Measurements of mass loss from Greenland and Antarctica by Grace satellites

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An invited presentation to the Metrology Society of Australasia

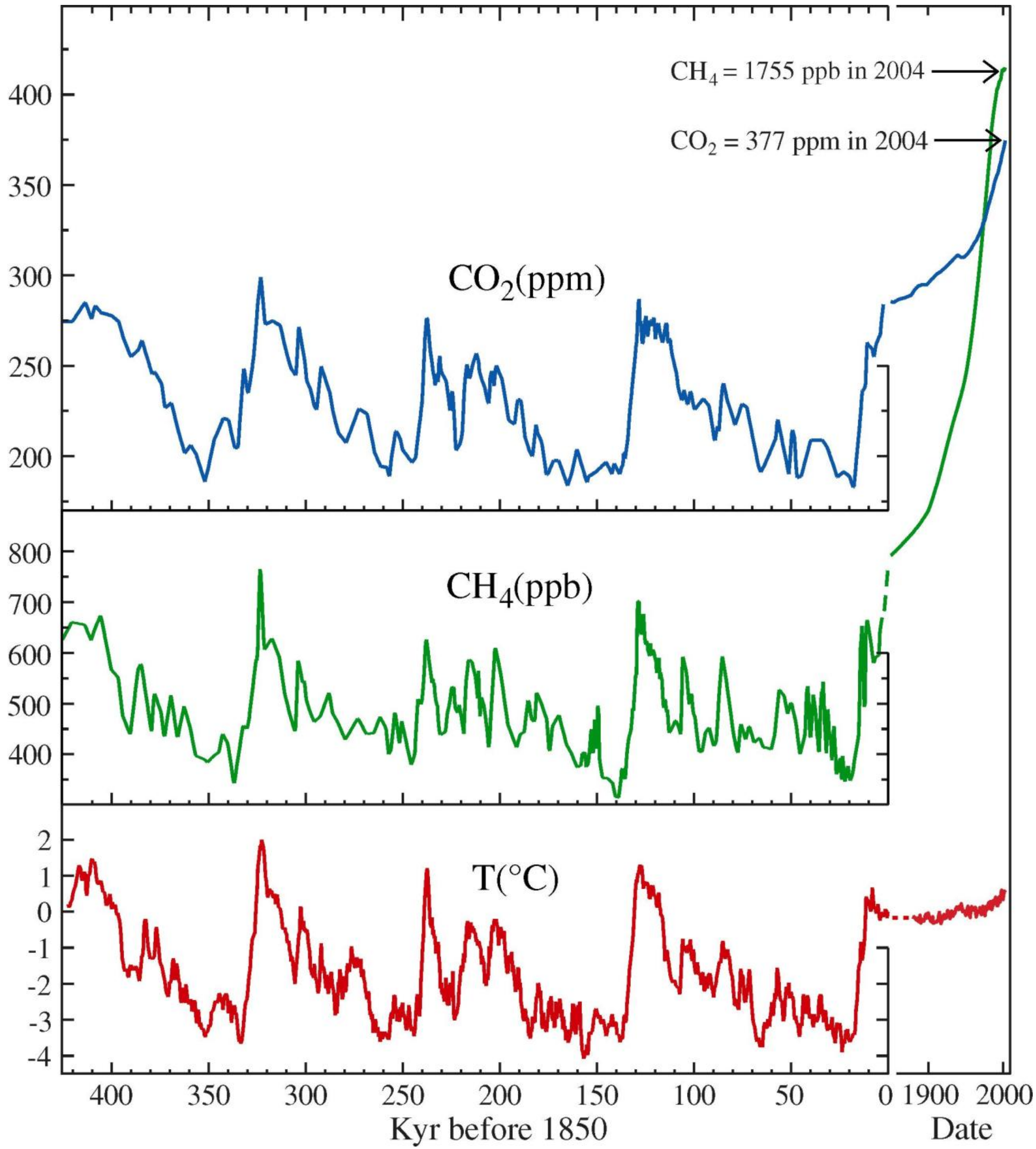
October 2010

Global warming

- Radiative heat transfer:
  - Incoming radiation peaks at ~500 nm;
  - Outgoing radiation peaks at ~10 µm
- Greenhouse gases:
  - H_2O, CO_2, CH_4, N_2O
  - Absorption bands in far IR:
  - Warm the earth by ~33 K

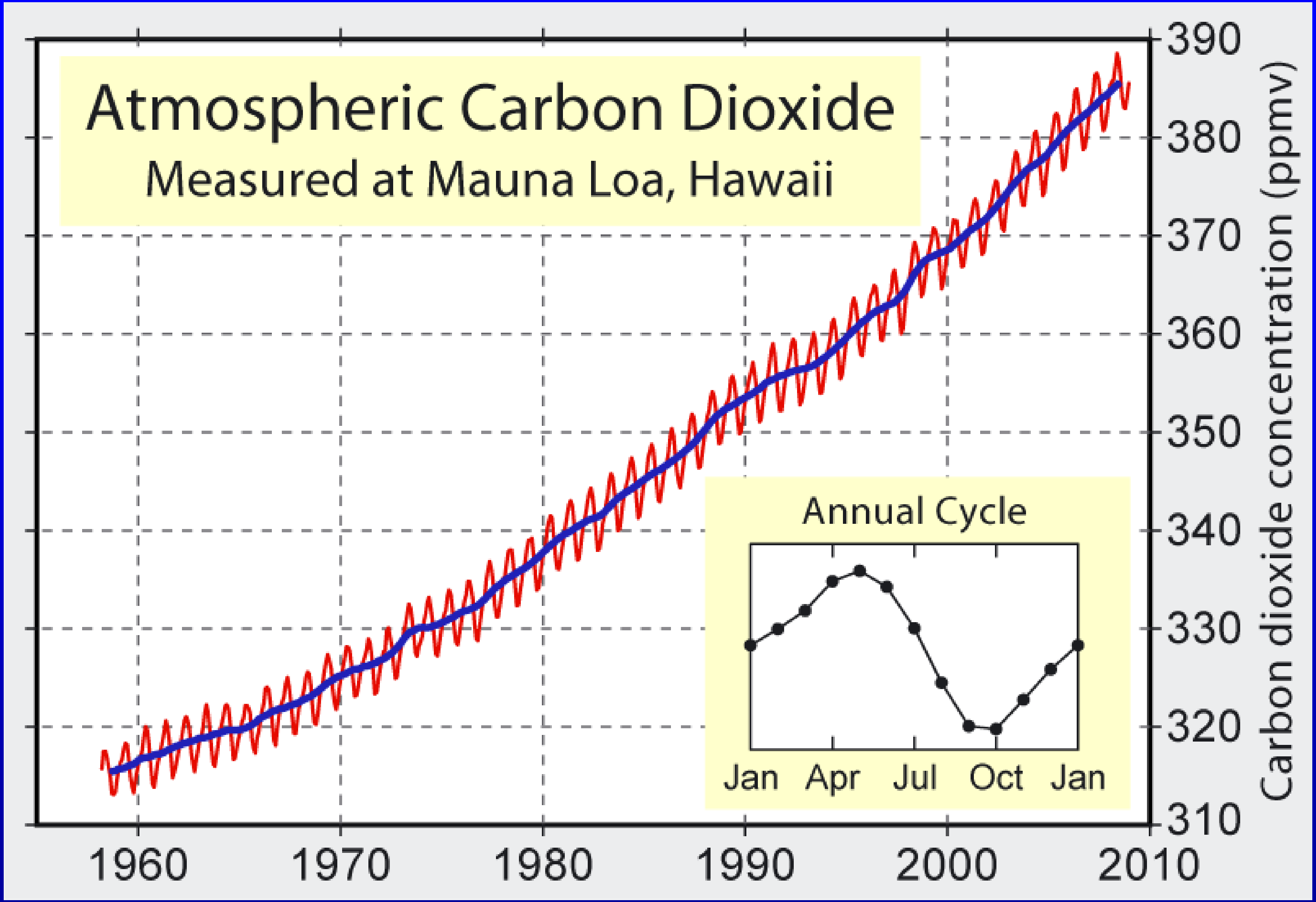
CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era) 0 = 1880-1899 mean.

Source: Hansen, *Clim. Change*, **68**, 269, 2005.

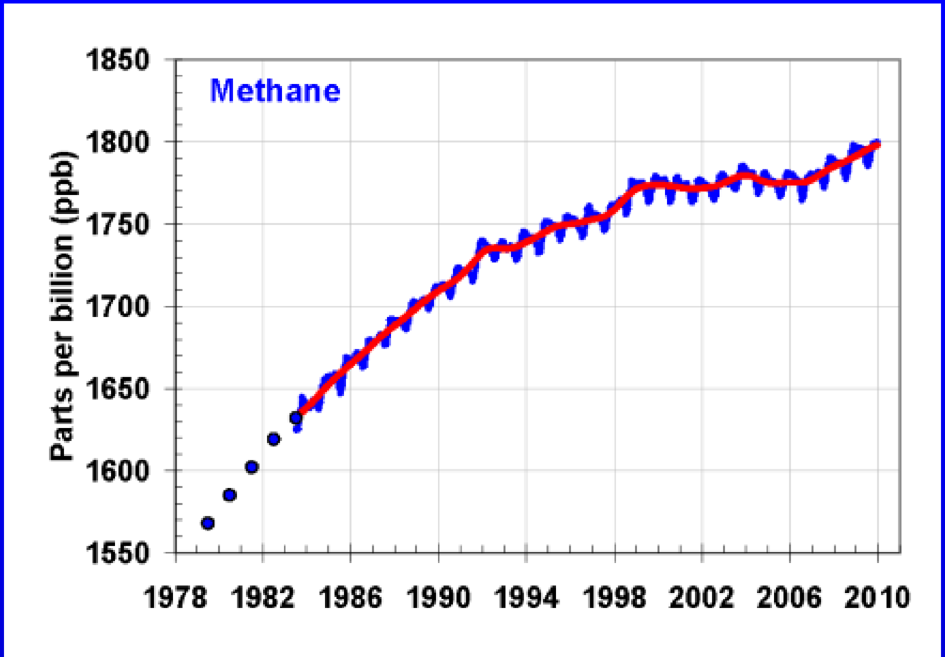


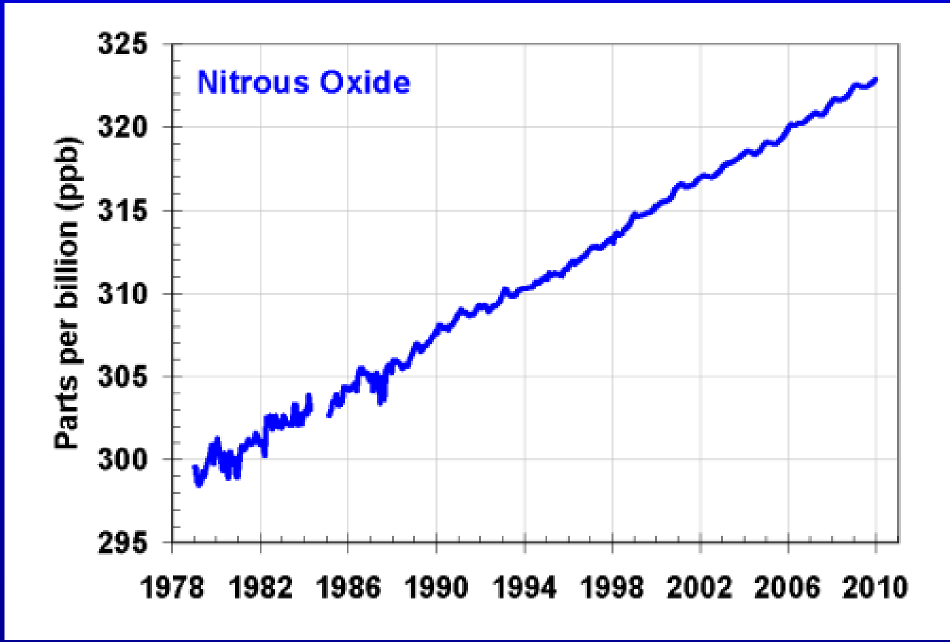
Petit J.R et al. *Climate and Atmospheric History of the past 420,000 years from the Vostok Ice Core, Antarctica*, **Nature**, 399:429-36. 3 June 1999.

Hansen et al. *Target atmospheric CO2: Where should humanity aim?* **Open Atmos. Sci. J.**, 2, 217-231, 2008 doi:10.2174/1874282300802010217.

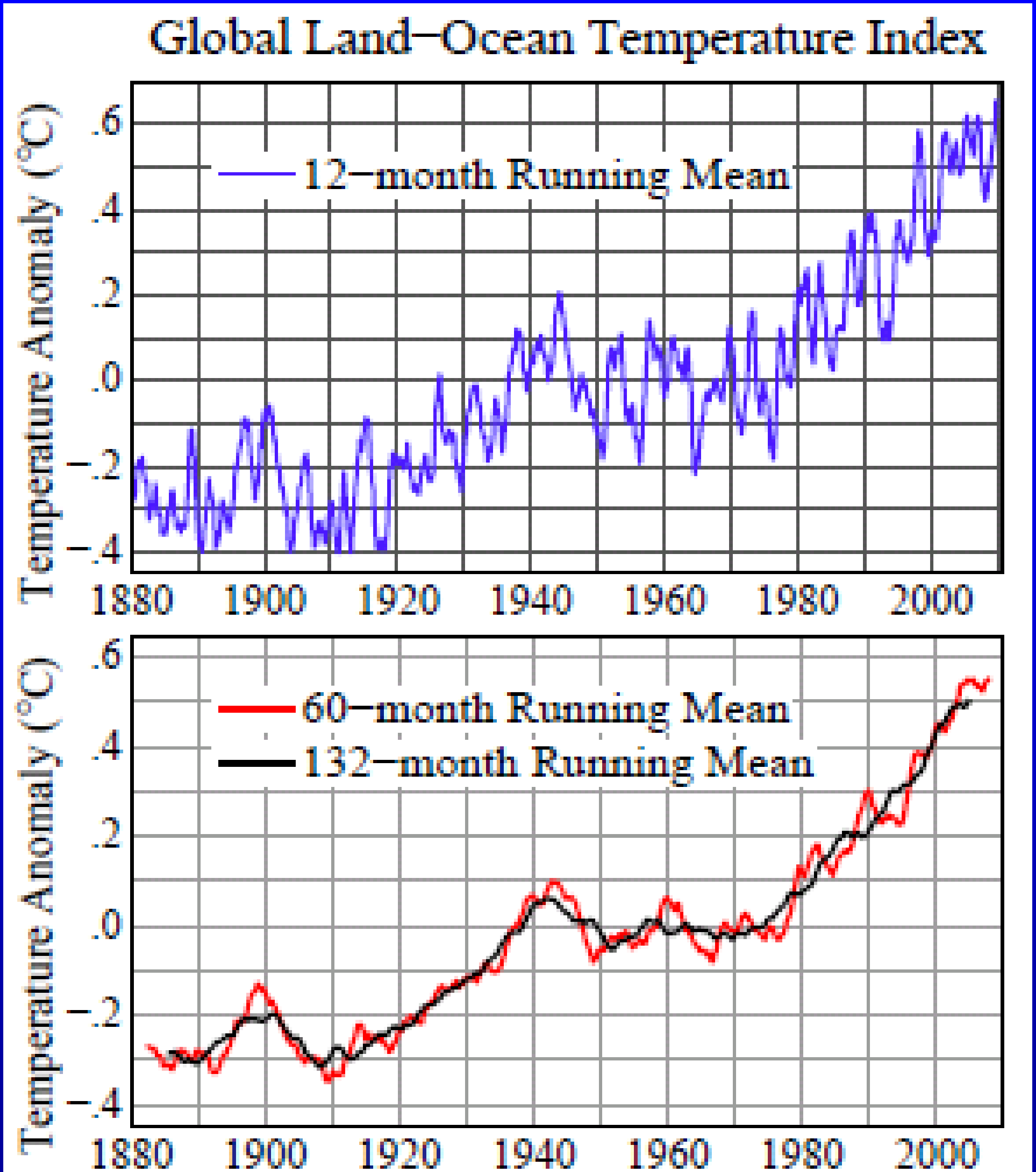


Keeling curve. August 2010: 388.15 ppm
http://upload.wikimedia.org/wikipedia/commons/8/88/Mauna_Loa_Carbon_Dioxide.png
http://co2now.org/





http://www.esrl.noaa.gov/gmd/aggi/ (National Oceanic and Atmospheric Administration USA)



http://www.columbia.edu/~jeh1/

Why are the ice sheets important?

- **IPCC:**
  - **Assumed small contribution of Greenland and Antarctic ice to sea level rise to 2100.**
  - **Thermal expansion + glacier melting**
- **Potential sea level rise from melting ice:**

Greenland	2.6×10^{6} Gt	:	7 m } 10–13m
West Antarctic	2.2×10^{6} Gt*	:	3 – 6 m } 10–13m
East Antarctic	23.2×10^{6} Gt*	:	60 m
Total:	28×10^{6} Gt	:	~ 70 m

* Lythe et al BEDMAP: A new ice thickness and subglacial topographic model of Antarctica. J Geophys Res, VOL. 106, NO. B6, PP. 11,335-11,351, 2001

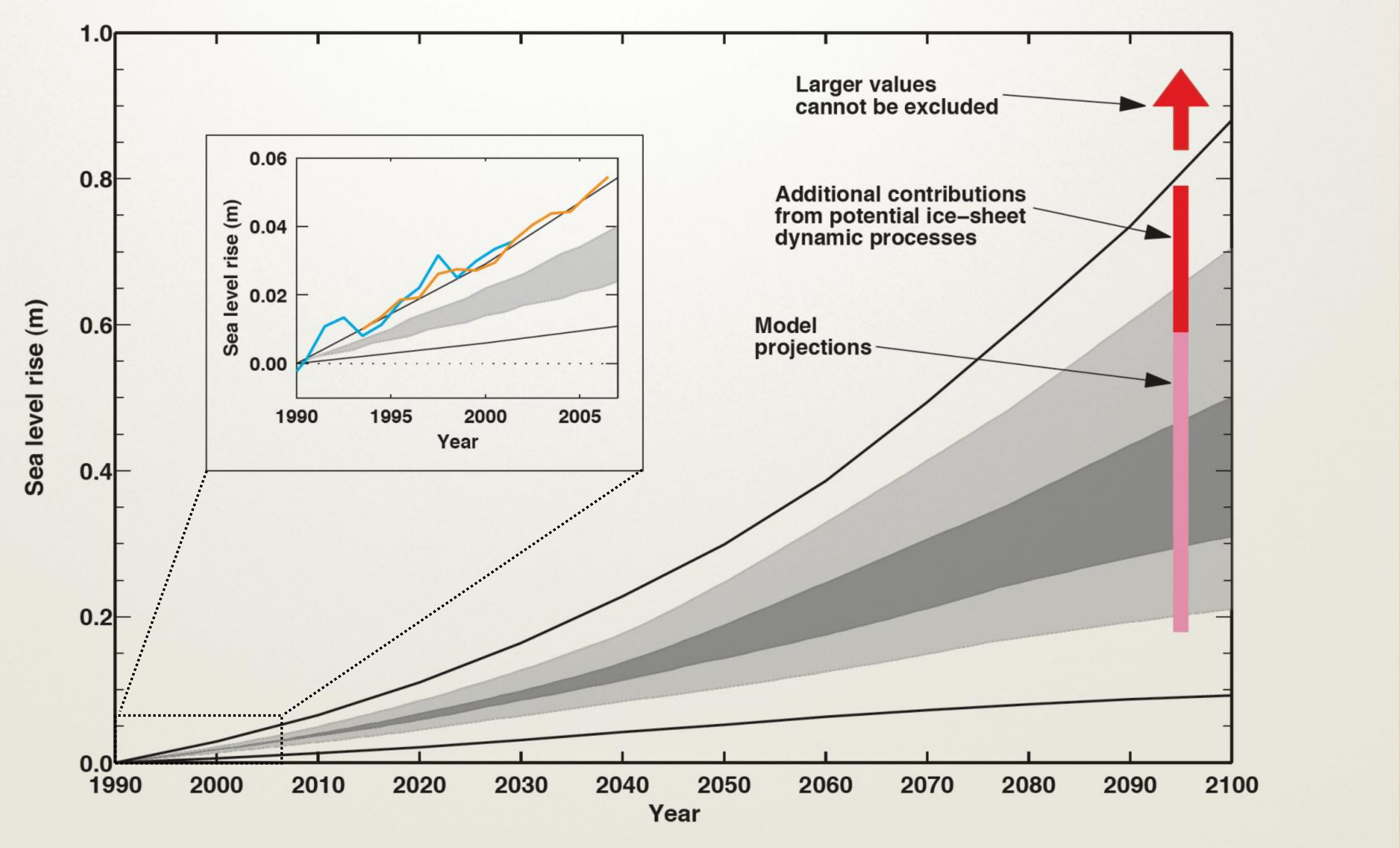
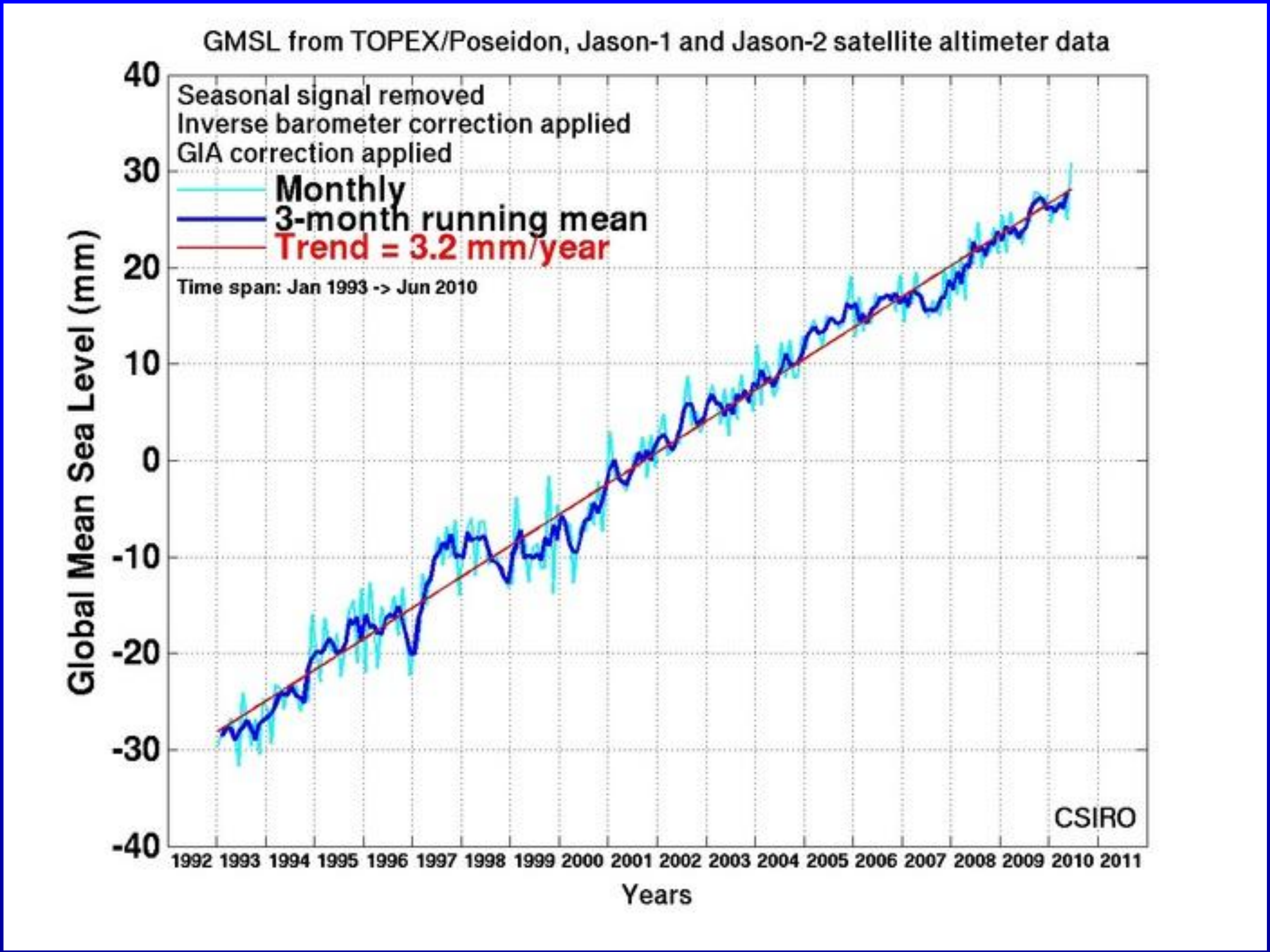


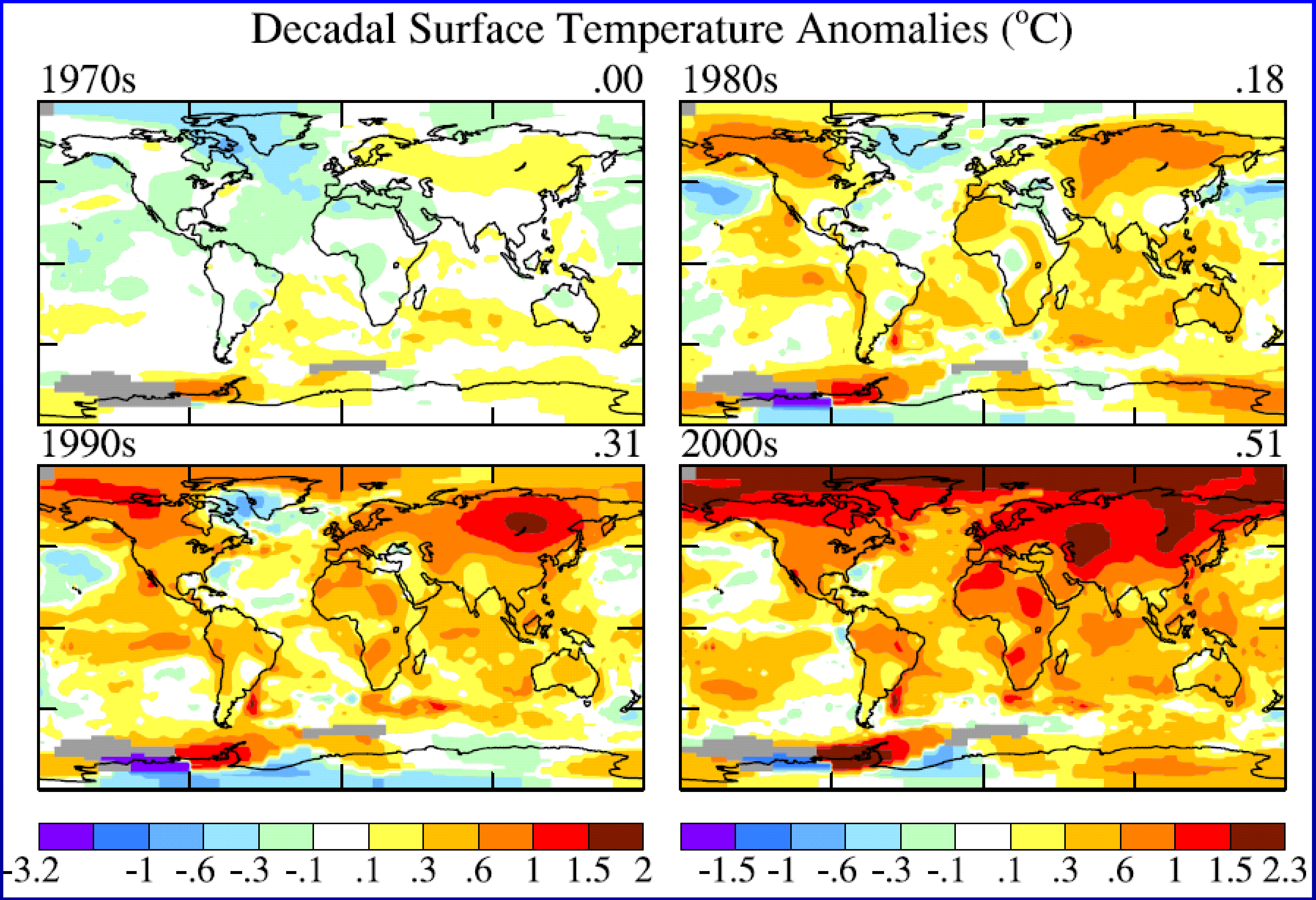
Figure 2.
TAR and AR4 projections of sea-level rise.[2,7]

The TAR projections are indicated by the shaded regions and the curved lines are the upper and lower limits. The AR4 projections are the bars plotted at 2095. The inset shows sea level observed with satellite altimeters from 1993 to 2006 (orange) and observed with coastal sea-level measurements from 1990 to 2001 (blue).

