Combustion in a Global Environmental Context

Part One: Planetary Thinking

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You can learn anything!

Human civilization is confronting global environmental limits. The assignment of “fitting on the earth” is unfamiliar, and it will lead to fundamental changes in the global energy system during the next half century.

You are learning about combustion, which is by far the dominant energy conversion process driving the global economy.

You are also learning how to think quantitatively and imaginatively. These are transferable skills. You can learn “planetary thinking,” which I want to introduce you to today.

Plan for this afternoon

Combustion in a Global Environmental Context

Part One: Planetary Thinking

- Combustion and climate science
- Future emissions

BREAK

Part Two: Stabilization Wedges

- The Wedge Model
- The Abundance of Fossil Fuels
- Specific Stabilization Wedges

Part One: Planetary Thinking

Combustion and climate science

Uncertainty in climate science

Future emissions and inequality

Inequality among nations

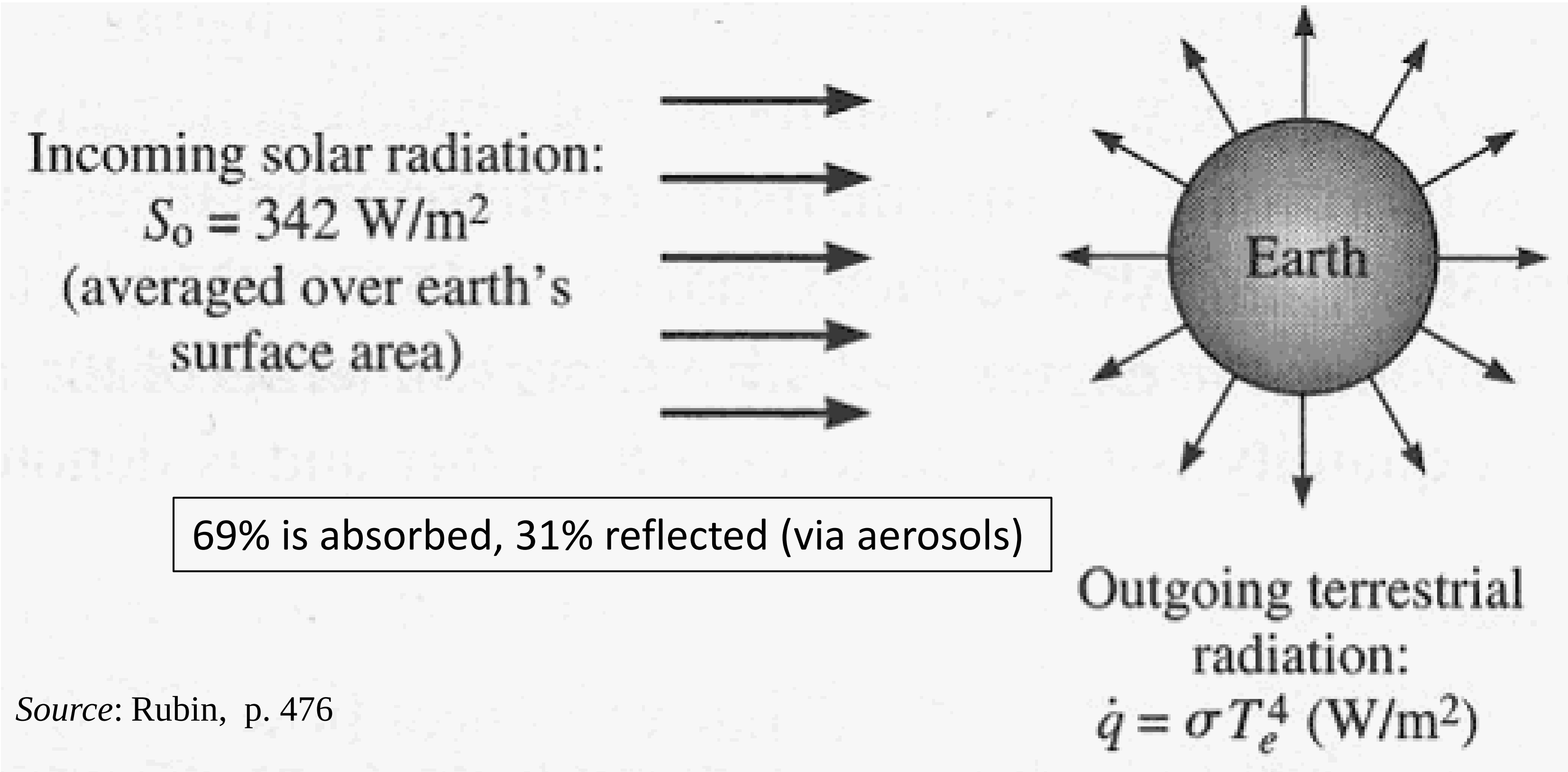
Combustion and the very poor

"One billion high emitters": A scheme to allocate national emissions reductions based on individual emissions

Combustion and Climate Science

They are linked through CO_2 and aerosols.

Earth's Energy Balance



69% is absorbed, 31% reflected (via aerosols)

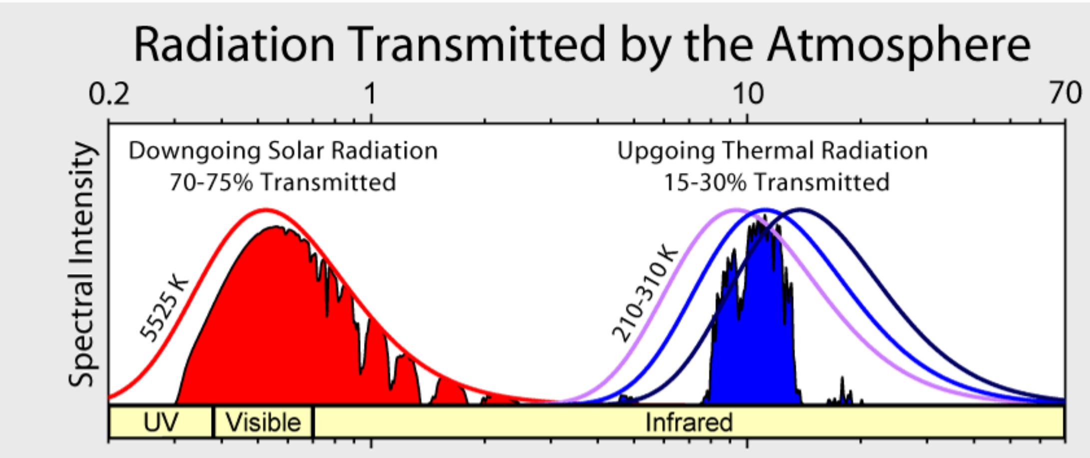
Source: Rubin, p. 476

Solar Input: **120x10^{15} W** 0.69 x 342 W/m^{2}x [4π x (6370 km)^2]

Human Use: **16x10^{12} W** 500 EJ/year , 2 kW/capita

Ratio ≈ 10,000.

The sun and earth are both black bodies



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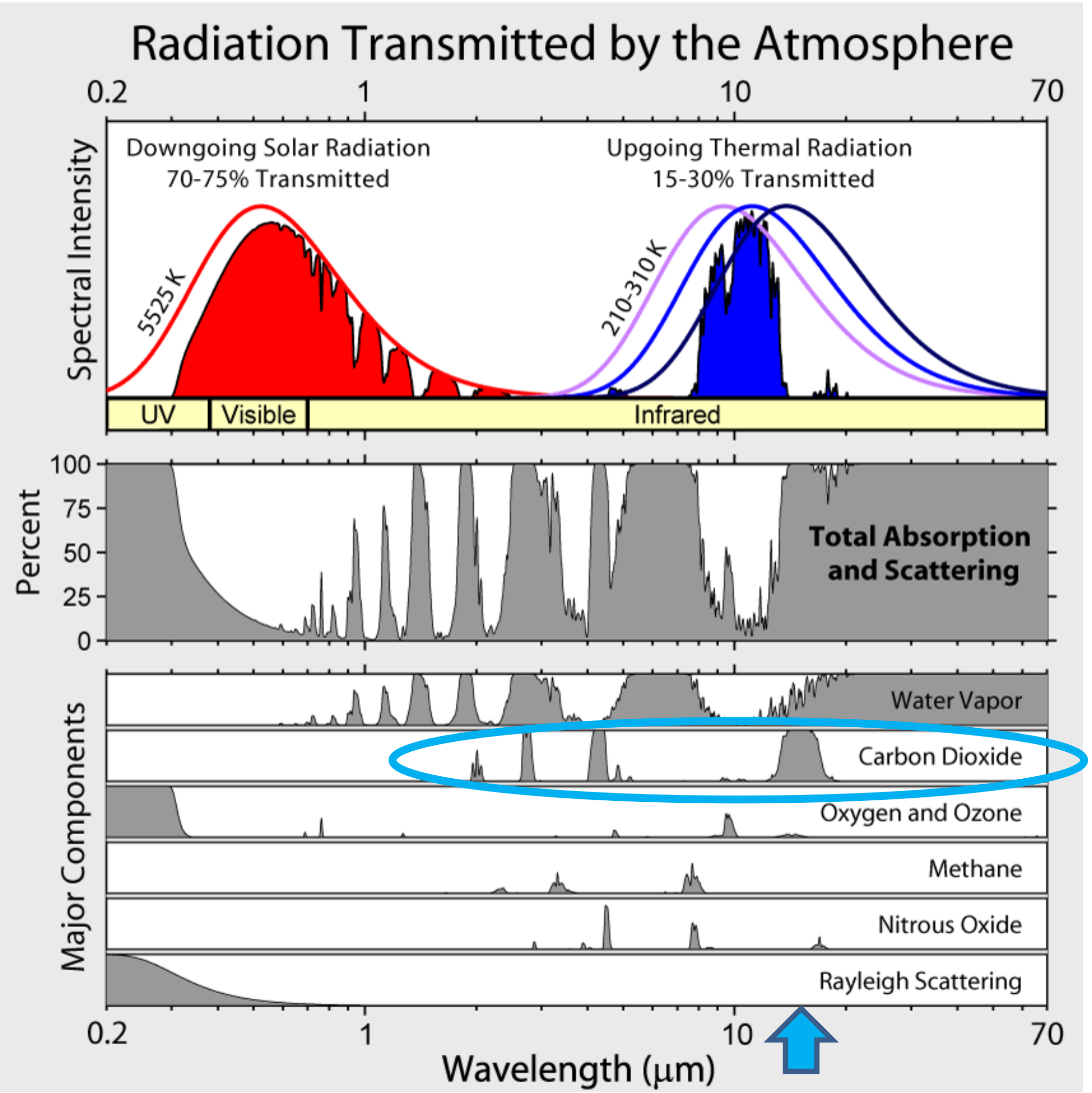

