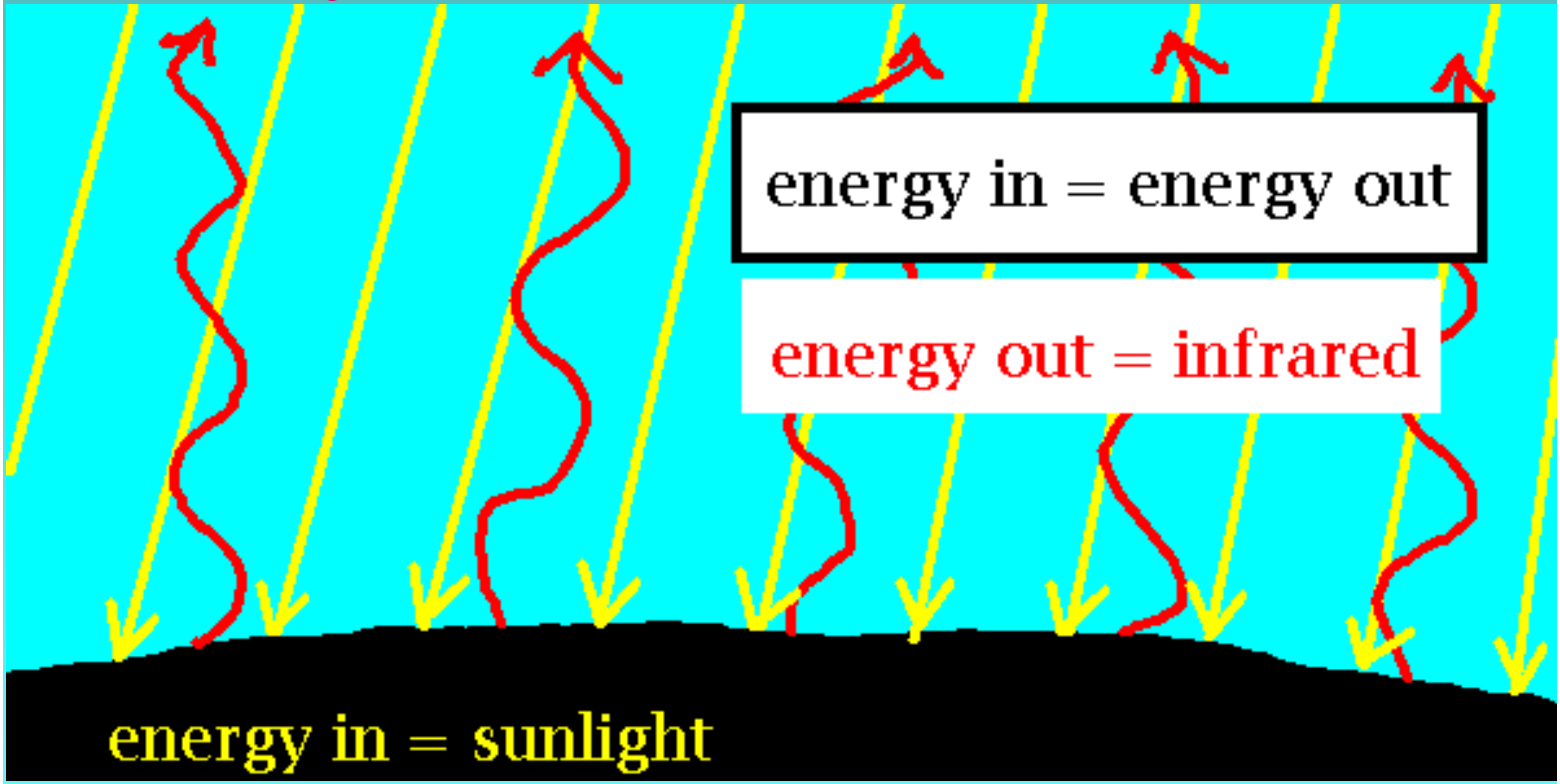
Climate Change: Basic Physics and Trends and Projections of Concentrations of Greenhouse Gases and Ambient Temperature

Mark Goldberg

Equilibrium Situation

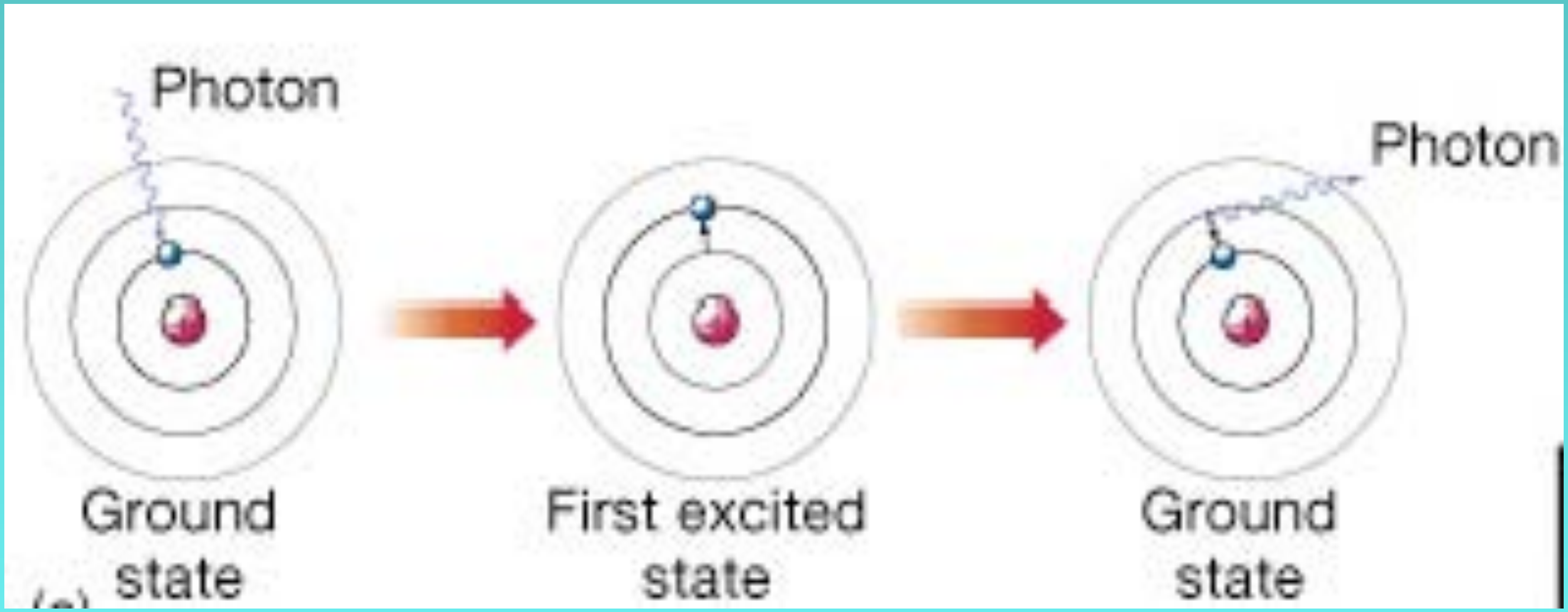
~5 km above ground and about -19°C



http://zebu.uoregon.edu/~soper/Earth/earthtemp.html

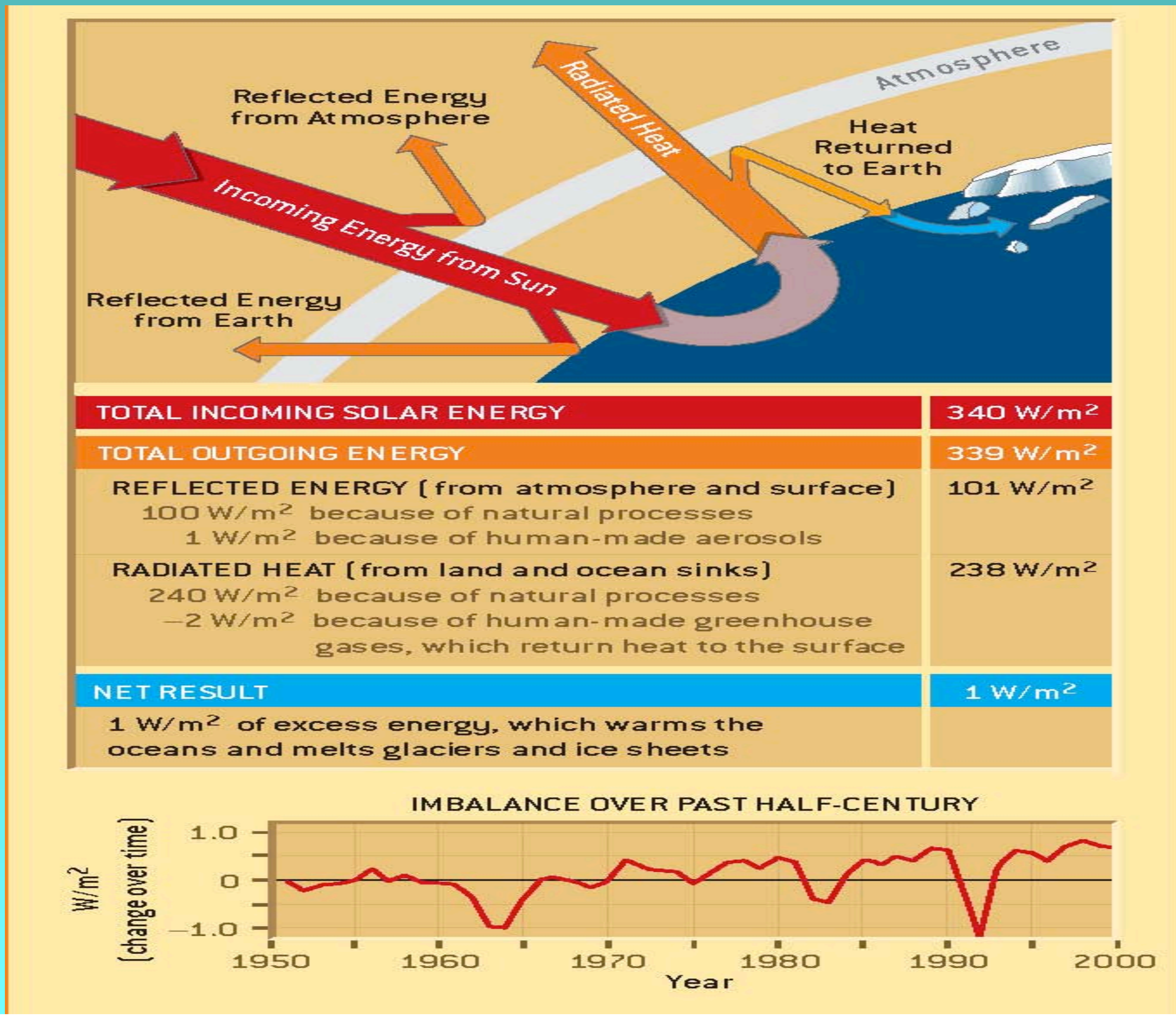
Infrared Radiation

Absorption and remission of photons



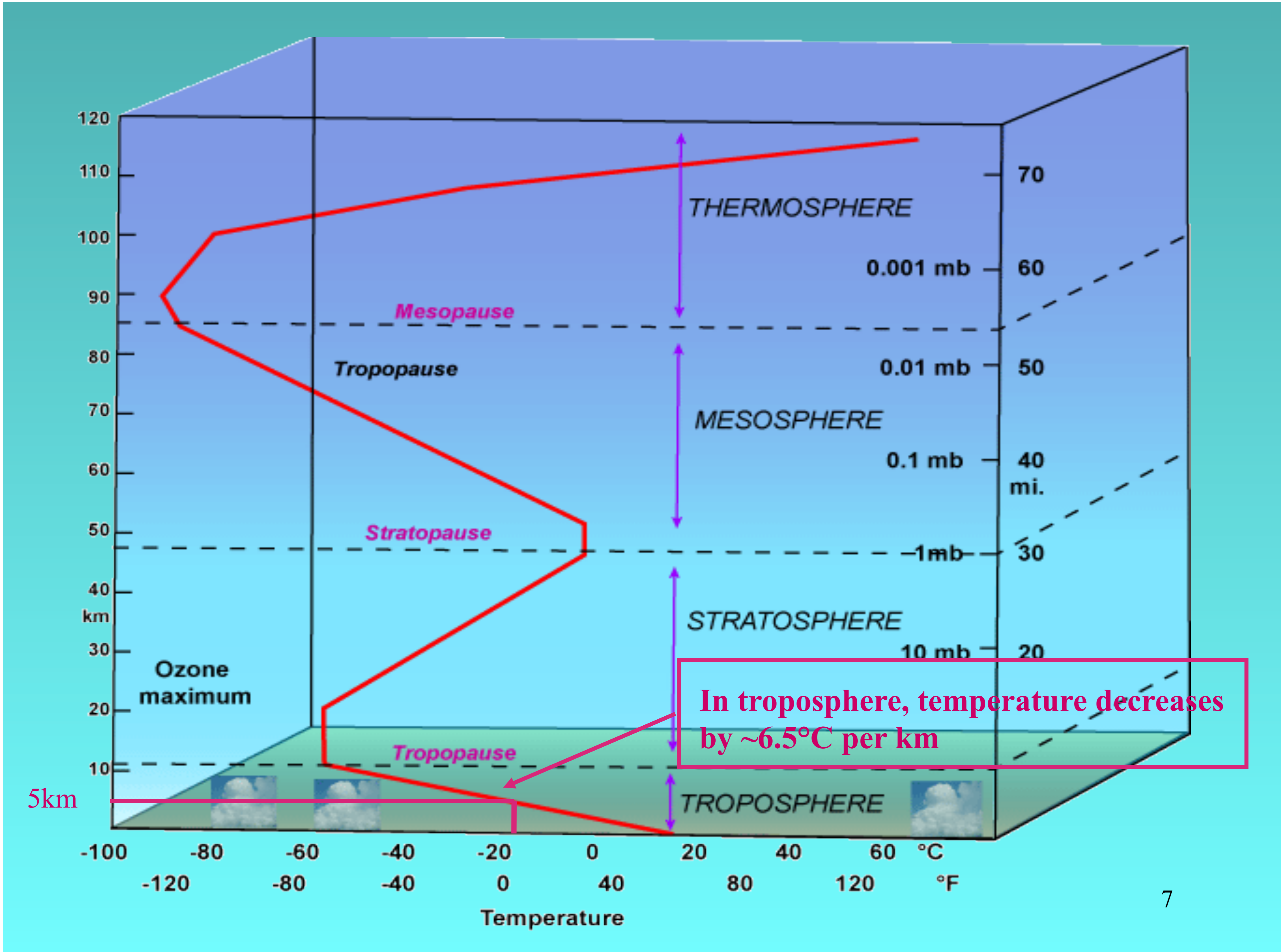
The emitted photon can go in any direction

Energy Imbalance (J Hansen)



Greenhouse Effect: Essential Concepts

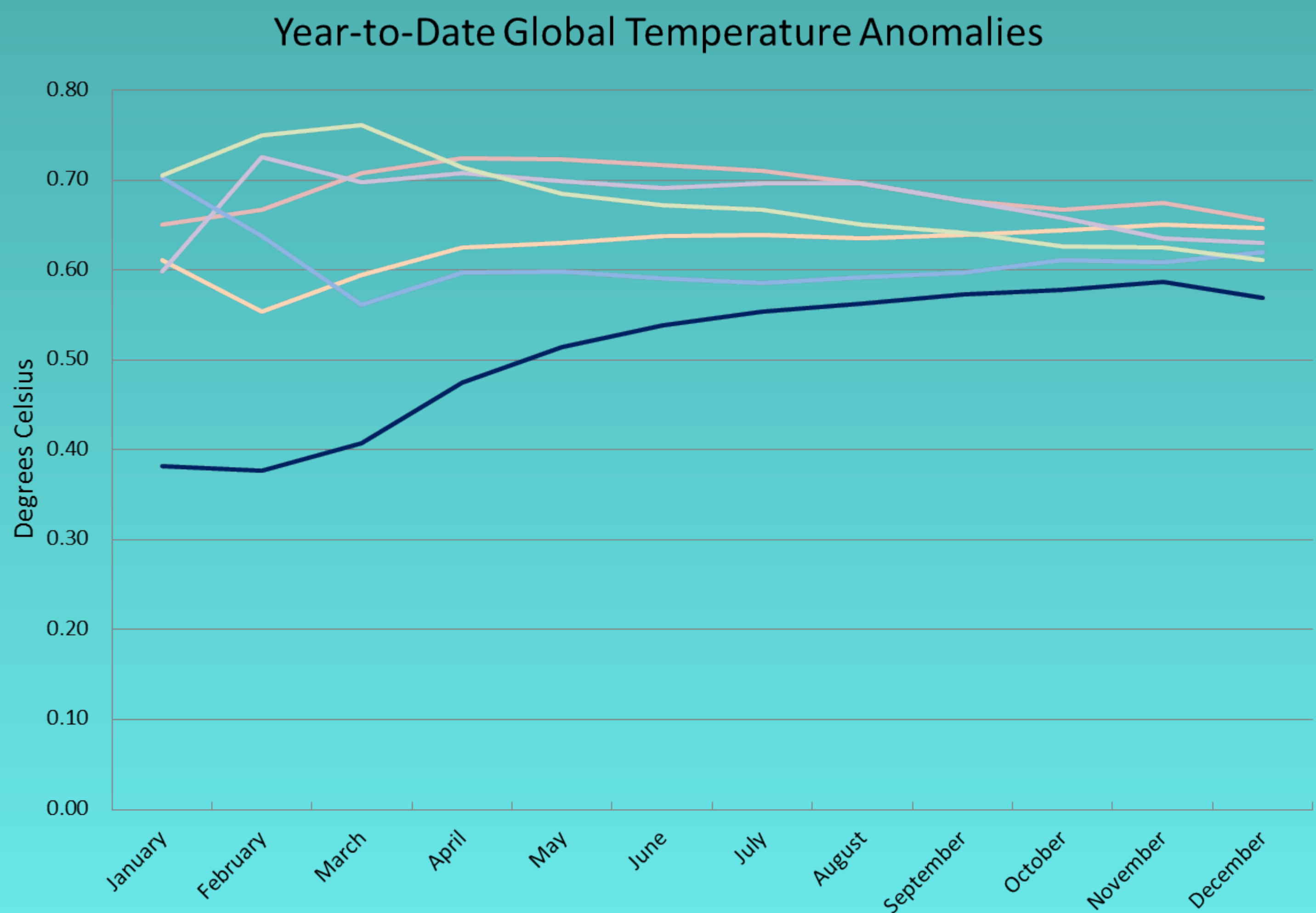
- Infrared radiation emitted to space originates from an altitude of ~5 km and it has a temperature of about −19°C
- The Earth's surface is at a much higher temperature of, on average, +14°C
  - $T_{surface}$= -19°C + 5km x 6.5°C/km=14°C



120
110
100
90
80
70
60
50
40
km
30
20
10
5km
Mesopause
Tropopause
Stratopause
Tropopause
Ozone maximum
THERMOSPHERE
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
0.001 mb
0.01 mb
0.1 mb
1 mb
10 mb
70
60
50
40
mi.
30
20
In troposphere, temperature decreases by ~6.5°C per km
-100 -80 -60 -40 -20 0 20 40 60 °C
-120 -80 -40 0 40 80 120 °F
Temperature

2012: Land and ocean average global temperature

- Average global temperature in 2012: 14.47°C
- 10th warmest year since records began in 1880
  - 20th century average of 13.9°C (57.0°F)



Anomaly = difference from the 20th century average of 13.9°C (57.0°F)

Selected Important Greenhouse Gases

Gas	Preindustrial concentration	Current concen-tration	Increase since 1750	Atmosph-eric lifetime (years)	Green-house Warming Potential
CO_2	280 ppm	393.8 ppm	113.8	100	1
Methane	700 ppb	1,874 ppb	1,174	12	25
Nitrous oxide (N_2O)	270 ppb	324 ppb	54	114	298
CFC-12	0	531 ppt	531	100	10,900

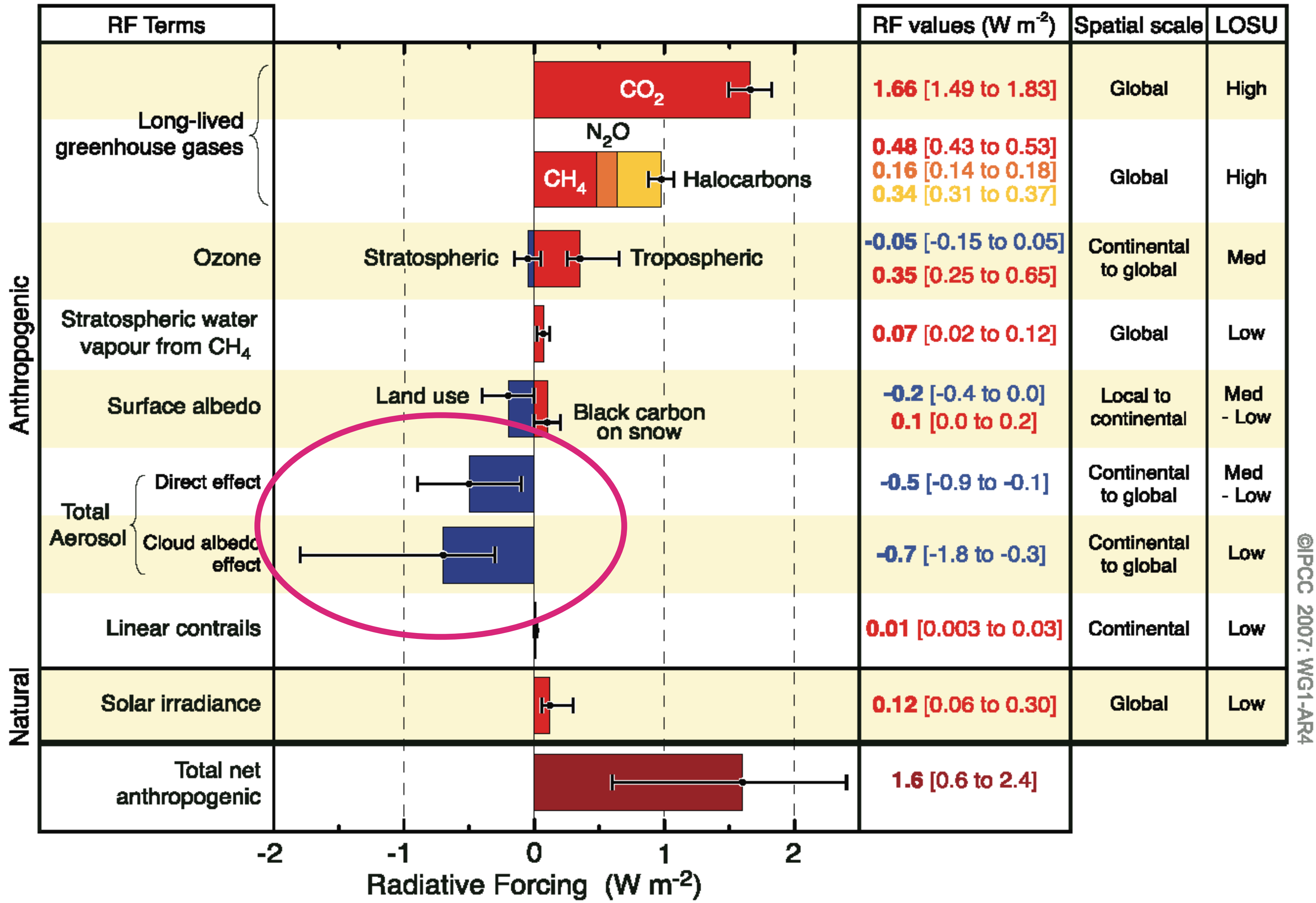
Definition: Radiative Forcing

- The difference between the incoming radiation energy and the outgoing radiation energy in a given climate system
- "A measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system" (IPCC WG1, 2007)

Radiative Forcing

- A positive forcing (more incoming energy) tends to warm
- A negative forcing (more outgoing energy) tends to cool
- Examples of positive forcing:
  - increases in incident solar radiation
  - increases in green house gases

Radiative Forcing Components



IPCC-Climate sensitivity: ~ 0.75 ± 0.25°C per watt per square meter.

