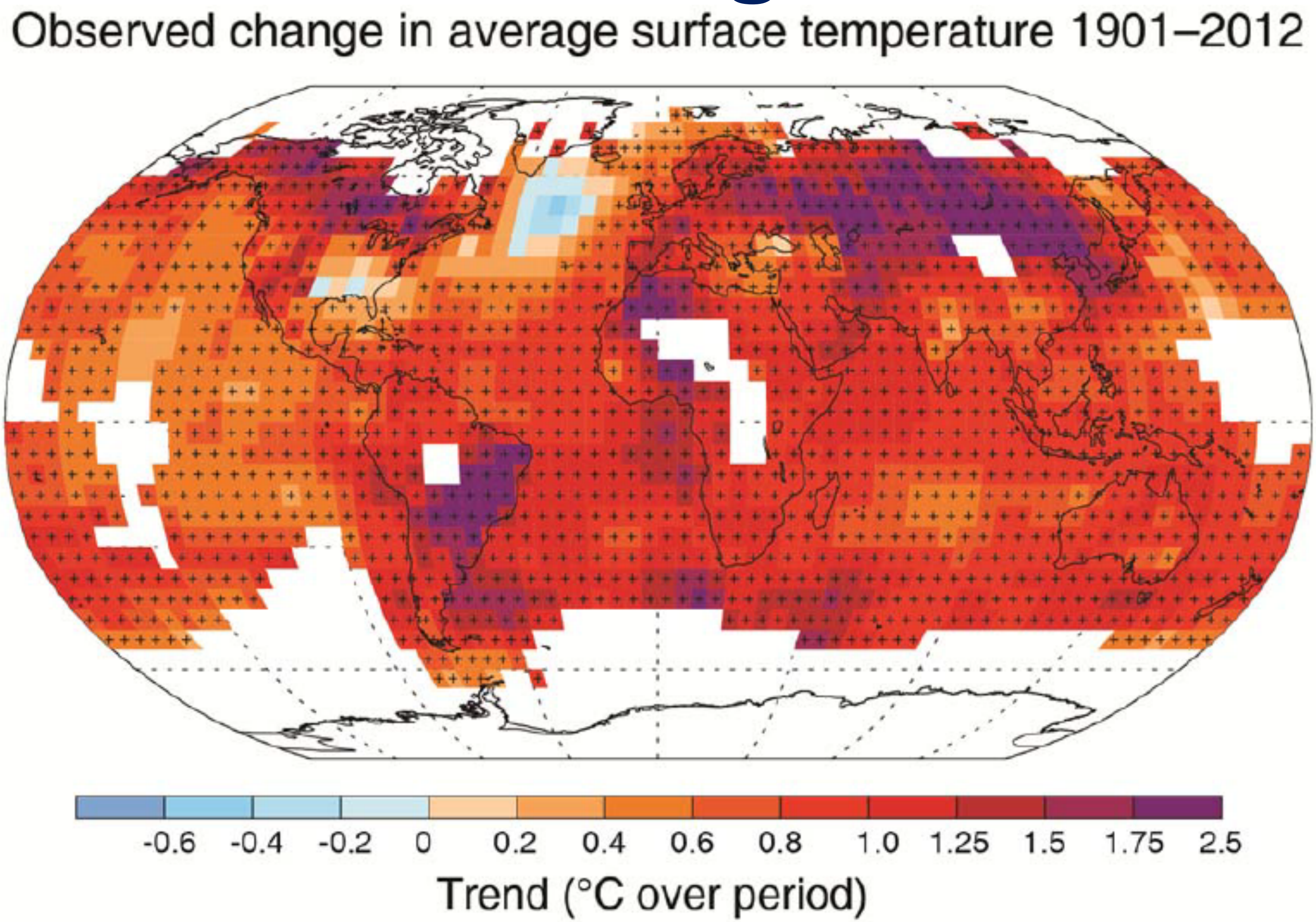
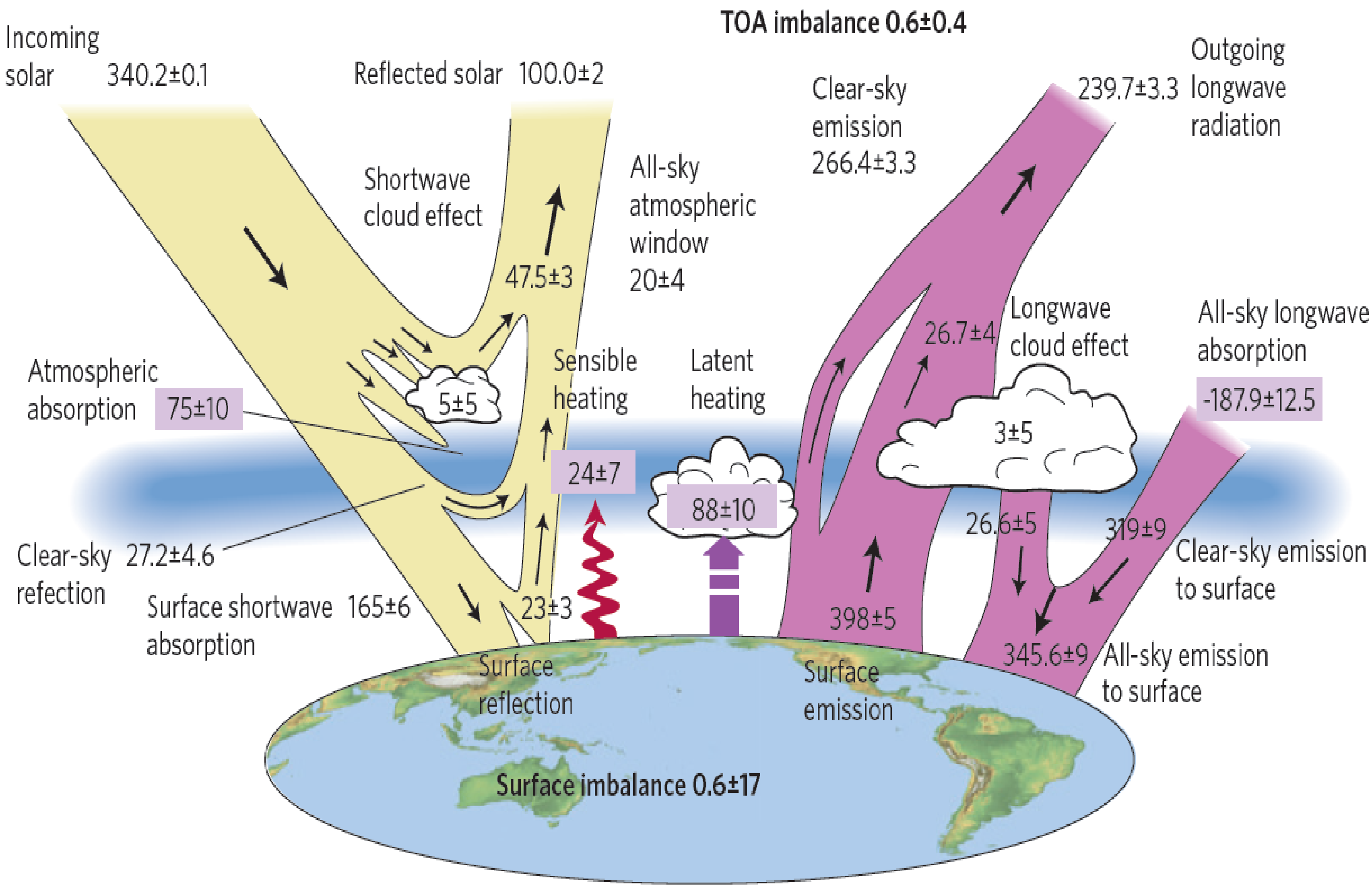
Climate Change Science



Daniel Cohan (cohan@rice.edu)
Dept. of Civil & Environmental Engineering

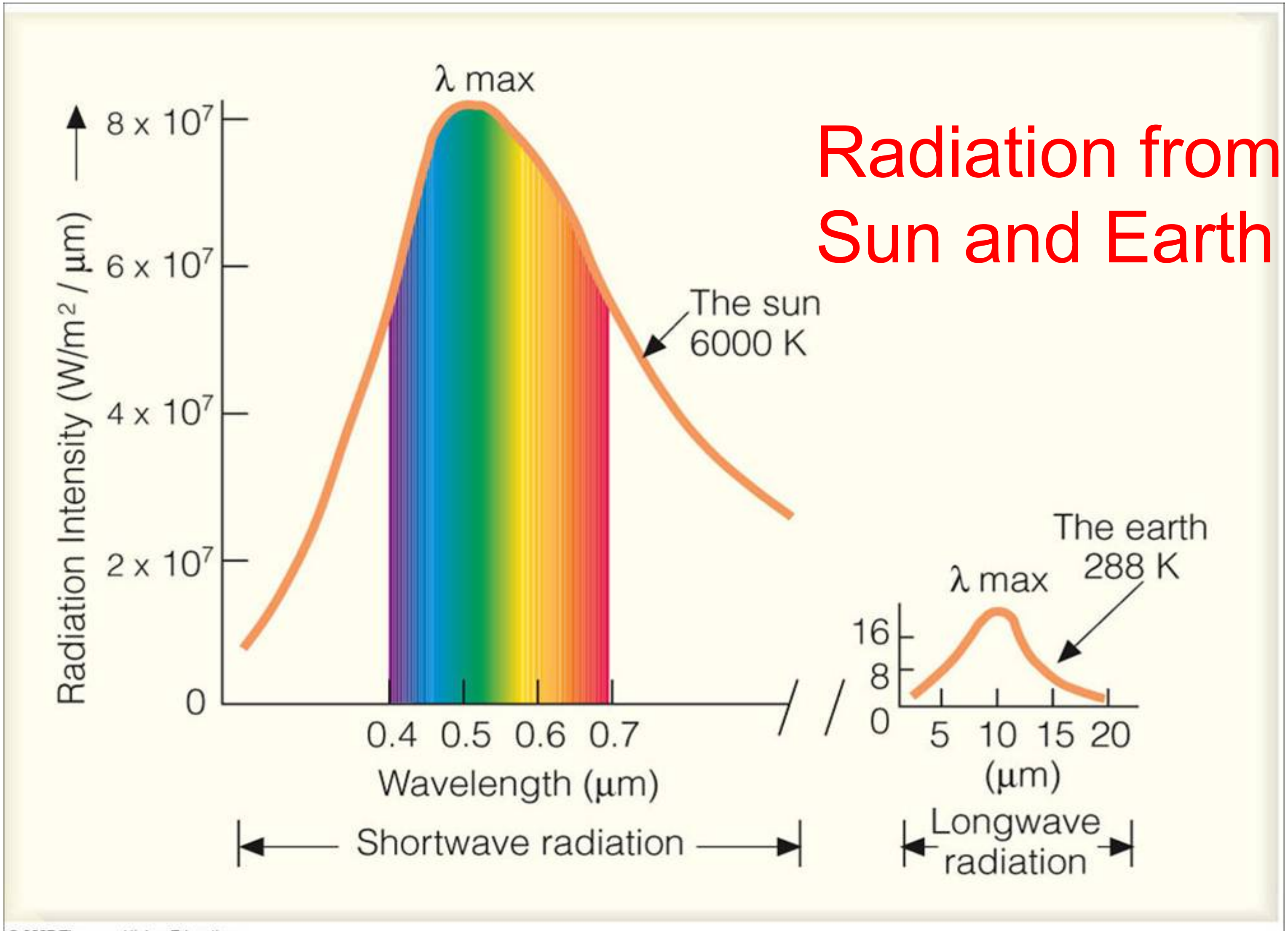
IPCC, 2013

Earth's Radiative Balance



Stephens et al., Nature Geoscience 2012. All fluxes are shown in W/m^2

Solar: shortwave; Earth: longwave



How do greenhouse gases absorb Earth's infrared energy?

<u>Greenhouse gases</u>: Undergo charge asymmetries ("dipoles") when interacting with <u>infrared</u> photons of <u>specific wavelengths</u>
• CO_2, H_2O, CH_4, N_2O, CFCs, …