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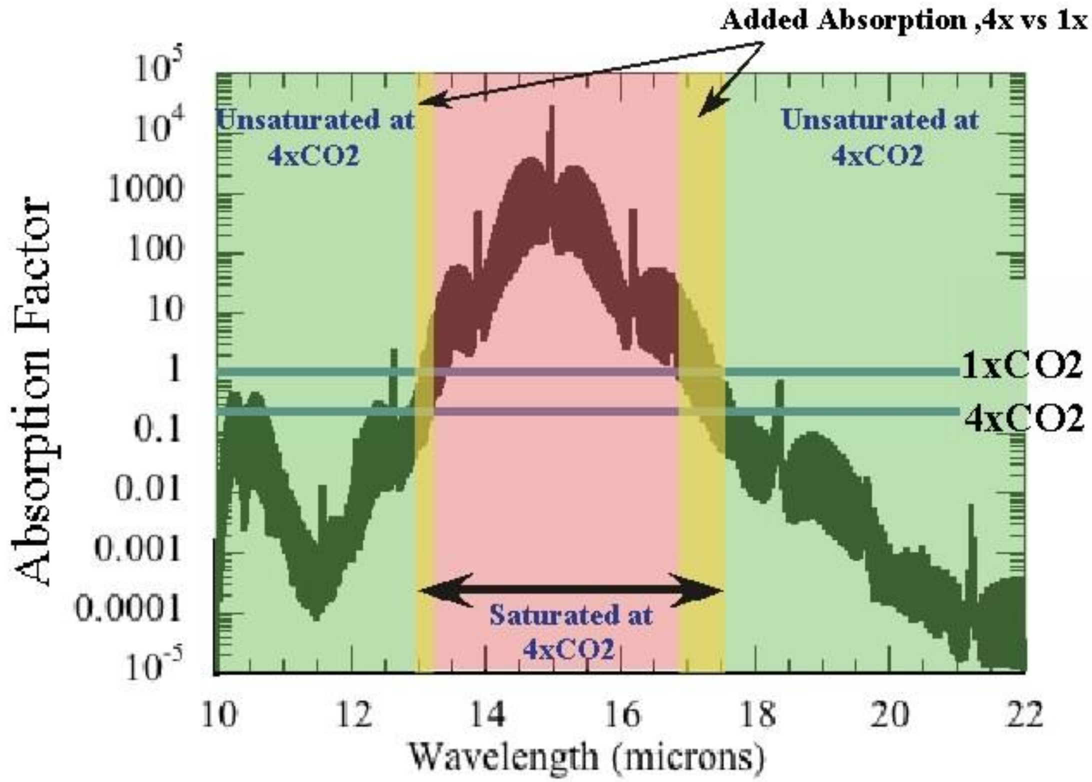
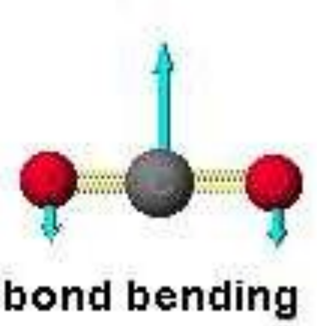
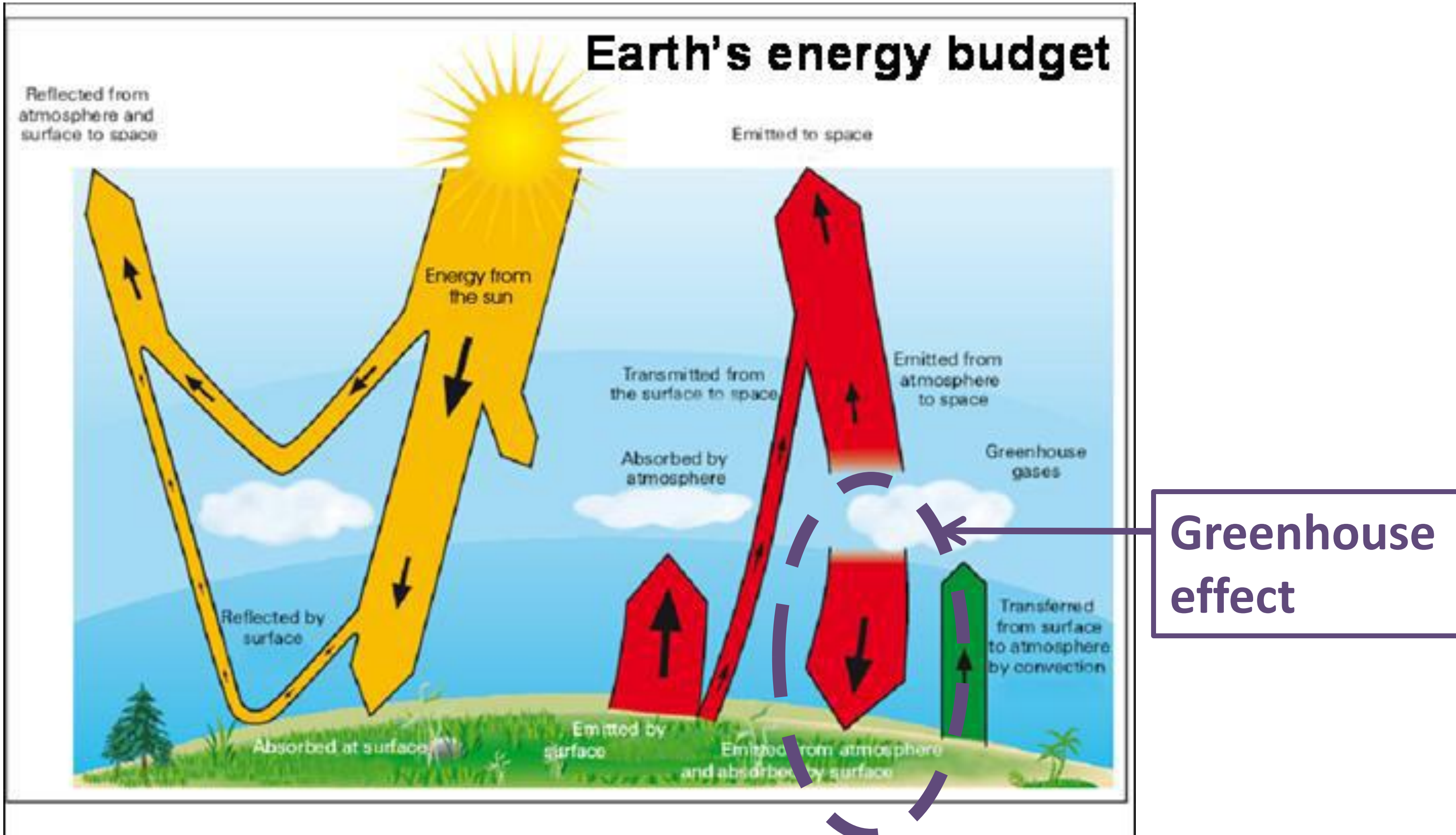
CO_2 absorption band



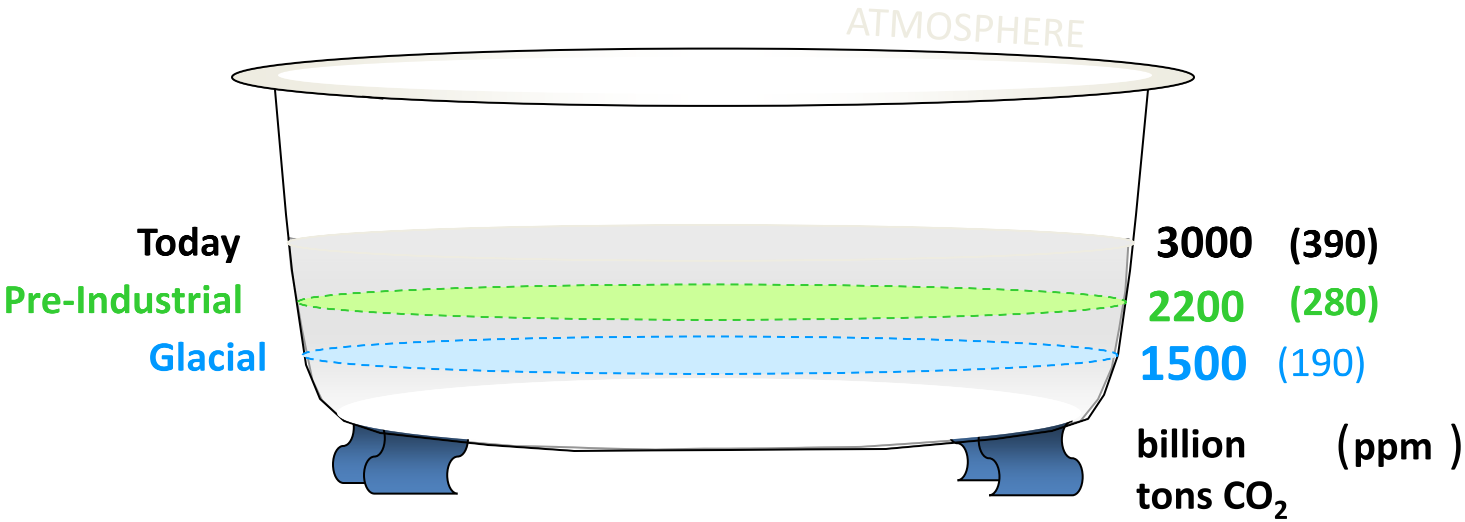


The Earth’s energy budget

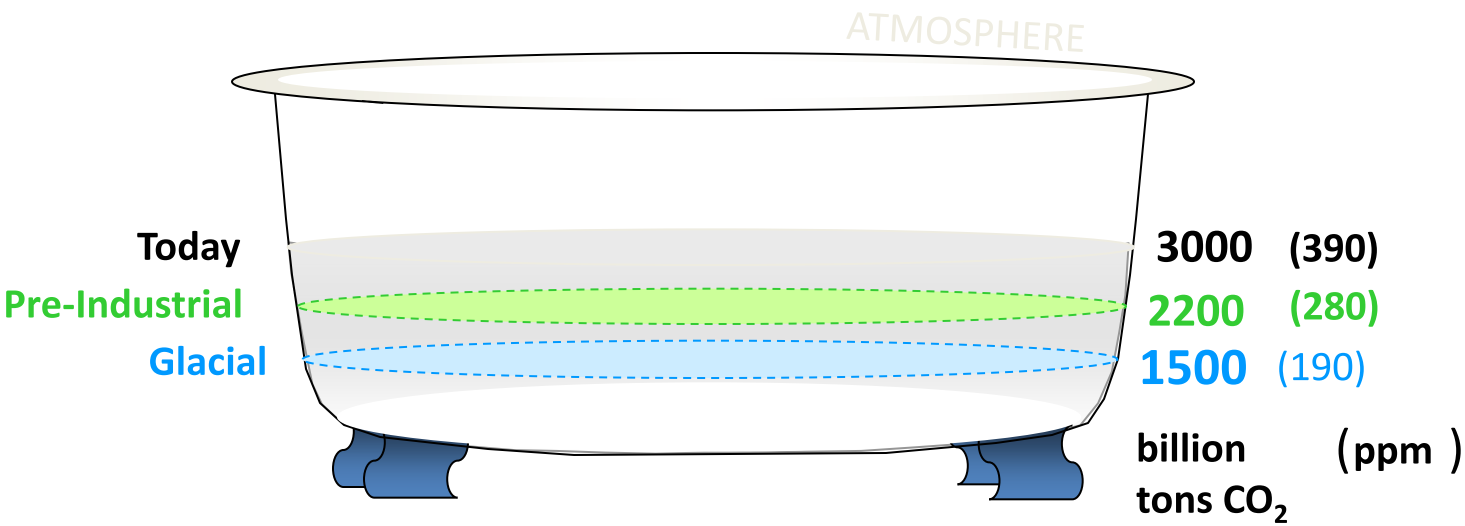


Source: Ipsos MORI, *Experiment Earth?* August 2010, p. 64

Past and present levels of CO_2 in the atmosphere



Past and present levels of CO_2 in the atmosphere



Rosetta Stone: To raise the concentration of CO_2 in the atmosphere by **one part per million:**

add **7.8 billion tons of CO_2,**

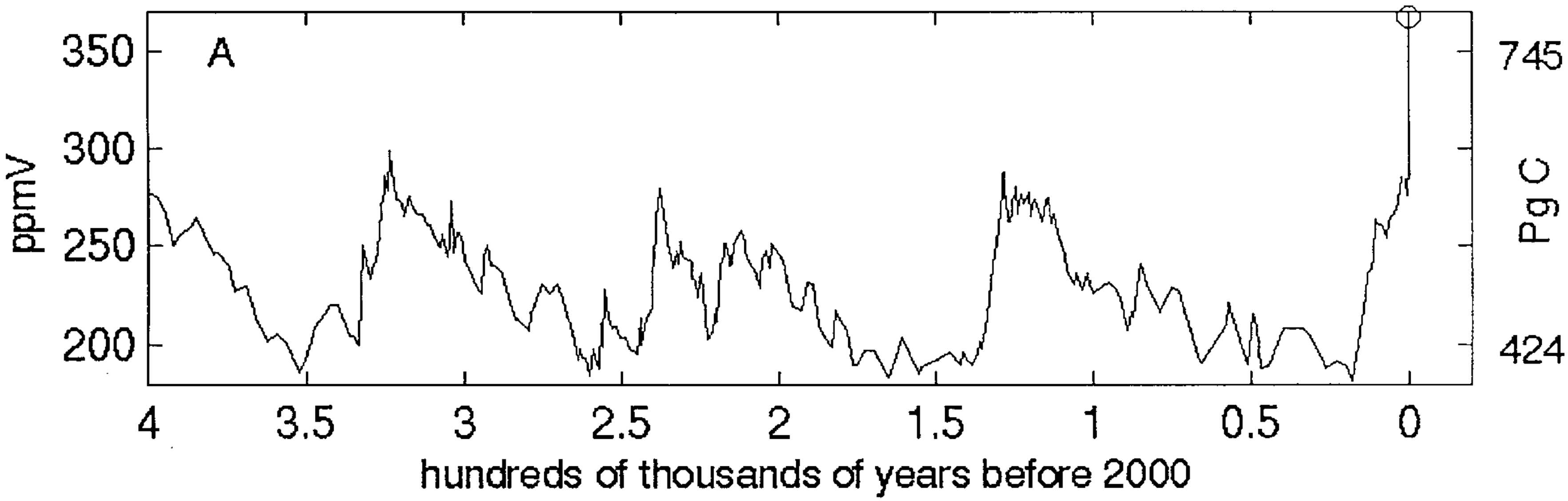
in which are **2.1 billon tons of carbon.**

Antarctic Ice Core

Source: Gabrielle Walker, "Frozen time," *Nature;* Jun 10, 2004; 429, 6992; Research Library Core, pg. 596

400,000 Years of CO_2 Data: Four Ice Ages

Today →

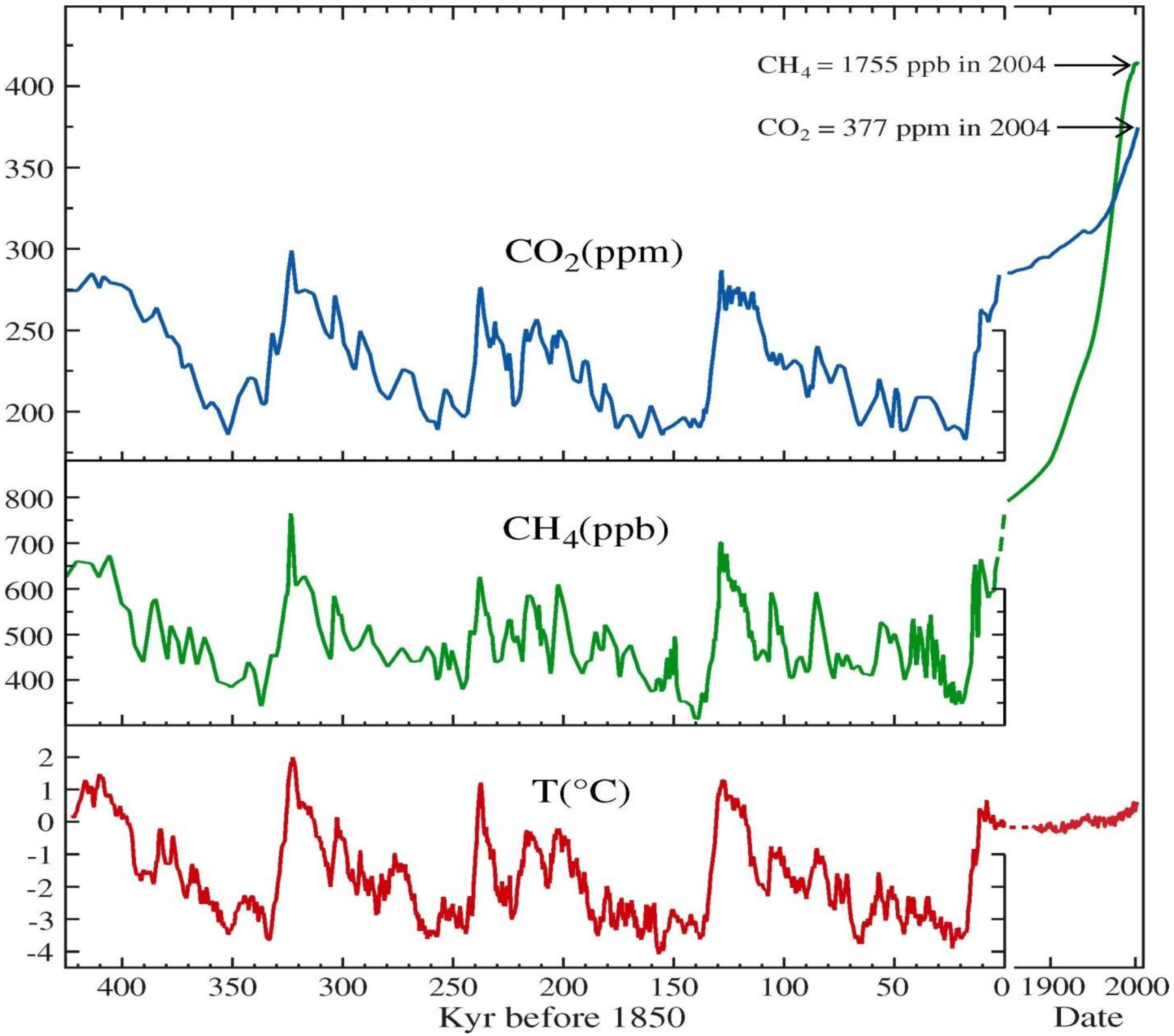


Old → New

Variations of atmospheric CO_2 over glacial/interglacial times (Petit et al. 1999, Keeling and Whorf 1999). Circle at upper right shows ~~current~~ concentration.
No

Paleoclimate studies are at the center of the unease among climate scientists about rising CO_2 . The phenomena are large, and the causes are still unknown.