Other Factors that Can Contribute to Global Warming

Changes in Solar Flux

- 11 year solar cycle
- Milankovitch cycles
  - See Wikipedia and the *Weather Makers*

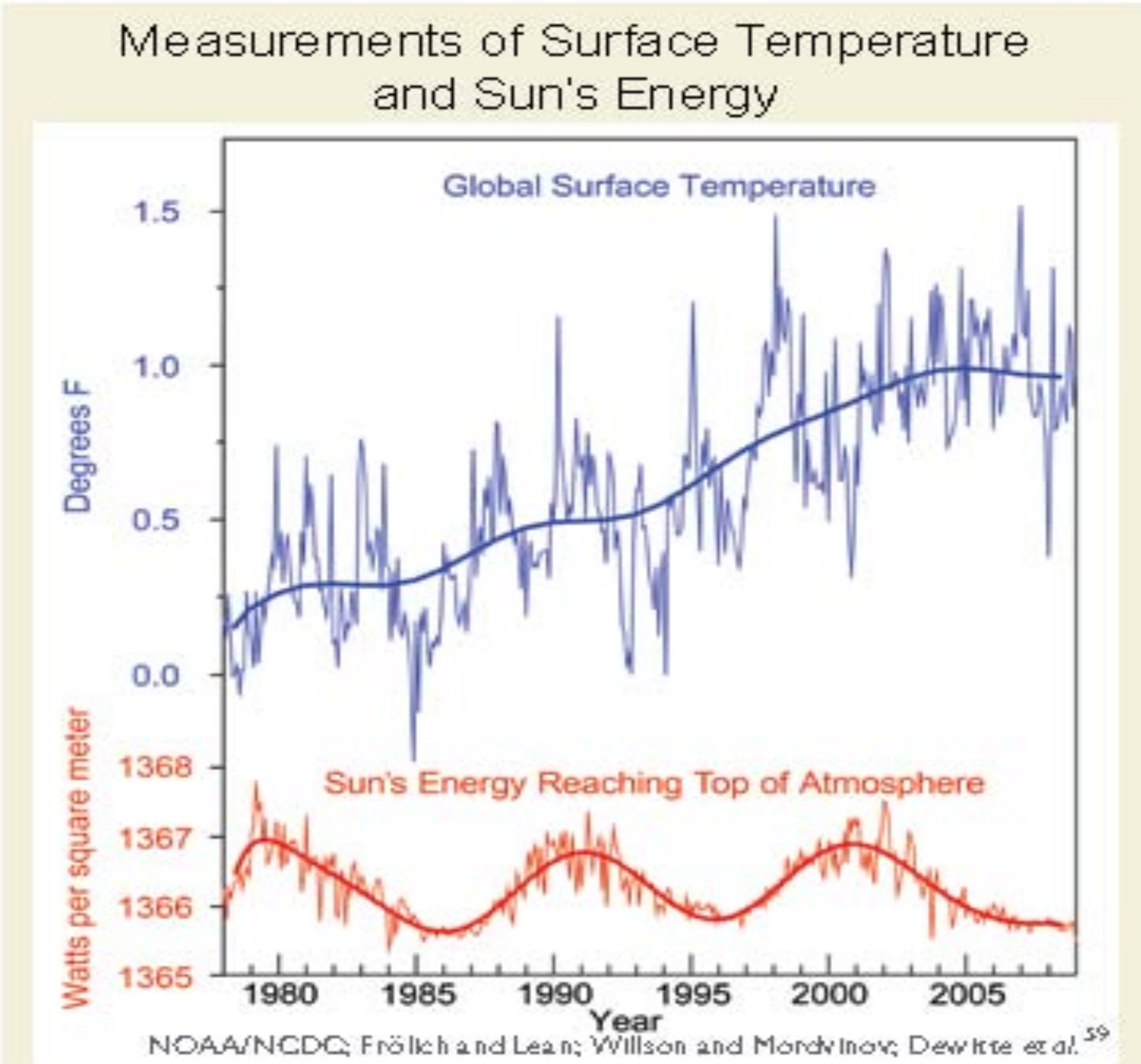
Milankovitch Cycles

- **Milankovitch cycles** are the collective effect of changes in the Earth's movements upon its climate, named after Milutin Milanković

- These variations in the earth's orbit have a profound effect on climate, but over very long periods of time

Short-term Solar Sunspot Activity

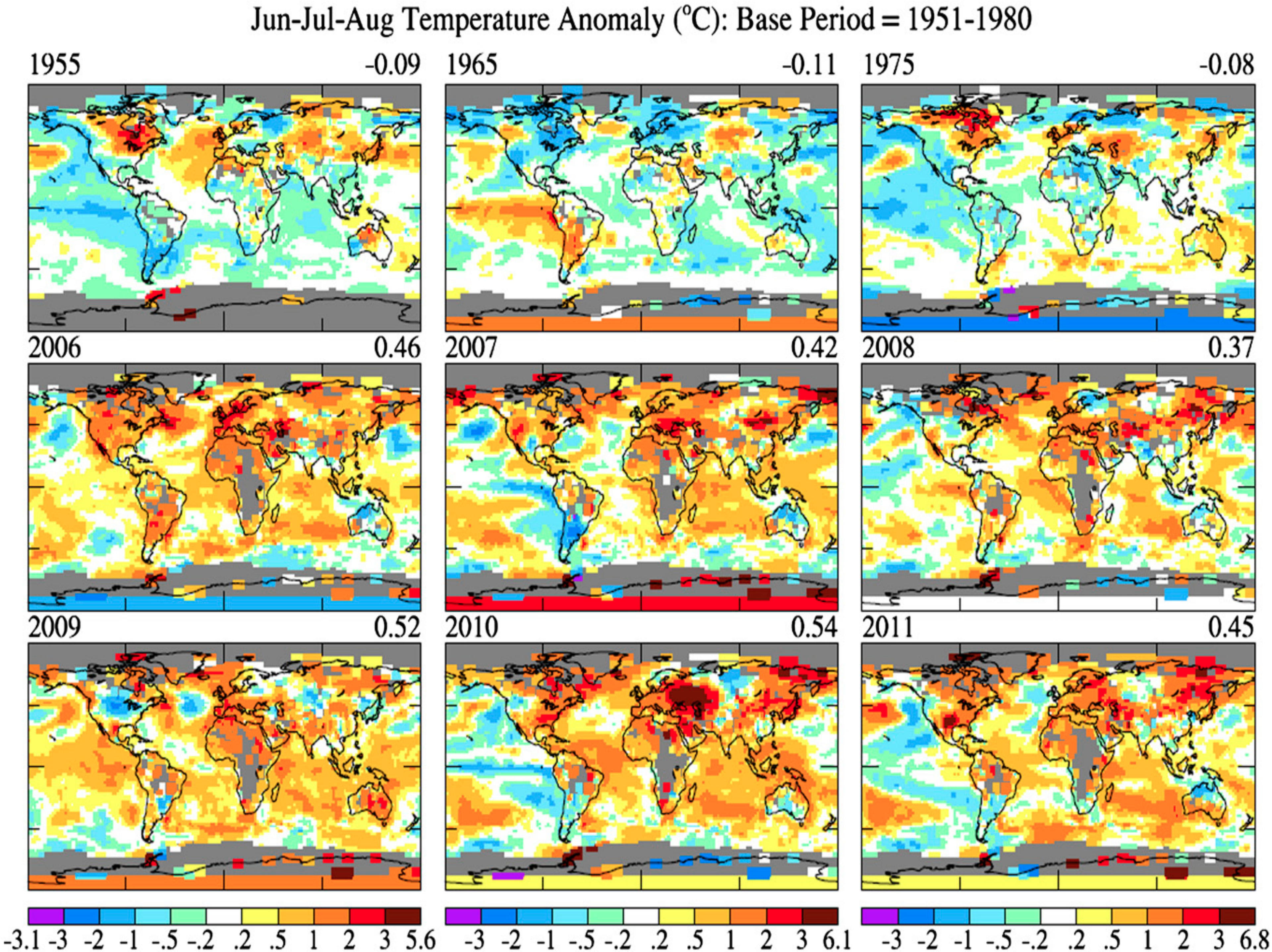
- Average duration of sunspot cycle is 11.1 years (range: 9-14 years)
- 28 year cycle in which there are minima and maxima in solar irradiance


Measurements of Surface Temperature
and Sun's Energy
Global Surface Temperature
Degrees F
1.5
1.0
0.5
0.0
Sun's Energy Reaching Top of Atmosphere
Watts per square meter
1368
1367
1366
1365
1980
1985
1990
1995
2000
2005
Year
NOAA/NCDC; Frölich and Lean; Willson and Mordvinov; Dewitte et al.59

Observations of Climate Change: Evidence for Anthropocentric Effect on Climate

Can we say that current weather is due to global warming, or is it just a statistical fluke?

From: Hansen et al. “Perception of Climate Change”
PNAS September 11, 2012, vol. 109 (37), p 14727ff


Jun-Jul-Aug Temperature Anomaly (°C): Base Period = 1951-1980
1955 -0.09
1965 -0.11
1975 -0.08
2006 0.46
2007 0.42
2008 0.37
2009 0.52
2010 0.54
2011 0.45
-3.1 -3 -2 -1 -.5 -.2 .2 .5 1 2 3 5.6
-3 -2 -1 -.5 -.2 .2 .5 1 2 3 6.1
-3 -2 -1 -.5 -.2 .2 .5 1 2 3 6.8

Changes in Climate this Century

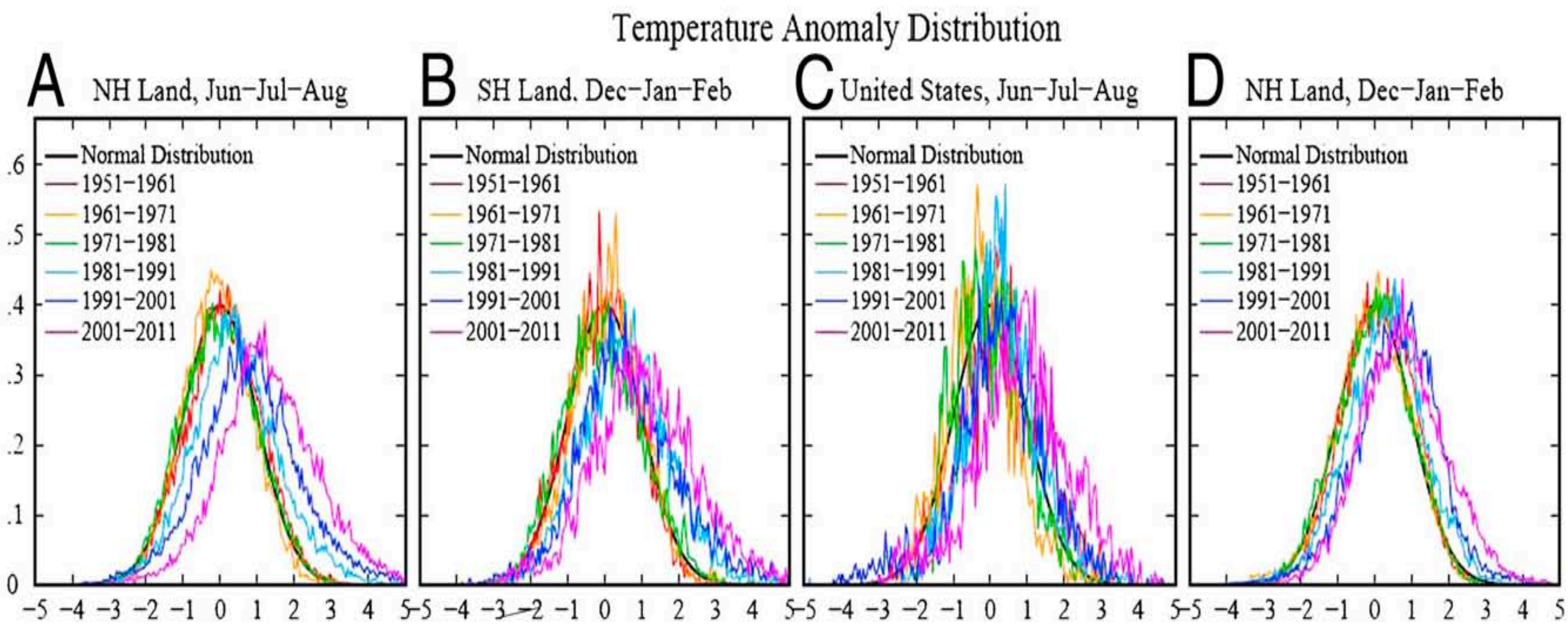
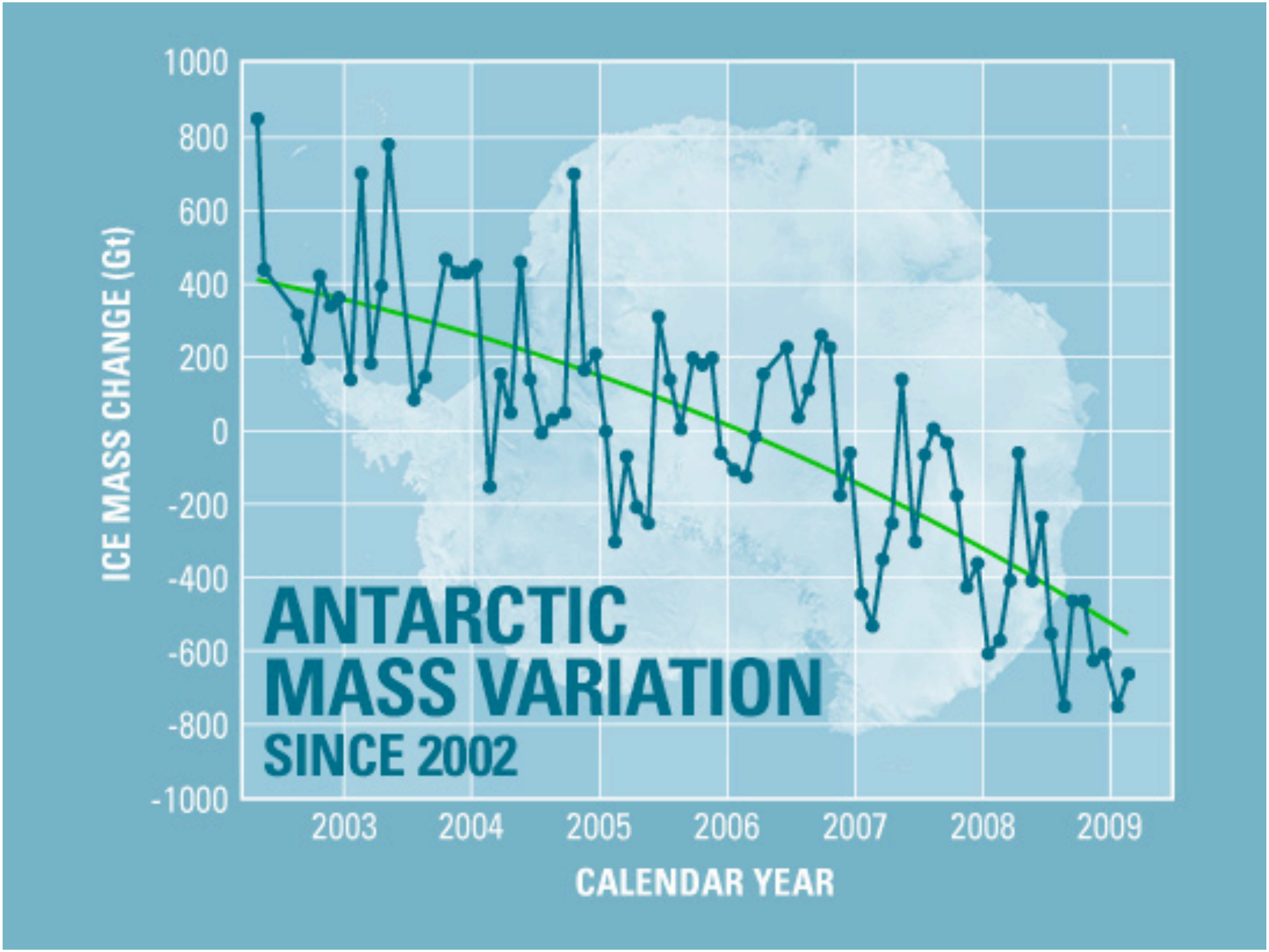
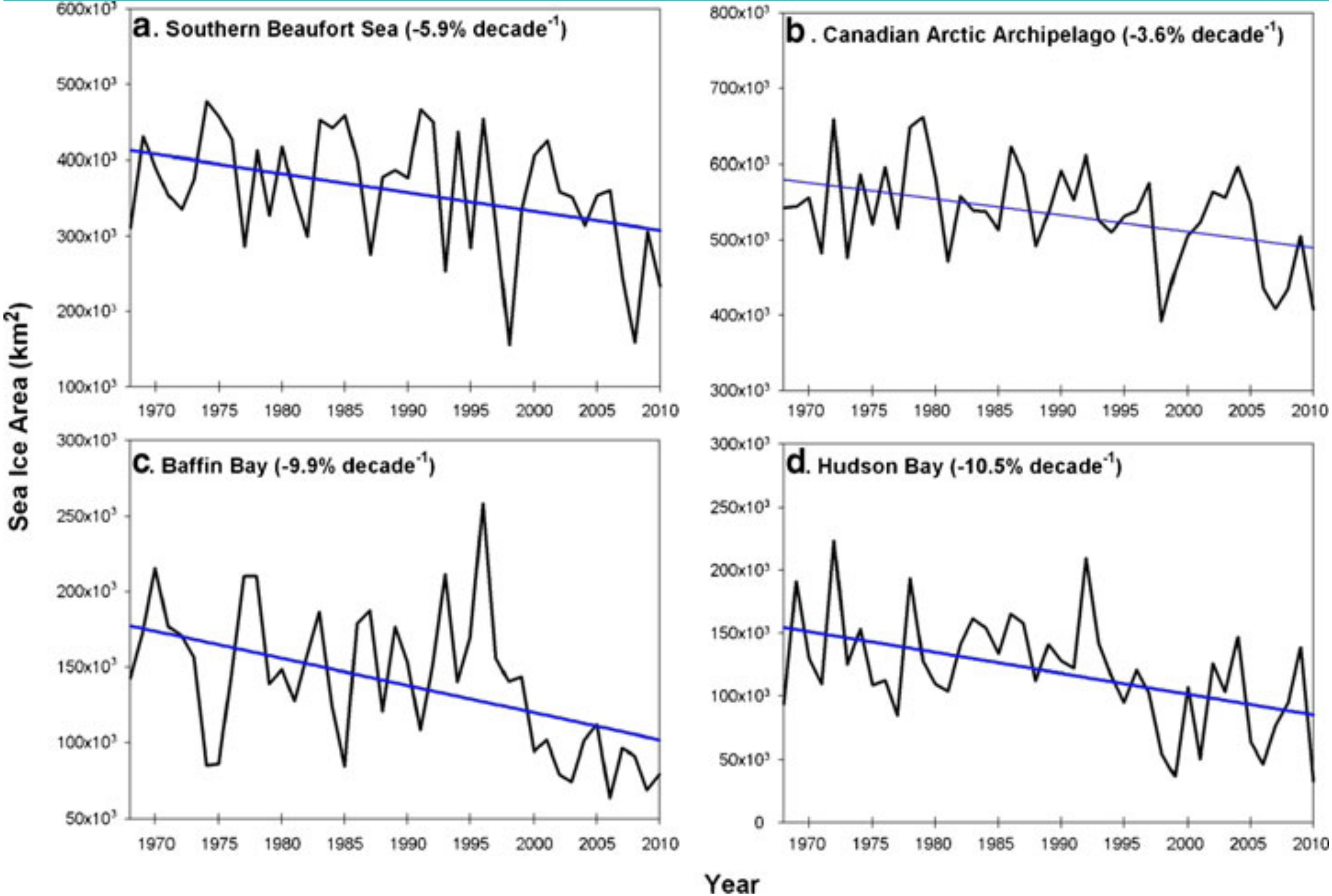


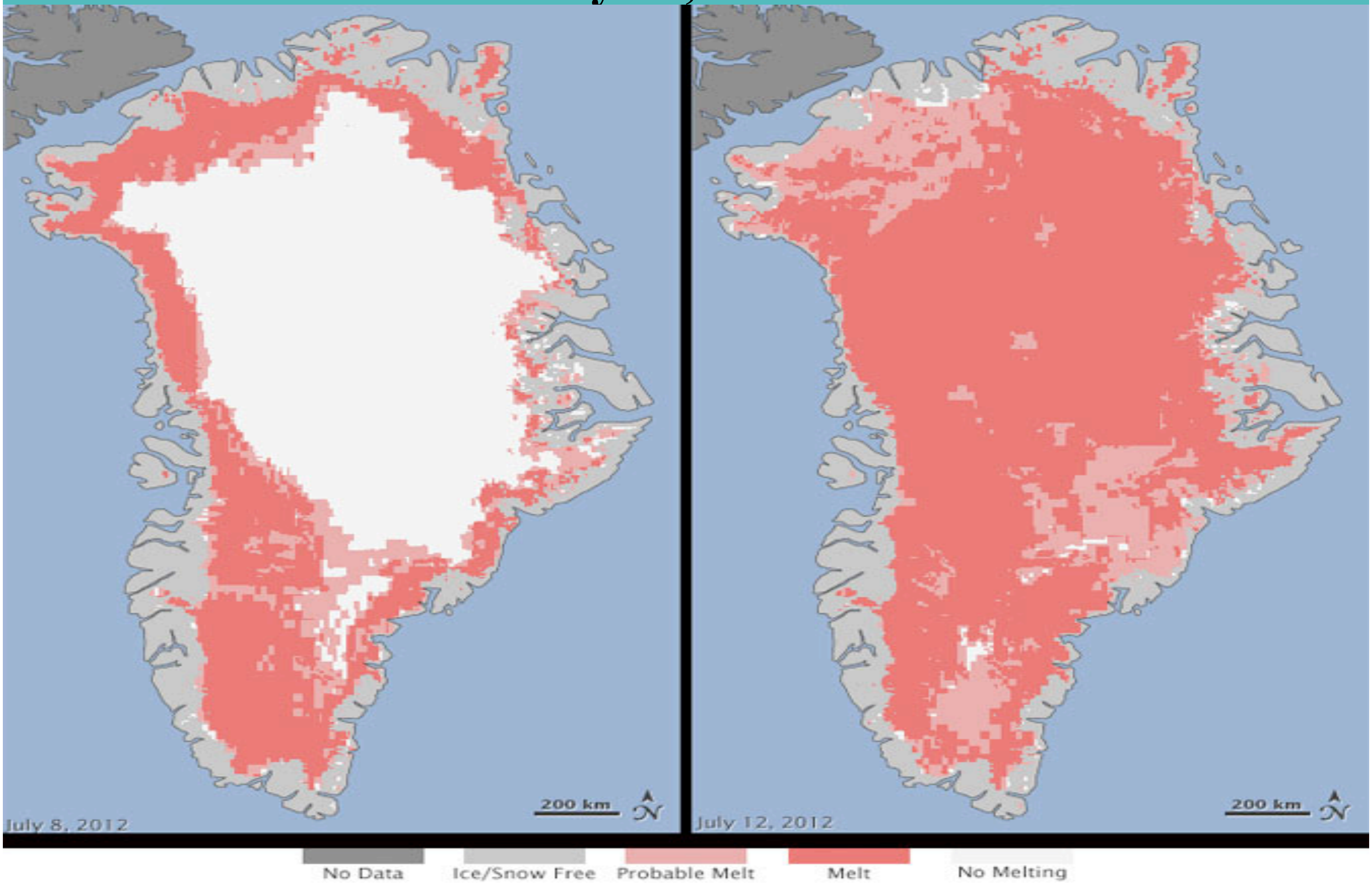
Fig. P1. Frequency of occurrence of local temperature anomalies (relative to 1951–1980 mean) divided by local standard deviation obtained by counting gridboxes with anomalies in each 0.05 interval of the standard deviation (*x* axis). Area under each curve is unity.

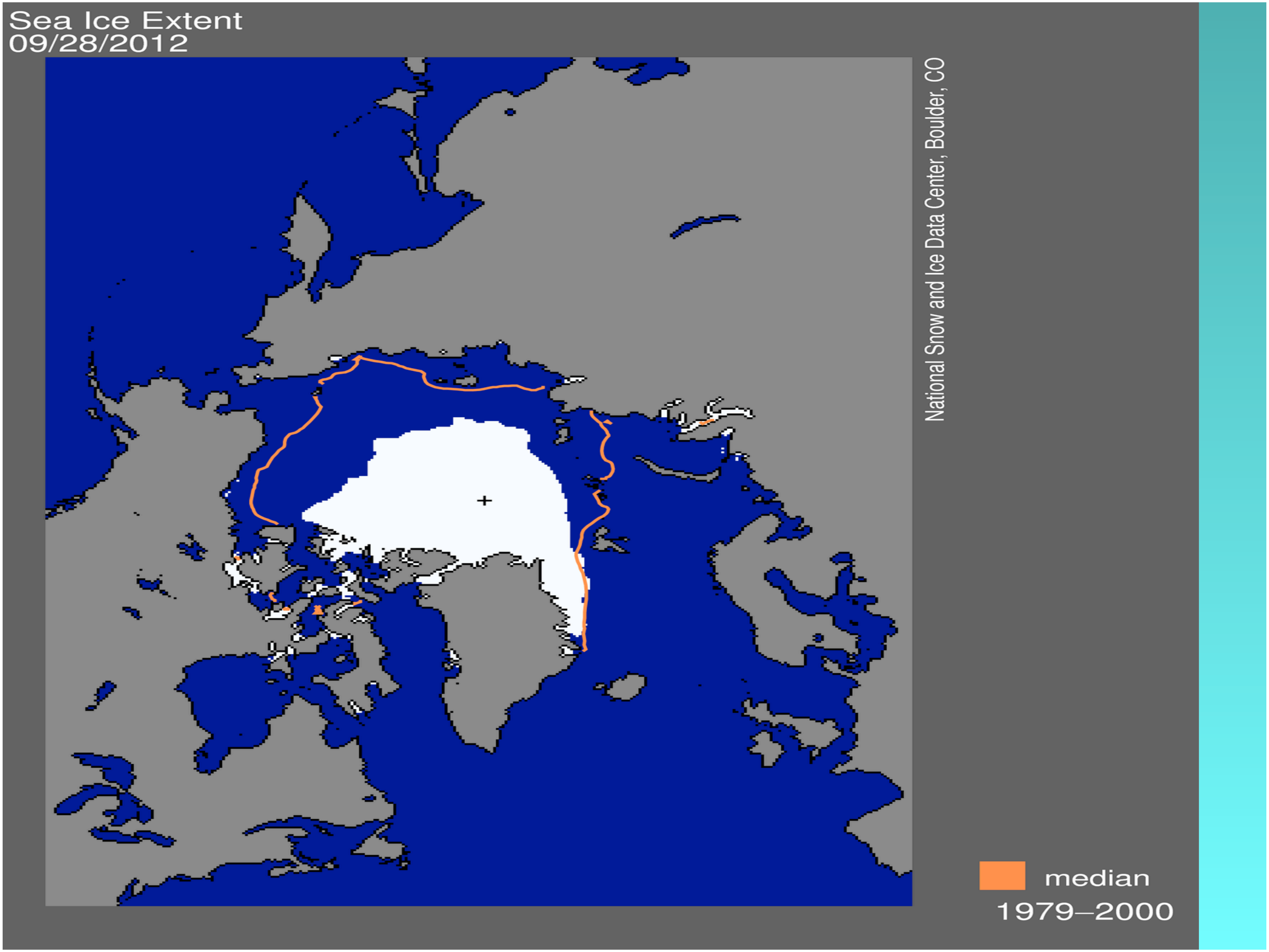

ANTARCTIC
MASS VARIATION
SINCE 2002
ICE MASS CHANGE (Gt)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
2003
2004
2005
2006
2007
2008
2009
CALENDAR YEAR