<u>Non-greenhouse gases</u>: Cannot experience a dipole
• N_2, O_2, Ar

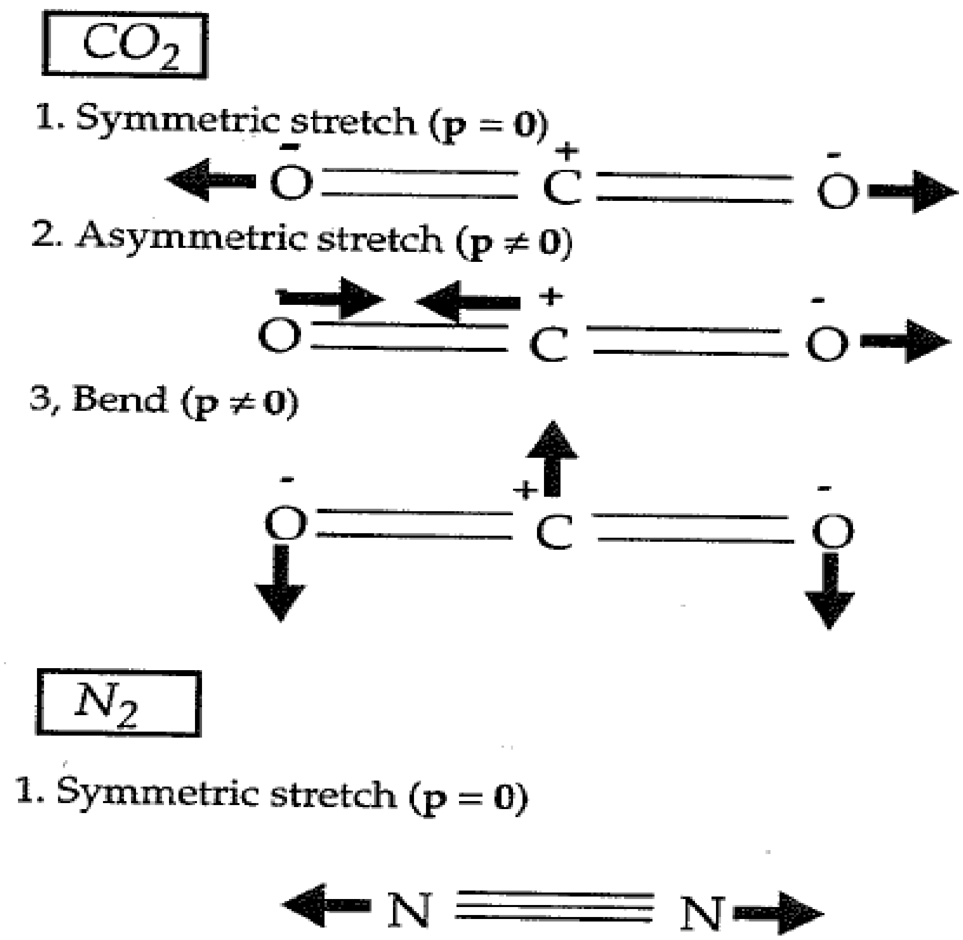
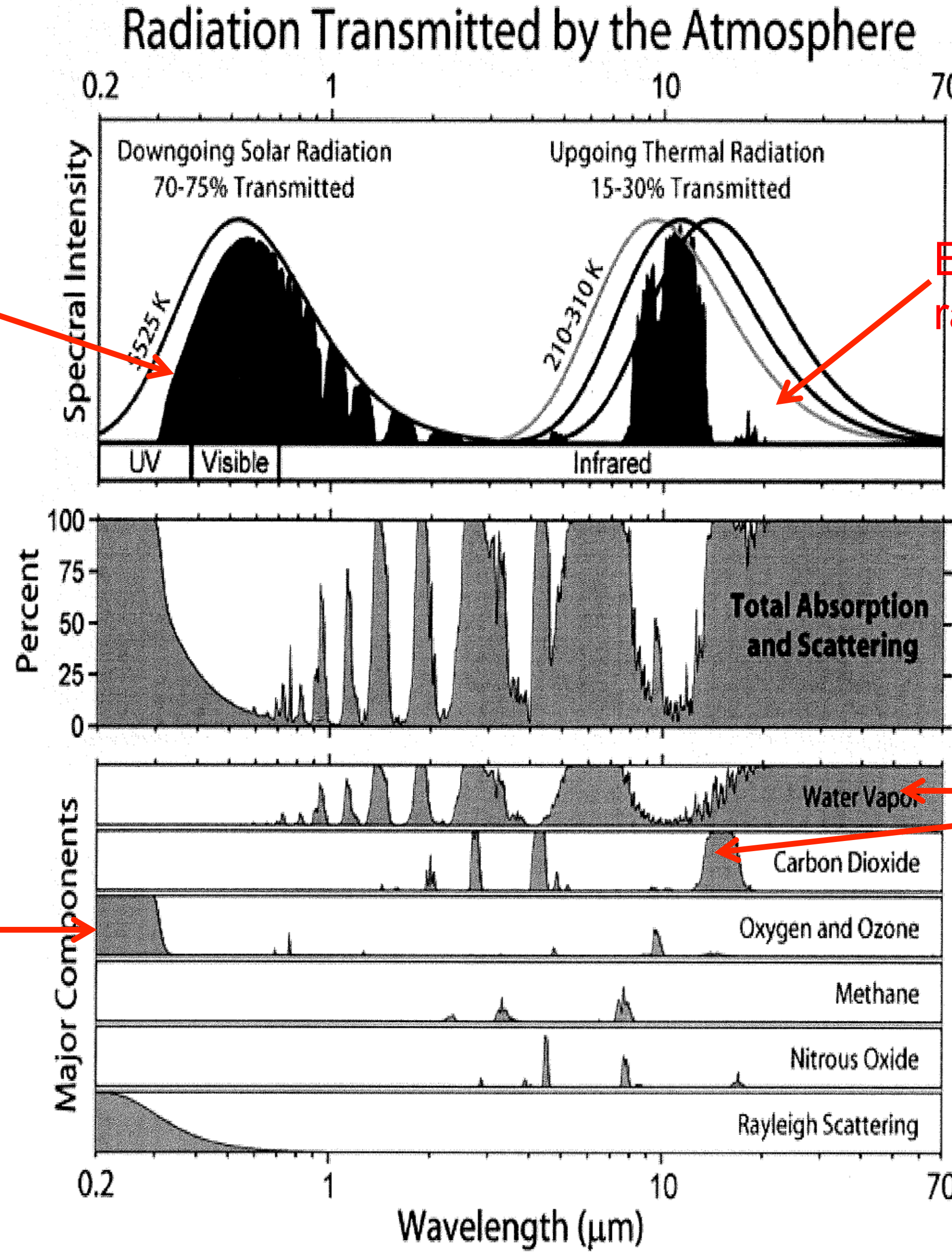


Fig. 7-10 Normal vibrational modes of CO_2 and N_2.

Sun emits shortwave radiation (mostly UV & visible)

Earth emits longwave radiation (infrared)



Longwave radiation absorbed by H_2O, CO_2

UV largely absorbed by oxygen & ozone, but visible passes through

Global Warming Art
(http://www.globalwarmingart.com/wiki/Image:Greenhouse_Effect_png)

Five Key Questions

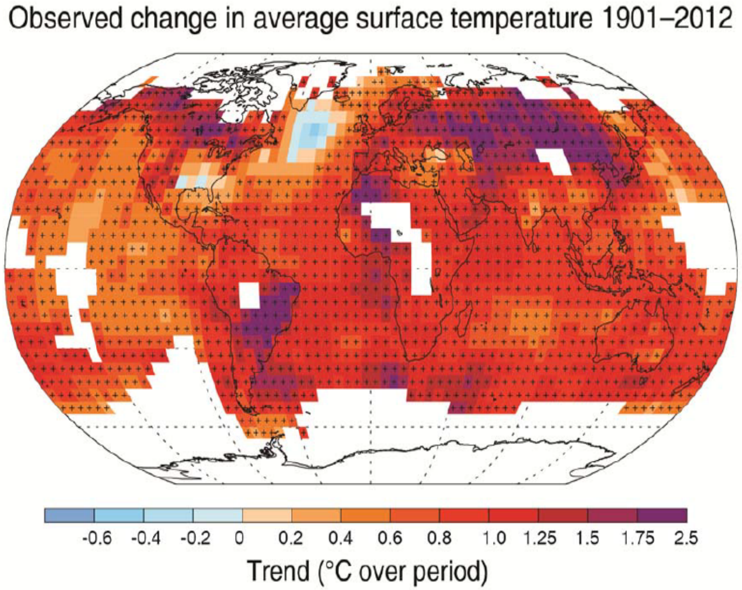
- Has Earth warmed? (Measurement)
- Are we responsible? (Attribution)
- Will warming continue? (Predictions)
- Is that a problem? (Impacts)
- What should we do? (Policy)

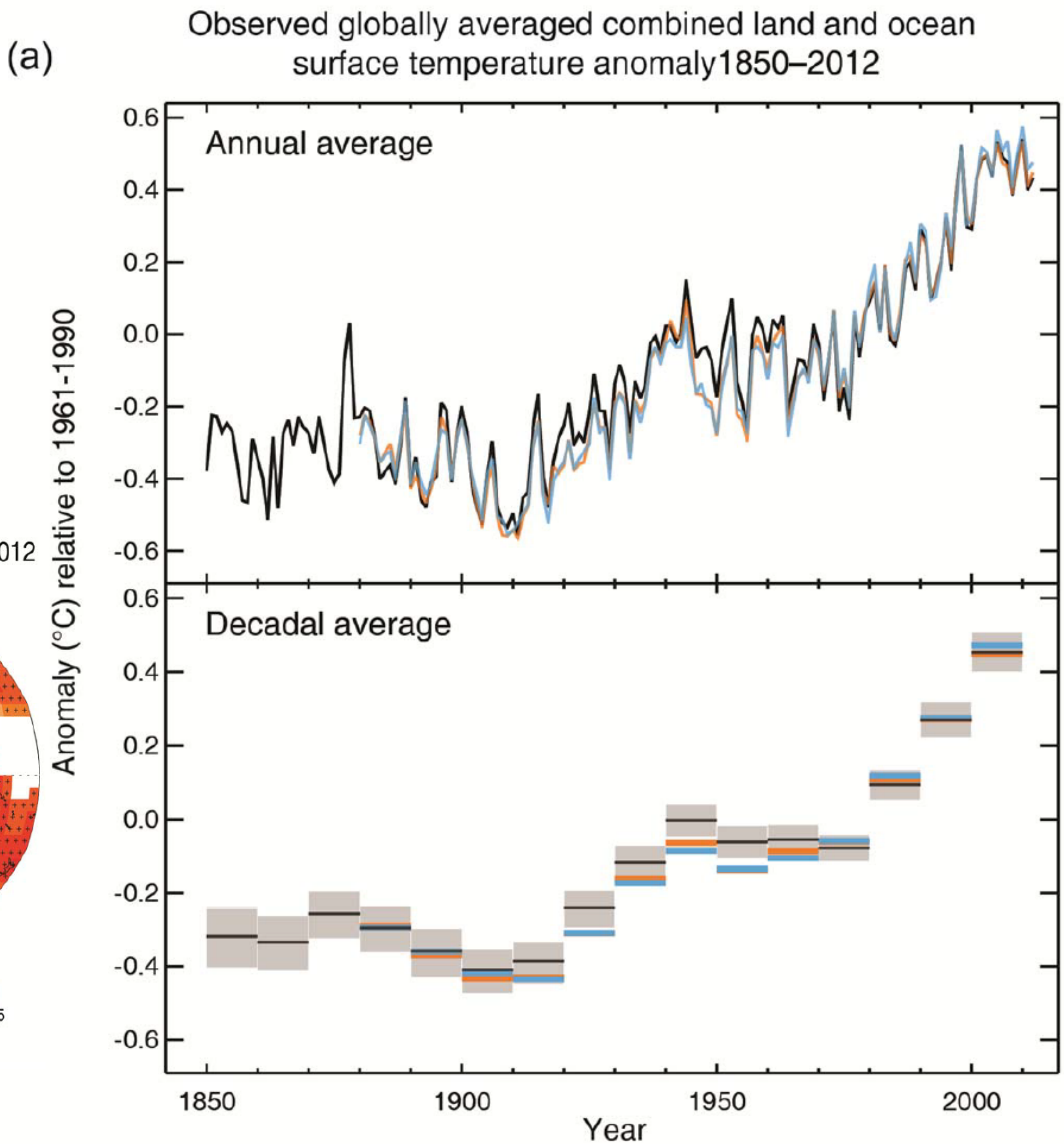
Source for most slides:

IPCC Fifth Assessment Report:
Summary for Policymakers (draft): 2013
Technical sections: 2014

Has Earth warmed?

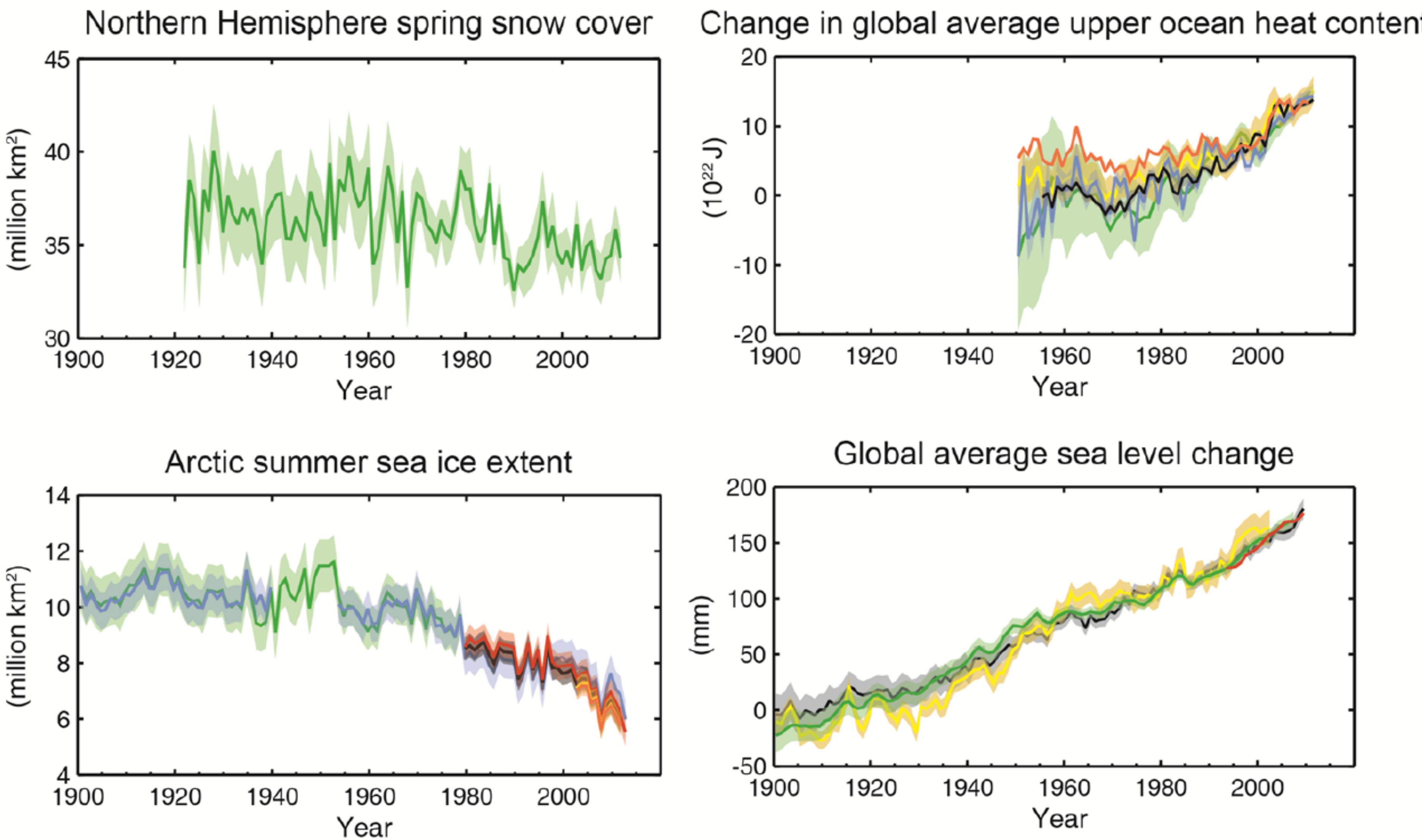
IPCC 2007 & 2013:
"Warming of the climate system is unequivocal"





