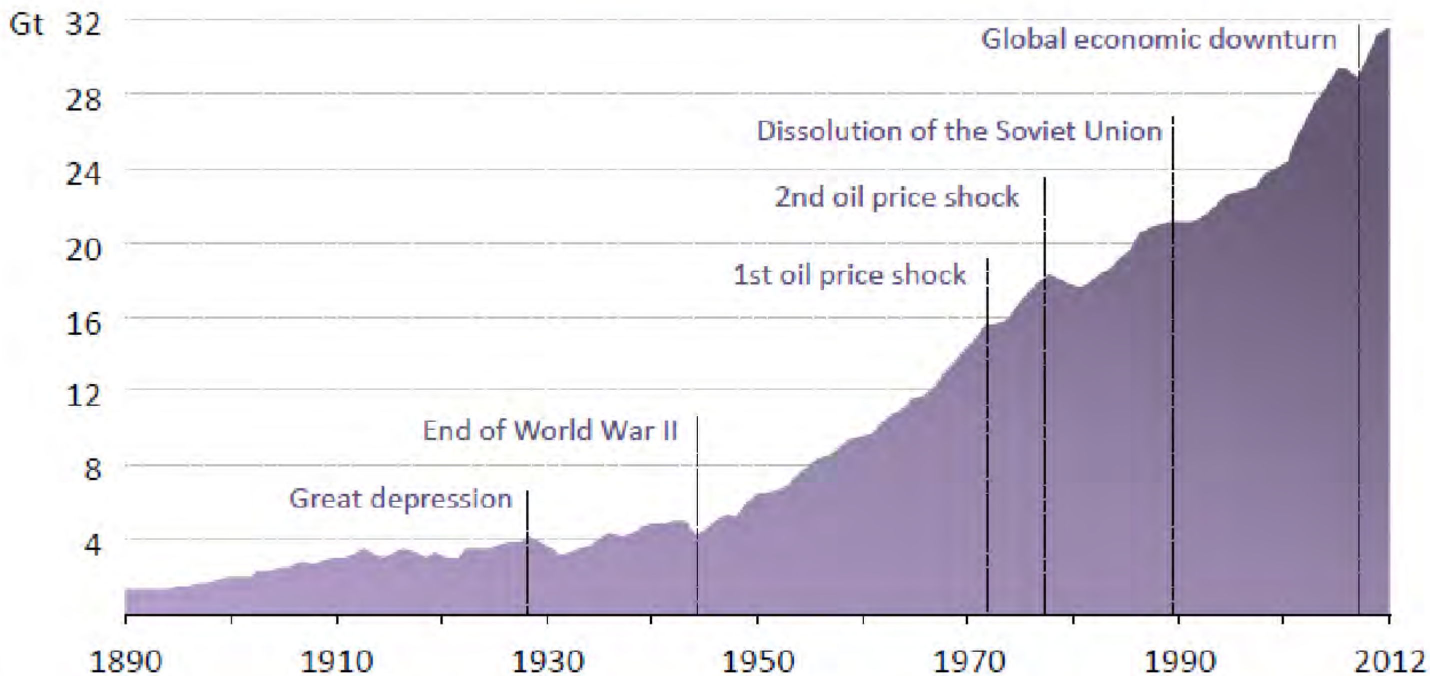
Class 4
Projecting the Future

L809

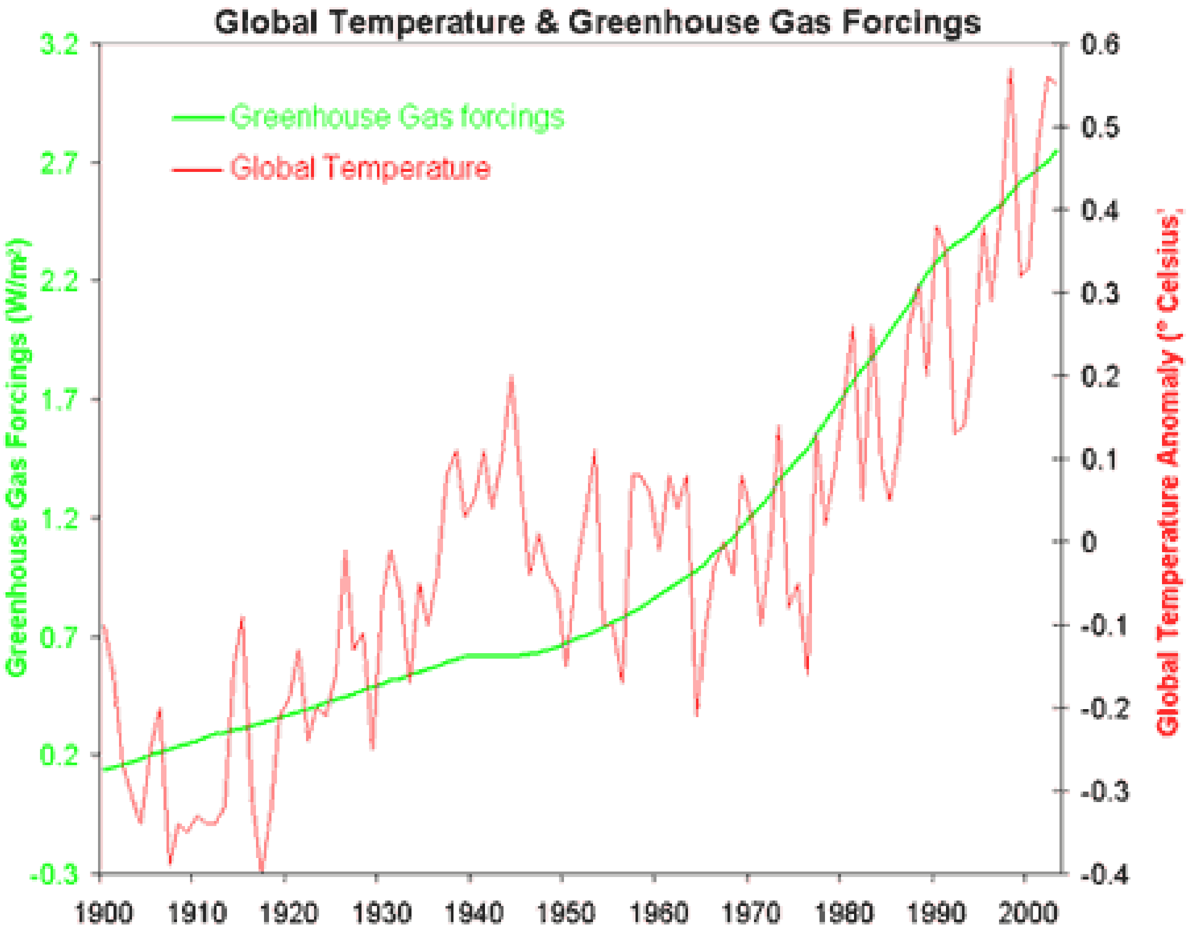
Winter 2014

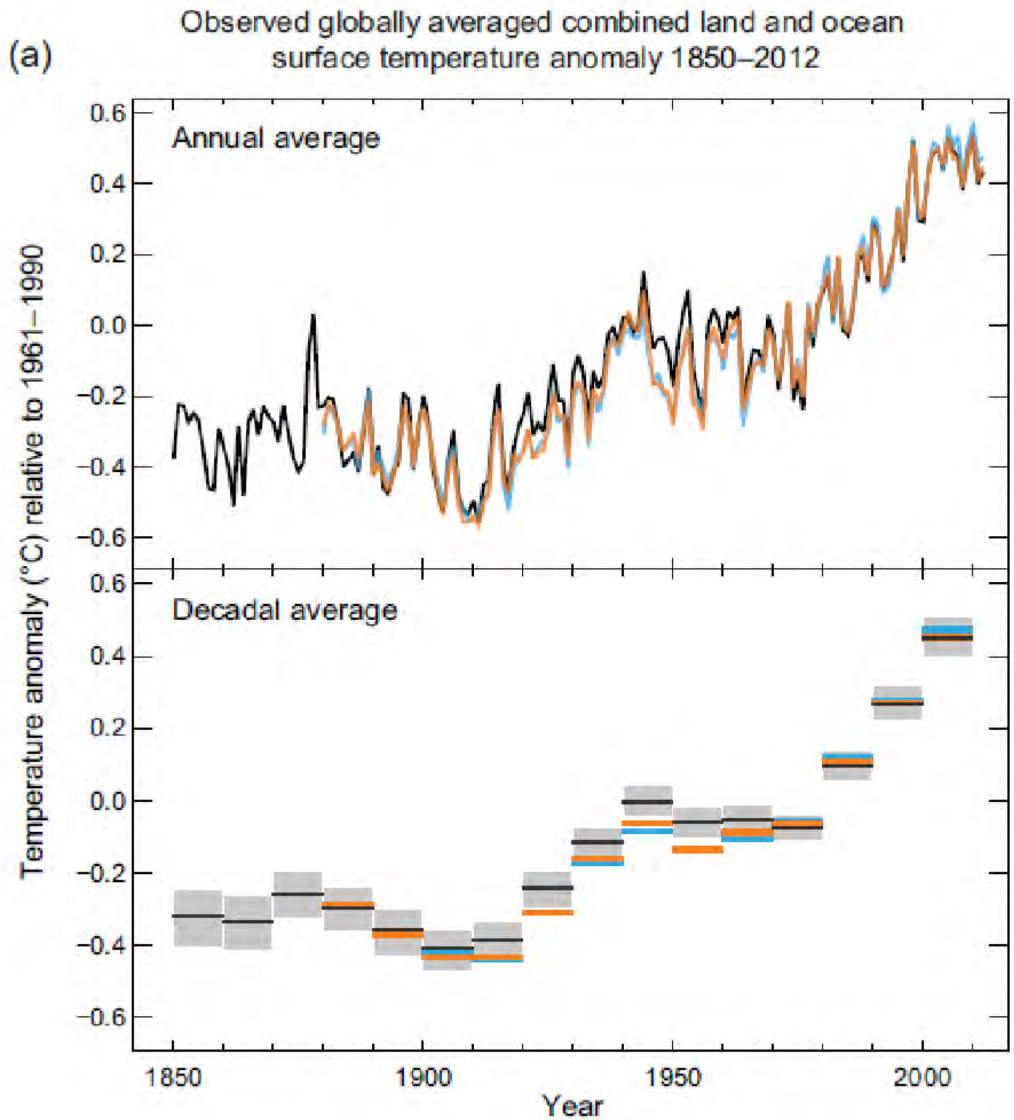
WHERE WE'VE BEEN

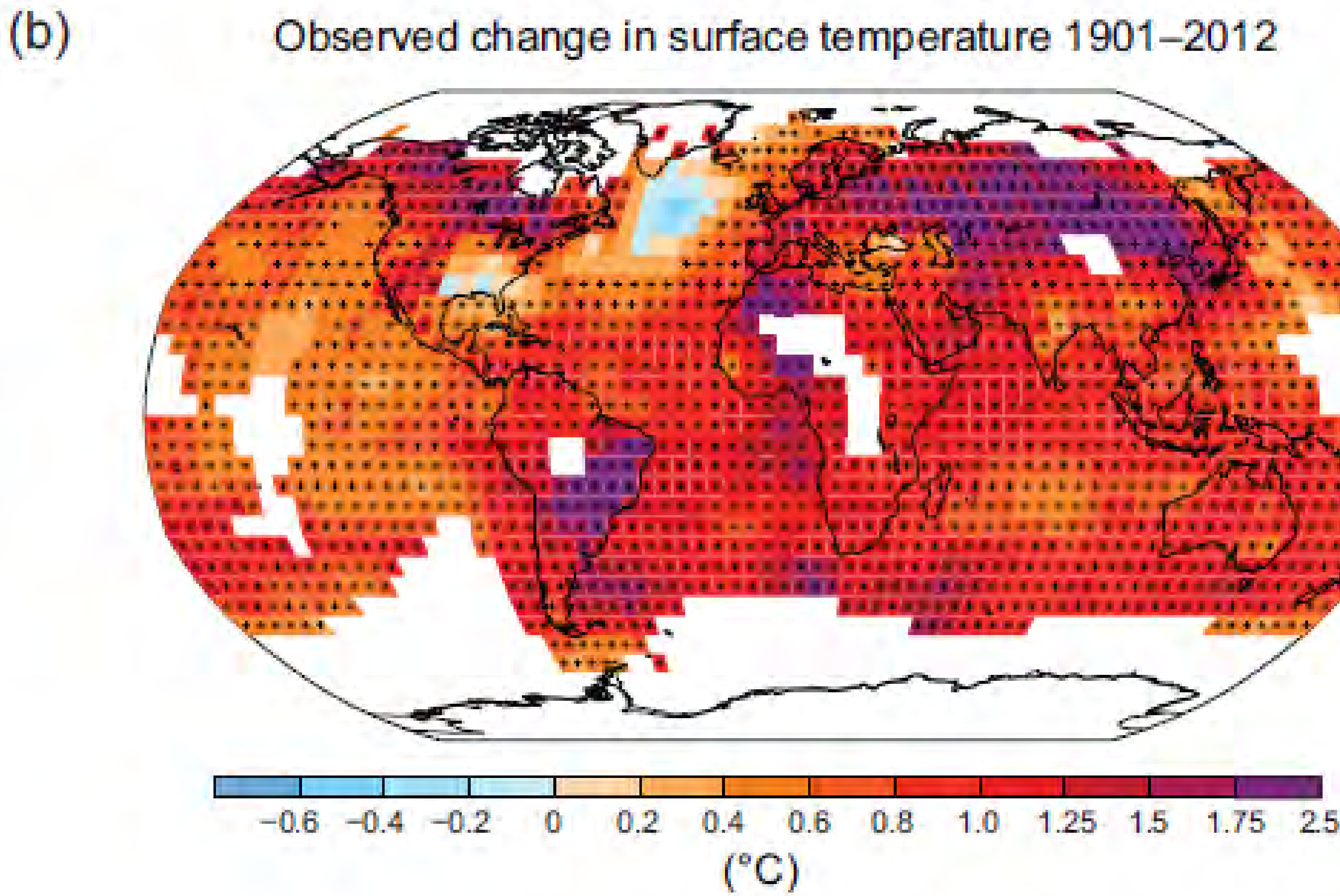
Global energy-related CO_2 emissions



CO_2 emissions trends point to a long-term temperature increase of up to 5.3 °C

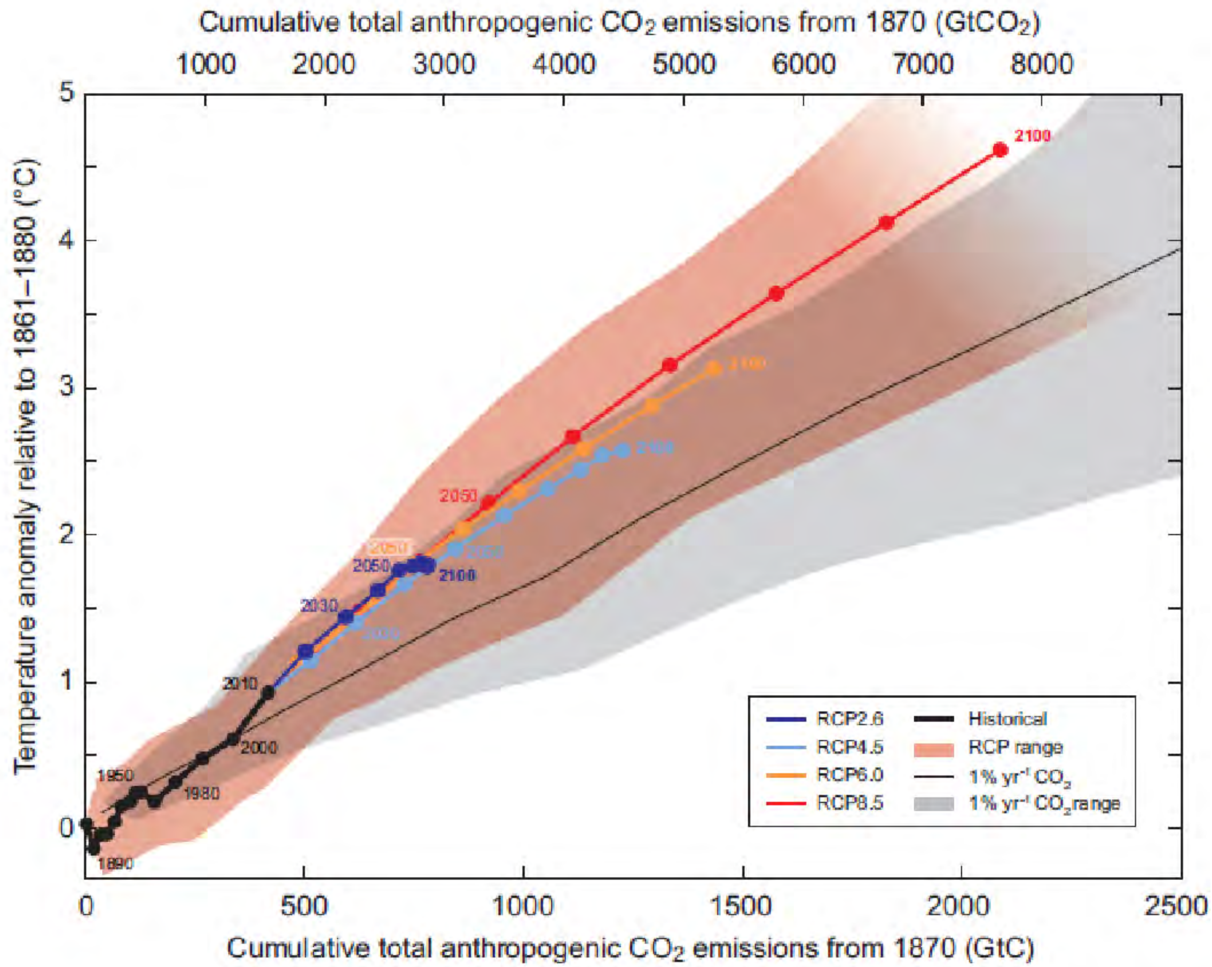

Global Temperature & Greenhouse Gas Forcings
Greenhouse Gas forcings
Global Temperature
Greenhouse Gas Forcings (W/m²)
Global Temperature Anomaly (° Celsius)
3.2
2.7
2.2
1.7
1.2
0.7
0.2
-0.3
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000


(a)
Observed globally averaged combined land and ocean
surface temperature anomaly 1850–2012
Annual average
Decadal average
Temperature anomaly (°C) relative to 1961–1990
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
1850
1900
1950
2000
Year


(b)
Observed change in surface temperature 1901–2012
−0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1.0 1.25 1.5 1.75 2.5
(°C)

- http://www.youtube.com/watch?v=H-BbPBg3vj8.

WHERE WE'RE (MAYBE) GOING


