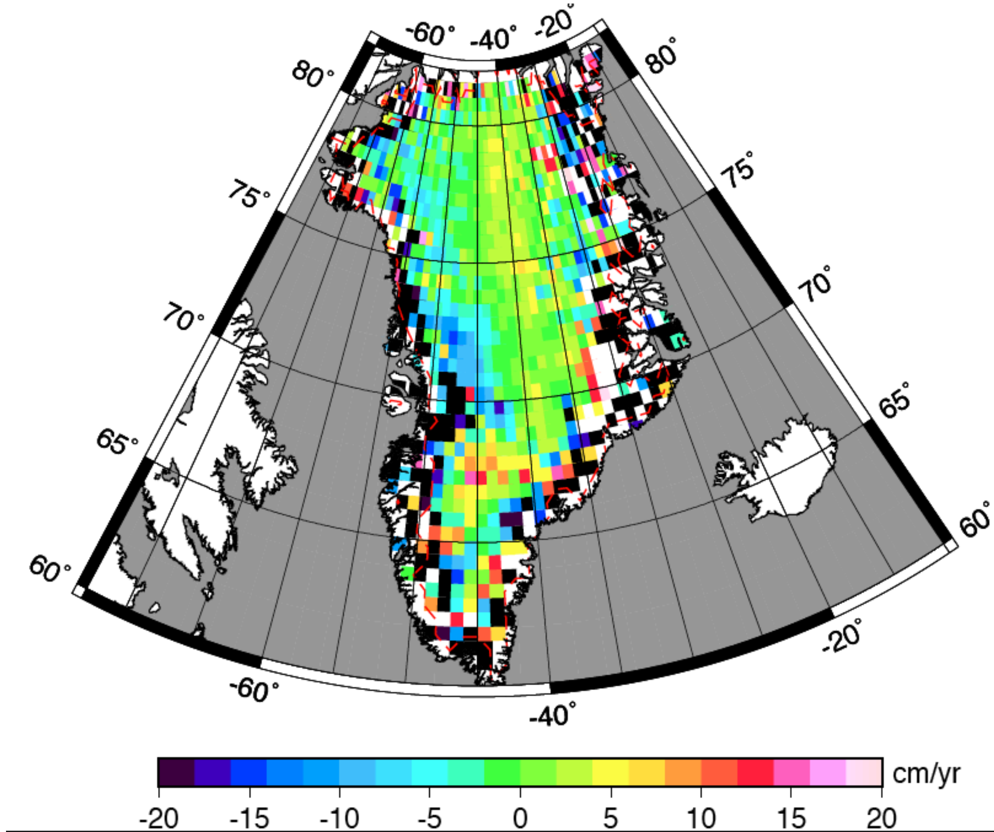


GRACE observed mass change, 4/2002–12/2010, –15.22 mm/yr, or –212.85 Gton/yr (this study)

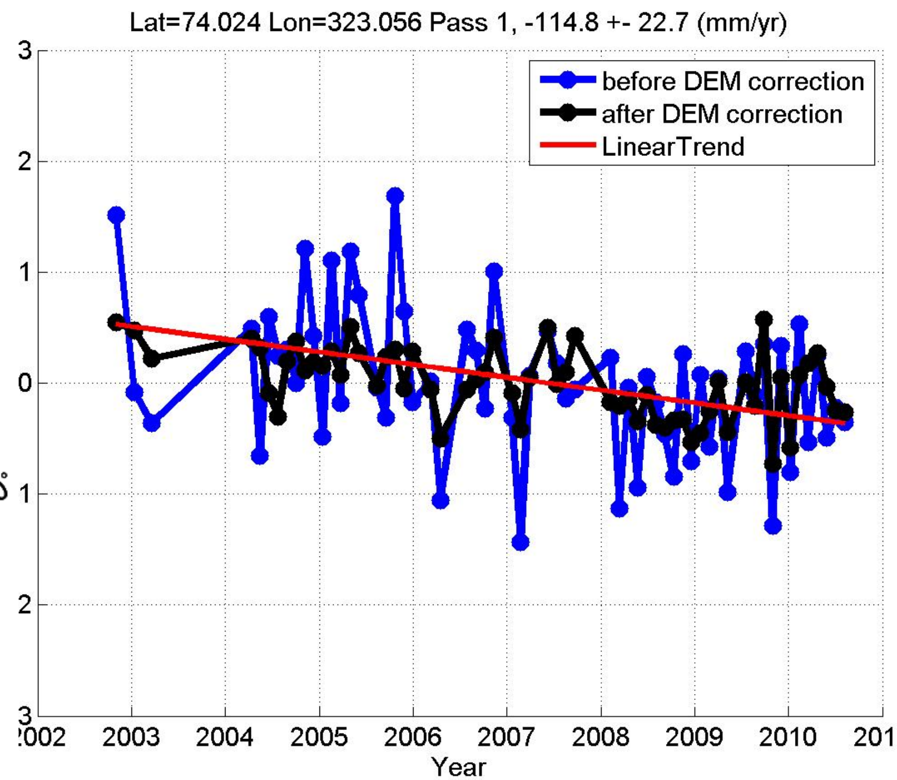
Contemporary Antarctica Mass Balance Estimates: +27 to –246 gton/yr

Identified error sources: GIA models, signal leakage, firn/ice density

Antarctic Present-day Ice Elevation Change from Envisat Radar Altimetry, 2003–2010 (Preliminary)



Ice Elevation Change



Standard Deviation

Collinear analysis used, gradient correction used DEM or mean profiles

Antarctic Present-day Ice-Sheet Mass Balance Estimates Using ICESat Altimetry [*Pritchard et al*. 2009]

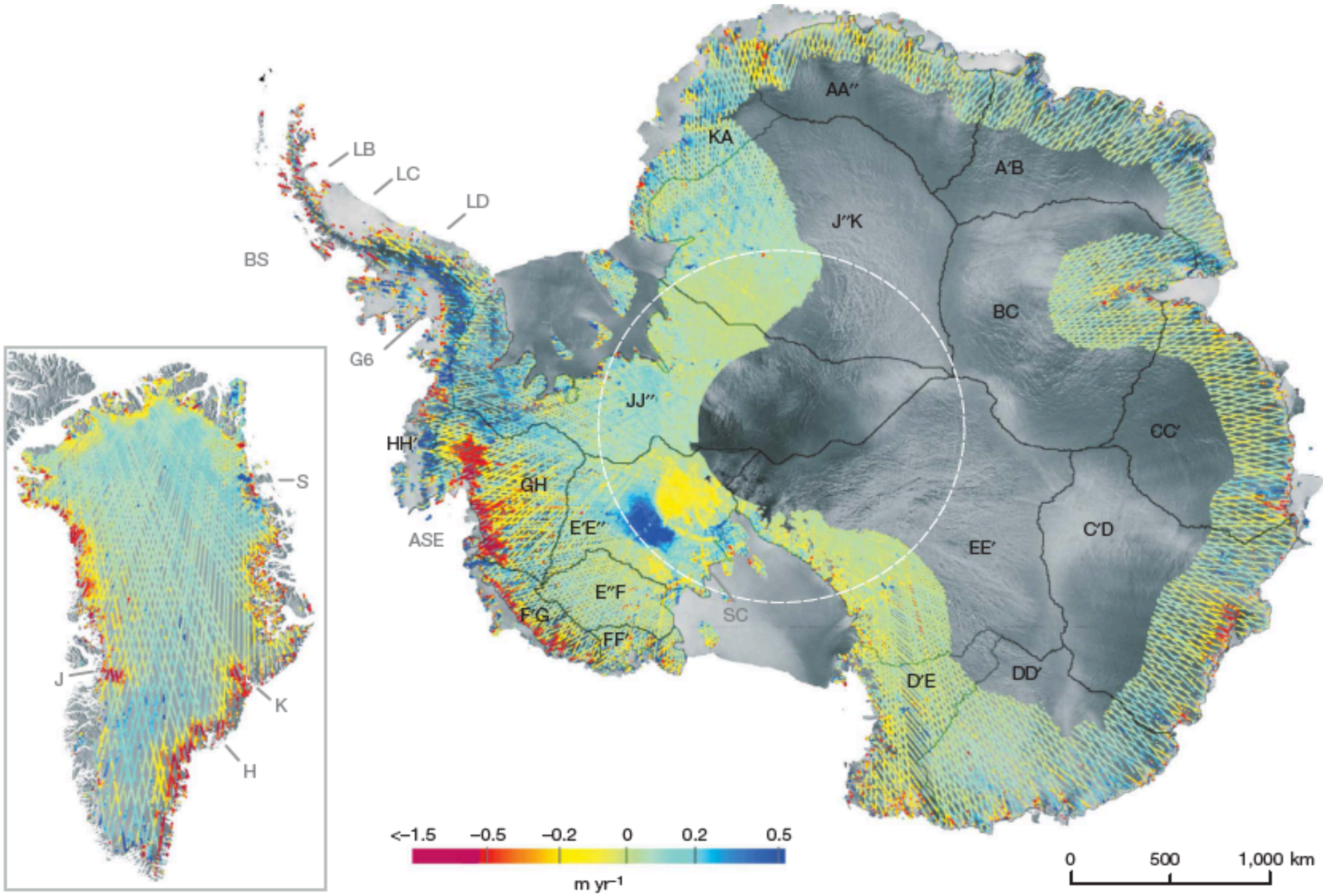
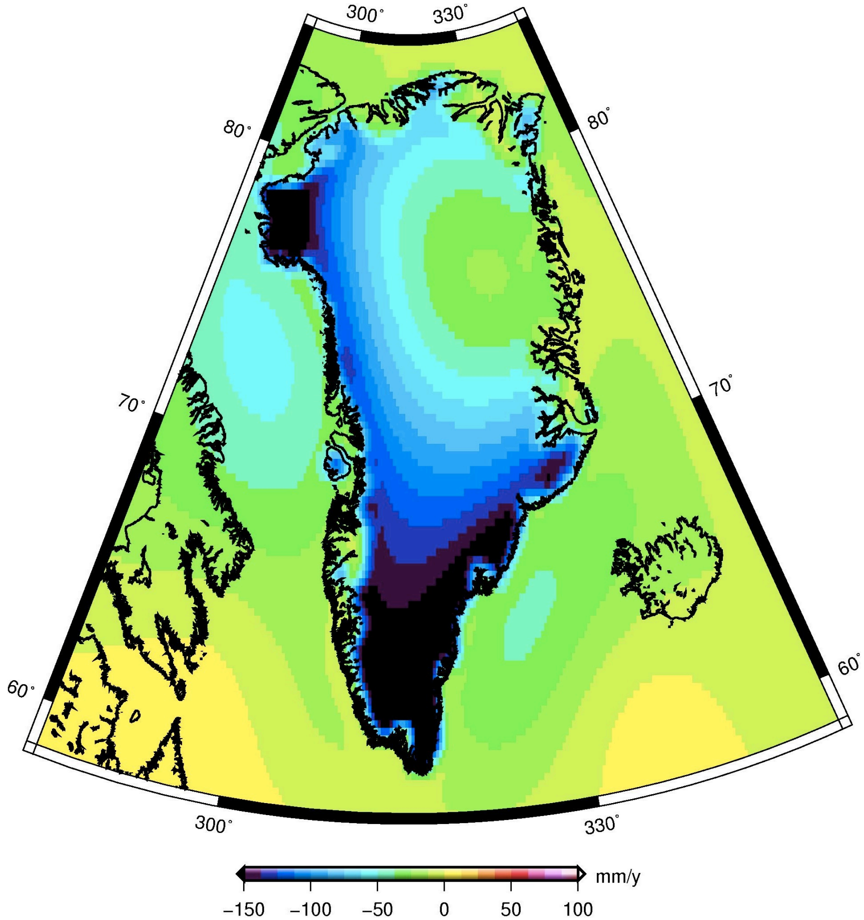
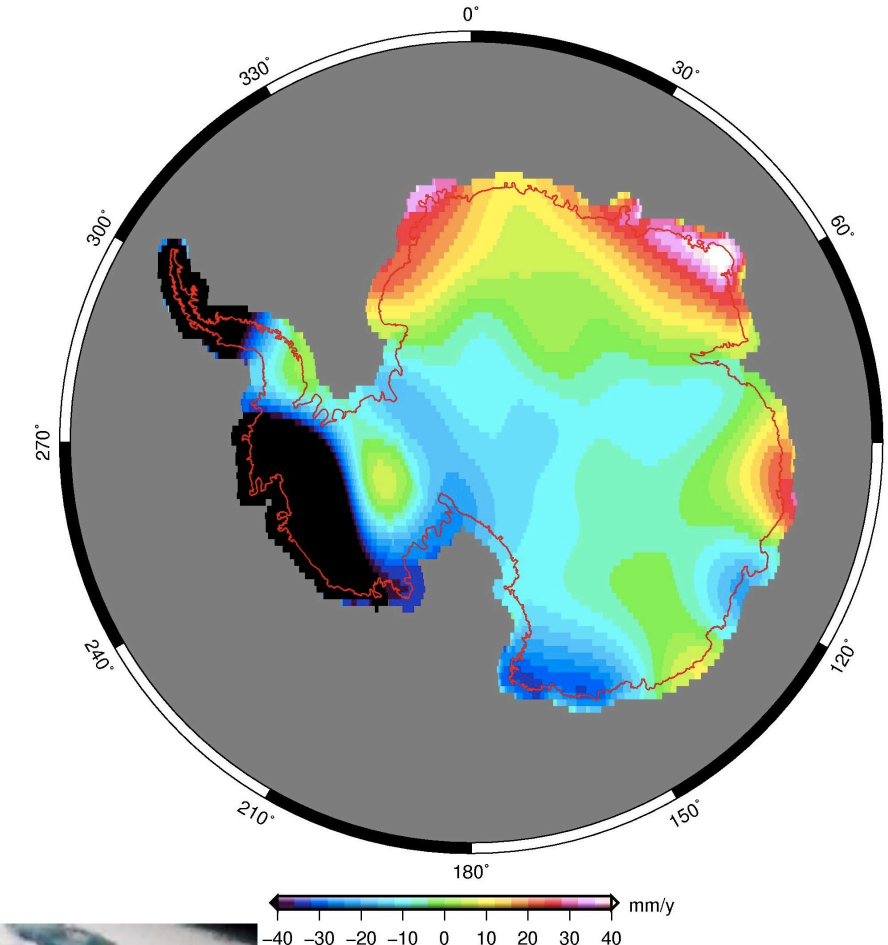


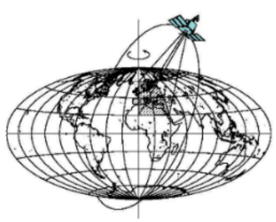
Figure 2 | Rate of change of surface elevation for Antarctica and Greenland. Change measurements are median filtered (10-km radius), spatially averaged (5-km radius) and gridded to 3 km, from intervals (Δt) of at least 365 d, over the period 2003–2007 (mean Δt is 728 d for Antarctica and 746 d for Greenland). East Antarctic data cropped to 2,500-m altitude. White dashed line (at 81.5° S) shows southern limit of radar altimetry measurements. Labels are for sites and drainage sectors (see text).