- *© Copyright 2008 The Antarctic Climate &*
- *Ecosystems Cooperative Research Centre. CSIRO*
- *TAR: Third assessment report of IPCC 2001; AR4: 4th Assessment report IPCC 2007*



http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html



Decadal surface temperature anomalies relative to 1951-1980 base period. GISS
http://www.columbia.edu/~jeh1/

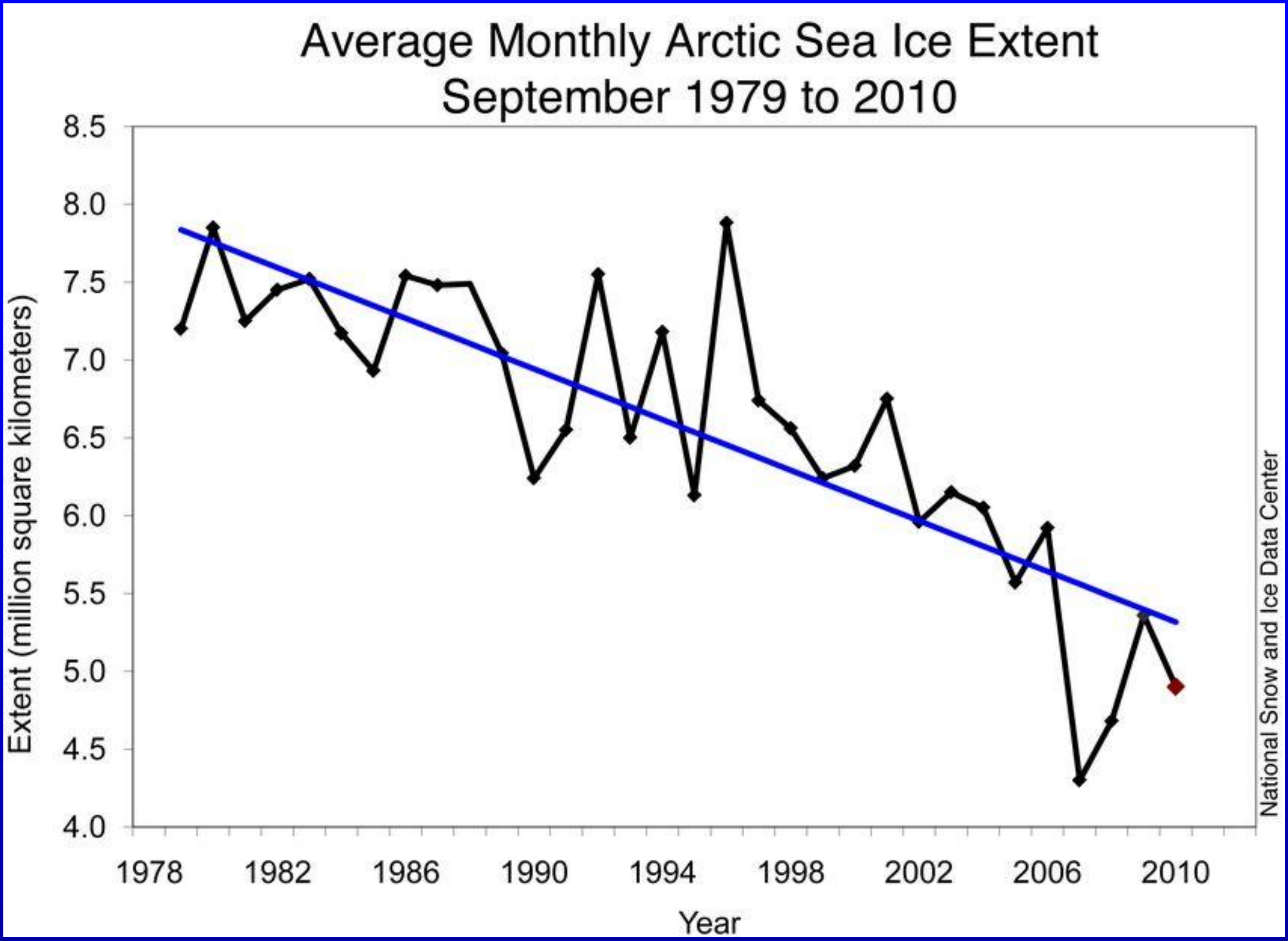
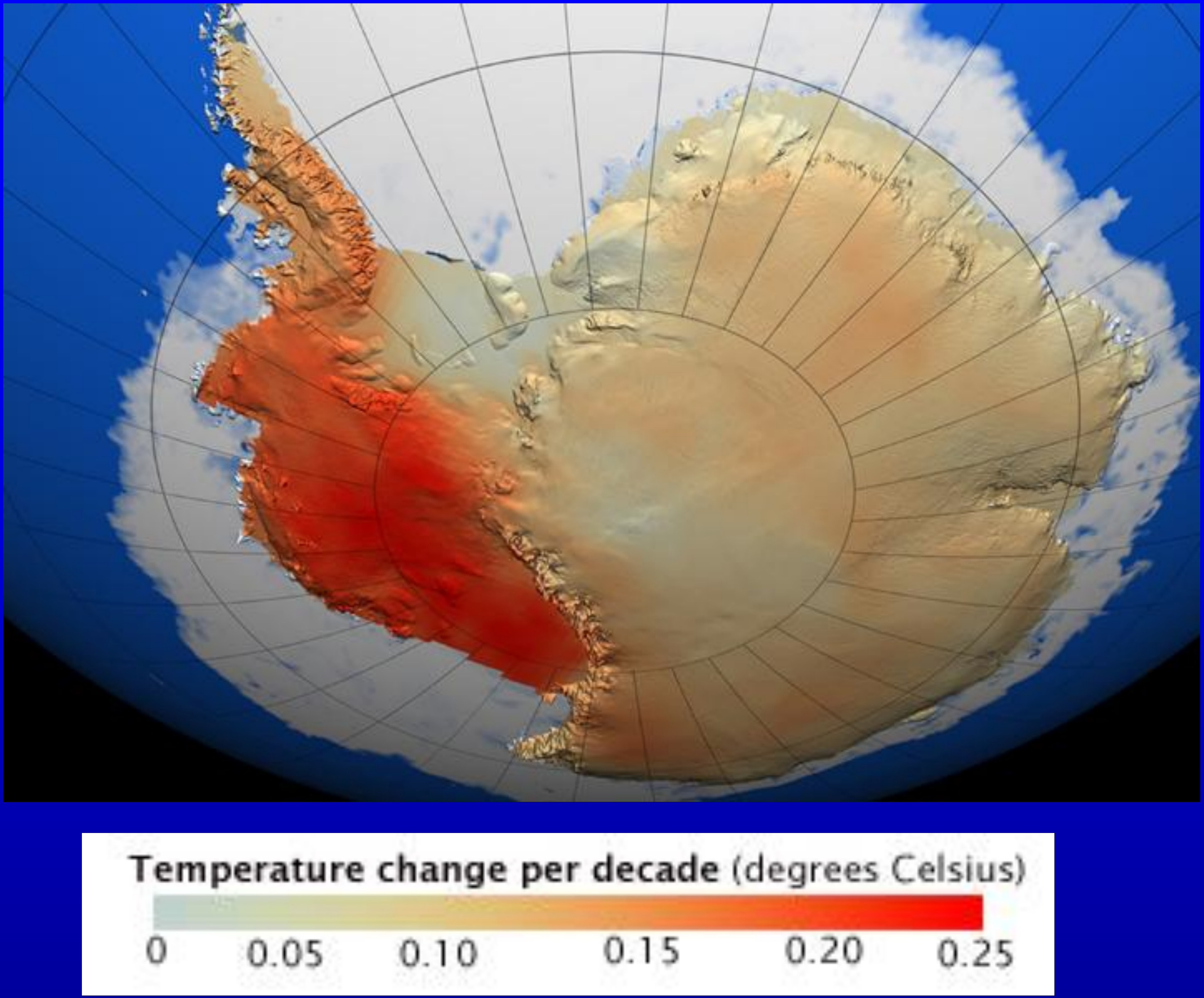


Figure 3. Monthly September ice extent for 1979 to 2010 shows a decline of 11.5% per decade.
http://nsidc.org/arcticseaicenews/index.html. National Snow and Ice Data Center, University of Colorado

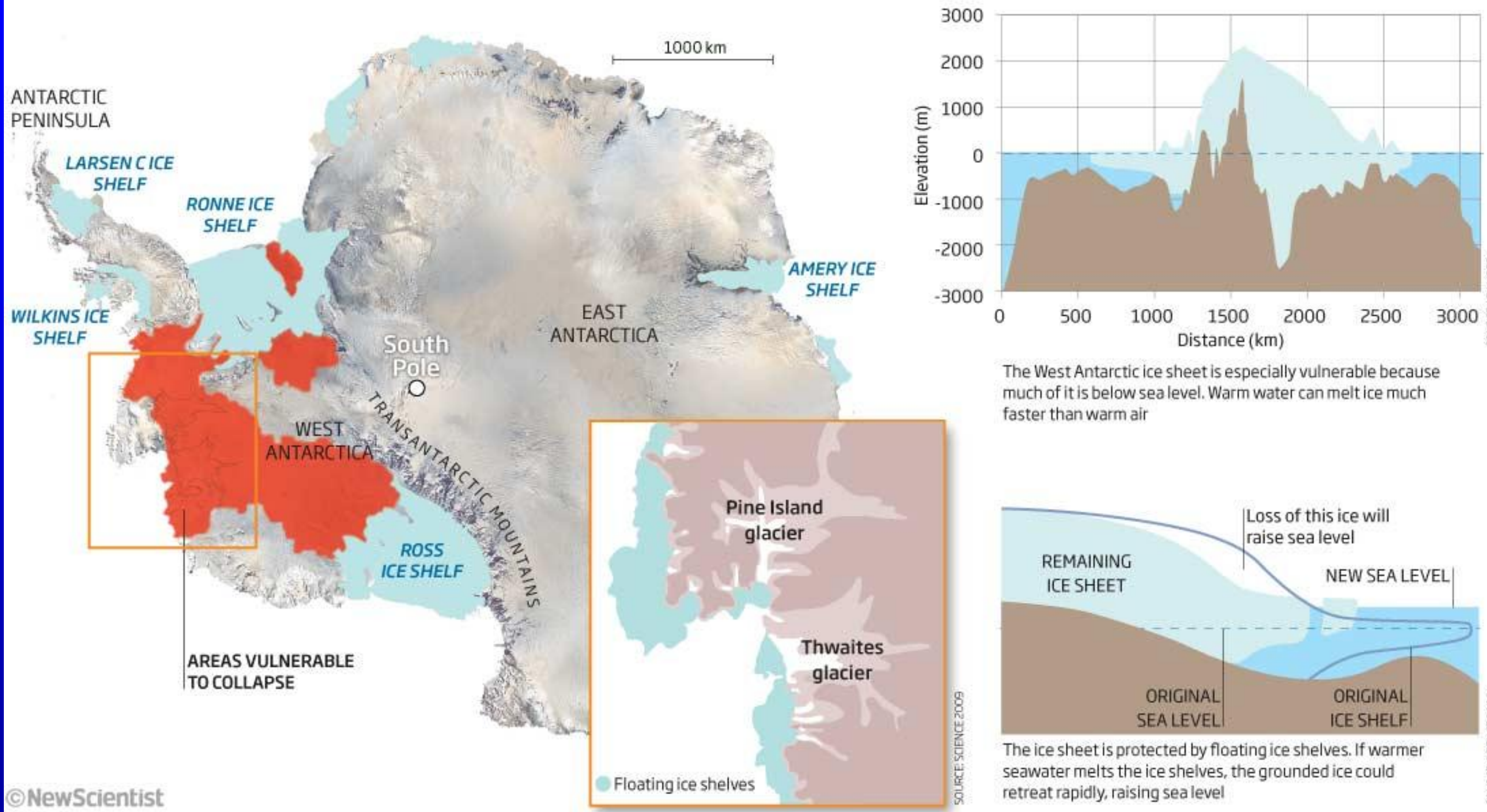


http://earthobservatory.nasa.gov/IOTD/view.php?id=36736

Steig, E., Schneider, D., Rutherford, S., Mann, M., Comiso, J., and Shindell, D. (2009, January 22). Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature*, 457, 459-463. doi:10.1038/nature07669.

The great unknown

While the vast East Antarctic ice sheet is stable and unlikely to lose much ice for centuries, substantial amounts of ice are already being lost from the Antarctic Peninsula and the West Antarctic ice sheet. Large parts of the West Antarctic ice sheet are vulnerable to collapse (red areas), which would add 3 metres to global average sea level



Surface Melt on Greenland

Melt descending
into a moulin,
a vertical shaft
carrying water
to ice sheet base.

Source: Roger Braithwaite,
University of Manchester (UK)

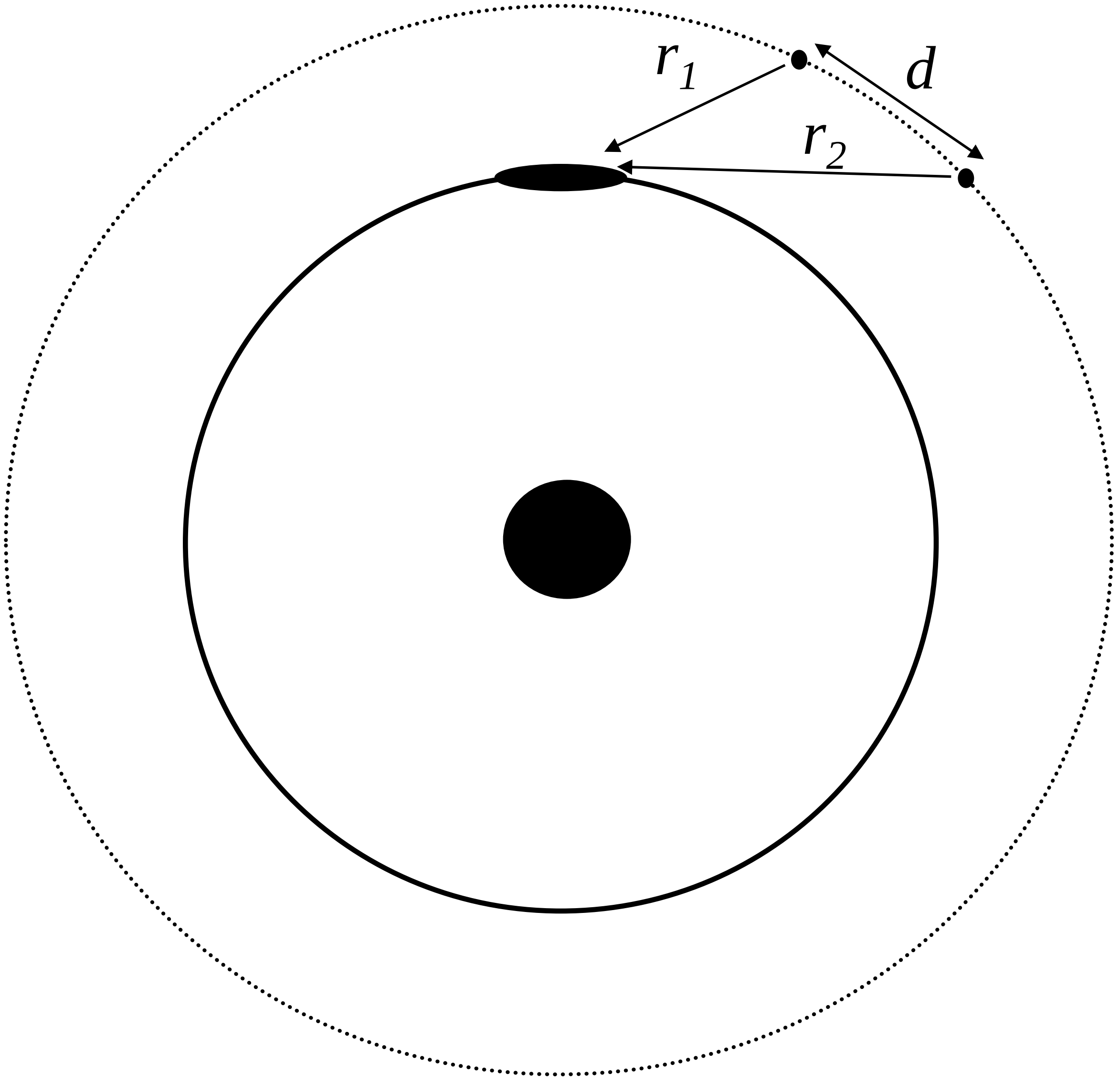
- 13,000 – 14,000 years ago sea level rose *3 – 5 m per century**
- In the previous interglacial period sea level was 6 – 9 m higher than today*
- Are the Greenland & Arctic ice sheets losing mass?
- If so how fast?

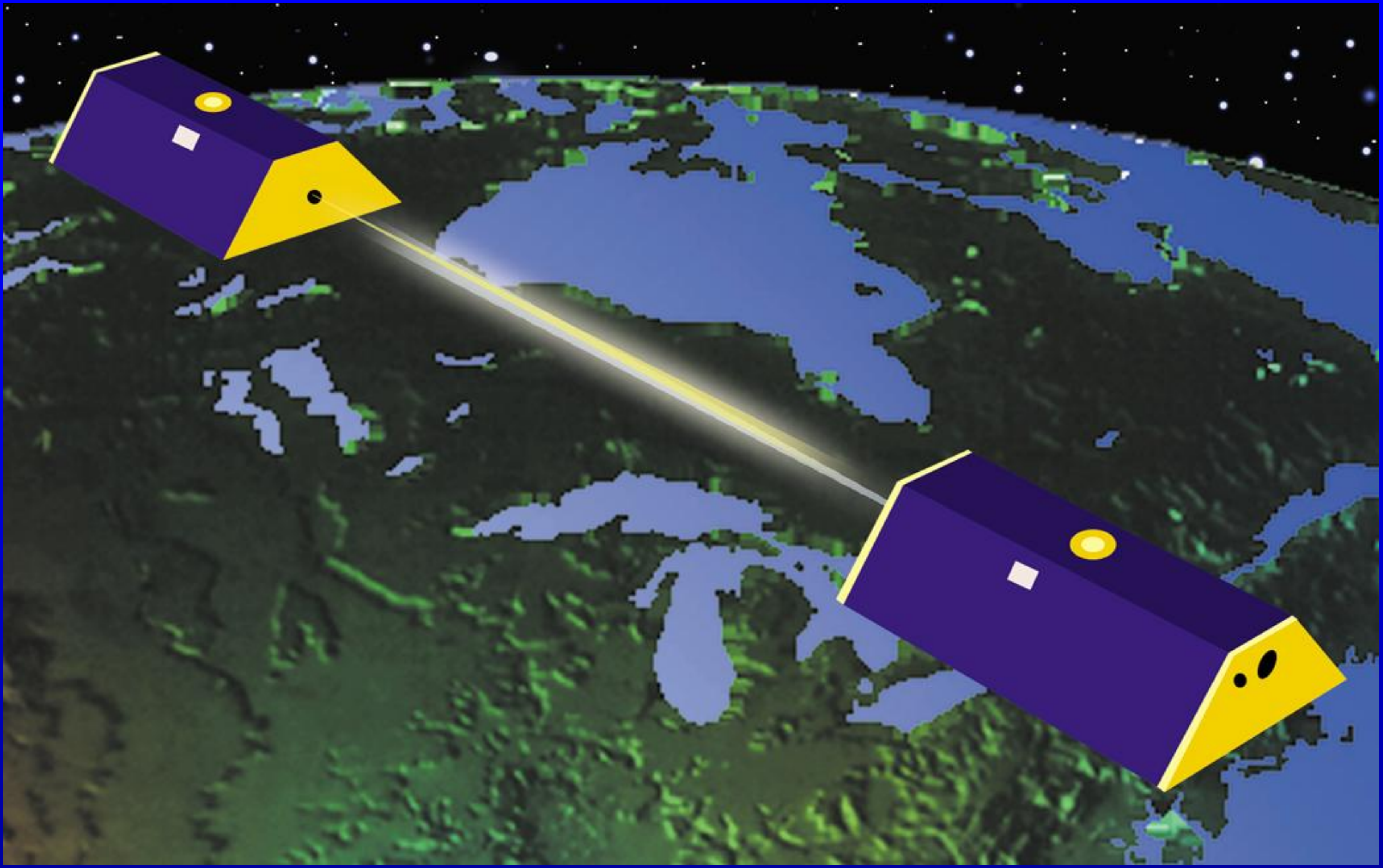
* Hansen JE. Storms of my Grandchildren. 2009 p143.