Ice-age temperature, CO_2, and CH_4 track each other

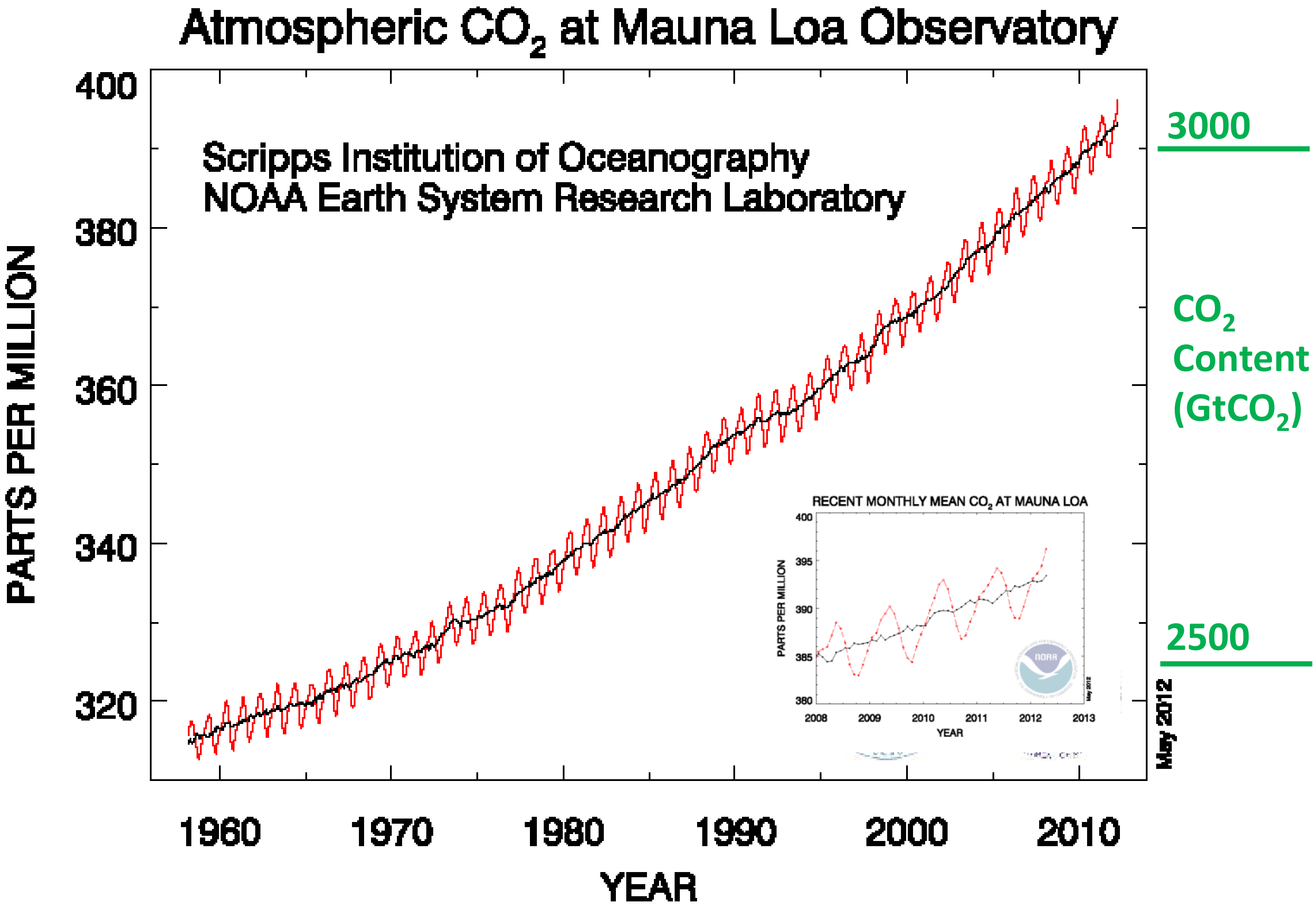


CO_2, CH_4 and estimated global temperature

Temperature in ice-core era: 0.5*(Antarctic ΔT),

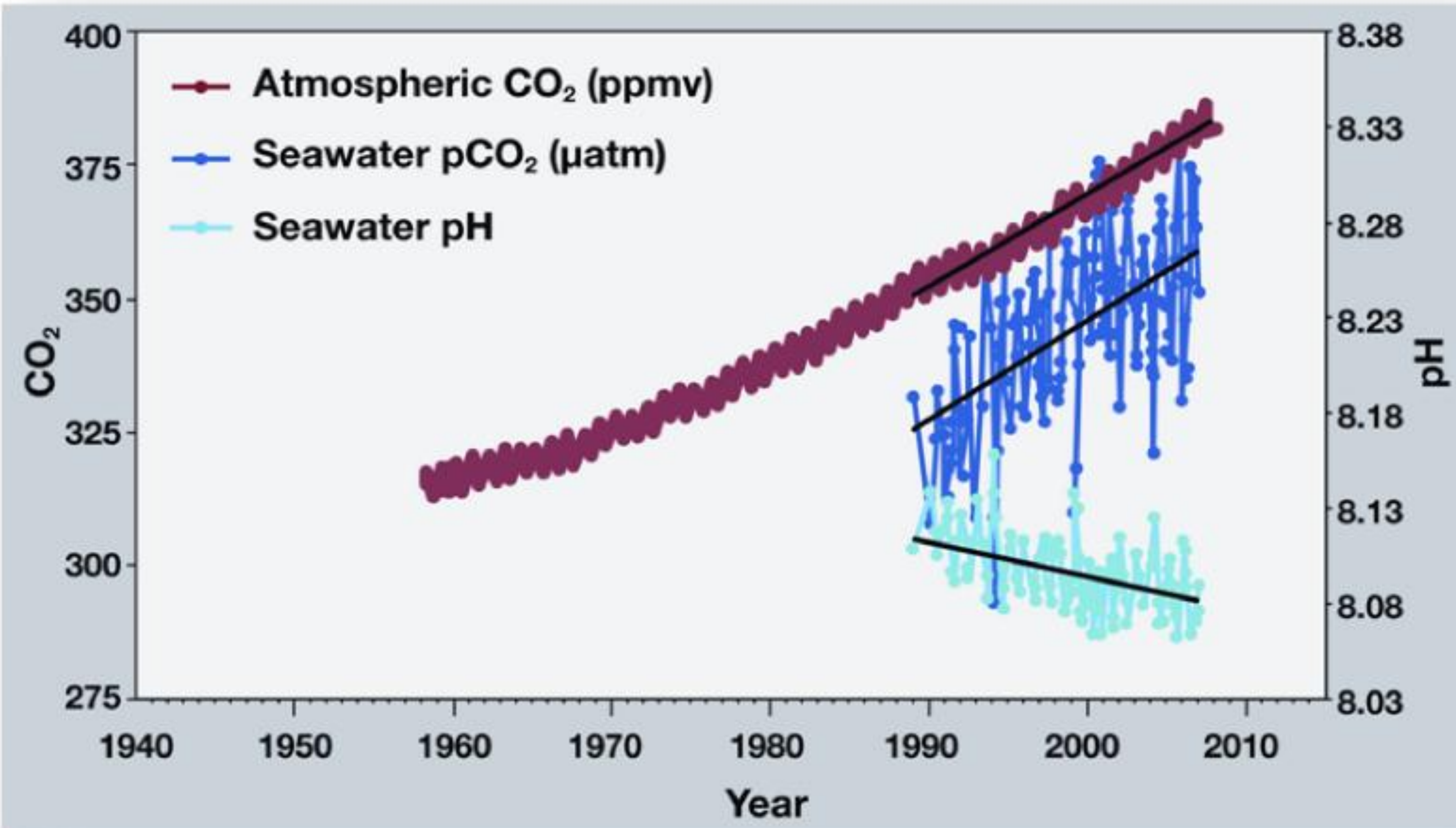
0 = 1880-1899 mean.

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



Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
RECENT MONTHLY MEAN CO_2 AT MAUNA LOA
PARTS PER MILLION
400
395
390
385
380
2008
2009
2010
2011
2012
2013
YEAR
May 2012
3000
CO_2 Content ($GtCO_2$)
2500

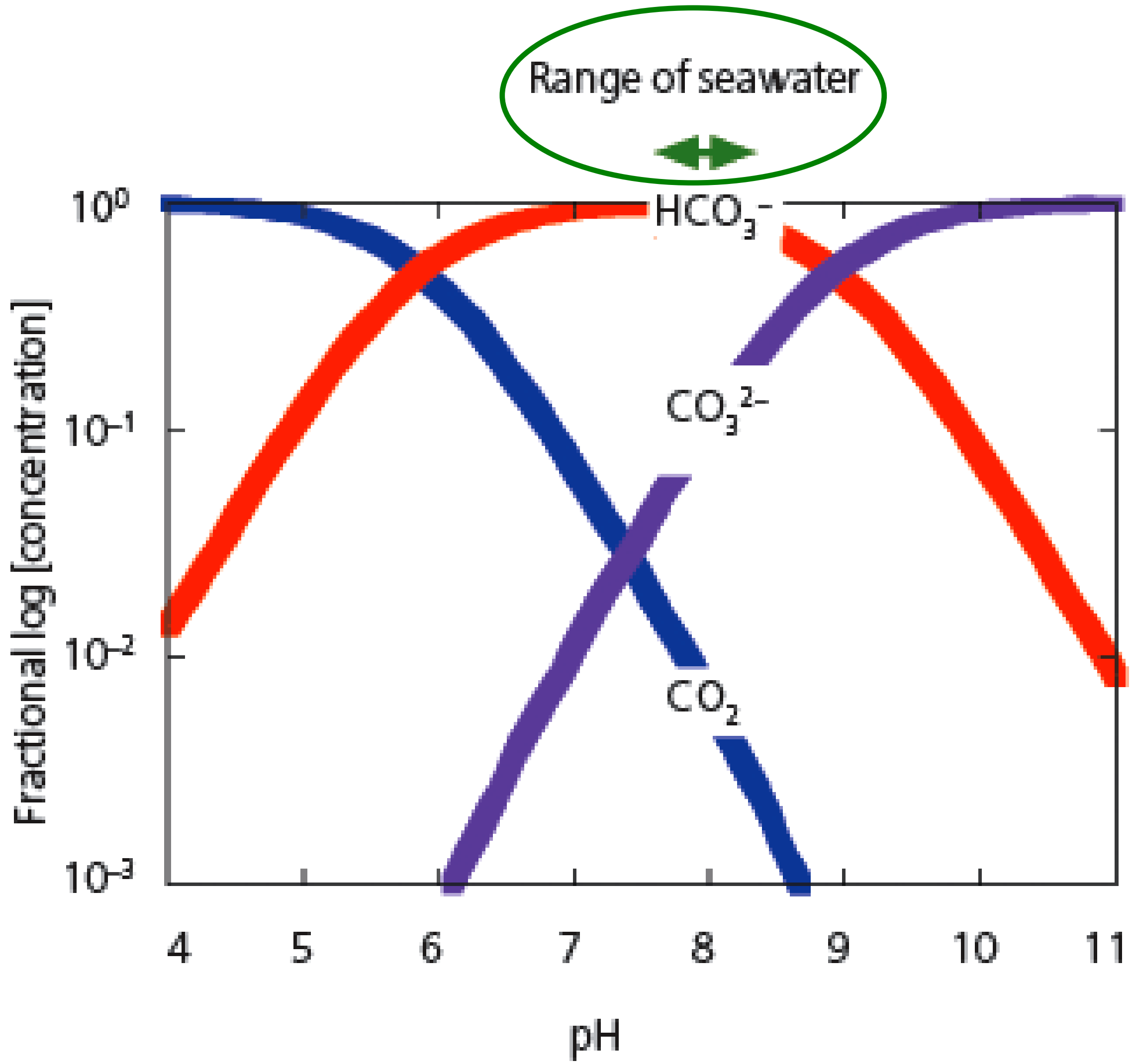
CO_2 concentration and Ocean pH



CO_2 level in atmosphere at Mauna Loa; CO_2 level and pH in nearby ocean at Station Aloha.