Summer Total Sea Ice in the Canadian Arctic

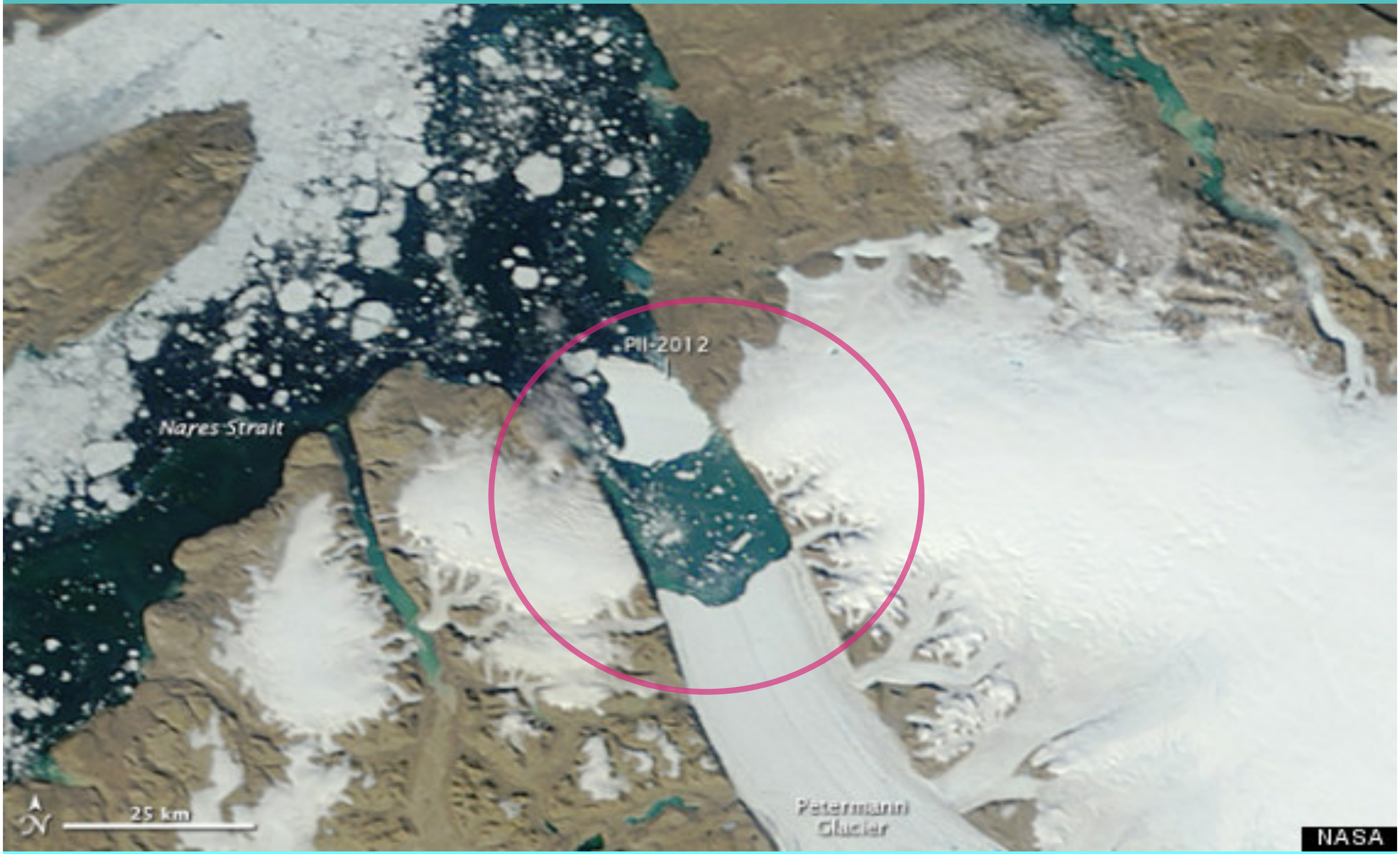


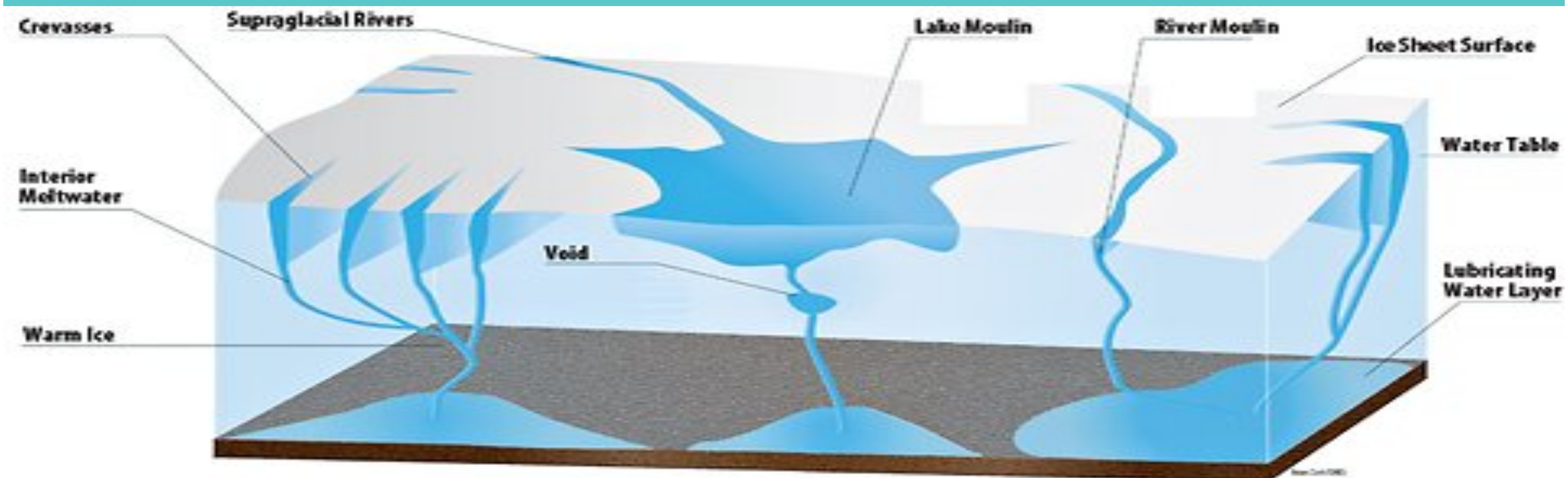
Ice melt Greenland from Satellites: L: July 8; R: July 12, 2012

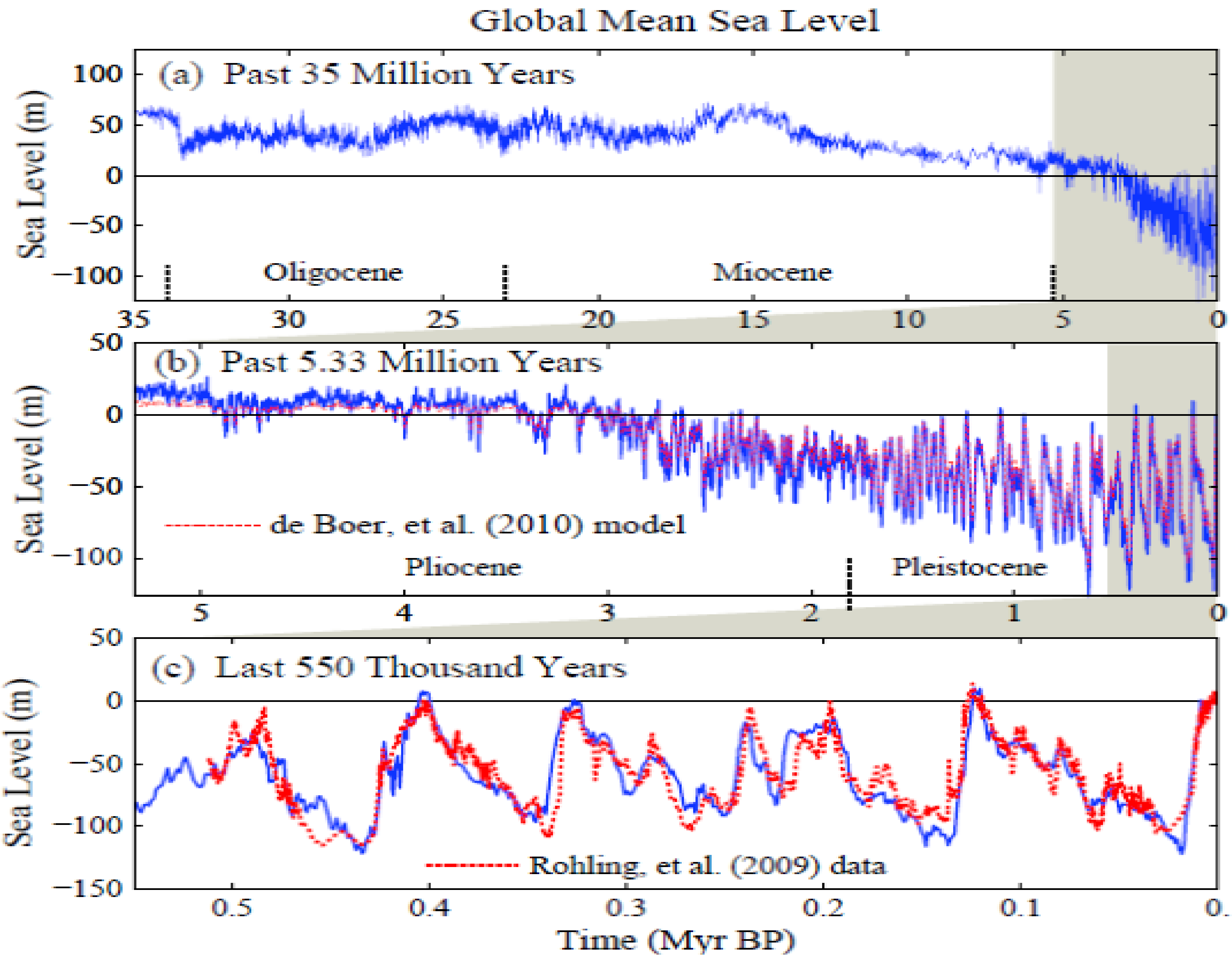



Sea Ice Extent
09/28/2012
National Snow and Ice Data Center, Boulder, CO
median
1979–2000

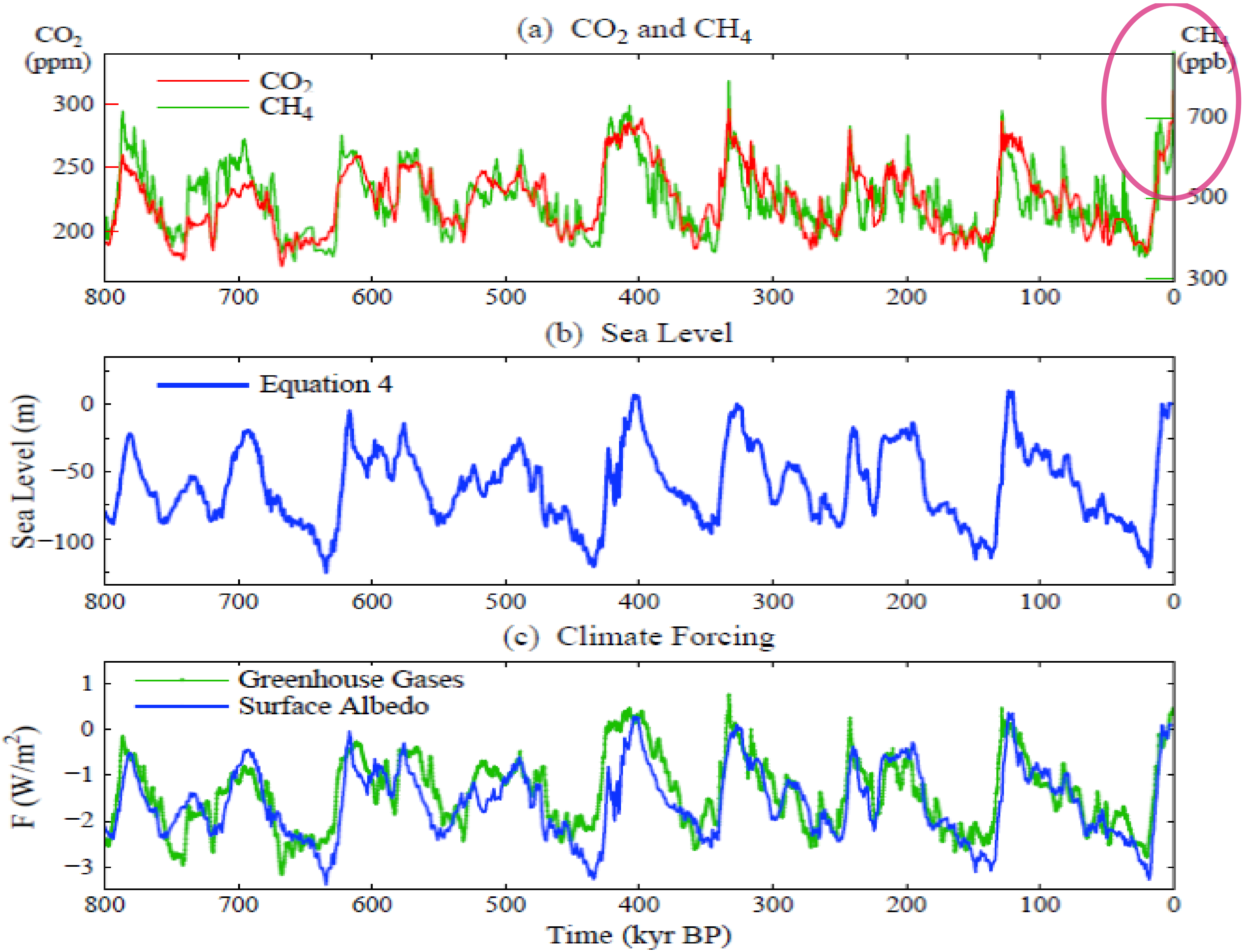
Petermann Glacier: Giant Calving Event (120 km^2) July 30, 2012




Crevasses
Supraglacial Rivers
Lake Moulin
River Moulin
Ice Sheet Surface
Water Table
Interior
Meltwater
Void
Warm Ice
Lubricating
Water Layer



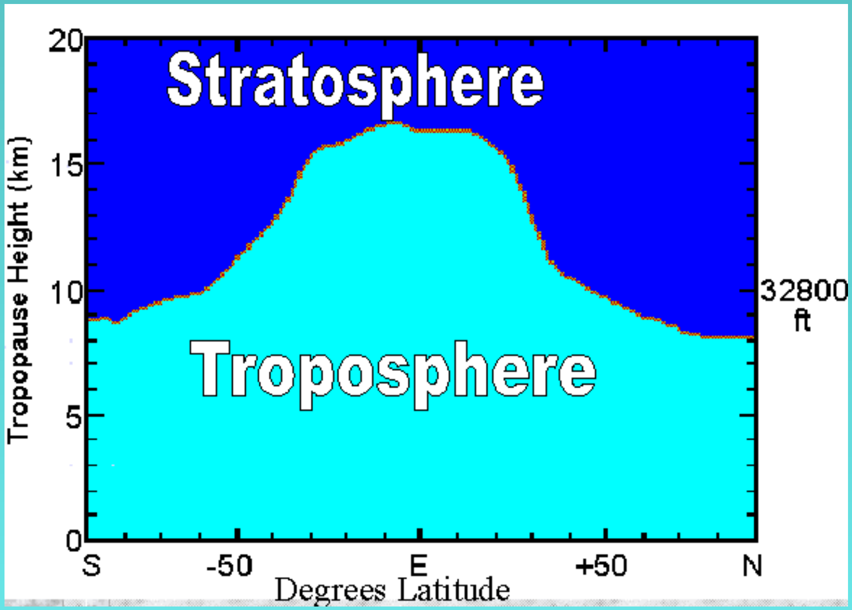
Global Mean Sea Level
(a) Past 35 Million Years
Sea Level (m)
100
50
0
−50
−100
Oligocene
Miocene
35
30
25
20
15
10
5
0
(b) Past 5.33 Million Years
50
0
−50
−100
de Boer, et al. (2010) model
Pliocene
Pleistocene
5
4
3
2
1
0
(c) Last 550 Thousand Years
50
0
−50
−100
−150
Rohling, et al. (2009) data
0.5
0.4
0.3
0.2
0.1
0.
Time (Myr BP)


(a) CO2 and CH4
CO2 (ppm)
CH4 (ppb)
CO2
CH4
300
250
200
700
500
300
800
700
600
500
400
300
200
100
0
(b) Sea Level
Equation 4
Sea Level (m)
0
−50
−100
(c) Climate Forcing
Greenhouse Gases
Surface Albedo
F (W/m2)
1
0
−1
−2
−3
Time (kyr BP)

Why is the Arctic highly affected by global warming

- **Ice-albedo feedback**: initial warming causes snow and ice to melt ➔exposes darker surfaces that absorb more sunlight➔warms the atmosphere
- **Less water vapour**: less energy used in evaporation➔more energy absorbed by the atmosphere

- **Cold air reduces convection**: shallower layer of air that gets heated as compared to non-Arctic areas



- **Reduction in sea-ice**: more energy being transferred from the warm ocean to the atmosphere

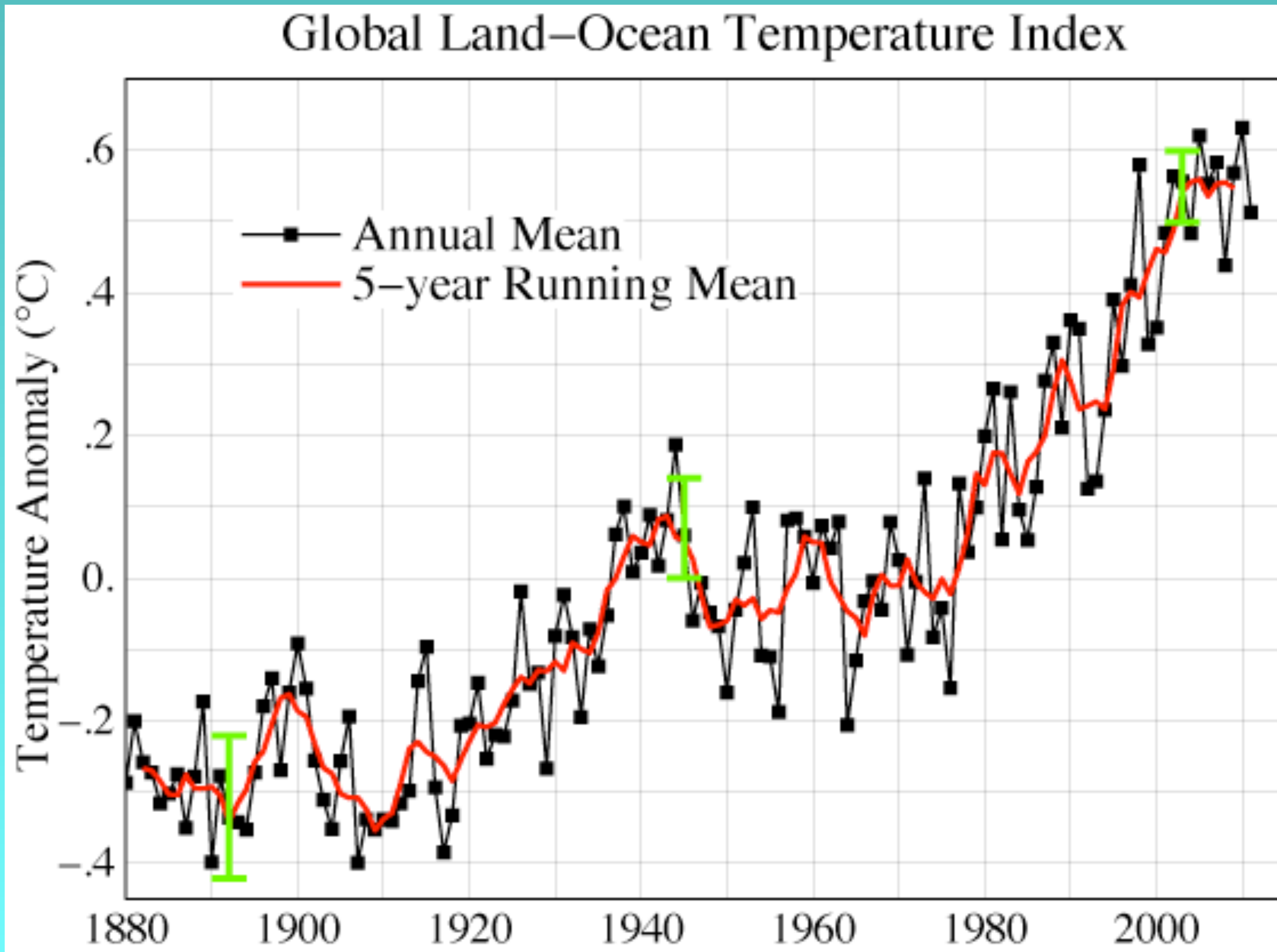
- **Transfer of heat from warmer areas:** changes in patterns of atmospheric and oceanic circulation ➔ more heat transferred to the Arctic

Global Warming Projections

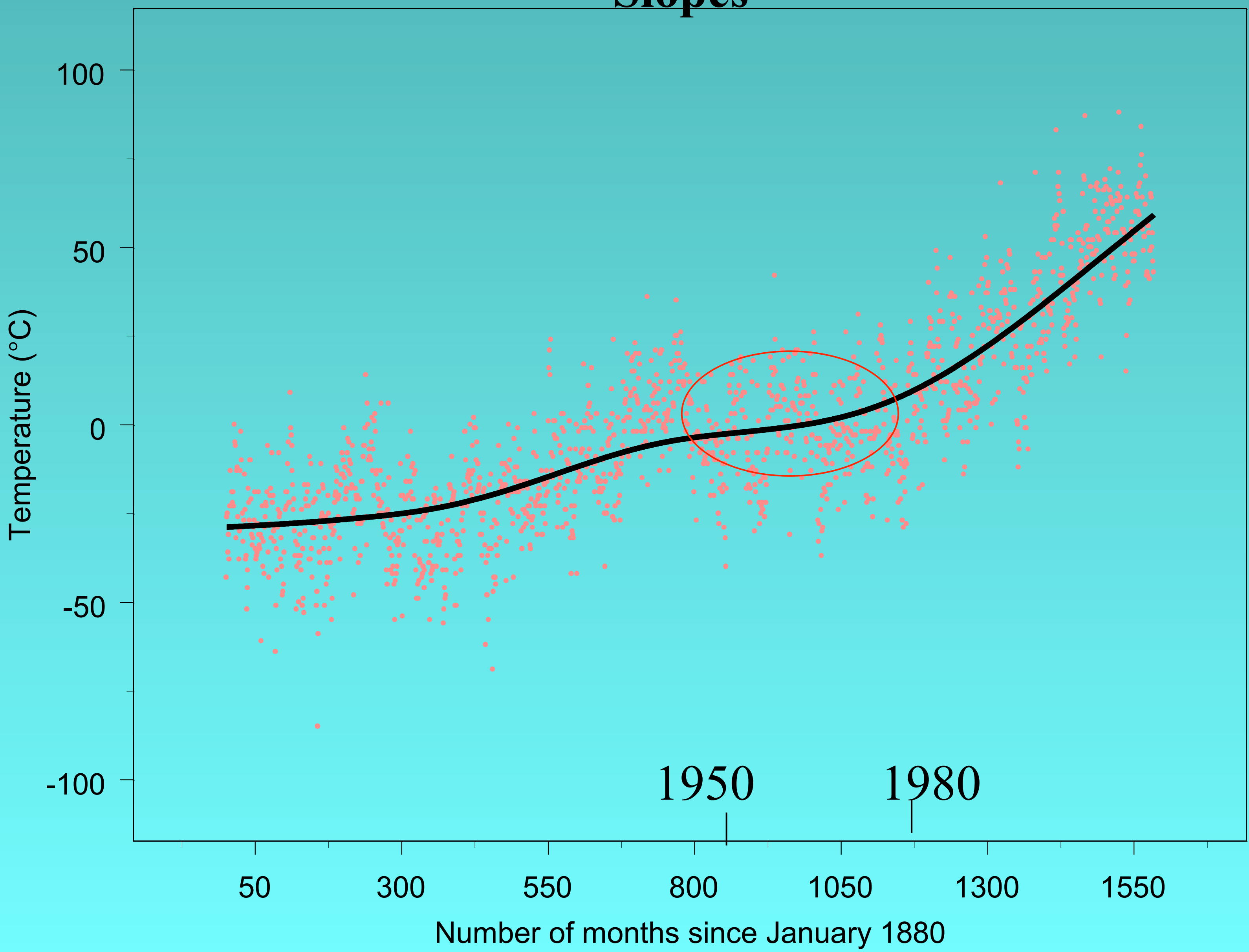
- Projections can be based on:
  - Extrapolations of existing observations
  - Complex General Circulation Models in which parameters are varied
  - Use of paleoclimatic data in conjunction with mathematical models

Projections Based on Time Trends

Recent Trends and Surface Distribution of Temperature Until 2011



Global Average Temperature: 1880-2011
Time Series Appears to Have at Least Two Different Slopes



Trend in Increase in Global Mean Temperature

- Chief assumption: patterns in the past will be the same in the future
- Assumes that the increase in temperature is the same throughout time (i.e., a linear response function) throughout the period of observation and into the future
- Use of all of the data is an underestimate as it neglects the steeper slope in the latter part of the 20th century

Simple Linear Regression Analysis of Global Mean Temperature by Time

2012 global temp was 14.5ºC

Data used	Slope (SE)	Projected temp. in 2100	95% confidence interval
1880-2011	0.005919ºCyr^{-1} (0.000109)	14.91ºC	14.87-14.94ºC
1950-2011	0.011267ºCyr^{-1} (0.000321)	15.52ºC	15.45-15.60ºC
	Ratio of slopes for the 2 models: 1.90		

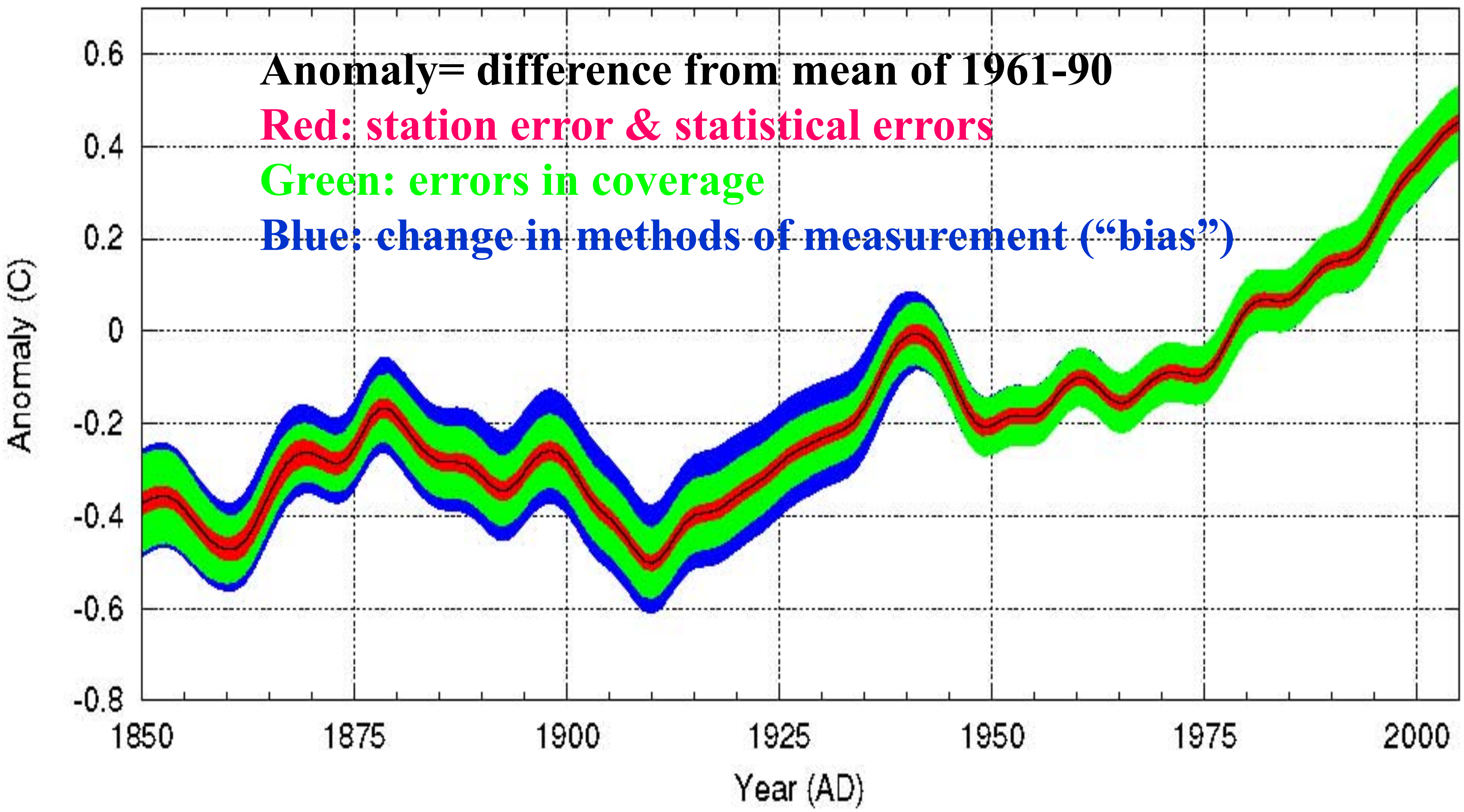
Can the Increase in Temperature Observed Since 1880 be Due to Errors in Measurement?