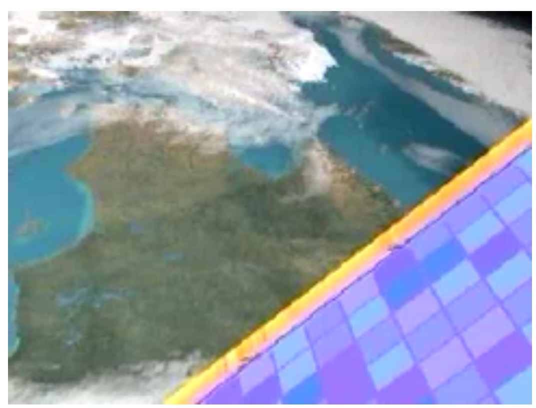
GRACE Observed Ice-Sheet Melting, 4/2002–12/2010





–180.65 Gton/yr
(0.67 mm/yr sea-level rise)





–212.85 Gton/yr

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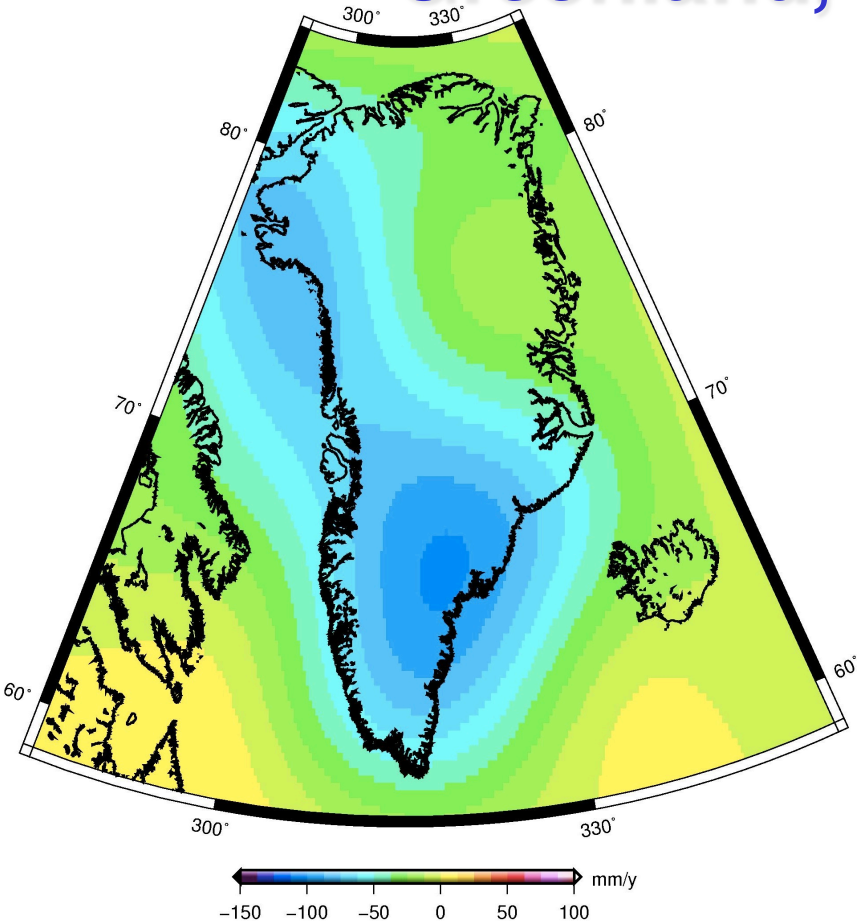
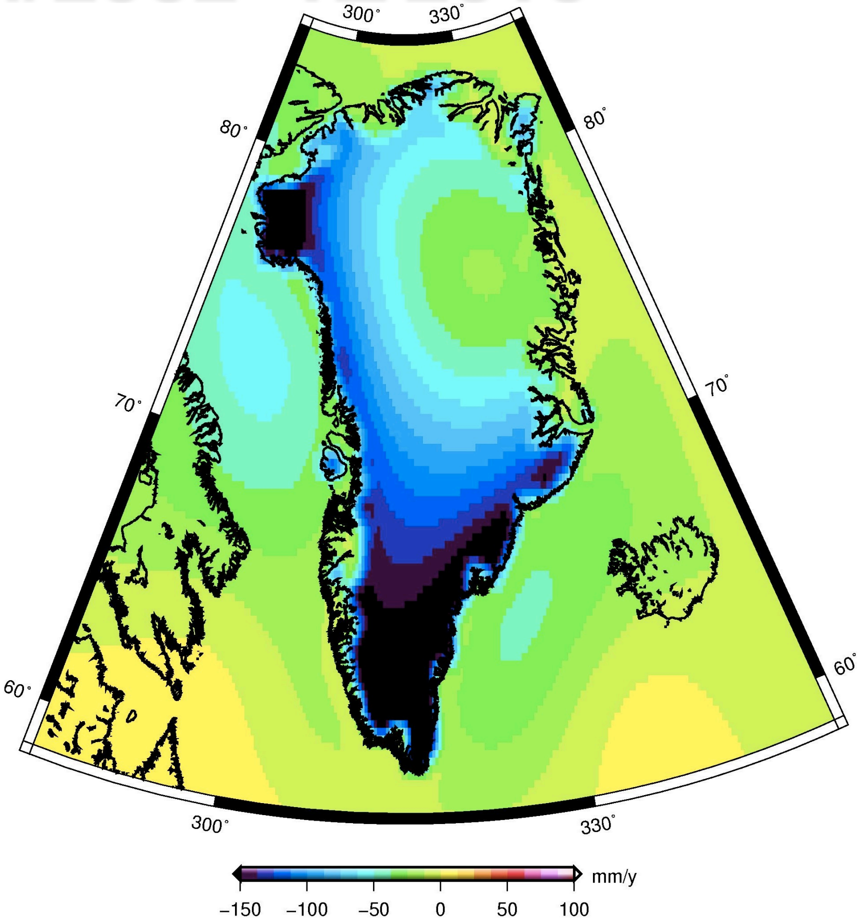
GRACE Water Thickness Trend Over Greenland, 4/2002–12/2010



Before leakage correction

–5.99 cm/yr (–110.30 Gton/yr)



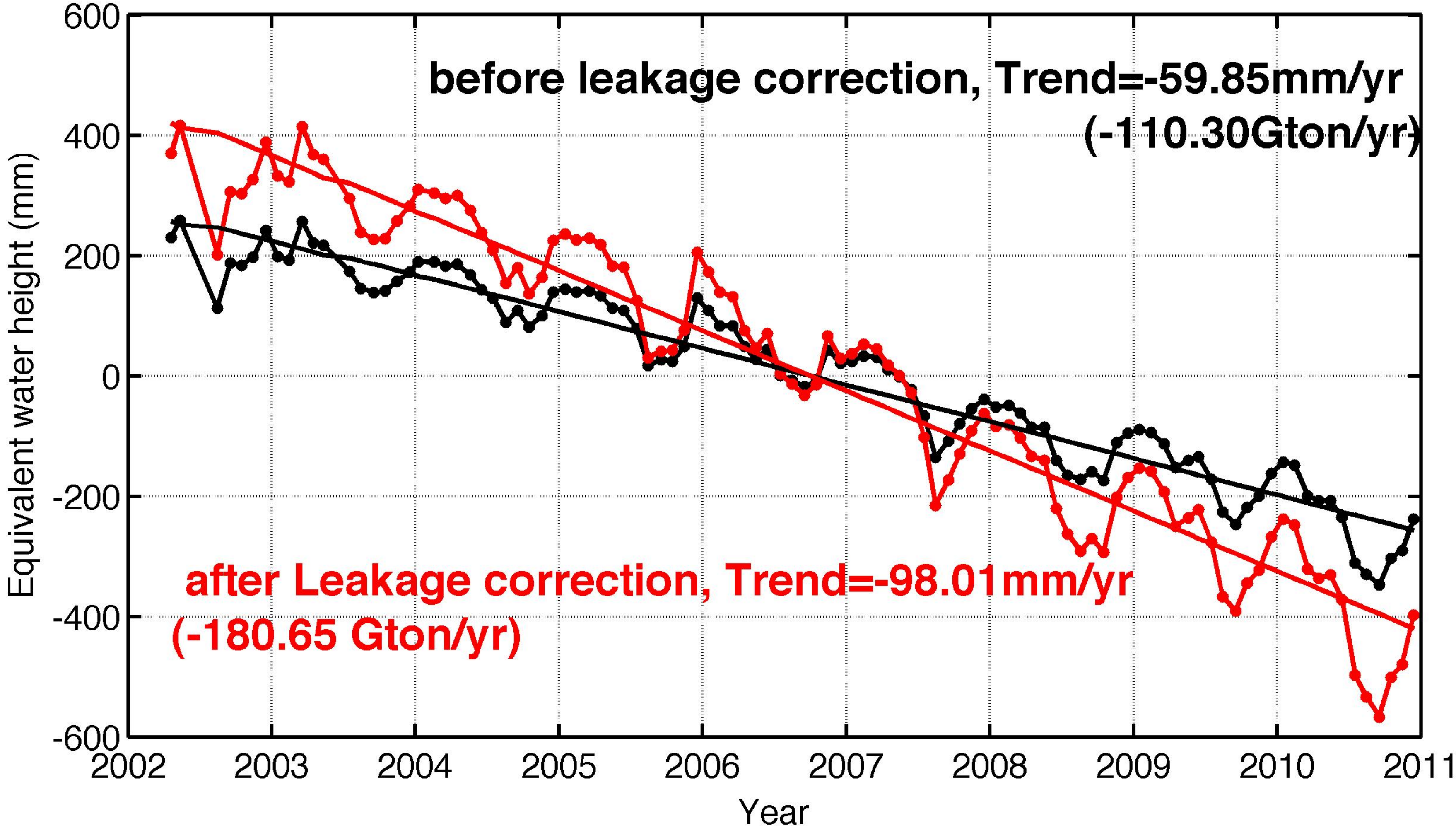
After leakage correction

–9.8 cm/yr (–180.65 Gton/yr or 0.67 mm/yr sea-level rise)

CSR RL04 Data Product, **300 km** filtering

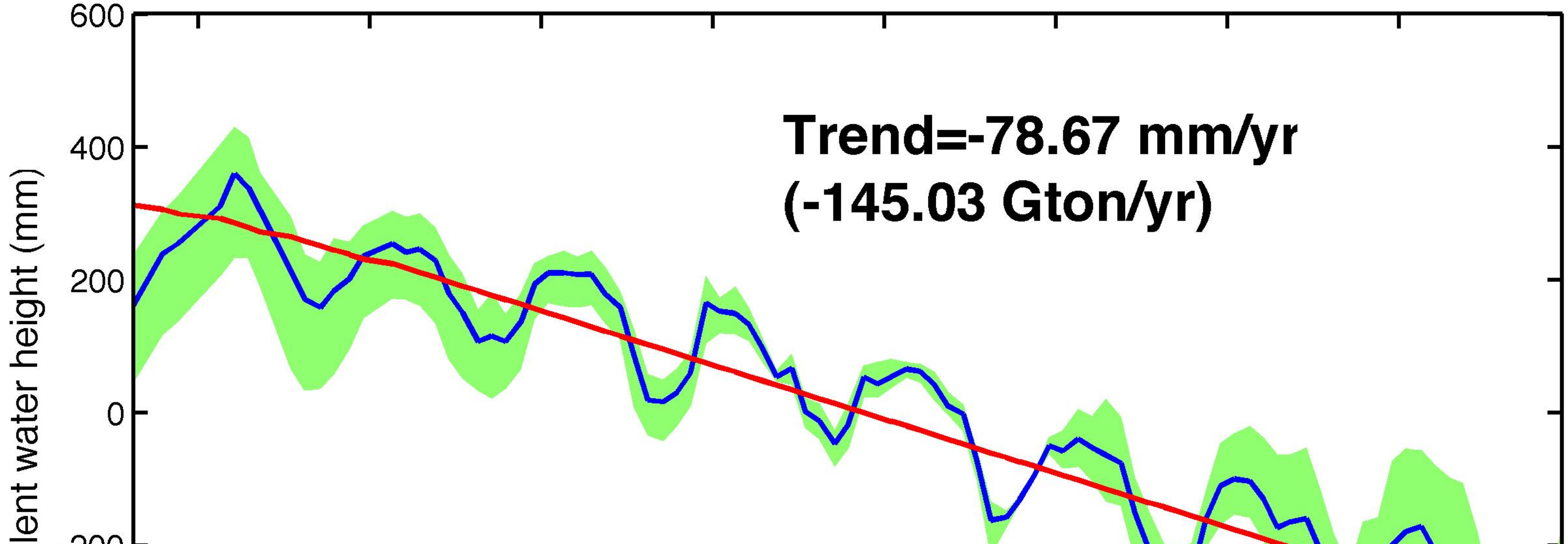
Paulson GIA and SLR geocenter corrections applied

GRACE Observed Mass (Water Thickness) Variation Over Greenland Ice-Sheet, 2002–2010



CSR RL04 Data Product, **300 km** filtering
Paulson GIA and SLR geocenter corrections applied

GRACE Observed Mass (Water Thickness) Variation Over Greenland Ice-Sheet, 2002–2010



–230 ± 33 Gton/yr (2002–2009, GRACE) [Velicogna, 2009]

–113 ± 17 Gton/yr (2002–2005, GRACE mascons) [*Luthcke* et al., 2008]

–239 ± 23 Gton/yr (2002–2005, GRACE) [*Chen* et al., 2008]