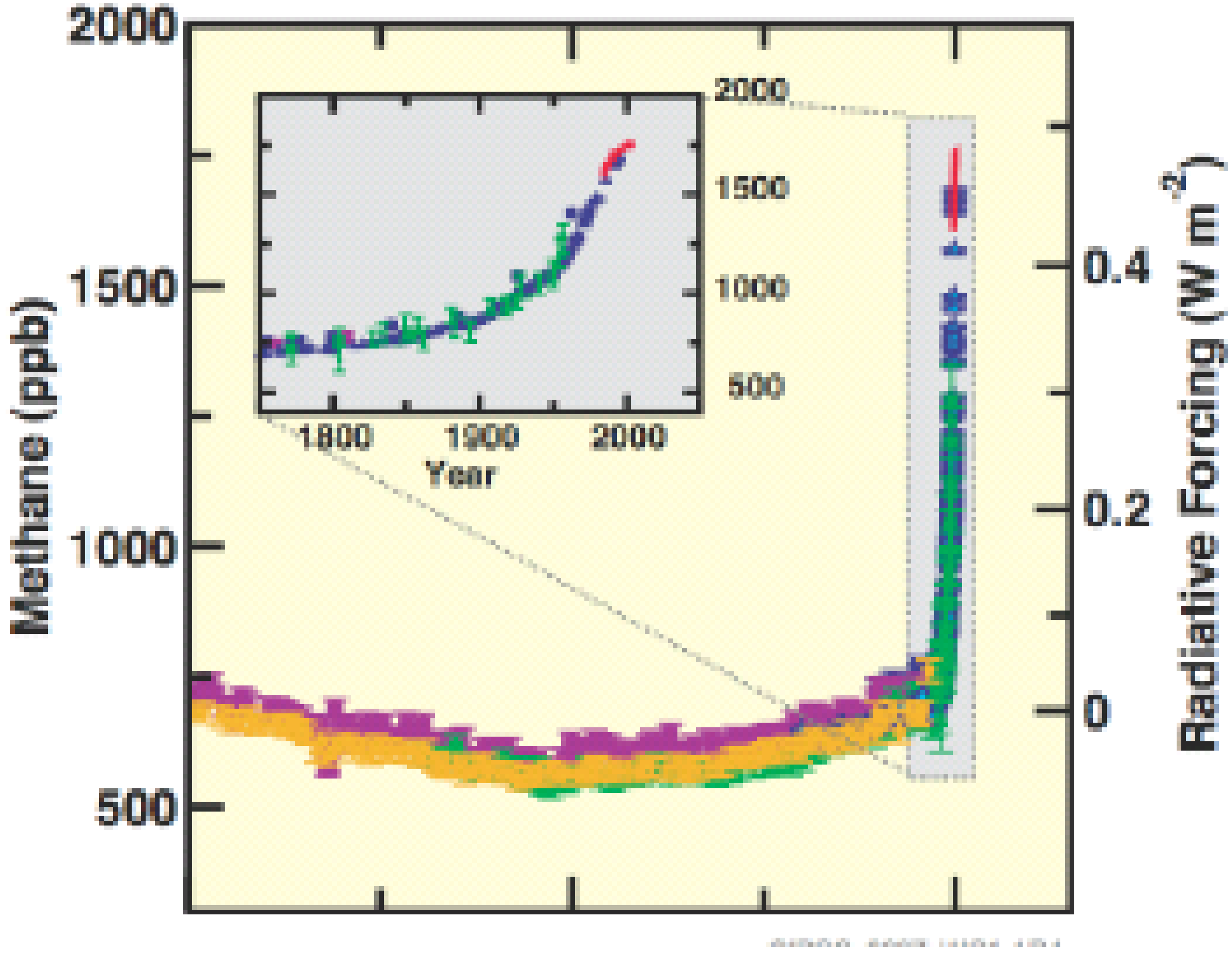
Modified after R.A. Feely, Bulletin of the American Meteorological society, July 2008. *Website*: Pacific Marine Environmental Laboratory, NOAA, http://pmel.noaa.gov/co2/files/hitimeseries2.jpg

Figure A. Relative proportions of the three inorganic forms of CO_2 dissolved in seawater. Note the ordinate scale (vertical axis) is plotted logarithmically.



Royal Society 2006

CH_4 Record (IPCC 2007)



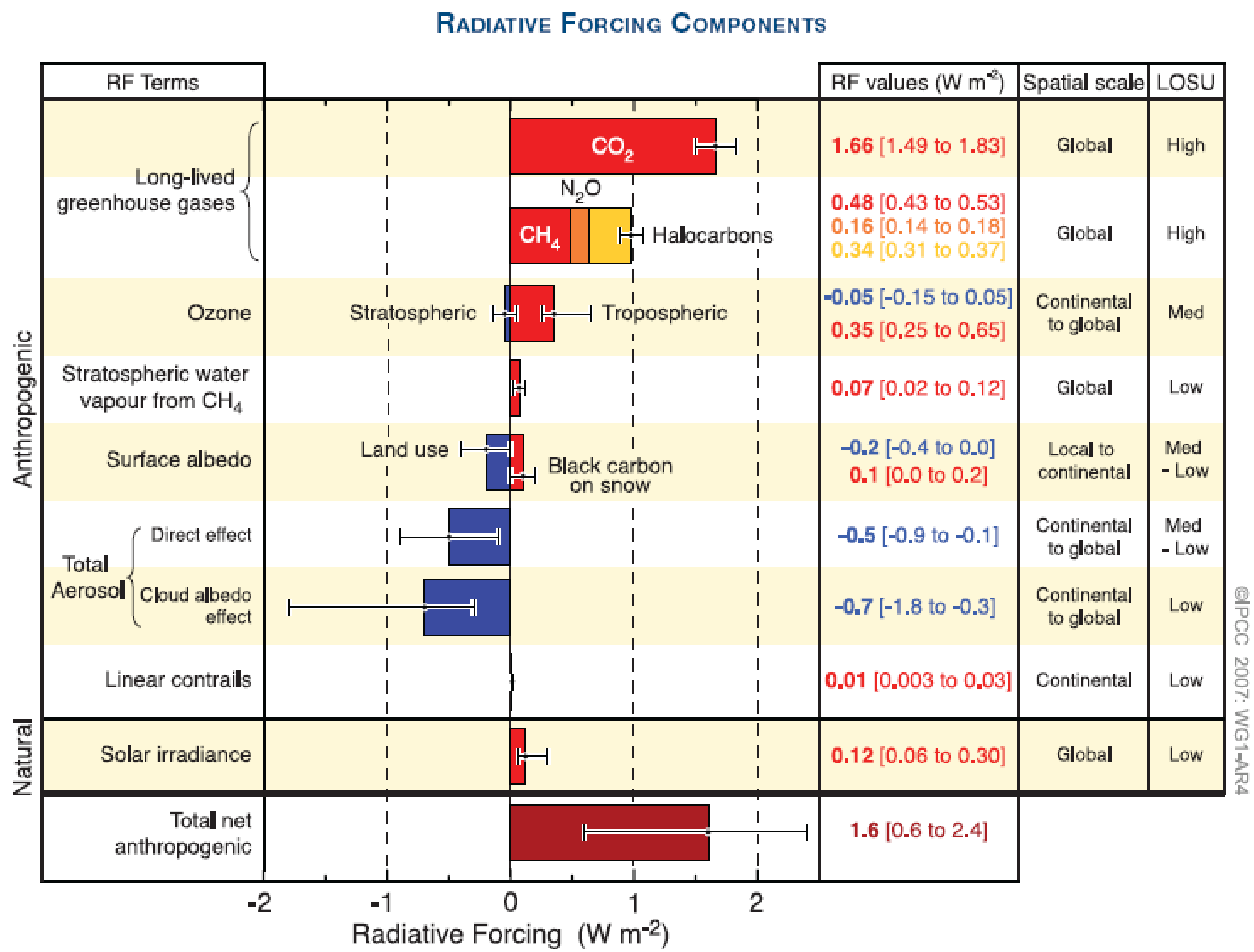


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Source: 2007 IPCC Summary for Policy Makers

Will we geoengineer the planet?

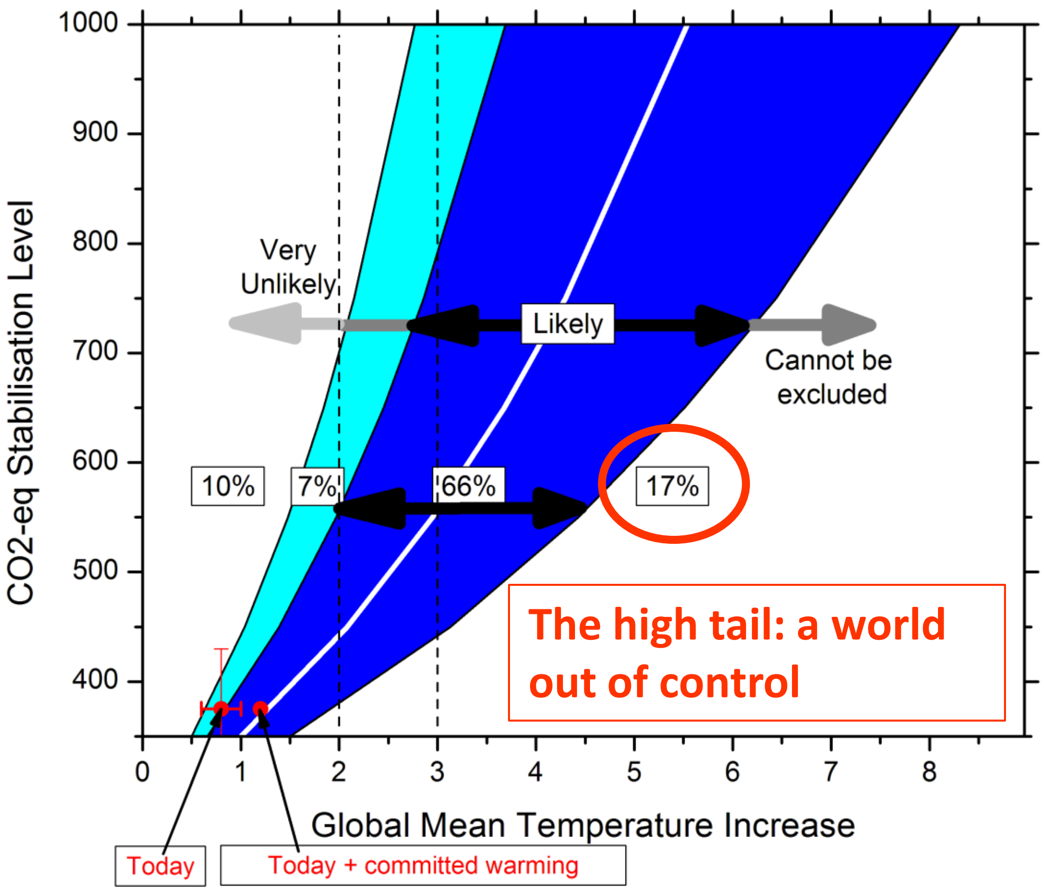
The idea is to imitate the cooling effect of large volcanoes.

On June 15, 1991 (three days after this photo) , Mt. Pinatubo injected 10 million tons of sulfur into the stratosphere.

The Earth's average surface temperature was 0.5^{o}C cooler six months later.

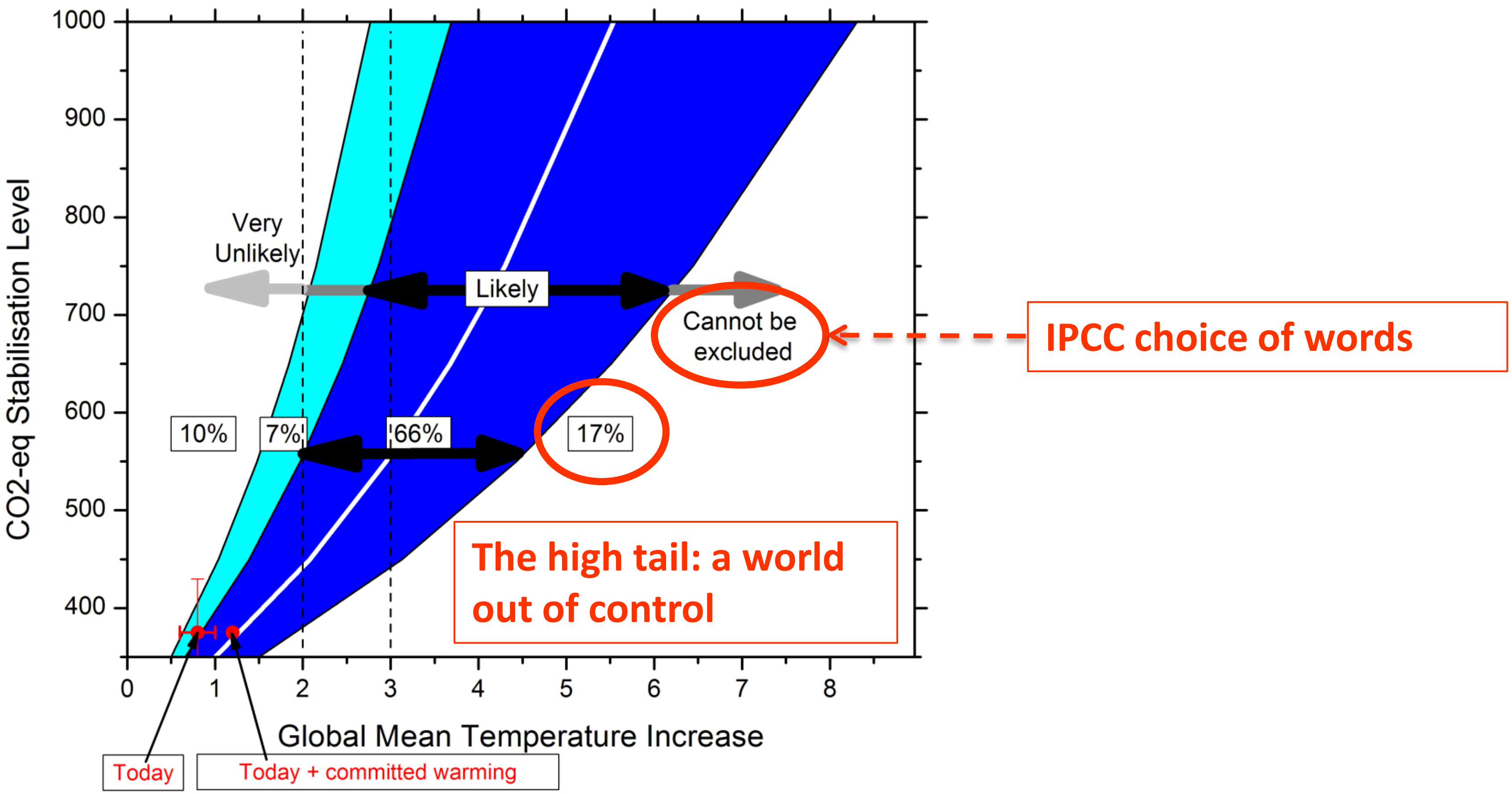
UNCERTAINTY

Don’t fudge our uncertainty



Source: From Martin Manning.