Grace satellites

- Gravity Recovery And Climate Experiment
- Primary objective: high-resolution (space and time) global models of Earth's gravity field
- NASA and the German Space Agency
- Designed and built by Astrium GmbH
- 2 identical 487 kg satellites
- Launched March 2002 by Eurockot Launch Services from Plesetsk Cosmodrome 500 km N of Moscow
- Coplanar polar orbits (89.5º; 500 km altitude; 220 km apart; 95 min orbit
- Nominal 5 year life – extended to 2015 (end of orbit life)
- http://www.csr.utexas.edu/grace/

$$f = \frac{Gm_1m_2}{r^2}$$



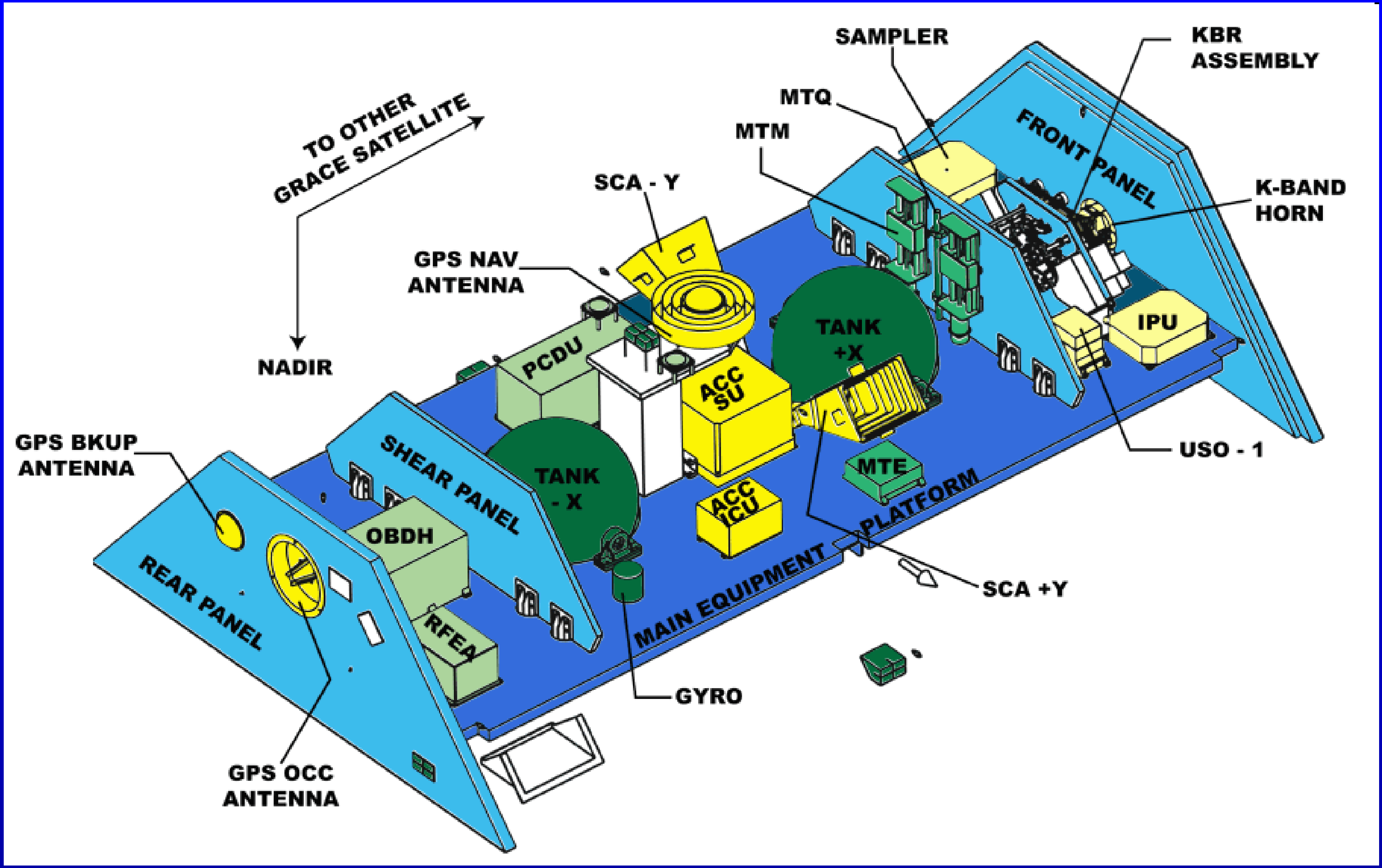


http://www.csr.utexas.edu/grace/gallery/other/misc/GRACE_Fact_Sheet_Cover.JPG

Instruments

- Dual frequency (24 and 32 GHz) microwave ranging system (shifted by 500 kHz on 2nd satellite)
  - Temperature controlled to 0.2 K
  - Ultra-stable oscillator freq reference $1 \cdot 10^{-10}$ per day
  - Measures phase changes to derive relative velocities
  - Resolution 1 μm/s
- Accelerometers measure non-gravitational acceleration
  - Electrostatic control & sensing of proof mass
  - Resolution: $1 \cdot 10^{-10}\ \mathrm{m \cdot s^{-2}}$;   full scale: $5 \cdot 10^{-5}\ \mathrm{m \cdot s^{-2}}$
- Mass trim System
  - Keeps accelerometers at COG within 50 μm
- GPS (±few cm)
- Attitude sensors & controllers (<1 mrad = 0.057°)

http://op.gfz-potsdam.de/grace/payload/payload.html



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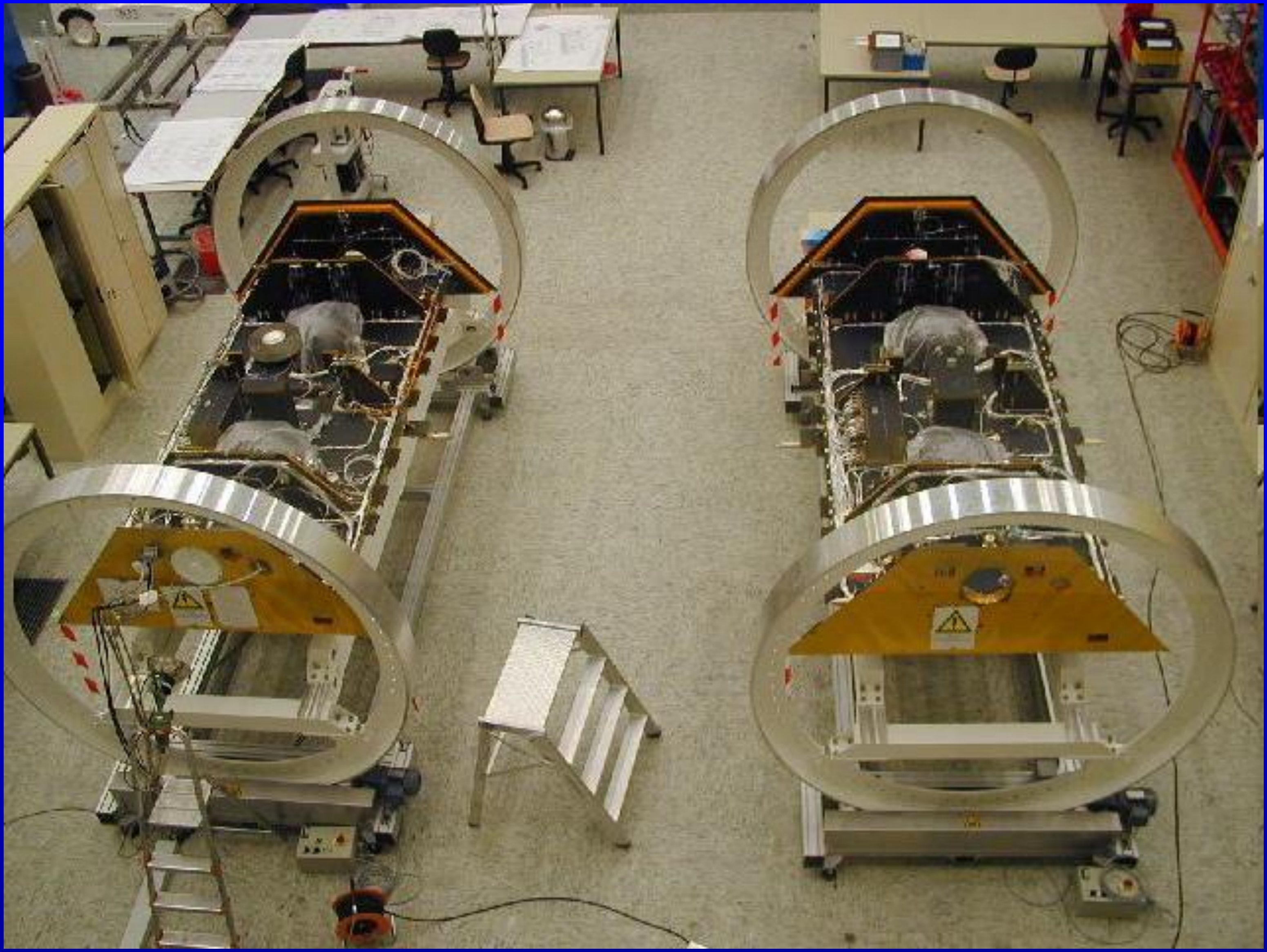

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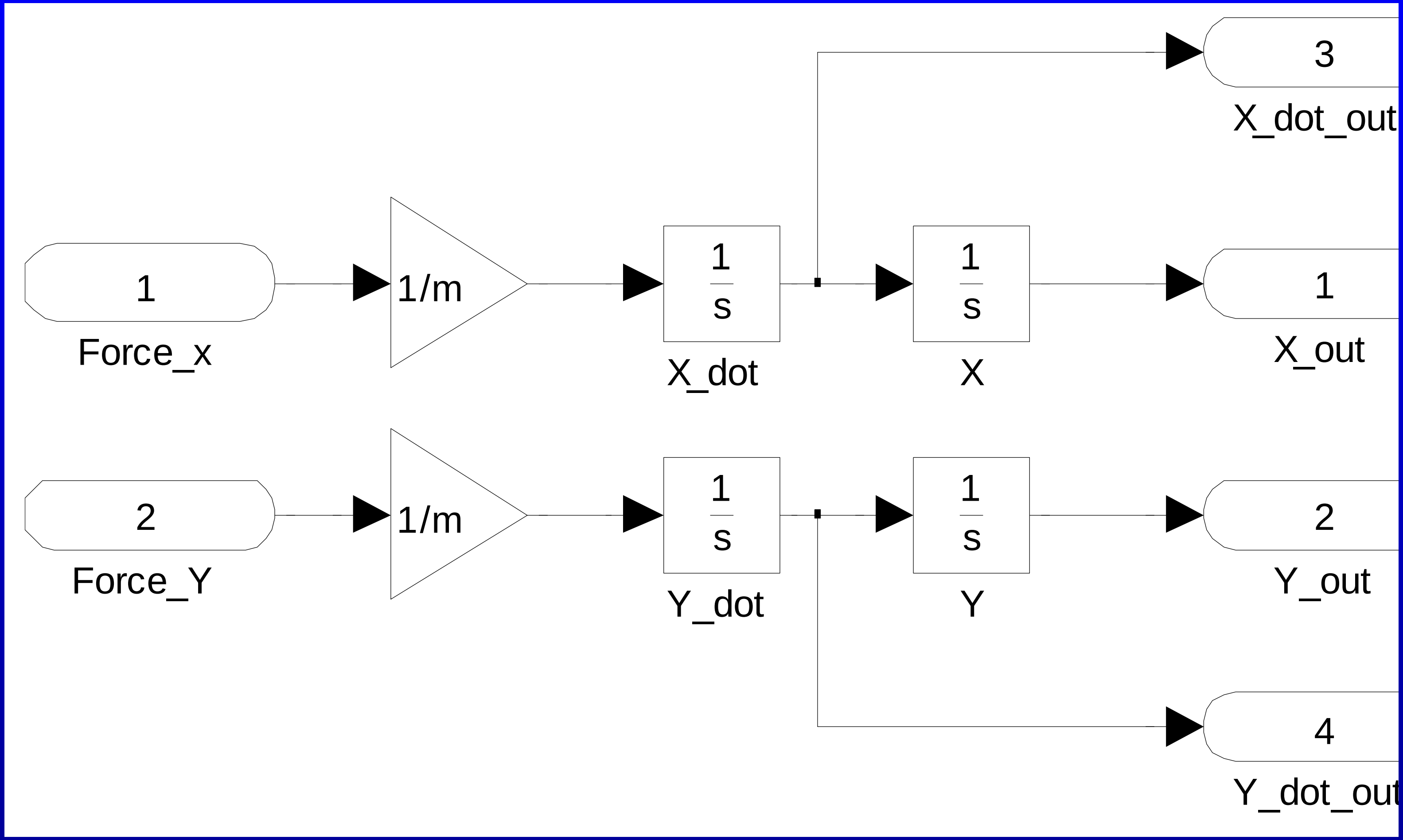
$$f = ma$$



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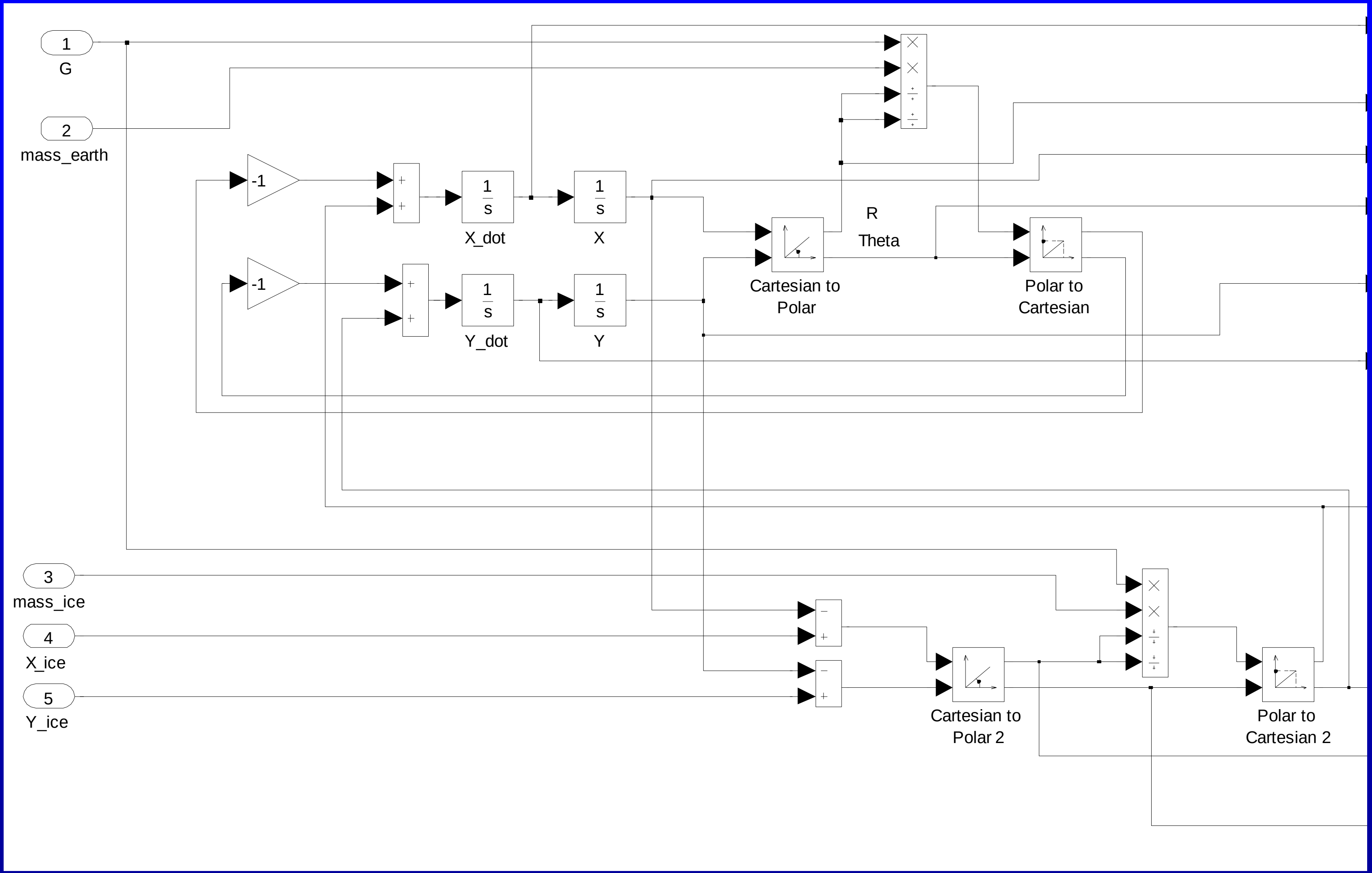
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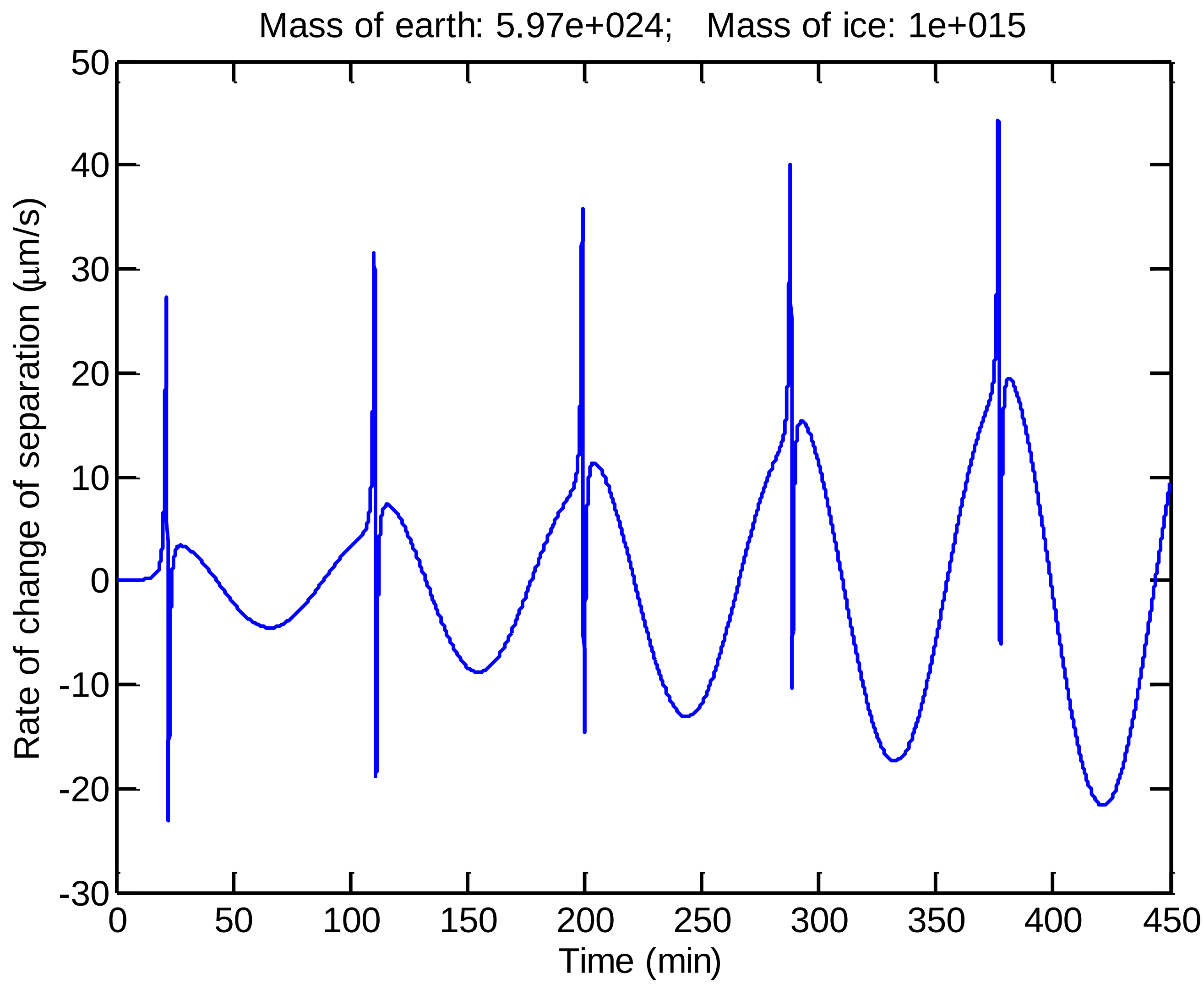
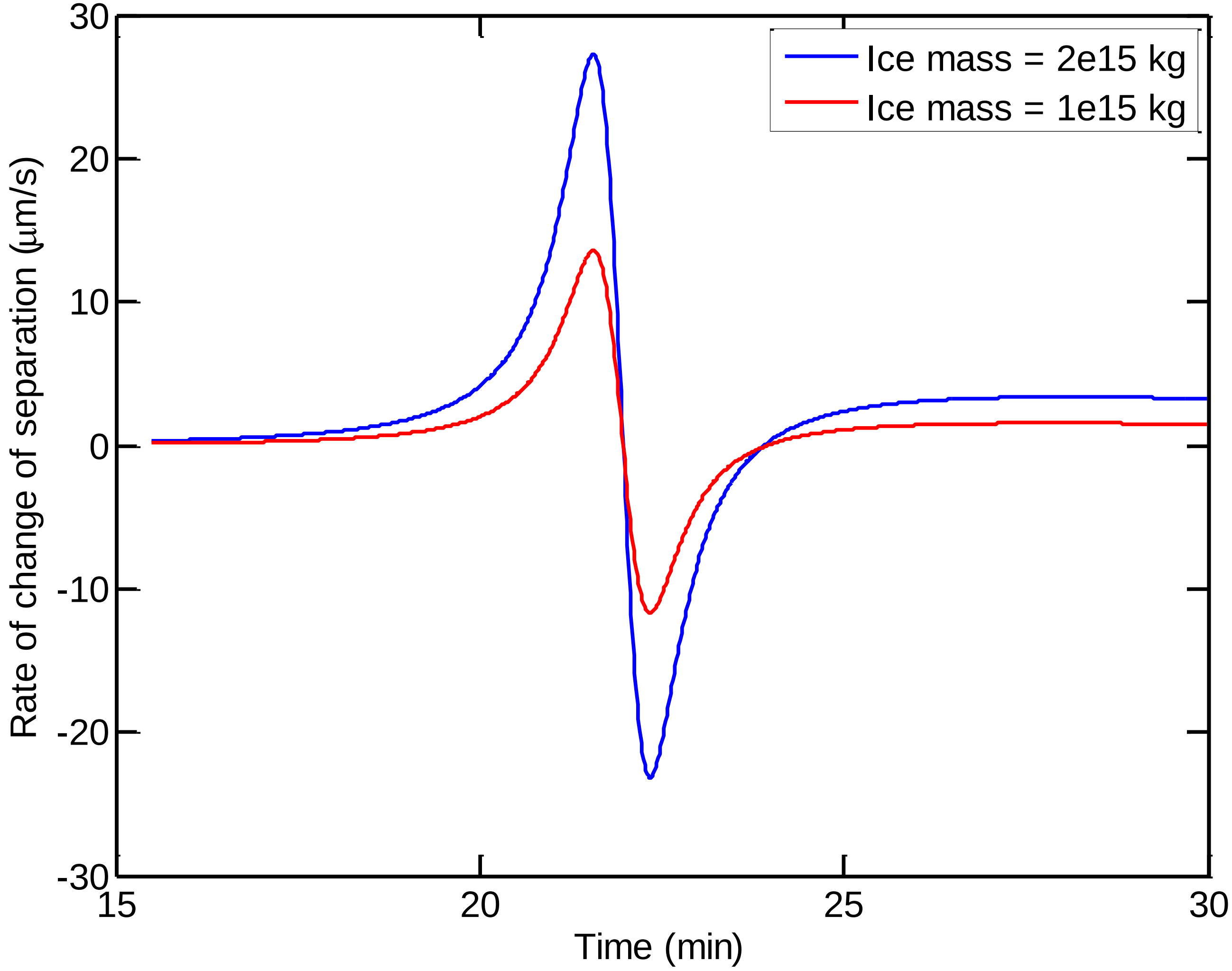
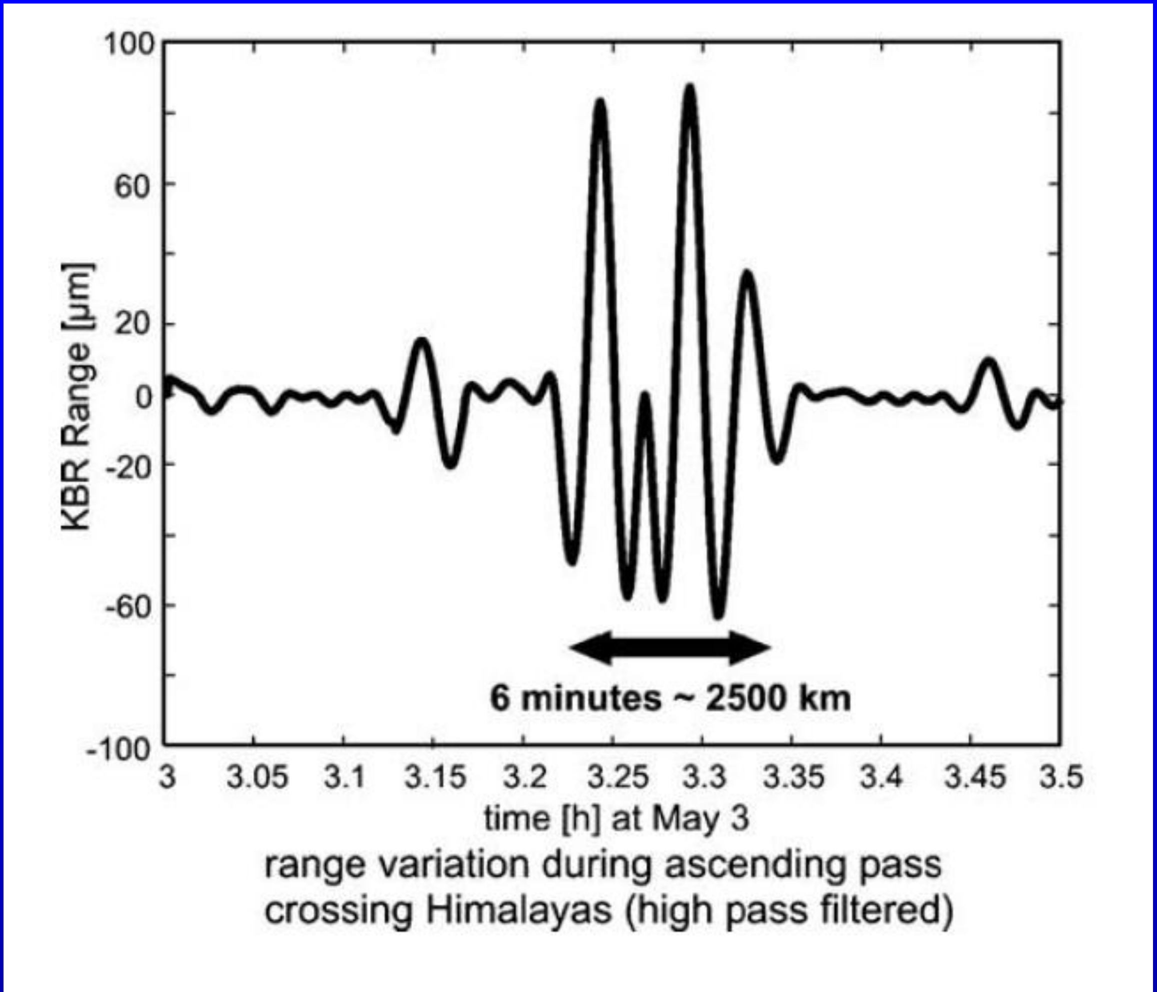
Polar to
Cartesian 2



Mass of earth: 5.97e+024;   Mass of ice: 1e+015
Rate of change of separation (μm/s)
Time (min)
50
40
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
300
350
400
450



Ice mass = 2e15 kg
Ice mass = 1e15 kg
Rate of change of separation (μm/s)
30
20
10
0
-10
-20
-30
15
20
25
30
Time (min)

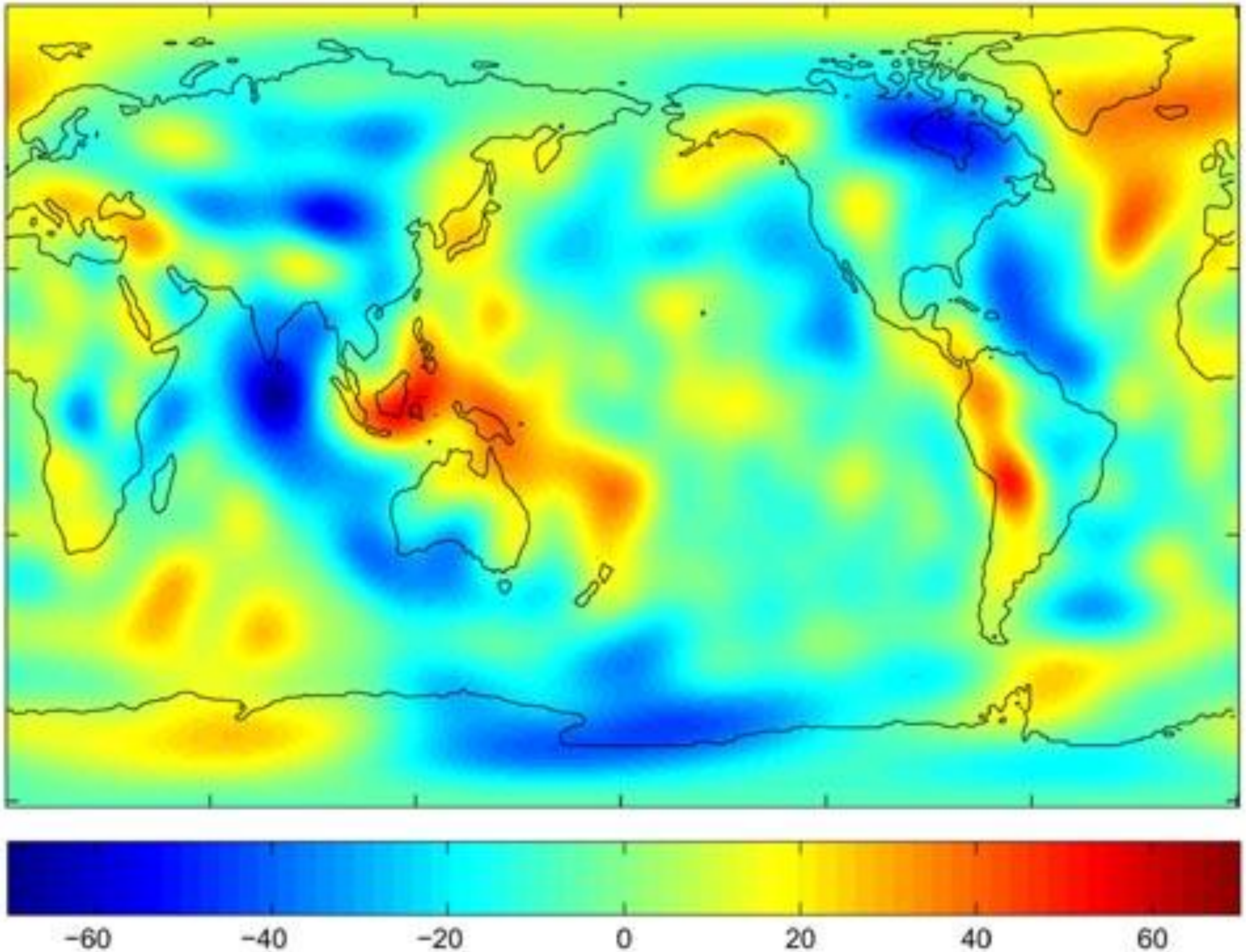


Reigber C et al. An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S. J Geodynamics 39:1-10 2005.