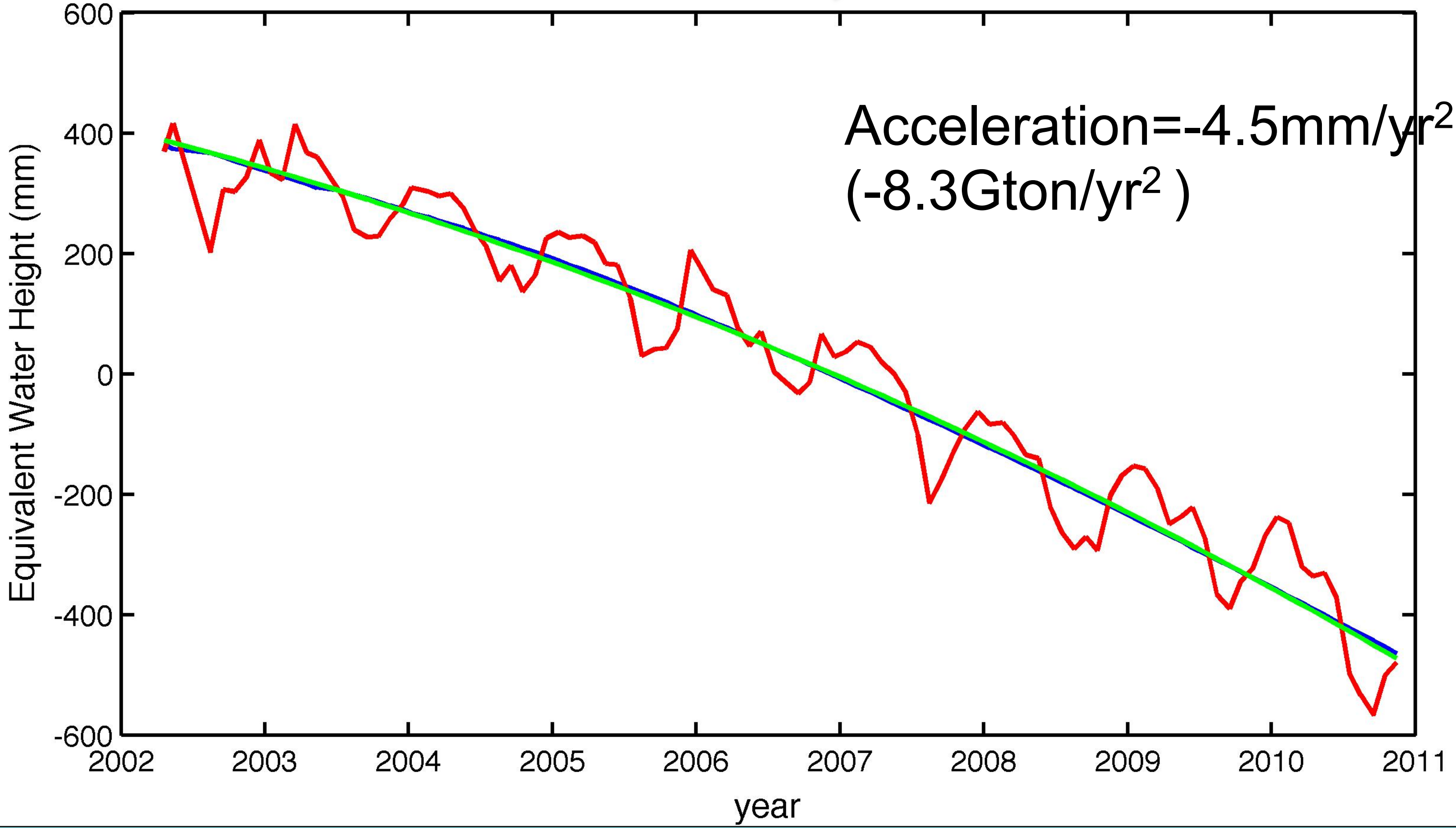
–224 ± 41 Gton/yr (1996–2005, InSAR) [*Rignot & Kanagaratnam*, 2006]

–248 ± 36 Gton/yr (2002–2006, GRACE) [*Velicogna & Wahr*, 2006]

Leakage repaired

CSR, GFZ, JPL Data Producst, **300 km** filtering
Paulson GIA and SLR geocenter corrections applied

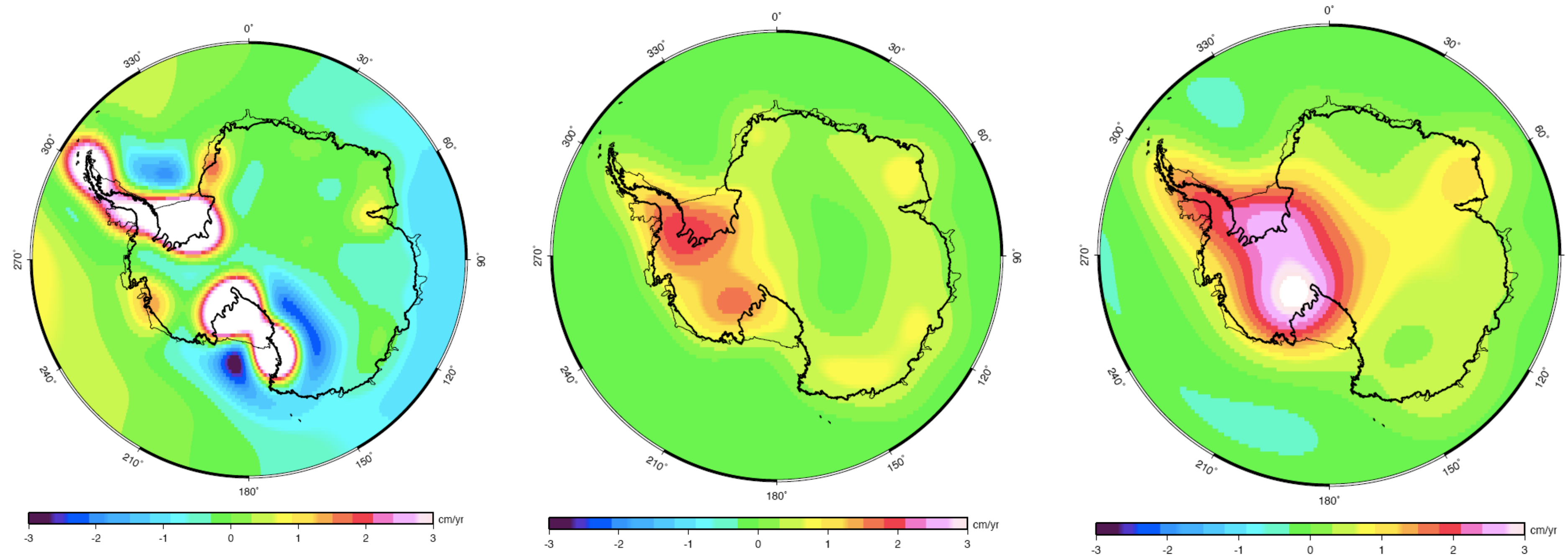
GRACE Observed Mass Variation Over Greenland Ice-Sheet, Acceleration?



–30 ± 11 Gton/yr^2 (2002–2009, GRACE) [Velicogna, 2009]

GRACE Observed Antarctica Mass Balance

Accuracy of Glacial Isostatic Adjustment Models

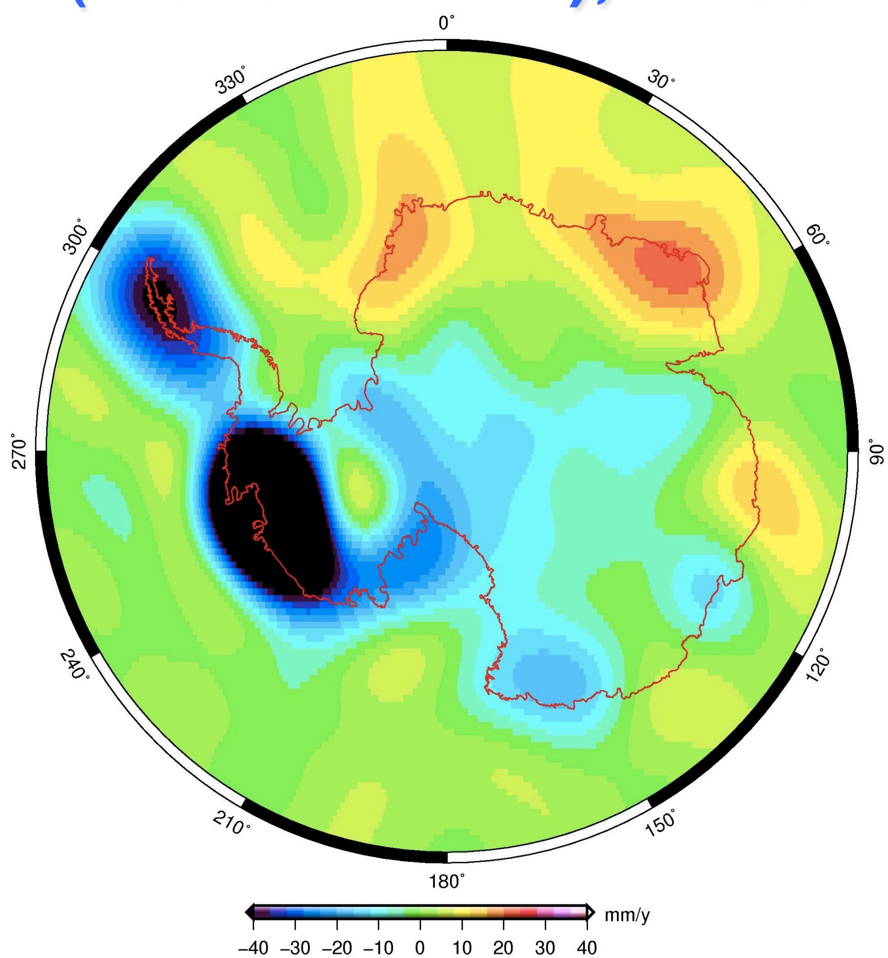


The discrepancy between current GIA models over Antarctica causes a possible 0.25 to 0.45 mm/yr increase in the equivalent sea level rise

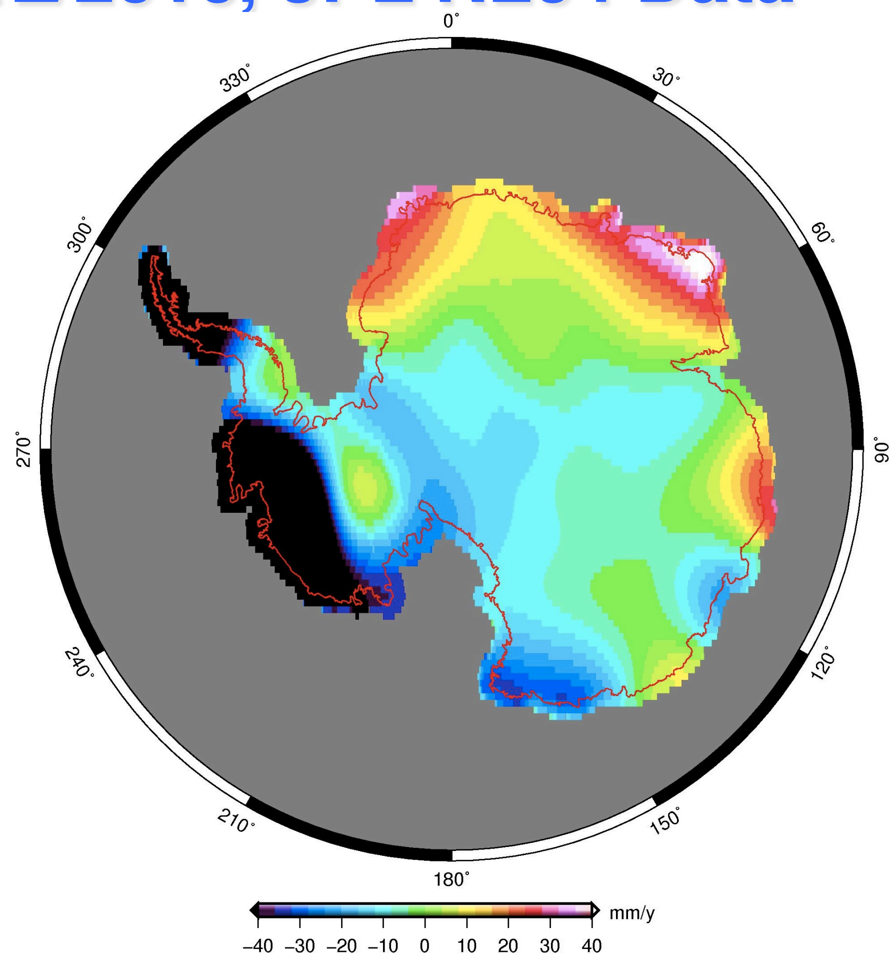
Water thickness change (cm/yr)

Shum, Kuo & Guo [2009]

GRACE Observed Antarctic Ice-Sheet Mass Balance (Trend in EWH), 4/2002–12/2010, JPL RL04 Data