Don’t fudge our uncertainty



This graph is not found in IPCC AR4 WG1. There was no consensus about the probability shown here as 17%.

Source: From Martin Manning.

We don't know how large a problem we face.

The best and worst future climate outcomes consistent with today's science are very different.

Climate science is incomplete. Feedbacks from clouds, ice, and vegetation are only partially understood.

Climate science is an evolving human enterprise where discordant views are the norm.

Uncertain emissions

Thirty year changes for Massachusetts, *controlling for the climate modeling*:

2010-2039:
Done!

2040-2069:
Princeton vs. Washington

2070-2099:
Baltimore vs. Augusta

This graph probably shows how winters could feel too (to be verified).

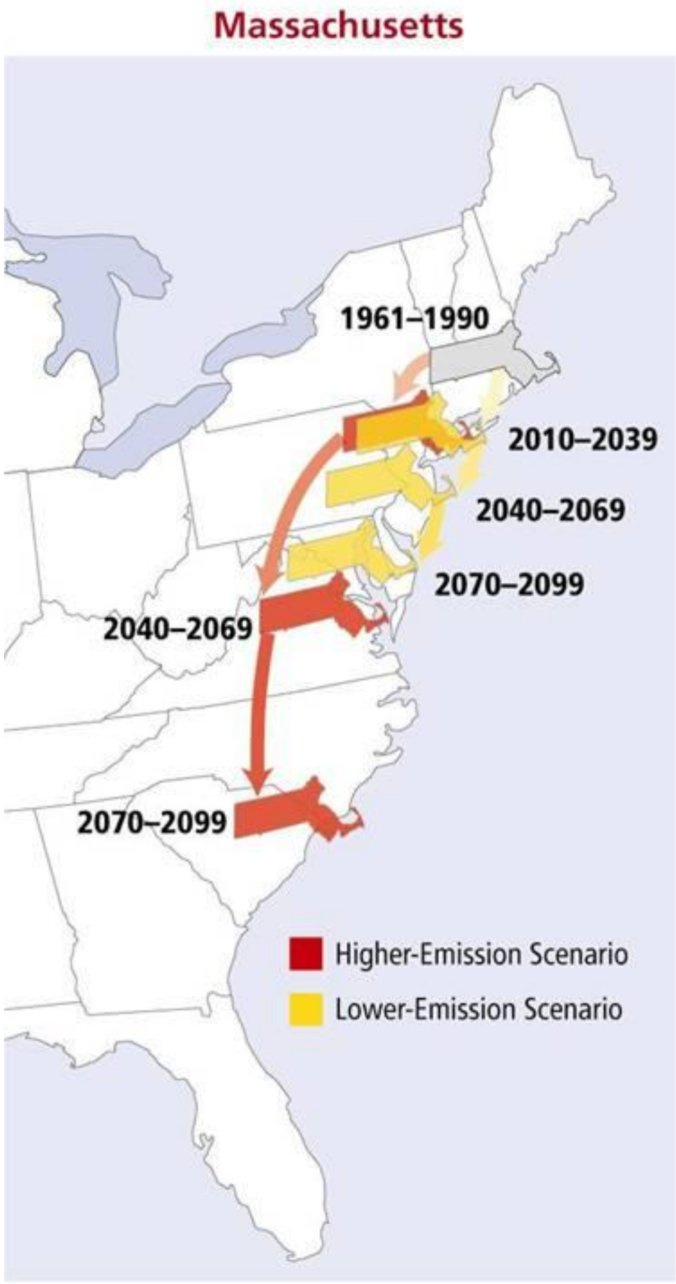
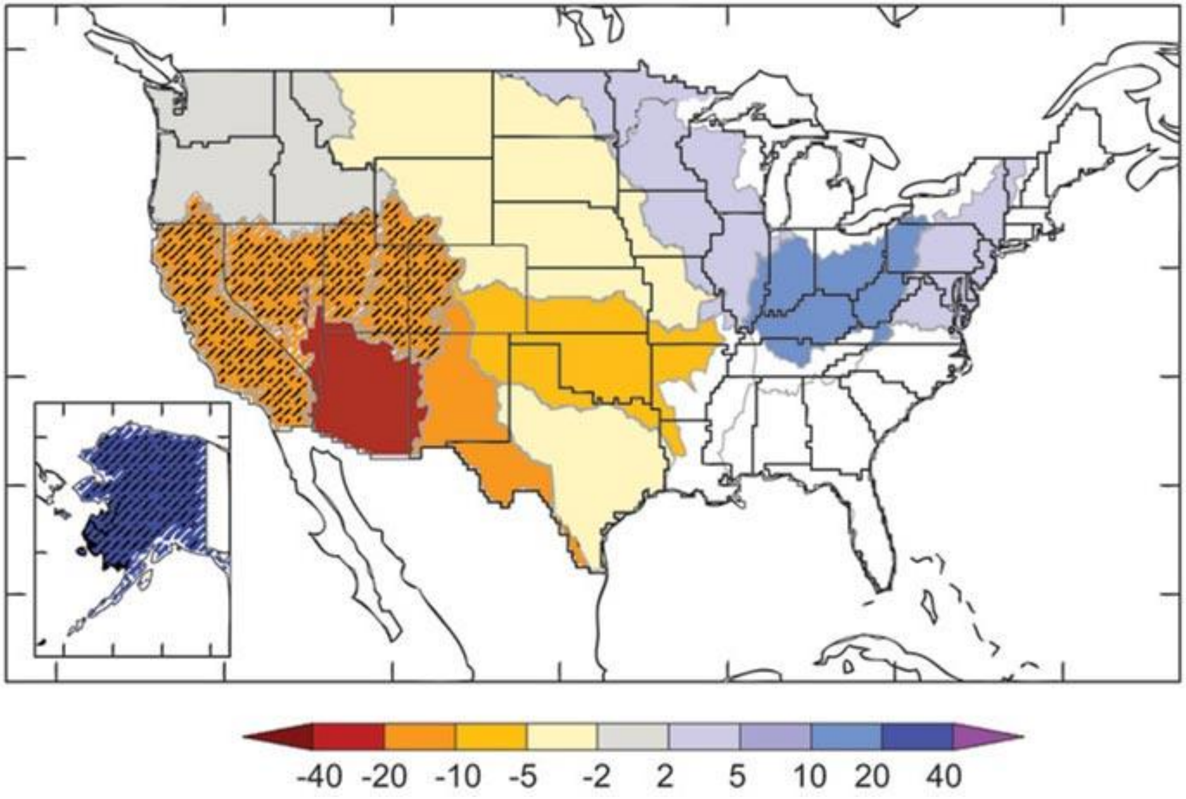


Figure from James McCarthy, Harvard

NECIA, 2007 (see: www.climatechoices.org/ne/)

Uncertainty across climate models



Projected Percent Changes in Annual Runoff, 2041-60 vs. 1901-70

Source: globalchange.gov/usimpacts

Hatched areas: strong agreement among model projections.
White areas: divergence among model projections.
A middle-of-the-road emissions scenario is assumed.

Monsters behind the door

Steve Pacala calls the worst credible climate outcomes "monsters behind the door." The monsters include:

a five-meter rise in sea level by the end of this century

major alterations of the global hydrological cycle

major changes in forest cover

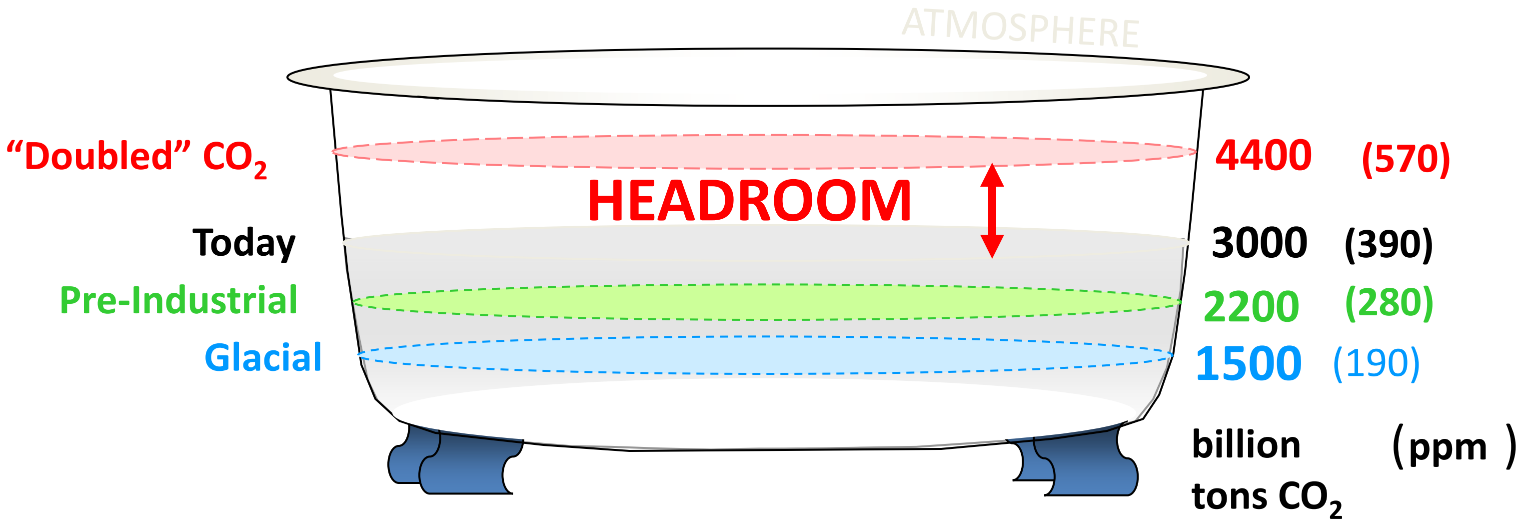
major emissions of greenhouse gases from the tundra.

The monsters open their door in a world of very strong positive feedbacks, a world that spirals out of control.

Today's science cannot predict how much atmospheric change would let these monsters in, nor how quickly they could enter.

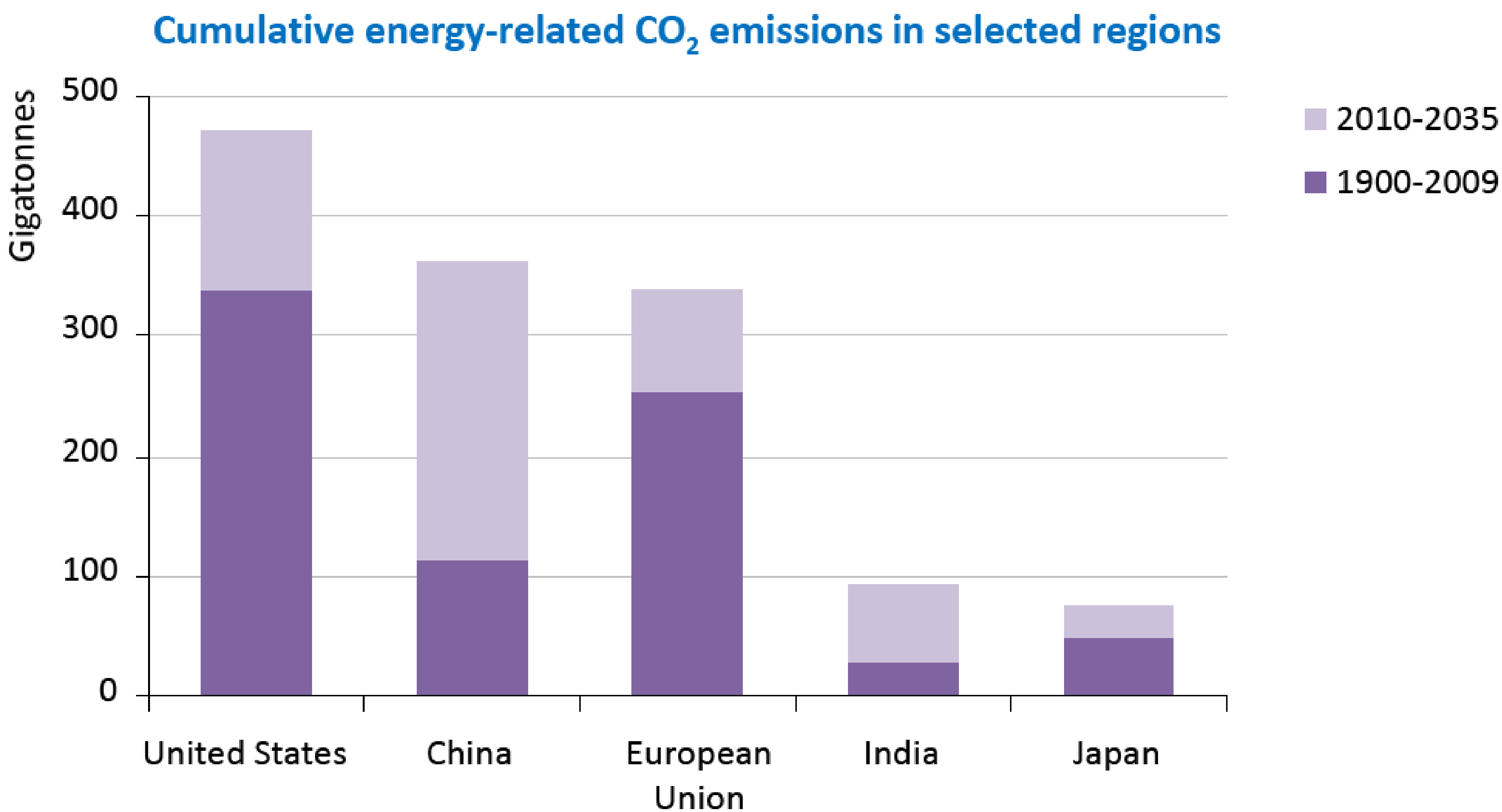
FUTURE EMISSIONS AND INEQUALITY

Past, present, and potential future levels of CO_2 in the atmosphere



Politics: Divide the headroom across the world's individuals alive today and still unborn.