Cumulative total anthropogenic CO2 emissions from 1870 (GtCO2)
1000
2000
3000
4000
5000
6000
7000
8000
Temperature anomaly relative to 1861–1880 (°C)
0
1
2
3
4
5
2100
2050
2030
2010
2000
1980
1950
1890
RCP2.6
RCP4.5
RCP6.0
RCP8.5
Historical
RCP range
1% yr⁻¹ CO2
1% yr⁻¹ CO2 range
0
500
1000
1500
2000
2500
Cumulative total anthropogenic CO2 emissions from 1870 (GtC)

Scenarios: Representative Concentration Pathways (RCPs)

Scenario	Cumulative CO_2 Emissions 2012 to 2100[a]			
	GtC		$GtCO_2$	
	Mean	Range	Mean	Range
RCP2.6	270	140 to 410	990	510 to 1505
RCP4.5	780	595 to 1005	2860	2180 to 3690
RCP6.0	1060	840 to 1250	3885	3080 to 4585
RCP8.5	1685	1415 to 1910	6180	5185 to 7005

Notes:
[a] 1 Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$.

2012: 35 Gt CO_2
Scenario Average Annual Emissions
2.6: 11
4.5: 33
6.0: 44
8.5: 70

8.5 Average Growth Rate: 1.5%

Likely Result: Change from 1986-2005

		2046–2065		2081–2100	
	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
	Scenario	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

Notes:

"Likely": Calculated from 5%-95% range with adjustments for additional uncertainties and levels of confidence.