Solving for gravitational field

- Start with existing gravity model obtained from measurements of satellite trajectories
- ~15,000 unknowns (coeffts of orthogonal spherical harmonics)
- Inputs: Range, acceleration, altitude, GPS data
- De-aliasing to remove high frequency components, e.g. tides
- Solve for model parameters using weighted least squares method
  - Several days on Cray SV1 supercomputer
- Correct for atmospheric mass signal

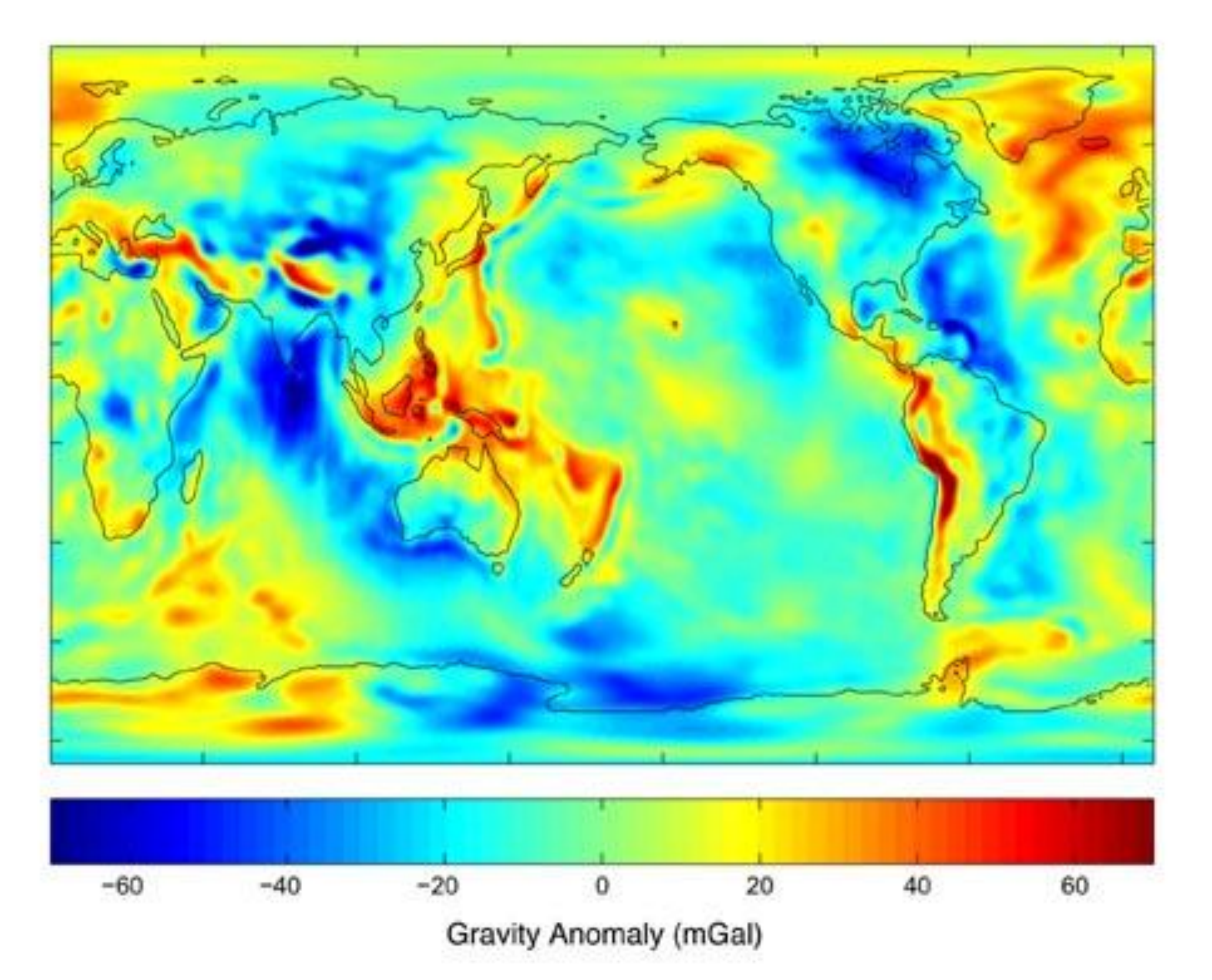
Gravity anomalies from decades of tracking Earth-orbiting satellites



gal = cm/s^2 (mgal = 10^{-5} m/s^2)

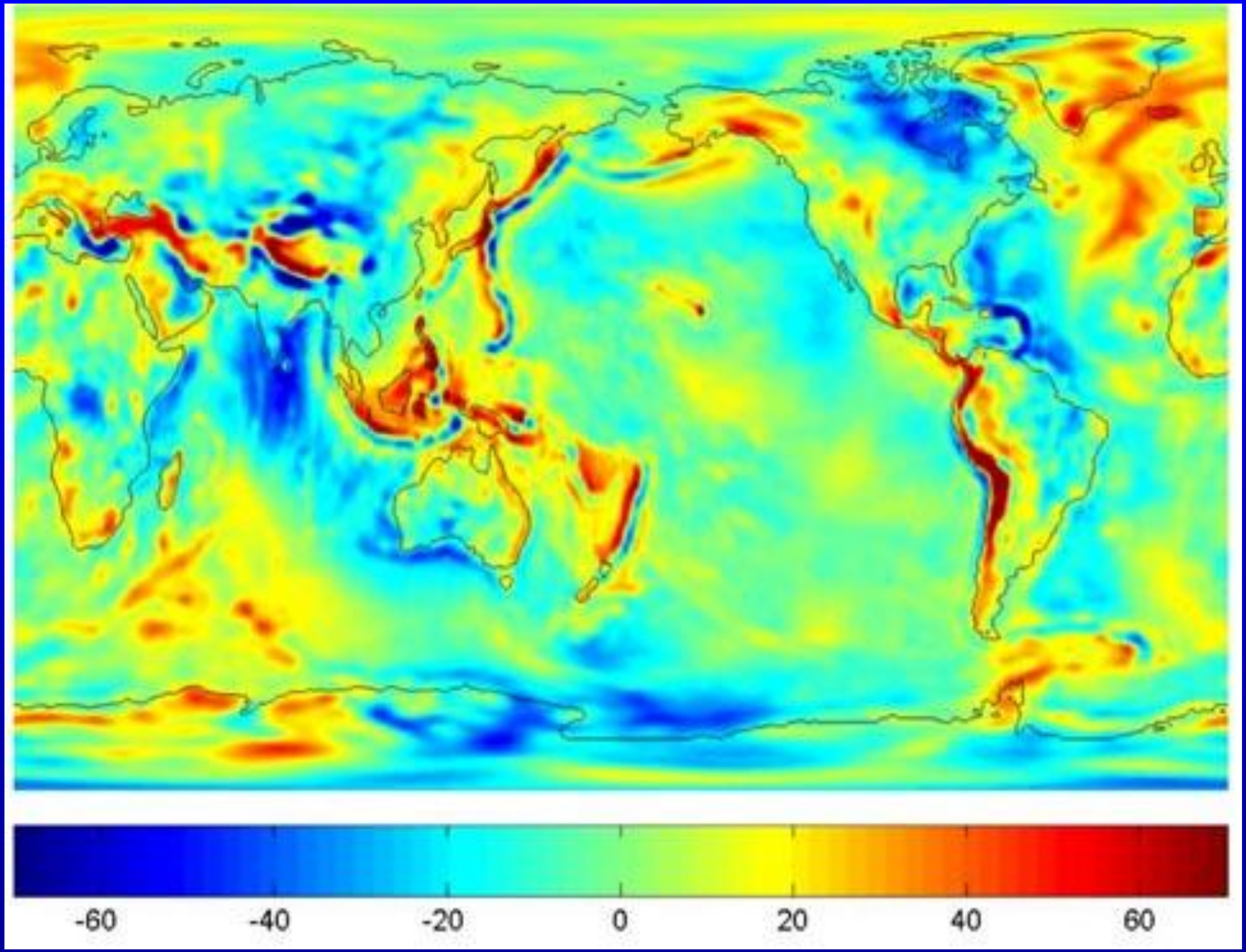
http://www.csr.utexas.edu/grace/gravity/

Gravity anomalies from 111 days of GRACE data (GGM01S)



http://www.csr.utexas.edu/grace/gravity/

Gravity anomalies from 363 days of GRACE data (GGM02S)



http://www.csr.utexas.edu/grace/gravity/

Uncertainty:

JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 25, No. 6, November–December 2002

Error Analysis of a Low–Low Satellite-to-Satellite Tracking Mission

Jeongrae Kim* and Byron D. Tapley†
University of Texas at Austin, Austin, Texas 78759

 Journal of Geodesy (2005) DOI 10.1007/s00190-005-0480-z

GGM02 – An Improved Earth Gravity Field Model from GRACE

B. Tapley, J. Ries*, S. Bettadpur, D. Chambers, M. Cheng, F. Condi, B. Gunter, Z. Kang, P. Nagel, R. Pastor, T. Pekker, S. Poole, and F. Wang
Center for Space Research, The University of Texas at Austin, 3925 W. Braker Lane, Suite 200, Austin, Texas 78759, USA

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Tel: 512-471-7486, Fax: 512-471-3570

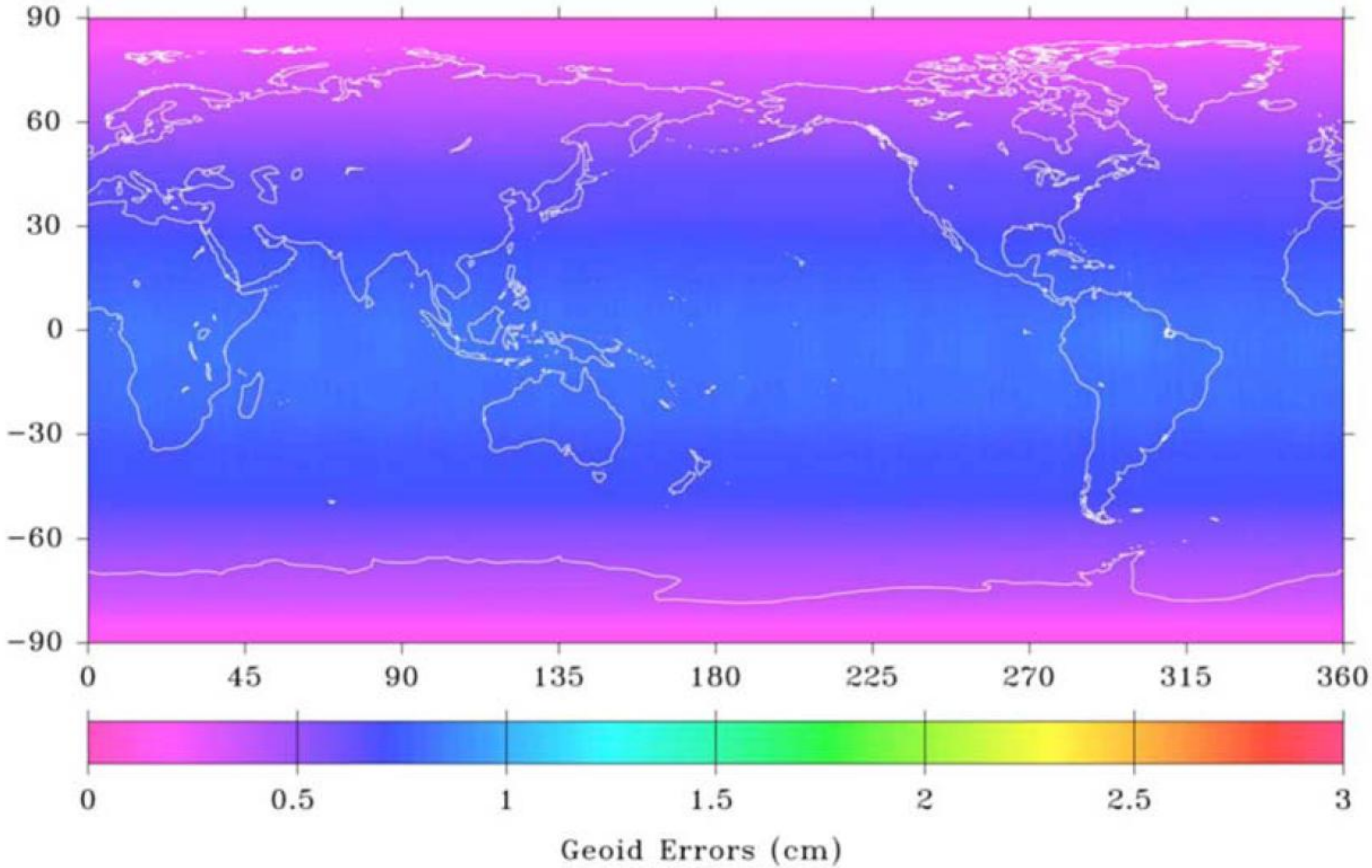
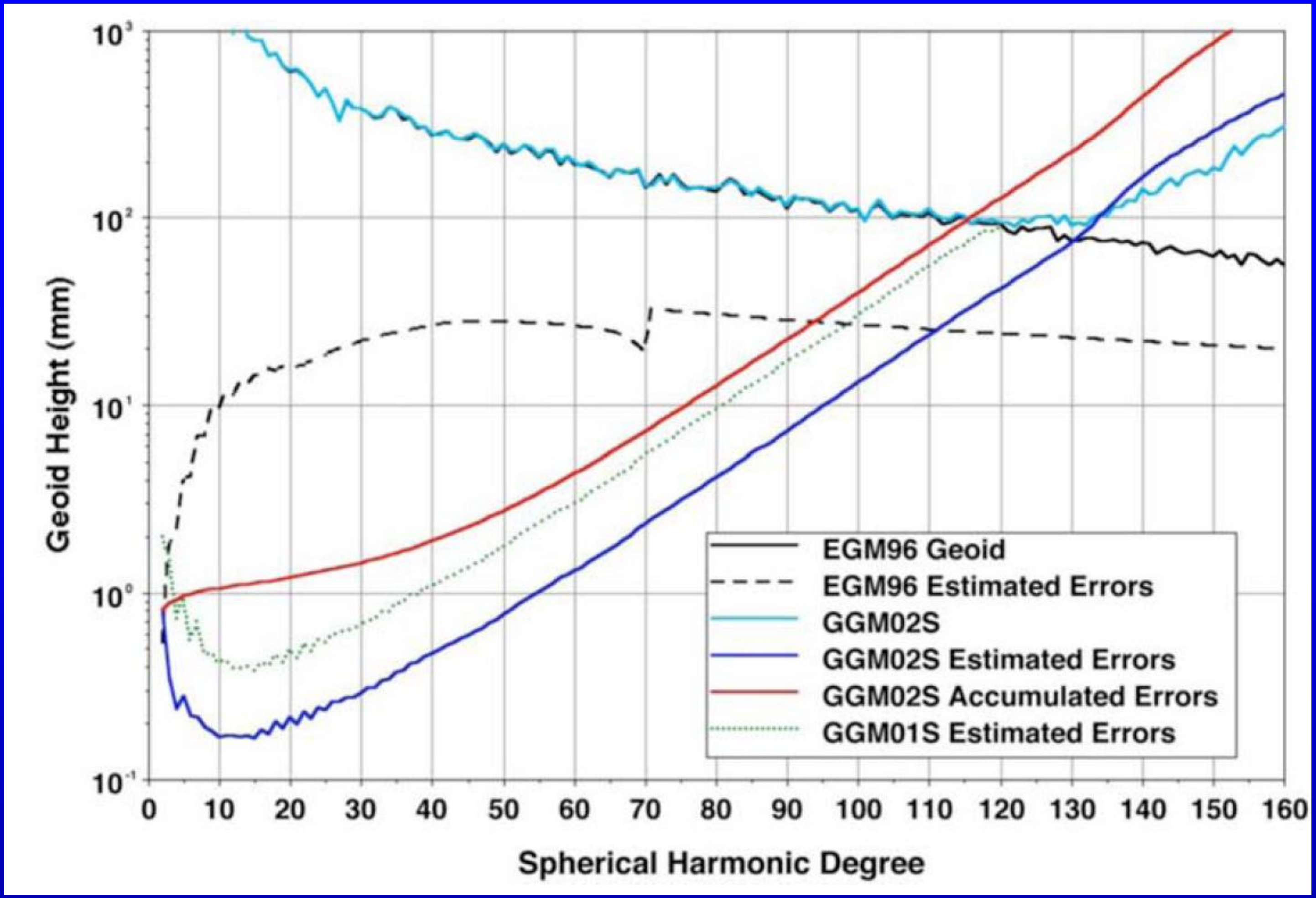


Fig. 4 Geoid height error predicted by the full covariance as a function of geographic location for GGM02S to degree/order 70. Due to the global, homogeneous nature of the GRACE data, the resulting geoid errors show no discrimination between land and sea. The global RMS of the GGM02S geoid height error is estimated to be ∼7 mm, with a maximum error of ∼9 mm. Units are centimetre

RMS Geoid height error: ~7 mm

Tapley B et al. *GGM02 – An improved Earth gravity field model from GRACE.* **J Geod** (2005) 79: 467–478
DOI 10.1007/s00190-005-0480-z



The estimated square-root degree variances and degree error variances for GGM02S, contrasted with GGM01S and EGM96, are shown as a function of degree in terms of geoid height (mm). For a given degree N, the root-sum-square of the coefficients (or their 1-sigma error estimates) for all orders (0 through N) is calculated. The lower degrees can be associated with longer wavelengths and the higher degrees with shorter wavelengths. For geopotential models, this provides useful statistical information about the nature of the gravity model and its errors as a function of wavelength.

Tapley B et al. *GGM02 – An improved Earth gravity field model from GRACE.* **J Geod** (2005) 79: 467–478 DOI 10.1007/s00190-005-0480-z

GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19503, doi:10.1029/2009GL040222, 2009

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Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE

I. Velicogna[1,2]

Received 28 July 2009; revised 26 August 2009; accepted 3 September 2009; published 13 October 2009.

[1]Department of Earth System Science, University of California, Irvine, California, USA.
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L06401, doi:10.1029/2005GL025305, 2006

Accuracy of GRACE mass estimates

John Wahr,[1] Sean Swenson,[1] and Isabella Velicogna[1]

Received 23 November 2005; revised 11 January 2006; accepted 7 February 2006; published 18 March 2006.

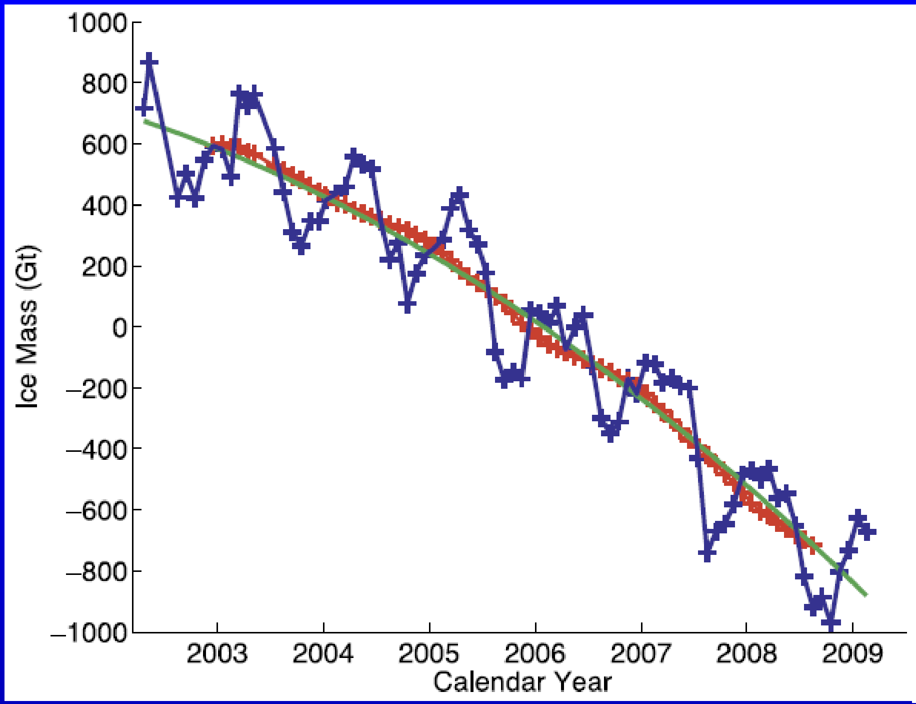
[1] The GRACE satellite mission is mapping the Earth's gravity field at monthly intervals. The solutions can be used to determine monthly changes in the distribution of water on land and in the ocean. Most GRACE studies to-date have

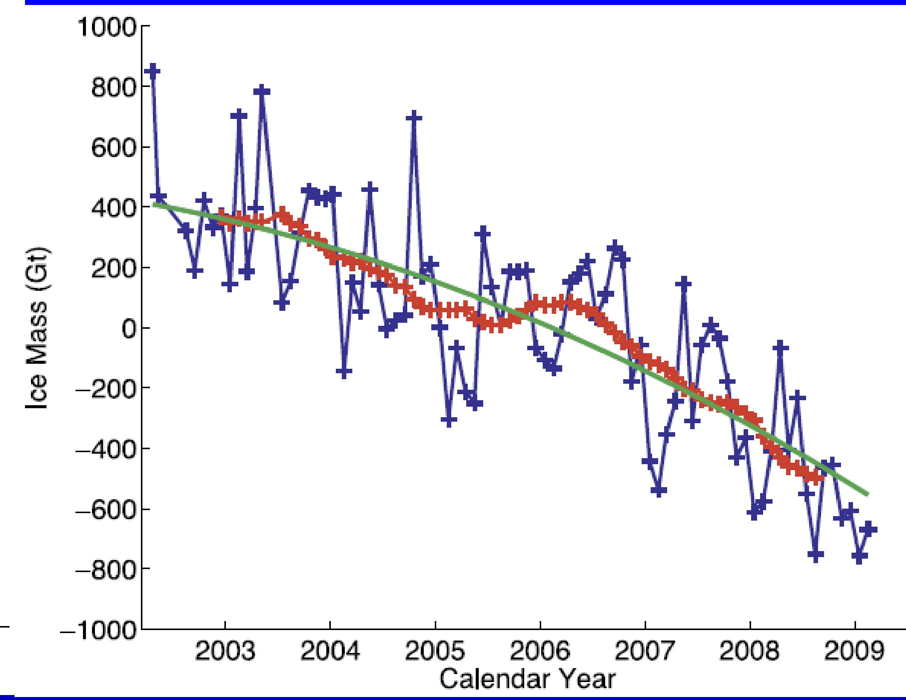
nental water storage. Measurement and processing errors contribute to (i). Contributions to (ii) could include gravity signals caused, for example, by unmodeled mass variations in the Earth's interior.

[1]Department of Physics and Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado, USA.