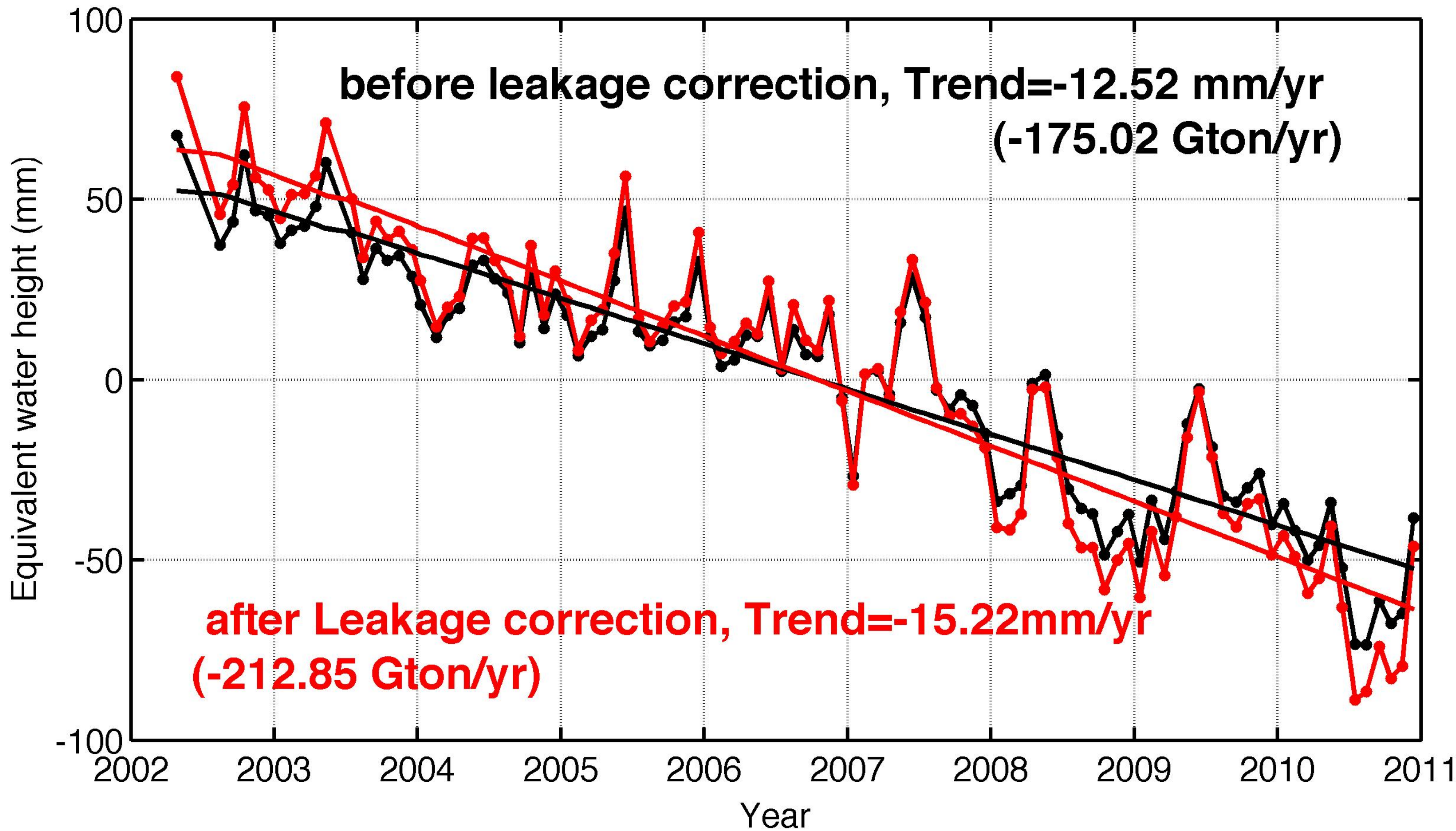
Leakage Not repaired
–12.52 mm/yr (–175.02 Gton/yr)



Leakage repaired [*Guo et al.*, 2010]
–15.22 mm/yr (–212.85 Gton/yr)

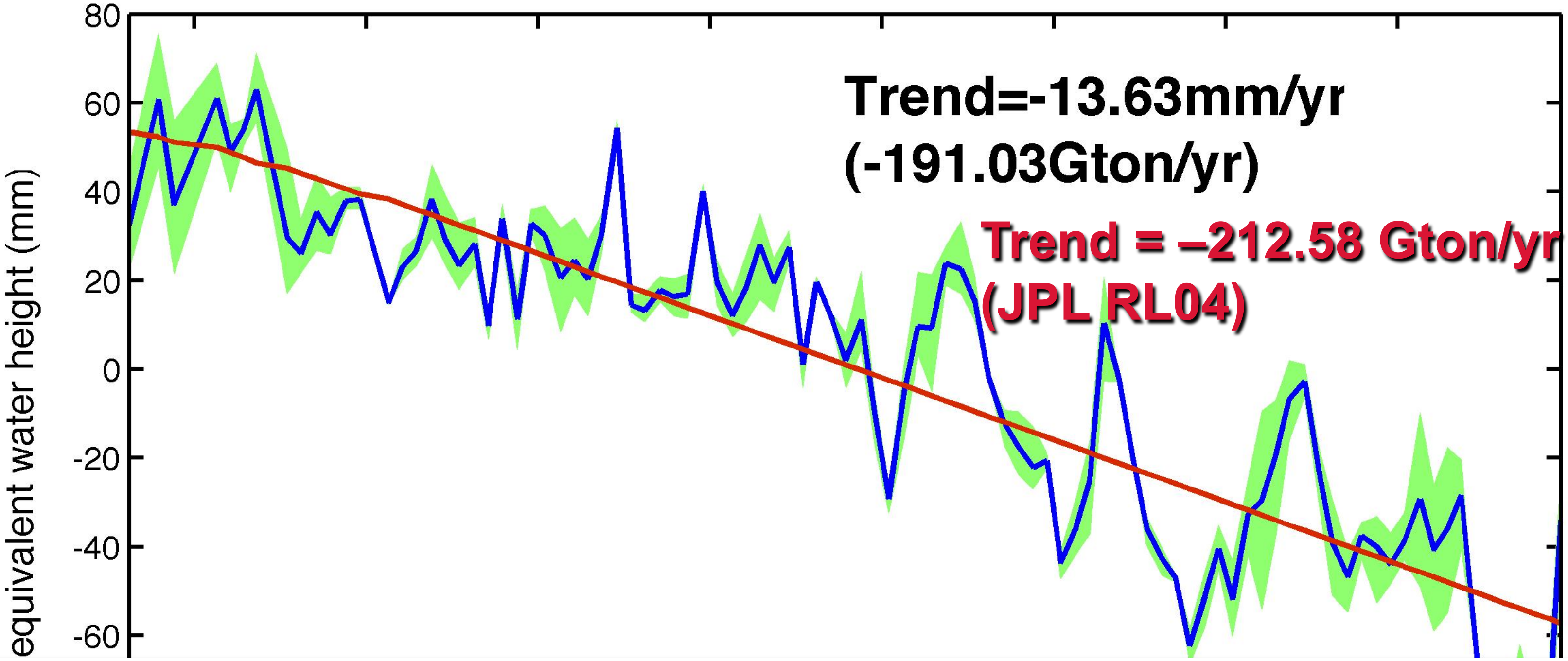
Decorrelation, 300 km filtering, land signal leakage repair [*Duan et al.*, 2009, *Guo & Shum*, 2009, *Guo et al.*, 2010]. Paulson GIA & SLR geocenter corrections

GRACE Observed Antarctic Mass Balance



JPL RL04 Data Product, 300 km filtering
Paulson GIA and SLR geocenter corrections applied

GRACE Observed Mass (Water Thickness) Variation Over Antarctic Ice-Sheet



–104 to –246 Gton/yr (2002–06,2007–09, GRACE) [*Velicogna*, 2009]

–190 ± 7 Gton/yr (2002–2009,GRACE) [*Chen et al*, 2009]

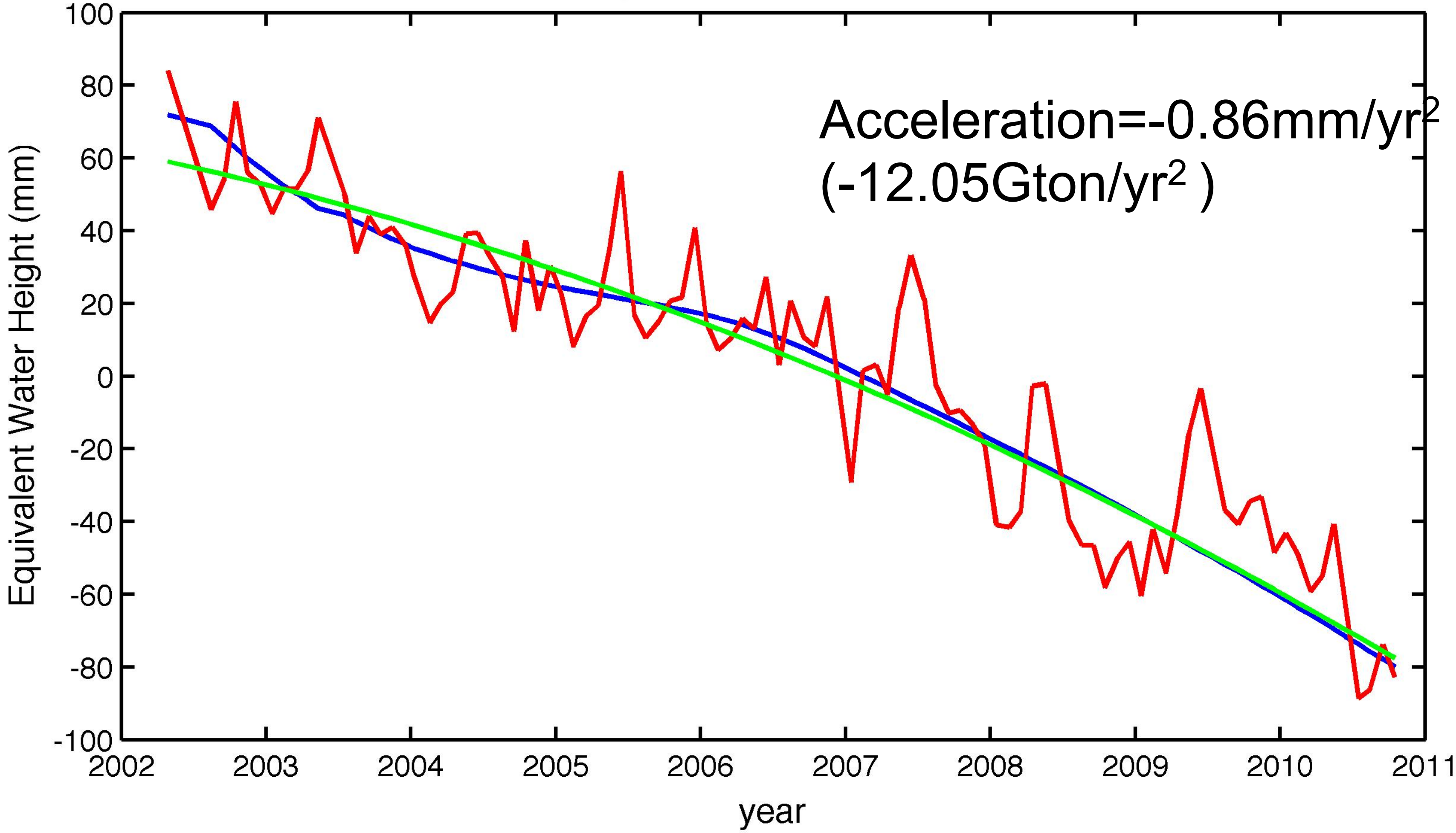
–143 ± 73 Gton/yr (2002–2009,GRACE) [*Velicogna & Wahr*, 2006]

–129 ± 15 Gton/yr (2002–2005, GRACE) [*Ramilien* et al., 2006]

–26 ± 37 Gton/yr (1995–2000, InSAR) [*Rignot & Thomas*, 2002]

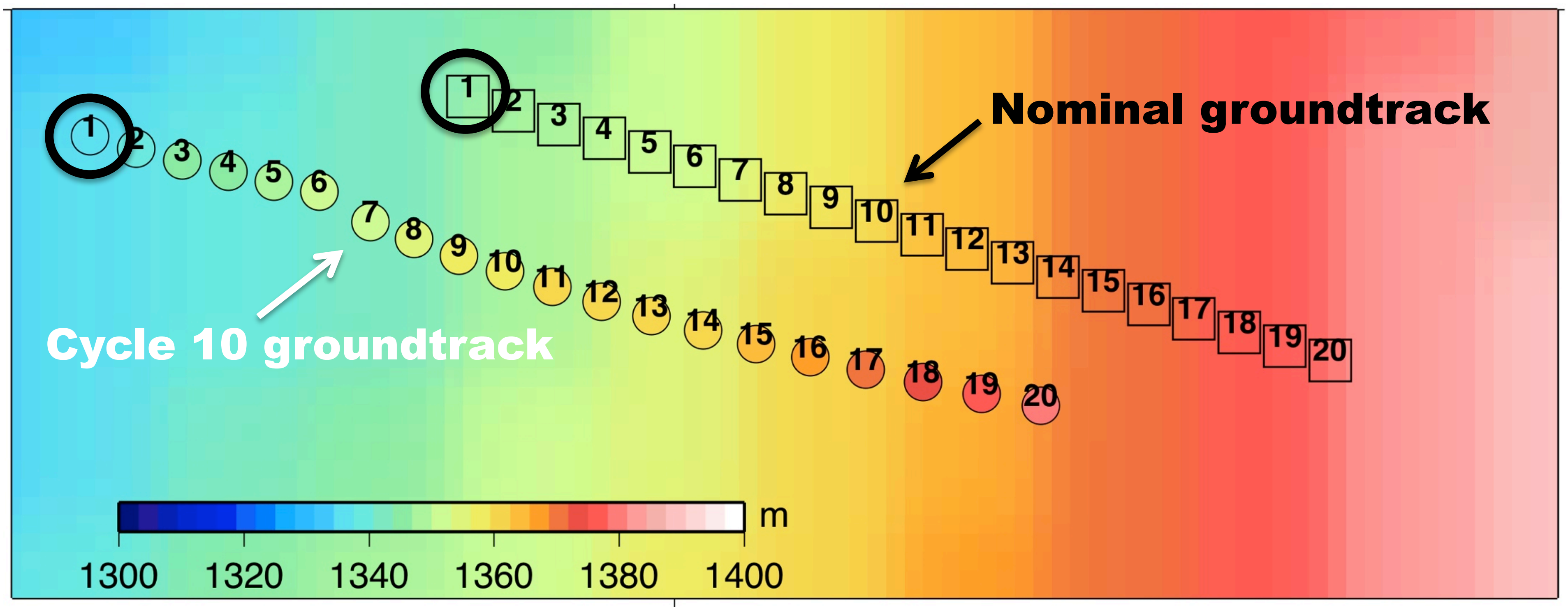
+27 ± 29 Gton/yr (1992–2003, Radar Alt) [*Wingham et al.*, 2006]x

GRACE Observed Mass Variation Over Antarctica Ice-Sheet, Is there an Acceleration?