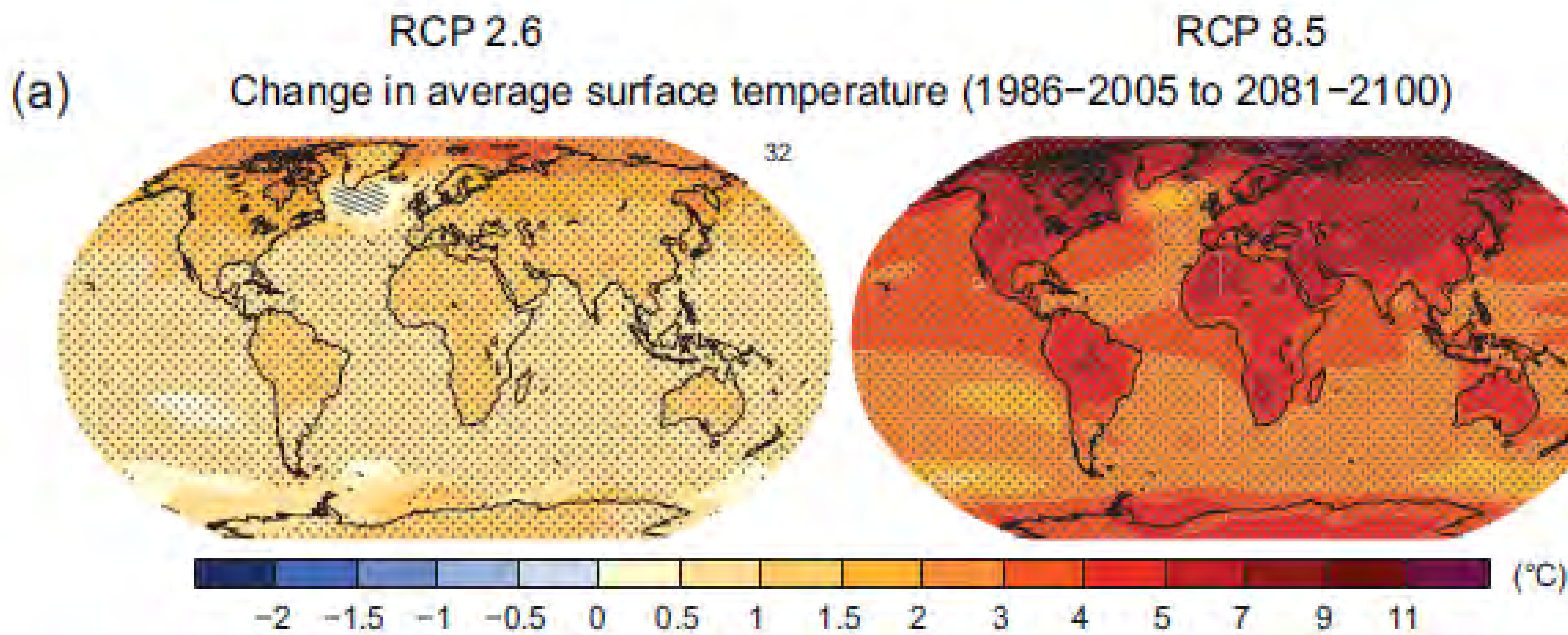
IPCC-Speak

The following terms have been used to indicate the assessed likelihood:

Term*	**Likelihood of the outcome**
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms (*extremely likely:* 95–100% probability, *more likely than not:* >50–100% probability, and *extremely unlikely:* 0–5% probability) may also be used when appropriate.

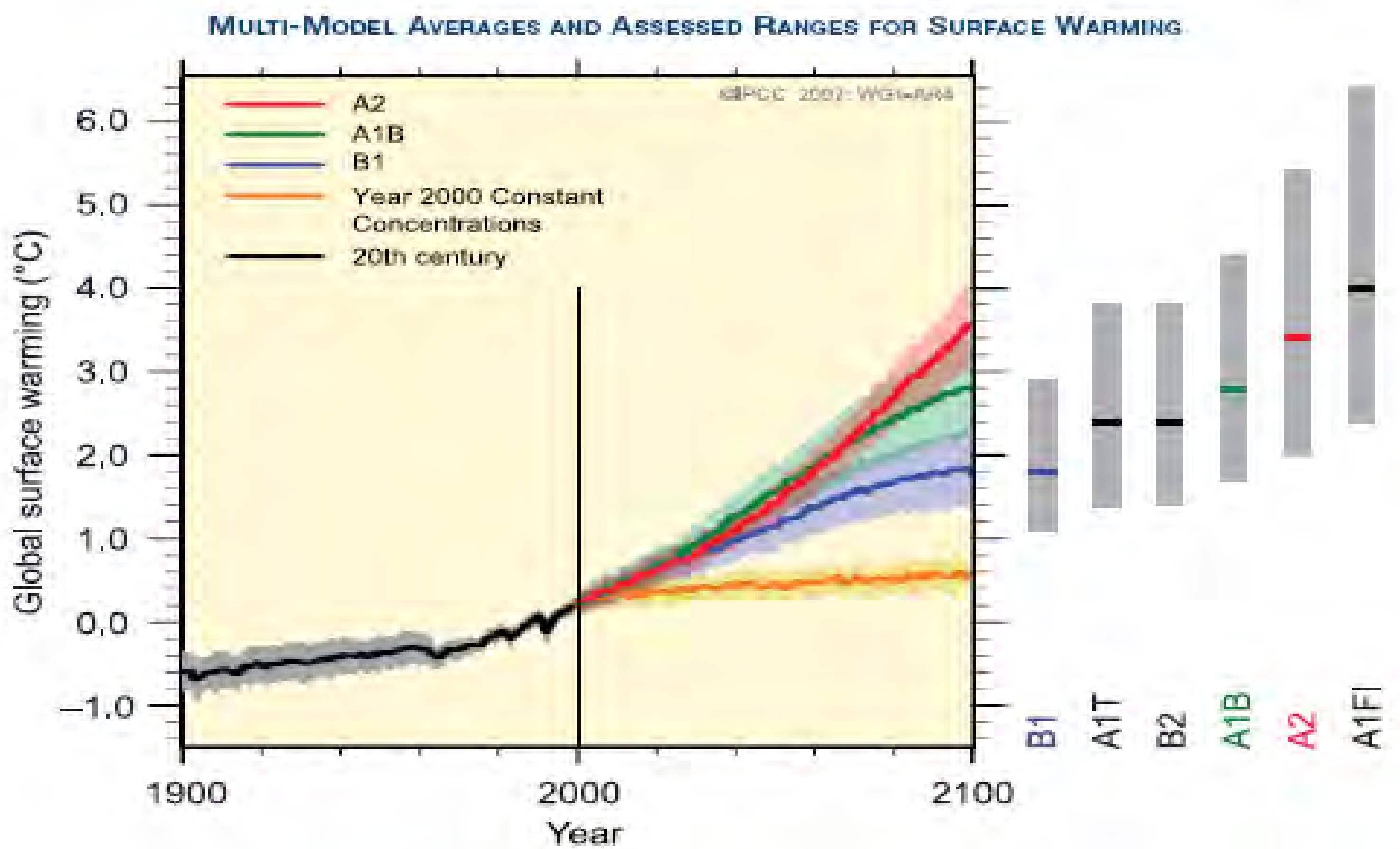
Confidence: Very low, Low, Medium, High, Very High



RCP 2.6
RCP 8.5
(a)
Change in average surface temperature (1986−2005 to 2081−2100)
32
39
(°C)
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2 3 4 5 7 9 11

DRIVERS OF CHANGE

IPCC 2007 Projections



2007 Assessment Report Scenarios: The Code

- Goals
  - A: Continued emphasis on material growth
  - B: Greater emphasis on non-material goals
- Values
  - 1: Spread of western values
  - 2: Non-western societies retain traditional values
- Energy technology
  - F: Dominance of fossil fuels
  - T: Technological change
  - B: Balanced