Uncertainties in Estimates of the Mean Global Temperature

- **Station Error:** uncertainty of the accuracy of measurements at each station
- **Sampling Error:** uncertainty in a "gridbox mean" caused by estimating the mean from a small number of point values
- **Coverage Error:** not all parts of the globe are measured
- **Bias Error:** uncertainty in large-scale temperatures caused by systematic changes in measurement methods

Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. P. Brohan, J. J. Kennedy, I. Harris, S. F. B. Tett & P. D. Jones (CDROM\Readings\Climate Change\Trends in Temperature \HadCRUT3_accepted.pdf)

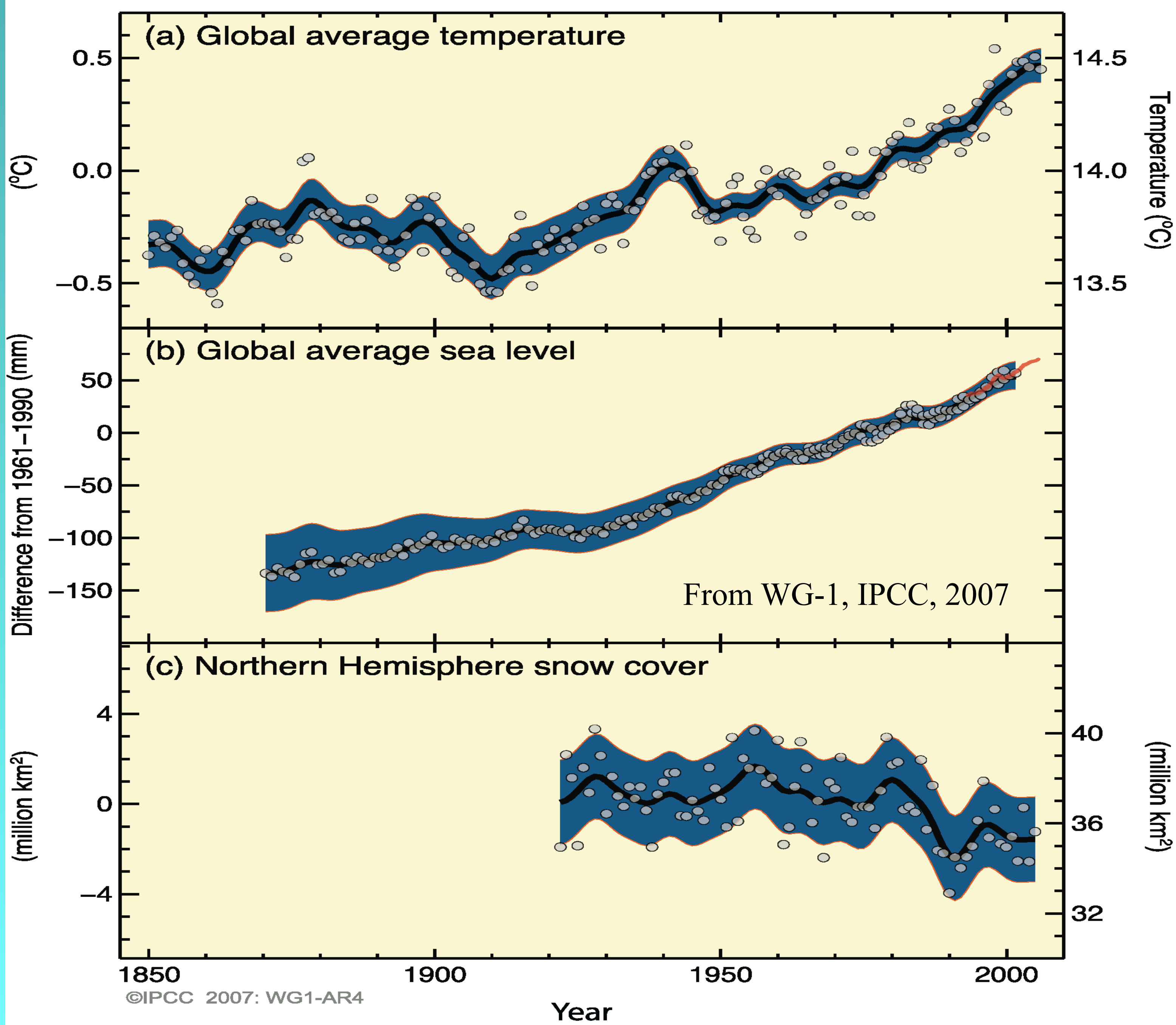
Global Temperature Change and Uncertainties in Measurement and Statistical Variability



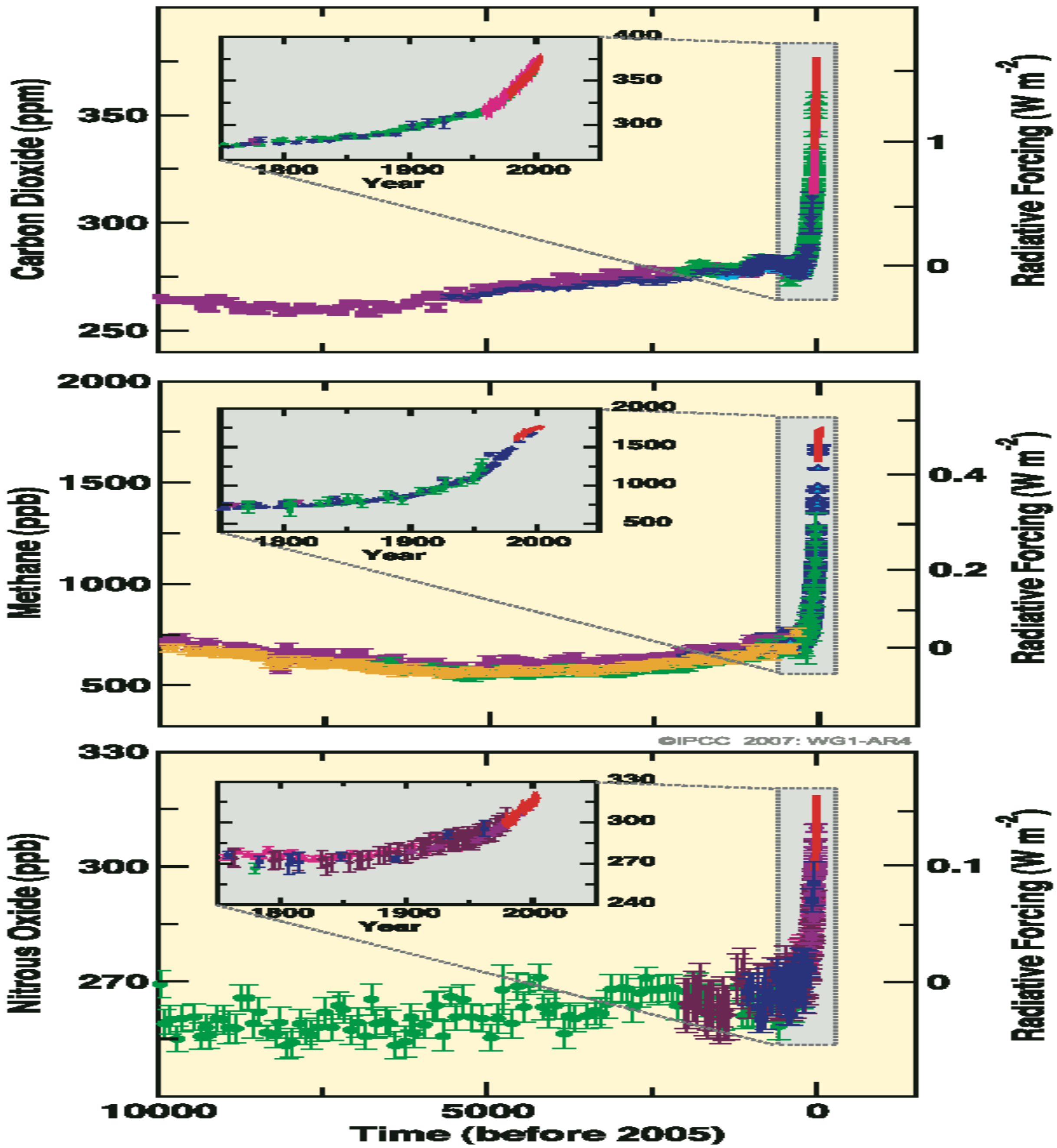
Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. P. Brohan, J. J. Kennedy, I. Harris, S. F. B. Tett & P. D. Jones

Trends in Ambient Concentrations of Greenhouse Gases

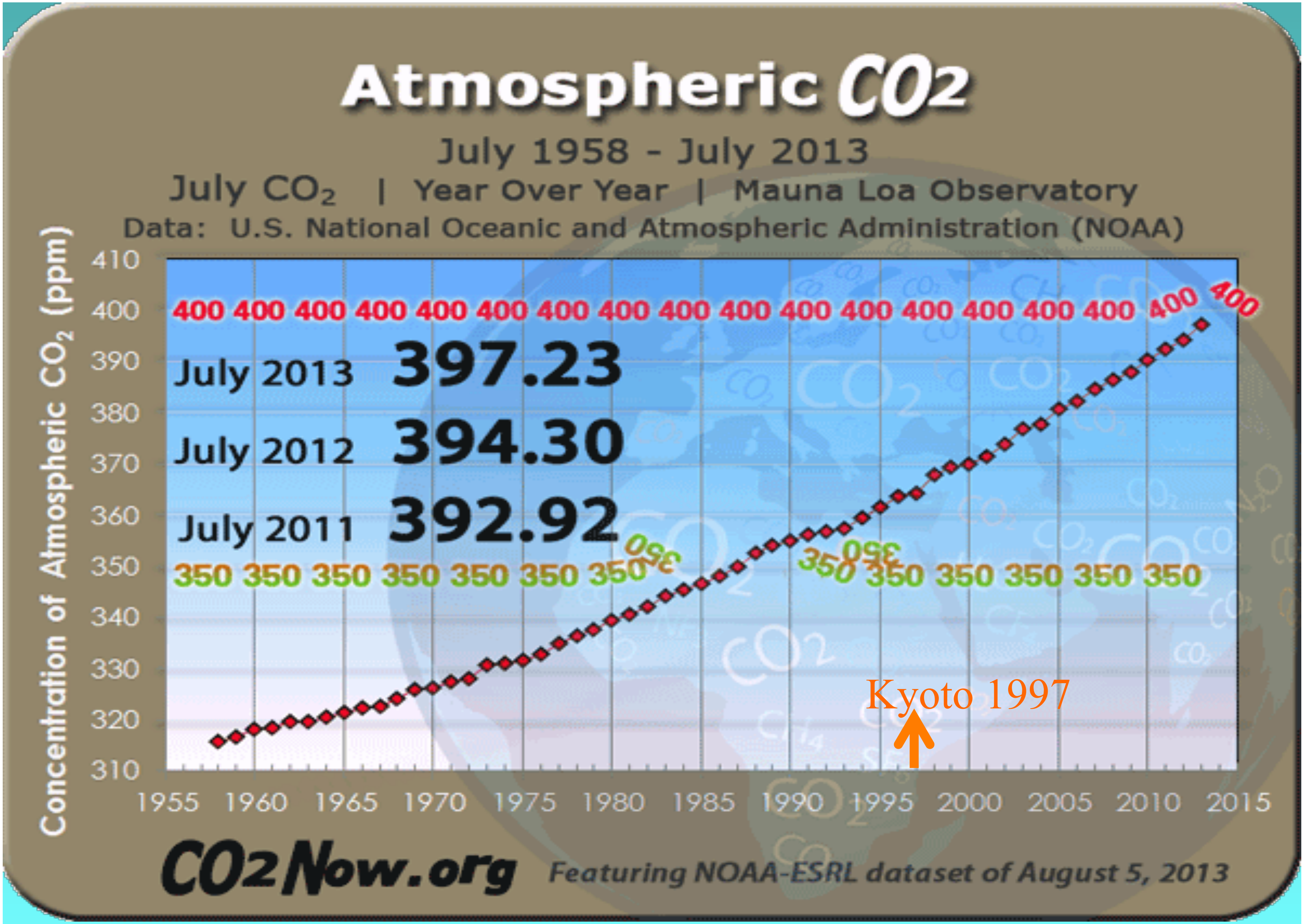
Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover



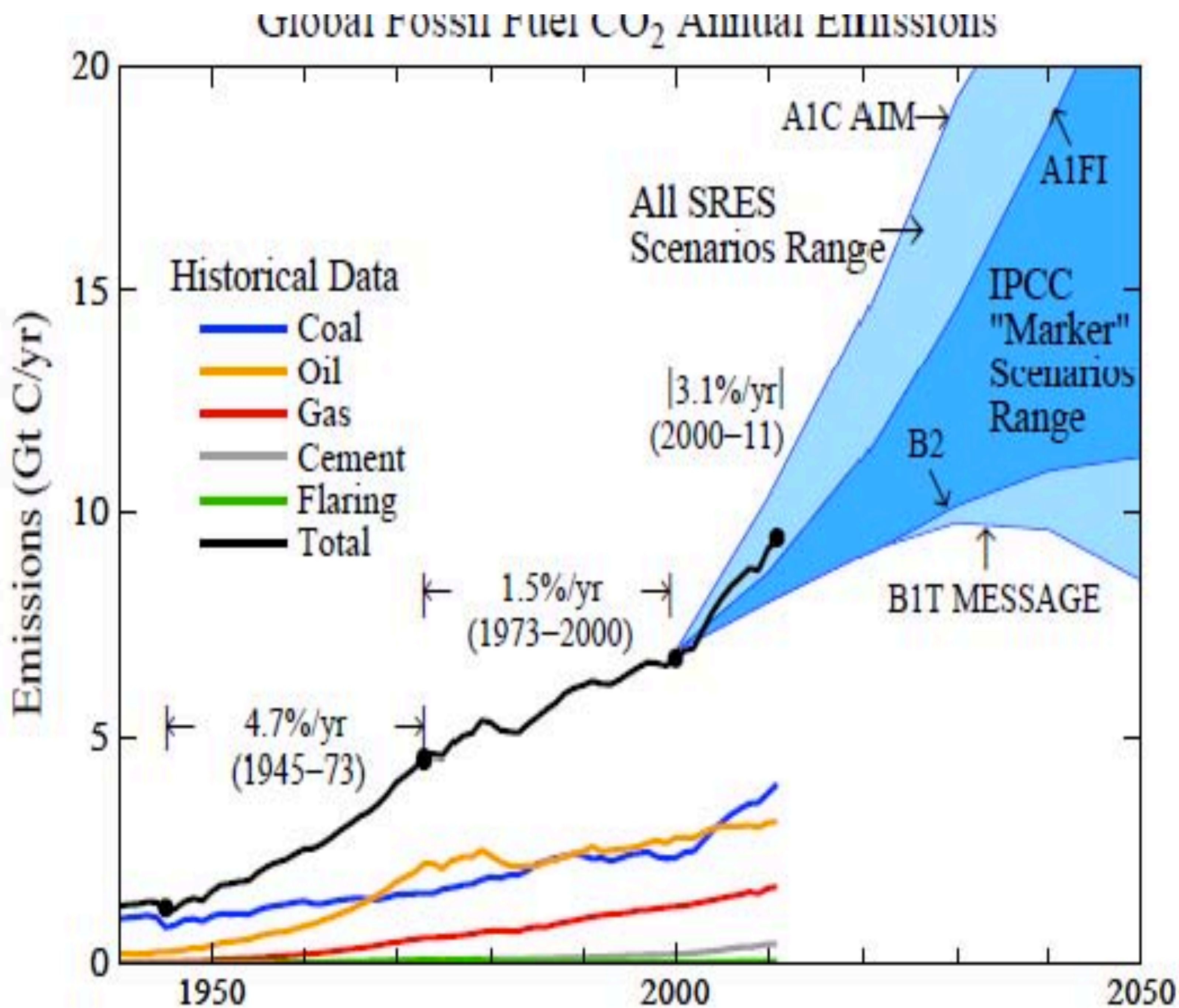
Changes in Greenhouse Gases from Ice Core and Modern Data



WG-1, IPCC, 2007



http://co2now.org/



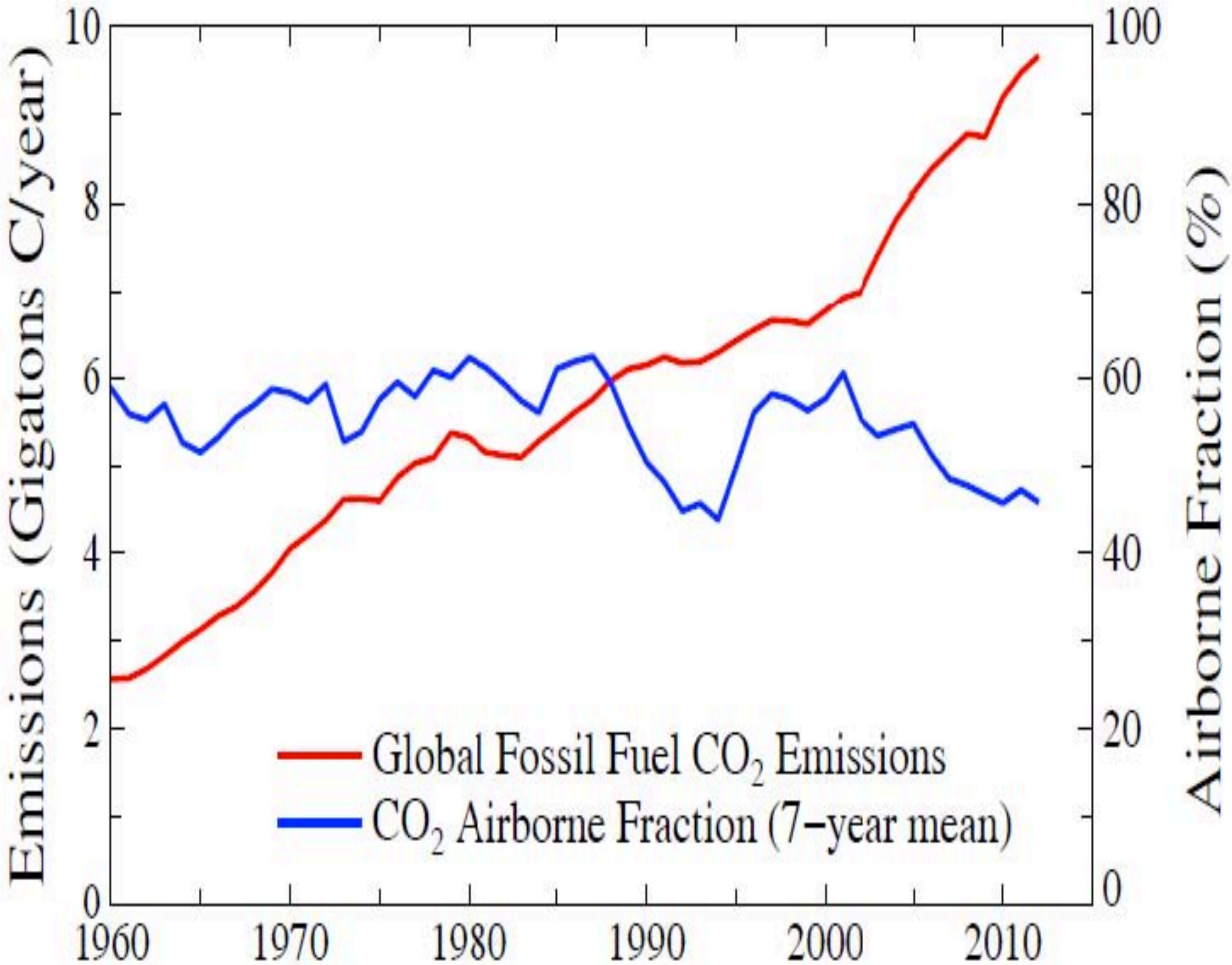
Global Fossil Fuel CO_2 Annual Emissions
Emissions (Gt C/yr)
20
15
10
5
0
1950
2000
2050
Historical Data
Coal
Oil
Gas
Cement
Flaring
Total
4.7%/yr (1945–73)
1.5%/yr (1973–2000)
3.1%/yr (2000–11)
All SRES Scenarios Range
A1C AIM
A1FI
IPCC "Marker" Scenarios Range
B2
B1T MESSAGE

CO_2

- Concentrations of CO_2 have increased from a pre-industrial value of about 280 ppm to 397 ppm in 2013 (July)
- Concentration of CO_2 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) (from ice cores)
- Annual growth rate 1995–2005 average: 1.9 ppm per year
  - Higher than the rate of increase since 1960–2005 (average: 1.4 ppm per year)

Projections of CO_2 from Trends

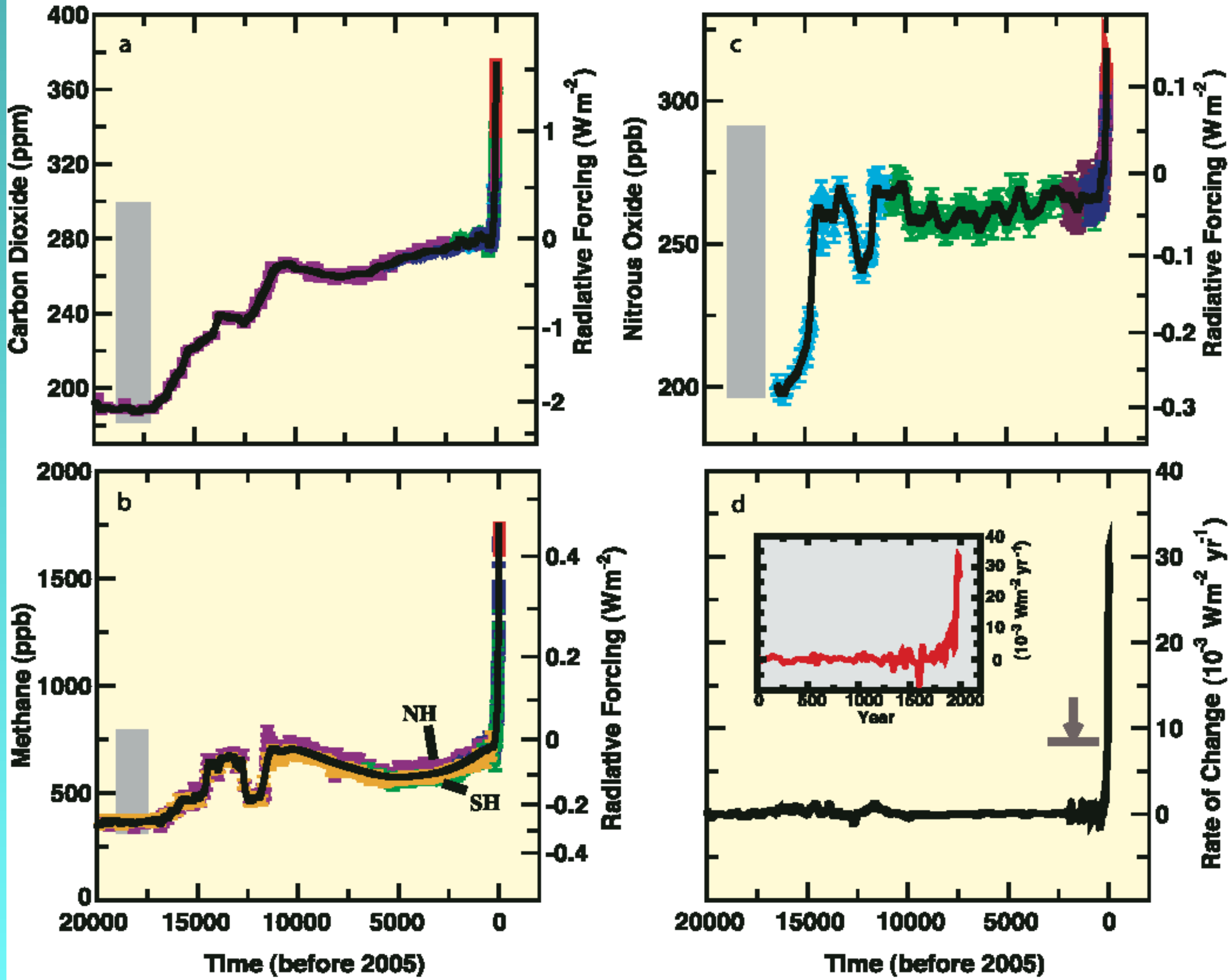
- Assuming business as usual:
  - year 2050: 443.78 with 95%Confidence Interval (440.72, 446.85)
  - year 2100: 517.33 with 95%CI (512.00, 522.65)


Emissions (Gigatons C/year)
Airborne Fraction (%)
10
8
6
4
2
0
100
80
60
40
20
0
1960
1970
1980
1990
2000
2010
Global Fossil Fuel CO_2 Emissions
CO_2 Airborne Fraction (7−year mean)