IPCC 2013

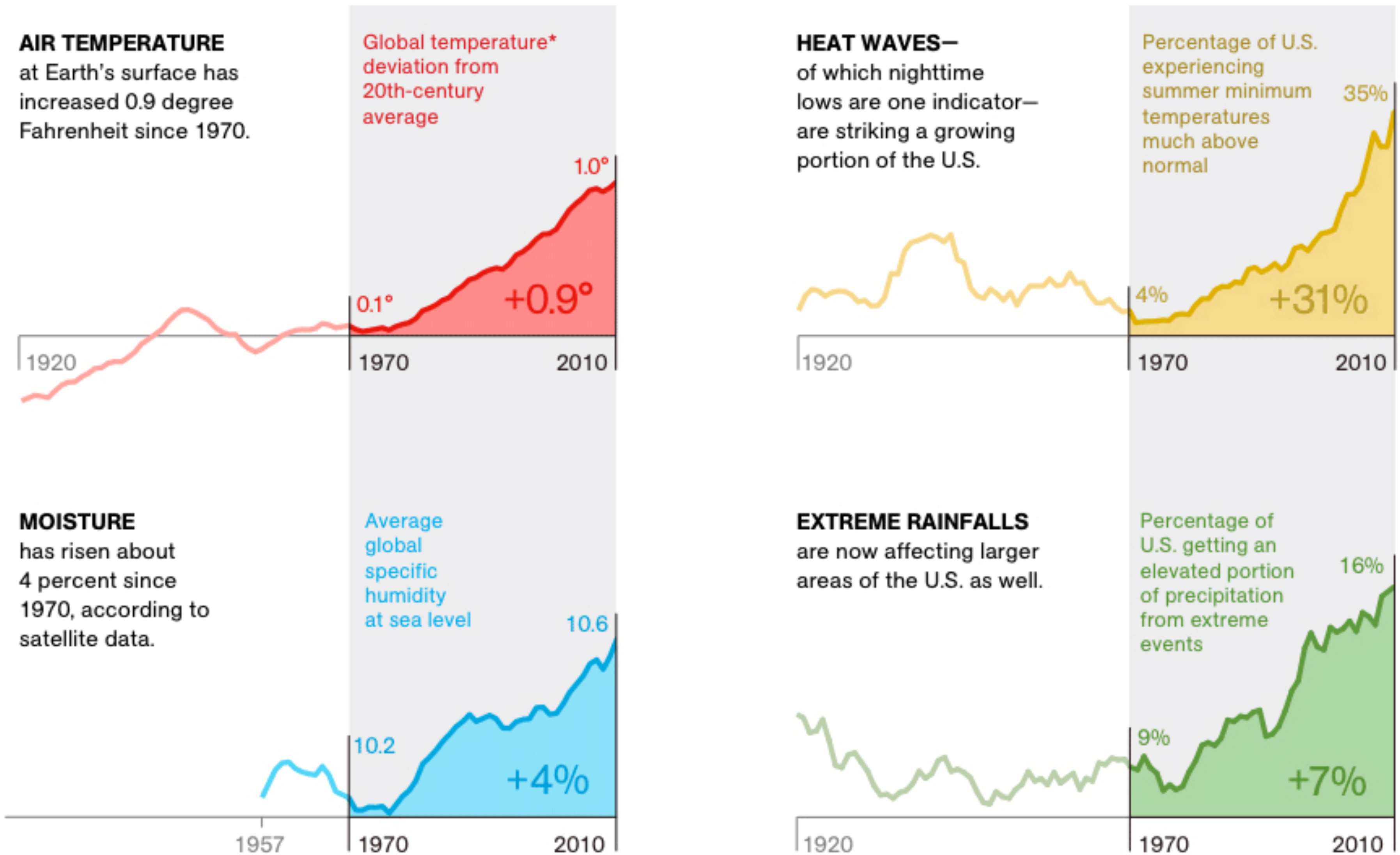
Additional evidence of warming



IPCC 2013

Global

US

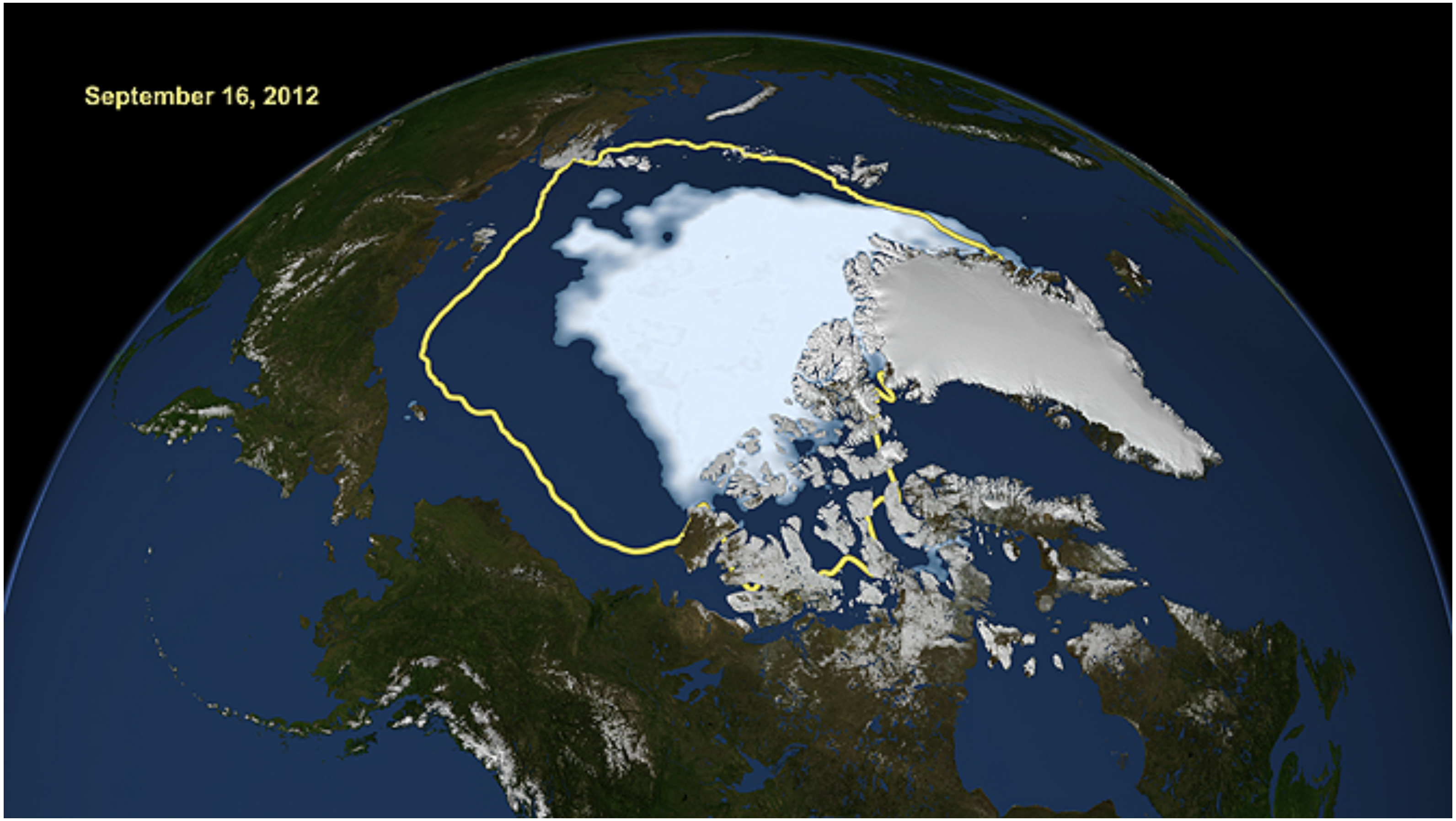


GRAPHS ARE SMOOTHED USING A TEN-YEAR MOVING AVERAGE.
*AVERAGE TEMPERATURE OVER LAND AND OCEAN

JOHN TOMANIO, NGM STAFF. ROBERT THOMASON. SOURCES: JEFF MASTERS, WEATHER UNDERGROUND; NATIONAL CLIMATIC DATA CENTER (TEMPERATURE, HEAT WAVES, AND RAINFALL); NOAA (HUMIDITY)

National Geographic

Arctic sea ice reached all time minimum extent, Sept. 2012



Yellow line shows average minimum, 1979-2010

NASA

Five Key Questions

- Has Earth warmed?
- Are we (greenhouse gases) responsible?
- Will warming continue?
- Is that a problem?
- What should we do?

Solar Variability

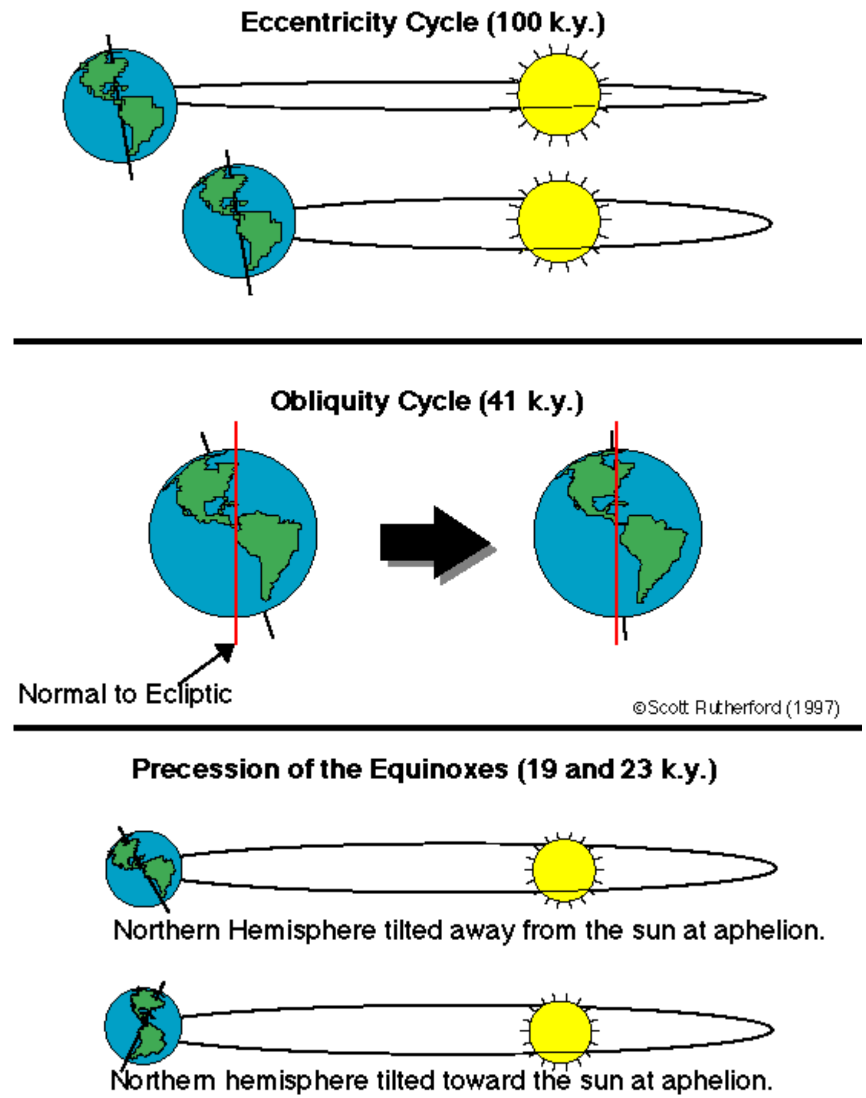
- Variability in solar energy output
  - Month-to-month: <0.2% variability as Sun rotates
  - 11-yr sunspot cycle: ~0.1% output variations
  - Past 2000 years: ~0.2% long term variability
- Recall that solar constant $F_S \sim 1360$ W/m^2
  - Earth absorbs F_s(1-albedo)/4 = <u>240</u> W/m^2
  - Thus, each 0.1% change in solar output is equivalent to ~0.2 W/m^2 radiative forcing
  - Recall: Radiative forcing from anthropogenic CO_2 <u>so far</u> is about 1.7 W/m^2

Orbital Variability: Milankovitch Cycles

Eccentricity: Cycle of how circular or elliptical Earth's orbit is (100,000 years)

Obliquity: Earth's tilt oscillates between 22° and 24.5° (41,000 years)
- Currently 23.5°

Precession: Cycle of when Earth is closest to Sun (19,000 & 23,000 years)
- Currently closest to Sun in January (Southern Hemisphere summer)
- Northern Hemisphere has most land; solar insolation at 65°N latitude influences glaciation



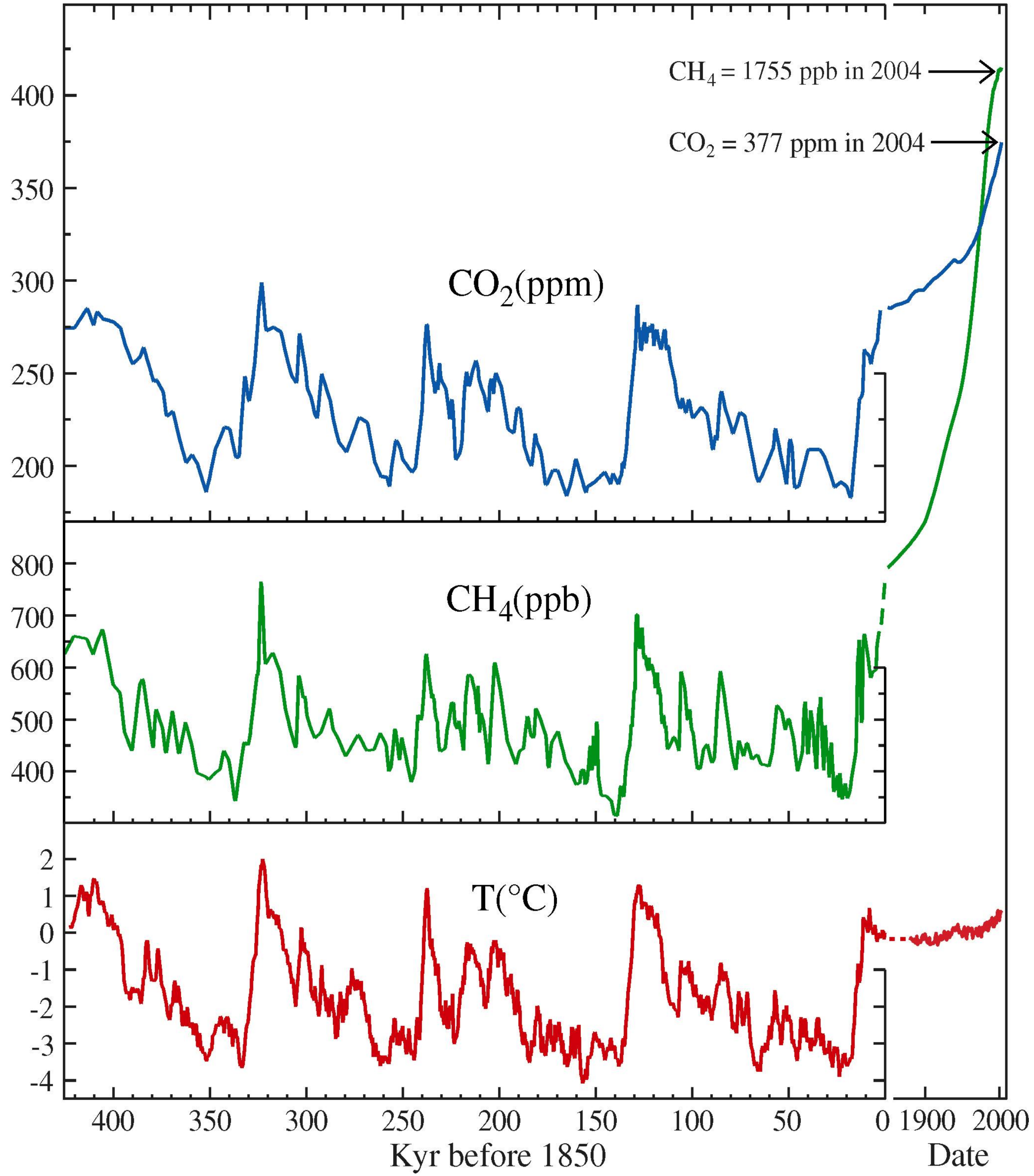
http://deschutes.gso.uri.edu/~rutherfo/milankovitch.html

Causes of natural glaciations and interglacial (warm) periods

- Milankovtich orbital cycles drive the 10 major glaciations of past 1 million years, **but**:
  - Direct radiative forcings are too small to explain ΔT
  - Appears that positive feedback cycles multiply the effects of an initial radiative forcing
    - Water vapor feedback: ↑T → ↑ H_2O (ghg) → ↑T
    - Ice albedo feedback: ↑T → ↓ice → ↓albedo → ↑T
    - Greenhouse gas feedbacks: CO_2 and methane levels increase as temperature increases
      - ↑T →melt permafrost, ↑ microbial processes→ ↑CH_4 → ↑T
      - ↑T→ ↓ solubility of CO_2, ↑ respiration→ ↑CO_2 → ↑T

Strong correlation between greenhouse gases and Temp

• Consistent with positive feedbacks accentuating impacts of orbital cycles



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.