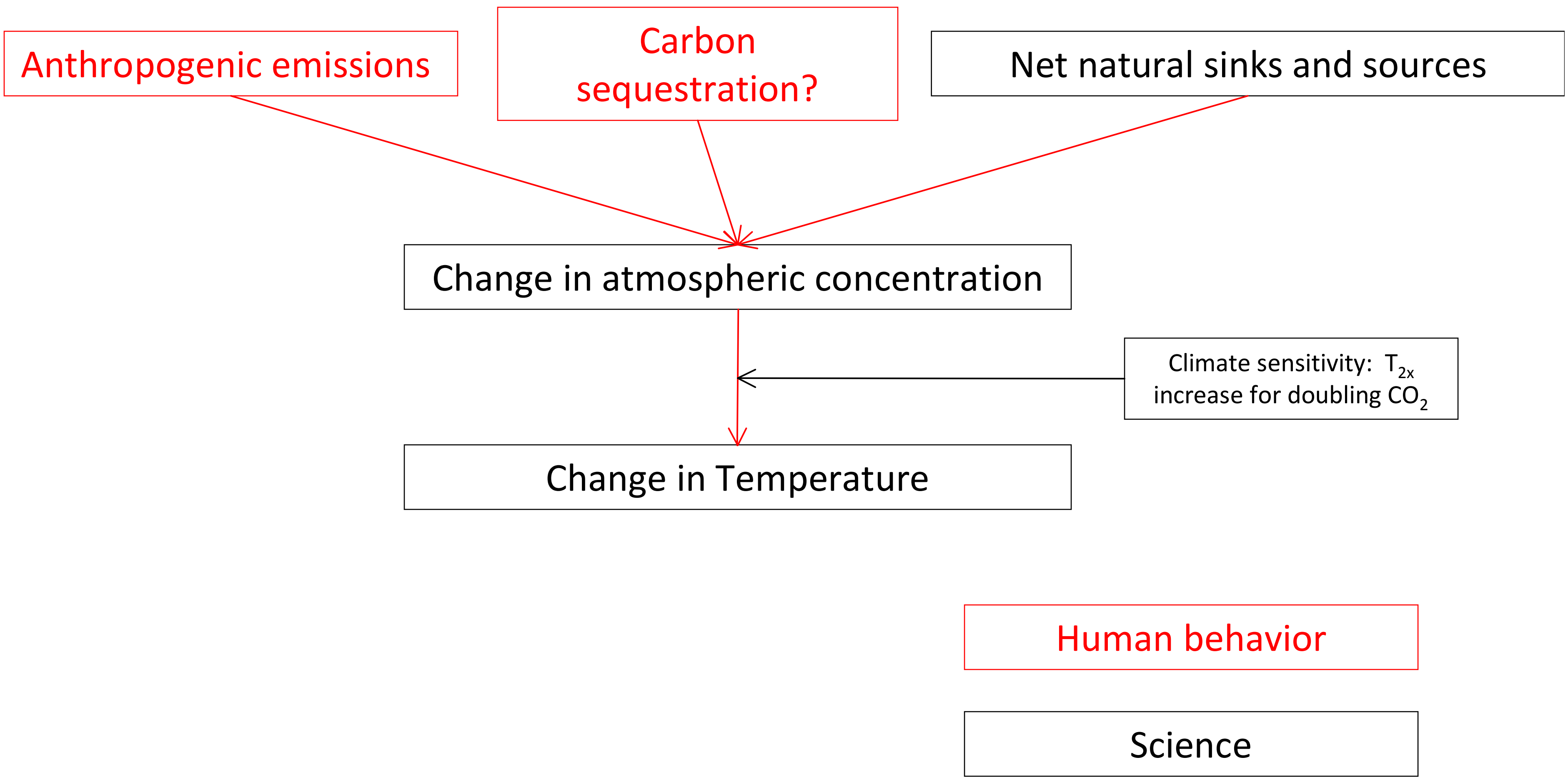
Highest Emissions Growth: A2F

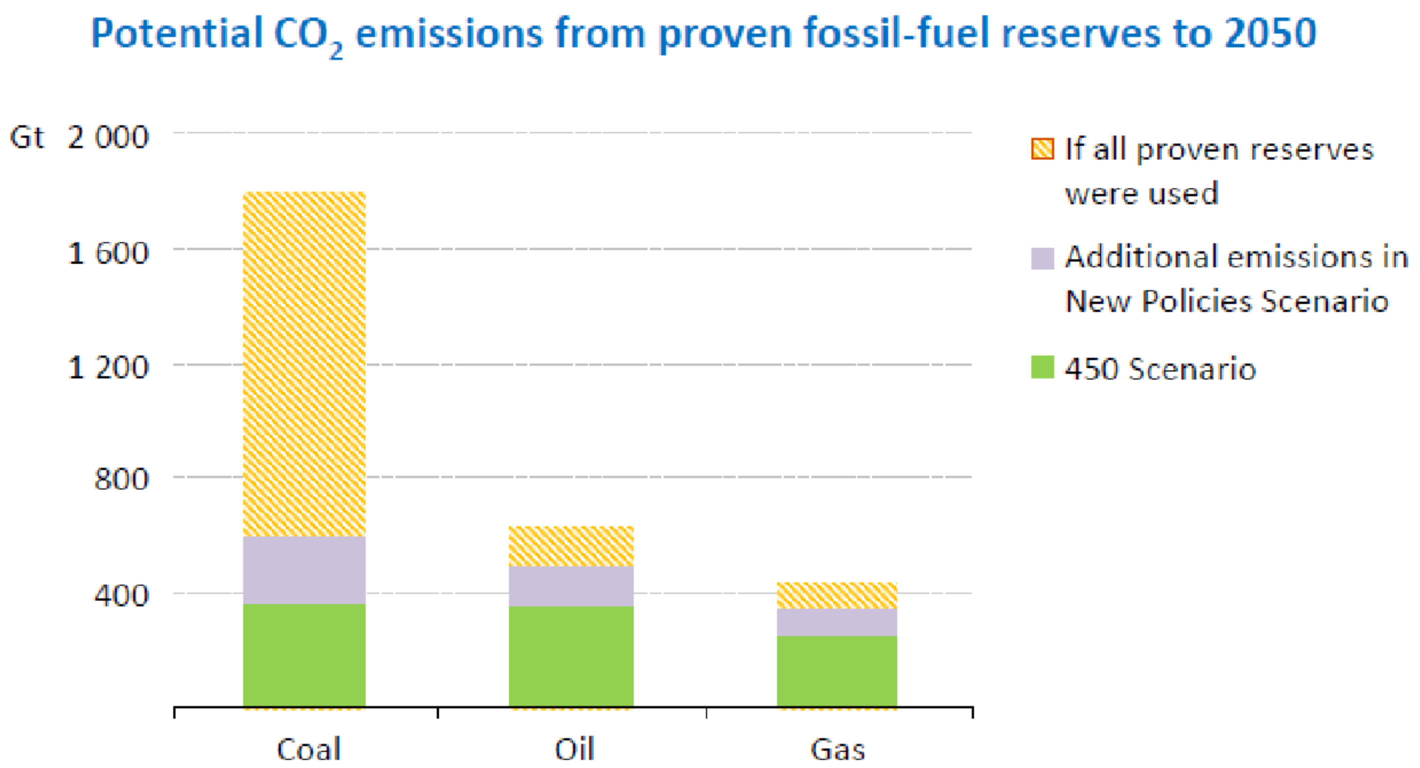
- Emphasis on rapid material growth
- Traditional values → rapid population growth
- Energy primarily from fossil fuels

Figuring Out How Warm It Will Get

- Behavioral issue: Future CO_2 emissions
- Scientific issue: Natural absorption of CO_2
- Behavioral issue: Human sequestration of CO_2?
- Scientific issue: Quantitative CO_2-temperature relationship (climate sensitivity)

The Causal Chain
(without radiation management)

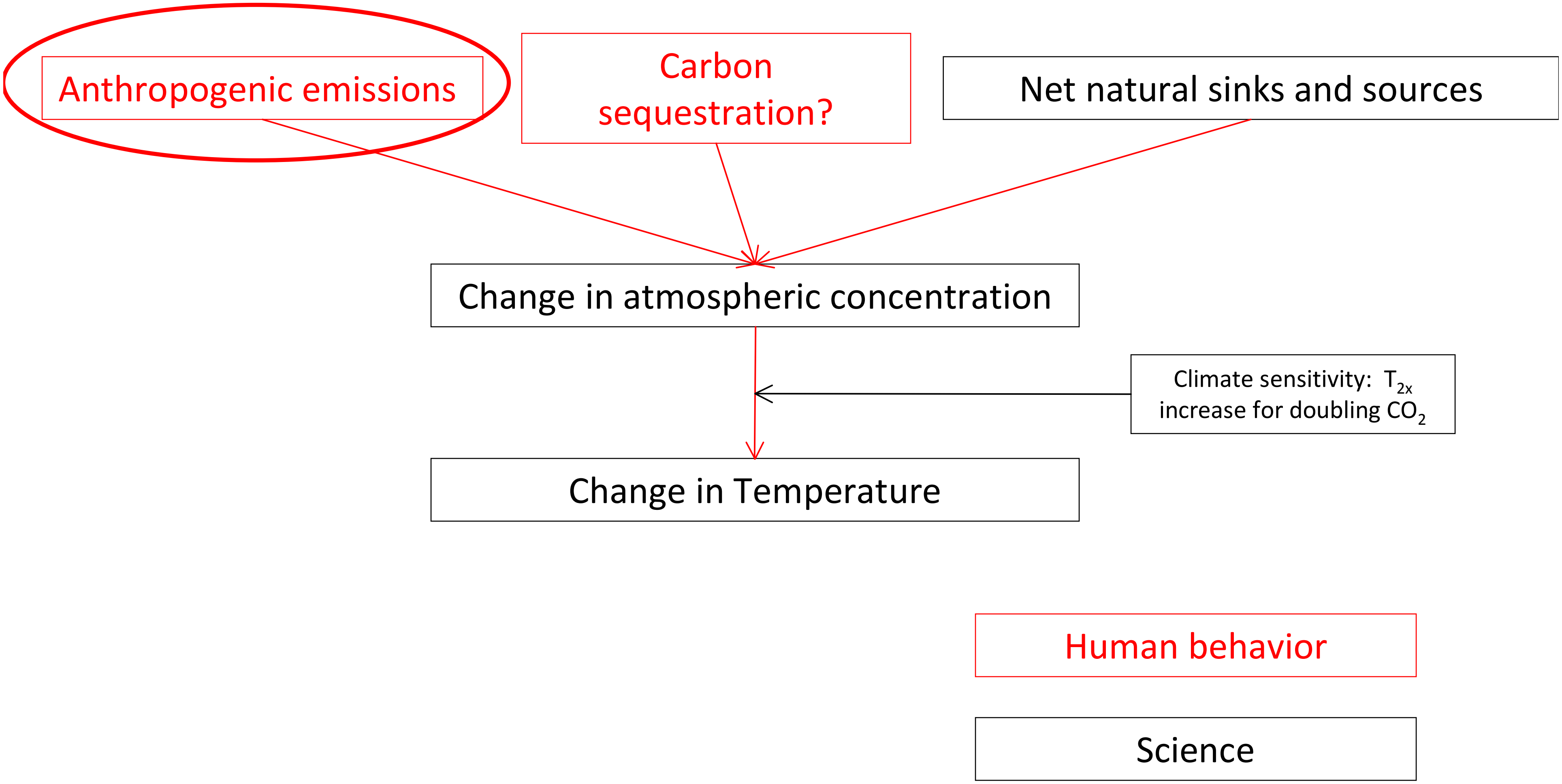




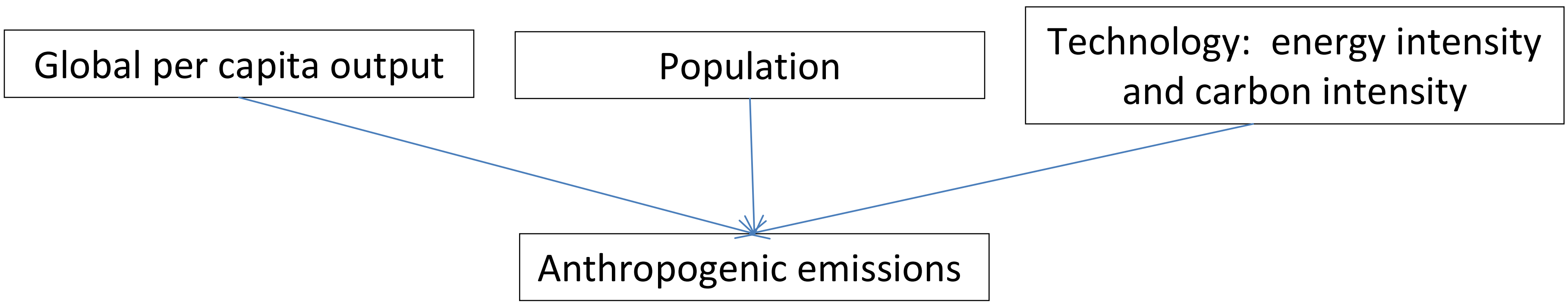
On today's trends, half of the proven fossil-fuel reserves would be left undeveloped to 2050 – stronger climate action would increase the share

"New Policies Scenario" assumes that announced policies and pledges are implemented and produces a temperature increase of >3.5° C.. The 450 Scenario assumes the adoption of measure to keep CO_2 concentration below that level.