Gravity Satellite Ice Sheet Mass Measurements

based on monthly gravity field solutions





Greenland Ice Sheet (2.6e6 Gt)

2002–3: 137 Gt/yr

2007–9: 286 Gt/yr

Change: 149 Gt/yr over 6 years

Antarctic Ice Sheet (27e6 Gt)

2002-6: 104 Gt/yr

2006-9: 246 Gt/yr

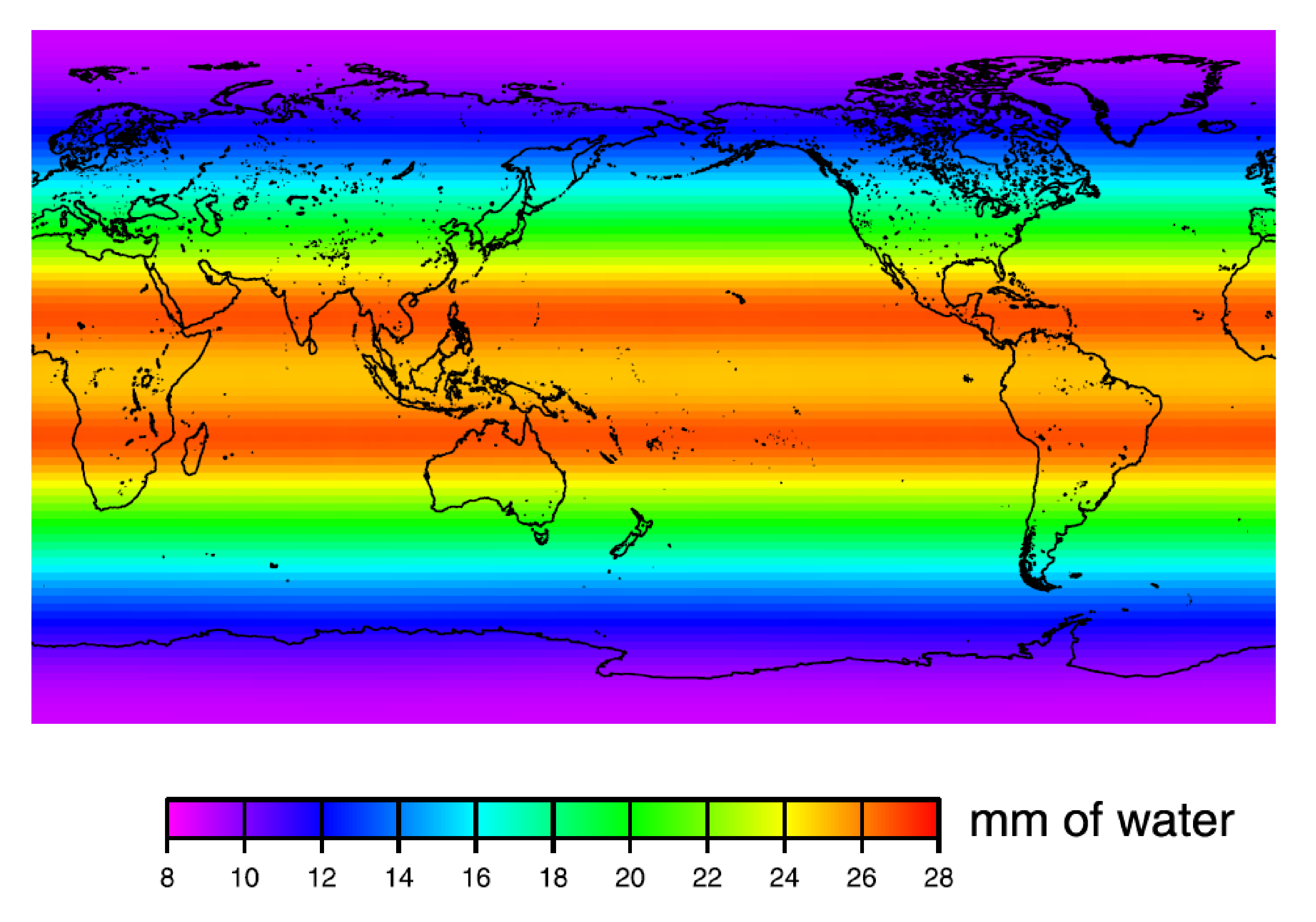
Change: 142 Gt/yr

Source: Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.

Uncertainties in mass loss

- GRACE gravity field solutions & mass estimates
- correction for post-glacial rebound (largest)
  - Greenland: 7 ± 9 Gt/yr
  - Antarctic: 176 ± 76 Gt/yr
- correction for leakage from nearby mass
- curve fit

Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.



Estimated uncertainties in the GRACE mass estimates, in mm of water thickness, for 750-km Gaussian averages and averaged over all 22 months. Obtained by propagating the Stokes coefficient errors through (4).

10 mm H_2O over Greenland (2e6 km^2) ≈ 20 Gt; Antarctica (13.7e6 km^2) ≈ 137 Gt

Wahr et al. (2006). *Accuracy of GRACE mass estimates.* **Geophys. Res. Lett**., 33, L06401, doi:10.1029/2005GL025305.

Linear trends

	Greenland	Antarctica
Velicogna 2009	230 ± 33 Gt/yr $\Rightarrow$ 0.68 mm/yr	143 ± 73 Gt/yr $\Rightarrow$ 0.42 mm/yr
Chen 2008 (West Antarctica)		132 ± 26 Gt/yr $\Rightarrow$ 0.39 mm/yr
Wu 2010 (West Antarctica)	104 ± 23 Gt/yr $\Rightarrow$ 0.31 mm/yr	64 ± 32 Gt/yr $\Rightarrow$ 0.19 mm/yr

Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.
Wu X et al. *Nature Geoscience* DOI: 10.1038/NGEO938 August 2010.
Chen et al. *Antarctic regional ice loss rates from GRACE* **Earth Planet. Sci. Lett**. 266:140-148

Acceleration

- 2nd order curve fit:
  - Antarctica: 26 ± 14 $Gt/yr^2 \Rightarrow 0.08 \pm 0.04$ mm/yr^2
  - Greenland: 30 ± 11 $Gt/yr^2 \Rightarrow 0.09 \pm 0.03$ mm/yr^2 sea level
- Not affected by post-glacial rebound errors
- 26 Gt/yr = 18% of 143, or 41% of 64

Velicogna, I. *Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.

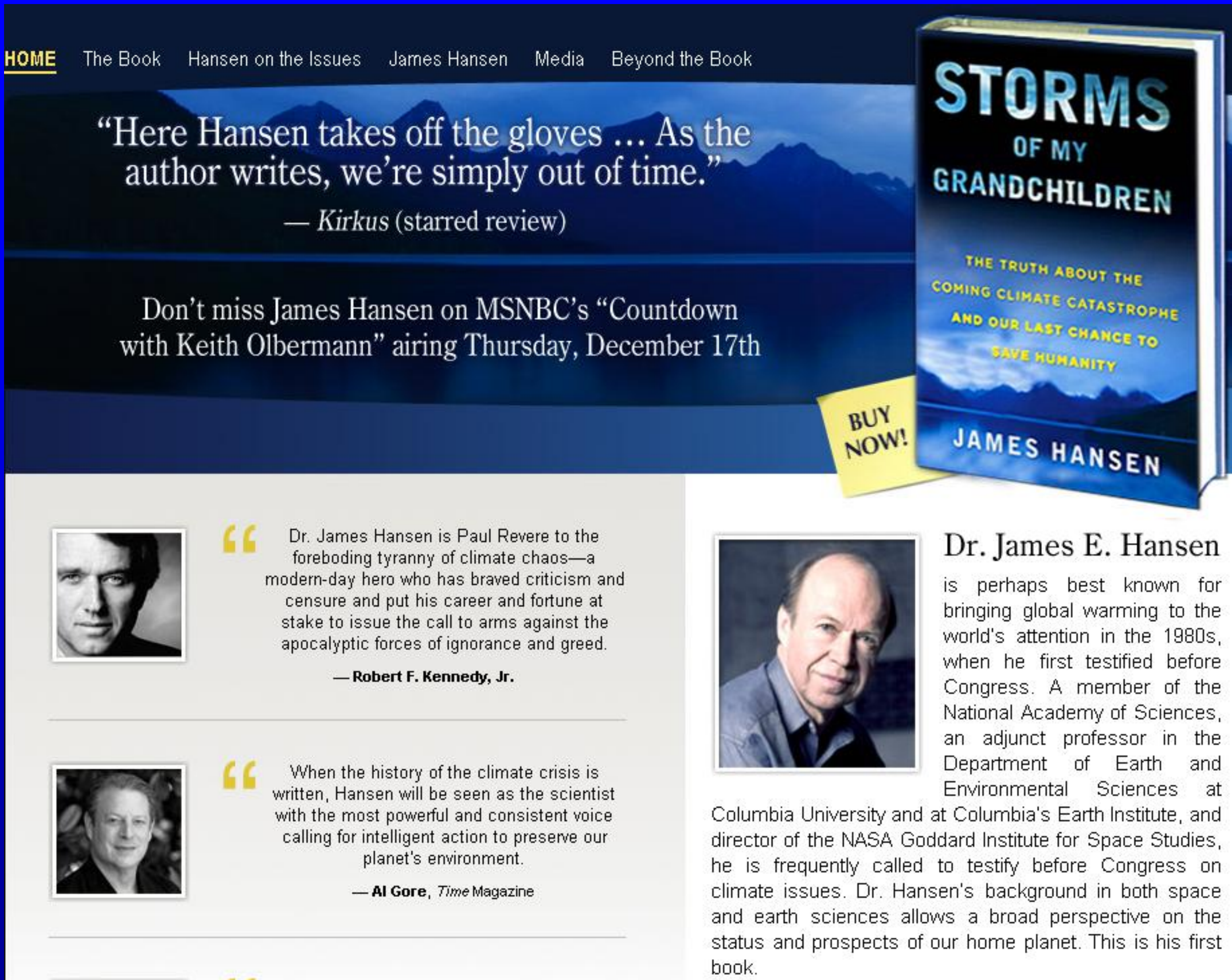
End

Grant us:

The ability to reduce the uncertainties we can;

The willingness to work with the uncertainties we cannot;

And the scientific knowledge to know the difference.

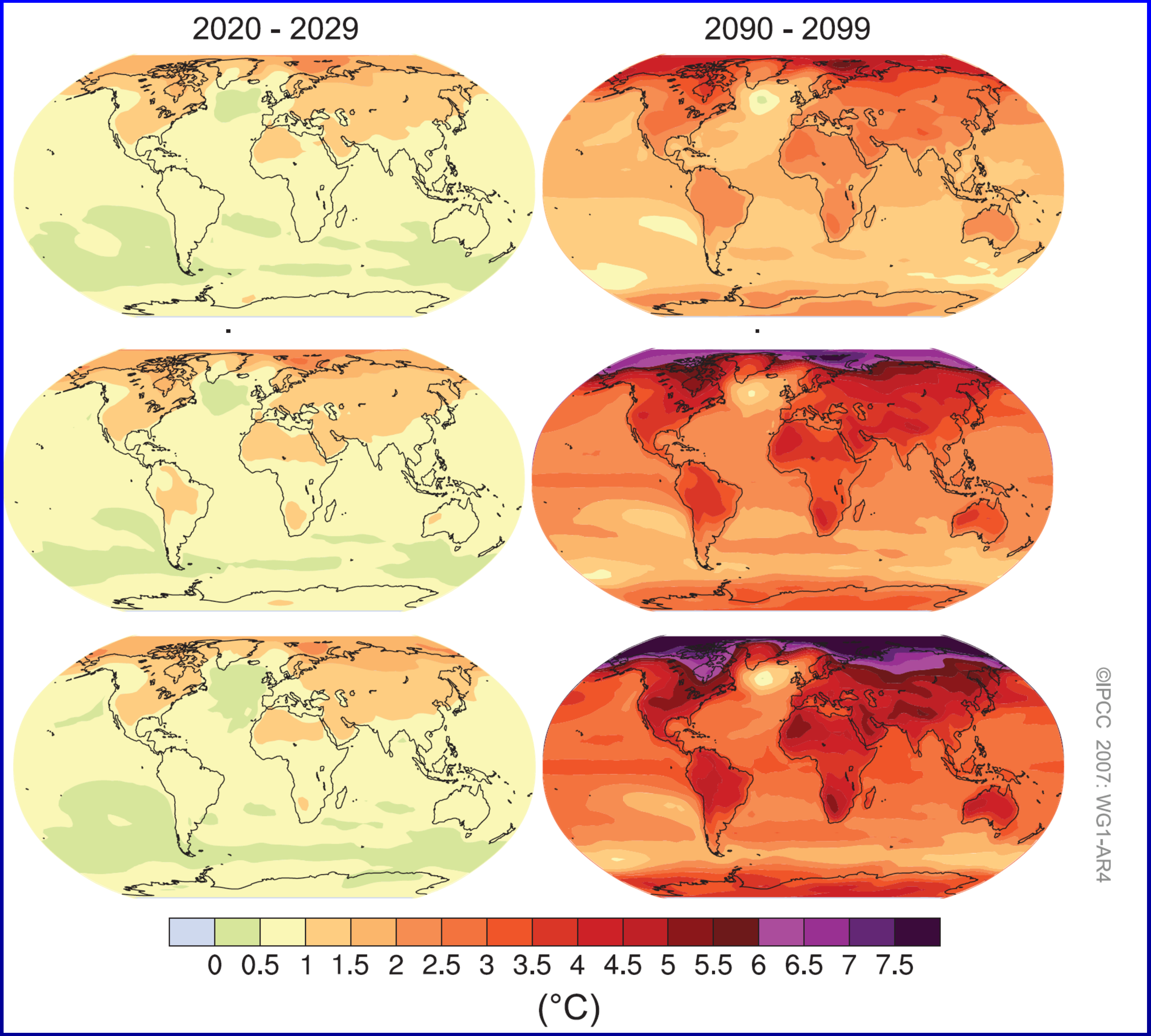


http://www.stormsofmygrandchildren.com/

Extra slides

GOCE

http://www.esa.int/SPECIALS/GOCE/index.html



2020 - 2029
2090 - 2099
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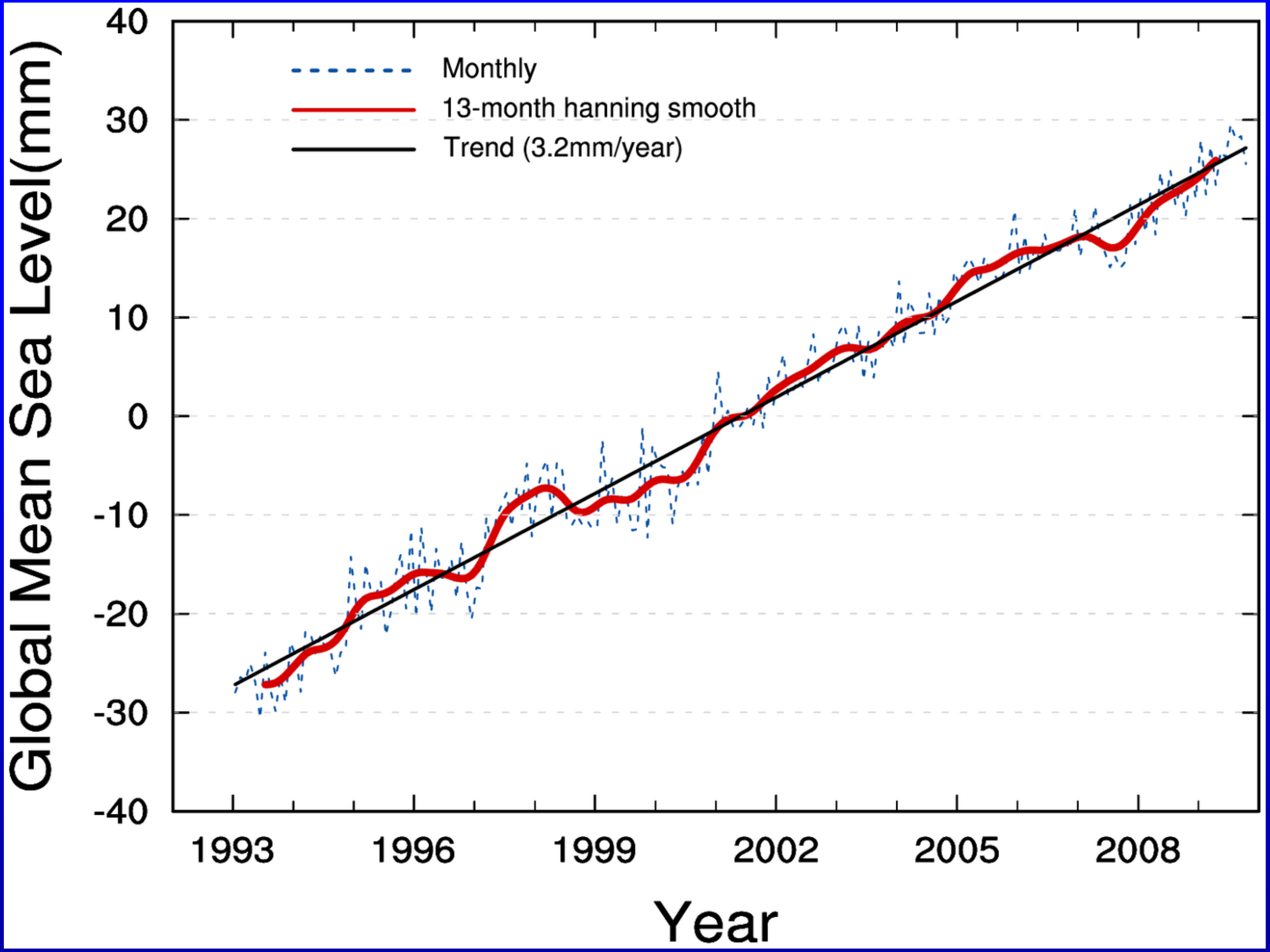
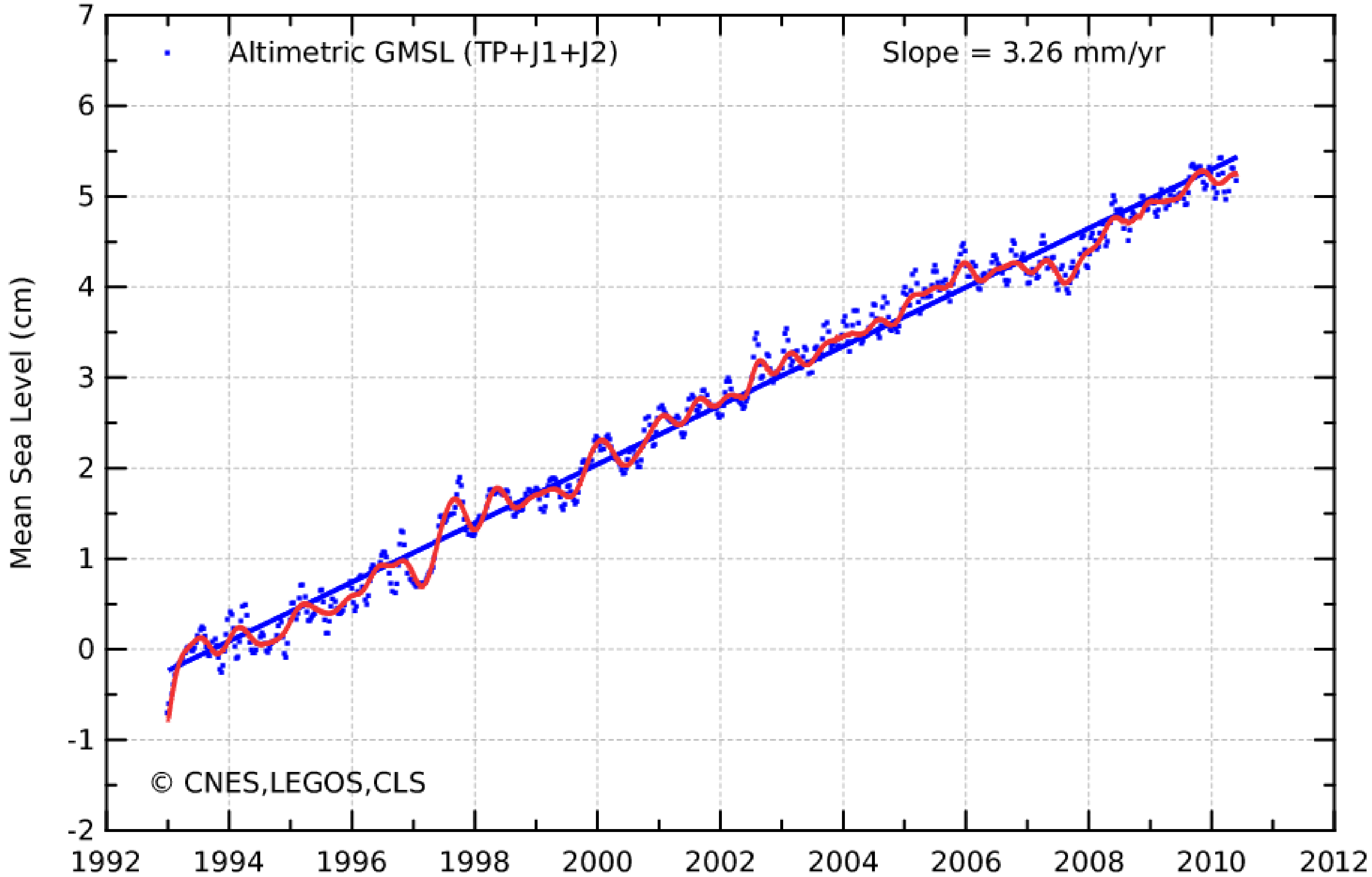
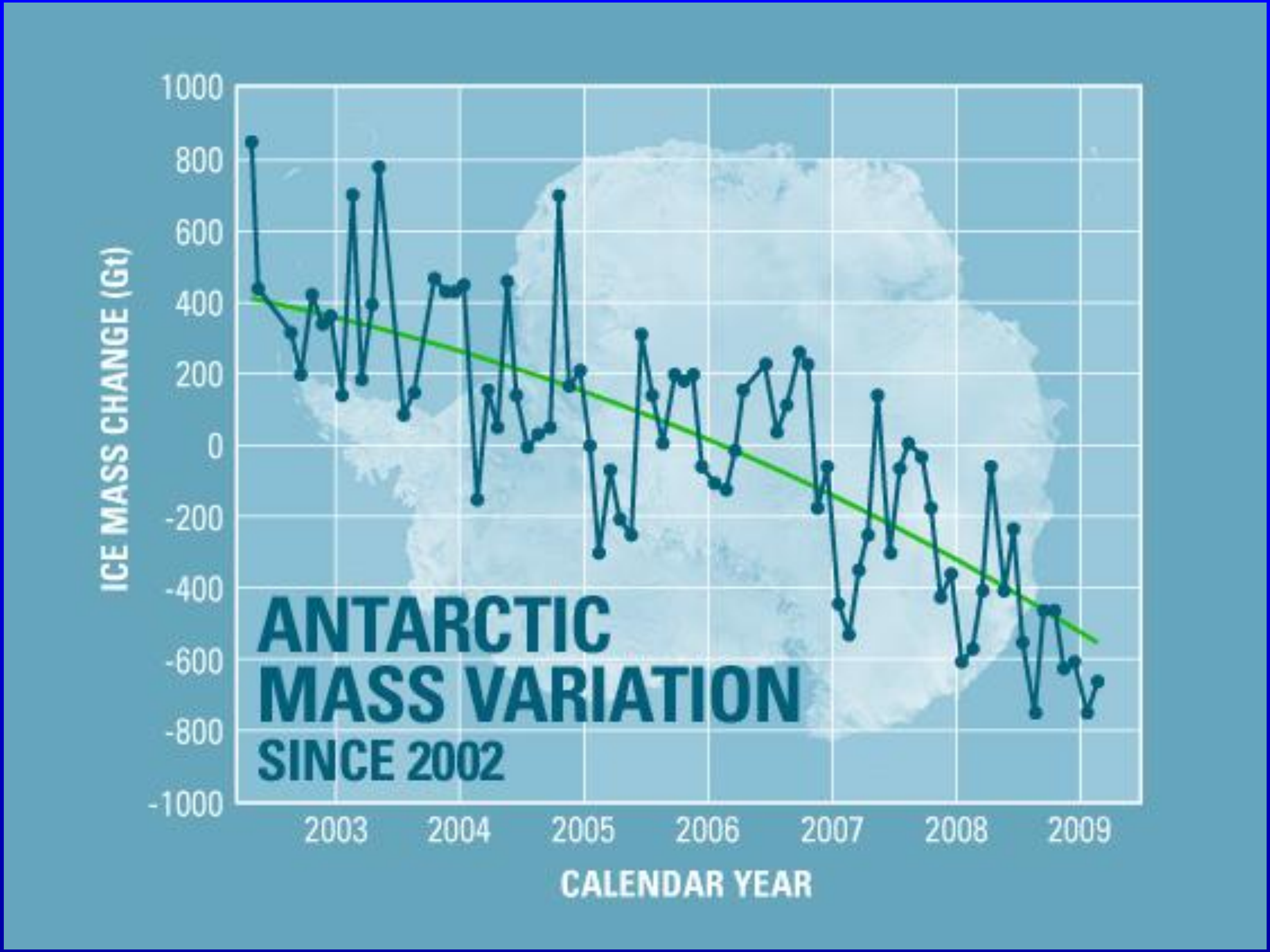
(°C)
©IPCC 2007: WG1-AR4