–26 ± 14 Gton/yr^2 (2002–2009, GRACE) [Velicogna, 2009]

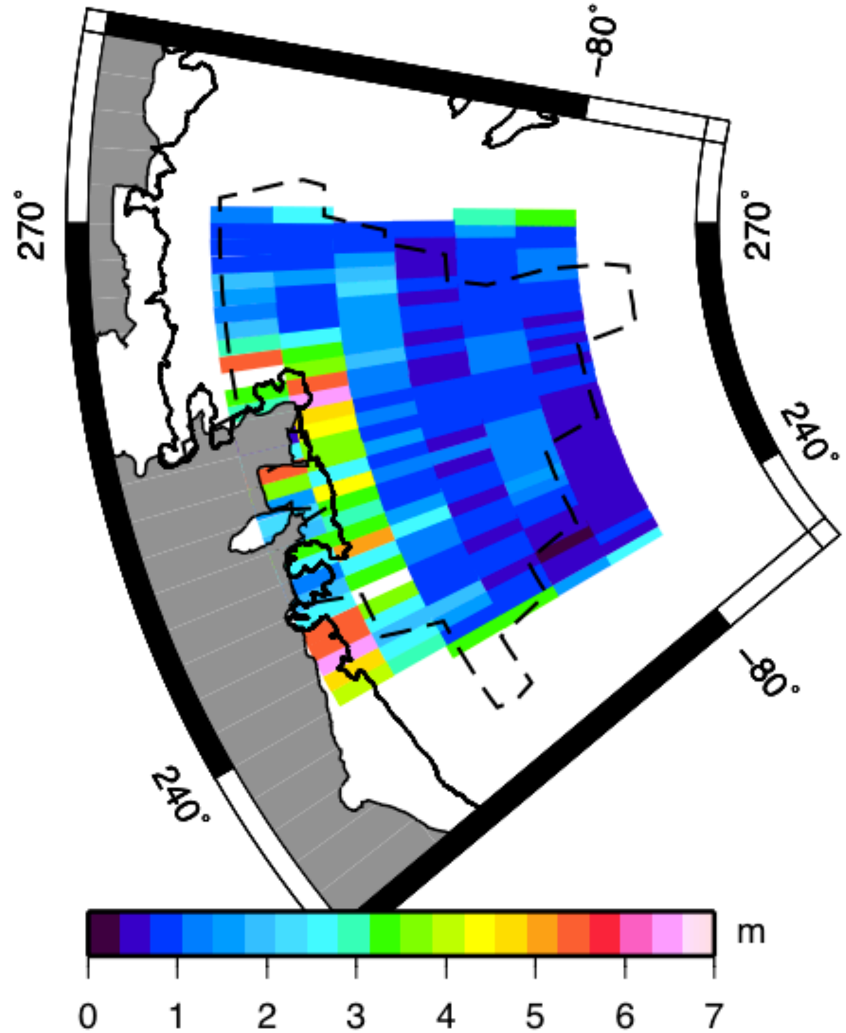
Ice-Sheet Surface gradient correction for Envisat altimetry collinear Analysis



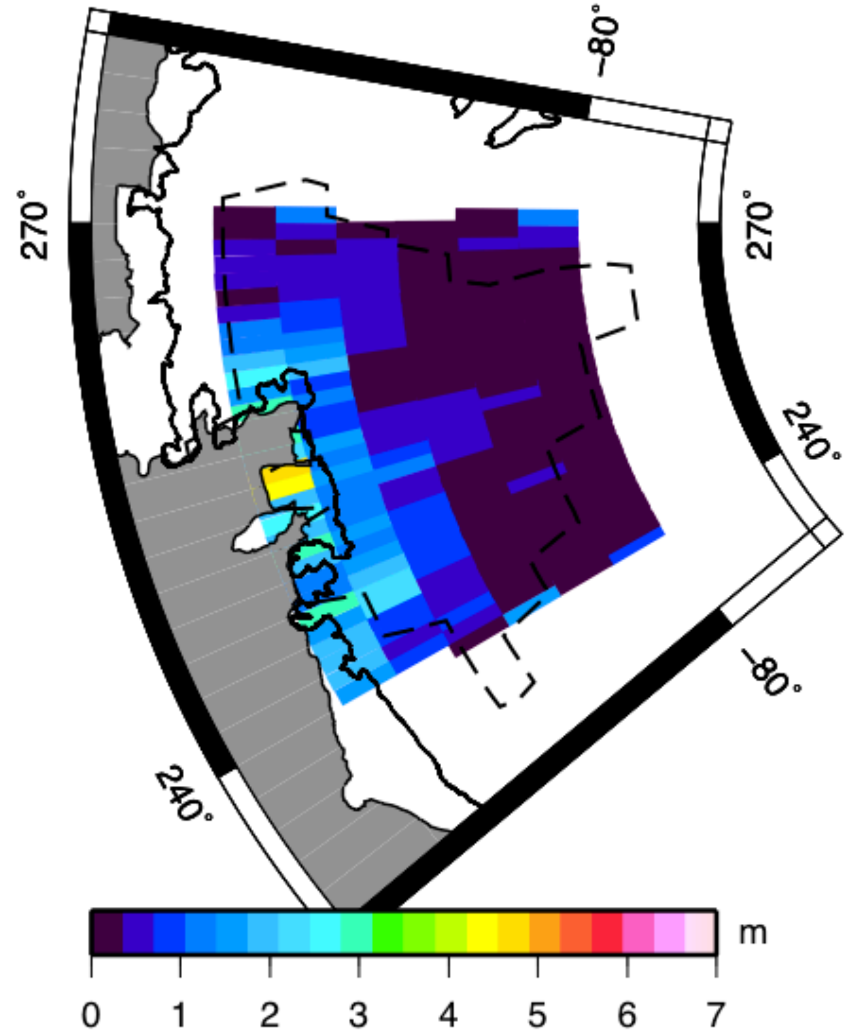
$$Height_{nominal} - Height_{cycle} = DEM_{nominal} - DEM_{cycle}$$

$$\Rightarrow \quad Height_{nominal} = Height_{cycle} + \left(DEM_{nominal} - DEM_{cycle} \right)$$

Standard deviations of Basin GH Envisat dH/dt (Cycle 10)

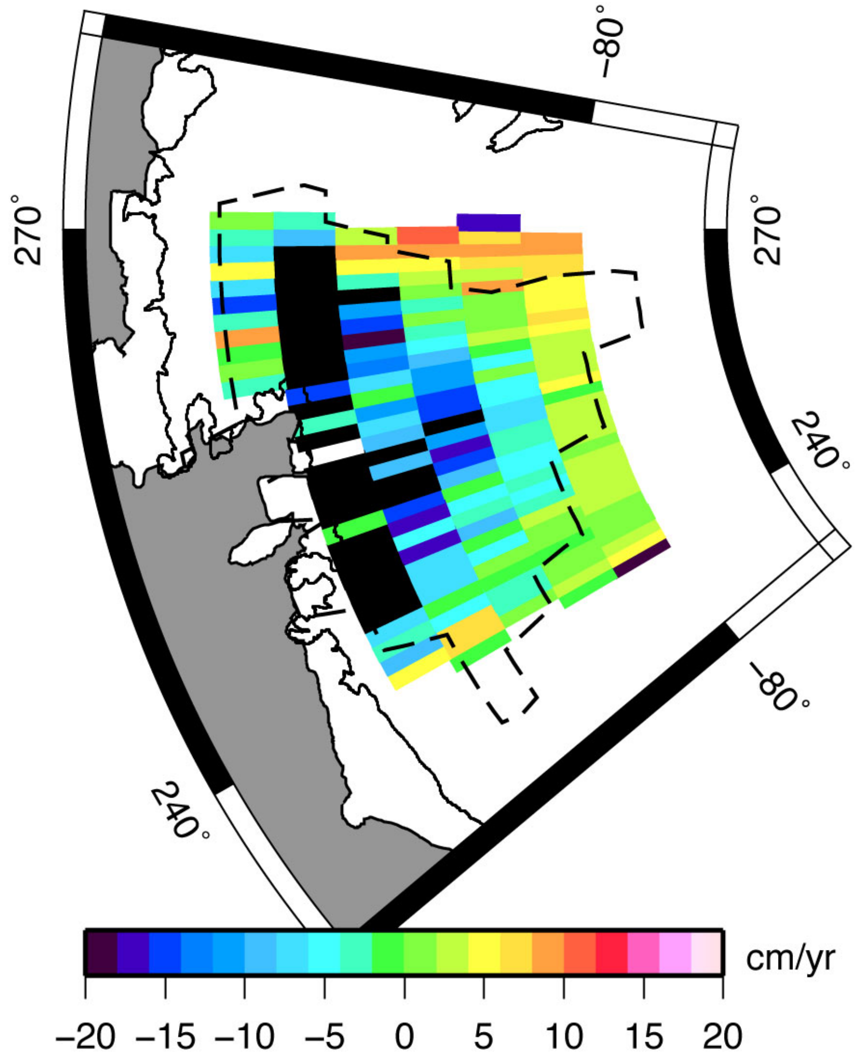


before gradient correction

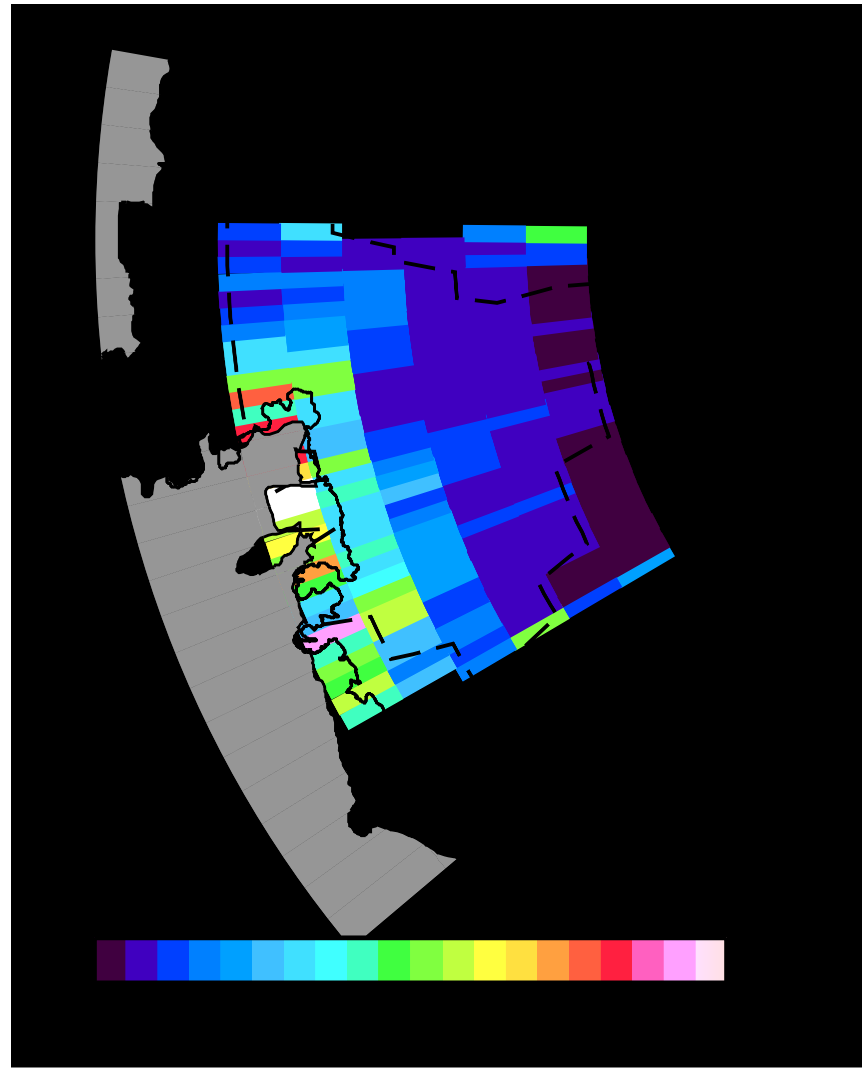


after gradient correction

Envisat dh/dt Using Collinear Analysis/DEM Gradient Corrections: Basin GH, W. Antarctica

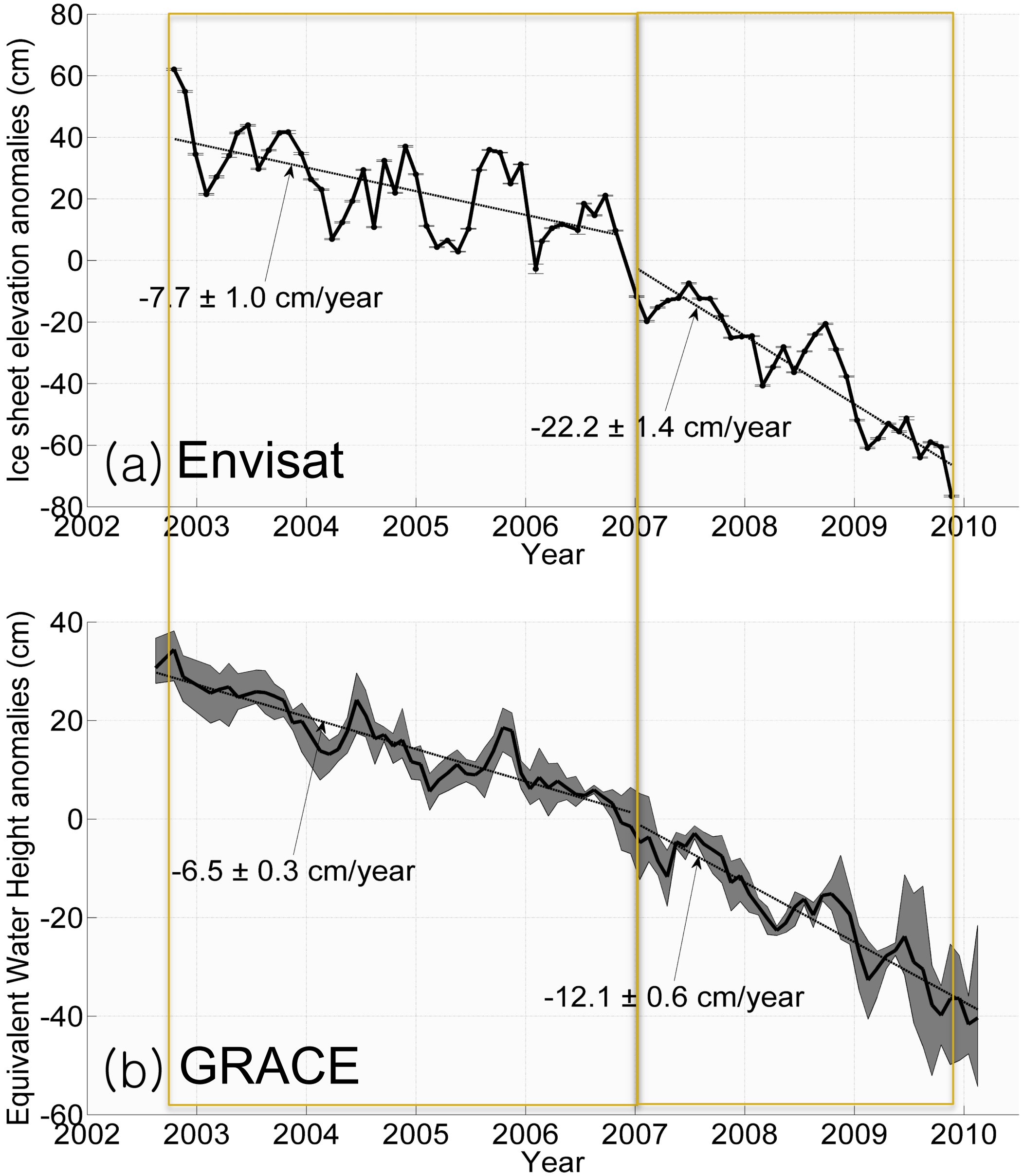


Ice sheet elevation change rates, dh/dt (9/2002–12/2009)