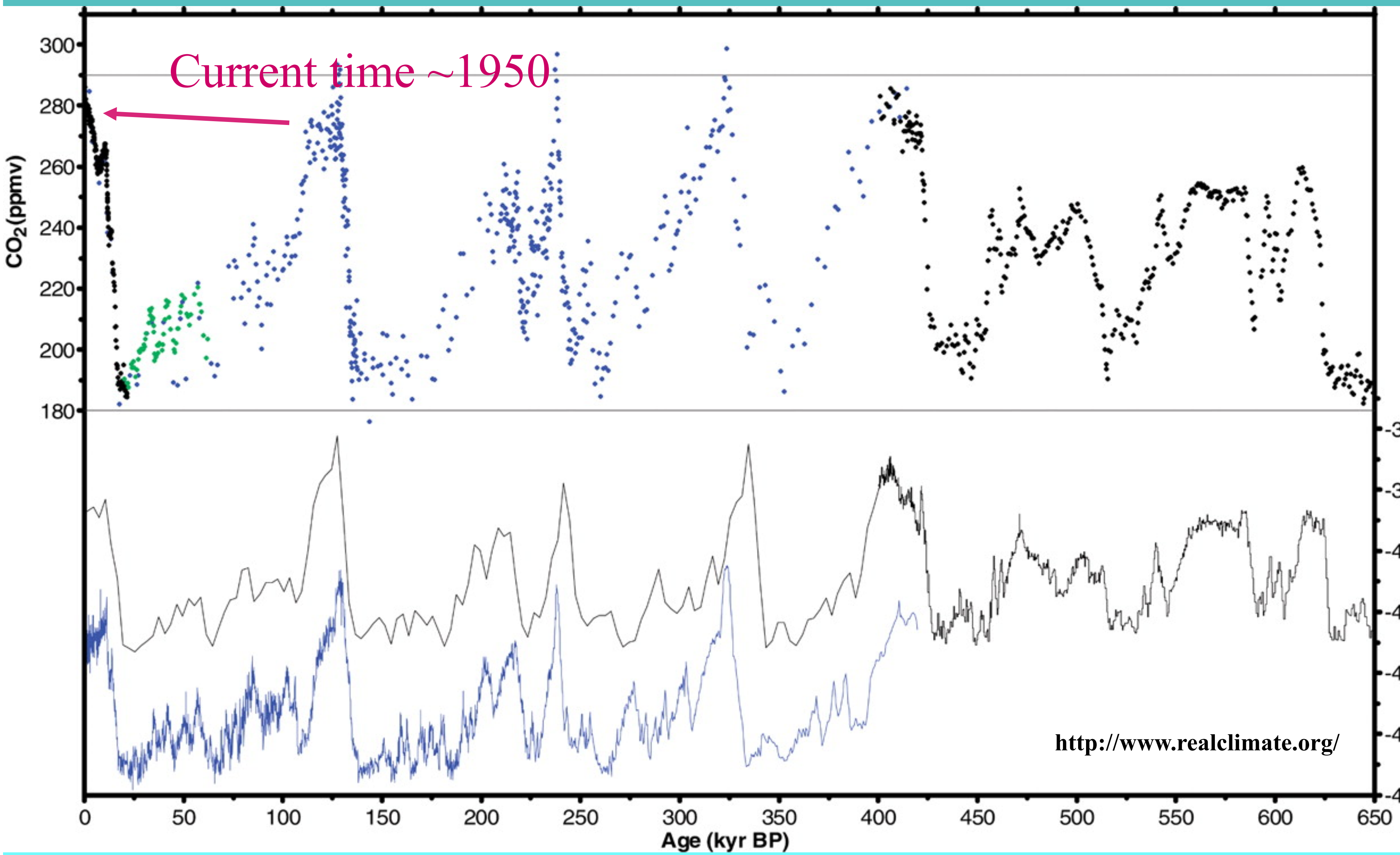
Other Pollutants

- NO, N_2O, CO are increasing → increases in tropospheric ozone, a greenhouse gas, by 40% since pre-industrial times

Changes in Greenhouse Gases from Ice Core and Modern Data

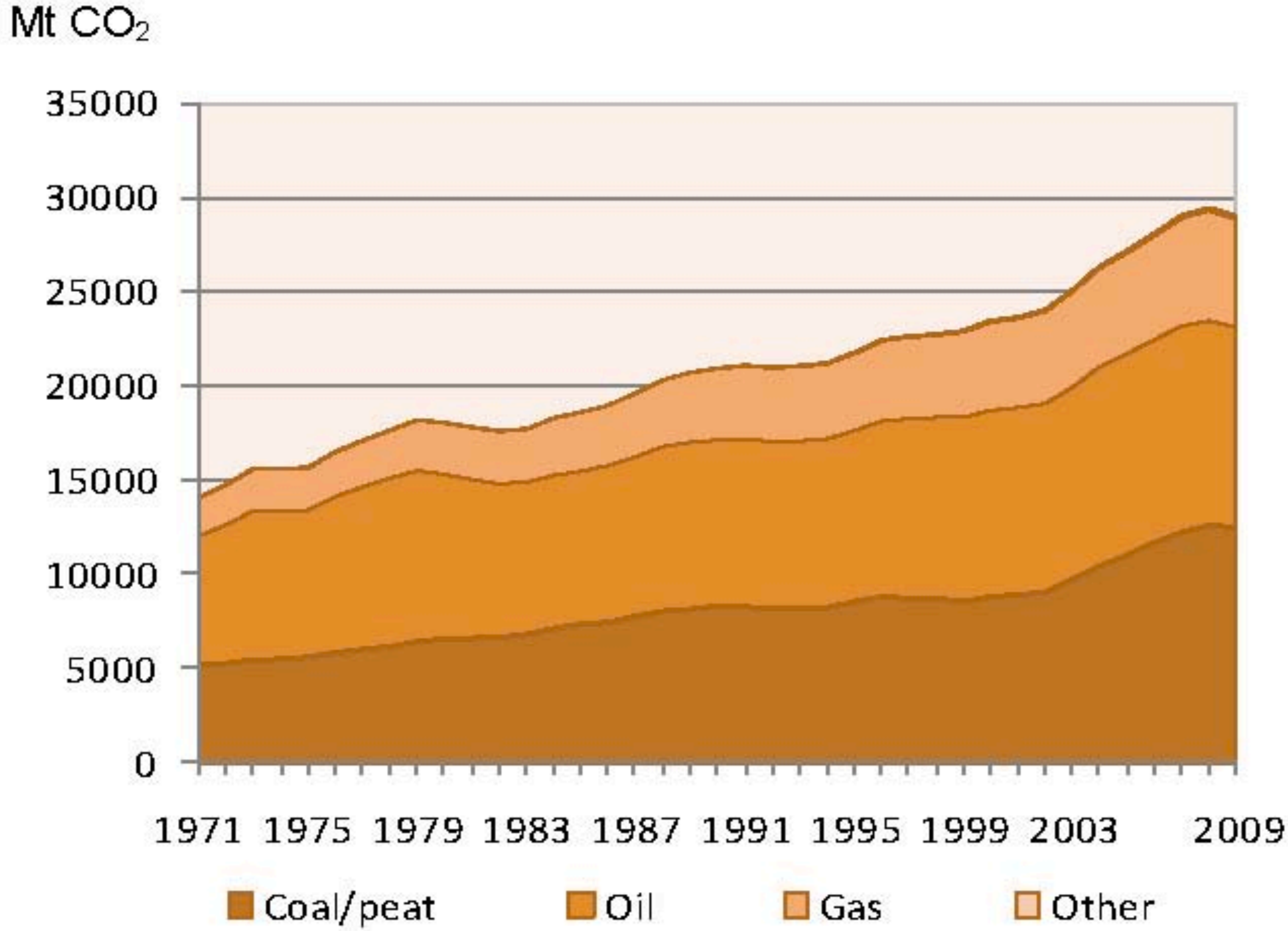


Antarctica Ice Core Data for CO_2 over the Last 650,000 Years



Historical Trends in Emissions of Greenhouse Gases

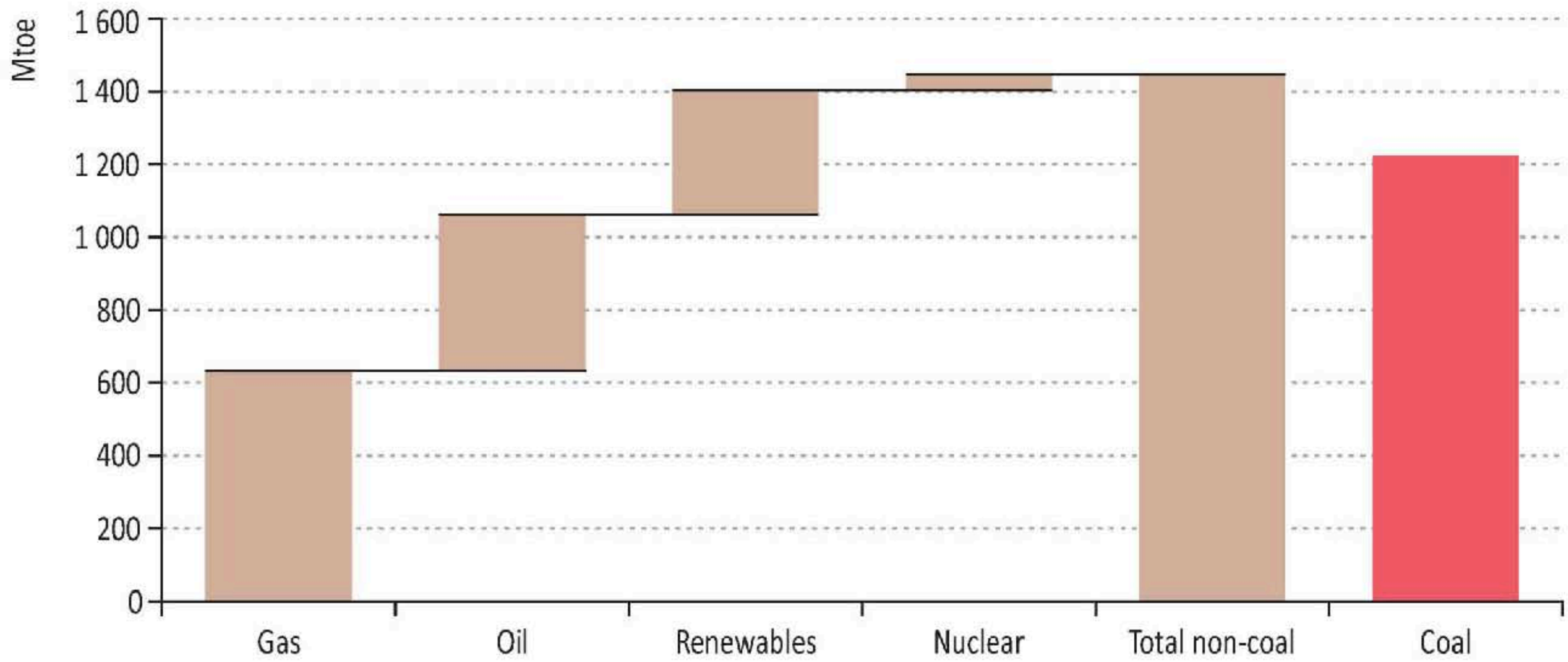
Figure 2. CO_2 emissions by fuel



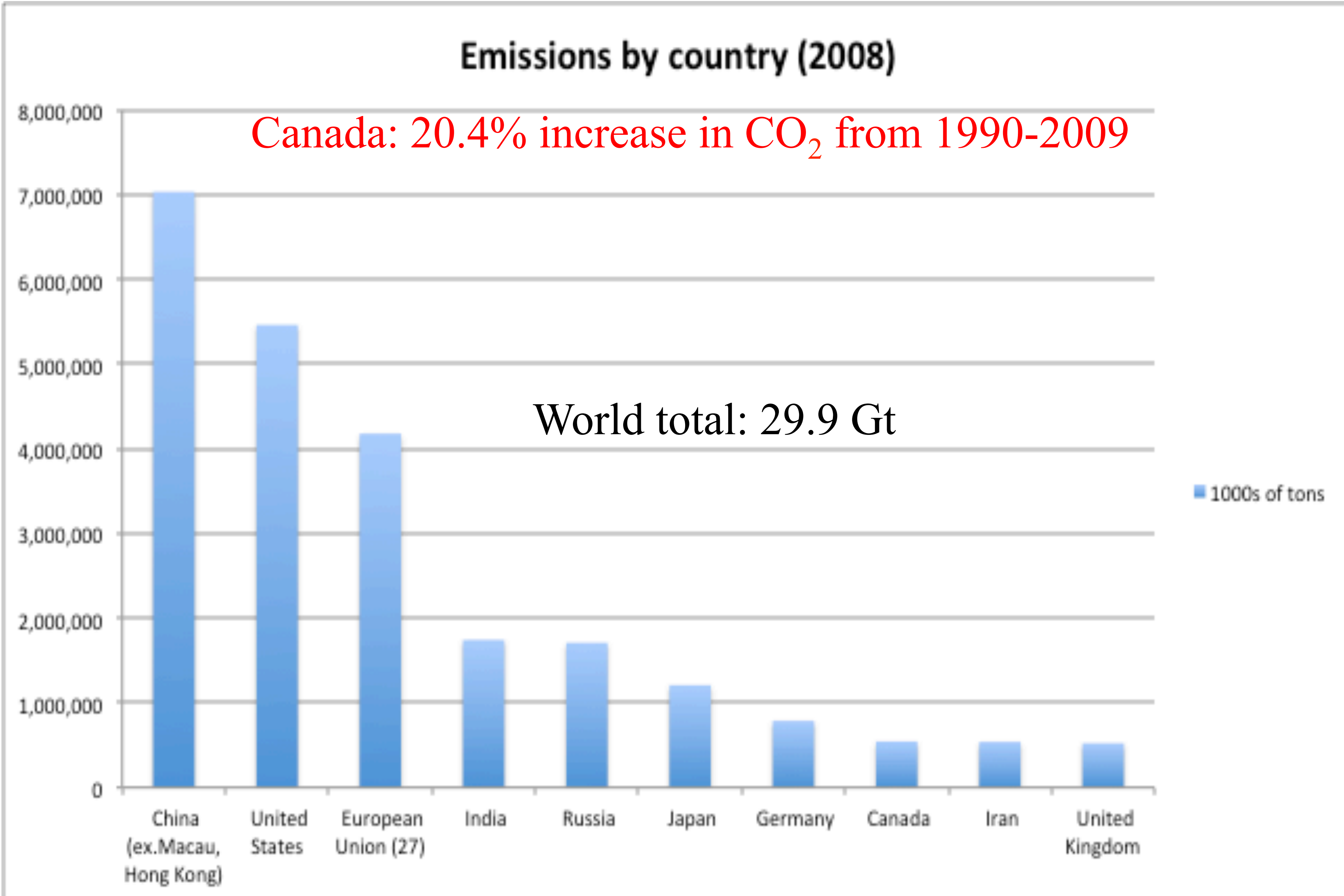
Coal won the energy race in the first decade of the 21st century

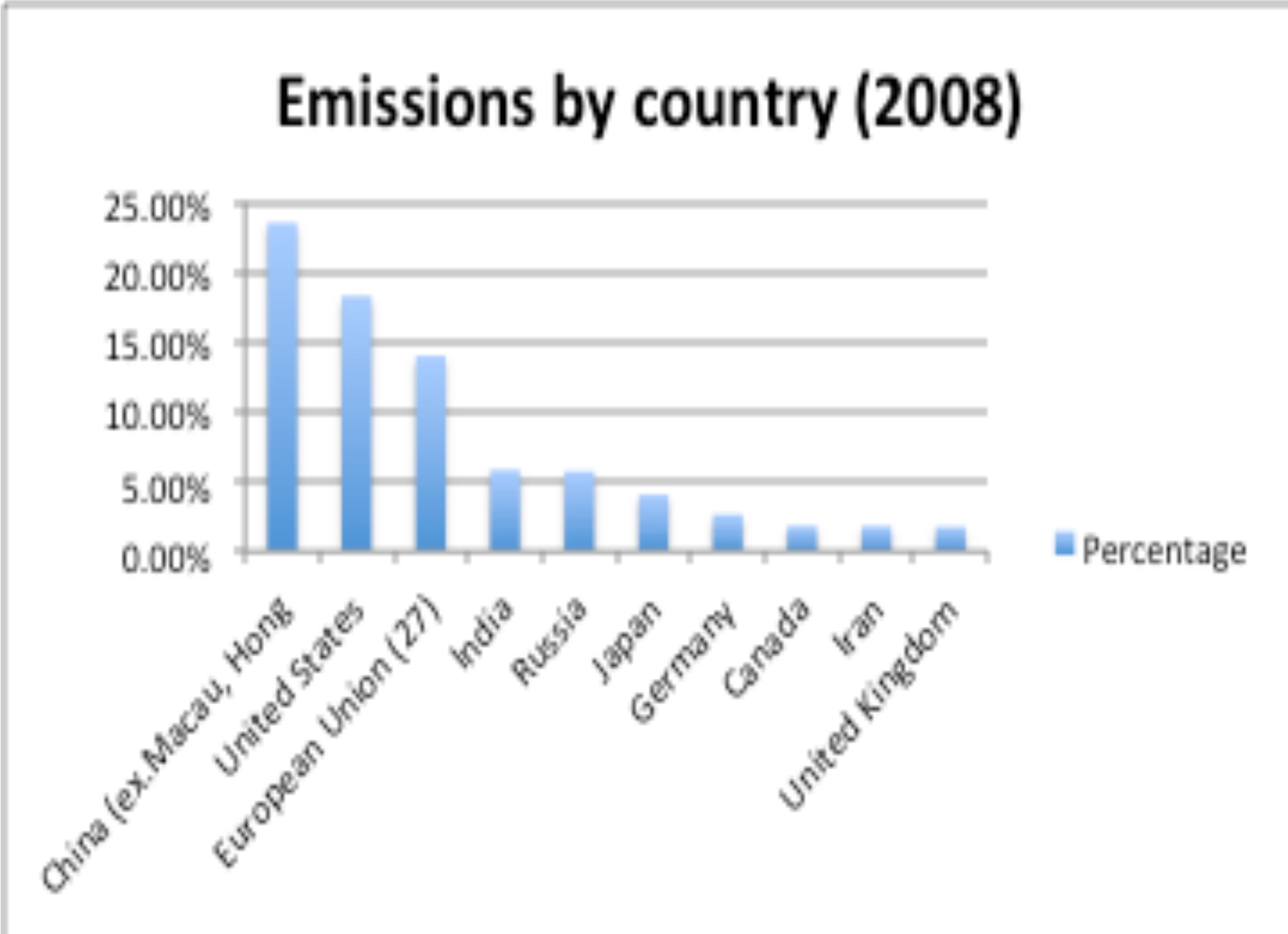
WORLD ENERGY OUTLOOK 2011

Figure 10.1: Incremental world primary energy demand by fuel, 2000-2010



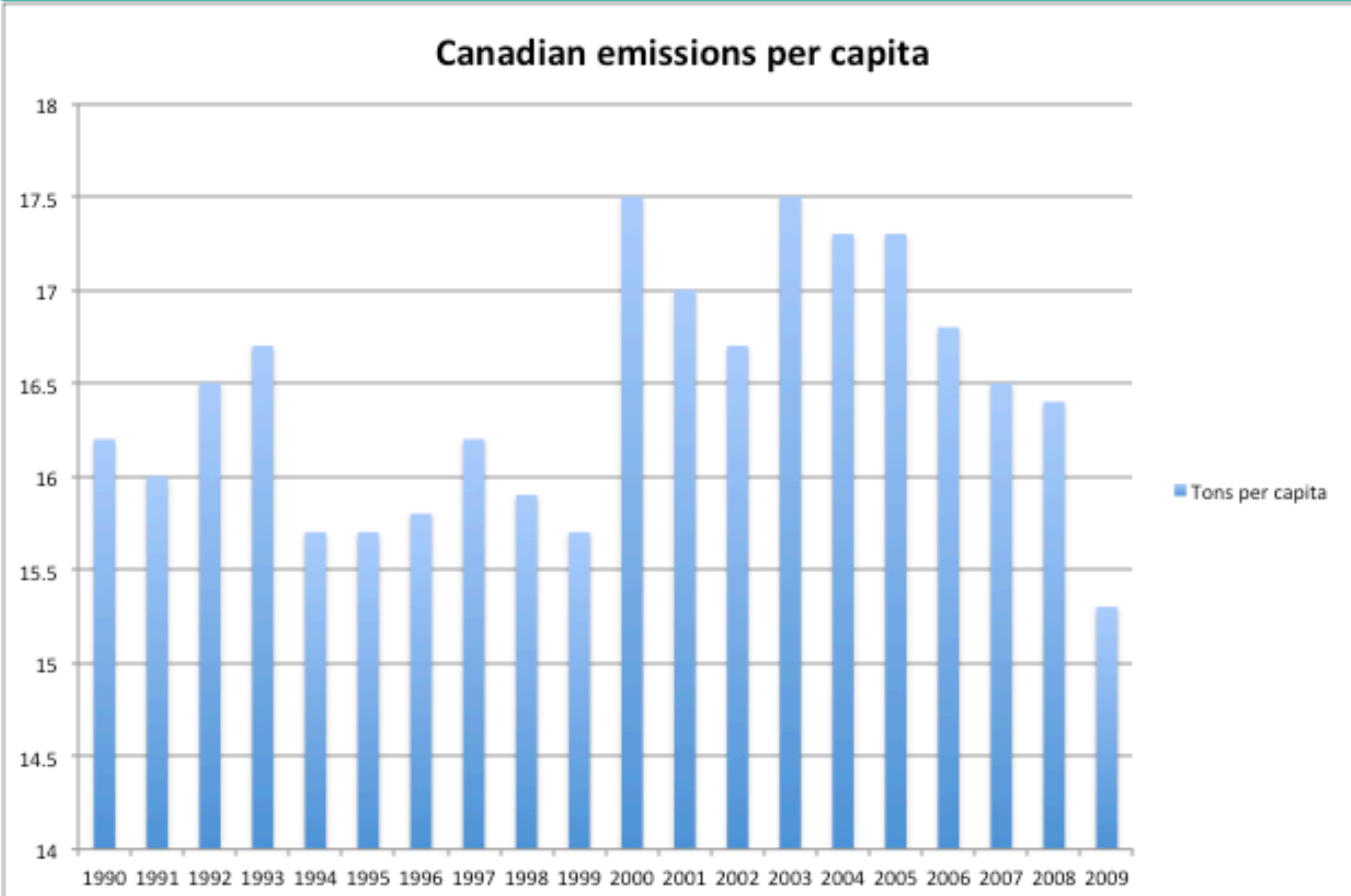
Coal accounted for nearly half of the increase in global energy use over the past decade, with the bulk of the growth coming from the power sector in emerging economies


Emissions by country (2008)
Canada: 20.4% increase in CO_2 from 1990-2009
World total: 29.9 Gt
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
1000s of tons
China (ex.Macau, Hong Kong)
United States
European Union (27)
India
Russia
Japan
Germany
Canada
Iran
United Kingdom



Emissions by country (2008)
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
China (ex.Macau, Hong
United States
European Union (27)
India
Russia
Japan
Germany
Canada
Iran
United Kingdom
Percentage

CO_2 Emissions in Canada


Canadian emissions per capita
18
17.5
17
16.5
16
15.5
15
14.5
14
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Tons per capita

Alberta Tar Sands

Tailings Ponds

Tailings Pond above Athabasca River

Tar Sands

- GHG emissions in 2007~ 39.3-41.4 million tones of CO_2 equivalent (~9% of total Canadian emissions)
- By 2011, annual greenhouse gas emissions from the tar sands plants alone will be over 80 million tones of CO_2 equivalent
  - ~50% of all emissions from transportation sources

http://www.greenpeace.org/canada/en/recent/tarsandsfaq

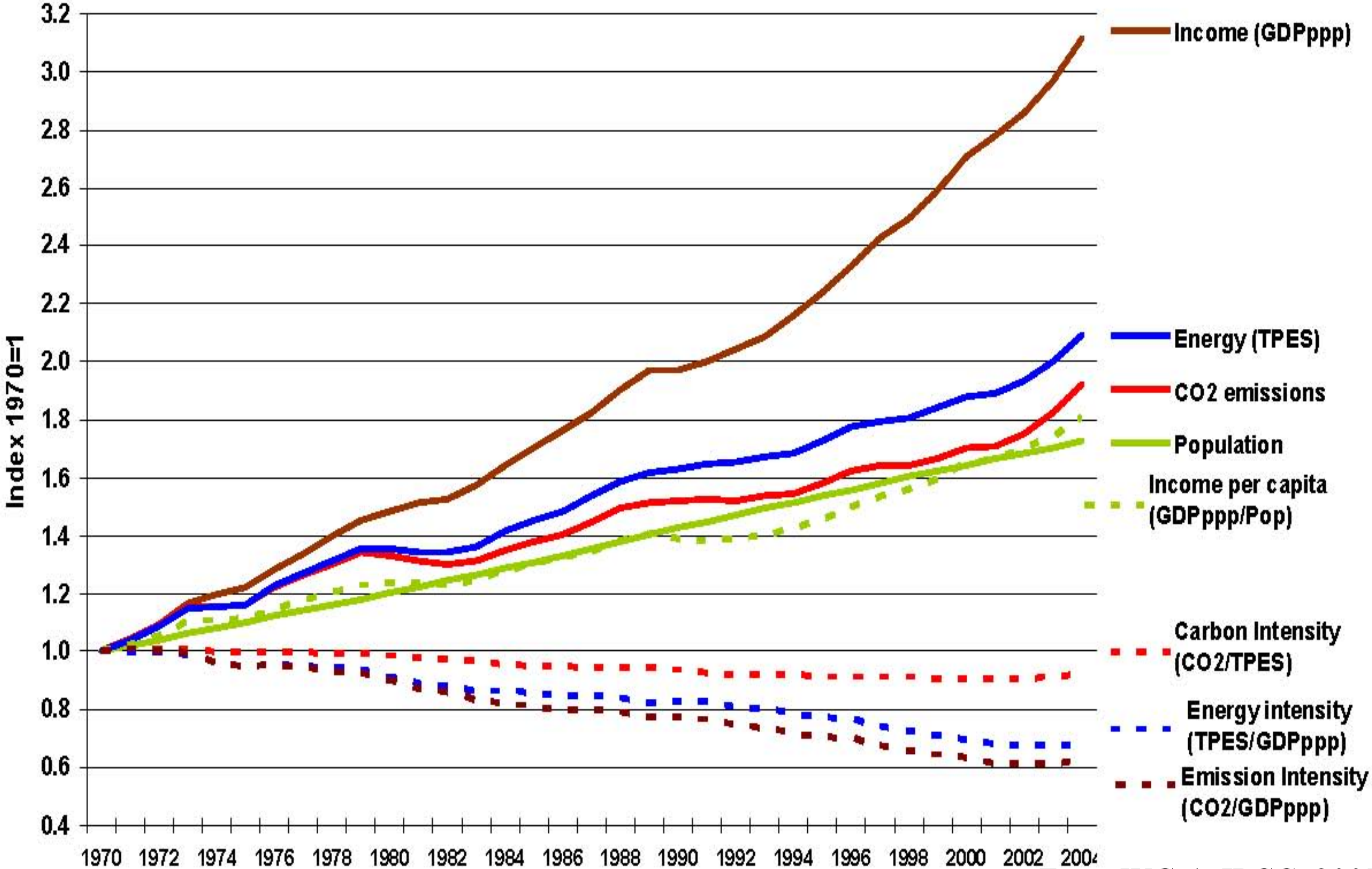
Tar Sands

- 1 barrel of Tars Sand oil emits 3-5X greenhouse gases than producing a barrel of conventional oil
- By 2020 the Tar Sands will release twice as many greenhouse gases as are currently produced by all the cars and trucks in Canada