Pre-industrial and Recent Carbon Cycle

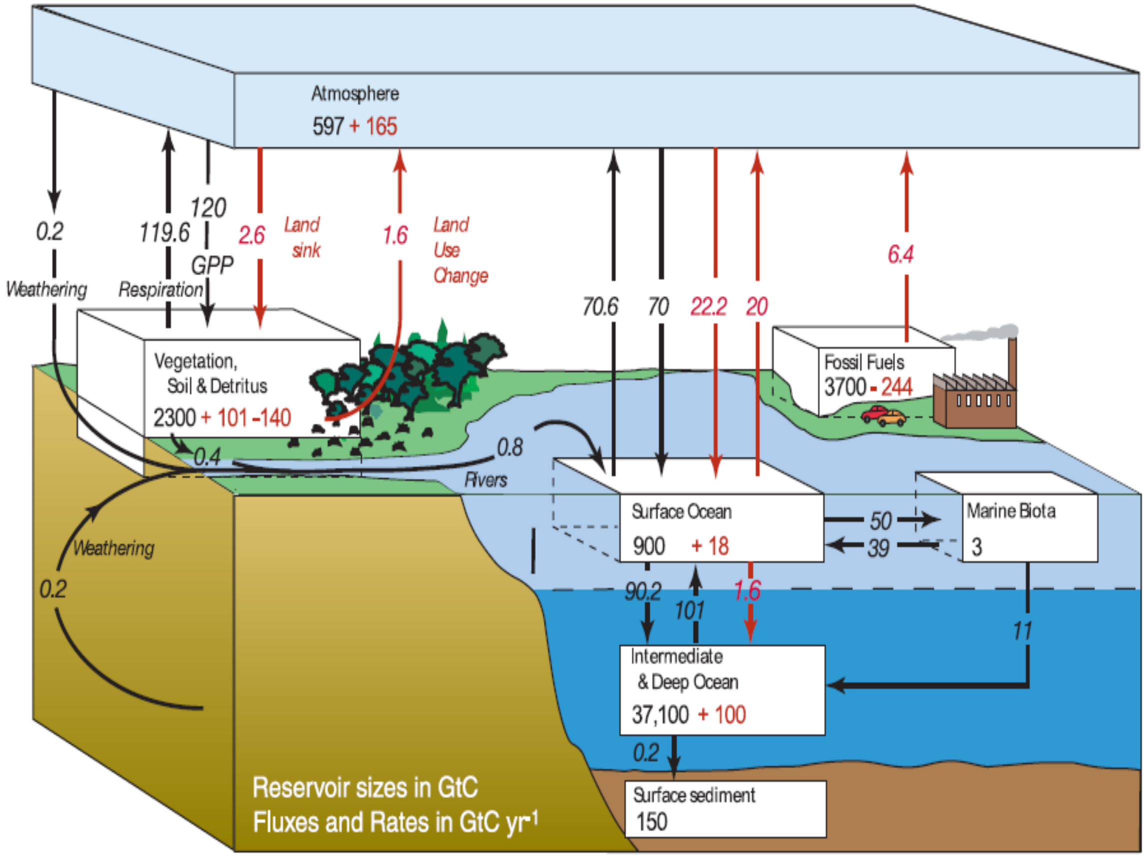


Figure 7.3. *The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr^{-1}: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004a). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr^{-1} for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994.*

(*IPCC 2007, Physical Basis Chapter 7*)

CO_2 Trends in Ice Core and Mauna Loa (inset)

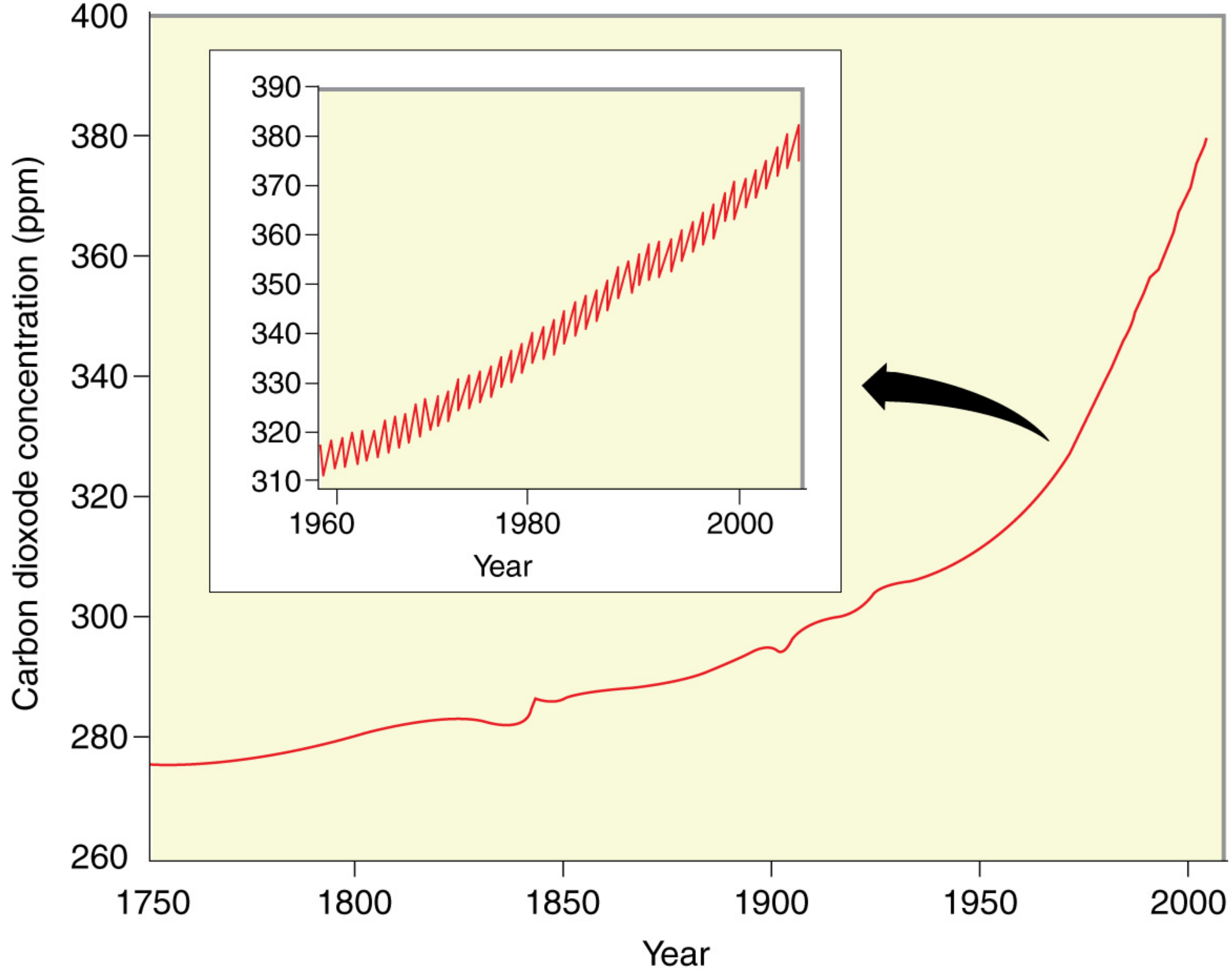
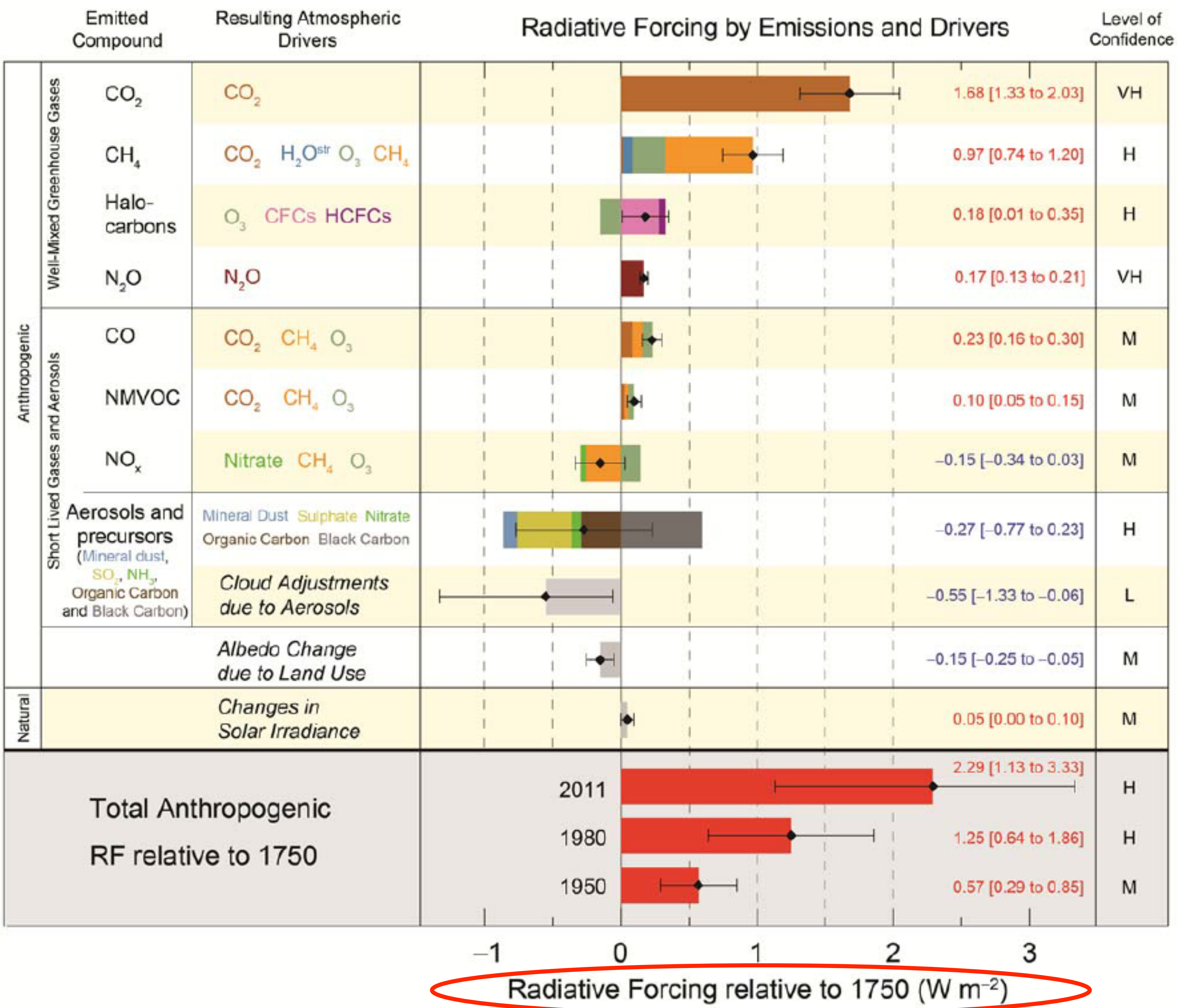