Formal uncertainty

Density Correction, Separation of Mass Balance & GIA: Basin GH, West Antarctica



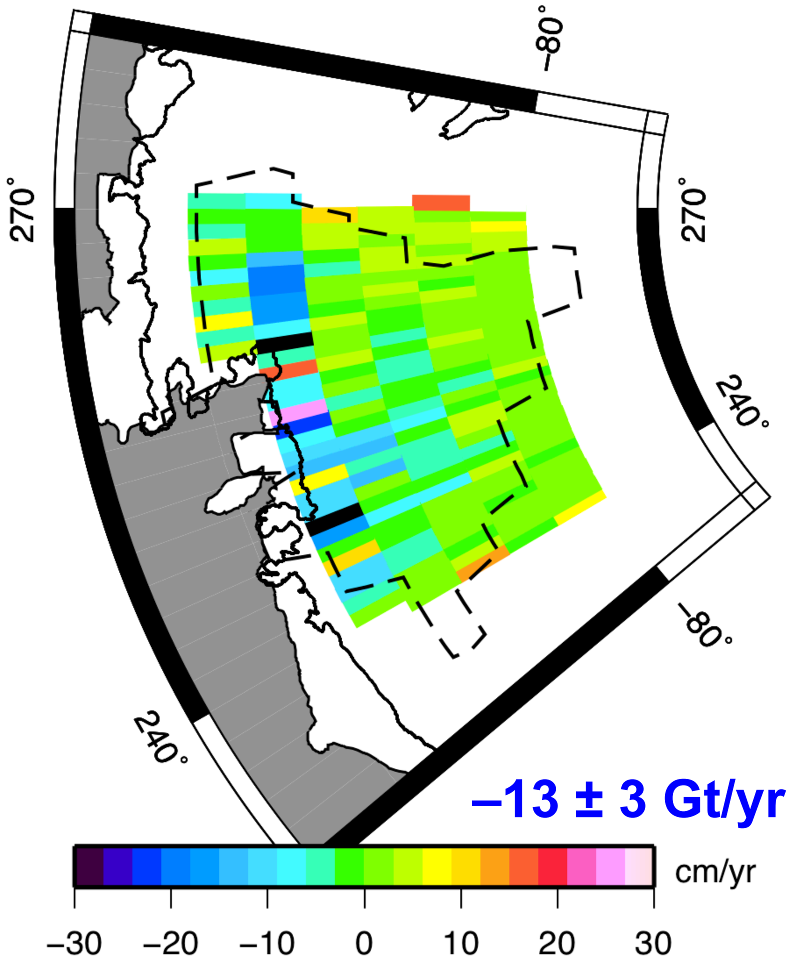
$$Density = \frac{Mass\ Changes}{Volume\ Changes}$$

2002-2006 estimated mean density: 400 kg/m^3

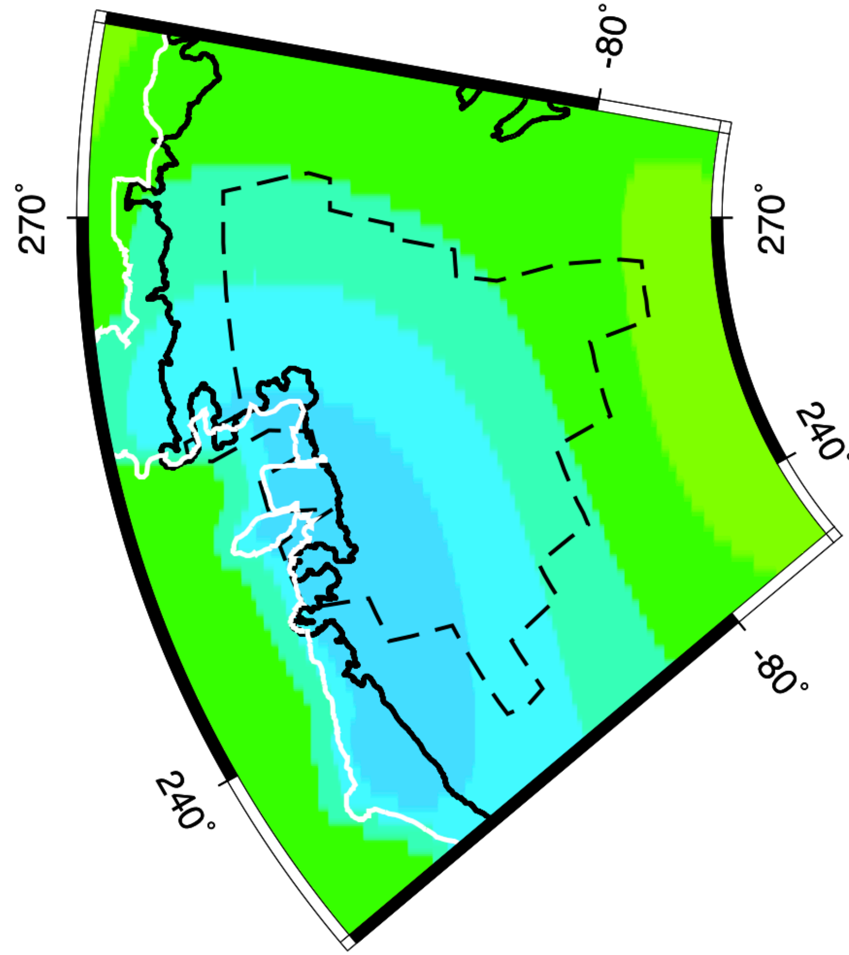
2007-2009 estimated mean density: 760 kg/m^3

- Due to decrease snowfall & increased ice discharge after 2007
- Accelerated mass loss is likely to continute
- GIA signal negligible

Corrected Basin GH Mass Balance, 2002–2006 (ρ=400 kg/m³)

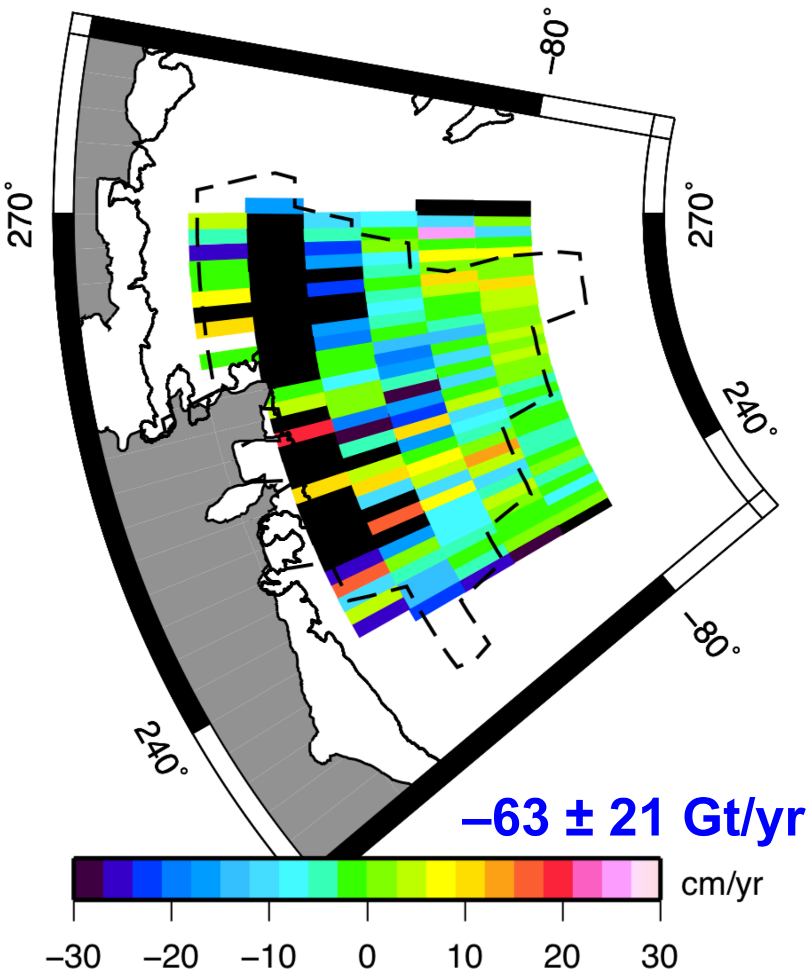


"Corrected" mass changes in water equivalent from Envisat (Sep 2002-Dec 2006)

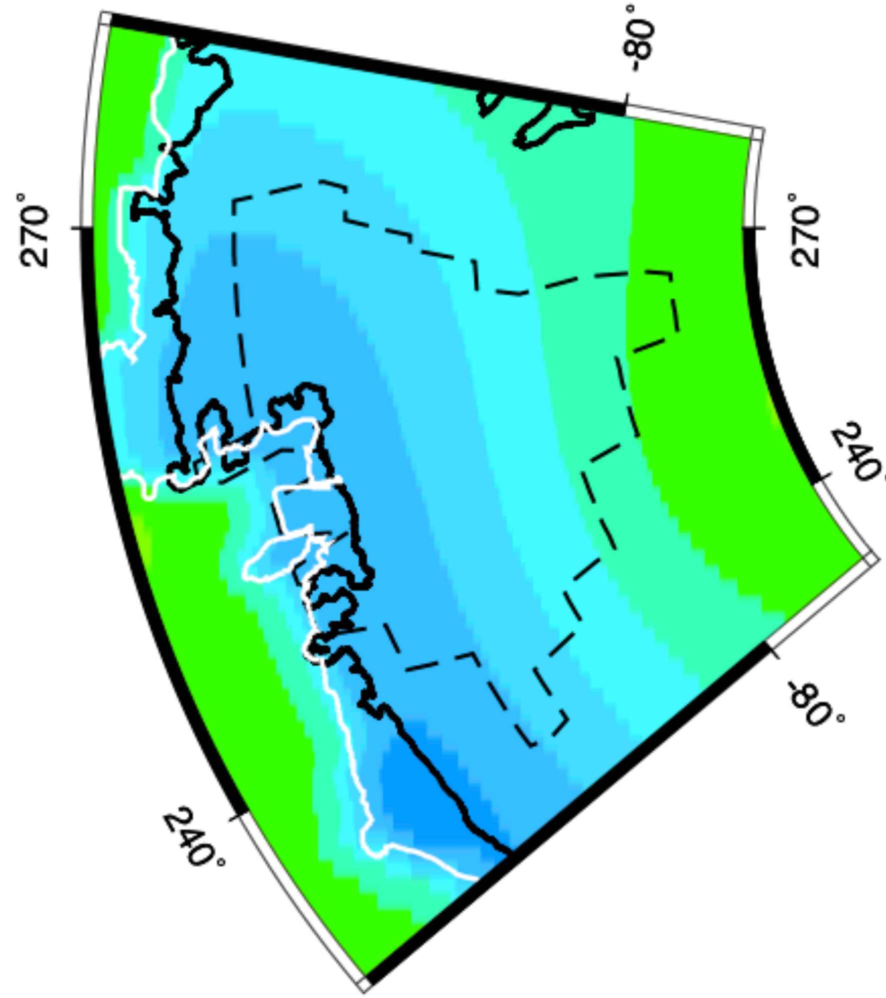


Mass changes in water equivalent From GRACE (Apr 2002-Dec 2006), JPL RL04, Paulson GIA, geocenter

Converted Basin GH Mass Balance, 2007–2009 (ρ=760 kg/m³)

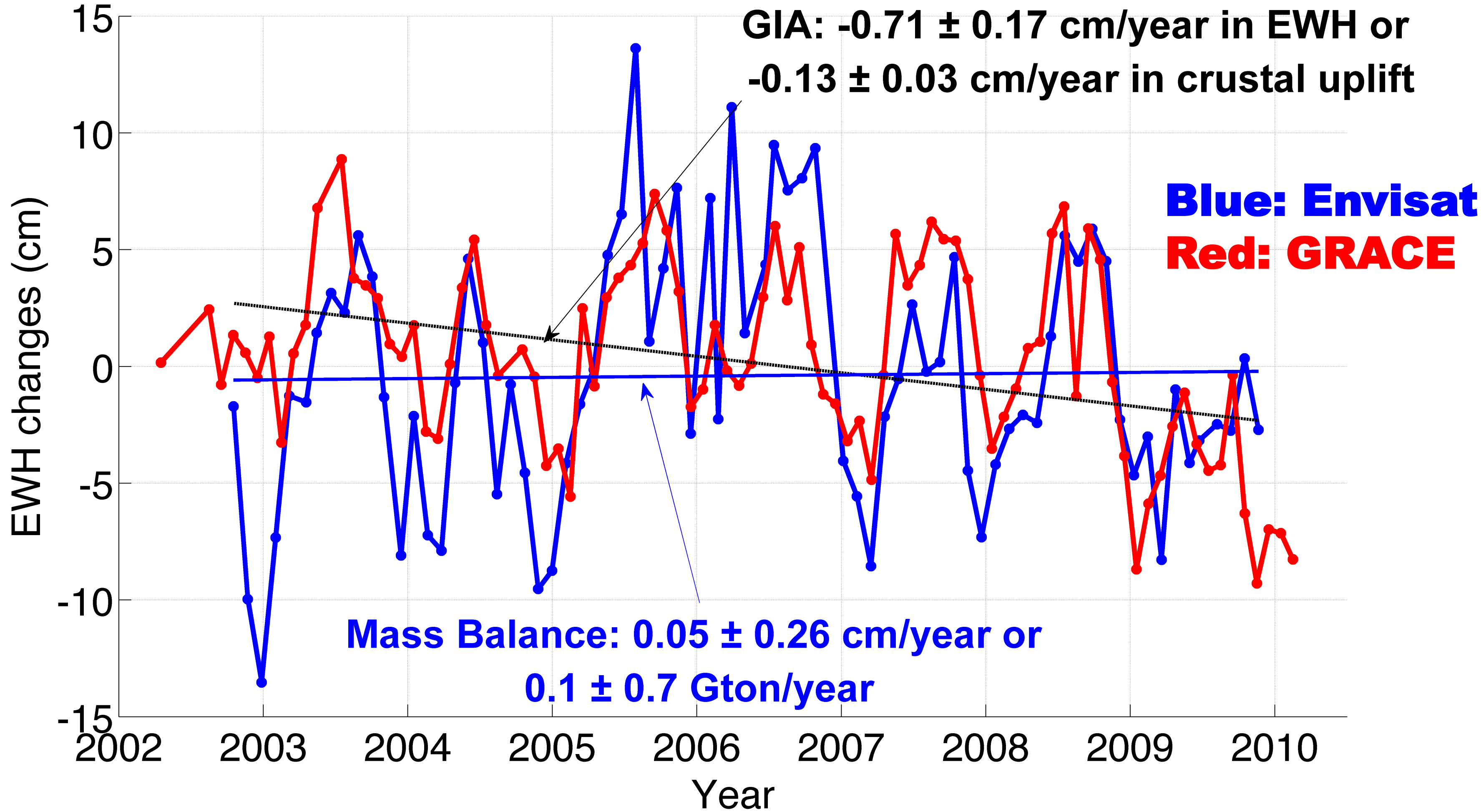


"Corrected" mass changes in water equivalent from Envisat (Jan 2007-Dec 2009)