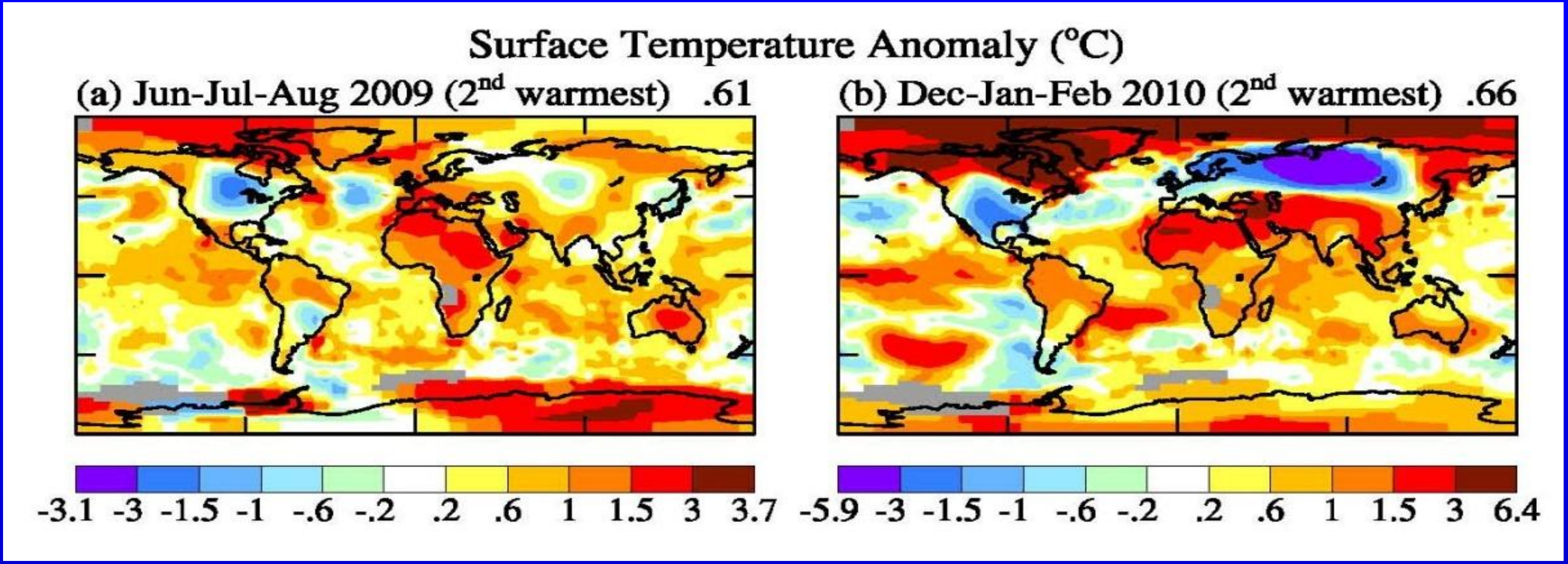
Global mean sea level Jan 1993 to Oct 2009 from satellite measurement with seasonal signal removed, inverted barometer applied and GIA correction applied. Data source: http://www.cmar.csiro.au/sealevel/sl_data_cmar.html



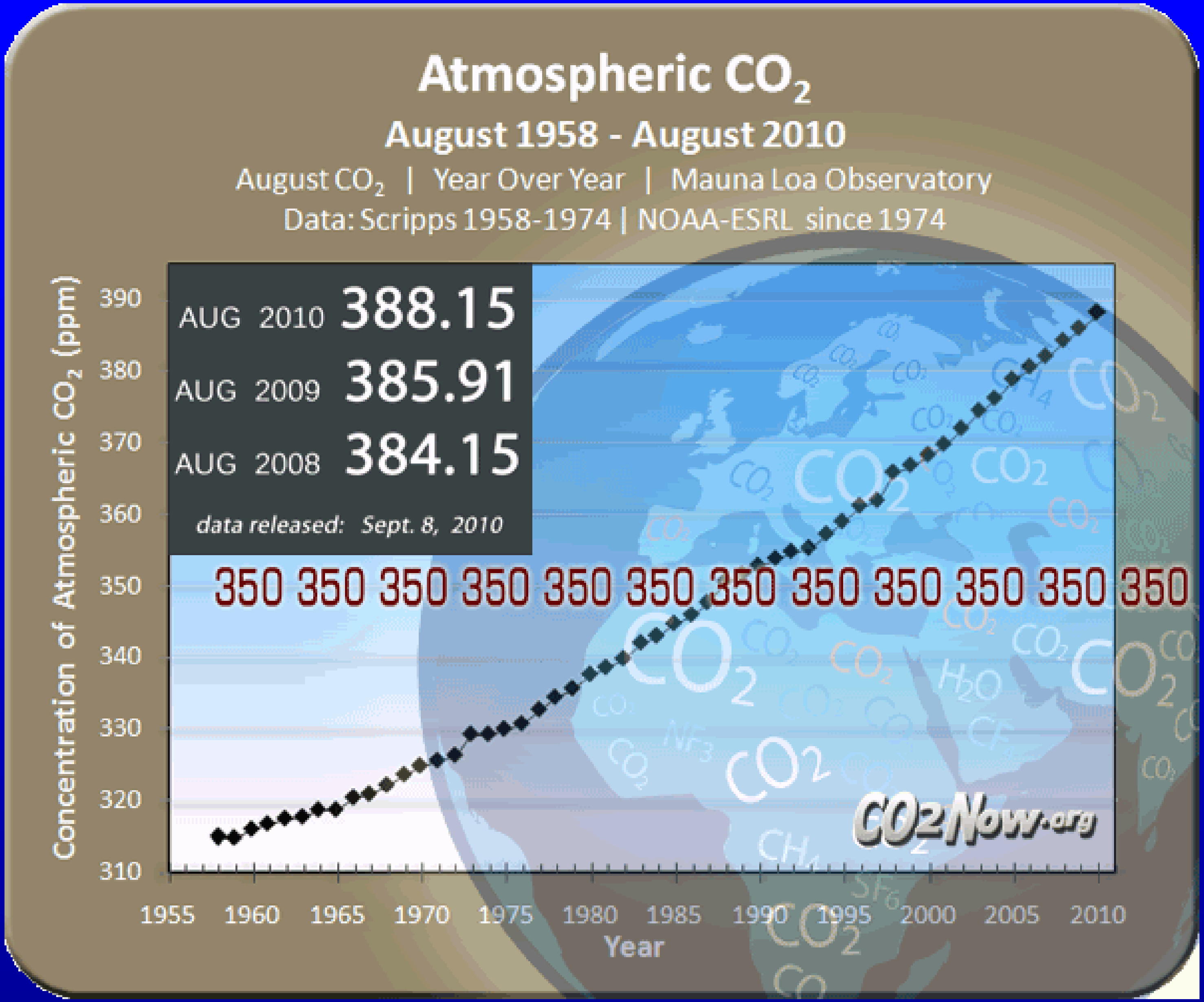
http://www.aviso.oceanobs.com/fileadmin/images/news/indic/msl/MSL_Serie_MERGED_Global_IB_RWT_GIA_Adjust.png



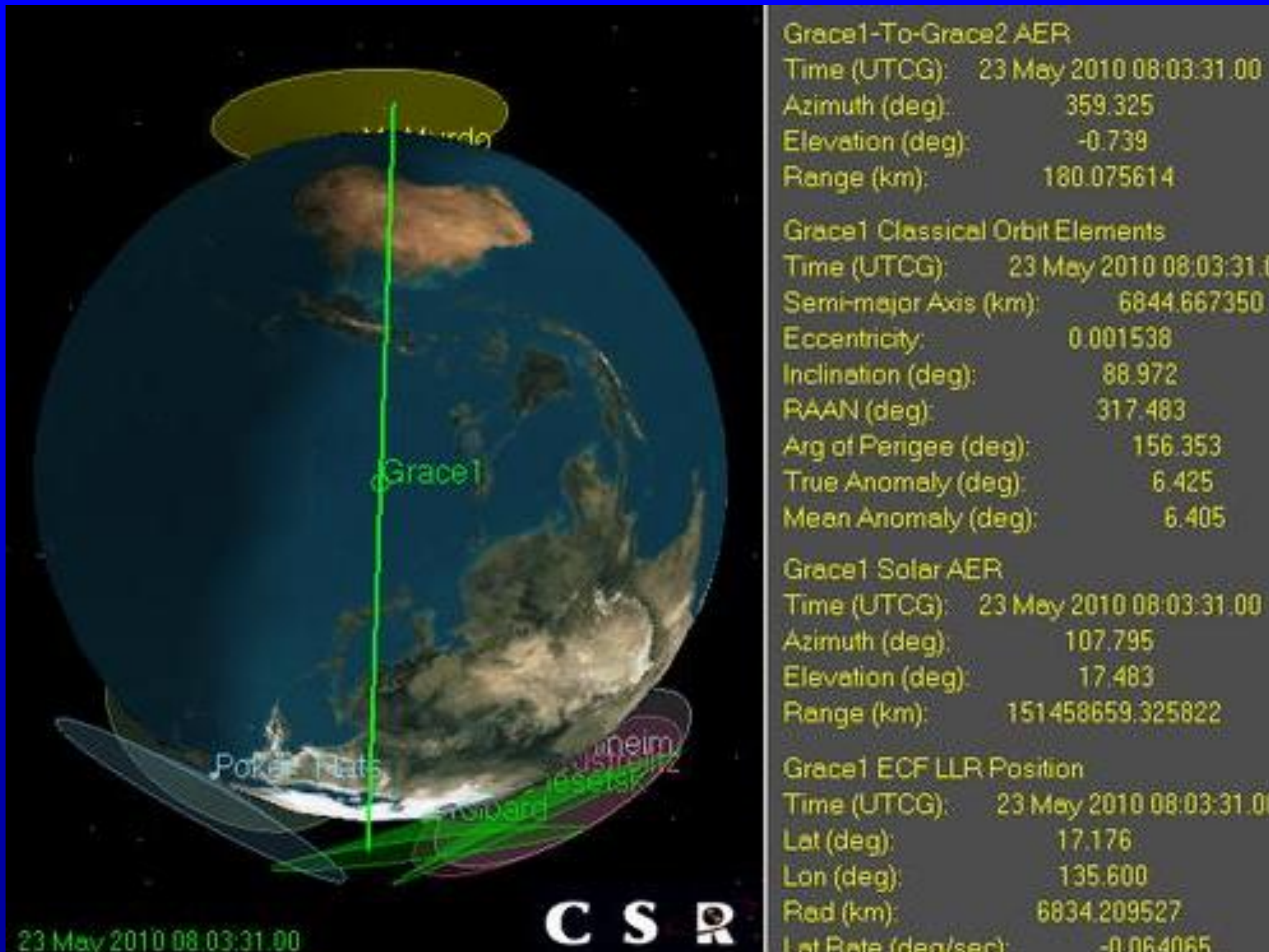
The continent of Antarctica has been losing more than 100 cubic kilometers (24 cubic miles) of ice per year since 2002.
http://www.nasa.gov/topics/earth/features/20100108_Is_Antarctica_Melting.html

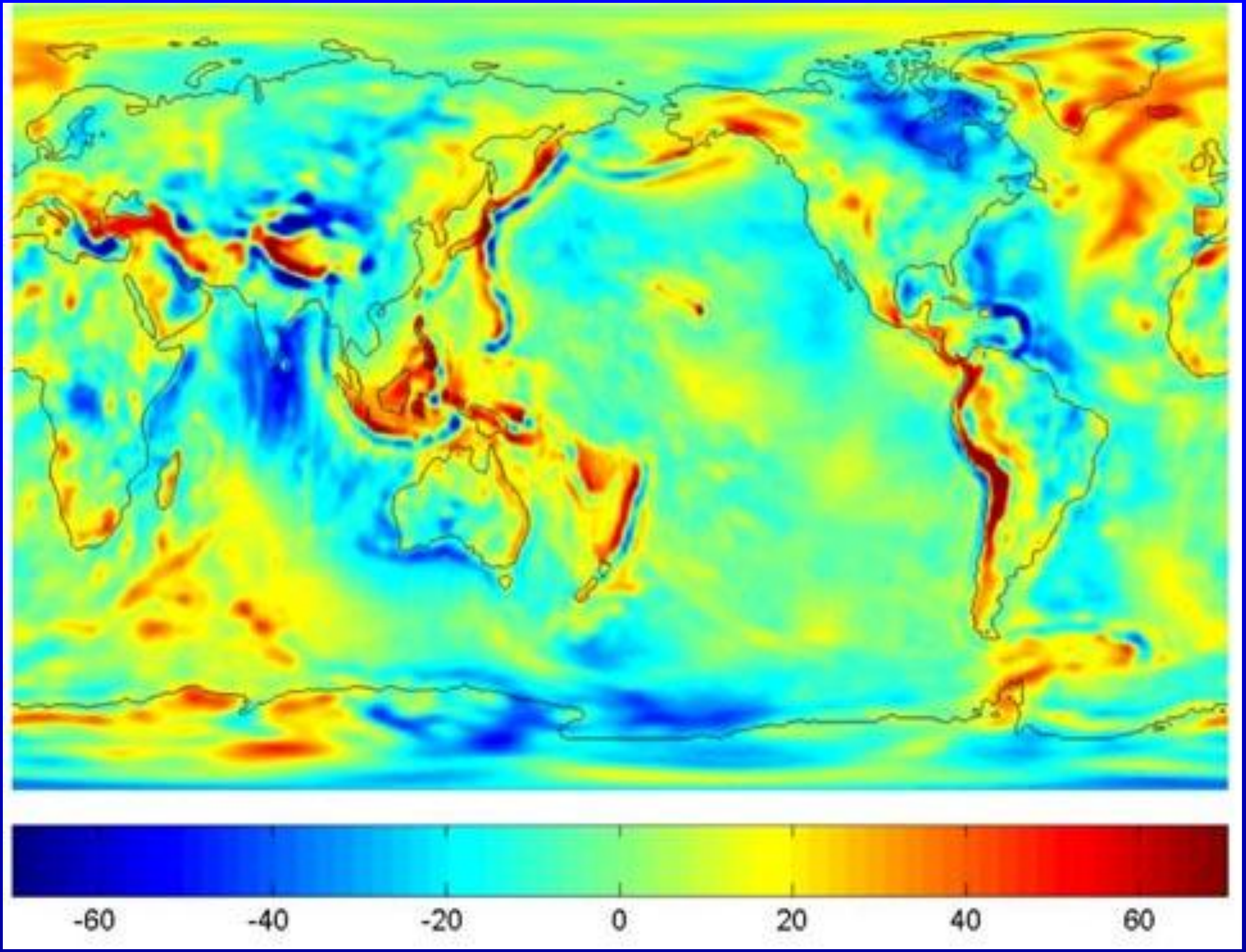


Surface temperature anomalies relative to 1951-1980 base period.
http://www.columbia.edu/~jeh1/

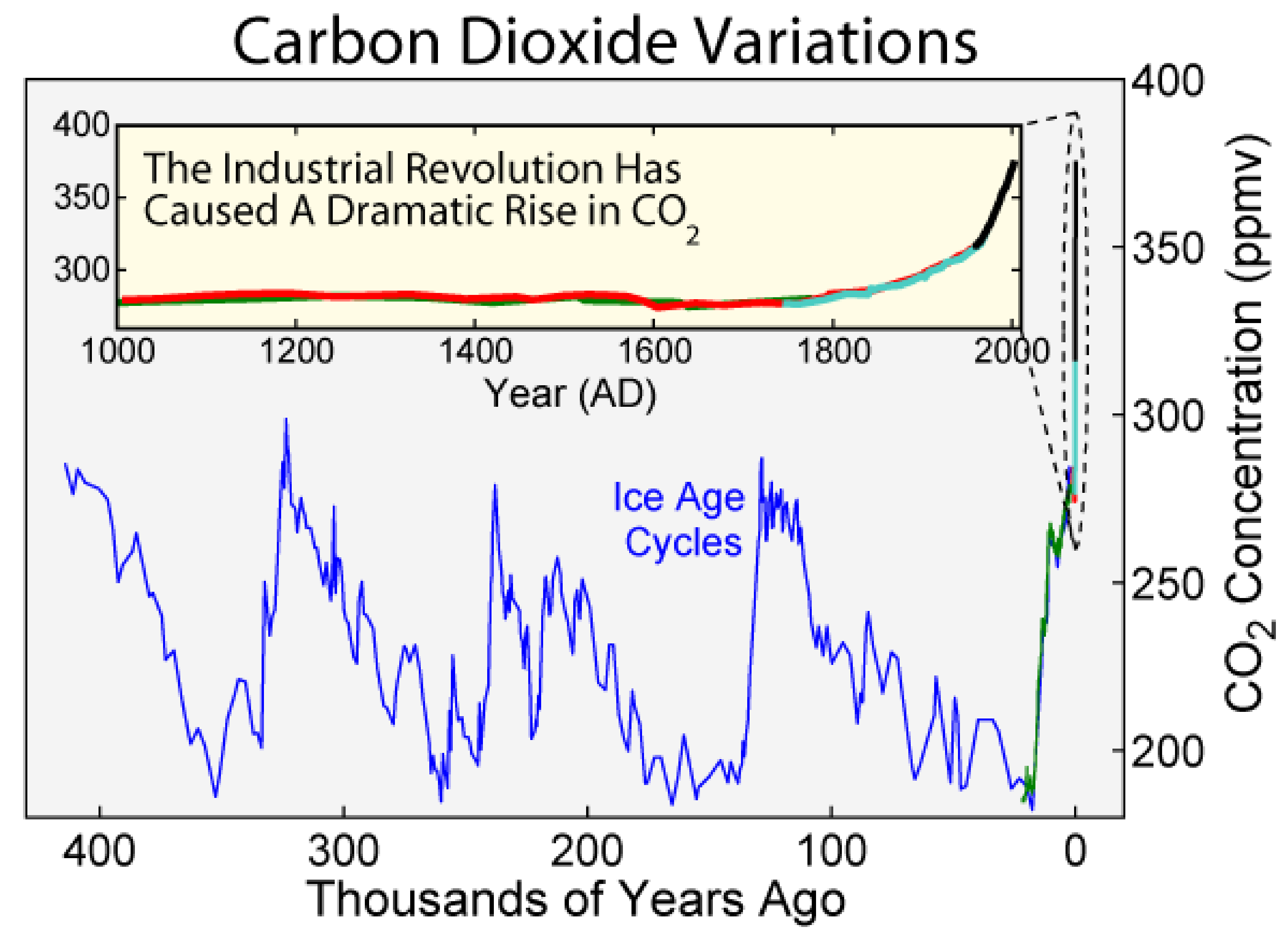


http://co2now.org/

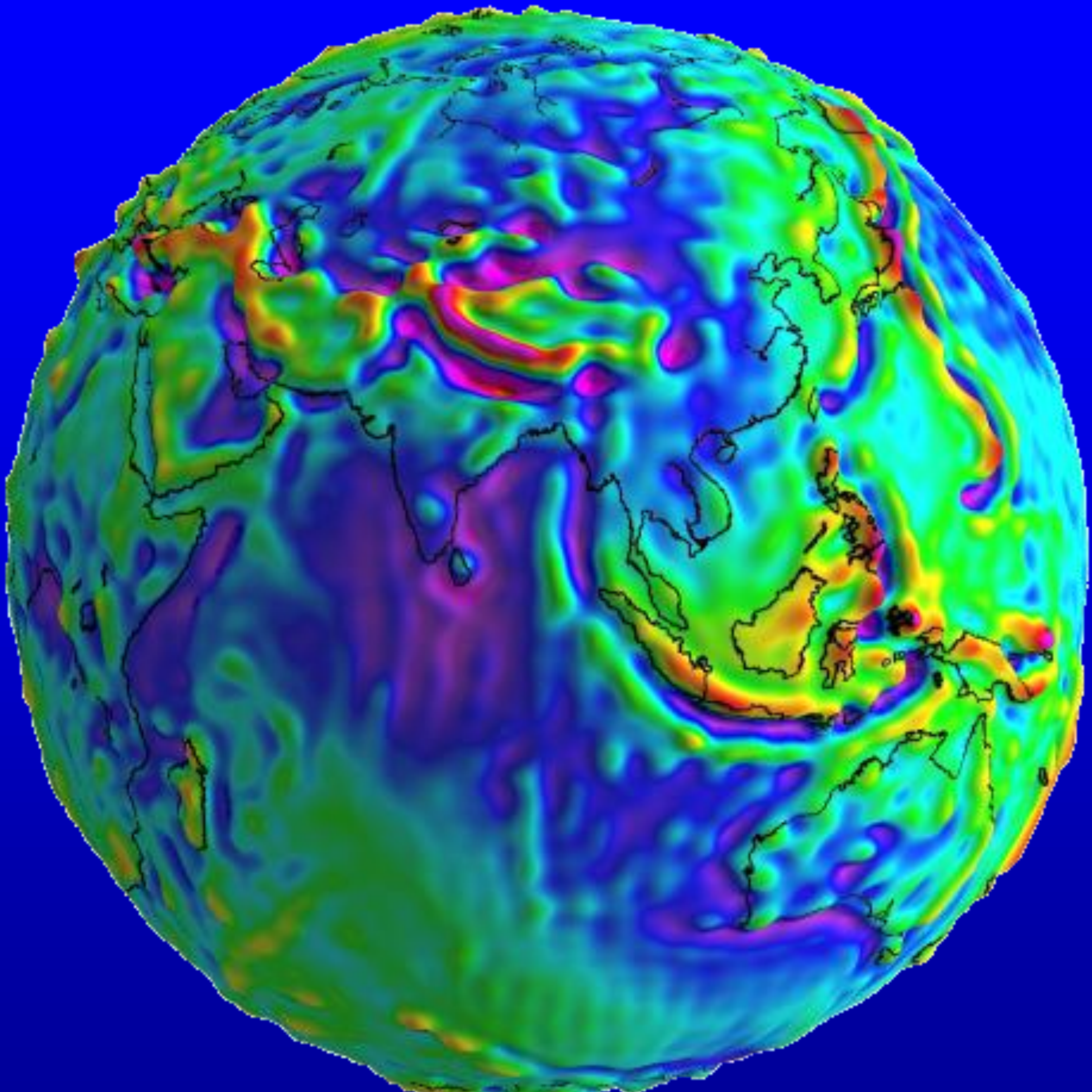

Grace1
Poker Flats
23 May 2010 08:03:31.00
CSR
Grace1-To-Grace2 AER
Time (UTCG): 23 May 2010 08:03:31.00
Azimuth (deg): 359.325
Elevation (deg): -0.739
Range (km): 180.075614
Grace1 Classical Orbit Elements
Time (UTCG): 23 May 2010 08:03:31.0
Semi-major Axis (km): 6844.667350
Eccentricity: 0.001538
Inclination (deg): 88.972
RAAN (deg): 317.483
Arg of Perigee (deg): 156.353
True Anomaly (deg): 6.425
Mean Anomaly (deg): 6.405
Grace1 Solar AER
Time (UTCG): 23 May 2010 08:03:31.00
Azimuth (deg): 107.795
Elevation (deg): 17.483
Range (km): 151458659.325822
Grace1 ECF LLR Position
Time (UTCG): 23 May 2010 08:03:31.00
Lat (deg): 17.176
Lon (deg): 135.600
Rad (km): 6834.209527
Lat Rate (deg/sec): -0.064065

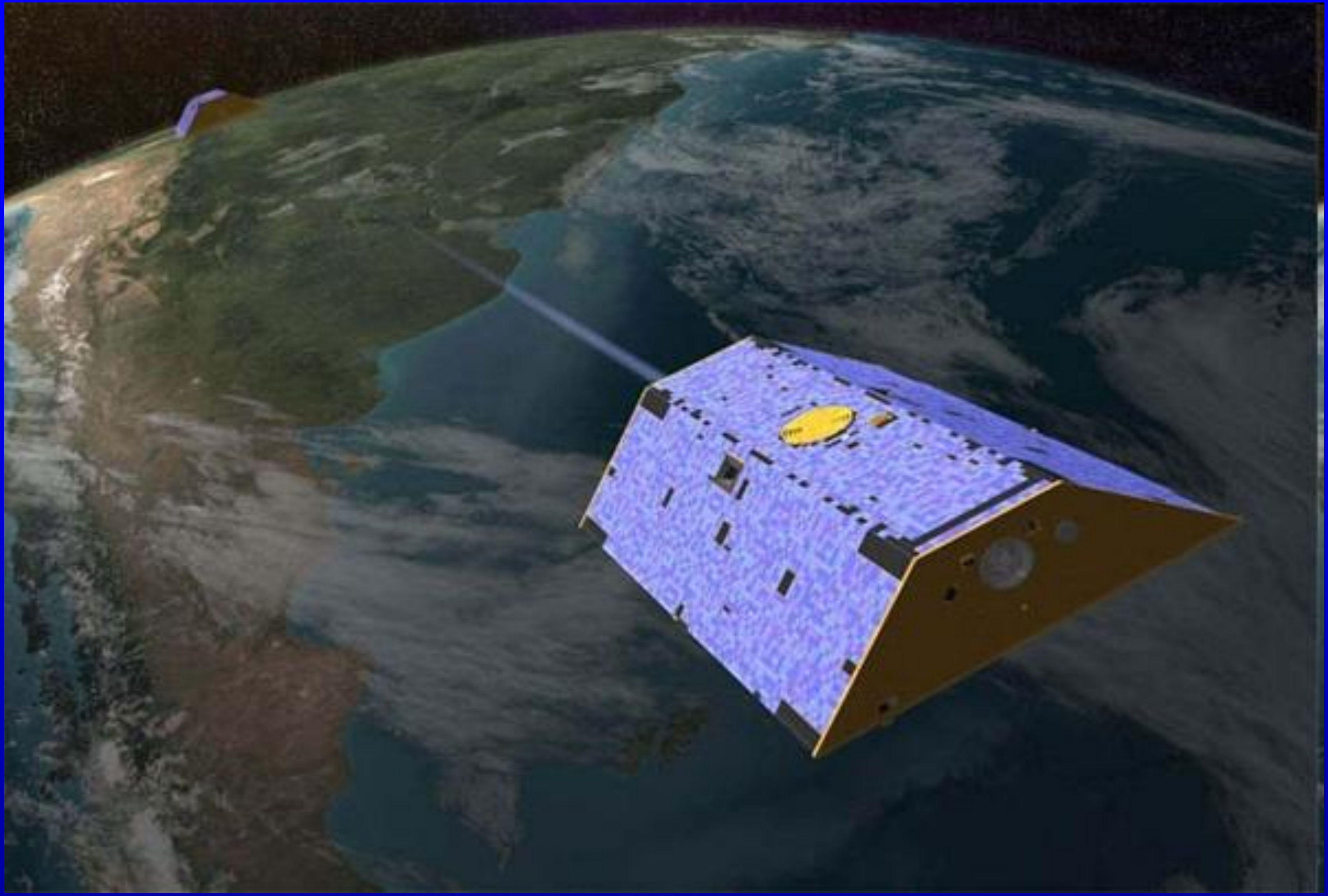


GGM02S model (mgal) [gal = cm/s^2]