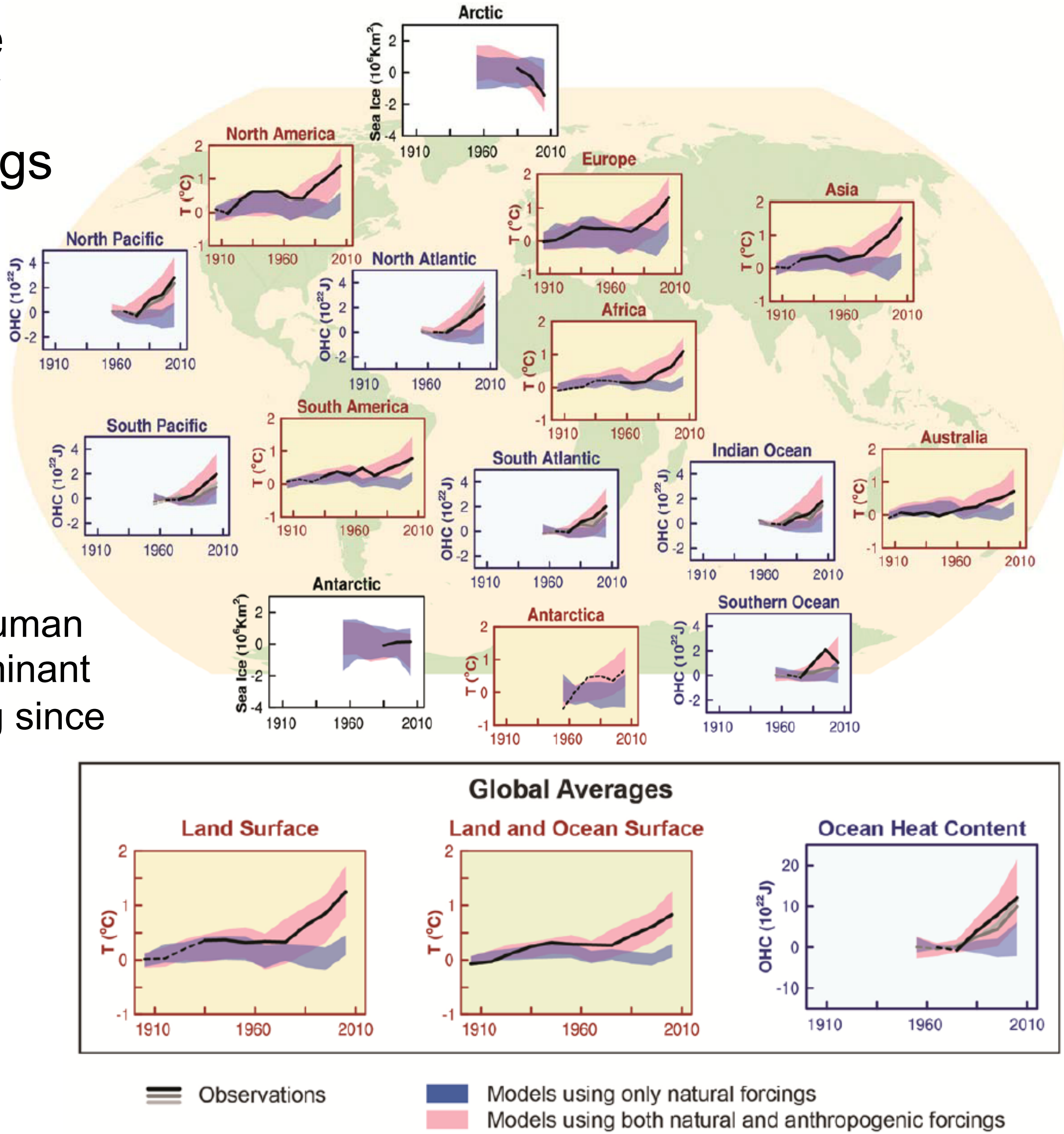
FIGURE 13-07



Emitted Compound
Resulting Atmospheric Drivers
Radiative Forcing by Emissions and Drivers
Level of Confidence
Anthropogenic
Well-Mixed Greenhouse Gases
CO2
CO2
1.68 [1.33 to 2.03]
VH
CH4
CO2 H2Ostr O3 CH4
0.97 [0.74 to 1.20]
H
Halo-carbons
O3 CFCs HCFCs
0.18 [0.01 to 0.35]
H
N2O
N2O
0.17 [0.13 to 0.21]
VH
Short Lived Gases and Aerosols
CO
CO2 CH4 O3
0.23 [0.16 to 0.30]
M
NMVOC
CO2 CH4 O3
0.10 [0.05 to 0.15]
M
NOx
Nitrate CH4 O3
−0.15 [−0.34 to 0.03]
M
Aerosols and precursors (Mineral dust, SO2, NH3, Organic Carbon and Black Carbon)
Mineral Dust Sulphate Nitrate Organic Carbon Black Carbon
−0.27 [−0.77 to 0.23]
H
Cloud Adjustments due to Aerosols
−0.55 [−1.33 to −0.06]
L
Albedo Change due to Land Use
−0.15 [−0.25 to −0.05]
M
Natural
Changes in Solar Irradiance
0.05 [0.00 to 0.10]
M
Total Anthropogenic RF relative to 1750
2011
2.29 [1.13 to 3.33]
H
1980
1.25 [0.64 to 1.86]
H
1950
0.57 [0.29 to 0.85]
M
−1
0
1
2
3
Radiative Forcing relative to 1750 (W m−2)

IPCC, 2013

Models can replicate observed T trends iff anthropogenic forcings are considered



"It is extremely likely that human influence has been the dominant cause of observed warming since the mid-20th century."

IPCC 2013

Five Key Questions

- Has Earth warmed?
- Are we responsible?
- Will warming continue?
- Is that a problem?
- What should we do?

IPCC climate projections

- 2016 – 2035 will "likely" be 0.3 – 0.7 °C warmer than 1986 – 2005
- "Continued emissions of greenhouse gases will cause further warming"
- Climate sensitivity to doubling CO_2 from pre-Industrial levels (275→550ppm)
  - "Likely" in range 1.5-4.5 °C
  - "Extremely unlikely" < 1 °C
  - "Very unlikely" > 6 °C

IPCC Probability Speak:

"Likely": ≥66% probability

"Extremely unlikely": ≤5%

"Very unlikely": ≤10%

IPCC 2013

IPCC Emission Scenarios and associated T and Sea Level predictions

Scenario	Cumulative CO_2 Emissions 2012–2100 (in GtC[a])	
	Mean	Range
RCP2.6	270	140 to 410
RCP4.5	780	595 to 1005
RCP6.0	1060	840 to 1250
RCP8.5	1685	1415 to 1910

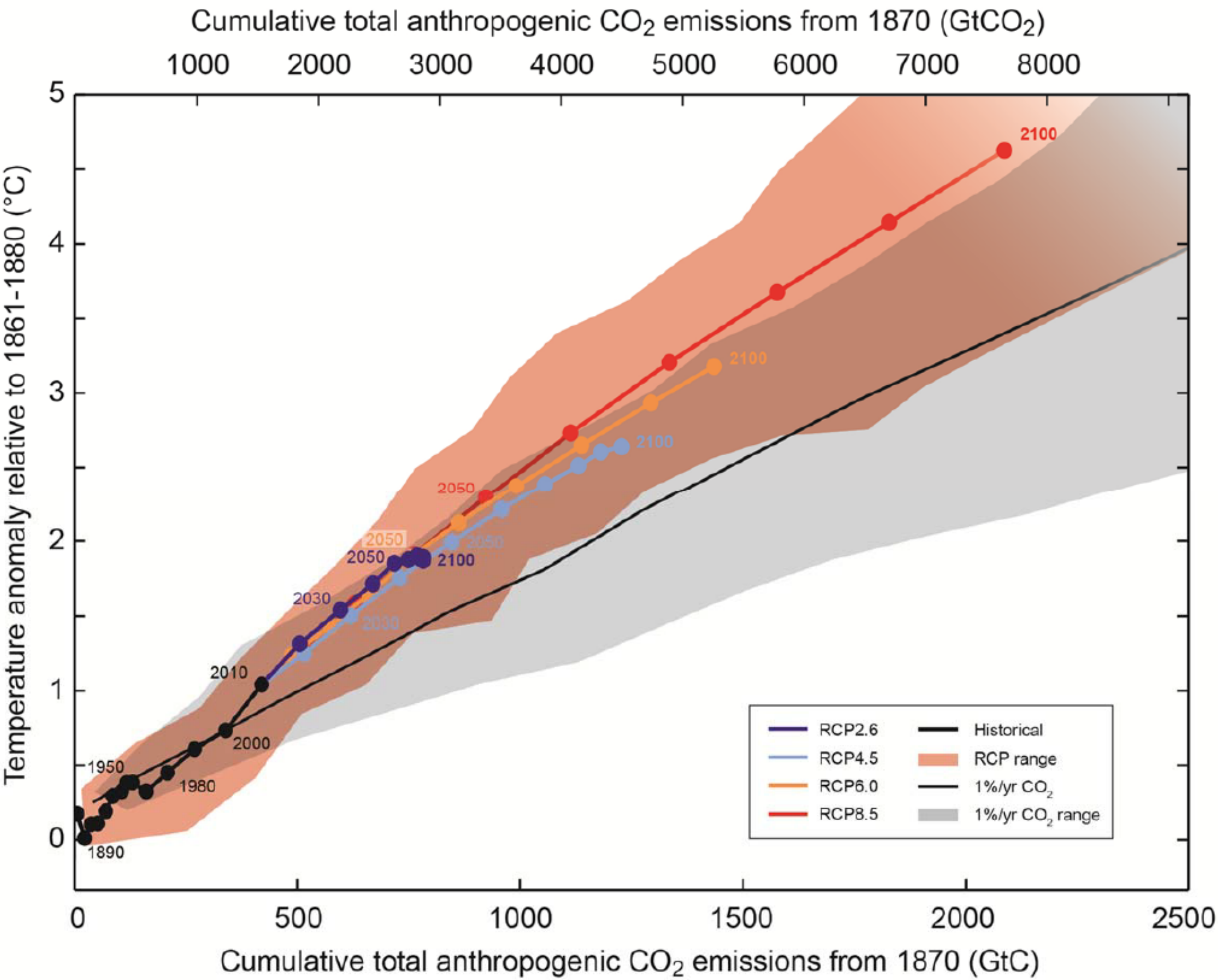
Notes:
(a) 1 Gigatonne of carbon corresponds to 3.67 $GtCO_2$.

Note: 2011 CO_2 emissions = 9.26 GtC

Continuing this 2012-2100 would be 825 GtC (close to RCP 4.5)

		2046–2065		2081–2100	
Variable	**Scenario**	mean	*likely* range [c]	mean	*likely* range [c]
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
		mean	*likely* range [d]	mean	*likely* range [d]
Global Mean Sea Level Rise (m) [b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

IPCC 2013



Cumulative total anthropogenic CO_2 emissions from 1870 ($GtCO_2$)
1000
2000
3000
4000
5000
6000
7000
8000
Temperature anomaly relative to 1861-1880 (°C)
0
1
2
3
4
5
0
500
1000
1500
2000
2500
Cumulative total anthropogenic CO_2 emissions from 1870 (GtC)
1890
1950
1980
2000
2010
2030
2050
2100
RCP2.6
RCP4.5
RCP6.0
RCP8.5
Historical
RCP range
1%/yr CO_2
1%/yr CO_2 range

IPCC 2013

Five Key Questions

- Has Earth warmed?
- Are we responsible?
- Will warming continue?
- Is that a problem?
- What should we do?

Expected Impacts of Climate Change

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes	
			Early 21st century	Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely*	*Likely* {11.3} – –	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely* (nights only)	*Likely* {11.3} – –	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia {2.6} *Medium confidence* in many (but not all) regions *Likely*	***Likely*** (a) {10.6} Not formally assessed *More likely than not*	Not formally assessed (b) {11.3} – –	*Very likely* {12.4} *Very likely* *Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation.	*Likely* more land areas with increases than decreases (c) {2.6} *Likely* more land areas with increases than decreases *Likely* over most land areas	***Medium confidence*** {7.6, 10.6} *Medium confidence* *More likely than not*	*Likely* over many land areas {11.3} – –	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions {12.4} *Likely* over many areas *Very likely* over most land areas
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely* changes in some regions (d) {2.6} *Medium confidence* in some regions *Likely* in many regions, since 1970 (e)	***Low confidence*** {10.6} *Medium confidence* (f) *More likely than not*	*Low confidence* (g) {11.3} – –	***Likely (medium confidence)*** on a regional to global scale (h) {12.4} *Medium confidence* in some regions *Likely* (e)
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes *Virtually certain* in North Atlantic since 1970 {2.6} *Low confidence* *Likely* (in some regions, since 1970)	***Low confidence*** (i) {10.6} *Low confidence* *More likely than not*	*Low confidence* {11.3} – –	***More likely than not*** in the Western North Pacific and North Atlantic (j) {14.6} *More likely than not* in some basins *Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) {3.7} *Likely* (late 20th century) *Likely*	***Likely*** (k) {3.7} *Likely* (k) *More likely than not* (k)	*Likely* (l) {13.7} – –	***Very likely*** (l) {13.7} *Very likely* (m) *Likely*

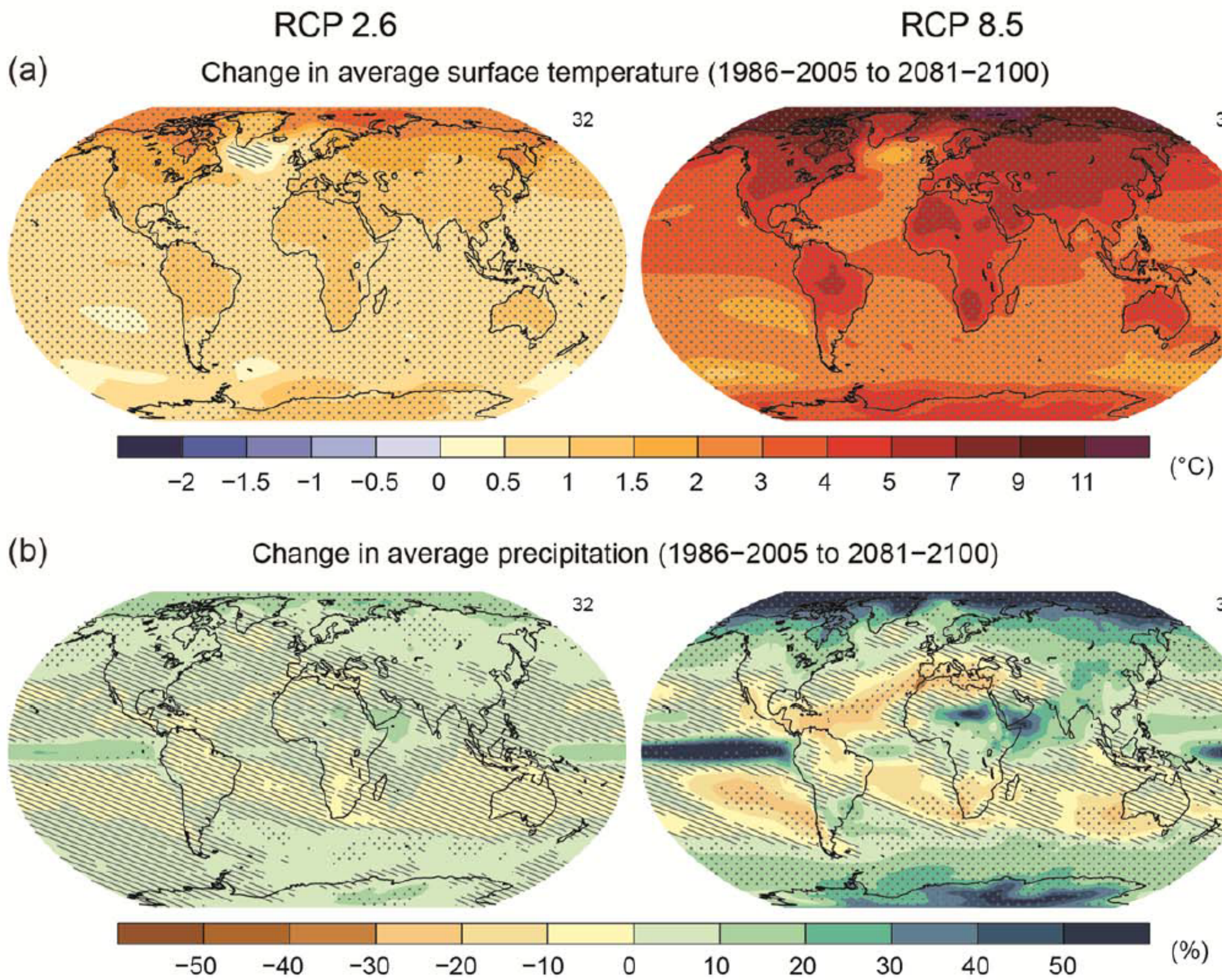
Virtually certain: ≥99%
Very likely: ≥90%