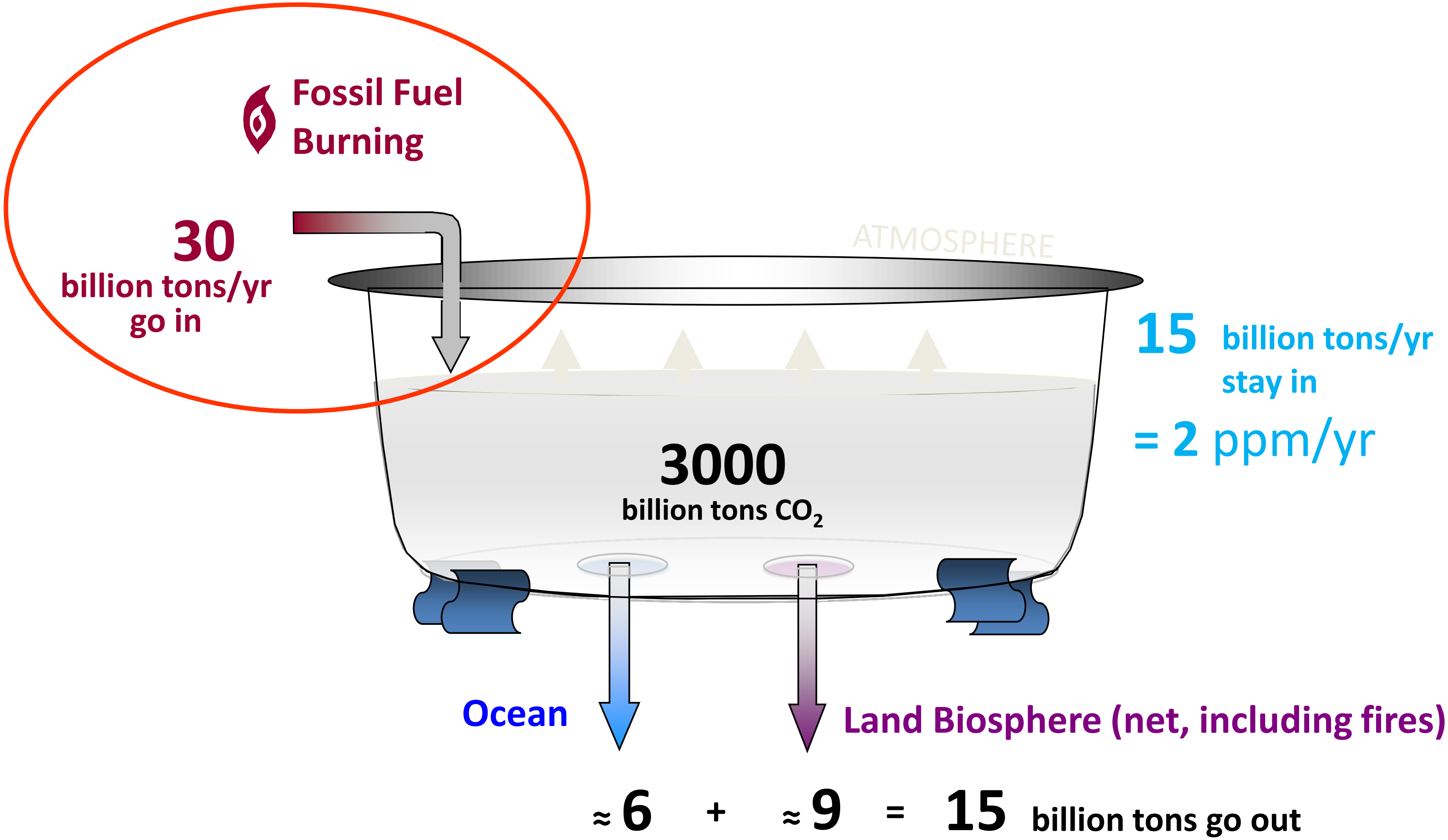
Cumulative emissions use up the headroom



By 2035, cumulative CO_2 emissions from today exceed three-quarters of the total since 1900, and China's per-capita emissions match the OECD average

Source: International Energy Agency, *World Energy Outlook 2011*

Sources and sinks of CO_2



Today, global per-capita emissions are ≈ 4 tCO_2/yr.

Four ways to emit 4 tonCO_2/yr (today's global per capita average)

Activity	**Amount producing 4 ton CO_2/yr emissions**
a) Drive	24,000 km/yr, 5 liters/100km
b) Fly	24,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	300 kWh/month when all coal-power (600 kWh/month, natural-gas-power)

Princeton University CO_2 in 2007

University emissions*	112,000 tCO_2
12,500 participants**	
Per-capita emissions	9 tCO_2

*On-site cogeneration plant, purchased electricity, fuel for University fleet.
**7,100 students and 5,400 employees

What about your university?

Climate change is a consequence of prosperity

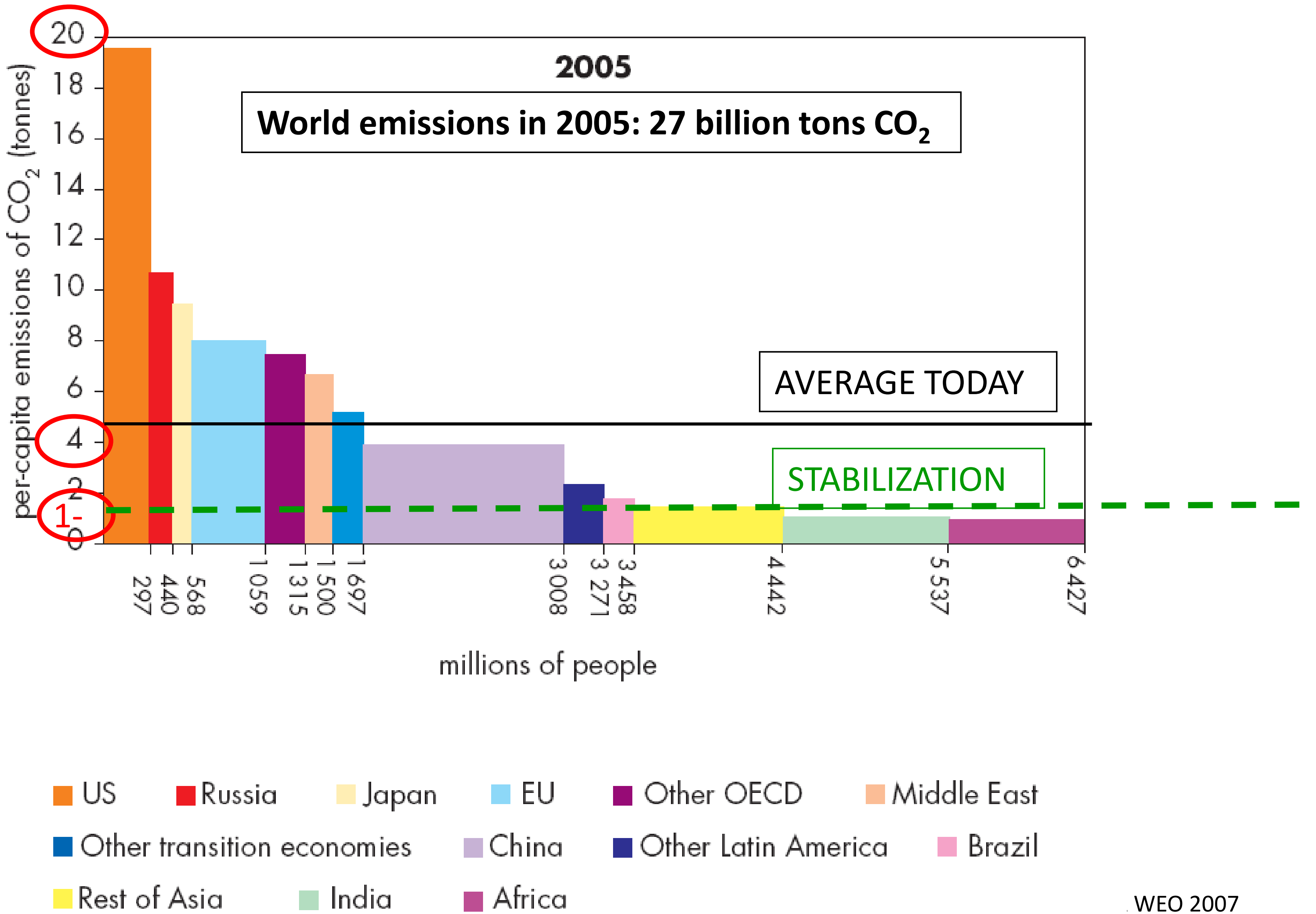
The CO_2 problem is a problem of modernity, a byproduct of choices about what to consume, how to spend time.

Today, it is nearly universally believed, a good life is one lived with exuberance.

We seek independence, privacy, safety, comfort, beauty, variety of experience – goals that can thwart low-consumption living.