Carbon Dioxide Variations
The Industrial Revolution Has
Caused A Dramatic Rise in CO_2
400
350
300
1000
1200
1400
1600
1800
2000
Year (AD)
Ice Age
Cycles
400
350
300
250
200
CO_2 Concentration (ppmv)
400
300
200
100
0
Thousands of Years Ago

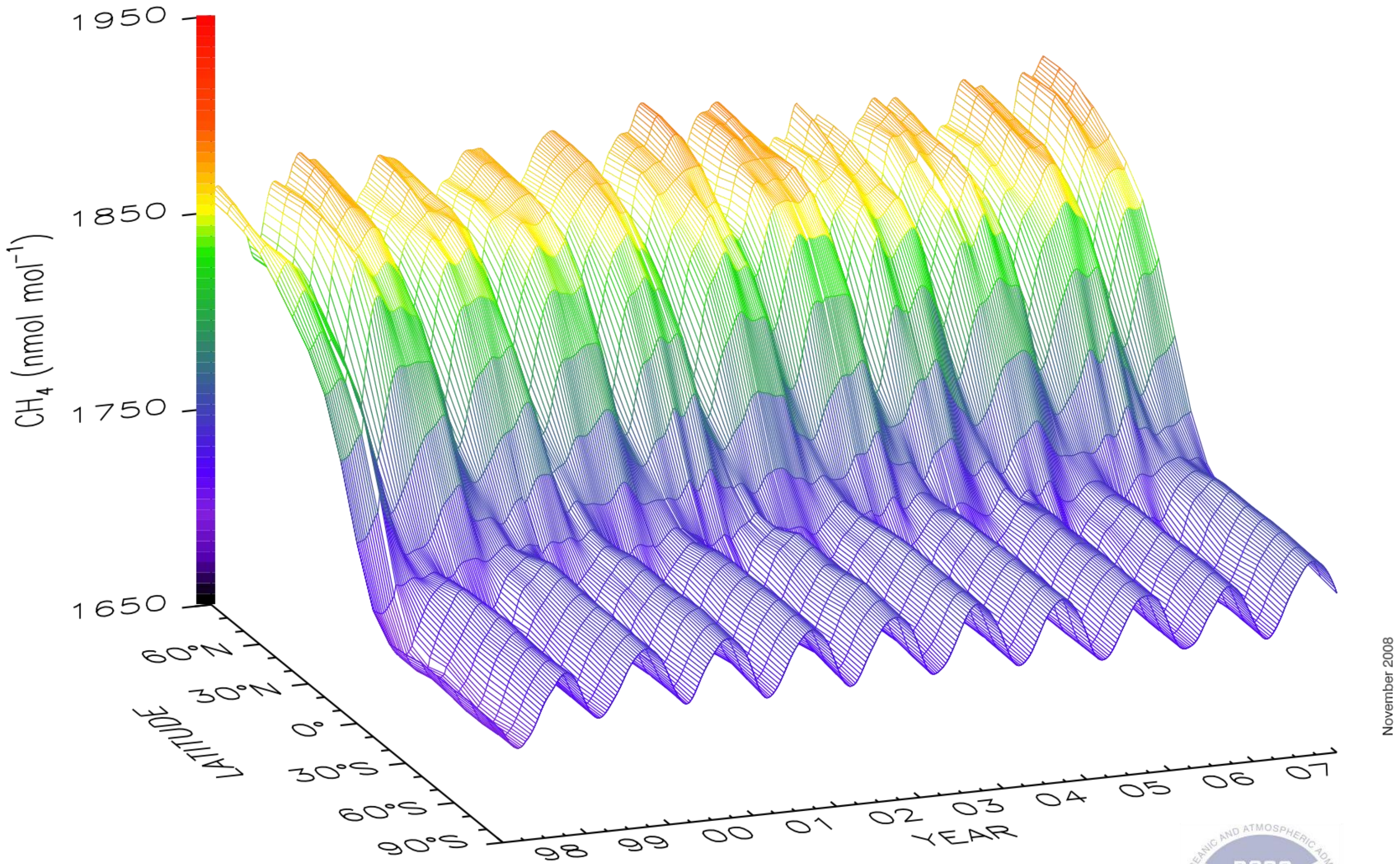




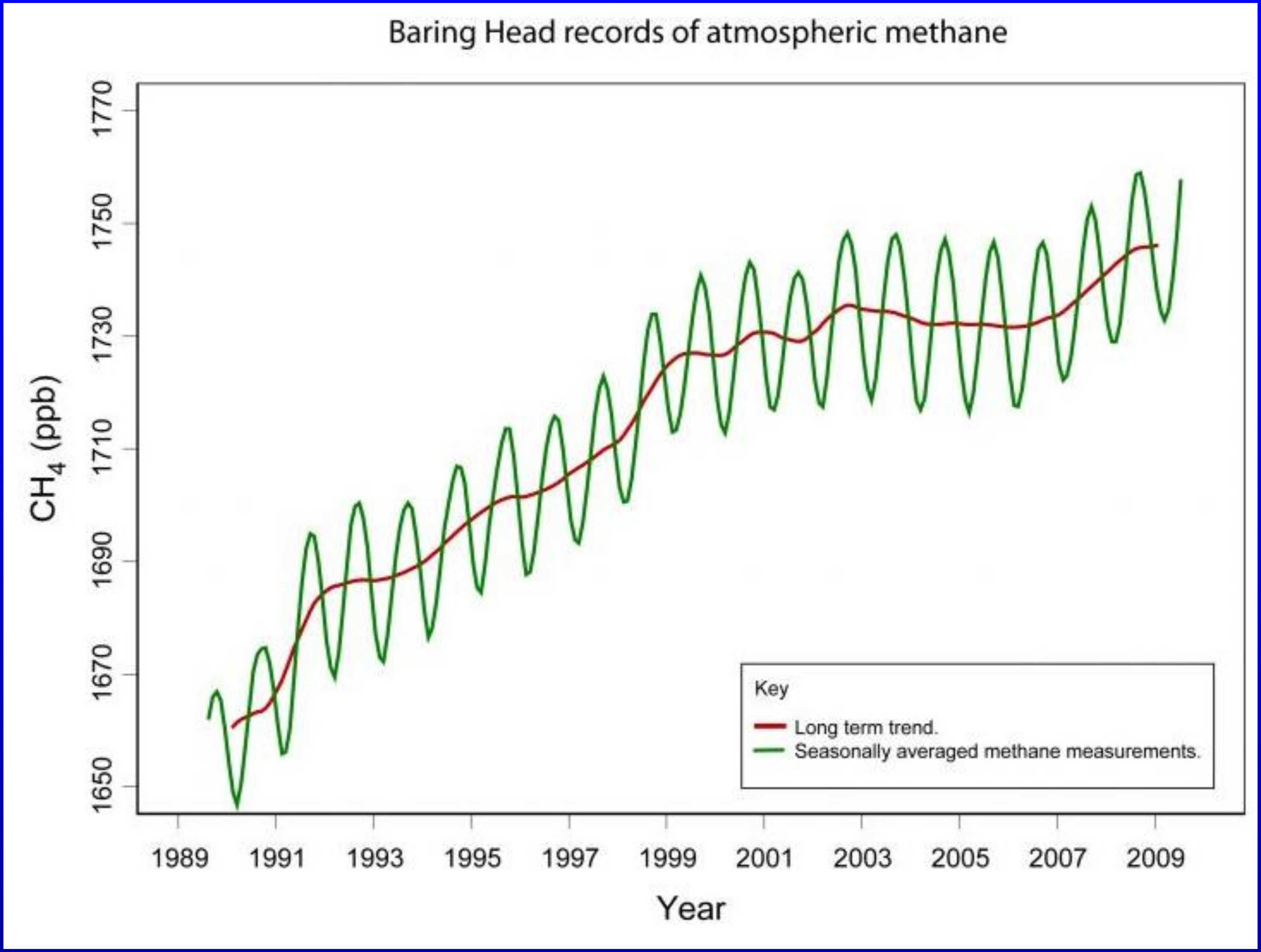
http://op.gfz-potsdam.de/grace/satellite/200009a_fm1_fm2_integration.jpg

Global Distribution of Atmospheric Methane

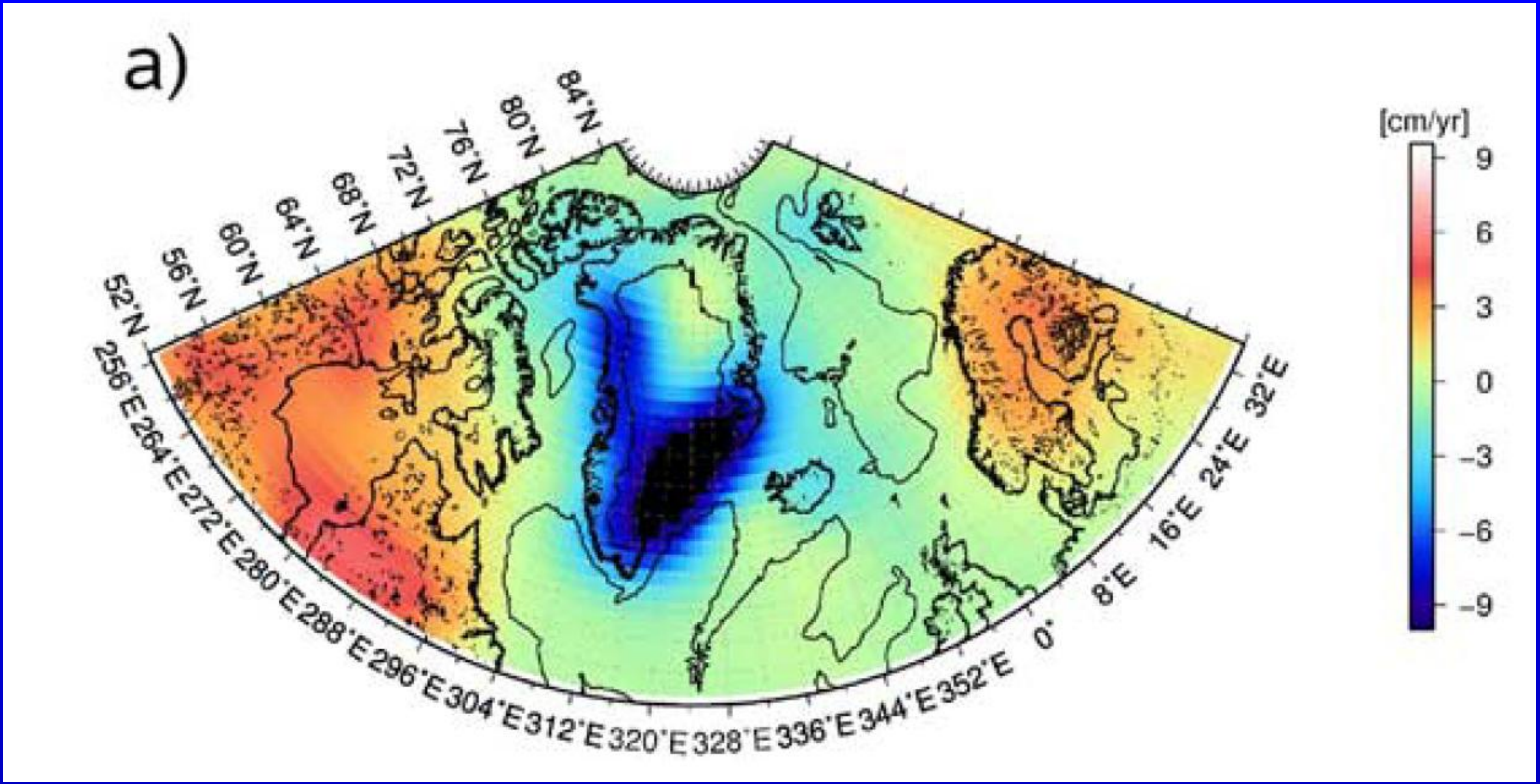
NOAA ESRL Carbon Cycle



Three-dimensional representation of the latitudinal distribution of atmospheric methane in the marine boundary layer. Data from the Carbon Cycle cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.



http://indymedia.org.au/files/Baring_Head_records_atmospheric_methane.png
Shakhova N et al. *Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. Science V3271246-50. 5 MARCH 2010*



Changes in equivalent water height over Greenland between February 2003 and January 2008 as observed by GRACE

Wouters et al Geophysical Research Letters, V. 35, L20501, doi:10.1029/2008GL034816, 2008 Fig 1

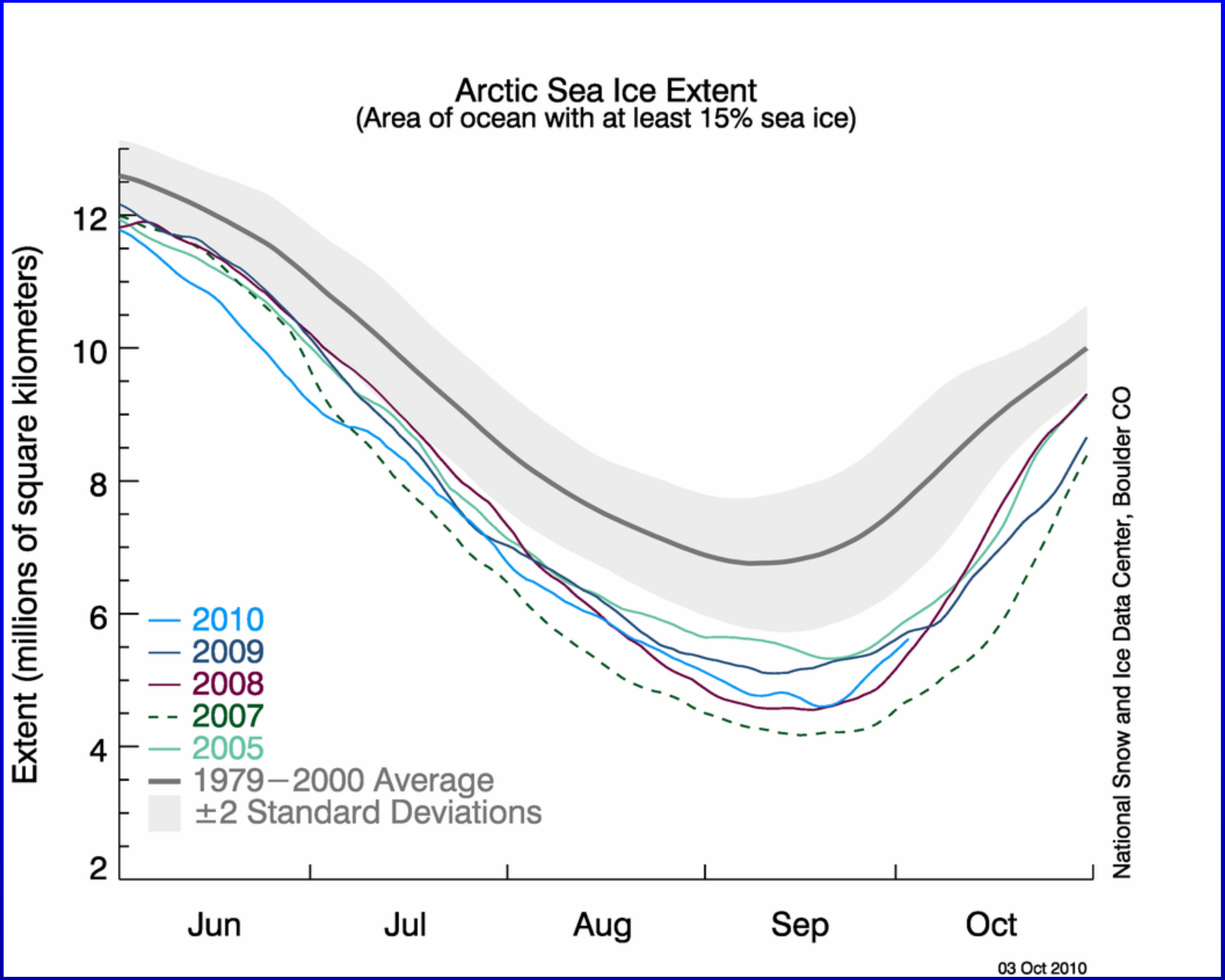
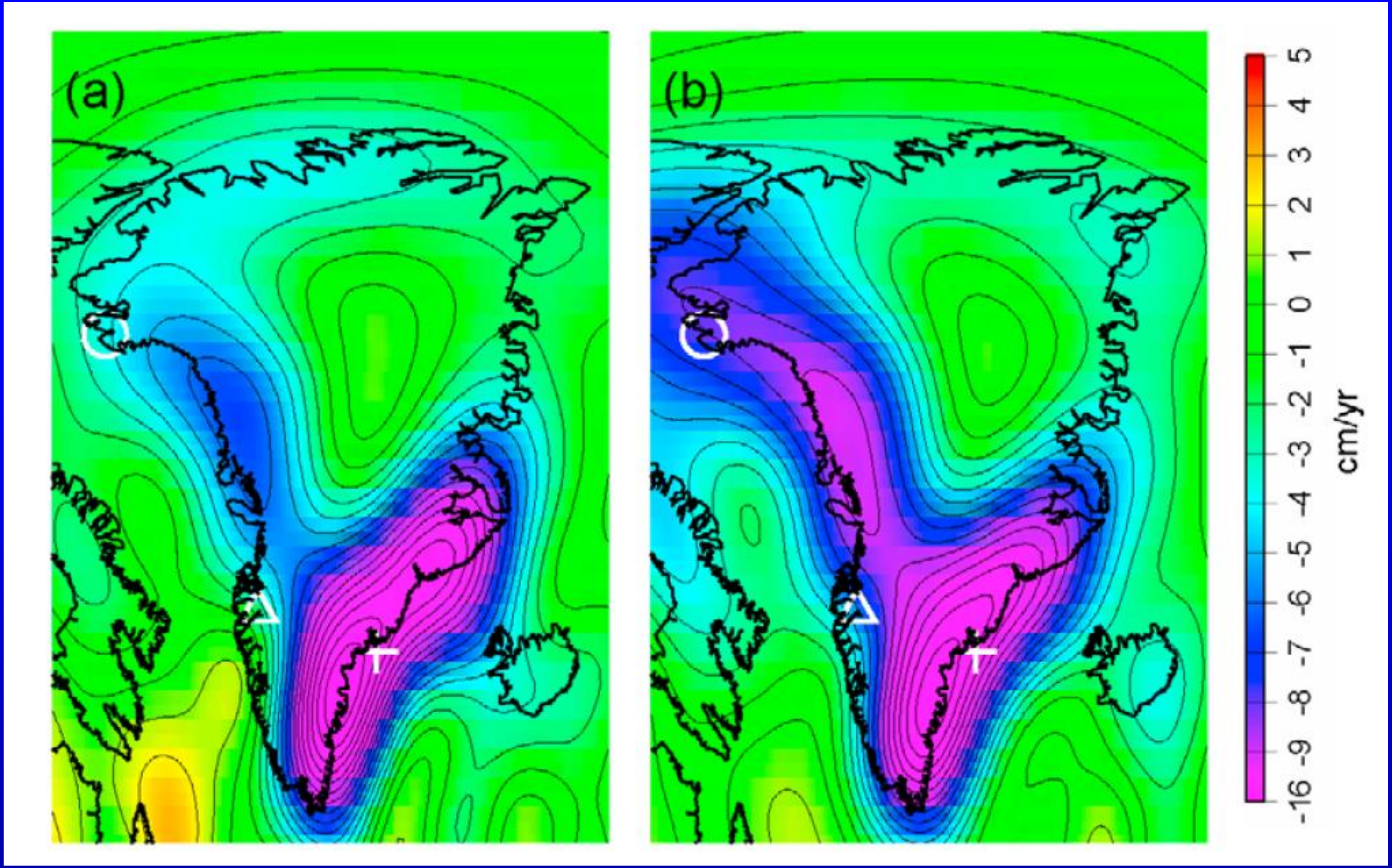


Figure 2. The graph above shows daily Arctic sea ice extent as of October 3, 2010, along with daily ice extents for years with the previous four lowest minimum extents. The solid light blue line indicates 2010; dark blue shows 2009, purple shows 2008; dashed green shows 2007; light green shows 2005; and solid gray indicates average extent from 1979 to 2000. The gray area around the average line shows the two standard deviation range of the data. Sea Ice Index data.

http://nsidc.org/arcticseaicenews/index.html. National Snow and Ice Data Center, University of Colorado



Feb 2003 – Feb 2007

Feb 2003 – Feb 2009

Average mass loss rate, in cm/yr water equivalent thickness, determined from monthly GRACE gravity field solutions.

Khan et al. Spread of ice mass loss into northwest Greenland observed by GRACE and GPS. Geophysical research letters, V37, L06501, doi:10.1029/2010GL042460, 2010

Effects on sea level

- Linear trends:
  - 230 ± 33 Gt/yr (Greenland) + 143 ± 73 Gt/yr (Antarctica) (Velicogna)

    ⇒ 1.1 ± 0.2 mm/yr sea level rise
  - 104 ±23 Gt/yr (Greenland) + 64 ± 32 Gt/yr (Antarctica) (Wu)

- 2nd order curve fit acceleration (Velicogna):
  - Antarctica: 26 ± 14 Gt/yr^2 ⇒ 0.08 ± 0.04 mm/yr^2
  - Greenland: 30 ± 11 Gt/yr^2 ⇒ 0.09 ± 0.03 mm/yr^2 sea level

Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.

Wu X et al. *Nature Geoscience* DOI: 10.1038/NGEO938 August 2010.

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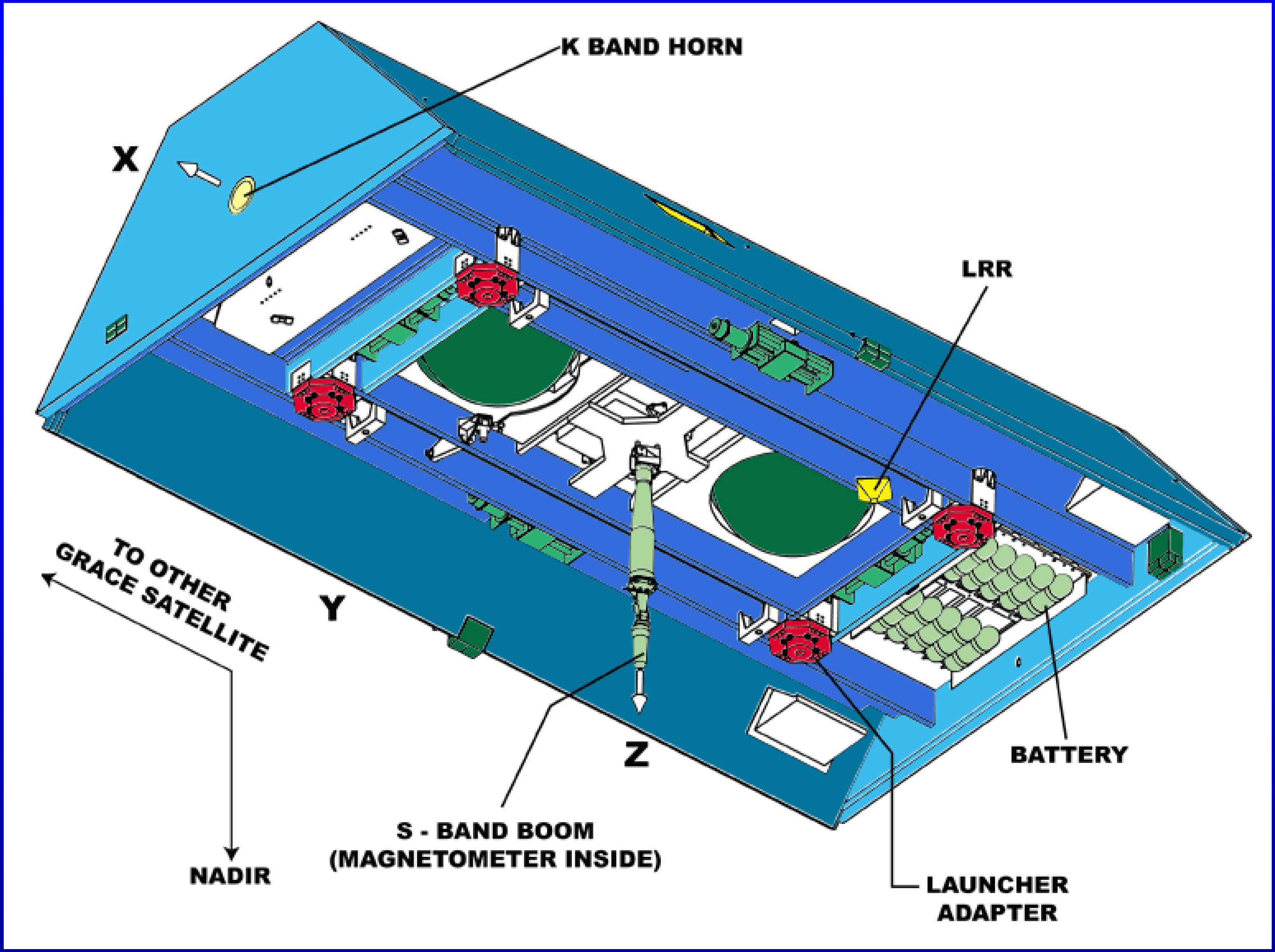
- Uncertainty components in mass loss figures:
  - GRACE gravity field solutions
  - curve fit
  - correction for post-glacial rebound
  - correction for leakage from nearby mass
  - averaging process

Velicogna, I. *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222, 2009.
Wu X et al. *Nature Geoscience* DOI: 10.1038/NGEO938 August 2010.