Likely: ≥66%
More likely than not: >50%

Black is IPCC 2013 assessment; Blue and Red are earlier assessments

Bold shows changes

Impacts on T and Precipitation



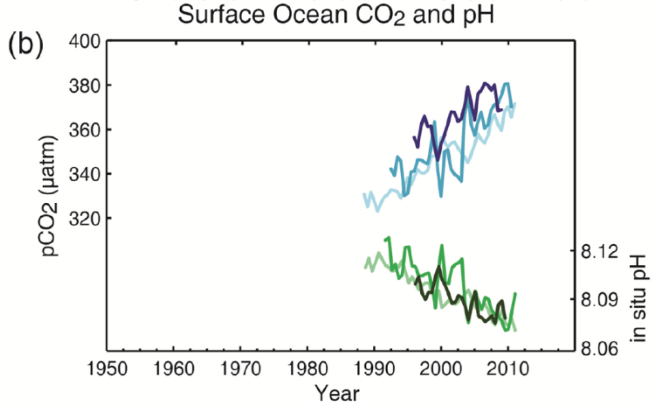
Stippling: ≥ 90% of models agree on sign of change

Hatching: Direction of change is highly uncertain between models

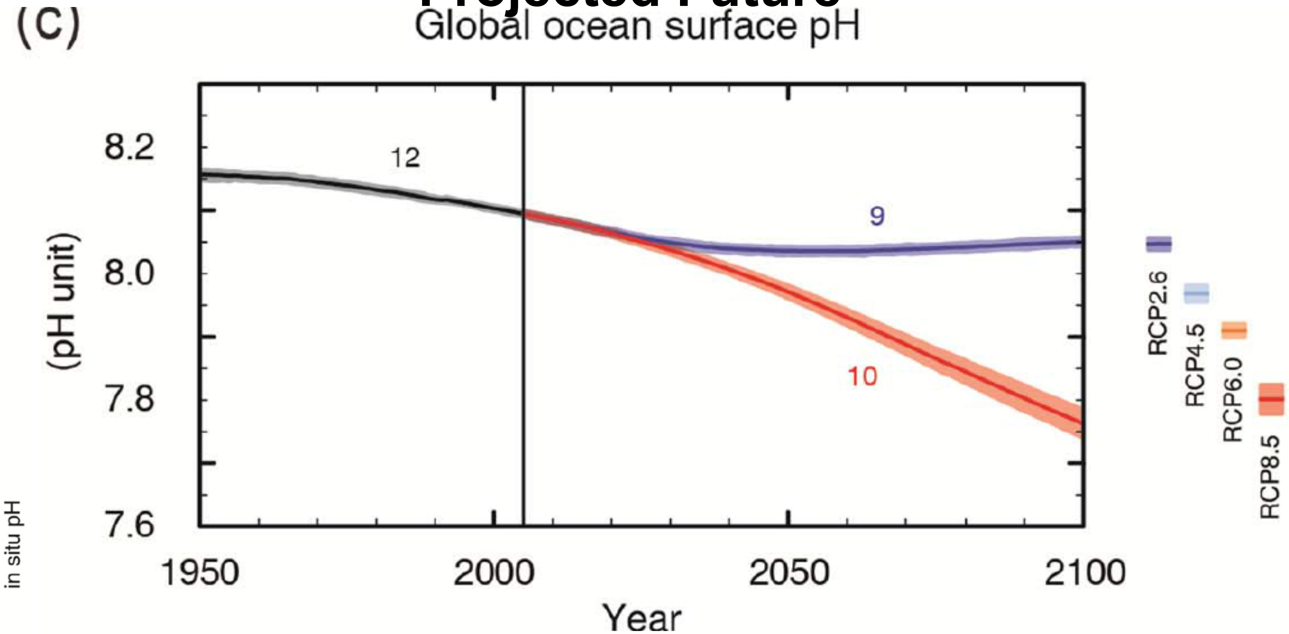
IPCC 2013

Impacts on ocean pH

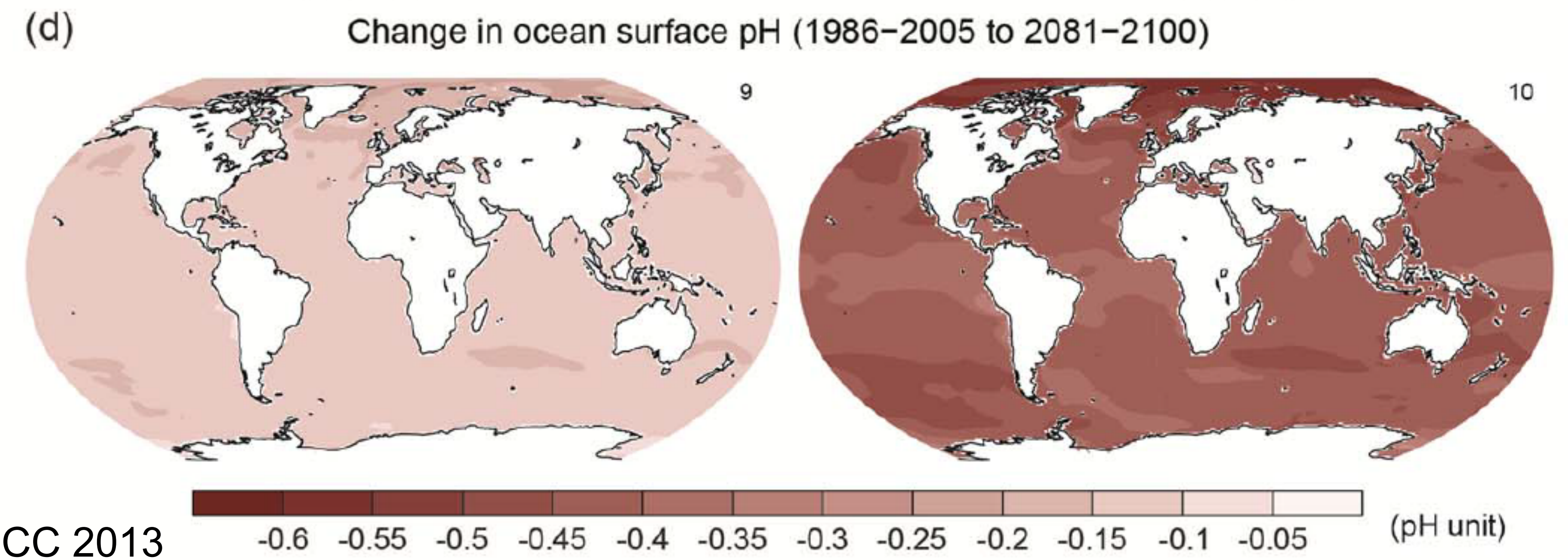
Observed Historical



Projected Future

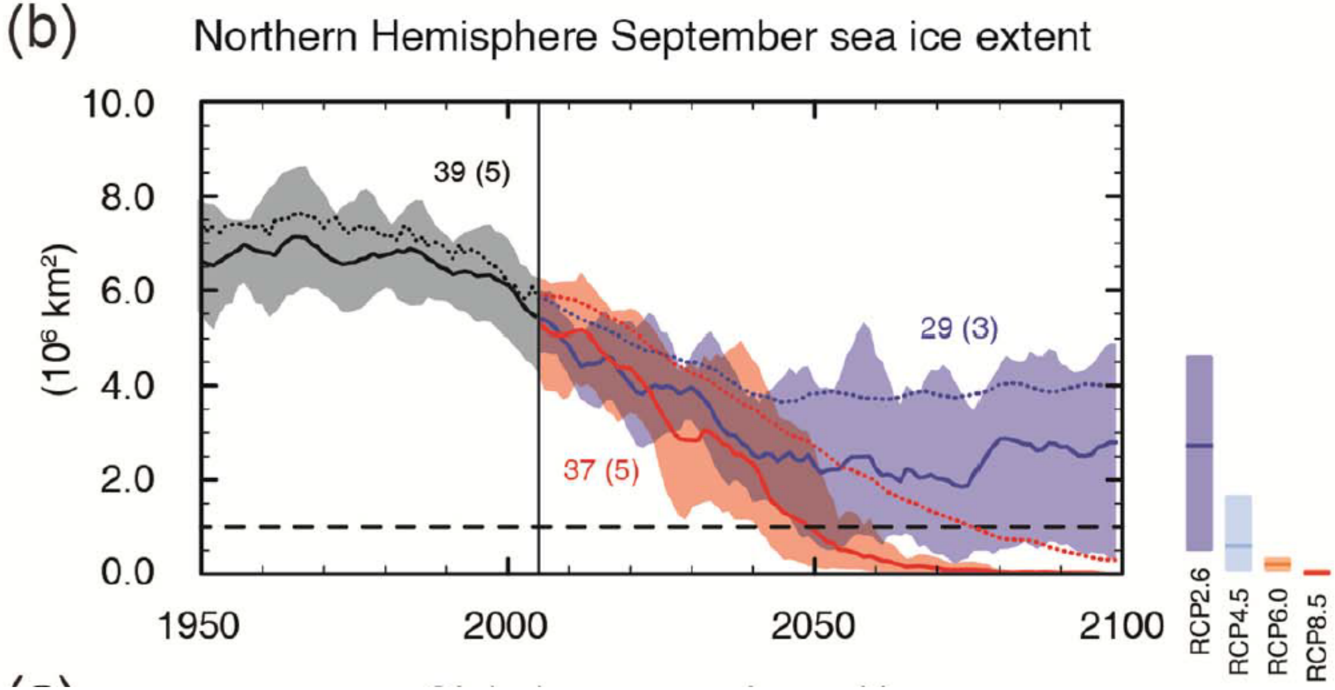


RCP 2.6 Low & High Emissions Scenarios RCP 8.5



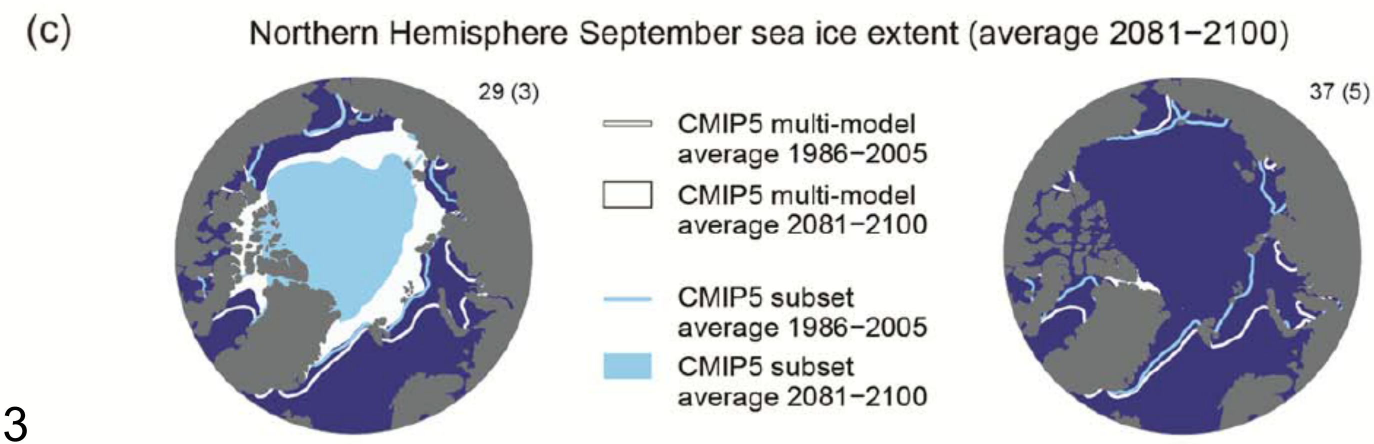
IPCC 2013

Impacts on Sea Ice



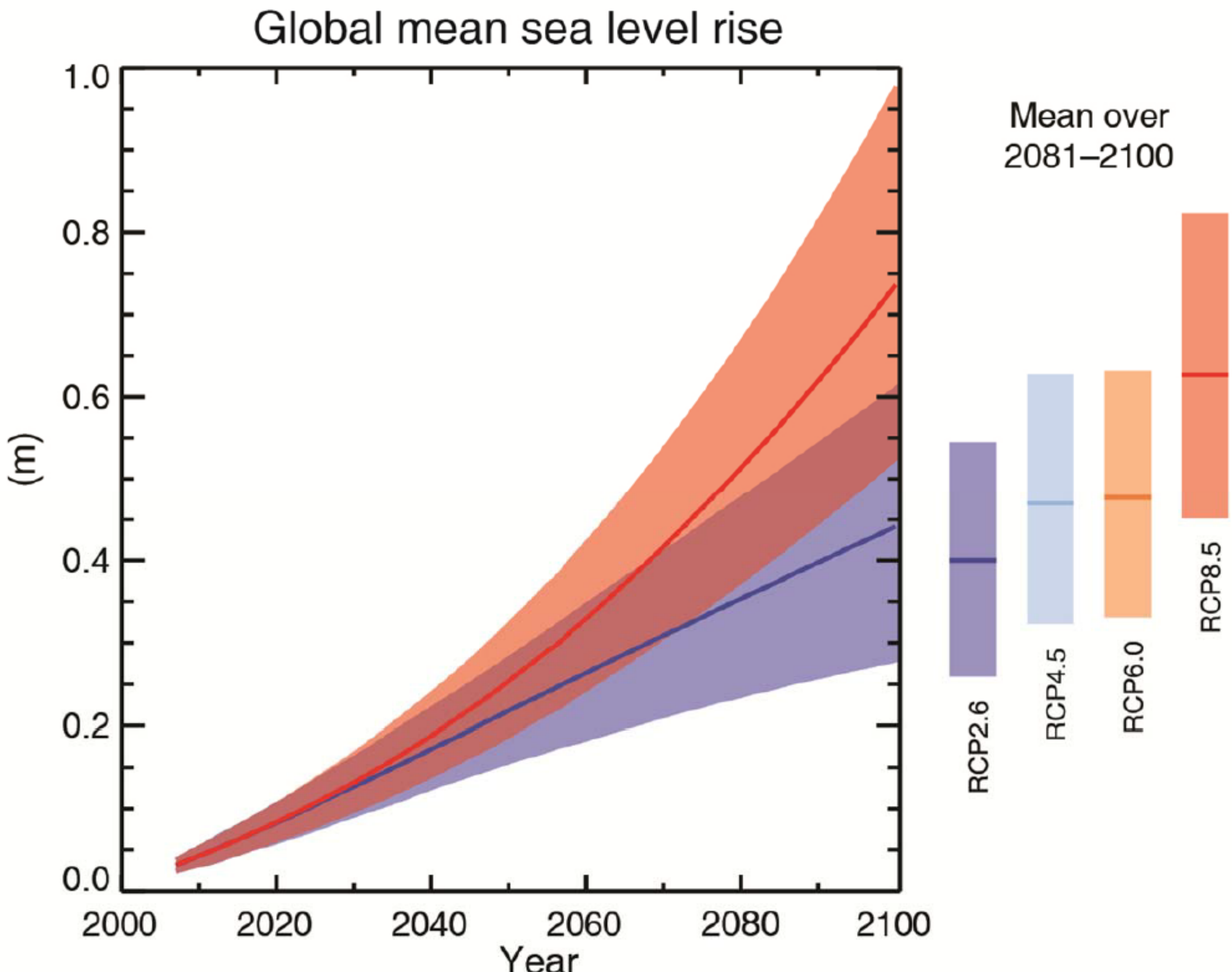
RCP 2.6

RCP 8.5



IPCC 2013

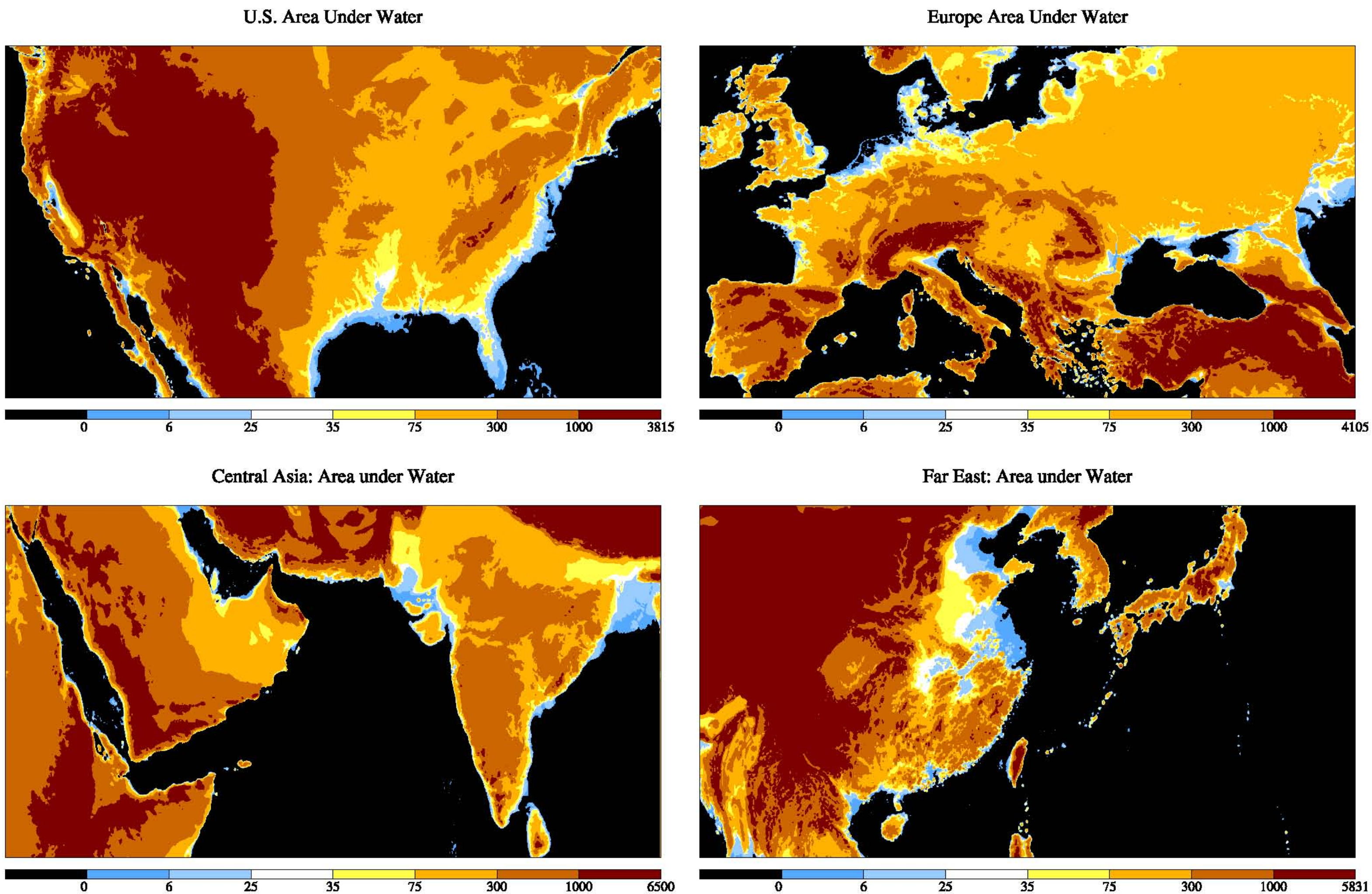
Sea Level Rise Projections



IPCC 2013

What if Sea Levels Rose 25 m?