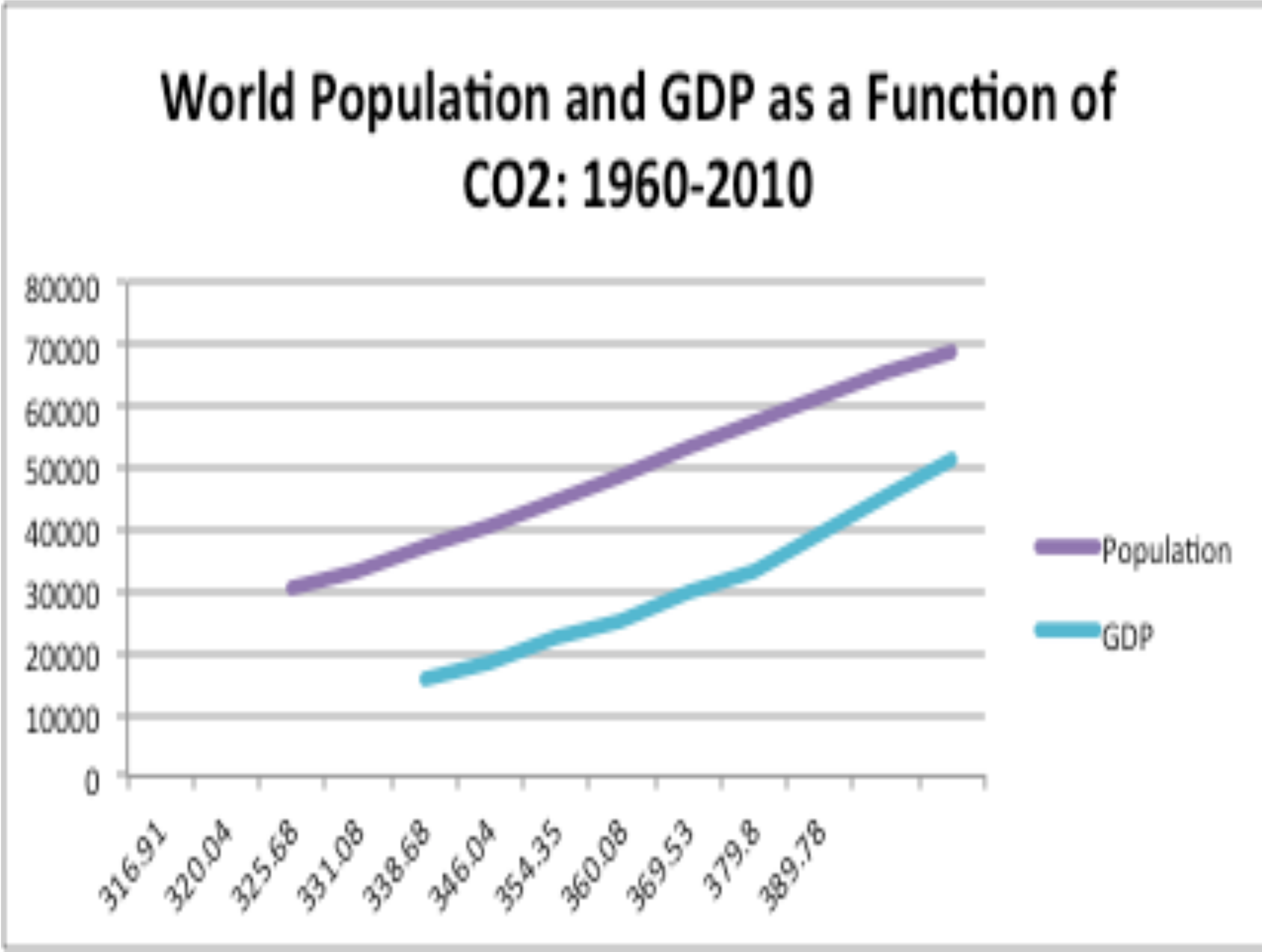
Climate Change Due to the Human Economy: Ehrlich and Holdren's IPAT(E) Paradigm

- Environmental Impact is a function of:
  - Population
  - Affluence
  - Technology
  - Ethics
    - Other drivers can also affect impact

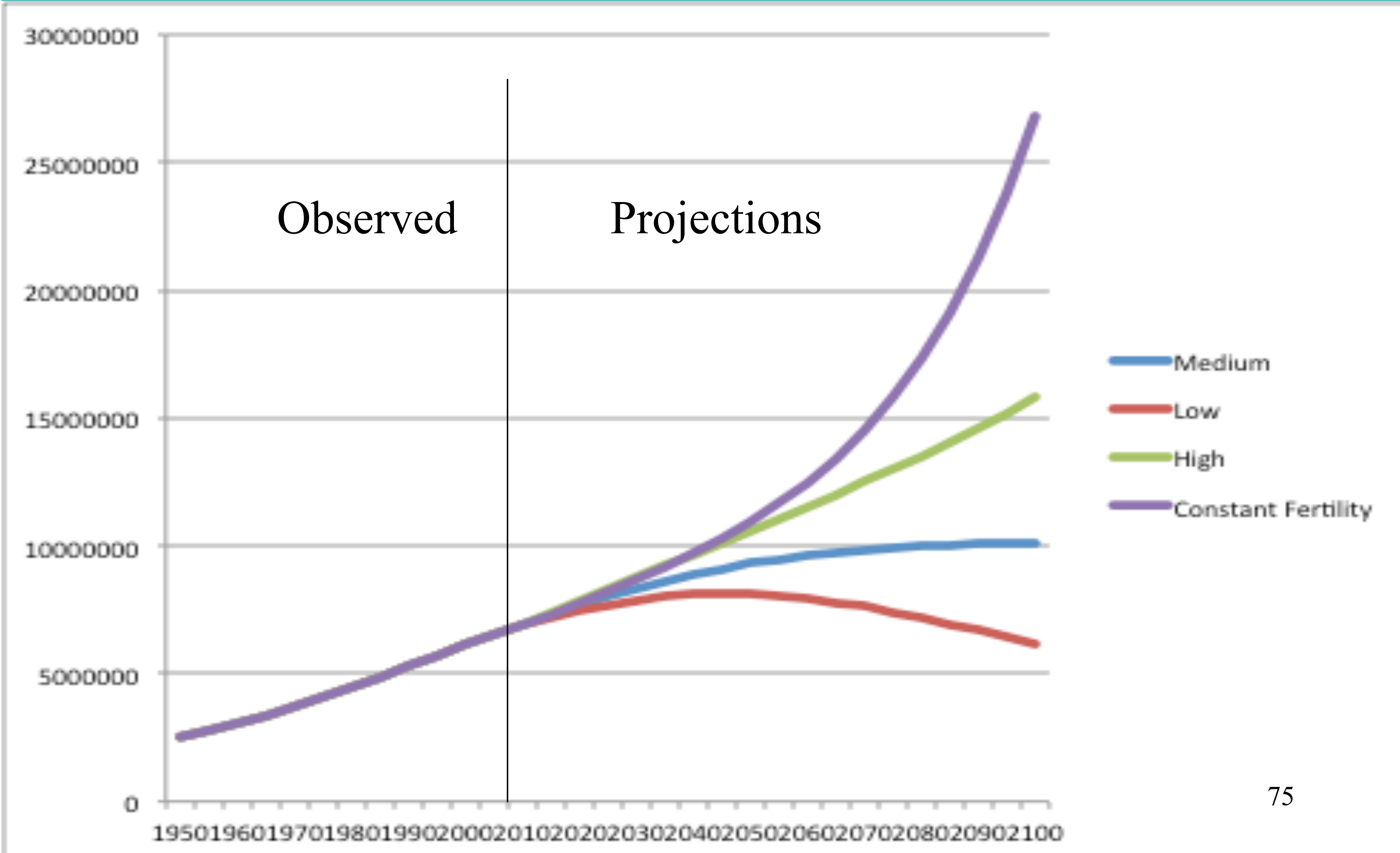
Drivers of Emissions of CO_2



From WG-1, IPCC, 2007


World Population and GDP as a Function of CO2: 1960-2010
80000
70000
60000
50000
40000
30000
20000
10000
0
316.91
320.04
325.68
331.08
338.68
346.04
354.35
360.08
369.53
379.8
389.78
Population
GDP

UN World Population Estimates (2010), by Type of Projection Model



Projections: Modelling the Future

General Circulation Models (GCM) Coupled to Future Scenarios of Emissions

Some Facts

- Global annual, average temperature
  - Pre-industrial ~13ºC
  - 1961-1990, average ~ 14.0ºC (57.2°F)
  - 2012: ~14.47ºC
- Average annual CO_2
  - Pre-industrial: ~280 ppm
  - **2009:** 387.37
  - **2010:** 389.85
  - **2011:** 391.63
  - **2012:** 393.82
  - Total GHG: >455 ppmCO_2-eq

Modelling the Future: General Circulation Models (GCMs) (http://www.cru.uea.ac.uk/cru/info/modelcc/)

- Represent the main components of the climate system in three dimensions
- Design and structure limited mostly by scientific understanding of the climate system
- Physical processes and feedbacks are simulated differently in GCMs

GCMs

- Global temperature change in response to a doubling of the atmospheric concentration of CO_2 varies from 1.5° - 4.5° C
- Initial conditions can change results
- Differences in regional estimates of climate change produced by different models (even for the same mean global warming)

GCMs

- There is no single "best" GCM nor estimate from the GCMs
- However, if one views the ensemble of plausible models/emission scenarios as coming from a real underlying distribution of possible futures, then:
  - All models are equally probable
  - The mean across all models is the "best" estimator
  - The variability of the estimates provides a plausible range of possibilities

Climate Change Scenarios

- Explores:
  - how human activities may change the composition of the atmosphere
  - how this may affect global climate
  - how the resulting climate changes may impact upon the environment and human activities
- Not predictions or forecasts of future climate, but internally-consistent pictures of possible future climates, each dependent on a set of prior assumptions

IPCC Special Report on Emission Scenarios

- Identifies 40 scenarios which follow four different 'storylines' and with increases in radiative forcing ranging between 0.4% and 1.2% per year
- Each scenario is considered equally probable
  - Forcing: "a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system" (IPCC WG1, 2007)

SRES Storylines

- A1 (pessimistic)
  - Rapid economic growth
  - Population peaks ~2050
  - Regions of the world converge to same level of affluence
    - A1F1: fossil fuel intensive (close to business as usual)
    - A1T: non-fossil fuel intensive
    - A1B: balance across energy sources

SRES Storylines

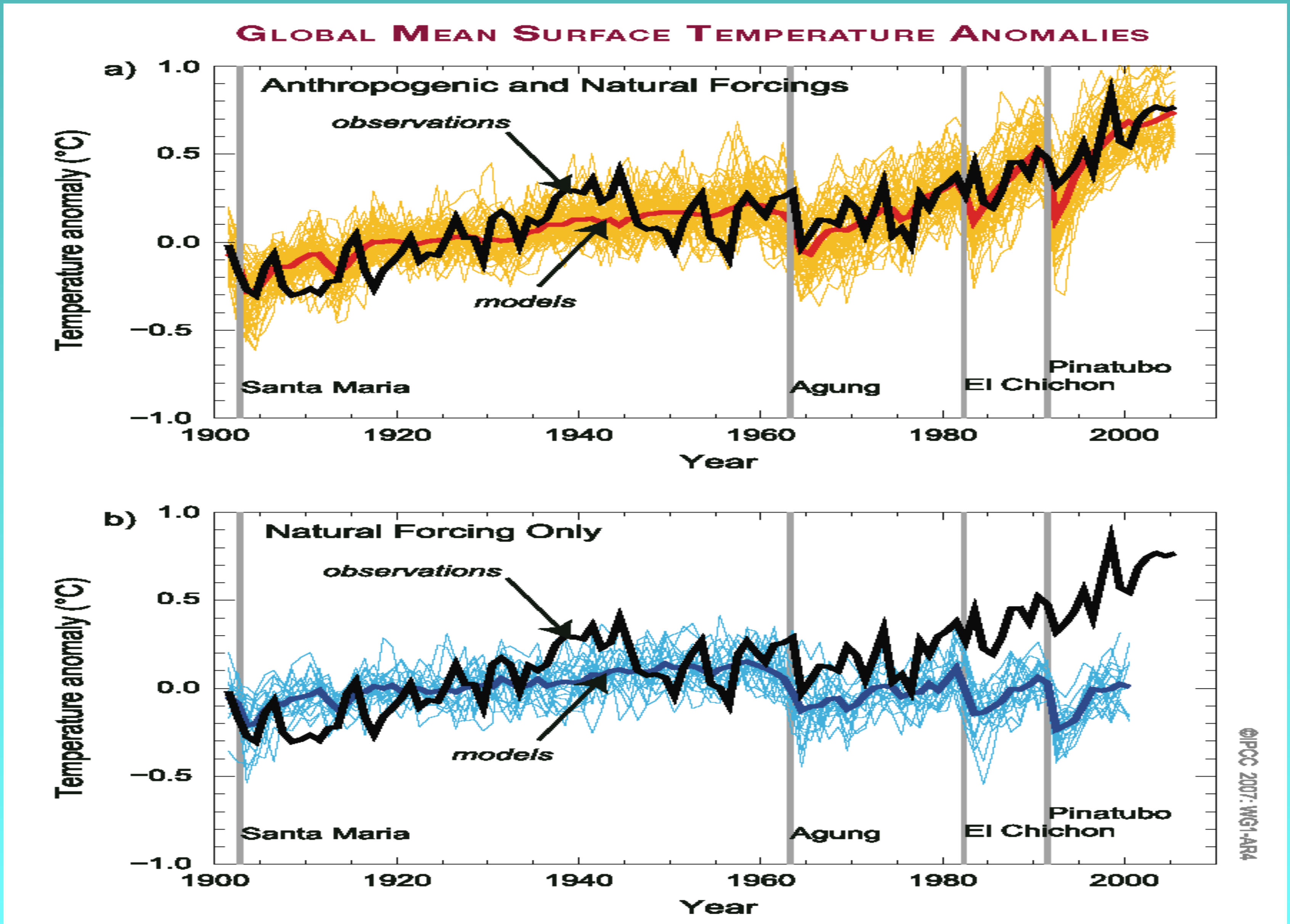
- B1 (optimistic)
  - Same as A1 in terms of population, convergence to same level of affluence
  - Moves toward a service/information economy
  - Reductions in material intensity
  - Clean technologies
  - No additional incentives to change climate

Validation of GCMs

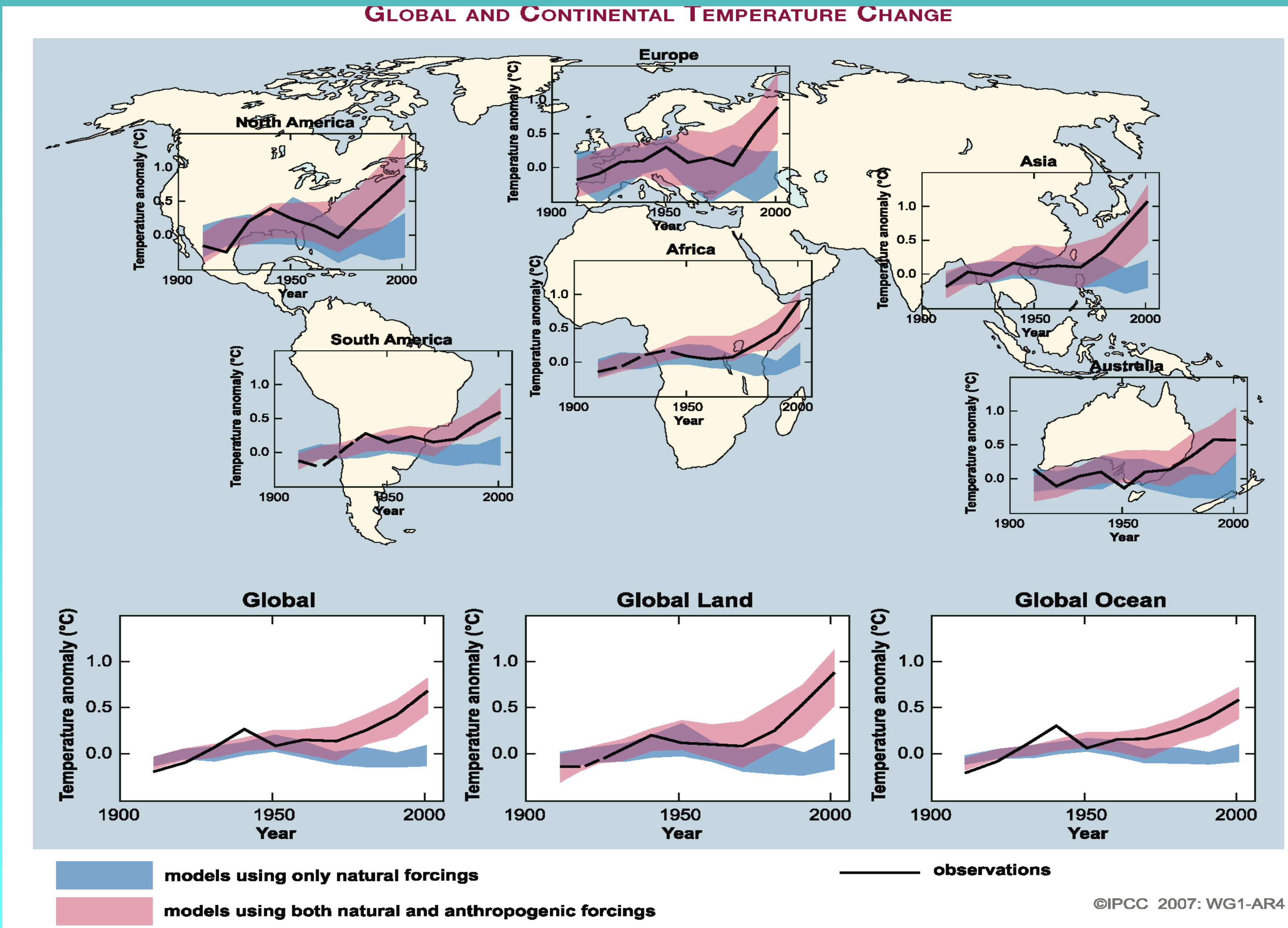
Short-term Validation

- IPCC-1990 projected global average temperature increase: 0.15°C-0.3°C per decade for 1990 to 2005
- Observed increase of 0.2°C per decade

Validation of Models: Is global warming due to human activities?



Global and Continental Change in Temperature from the Average of 1901-1950



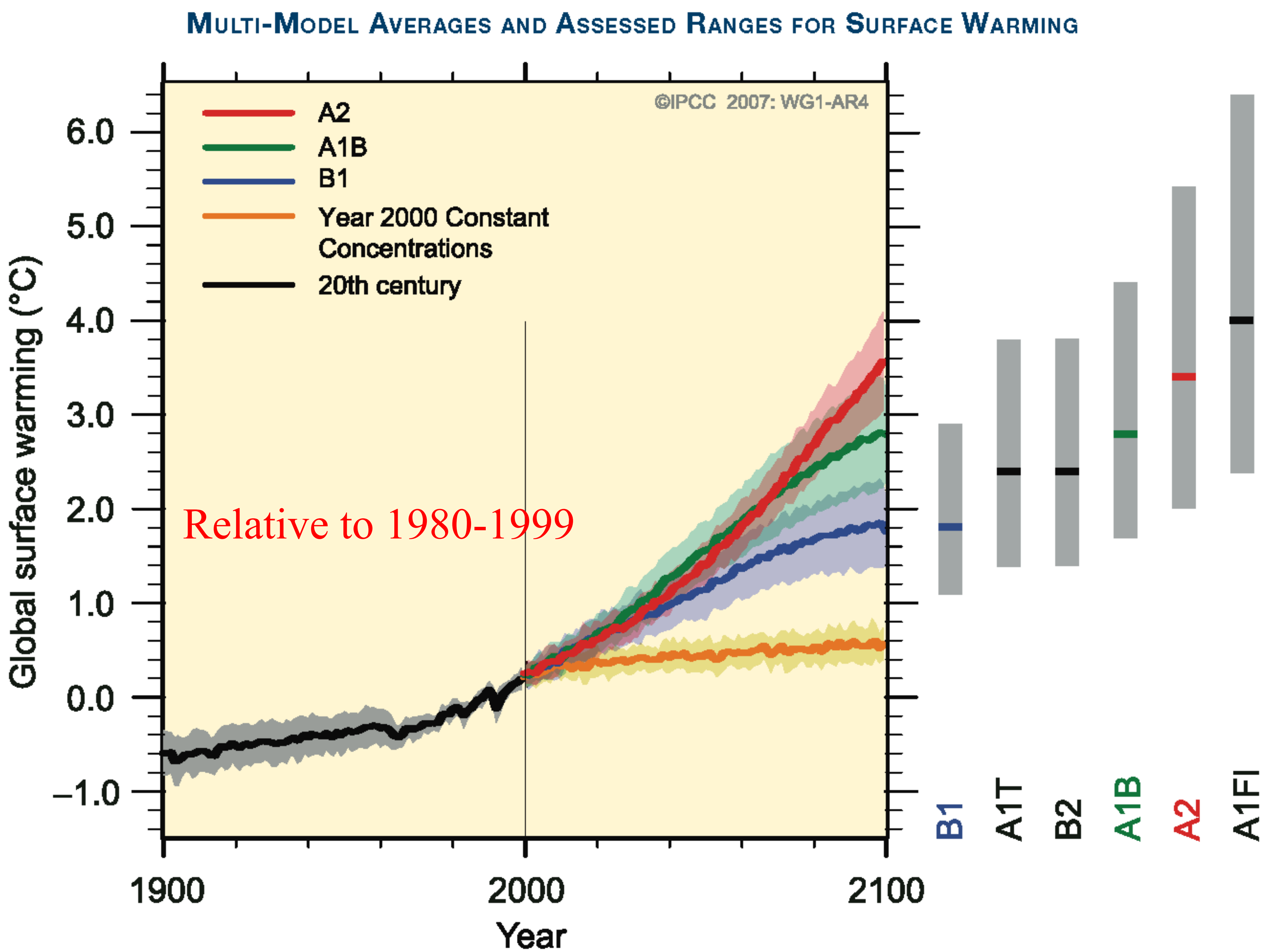
Projections into the Future

Short-term Projections

- For the next two decades, expect a warming of about 0.2°C per decade
- Even if concentrations of all greenhouse gases and aerosols are at 2000 levels, a further warming of about 0.1°C per decade would occur

IPCC: Special Report on Emission Scenarios (SRES)

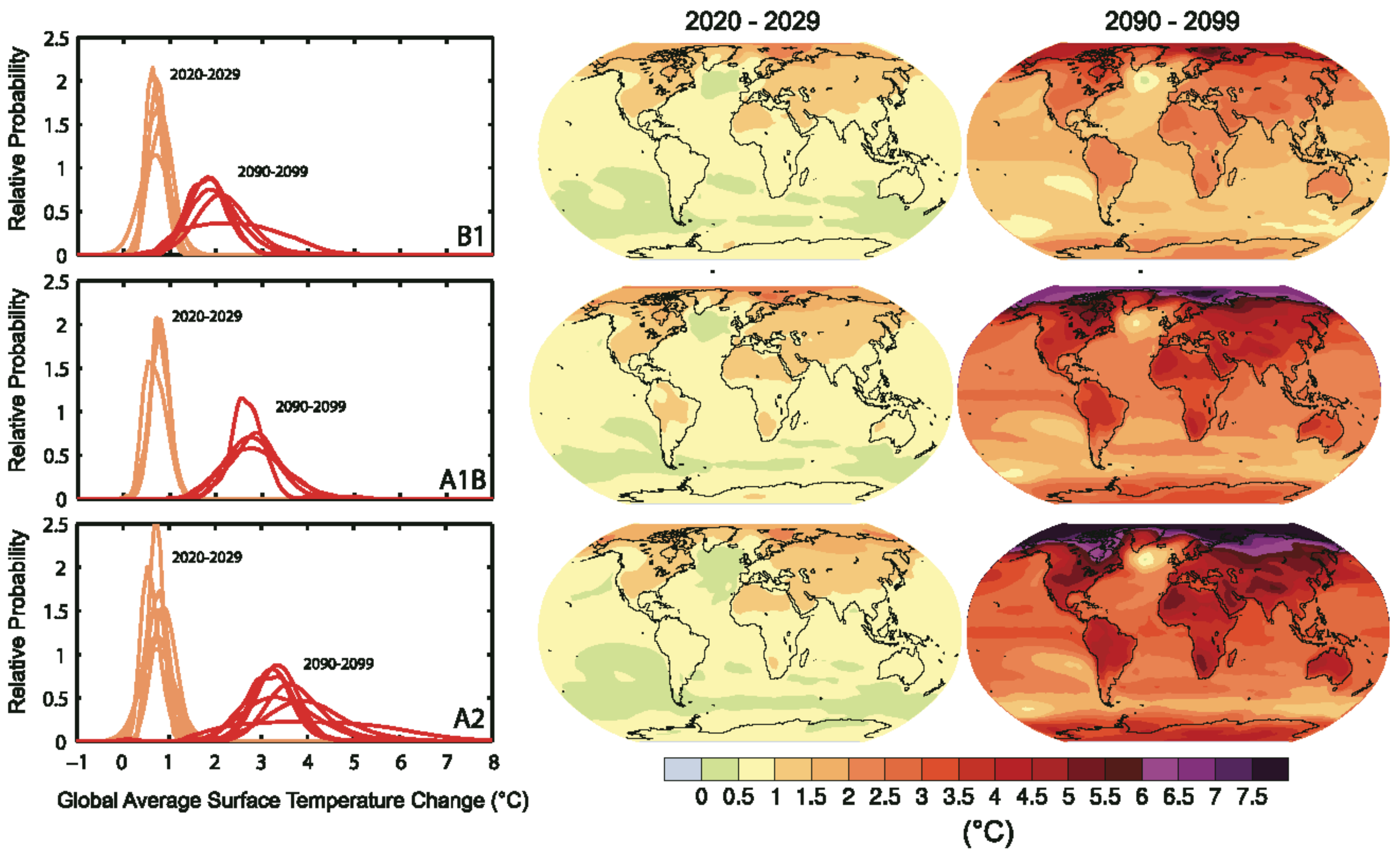
- None of the scenarios assume that any policies are in place to battle global warming



Multi-Model Averages and Assessed Ranges for Surface Warming
©IPCC 2007: WG1-AR4
A2
A1B
B1
Year 2000 Constant Concentrations
20th century
Relative to 1980-1999
Global surface warming (°C)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
1900
2000
2100
Year
B1
A1T
B2
A1B
A2
A1FI

Table SPM.3. *Projected global average surface warming and sea level rise at the end of the 21st century. {10.5, 10.6, Table 10.7}*

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a] Best estimate	*Likely* range	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59



Global baseline (1980-99) temperature is ~14°C

2012 global temp is 14.5°C

Stabilization Targets (above pre-industrial of 13ºC)