The Causal Chain
(without radiation management)



Determining Emissions



Kaya <u>Identity</u>

Emissions = Per capital production x population x energy intensity x carbon intensity

Projections' Technological Vulnerability

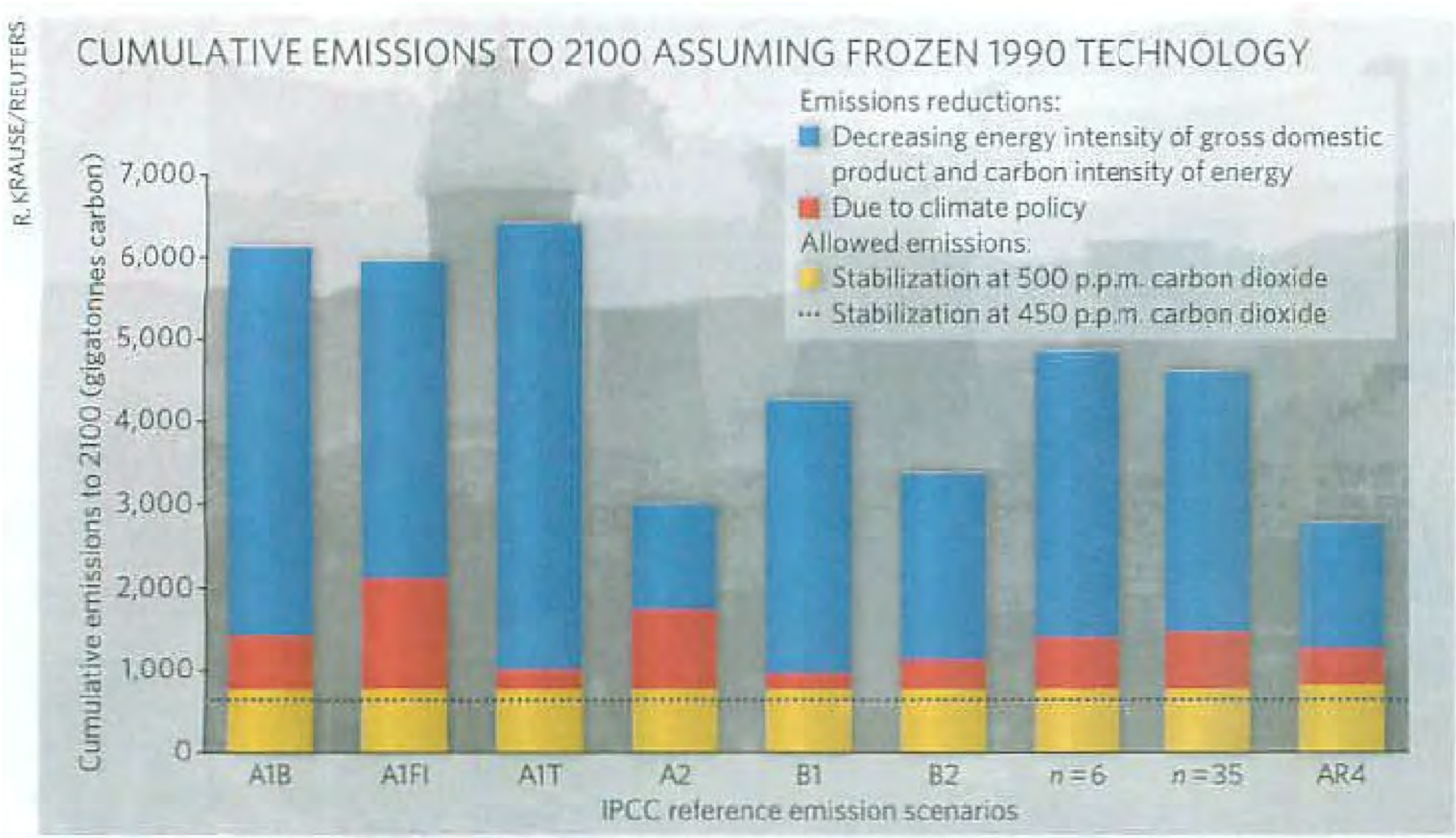
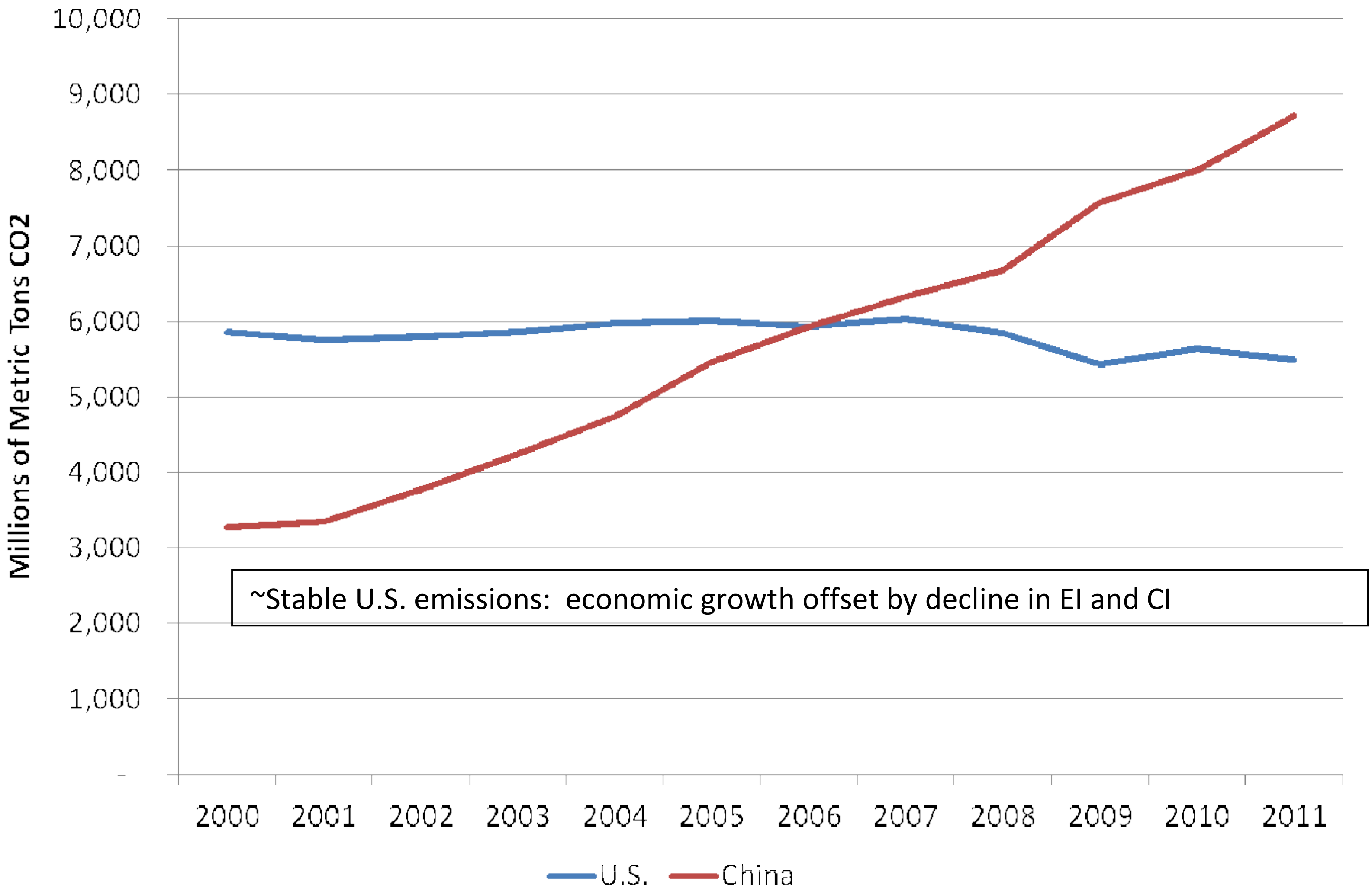


Figure 1 | Cumulative emissions. A range of 'built-in' emissions reductions (blue) in the scenarios used