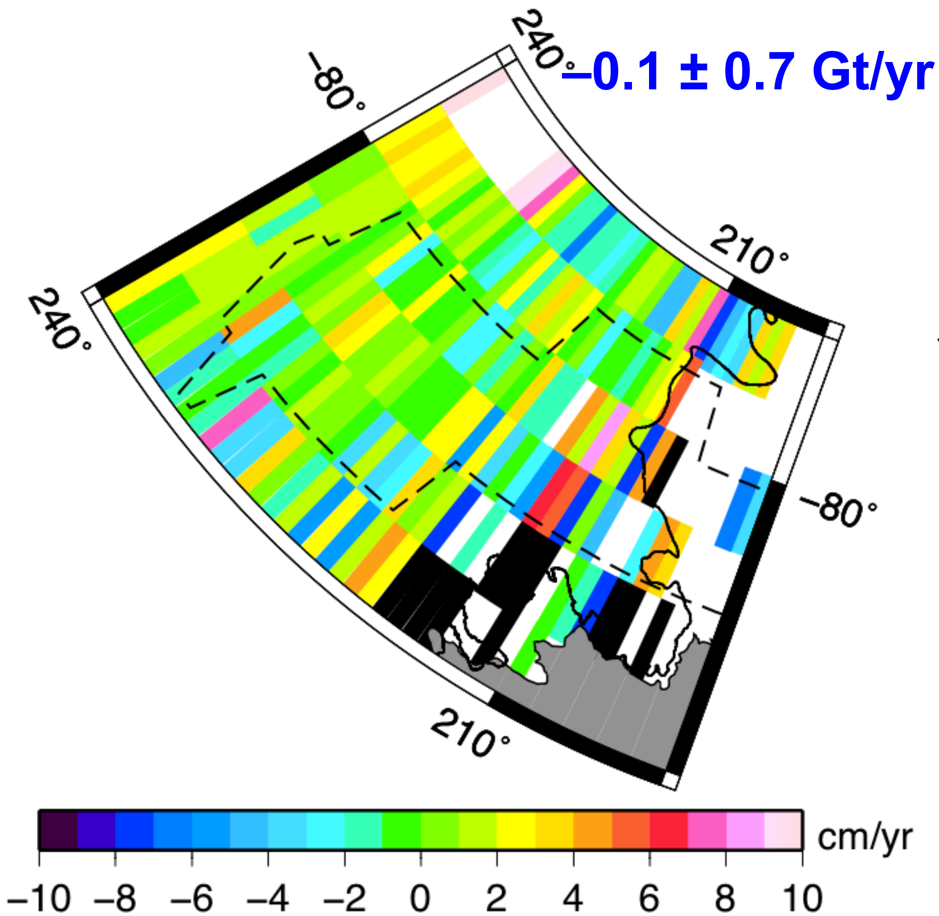
Mass changes in water equivalent From GRACE (Jan 2007-Dec 2010)

Density Correction, Separation of Mass Balance & GIA: Basin E”F, W. Antarctica

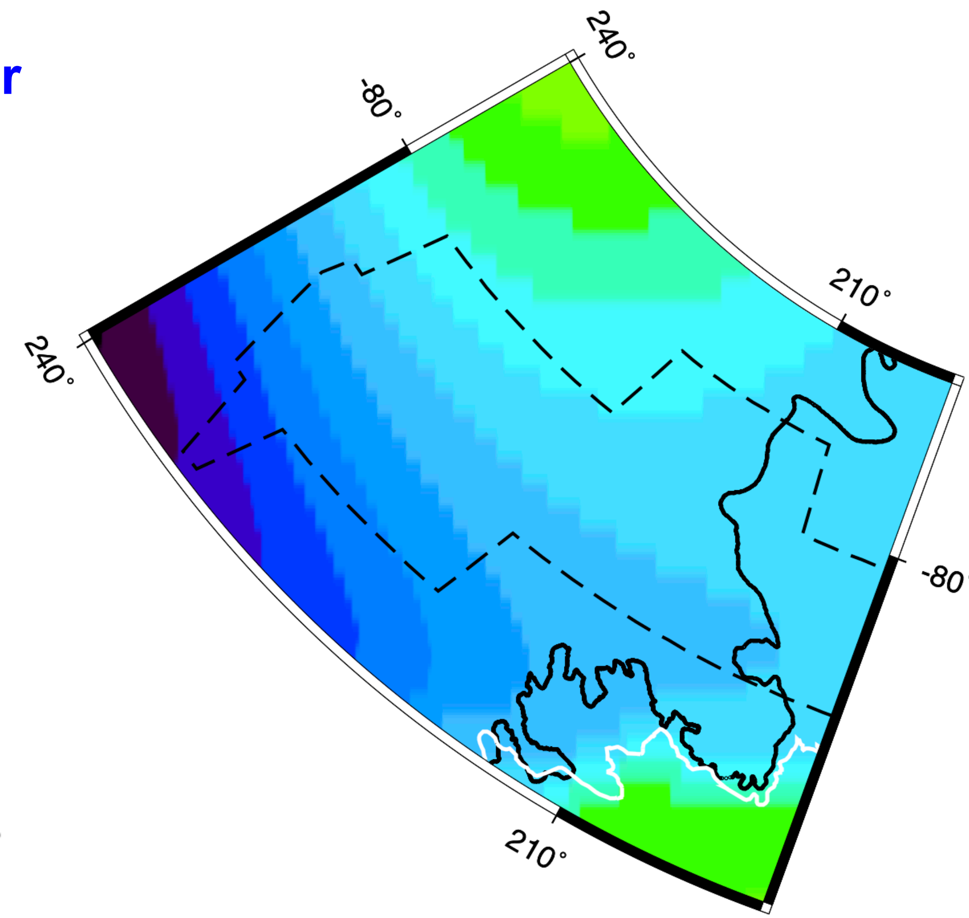


Basin-wide ice-column density: 420 kg m^{-3}

Corrected Mass Balance Basin E"F, West Antarctica

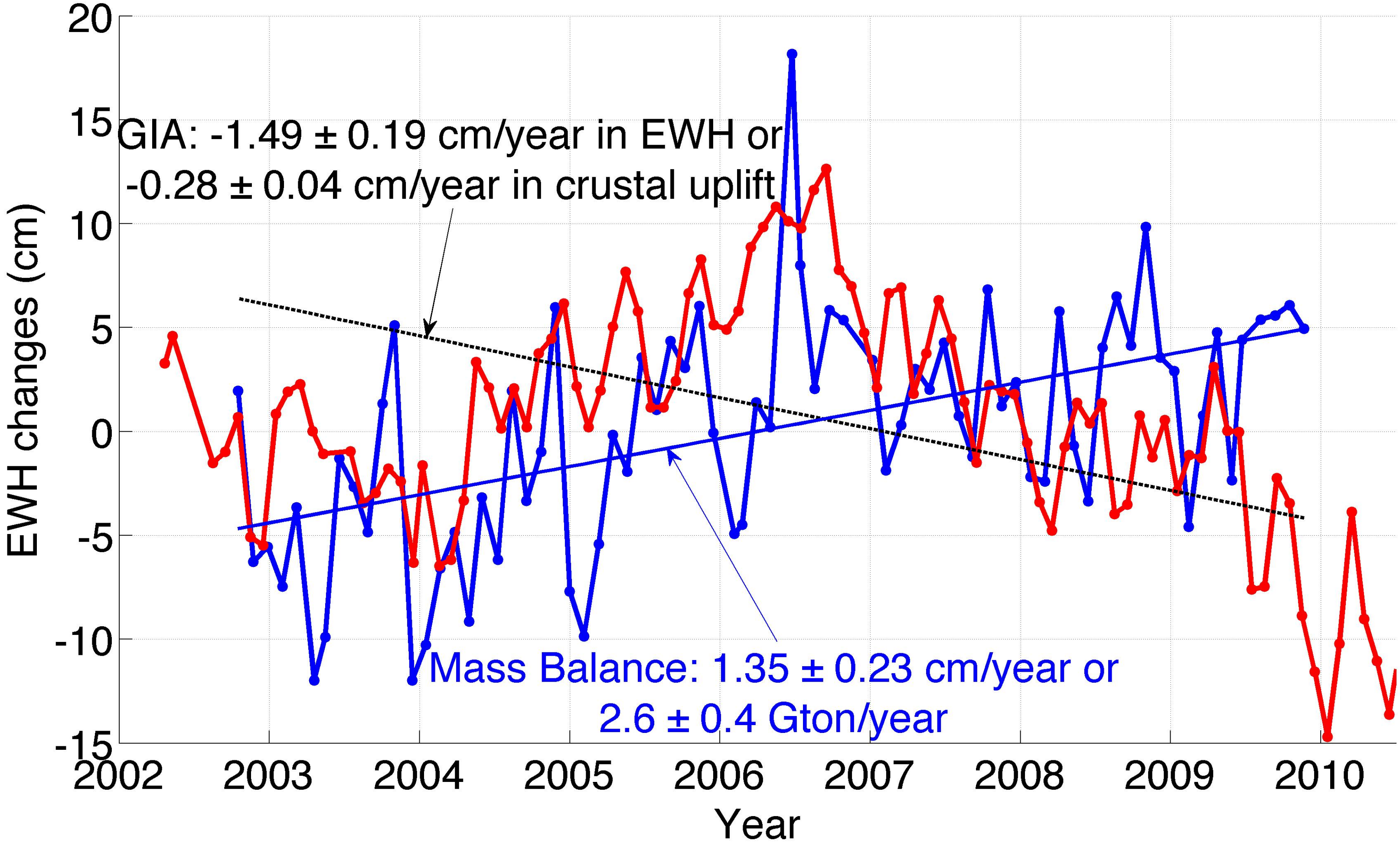


Corrected mass changes in water equivalent from Envisat (Sep 2002-Dec 2009)



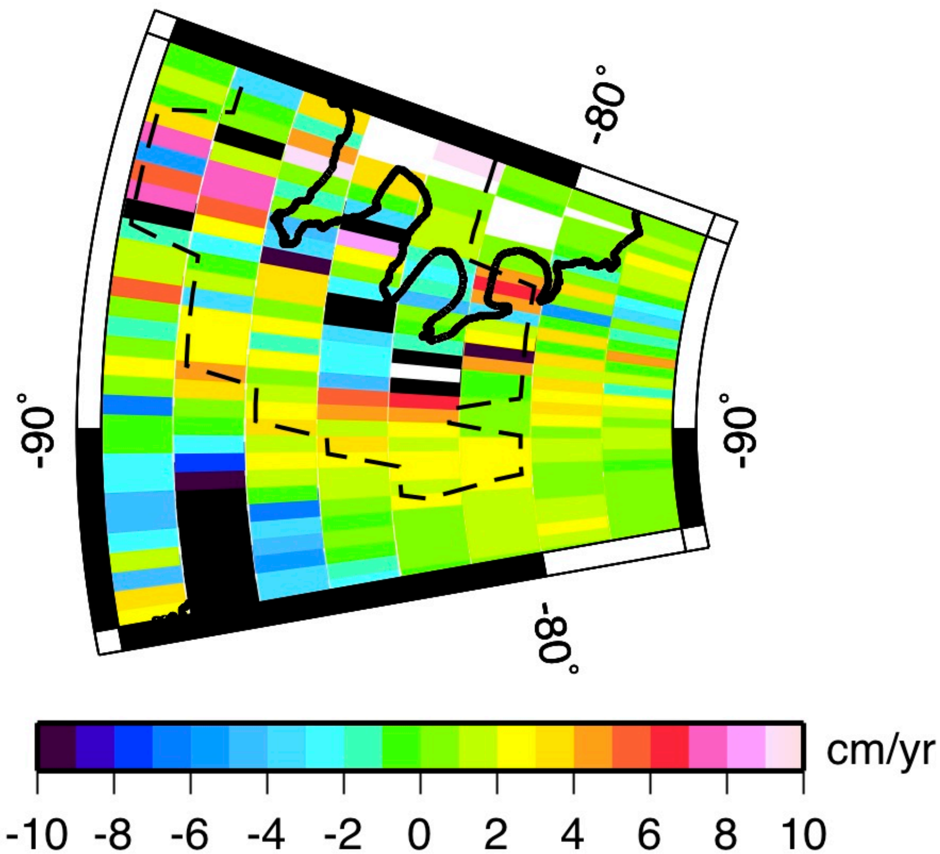
Mass changes in water equivalent From GRACE (Apr 2002-Dec 2010)

Basin JJ' (West Antarctica)