(Paleoclimate data may indicate that
3°C → ~25 m sea level rise long-term)



Images from James Hansen

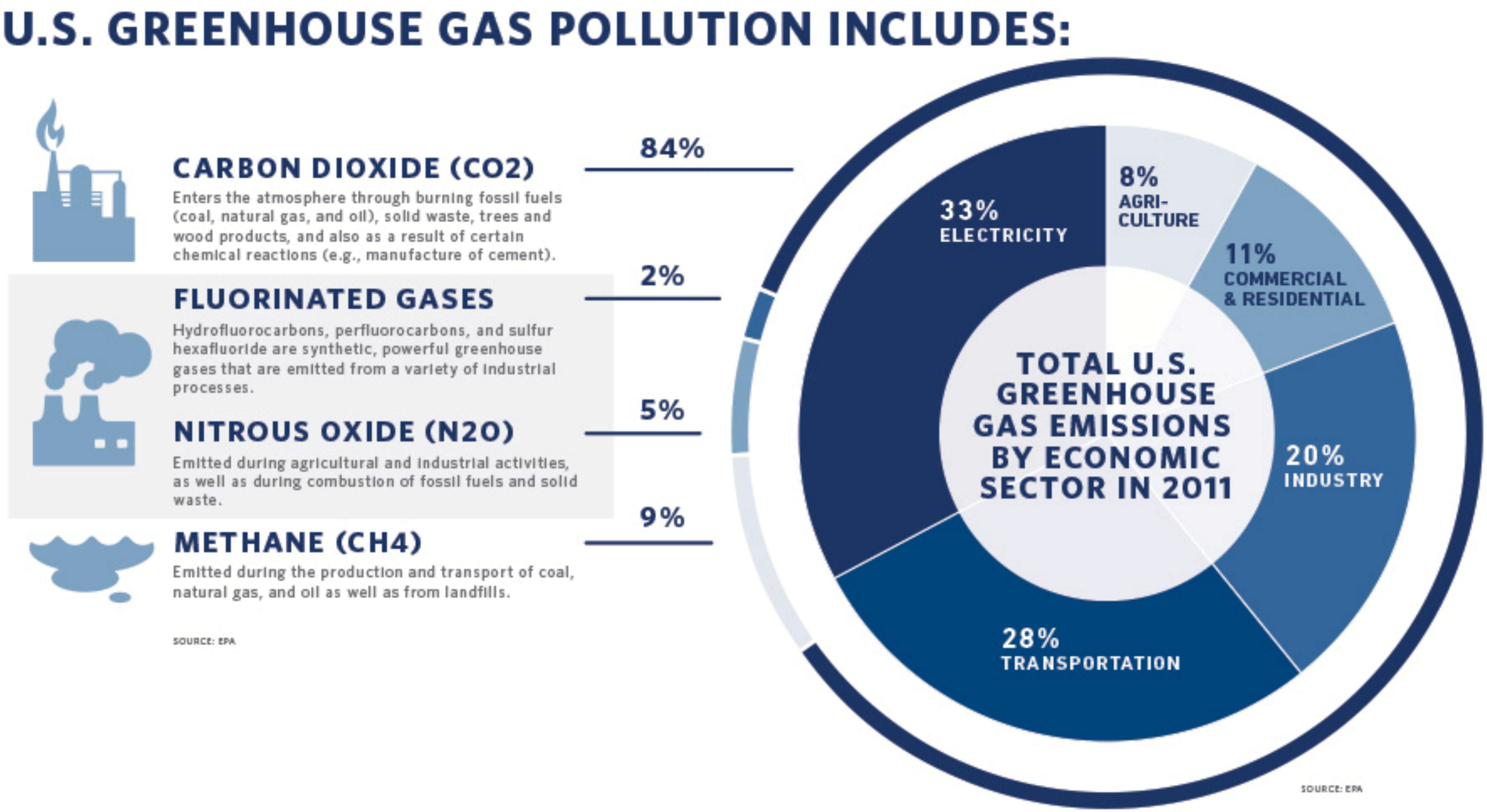
Other Negative and Positive Impacts

- More droughts
  - ↑T → ↑evaporation
  - Shifts in precipitation patterns
- More floods
  - ↑T → ↑evaporation → ↑precipitation overall
  - ↑T → greater portion of rain in extreme events
  - ↑ Sea surface T → Tropical cyclones intensify??
    - However, frequency may stay same or decrease??
- Tropical diseases
- CO_2 fertilization of crops and forests
- Arctic shipping routes and resources

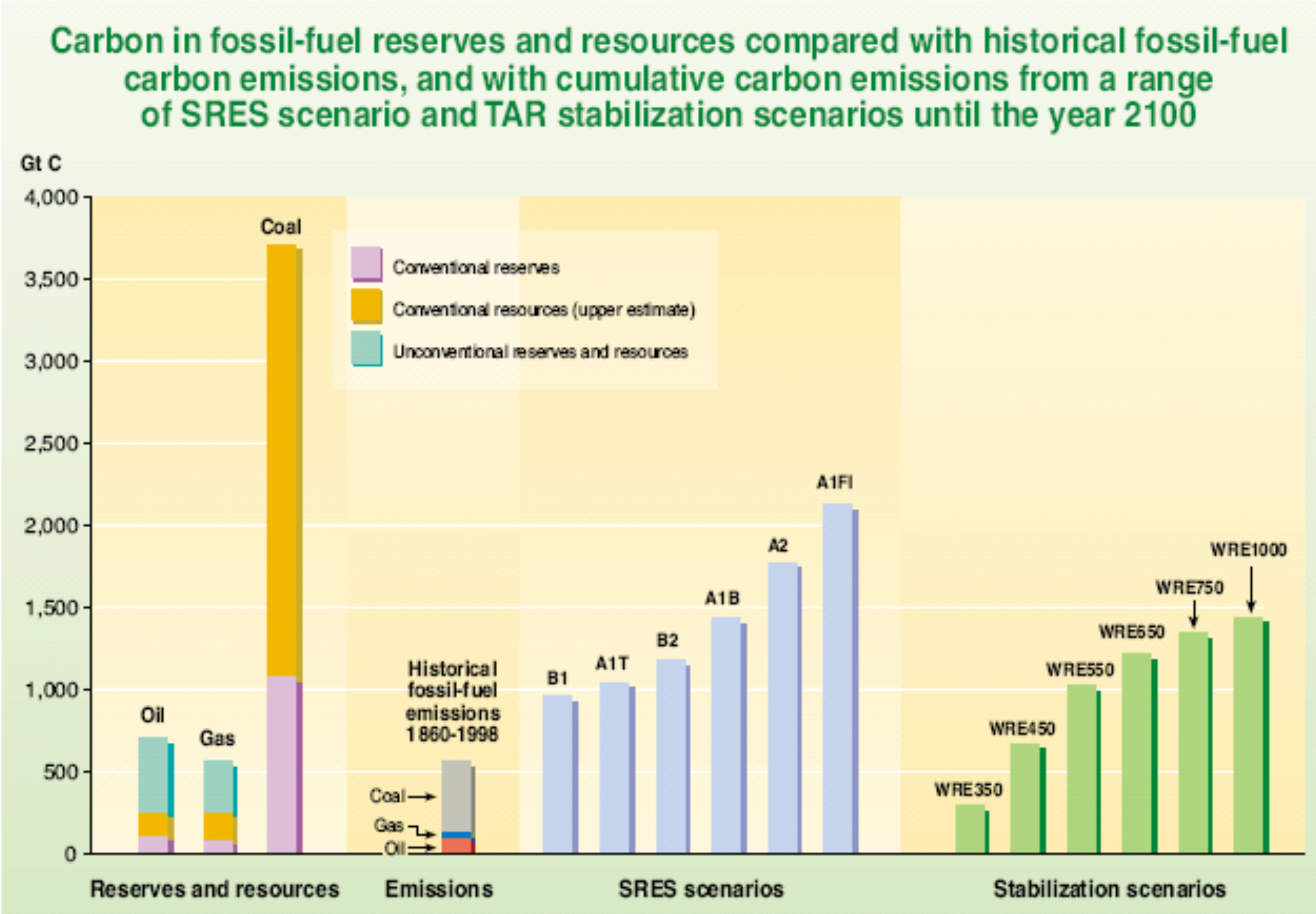
What should we do?? Policy Options

- Mitigation
  - Control CO_2 emissions
    - Who?
    - How?
  - Control other greenhouse gases or black carbon particles
- Adaptation
- Geo-engineering