Example: U.S. and China CO_2 Emissions



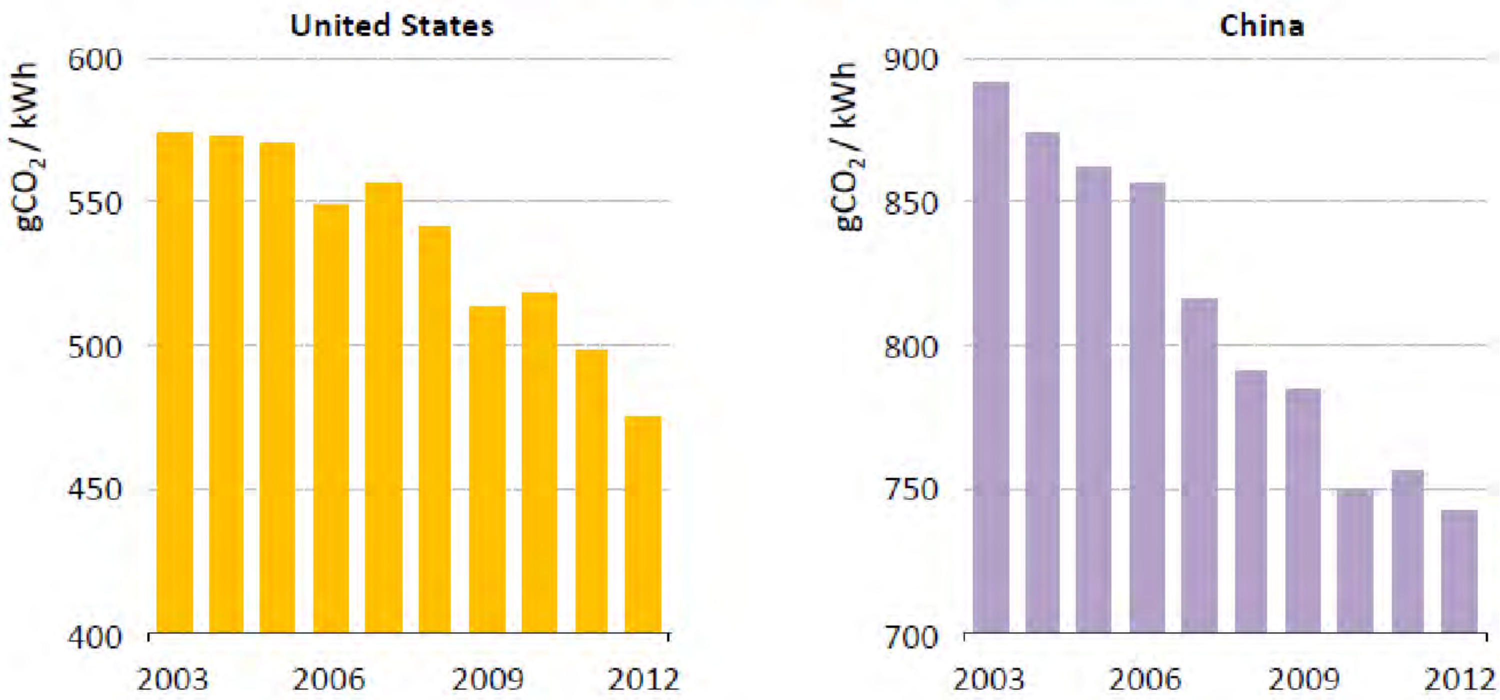
What is the appropriate metric?

	China	U.S.
Energy-related missions (2011 million MT)	8,715	5,491
Estimated population (2013 millions)	1350	316
MT/person	6.46	17.38
GDP (2012 $trillion PPP)	12.26	16.24
MT/$1000	0.71	0.34

Other Possible Metrics

- National attribution of emissions
  - Standard measure: emissions produced within country’s borders
  - Alternative: emission’s caused by consumption within its borders
    - Increases U.S. emissions and reduces China’s
    - Too imprecise for national obligations or goals
  - Policy relevance: import/export adjustment for carbon tax or cap-and-trade
- Sector-specific carbon intensity

CO_2 emissions per unit of electricity generation



Generating Electricity

	30% Efficient Coal Plant	50% Efficient Combined Cycle Natural Gas Plant
Energy intensity: energy consumed per MWh (GJ)	10.8	7.2
Carbon intensity: CO_2 emissions per GJ (kg)	93	53
CO_2 emissions per MWh (kg)	1004	382

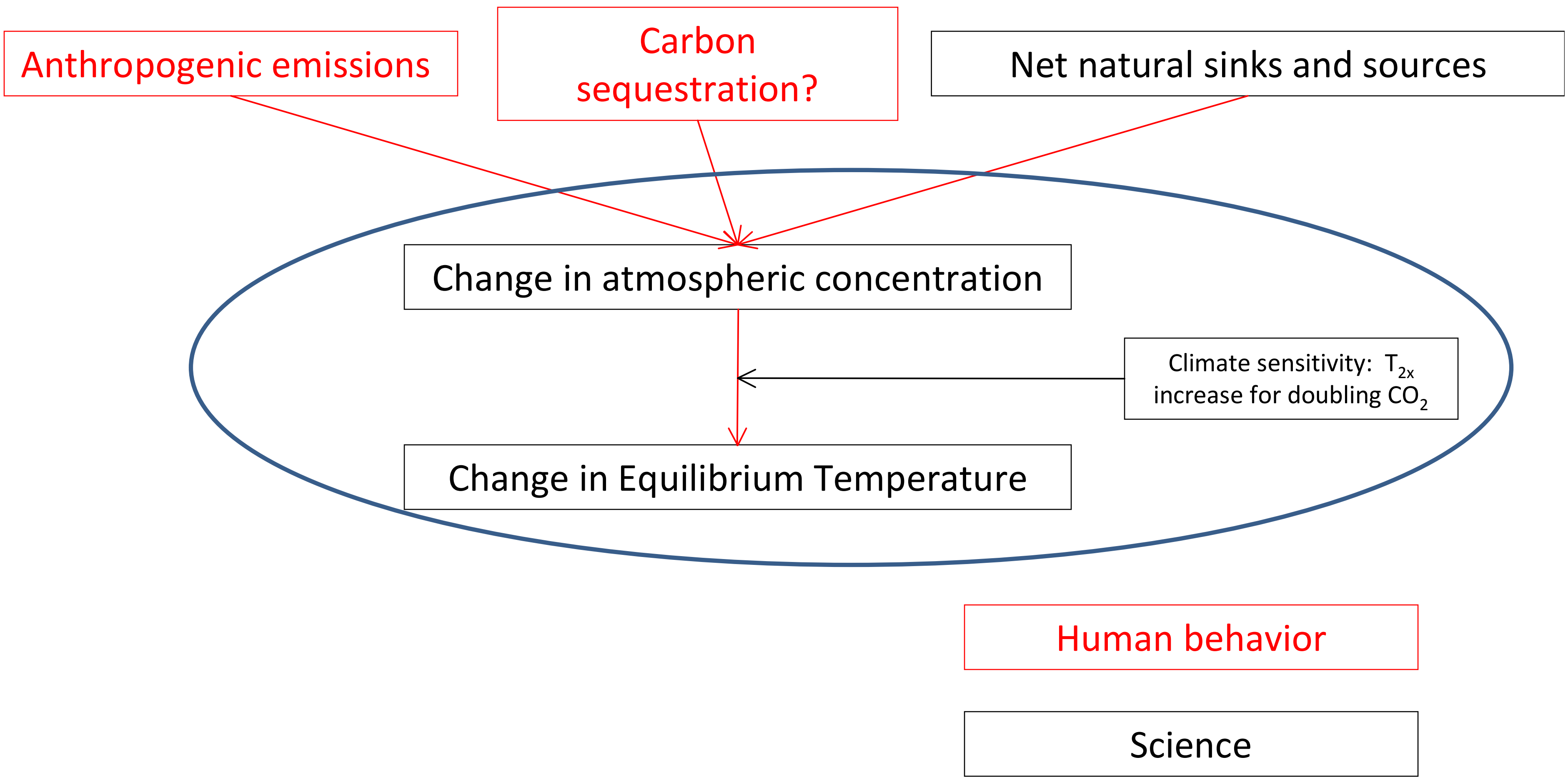
Effect of Low Natural Gas Prices

- Displaces output from existing coal plants: To date, more important than coal plant closures

- Low electricity prices
  - Reduces profitability of wind and solar
  - Shrinks boundaries of markets where they are profitable with any given subsidy

CLIMATE SENSITIVITY

The Role of Climate Sensitivity



They Weren't Entirely Wrong

- Don't worry: oceans will absorb the CO_2
  - In fact, they don't absorb all of it (Revelle)
  - But much higher concentration without them
- Don't worry: the atmosphere already is saturated with greenhouse gases
  - In fact, more greenhouse gases mean more radiative forcing even at Venusian level
  - But additional ton has a smaller impact at higher concentration

Climate Sensitivity

- ΔT_{2x}: Increase in equilibrium temperature from doubling CO_2 concentration
  - Most estimates: 1.5^o to 4.5^o C
  - Not an estimate of temperature at time CO_2 doubles: transient temperature

- Formula: $\Delta T = \Delta T_{2X} * (Ln(New\ CO_2/Old\ CO_2)/Ln(2)$

- For doubled CO_2: $\Delta T = \Delta T_{2X} * Ln\ 2/Ln2 = \Delta T_{2X}$

Logarithms

- Power to which a base number must be raised in order to equal a certain number
  - $Log_{10}(100) = 2$ because $10^2 = 100$
  - Natural logs (Ln) use base e (2.718 . . .)
    - $Ln(100) = 4.6017$ because $e^{4.6017} = 100$

- Pre-computer practical use: slide rules

- Today: describes relationship between rates of change

Increase from 280 ppm to 400 ppm With 3^o Sensitivity

- Linear relationship: $400/280 \times 3^o = 4.29^o$
- Logarithmic relationship: $\Delta T_{2x} = 3^o$
  - $\ln(400/280) = 0.36$
  - $\ln(2) = 0.69$
  - $3^o * 0.36/0.69 = 1.54^o$ temperature increase