Update

- Recent GPS measurements of vertical bedrock velocity by a group at Ohio State University suggests that:
  - Postgacial rebound is over-predicted by current models
  - Hence ice loss in Antarctica may be overestimated
  - But: postgalcial rebound rate is constant
  - Therefore acceleration estimates are not contaminated

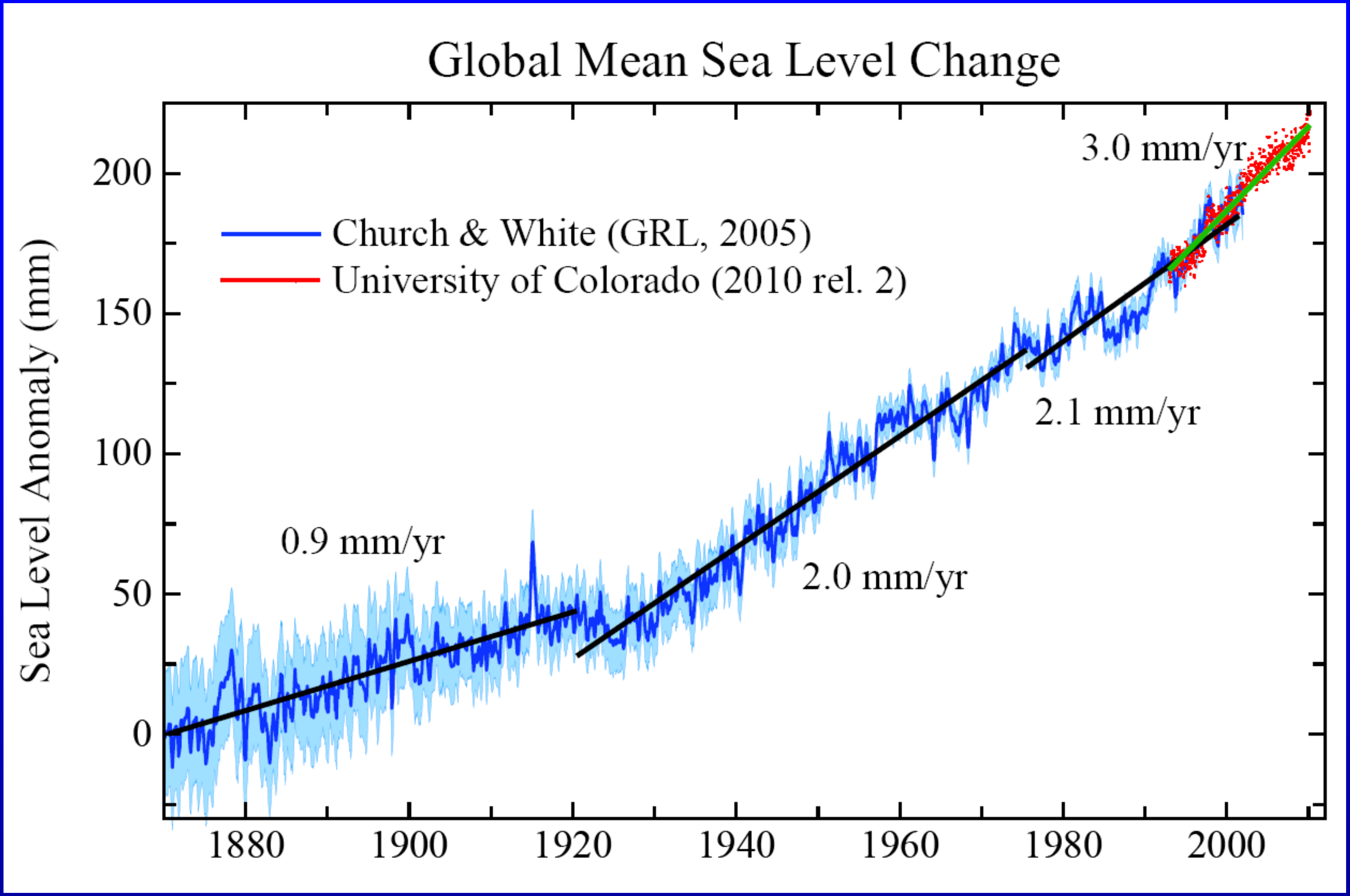
Bevis, M., et al. (2009), Geodetic measurements of vertical crustal velocity in West Antarctica and the implications for ice mass balance, *Geochem. Geophys. Geosyst.*, 10, Q10005, doi:10.1029/2009GC002642.



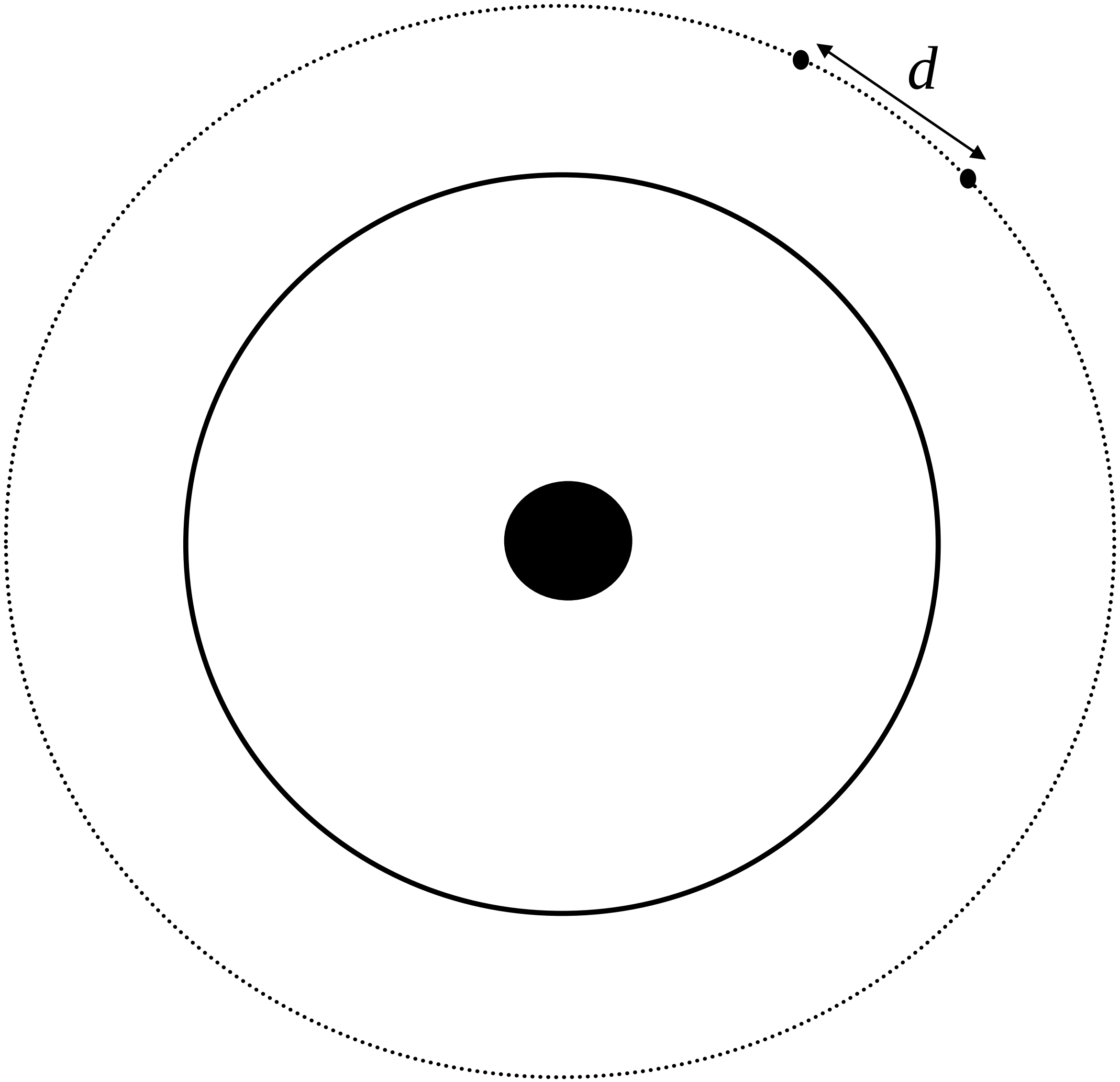
http://op.gfz-potsdam.de/grace/satellite/satellite.html

GAS	Pre-1750 tropospheric concentration[1]	Recent tropospheric concentration[2]	GWP[3] (100-yr time horizon)	Atmospheric lifetime[4] (years)	Increased radiative forcing[5] (W/m^2)
Concentrations in parts per million (ppm)					
Carbon dioxide (CO_2)	280[6]	386.3[7]	1	~ 100[4]	1.66
Concentrations in parts per billion (ppb)					
Methane (CH_4)	700[8]	1866[9]/1742[9]	25	12[4]	0.48
Nitrous oxide (N_2O)	270[10]	323[9]/321[9]	298	114[4]	0.16
Tropospheric ozone (O_3)	25[1]	34[4,1]	n.a.[4]	hours-days	0.35[4]
Concentrations in parts per trillion (ppt)					
CFC-11 (trichlorofluoromethane) (CCl_3F)	zero	243[9]/241[9]	4,750	45	0.063
CFC-12 (CCl_2F_2)	zero	537[9]/535[9]	10,900	100	0.17
CF-113(CCl_2FCClF_2)	zero	76[9]/76[9]	6,130	85	0.024
HCFC-22($CHClF_2$)	zero	210[9]/186[9]	1,810	12	0.033
HCFC-141b(CH_3CCl_2F)	zero	21[9]/19[9]	725	9.3	0.0025
HCFC-142b(CH_3CClF_2)	zero	21[9]/19[9]	2,310	17.9	0.0031
Halon 1211 ($CBrClF_2$)	zero	4.4[9]/4.2[9]	1,890	16	0.001
Halon 1301 ($CBrClF_3$)	zero	3.3[9]/3.2[9]	7,140	65	0.001
HFC-134a(CH_2FCF_3)	zero	57[9]/47[9]	1,430	14	0.0055
Carbon tetrachloride (CCl_4)	zero	88[9]/87[9]	1,400	26	0.012
Methyl chloroform (CH_3CCl_3)	zero	9.7[9]/9.3[9]	146	5	0.0011
Sulfur hexafluoride (SF_6)	zero	6.84[9,11]/6.44[9,11]	22,800	3200	0.0029
Other Halocarbons	zero	Varies by substance			collectively 0.021

http://cdiac.ornl.gov/pns/current_ghg.html



http://www.columbia.edu/~mhs119/SeaLevel/SL_1870-2010.pdf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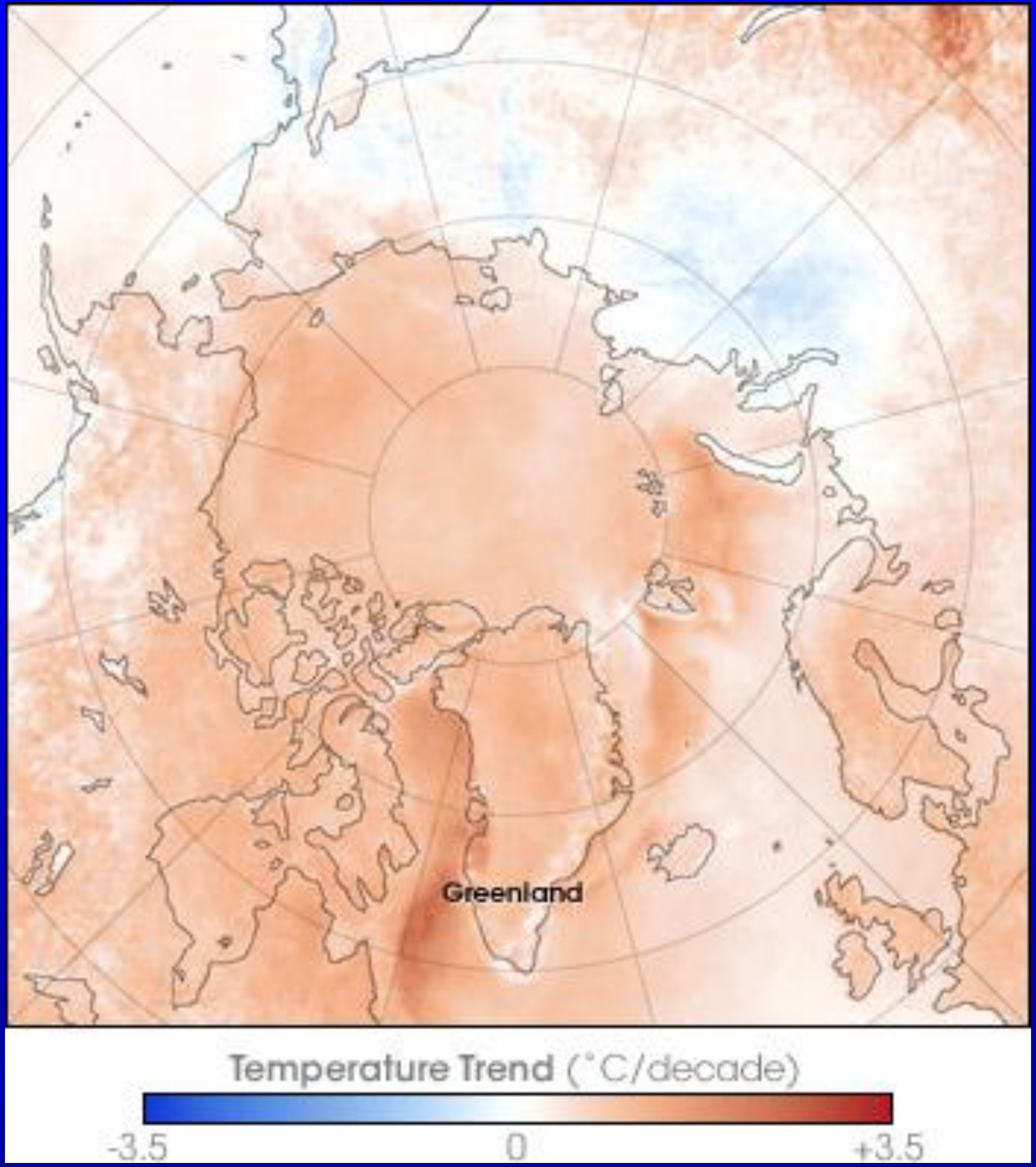
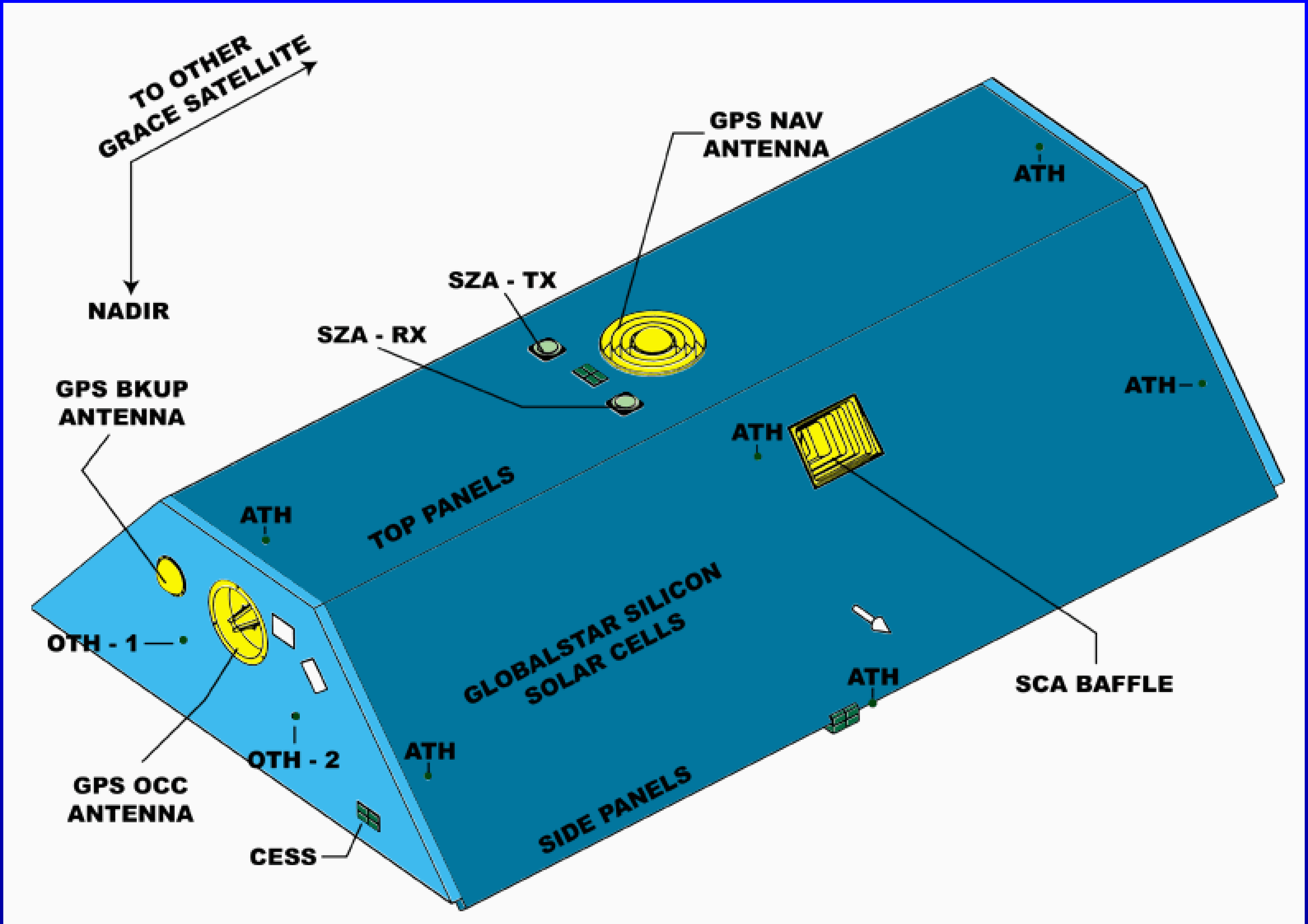
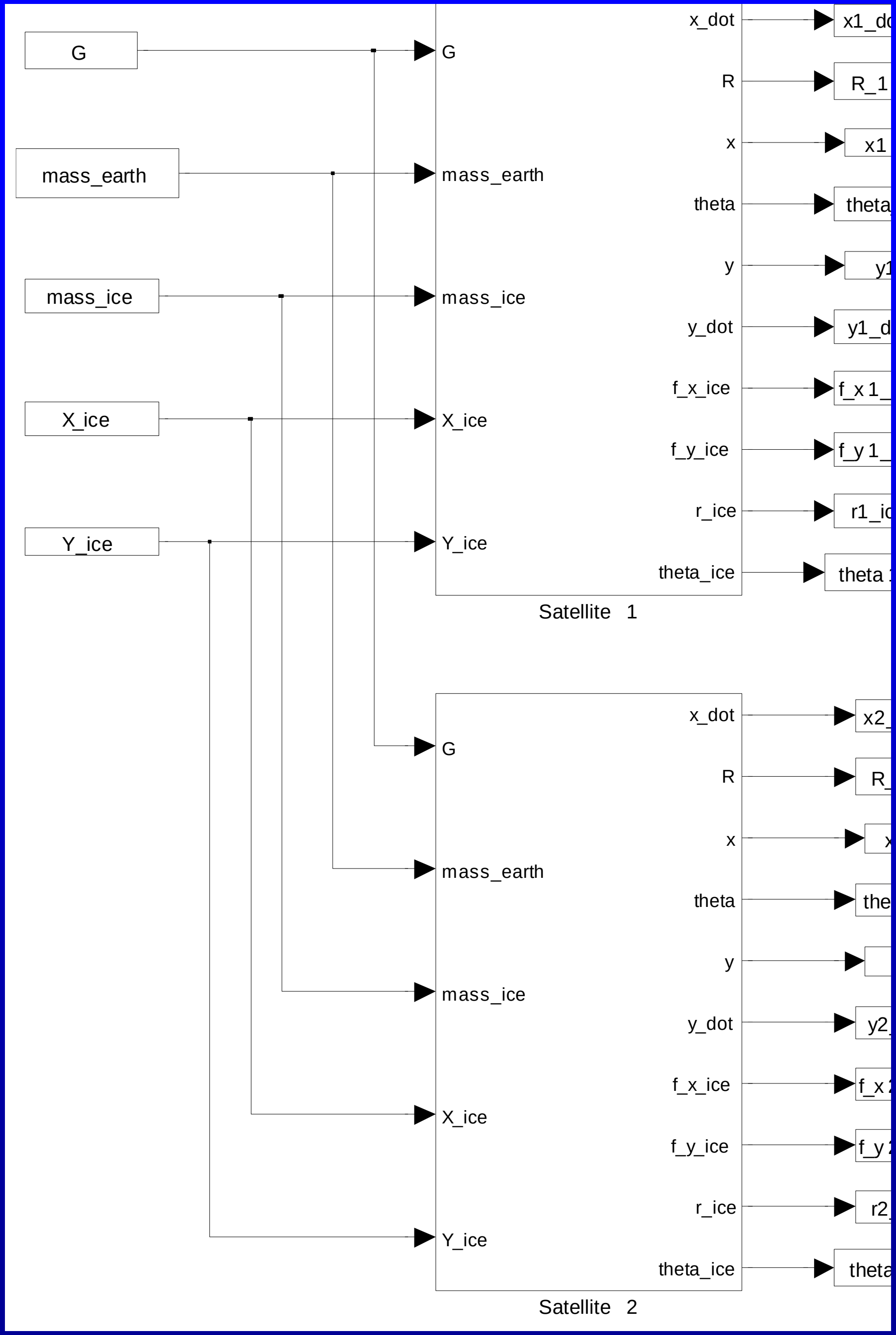


Arctic temperature trend 1987 – 2007. (NASA)
http://en.wikipedia.org/wiki/File:Arctic_Temperature_Trend_1987-2007.jpg



http://op.gfz-potsdam.de/grace/satellite/satellite.html



G
mass_earth
mass_ice
X_ice
Y_ice
G
mass_earth
mass_ice
X_ice
Y_ice
x_dot
R
x
theta
y
y_dot
f_x_ice
f_y_ice
r_ice
theta_ice
Satellite 1
G
mass_earth
mass_ice
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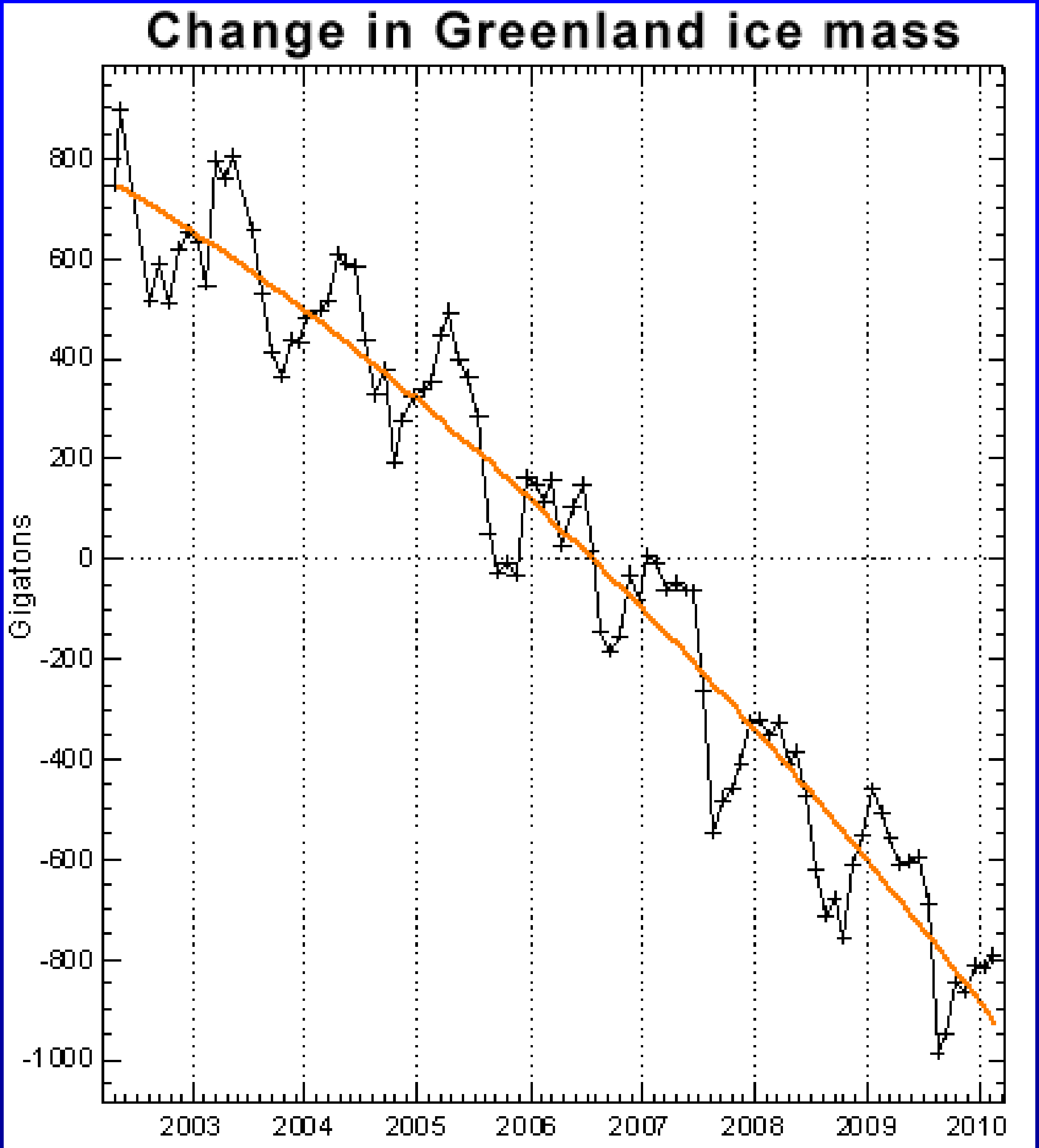
r_ice
theta_ice
Satellite 2



Unpublished results. John Wahr Dept Physics Univ of Colorado, 2010

$$f = \frac{Gm_1m_2}{r^2}$$