U.S. Greenhouse Gas Emissions



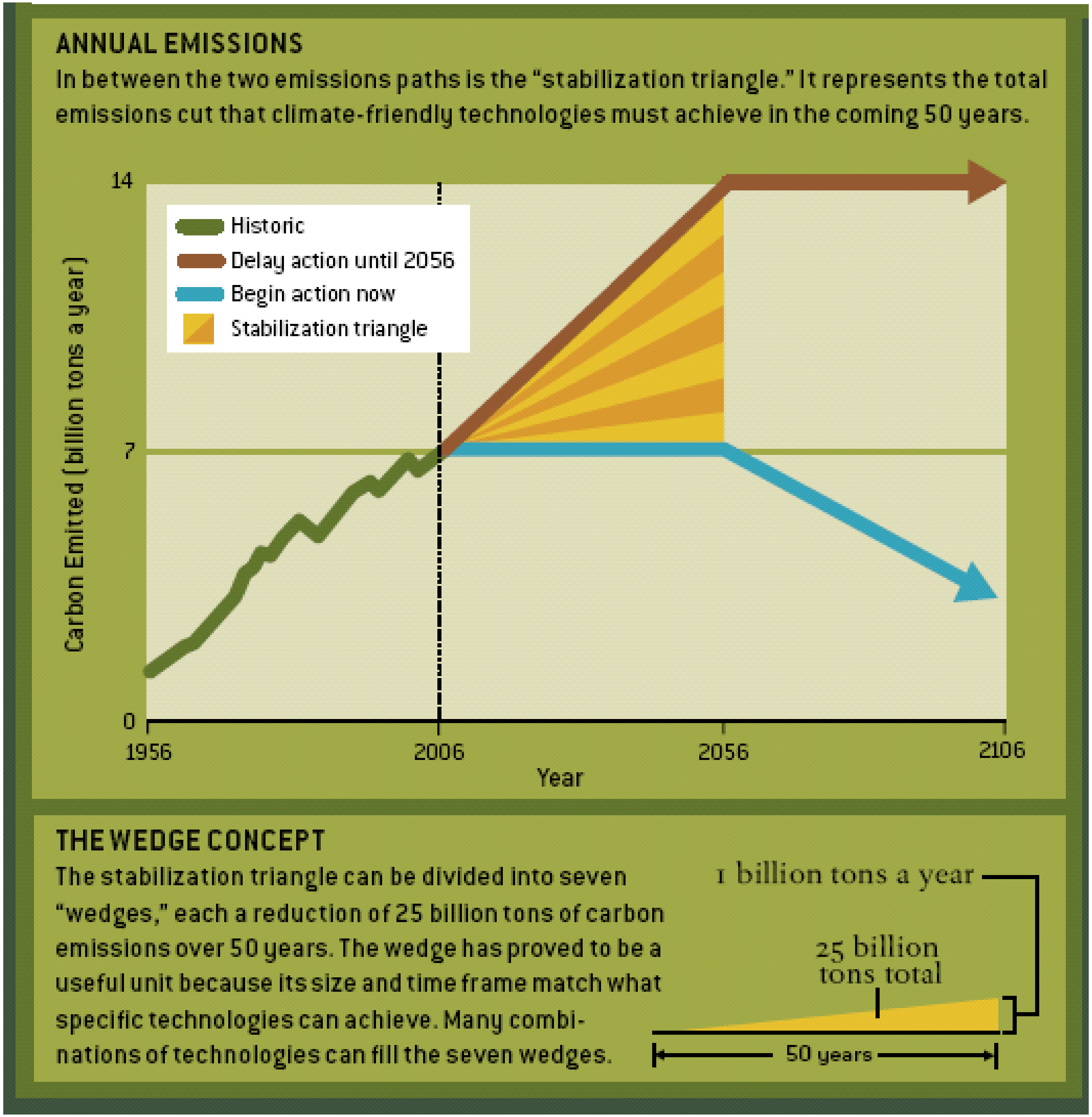
US EPA



WGIII TAR Section 3.8.1

Figure 7-5: Carbon in oil, gas, and coal reserves and resources is compared with historic fossil-fuel carbon emissions over the period 1860–1998, and with cumulative carbon emissions from a range of SRES scenarios and TAR stabilization scenarios until the year 2100. Data for current reserves and resources are shown in the lefthand columns. Unconventional oil and gas includes tar sands, shale oil, other heavy oil, coal bed methane, deep geopressured gas, gas in aquifers, etc. Gas hydrates (clathrates) that amount to an estimated 12,000 Gt C are not shown. The scenario columns show both SRES reference scenarios as well as scenarios that lead to stabilization of CO_2 concentrations at a range of levels. Note that if by the year 2100 cumulative emissions associated with SRES scenarios are equal to or smaller than those for stabilization scenarios, this does not imply that these scenarios equally lead to stabilization.

IPCC



Socolow and Pacala, Scientific American, 2006 (and related Science paper)

*Now need 8 wedges to stabilize at 500 ppm (vs. 850 ppm on current path)

Example "Wedges"

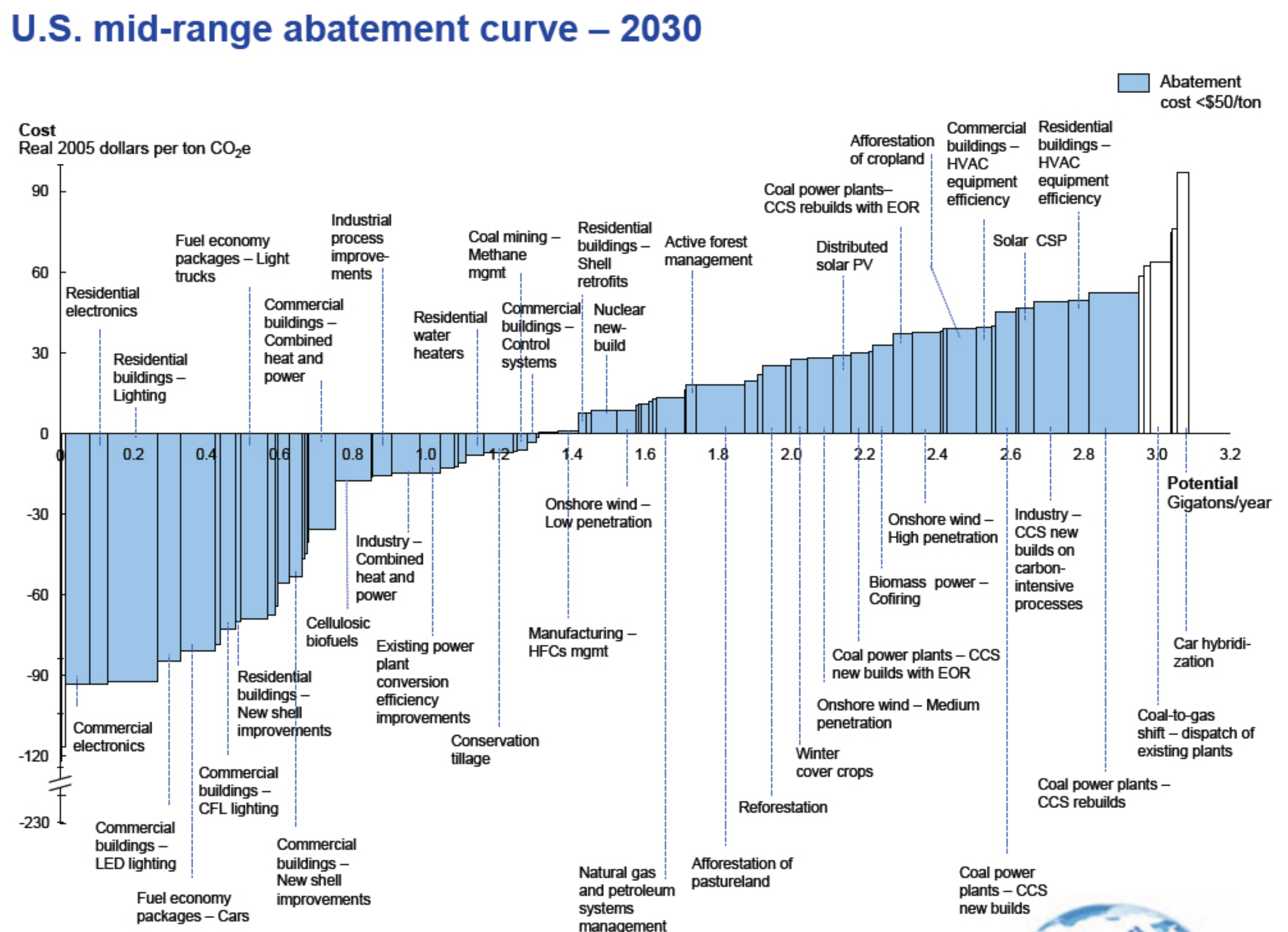
Table 1. Potential wedges: Strategies available to reduce the carbon emission rate in 2054 by 1 GtC/year or to reduce carbon emissions from 2004 to 2054 by 25 GtC.

Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
	Energy efficiency and conservation	
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)	Can be tuned by carbon policy
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year	Urban design, mass transit, telecommuting
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
	Fuel shift	
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)	Competing demands for natural gas
	CO_2 Capture and Storage (CCS)	
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production

http://cmi.princeton.edu/wedges/

Pacala and Socolow, Science, 2004

CO_2 control options and costs



Source: McKinsey analysis

Controlling non-CO_2 emissions

- Methane (rice paddies, landfills, cattle, etc.)
  - Global warming potential (100-yr basis): 23
  - Co-benefits: Reduce tropospheric O_3; cost-effective energy source (e.g., burn landfill gas)
- Black carbon (diesel vehicles, other combustion)
  - Controls would reduce the regional scale warming of atmosphere caused by absorption
  - Co-benefit: Reduce $PM_{2.5}$ (health, visibility)
- Halocarbons (CFCs, HCFCs, HFCs)
  - Very high global warming potential (100-over 10,000)
  - Co-benefit: Protect stratospheric ozone

Adaptation

- IPCC 2007: “Adaptation will be necessary to address impacts resulting from the warming that is already unavoidable due to past emissions.
  - “Adaptation alone is not expected to cope with all the projected effects of climate change, and especially not over the long term as most impacts increase in magnitude.”
  - “Sustainable development can reduce vulnerability to climate change.”
  - Developing countries likely to face greatest challenges

Geoengineering

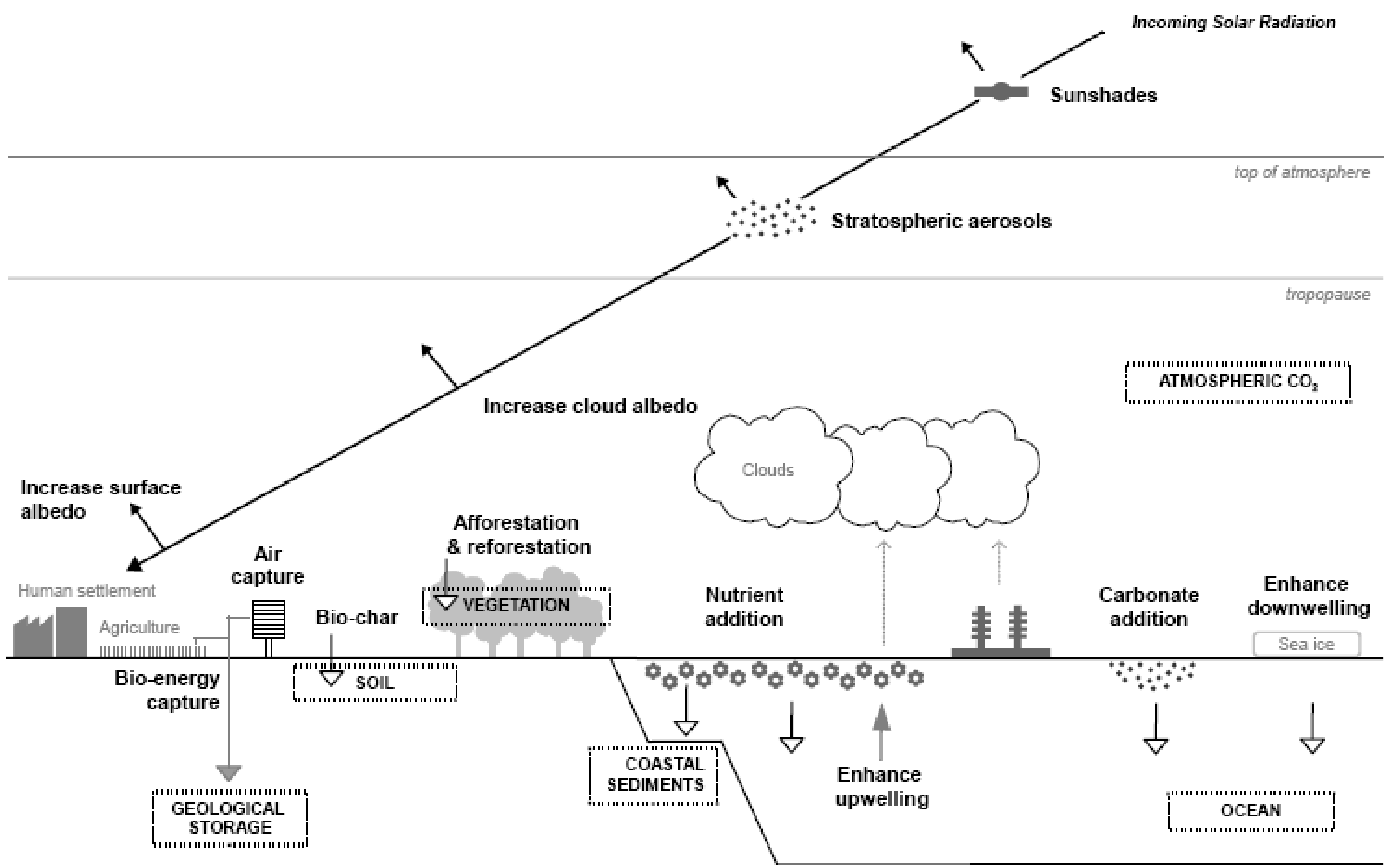


Fig. 1. Schematic overview of the climate geoengineering proposals considered. Black arrowheads indicate shortwave radiation, white arrowheads indicate enhancement of natural flows of carbon, grey downward arrow indicates engineered flow of carbon, grey upward arrow indicates engineered flow of water, dotted vertical arrows illustrate sources of cloud condensation nuclei, and dashed boxes indicate carbon stores. From Vaughan and Lenton (2009), not to scale.

Lenton and Vaughan, Atmospheric Chemistry and Physics Discussions, 2009

Geoengineering

- Inject sulfur to create stratospheric aerosol
  - Need equivalent of Mt Pinatubo eruption each 2 years (7% of fossil fuel SO_2) to offset warming (Wigley, 2006)
- Sunshades orbiting Earth
  - Need 4.1 million km^2 of sunshades (135,000 launches/year) to offset $2xCO_2$ (Lenton & Vaughan, 2009)
- Increase albedo of clouds (e.g., cloud seeding) or land (e.g., reflective surface on deserts)
- Ocean fertilization: phytoplankton uptake of CO_2
  - Unlikely to be effective (Lenton & Vaughan, 2009)
- Biochar: Burn biomass & bury to enhance soil

Comments/Questions/Discussion

- Has Earth warmed? (Measurement)
- Are we responsible? (Attribution)
- Will warming continue? (Predictions)
- Is that a problem? (Impacts)
- What should we do? (Policy)