Difficulty of Determining Climate Sensitivity

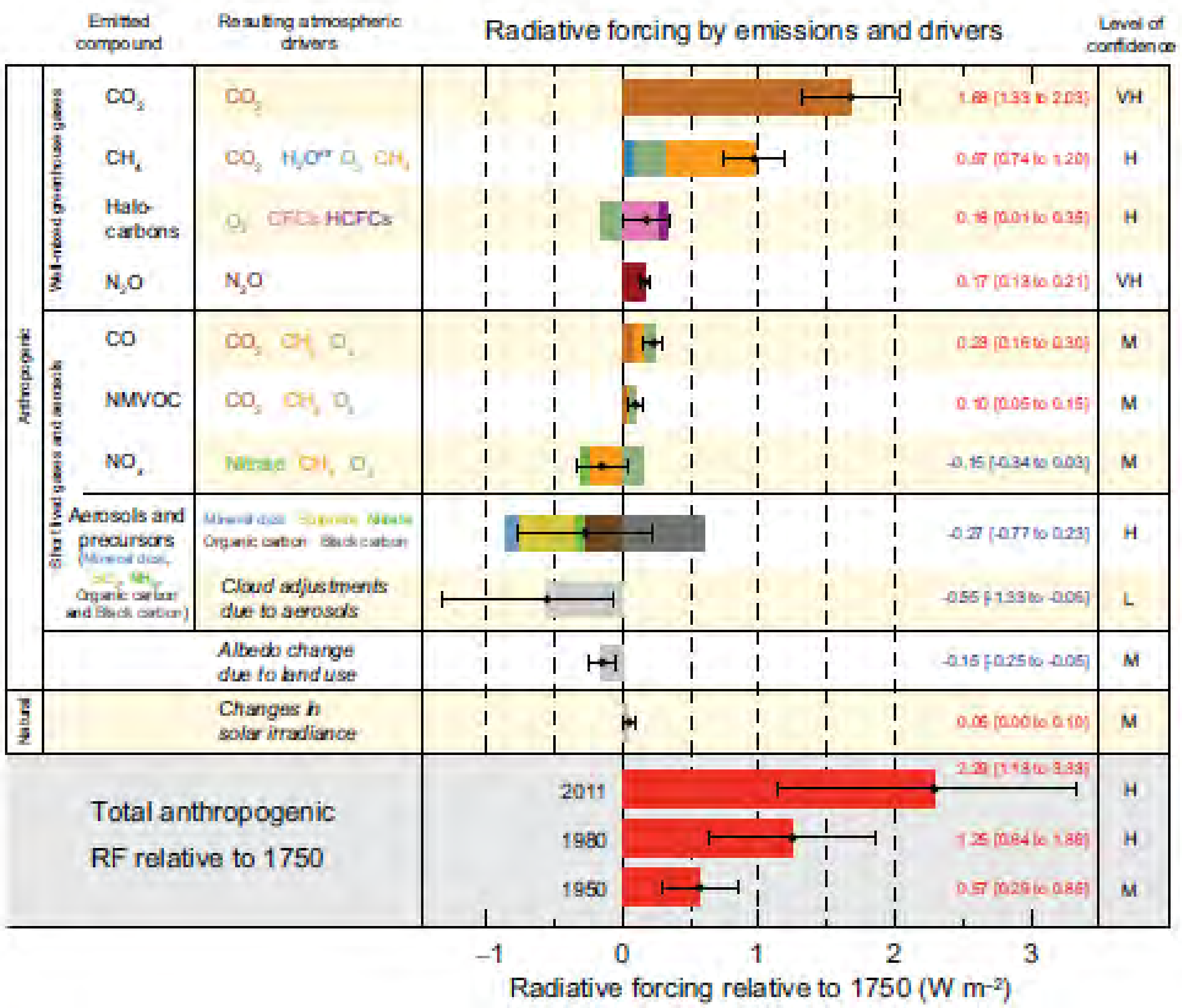
- Empirical
  - Temperature and CO_2 at two points in time
  - Solve for climate sensitivity

- Problems
  - Soldiers in a ditch
  - Equilibrium temperature

Soldiers in a Ditch

- Task: Determine height of soldiers on other side of field
- Known distance and surveying instruments
- But they're standing in a ditch
- How deep is the ditch? <u>We don't know</u>

The Aerosol "Ditch"



Why?

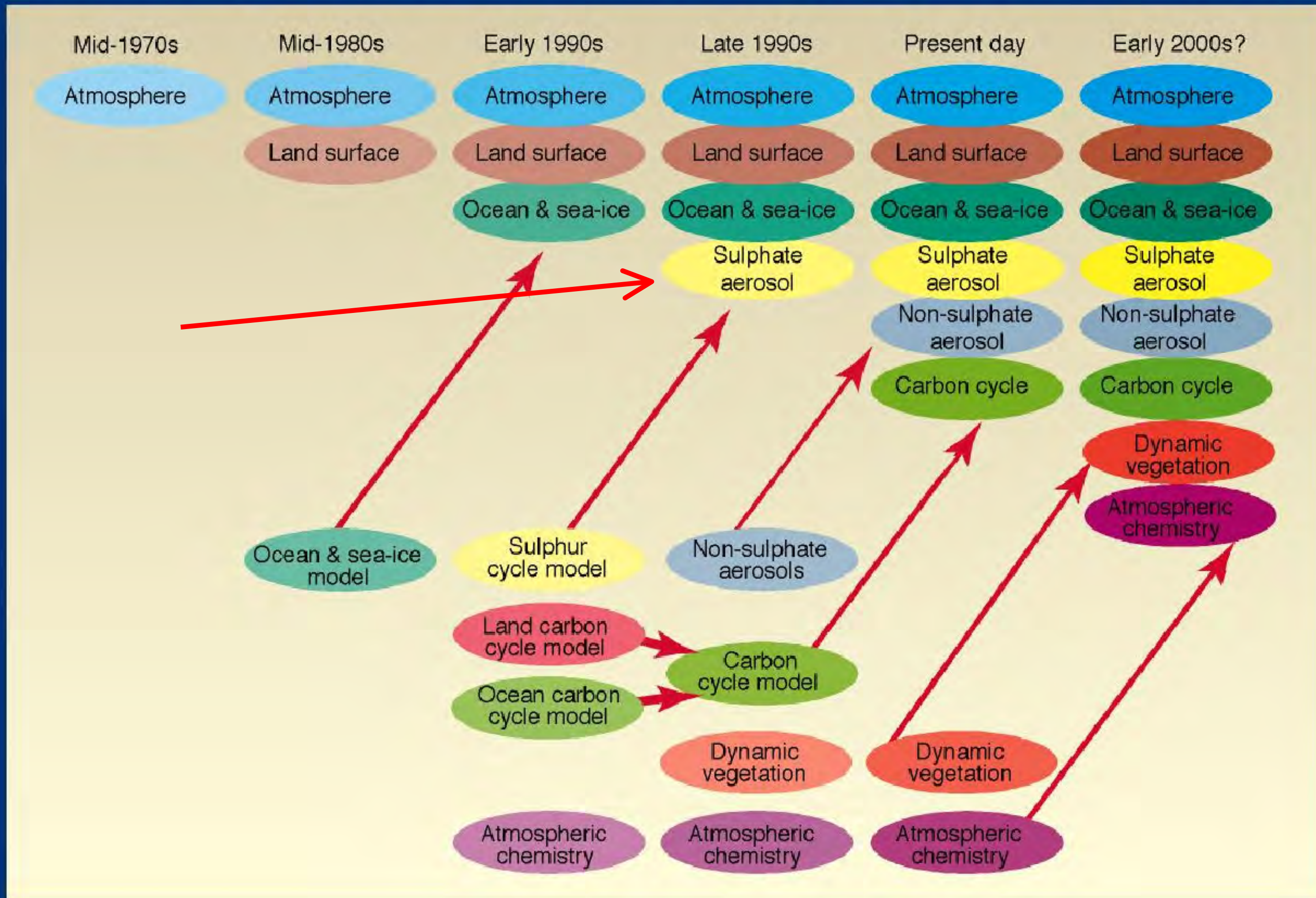
- Incomplete scientific understanding

- Scale of processes much smaller than climate model resolution

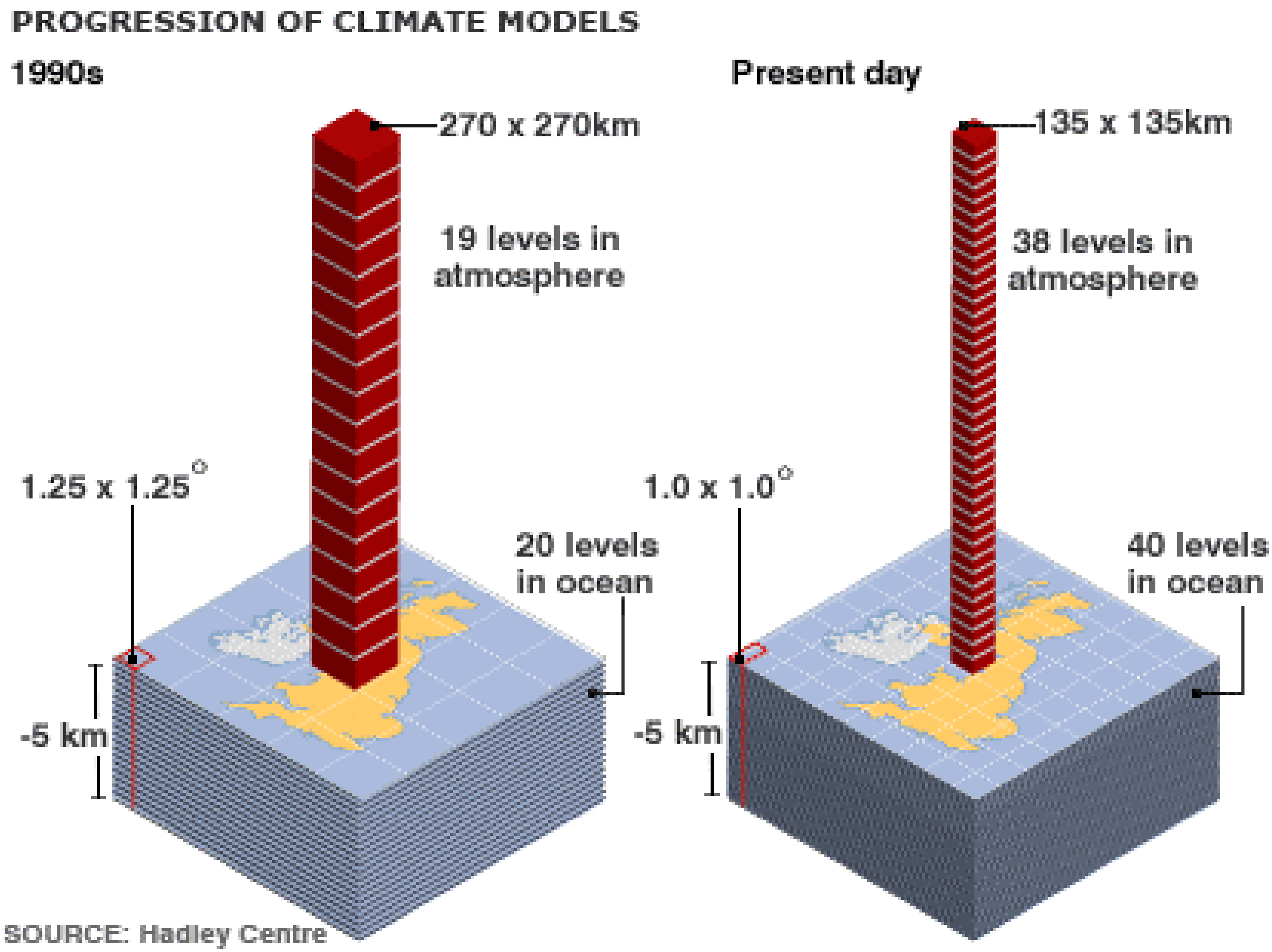
Computer Models

- More powerful computers plus increased scientific understanding
  - Smaller grid cells –still too large for some features
- Result
  - More confidence but little reduction in uncertainty range
  - Role for simpler models to permit multiple runs: intermediate complexity models