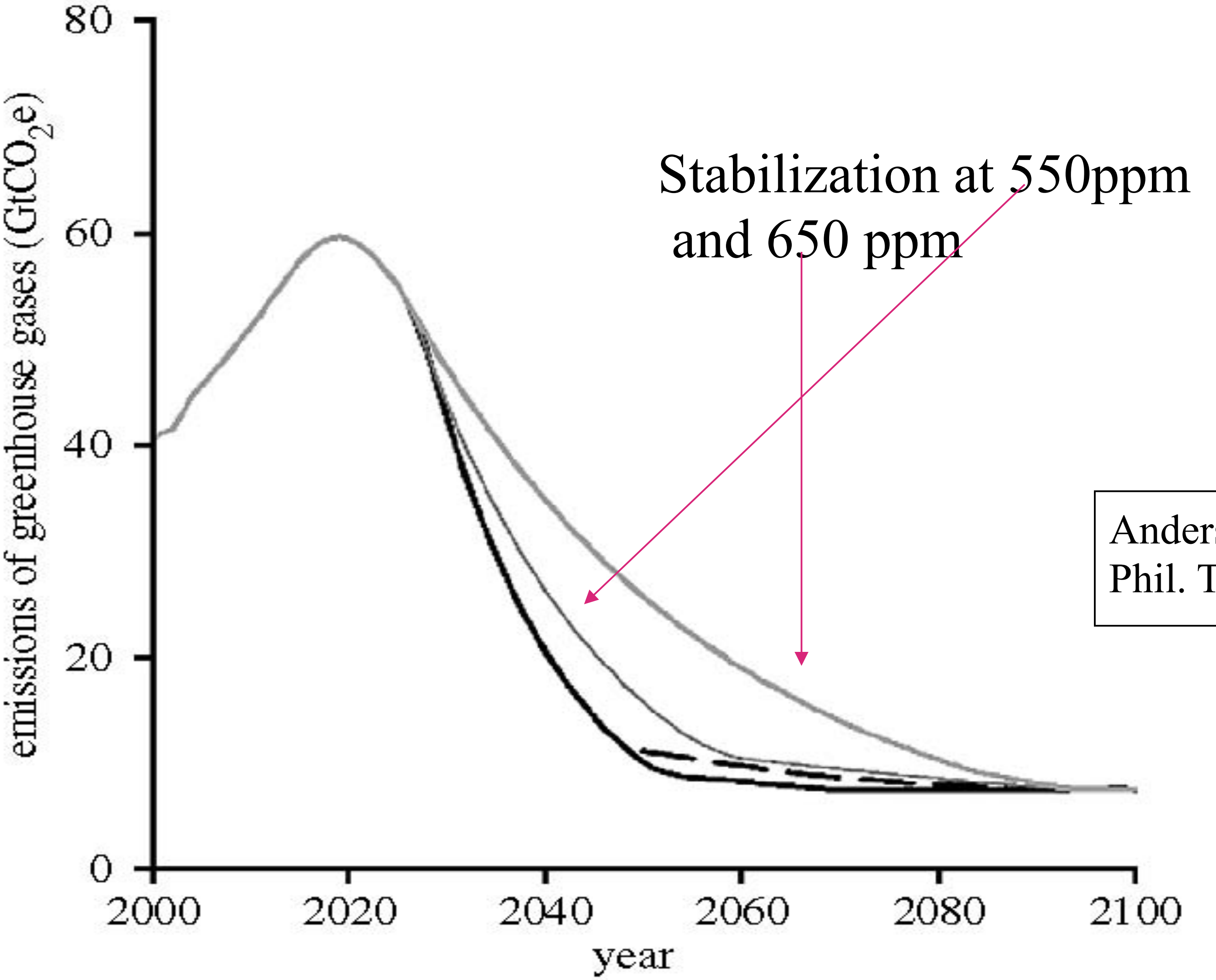
Equilibrium CO_2–eq (ppm)	Temperature Increase (°C)		
	Best Estimate	*Very Likely* Above	*Likely* in the Range
350	1.0	0.5	0.6–1.4
450	2.1	1.0	1.4–3.1
550	2.9	1.5	1.9–4.4
650	3.6	1.8	2.4–5.5
750	4.3	2.1	2.8–6.4
1000	5.5	2.8	3.7–8.3
1200	6.3	3.1	4.2–9.4

Pre-industrial ~13ºC Current ~14.4ºC
Pre-industrial: 280ppm 2005 CO_2: 384 ppm
Total GHG: 455 ppmCO_2-eq

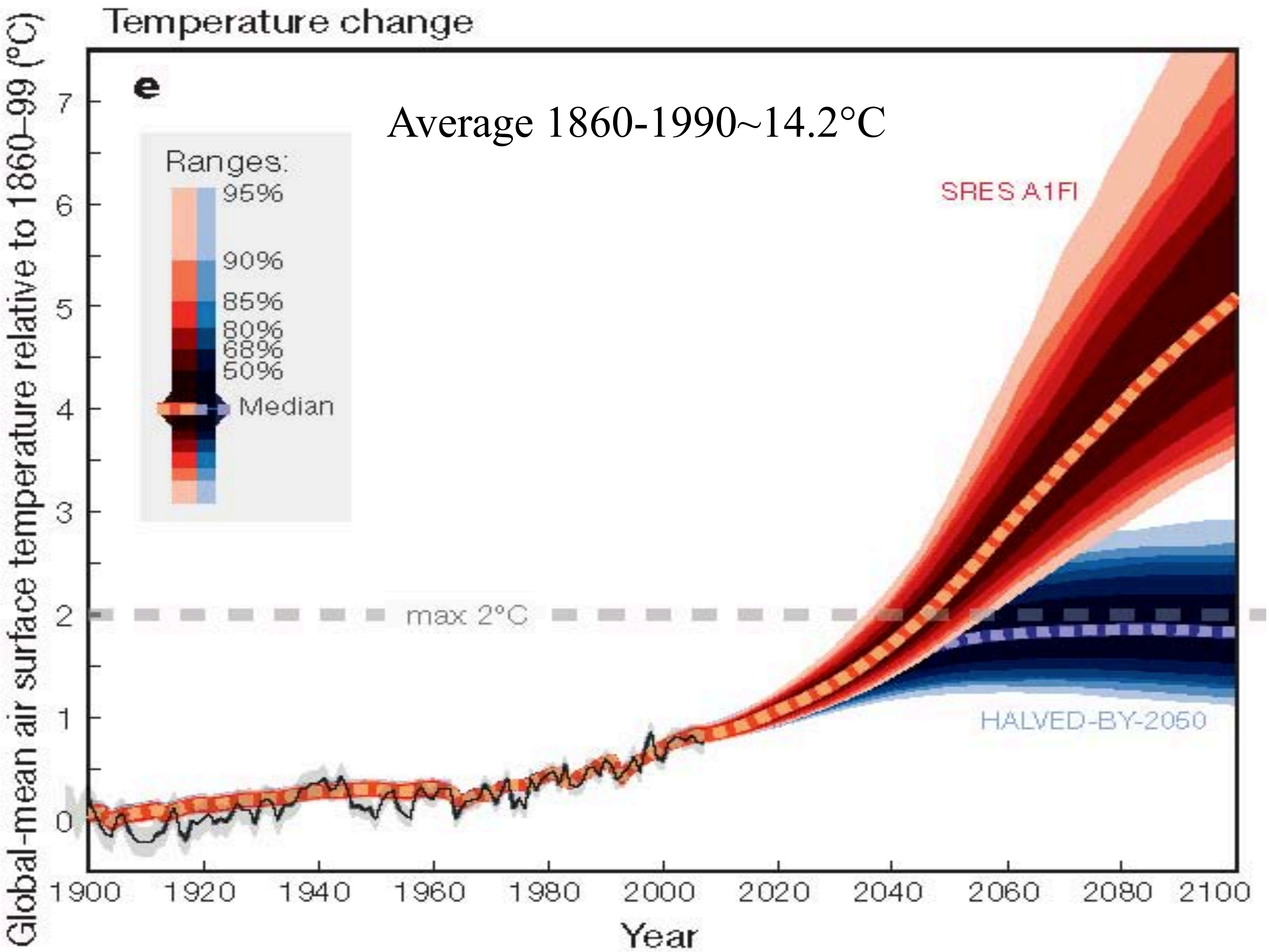
Comparison of Models

Projection Model	Temperature ºC in 2100 (~ppm CO_2)	Plausible Range (ºC)
Regression of historical trends	15.5 (547)	15.5 – 15.6
A1F1 scenario	18.0 (1550)	16.0 – 20.4
A2 scenario	17.4 (1250)	16.0 – 19.4
Stabilization at:		
350 ppm	14.0	13.6-14.4
450 ppm	15.1	14.4-16.1
550 ppm	15.9	14.9-17.4
650 ppm	16.6	15.4-18.5

Possible CO_2 Emission Pathways that Account for Lack of Progress in Current Trends



Anderson and Bows, Phil. Trans. R. Soc. , 2008

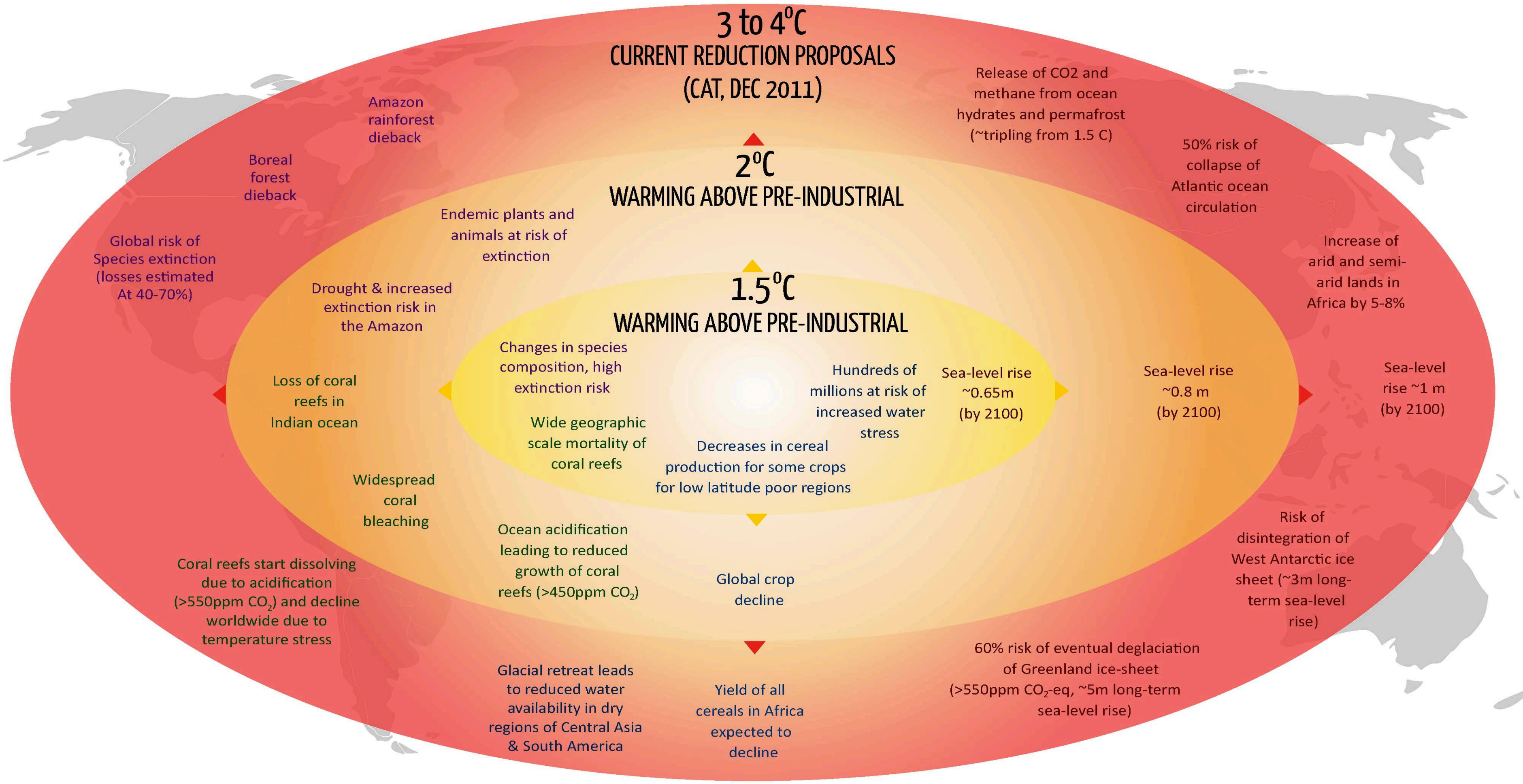


Temperature change
e
Average 1860-1990~14.2°C
Ranges:
95%
90%
85%
80%
68%
50%
Median
SRES A1FI
max 2°C
HALVED-BY-2050
Global-mean air surface temperature relative to 1860–99 (°C)
Year

A SNAPSHOT OF A WARMING WORLD

As the agreements in Durban do not propose additional action before 2020 the risk of exceeding 2°C remains very high. Action to implement the Durban Agreements will need to be quick to increase emission mitigation, for having a chance of deviating projected warming from the current pathway leading to 3.5°C by 2100. A limit of 1.5°C will already lead to considerable impacts, and more with 2°C. But with temperature increases heading towards 3.5°C, the impacts reach a distinctly higher level of risk. The impact examples in this figure are illustrative and not comprehensive.

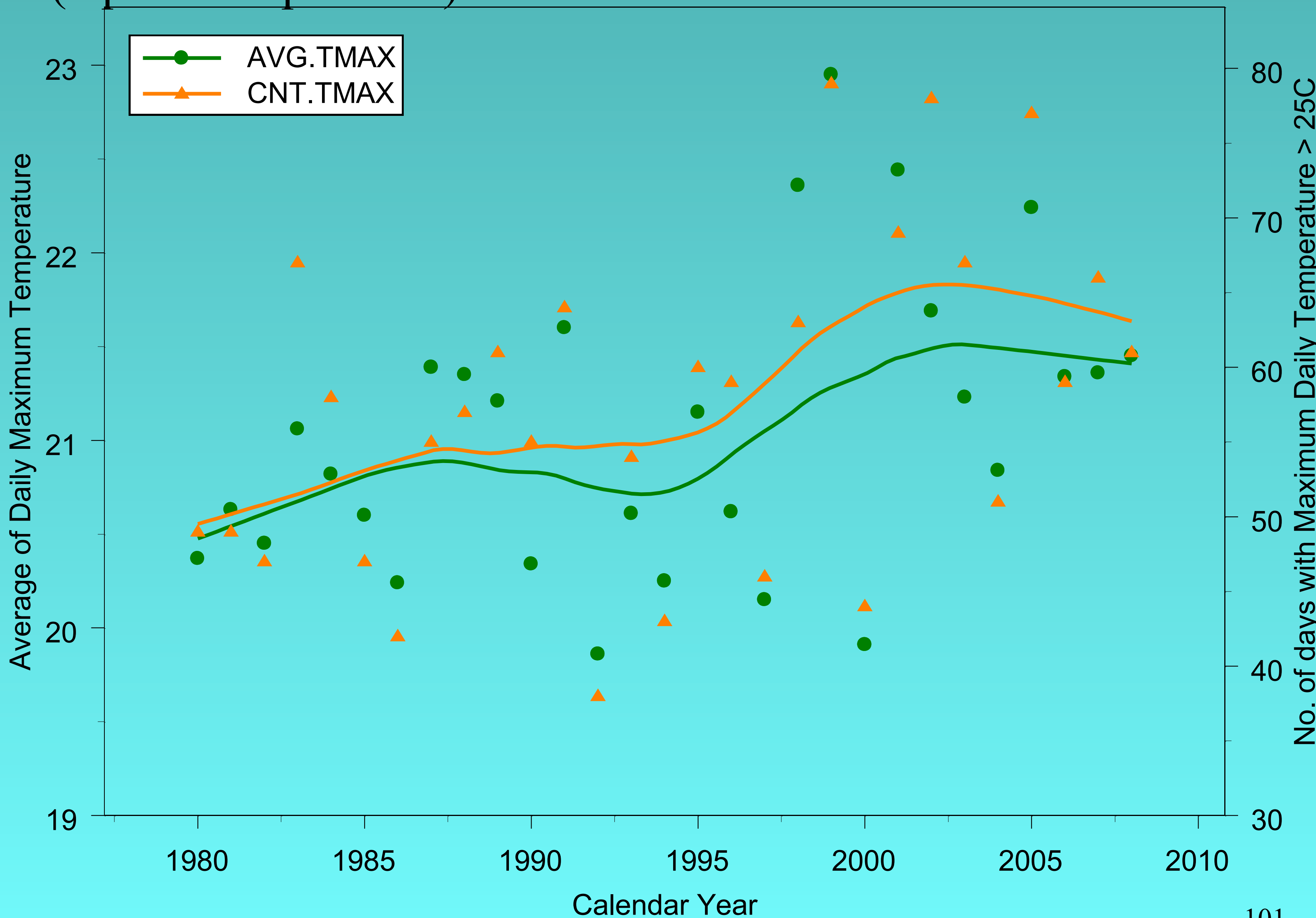
Current mean temp: 14.4°C
Pre-industrial: 13°C



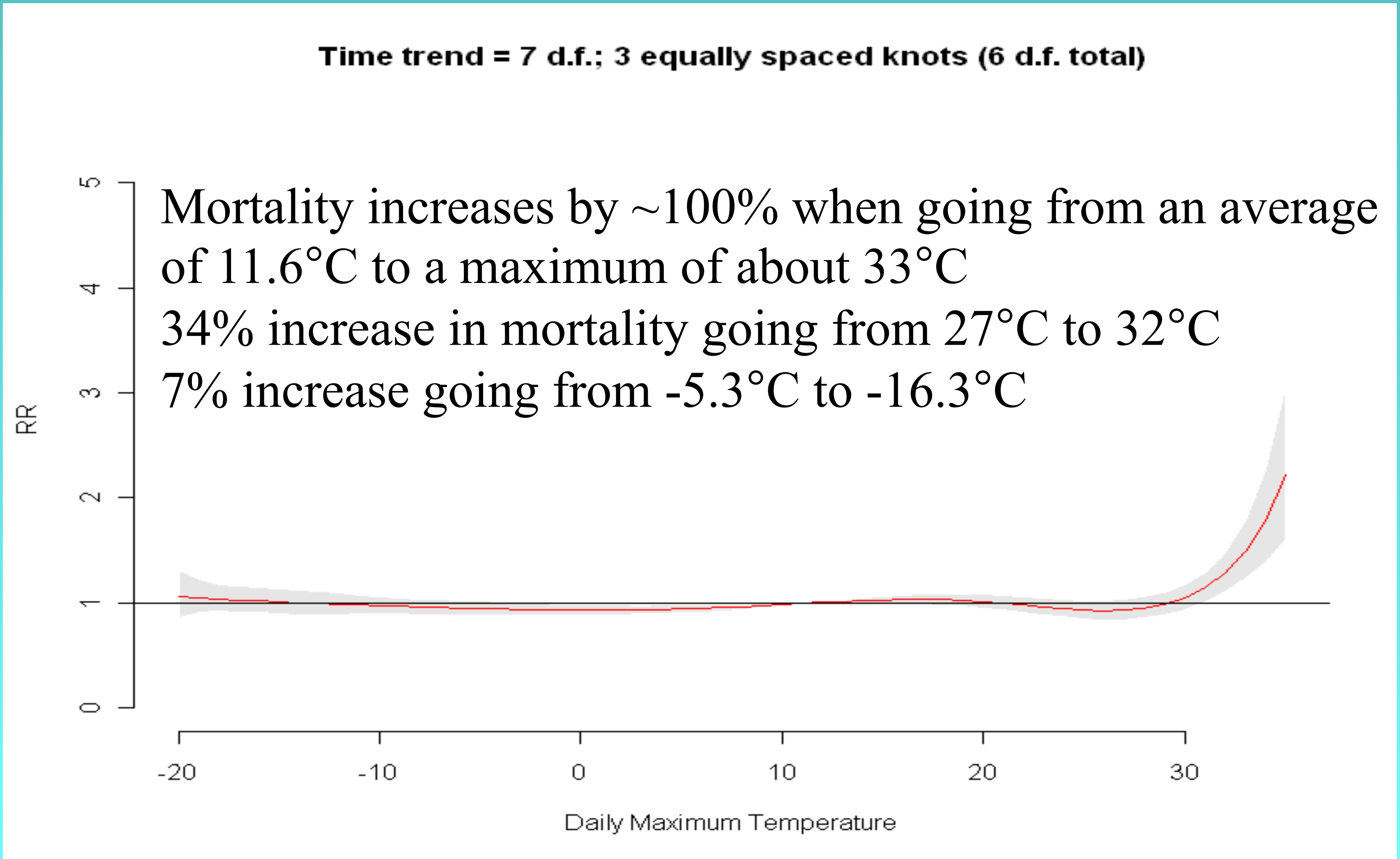
DOWNLOAD THE FULL REPORT AT WWW.CLIMATEACTIONTRACKER.ORG

Consequences of Global Warming

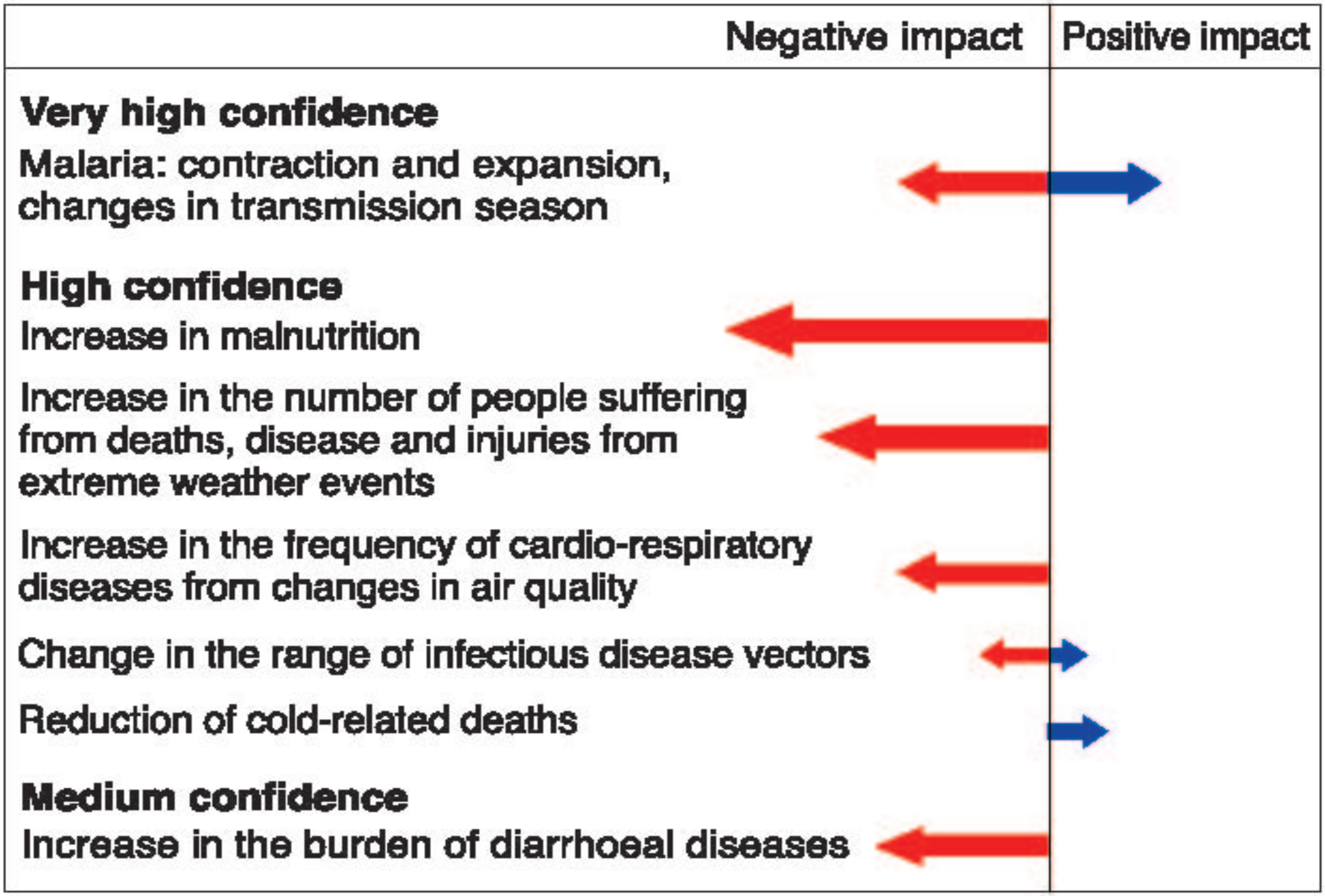
Montreal: Recent Trends in Daily Maximum Temperature (April to September)



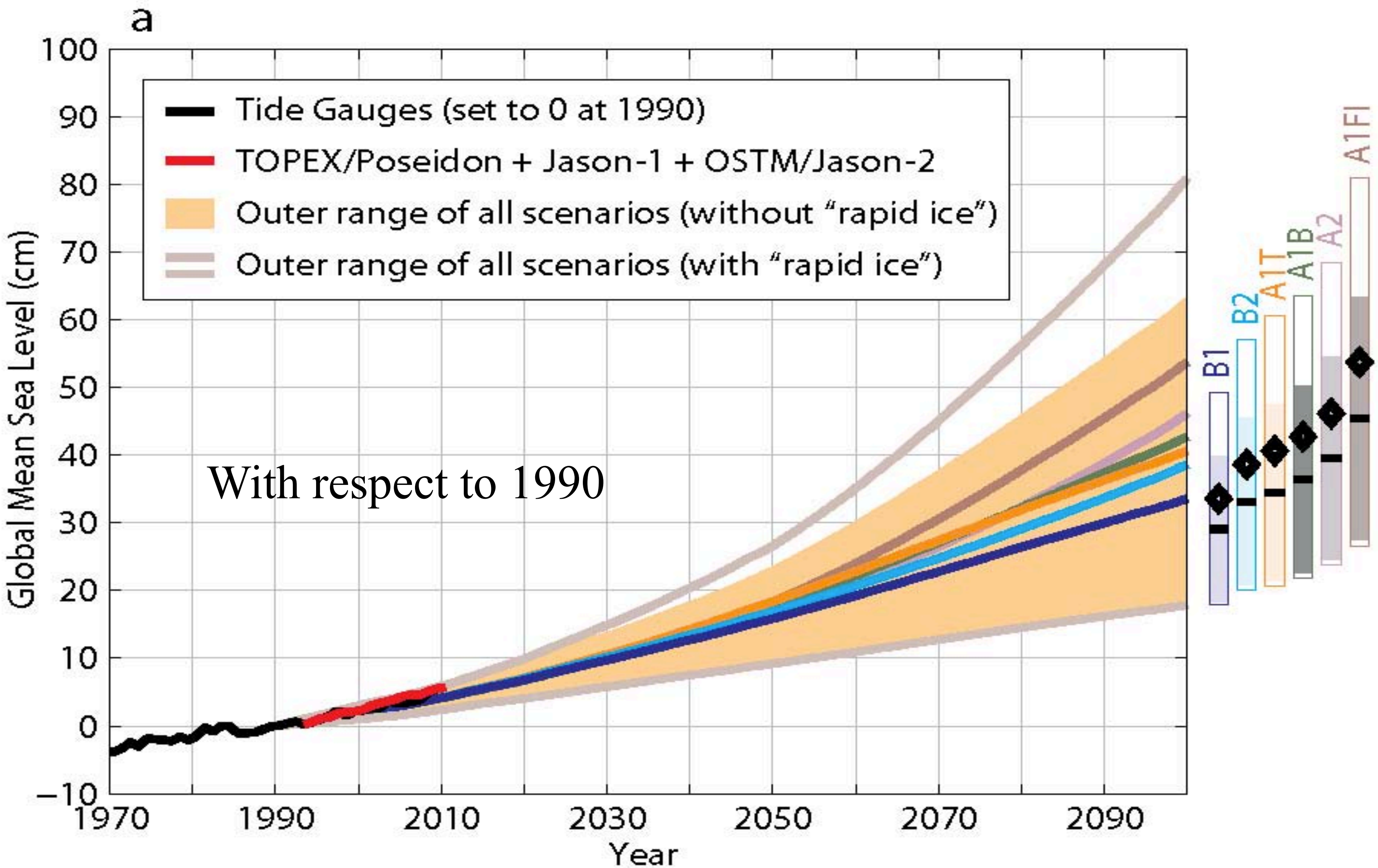
The Effect of Temperature on Non-accidental Daily Mortality, Montreal, 1984-2007