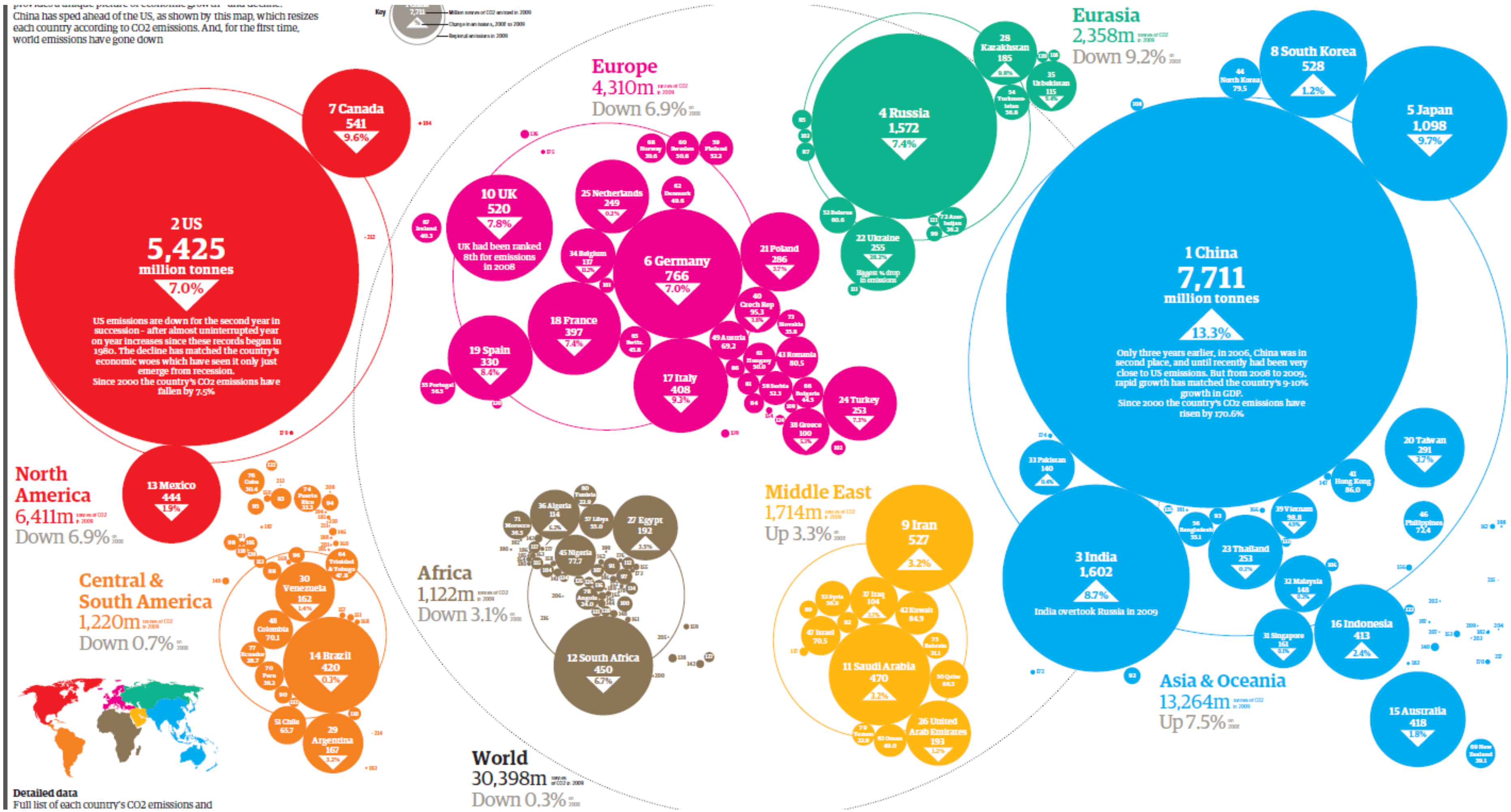
INEQUALITY AMONG NATIONS

Per-capita fossil-fuel CO_2 emissions, 2005



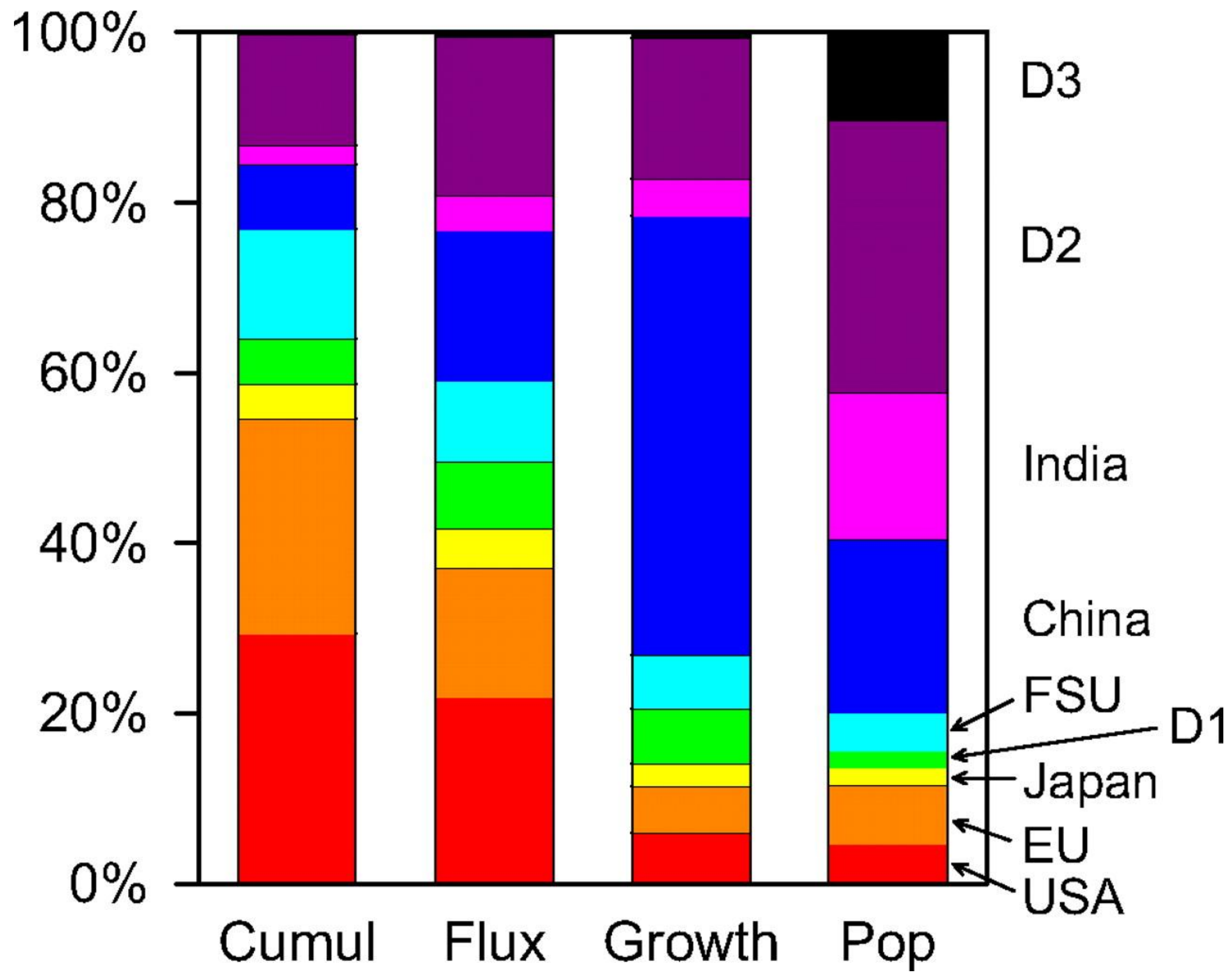
WEO 2007

The developing world will decide what kind of planet we live on



Global CO_2 Emissions, 2009

Source: EIA data; Guardian.co.uk "atlas of pollution"

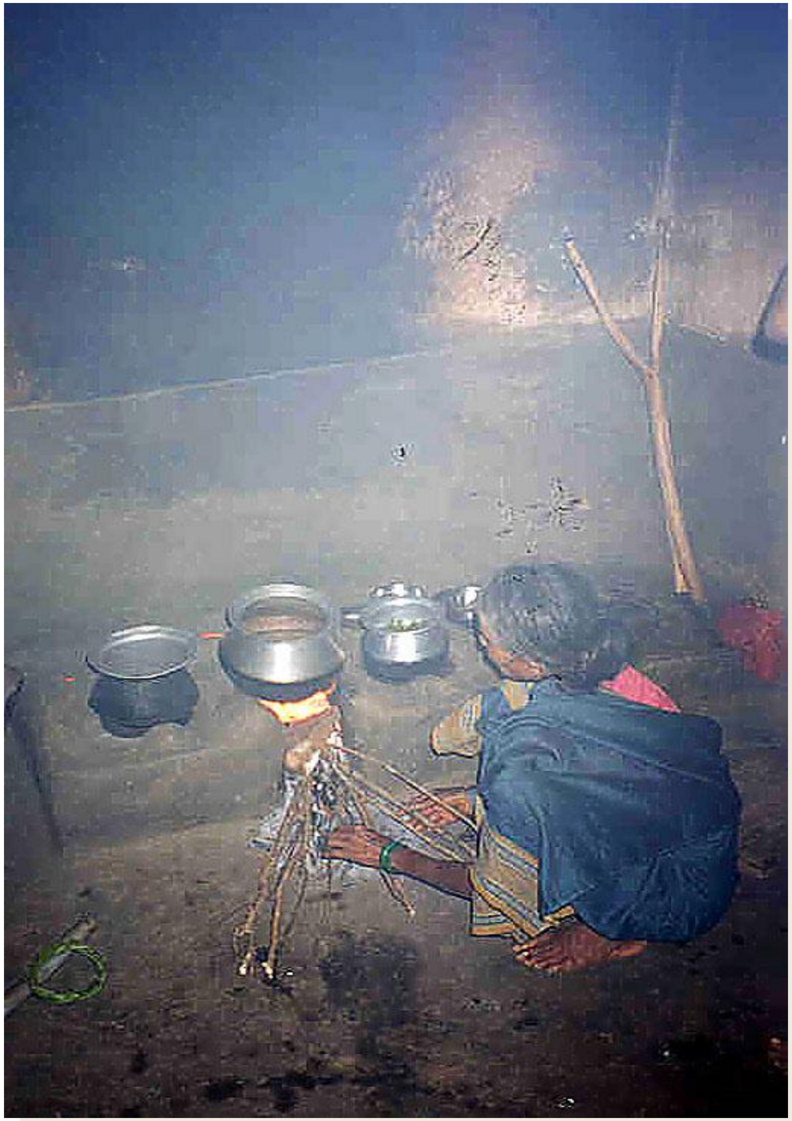


Relative contributions of nine regions to cumulative global emissions (1751–2004), current global emission flux (2004), global emissions growth rate (5 year smoothed for 2000–2004), and global population (2004)

Source: Raupach M. R. et.al. PNAS 2007;104:10288-10293

COMBUSTION AND THE VERY POOR

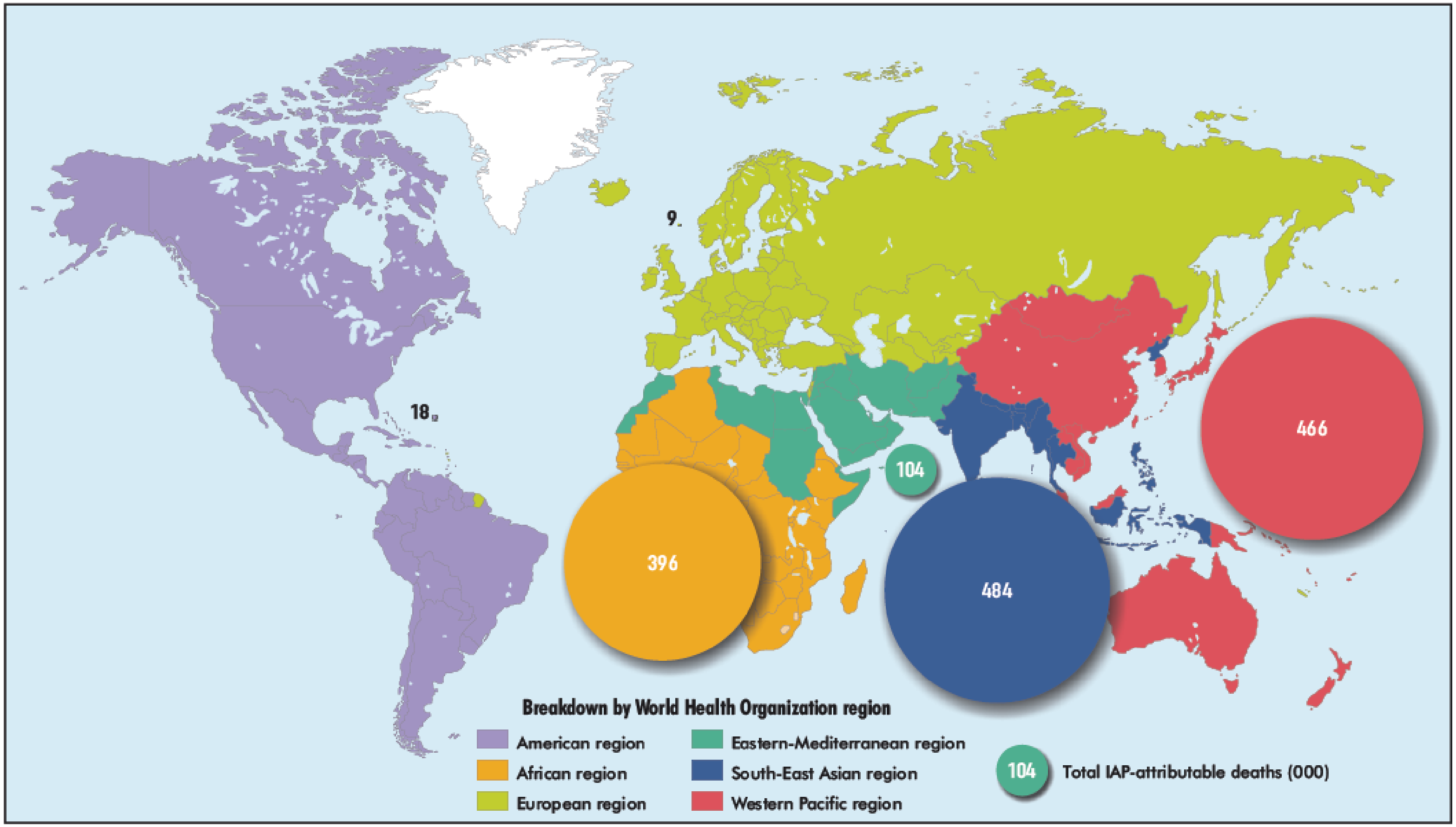
Fuels for Cooking and Indoor Air Pollution



Indoor air pollution from incomplete combustion is the single largest health impact of energy production and use.

Respiratory disease from cooking with traditional fuels kills over two million people annually in India alone

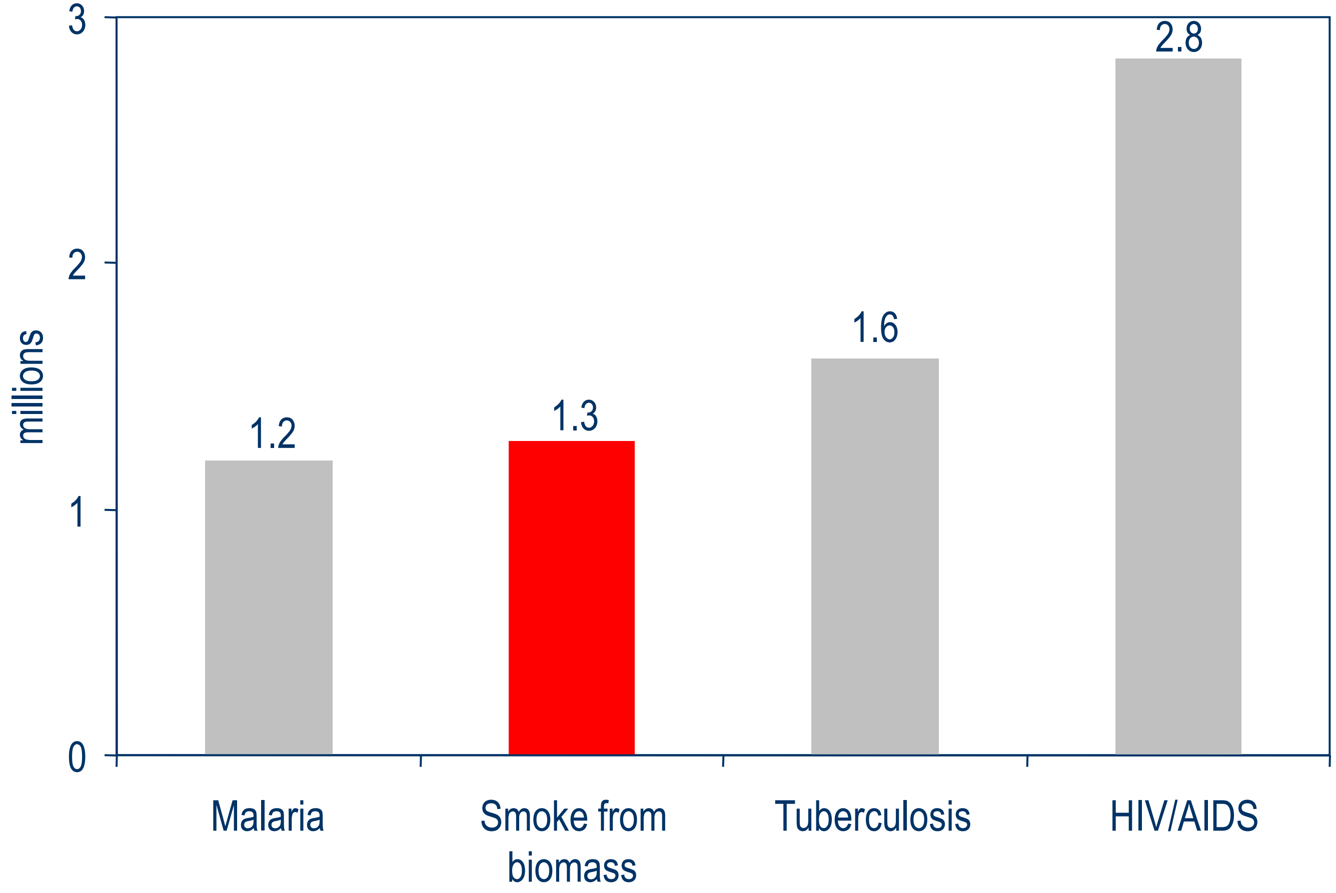
Deaths per year caused by indoor air pollution