The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE **1**


PROGRESSION OF CLIMATE MODELS
1990s
Present day
270 x 270km
19 levels in atmosphere
1.25 x 1.25°
20 levels in ocean
-5 km
135 x 135km
38 levels in atmosphere
1.0 x 1.0°
40 levels in ocean
-5 km
SOURCE: Hadley Centre

Computer Models and Effect of Aerosols and Clouds

- Incomplete scientific understanding of processes

- Scale of processes is smaller than computer model grid

EQUILIBRIUM TEMPERATURE

Forcing, Heat and Temperature

- Forcing: Rate of change in Earth system heat content
- Rate of temperature change depends on thermal inertia: $\Delta T / \Delta$ heat content
- Most of Earth system's thermal inertia is in the ocean

Transient and Equilibrium Temperature

- Thermal inertia → Temperature change lags behind change in forcing
- Transient temperature – temperature on (e.g.) January 1, 2100 or day CO_2 doubles
- Equilibrium temperature: No net forcing – outgoing thermal and reflected solar equal incoming solar

Without Thermal Inertia

- Earth system as a cheap pan

- Instantaneous response to change in radiative balance: temperature always at equilibrium and no radiative forcing

- “Transient temperature” is meaningless

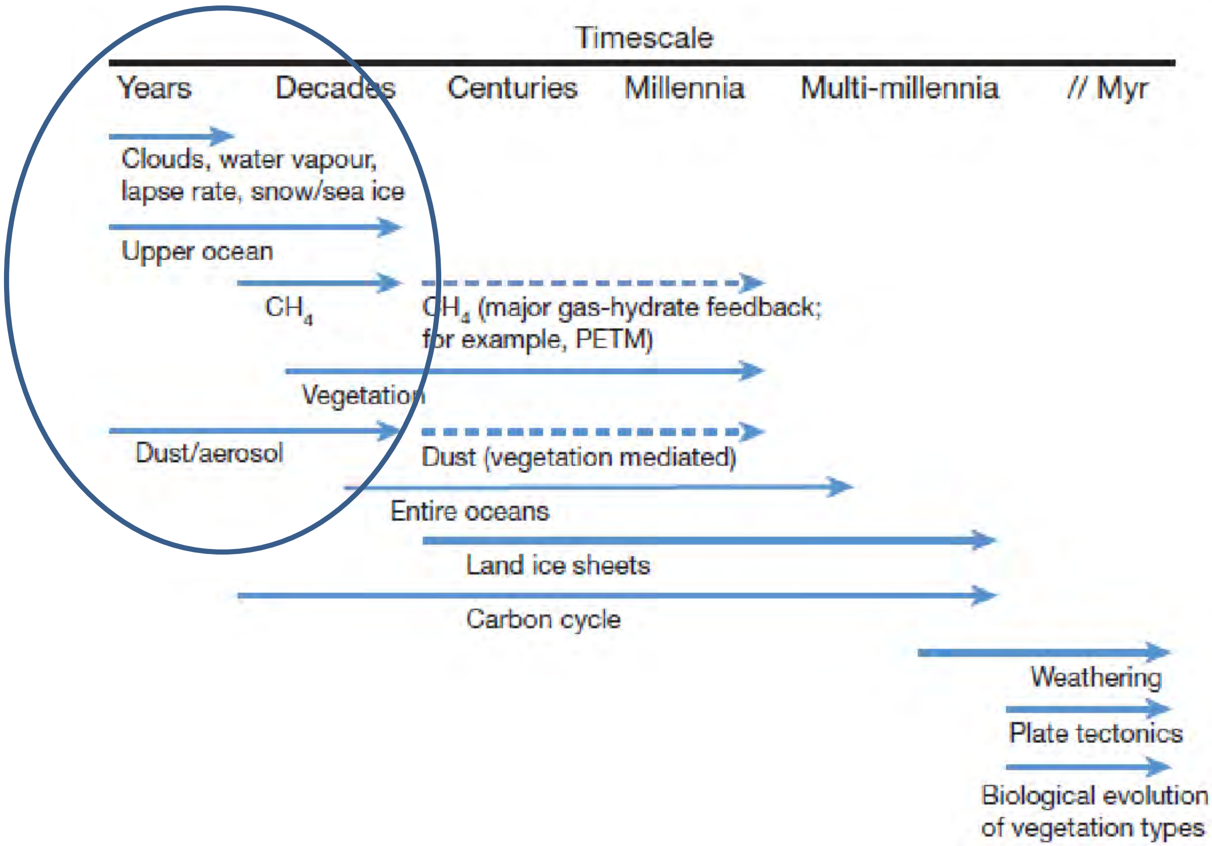
Implications of Forcings as of 2005: Time and Inertia

- Temperature increase to date: 0.7^0 C: full response to ~one w/m^2 of net forcing
- Assuming ~1.85 w/m^2 <u>cumulative</u> net forcing since 1880, 0.85 w/m^2 forcing still "in the pipeline"
- Implies ~0.6^0 further increase <u>with no further change in GHG, aerosols, etc.</u>

Cumulative forcing vs. current forcing

- Assume GHG concentration and albedo immediately changed to 2005 level in 1880
- Resulting forcing of 1.85 watts/m^2 is cumulative forcing since 1880.
- Partly “used up” since 1880 by temperature increase
- If GHG concentration unchanged, further 0.7^o temperature increase eliminates radiative forcing

Time Scale for Different Feedbacks



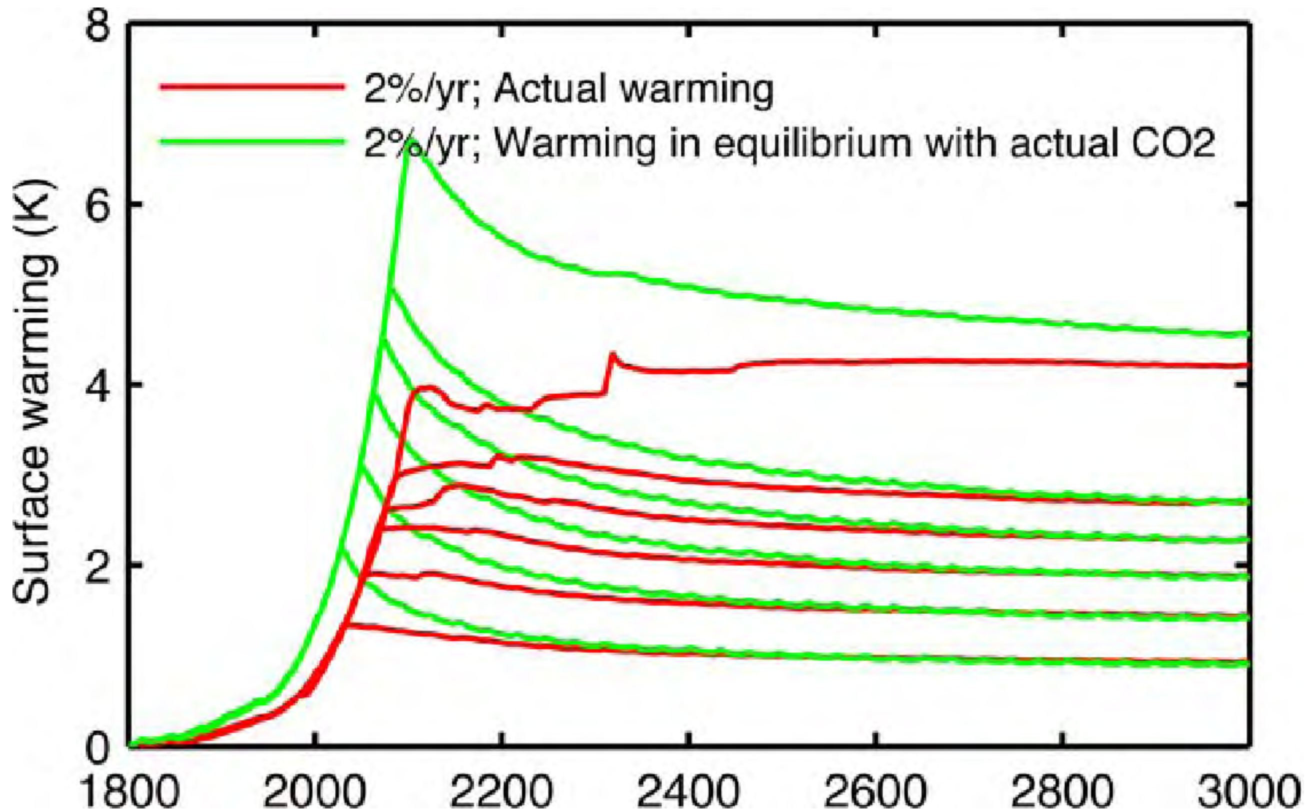
Climate Sensitivity: The Pragmatic Version

- Incorporate feedbacks occurring within decades, including:
  - Water vapor
  - Upper ocean
  - Sea ice
- Excludes
  - Deep ocean
  - Ice sheets of Greenland and Antarctica

The Long Term

- Short-term CO_2 concentration: 50% absorbed, mostly in ocean
  - Good news: Cuts atmospheric increase in half
  - Bad news: ocean acidification

- Long term: Next 1000 years dominated by ocean turnover
  - Absorbs CO_2 -- reduces cumulative radiative forcing
  - Ocean warms – less heat transfer from atmosphere



Curves represent peak CO_2 of 450 to 1200 ppm

What's Happening?

- At millennial time scale, CO_2 largely equilibrates between ocean (~80%) and atmosphere (~20%)
  - Result: Radiative forcing reduced from peak
- But oceans gradually warm
  - Result: reduced transfer of heat to ocean
- Net result: near-constant temperature over millennium