Health Impacts



Estimates of Sea Level Increases that do not Incorporate Non-linear Effects



Key Assumptions

- Reasonable models for expansion of volume (thermosteric)
- Coupled to GCMs and SRES scenarios

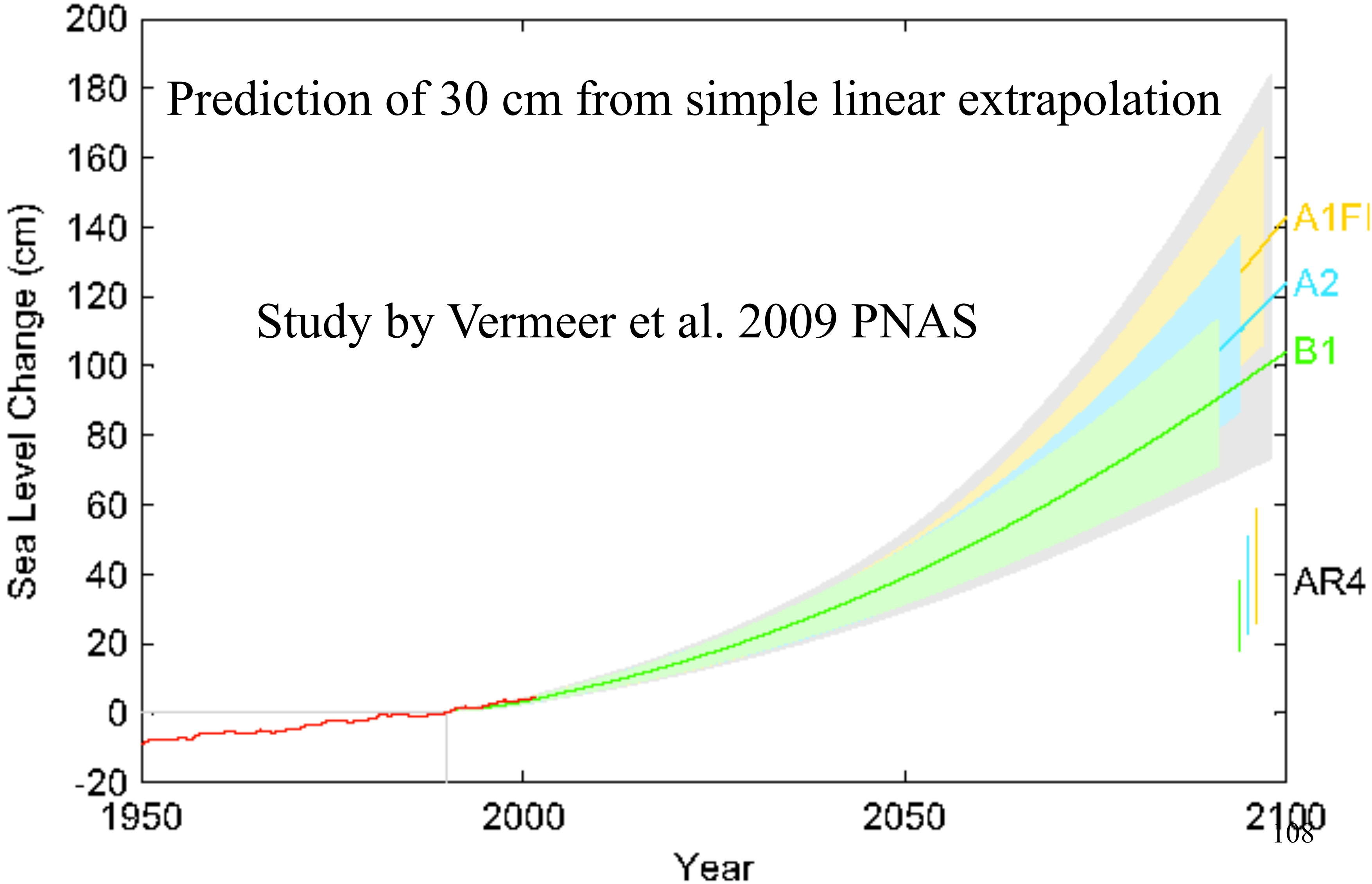
Did not Estimate Non-Linear Effects

- “Further mass loss from the ice sheets could occur if they discharged more ice into the ocean as icebergs. Indeed, recent observations have identified an acceleration of the outlet glaciers in some regions of both the Greenland and Antarctic ice sheets... However, there is incomplete understanding of the reasons for these changes, which depend on processes not simulated in the ice sheet models available for the AR4.”

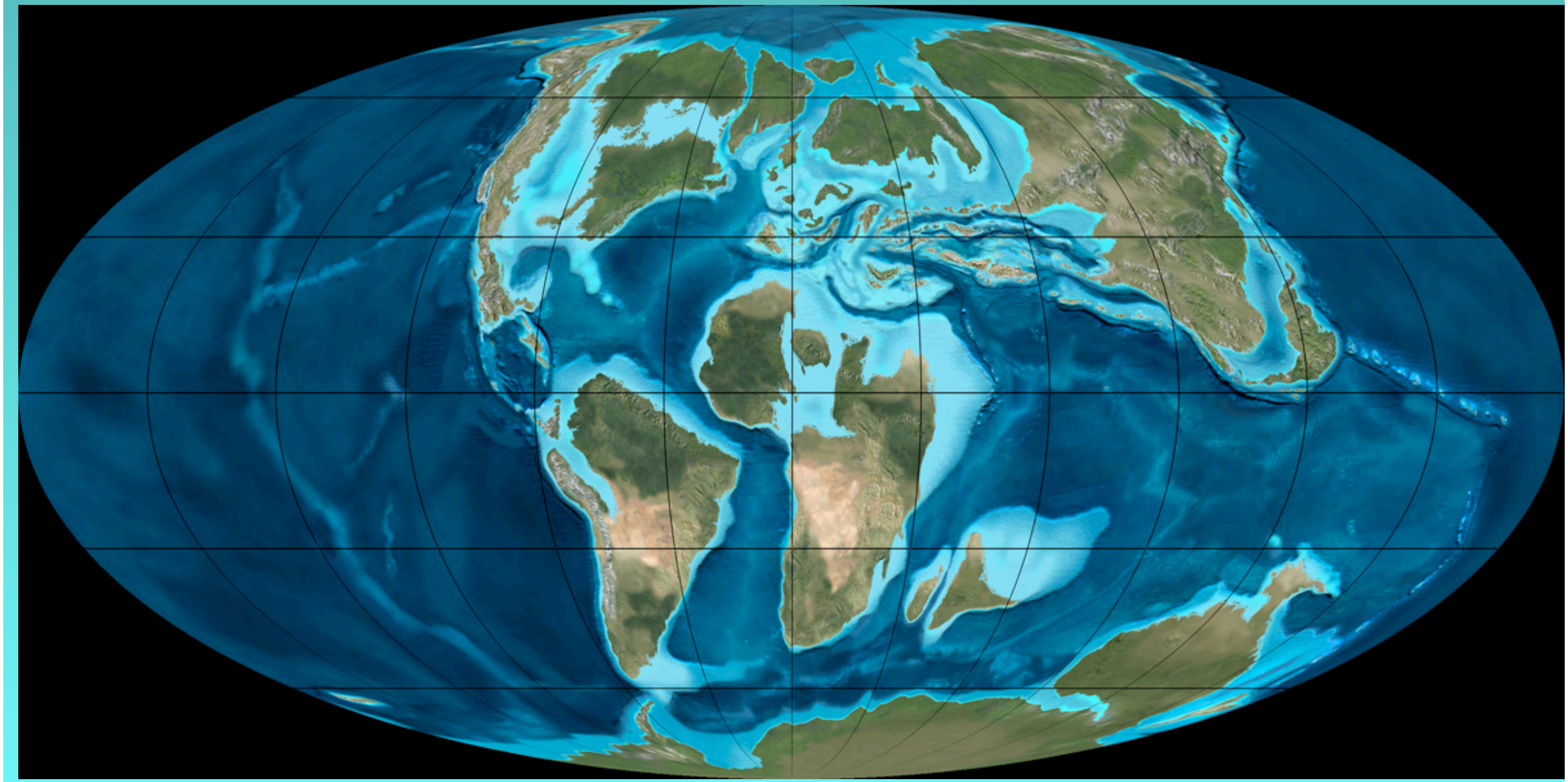
Did not Estimate Non-Linear Effects

- "Perhaps the major challenge is the response of the ice sheets, particularly those parts grounded below sea level."

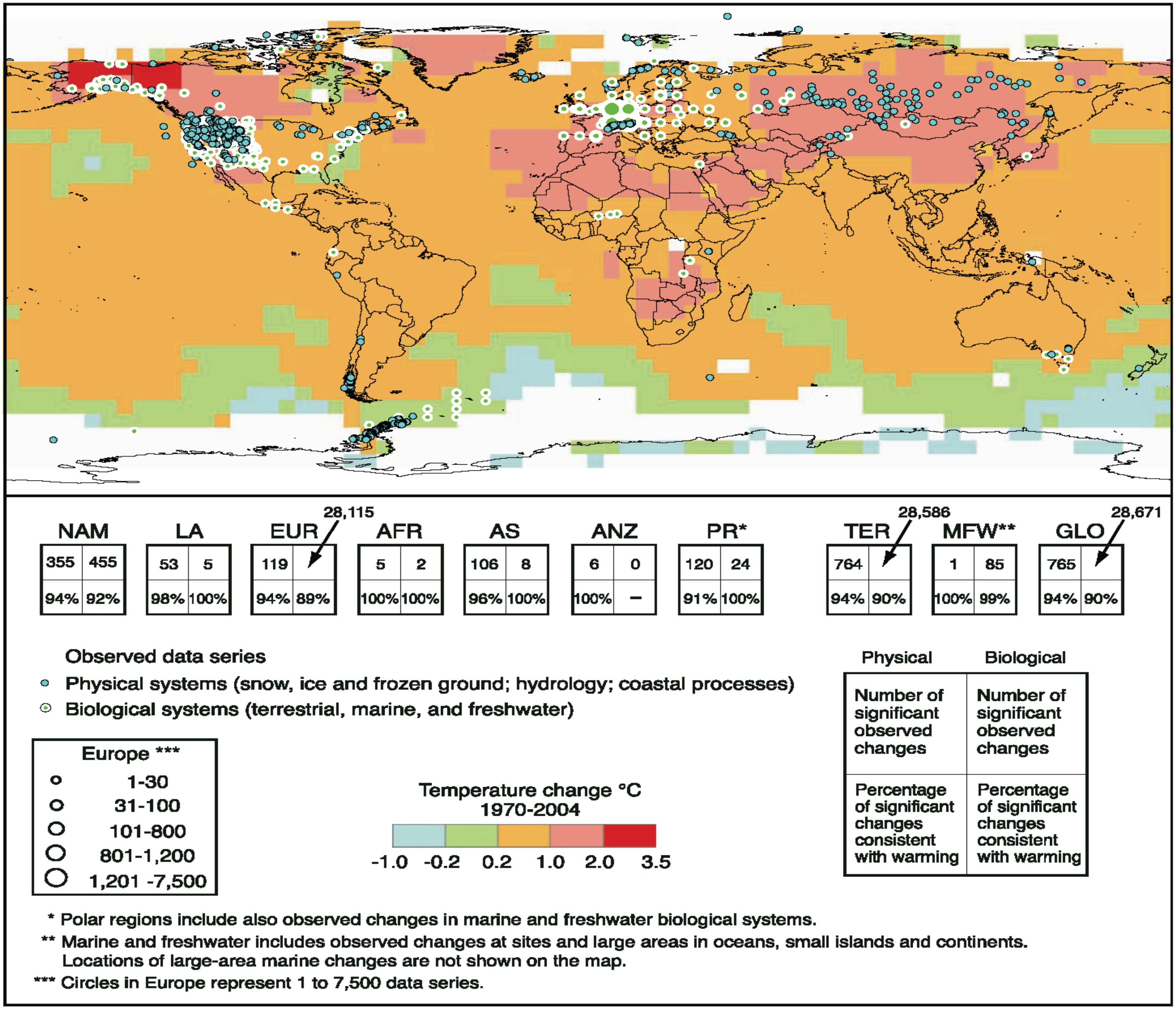
Projected Sea Level Increases



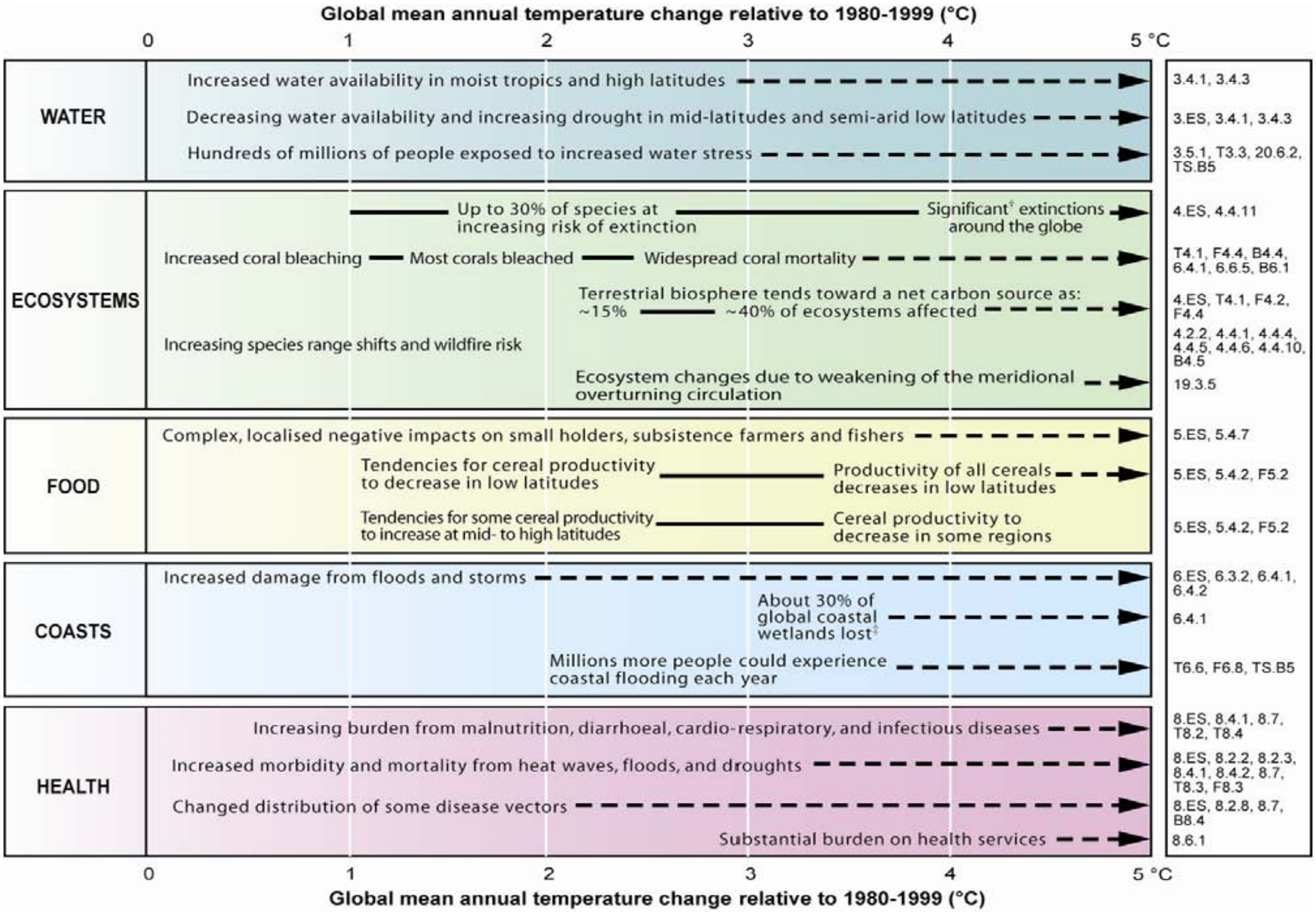
Late Cretaceous Period (145-65 million years ago): No Ice Caps



Potential Impacts: Ecosystems


NAM
355
455
94%
92%
LA
53
5
98%
100%
EUR
28,115
119
94%
89%
AFR
5
2
100%
100%
AS
106
8
96%
100%
ANZ
6
0
100%
–
PR*
120
24
91%
100%
TER
28,586
764
94%
90%
MFW**
1
85
100%
99%
GLO
28,671
765
94%
90%
Observed data series
Physical systems (snow, ice and frozen ground; hydrology; coastal processes)
Biological systems (terrestrial, marine, and freshwater)
Europe ***
1-30
31-100
101-800
801-1,200
1,201 -7,500
Temperature change °C
1970-2004
-1.0
-0.2
0.2
1.0
2.0
3.5
Physical
Biological
Number of significant observed changes
Number of significant observed changes
Percentage of significant changes consistent with warming
Percentage of significant changes consistent with warming
* Polar regions include also observed changes in marine and freshwater biological systems.
** Marine and freshwater includes observed changes at sites and large areas in oceans, small islands and continents. Locations of large-area marine changes are not shown on the map.
*** Circles in Europe represent 1 to 7,500 data series.

Key Impacts of Increasing Global Average Temperature Change



† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

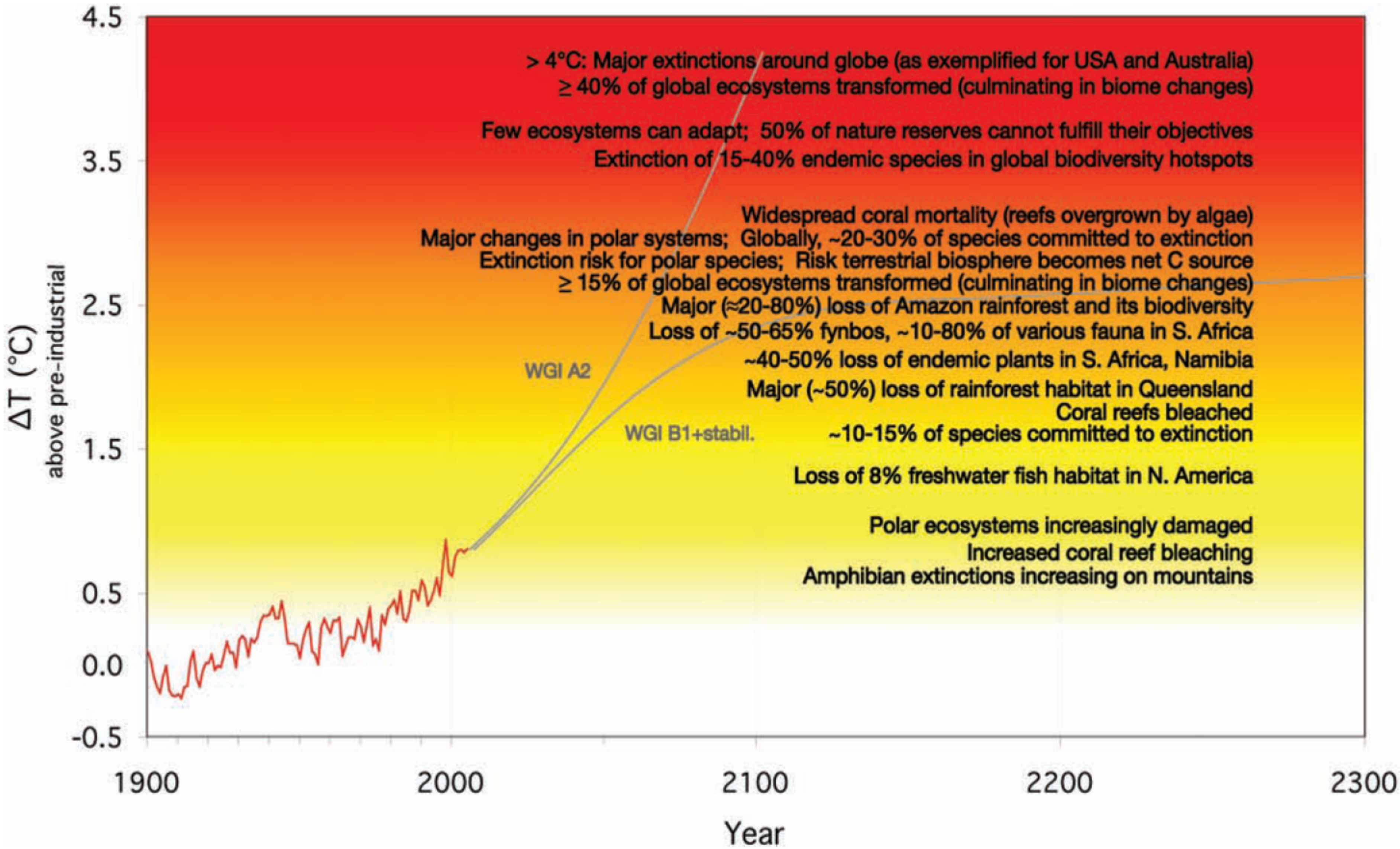
Example: Pollen

- Production of pollen sensitive to temperature, duration of sunshine and ambient CO_2
- Climate change ➔ earlier start to the pollen season, an increase in the number of growing days, and greater pollen production
- Possible health effects: allergies, asthma

Impact: Water Shortages

- No. of people living in stressed water basins to increase from 1.4-1.6 billion to 4.3-6.9 billion in 2050
- Semi-arid and arid regions will be affected by global warming

Impact: Ecosystems



Vulnerability of Coastal Deltas

Extreme: >1 million
High: 1 million to 50,000
Medium: 50,000 to 5,000

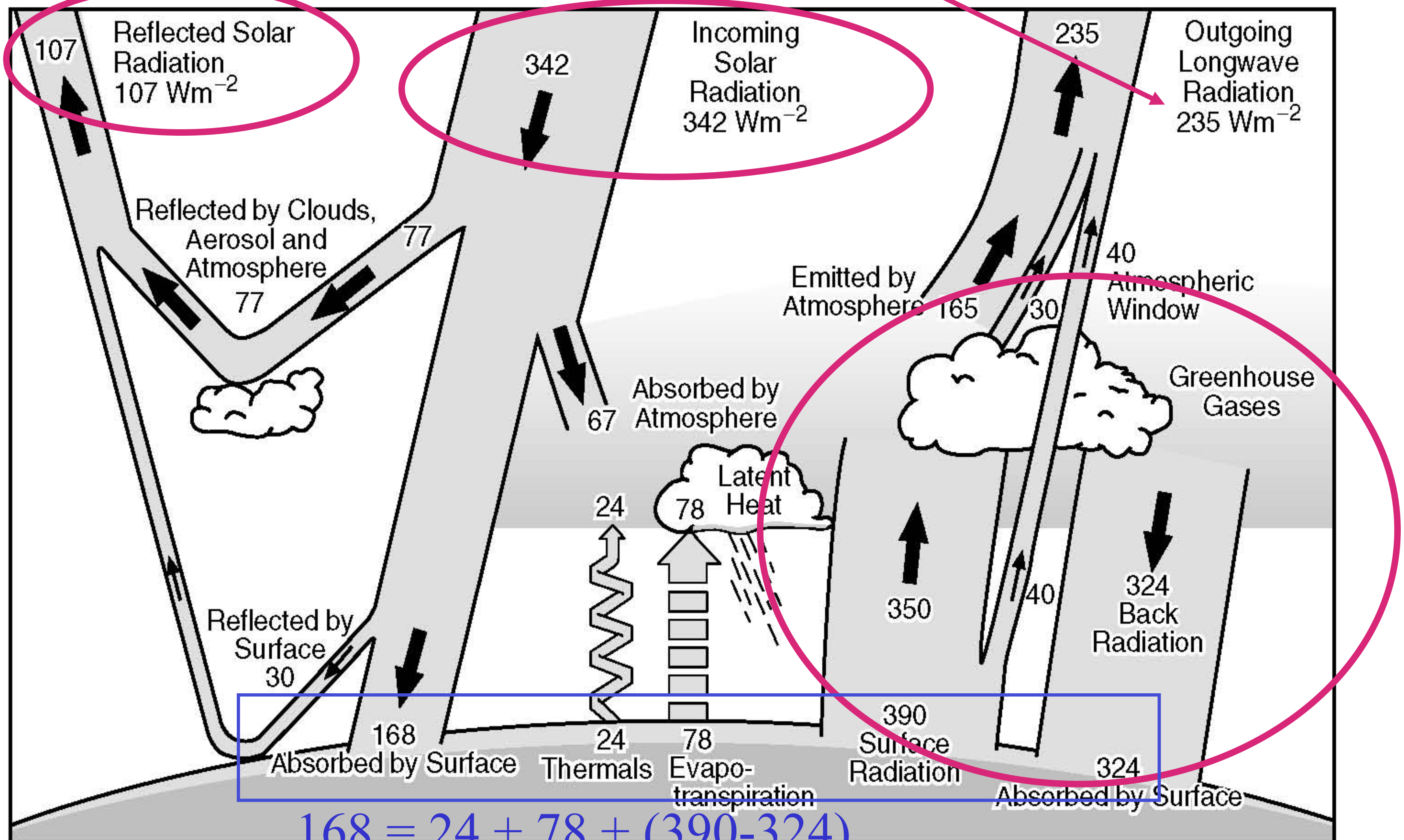
Policy-Relevant Messages from WG-II

- Coasts highly vulnerable from climate and sea level
  - Rise in sea level by 0.2-0.6m by 2100
  - Increase in ocean temperatures by 1-3ºC
  - More intense tropical and extra-tropical cyclones
  - Larger extreme wave surges
  - Altered precipitation/runoff
  - Ocean acidification
  - Exacerbations by human-induced pressures
  - Adaptation more difficult in developing countries
  - Costs of inaction much higher than adaptation

Additional Slides

342-107=235=net energy absorbed

Equilibrium



168 = 24 + 78 + (390-324)

Figure 1.2: The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm^{-2}) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, *Bull. Am. Met. Soc.* 78, 197-208.