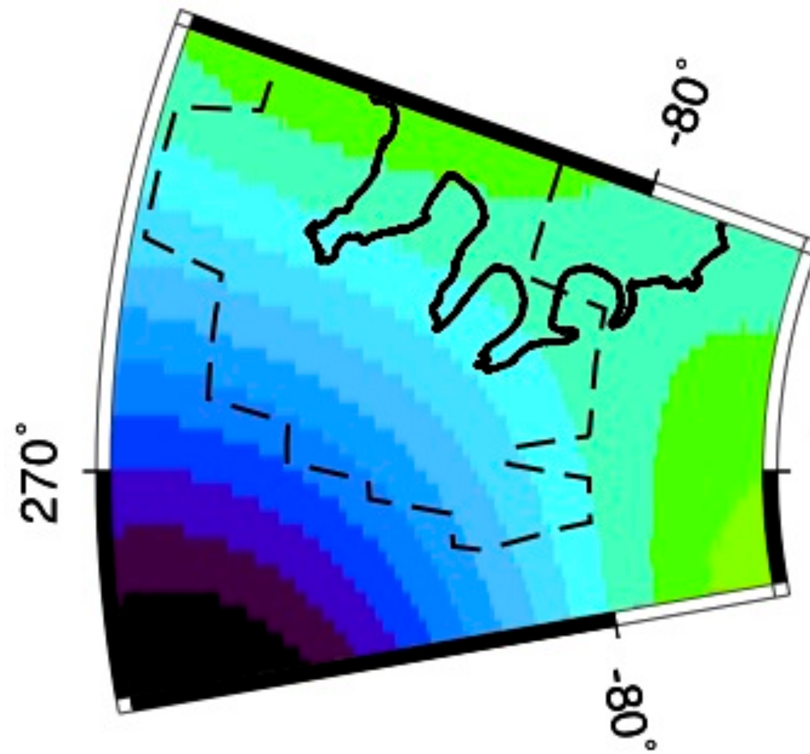


Basin-wide ice-column density 300 kg/m^3

Basin JJ' (West Antarctica)



Corrected mass changes in water equivalent from Envisat (Sep 2002 – Dec 2009)



Mass changes in water equivalent from GRACE (Apr 2002 – Dec 2010) JPLRL04, Paulson GIA, geocenter

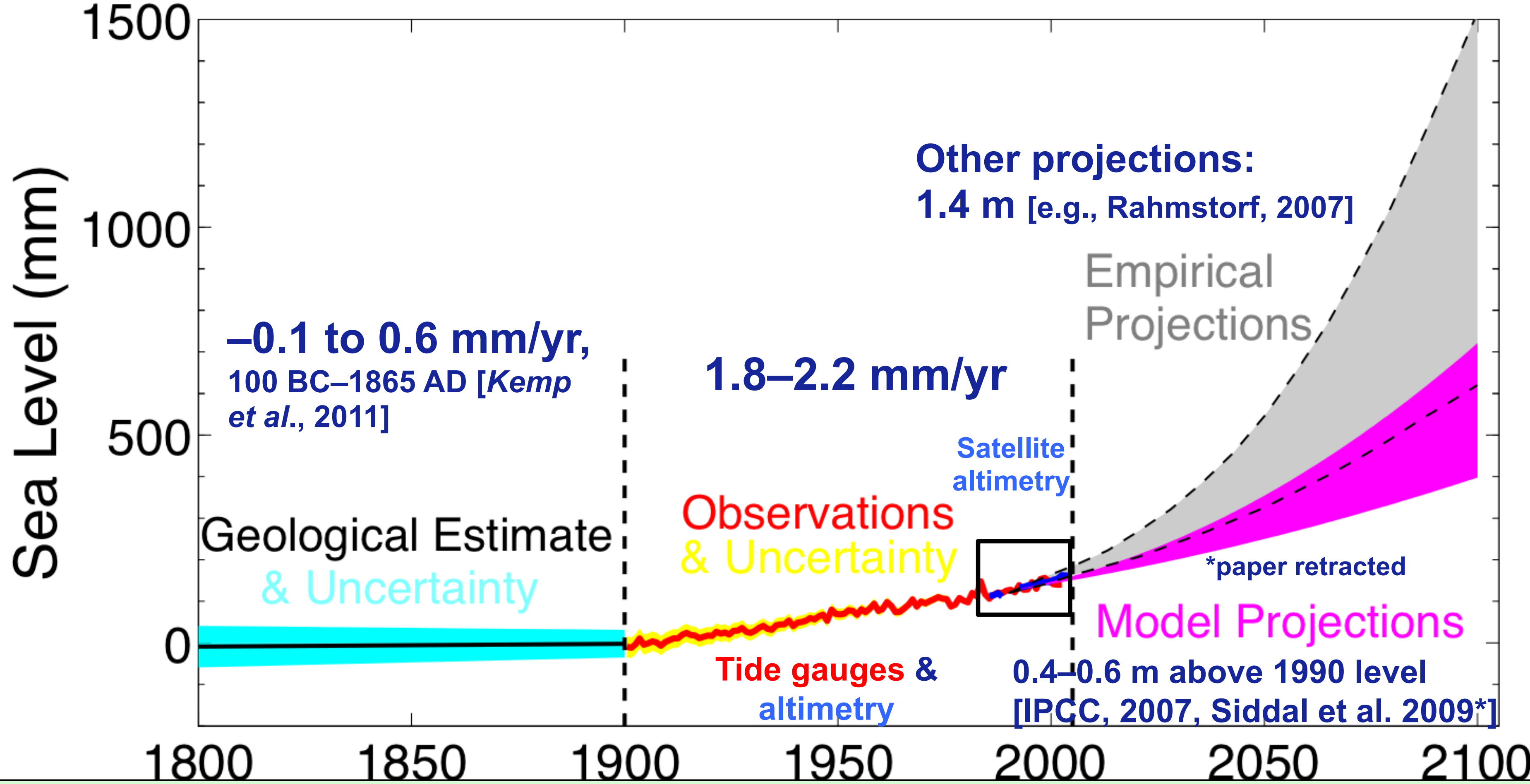
Climate Change and Sea-Level: Science Questions

- Can we measure the 20th and present-day sea-level accurately (to sub-mm/yr accuracy)?
- Do we have evidence of anthropogenic warming on sea-level rise?
- Has sea-level rise been accelerating? If so, when and can we detect the acceleration and their epochs?
- What are the geophysical causes and the least known contributors of present-day sea-level rise?
- Sea-Level Budget: can we fully explain the roles of each contributor of present-day sea-level rise commensurate with the observed sea-level rise?
- How accurate are the sea-level projection to the end of the 21st century?
- How could modern geodetic sensors help?

Current ice-sheet and glacier mass balance estimates:

Greenland: –0.03 to 0.63 mm/yr; Antarctica: –0.12 to 0.40 mm/yr

Mountain glaciers/ice caps: 0.52 to 1.40 mm/yr



2007 IPCC sea-level budget (explanation vs obs.) [*Bindoff et al*. 2007]:

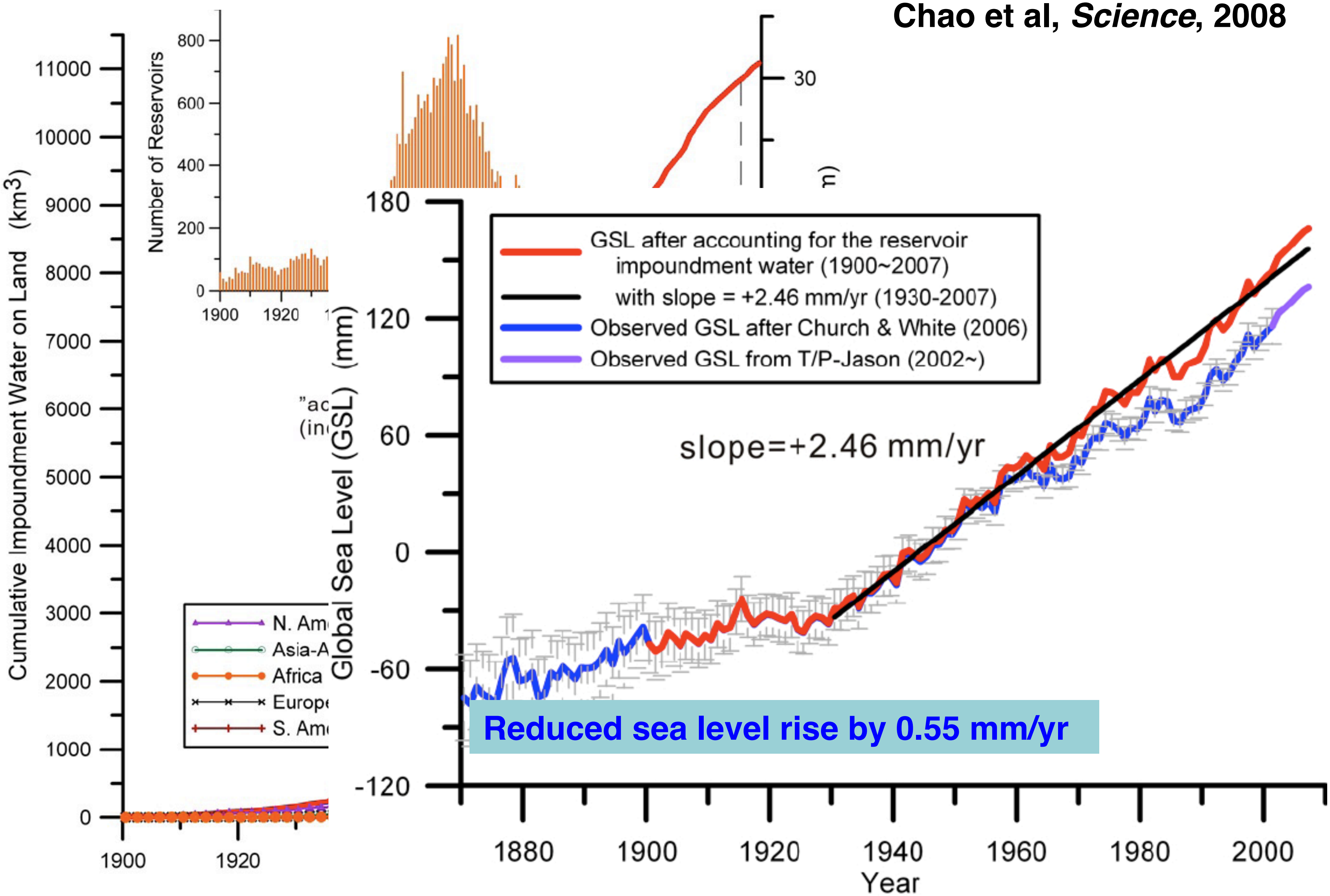
1.1±0.5 vs 1.8±0.5 mm/yr (improved over 2001 IPCC [*Church et al.*, 2001])

Post-2007 IPCC assessment [e.g., *Shum et al*. 2010]:

1.42±0.82 vs 2.0±0.2 mm/yr *Unexplained:* –0.62 to 1.42 mm/yr

Human-Impoundment of Water in Reservoirs

Chao et al, *Science*, 2008



Groundwater Depletion

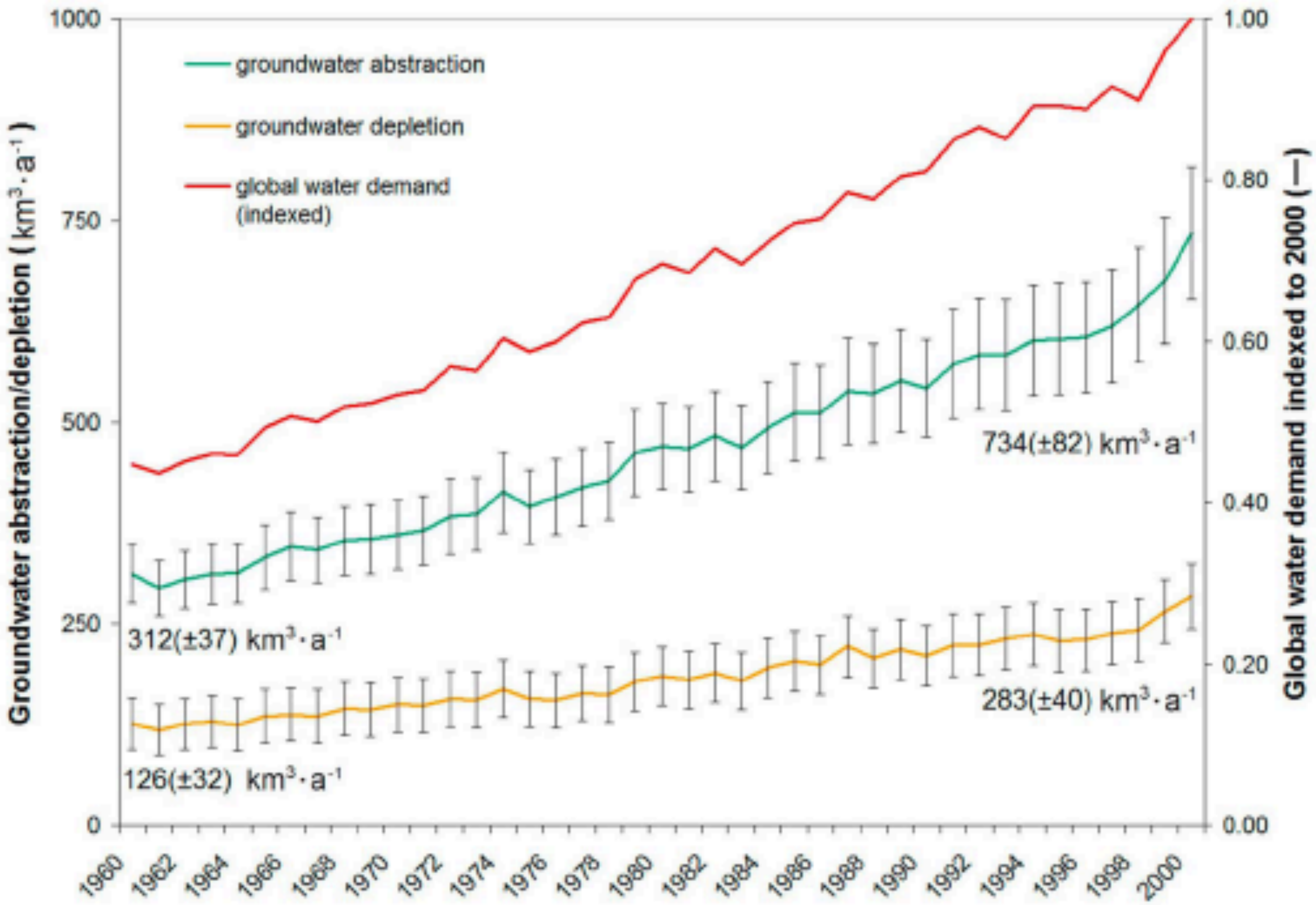


Figure 3. 1960–2000 trends in total global water demand (right axis; indexed for the year 2000), global groundwater abstraction (left axis; $km^3\ a^{-1}$) and global groundwater depletion (left axis; $km^3\ a^{-1}$).

Contribute to global sea-level rise: 0.8±0.1 mm/yr [*Wada et al.* 2000]