Exposure to indoor air pollution from inefficient biomass use causes 1.3 million deaths per year, 70% in developing Asia

Source: International Energy Agency, *World Energy Outlook 2006*

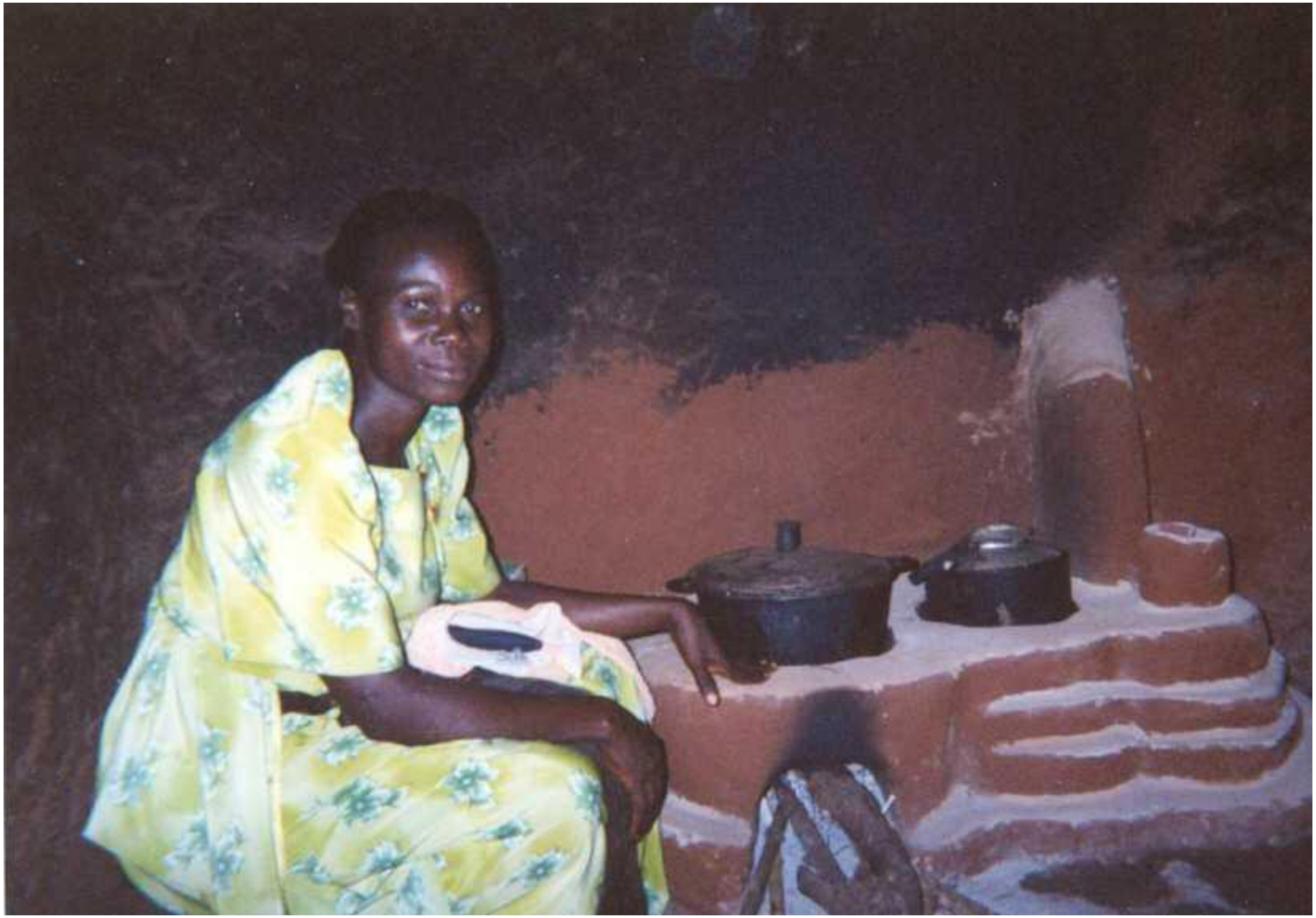
Energy Poverty: Annual Deaths from Indoor Air Pollution



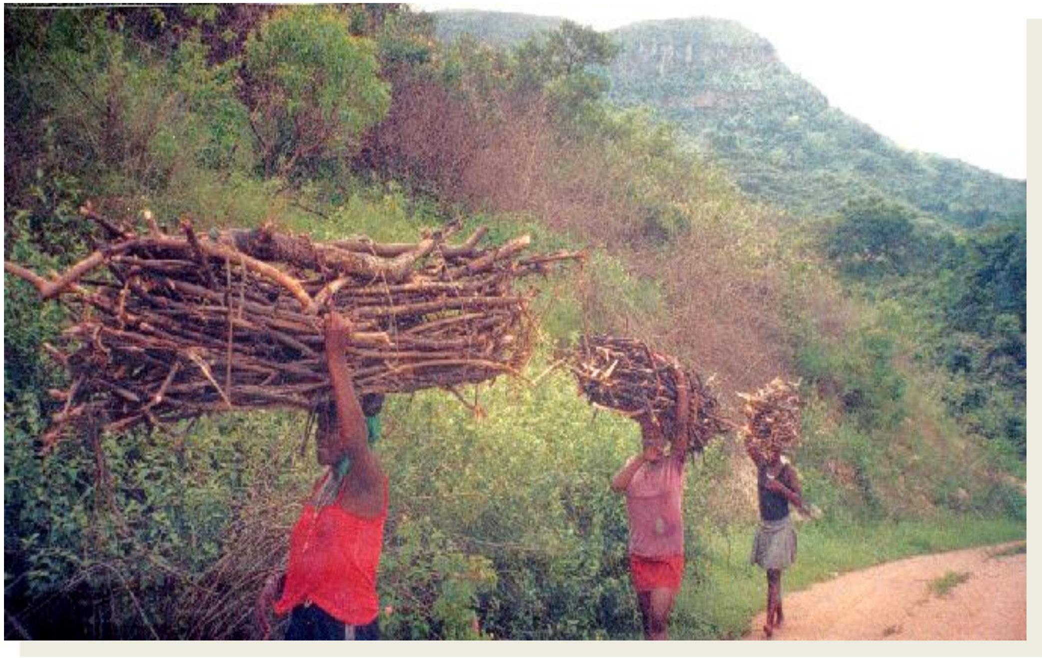
The number of people using dirty traditional biomass for cooking is set to grow from 2.5 billion now to 2.7 billion in 2030 absent new policies

Source: International Energy Agency, *World Energy Outlook 2006*

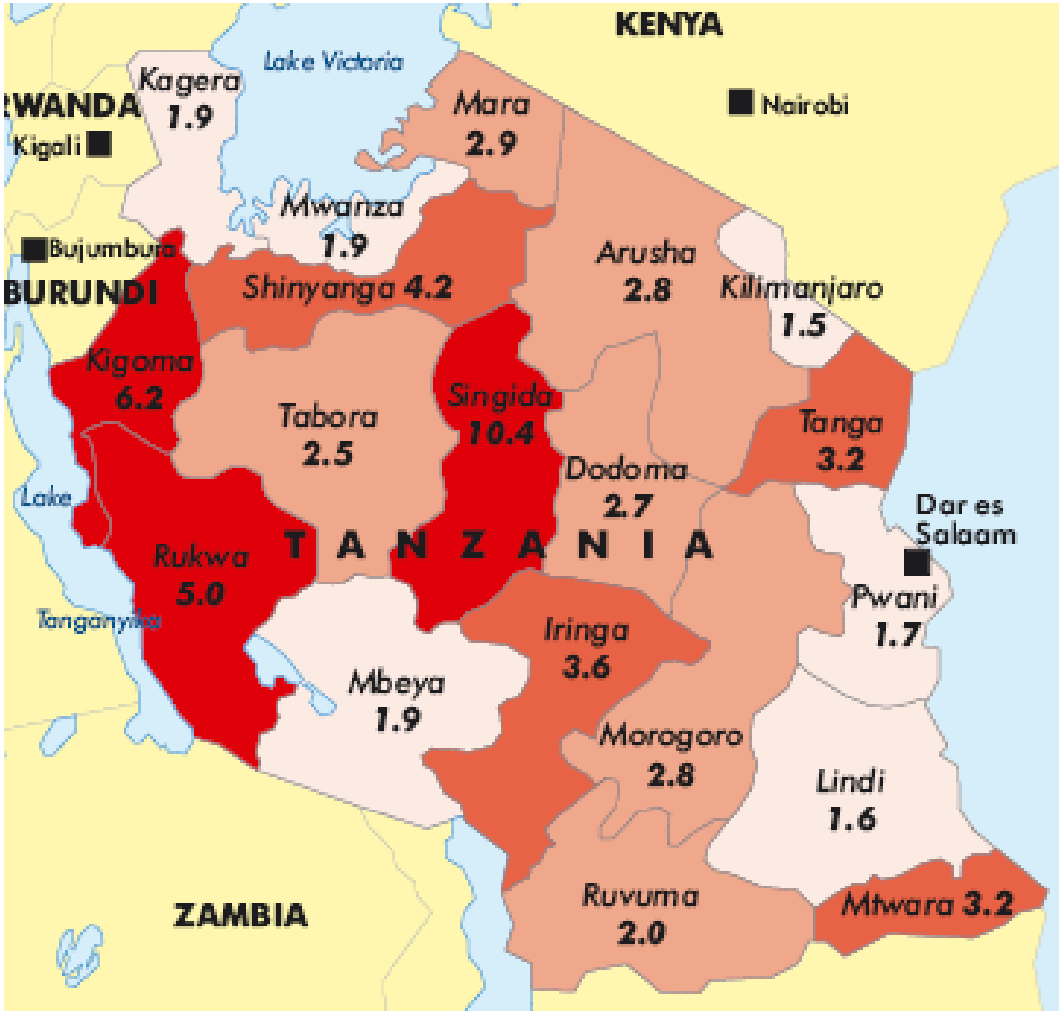
Improved combustion and venting



Rural Energy: Traditional Fuels

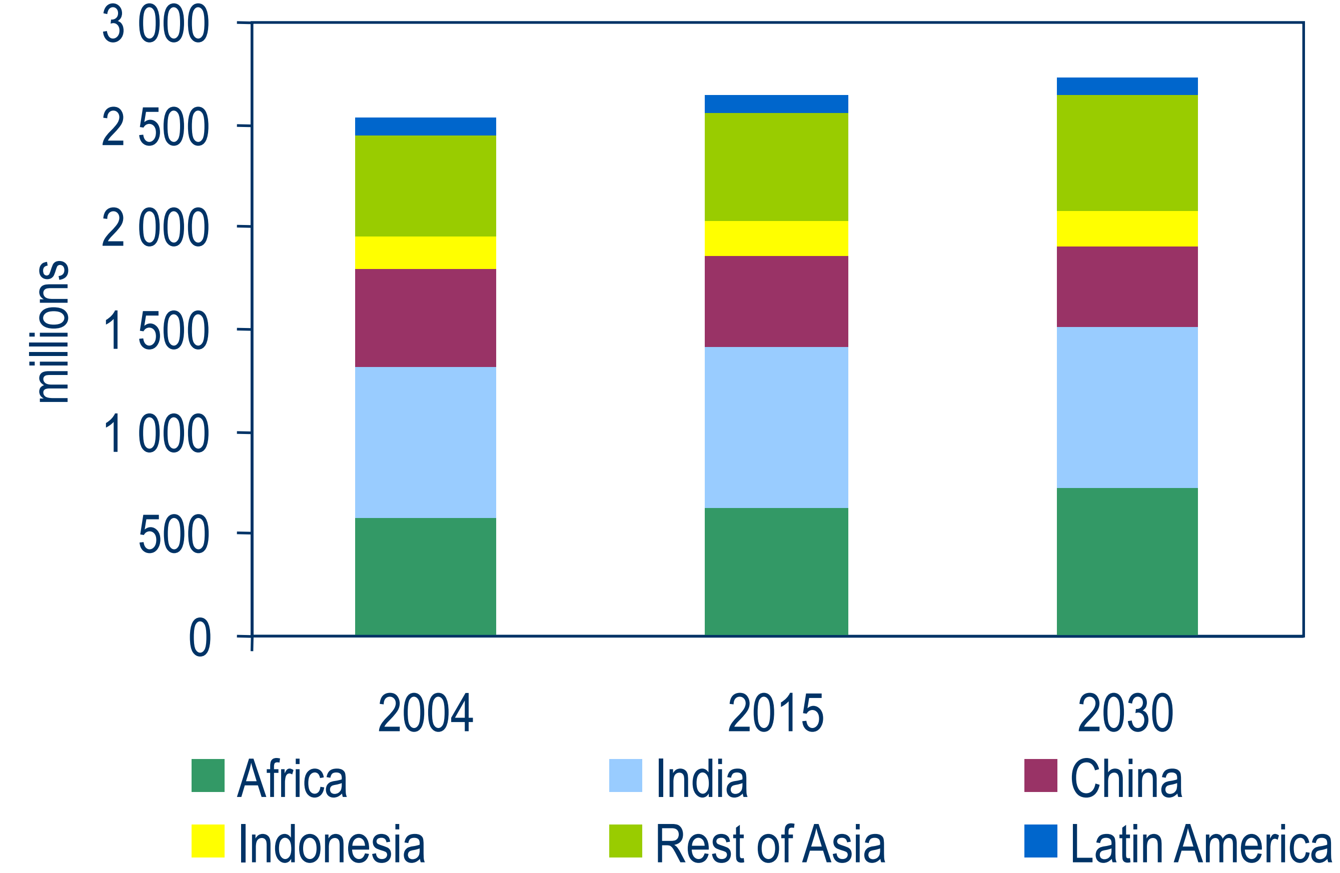


Distance travelled (kilometers) to collect fuelwood in rural areas



Source: International Energy Agency, *World Energy Outlook 2006, p. 430*

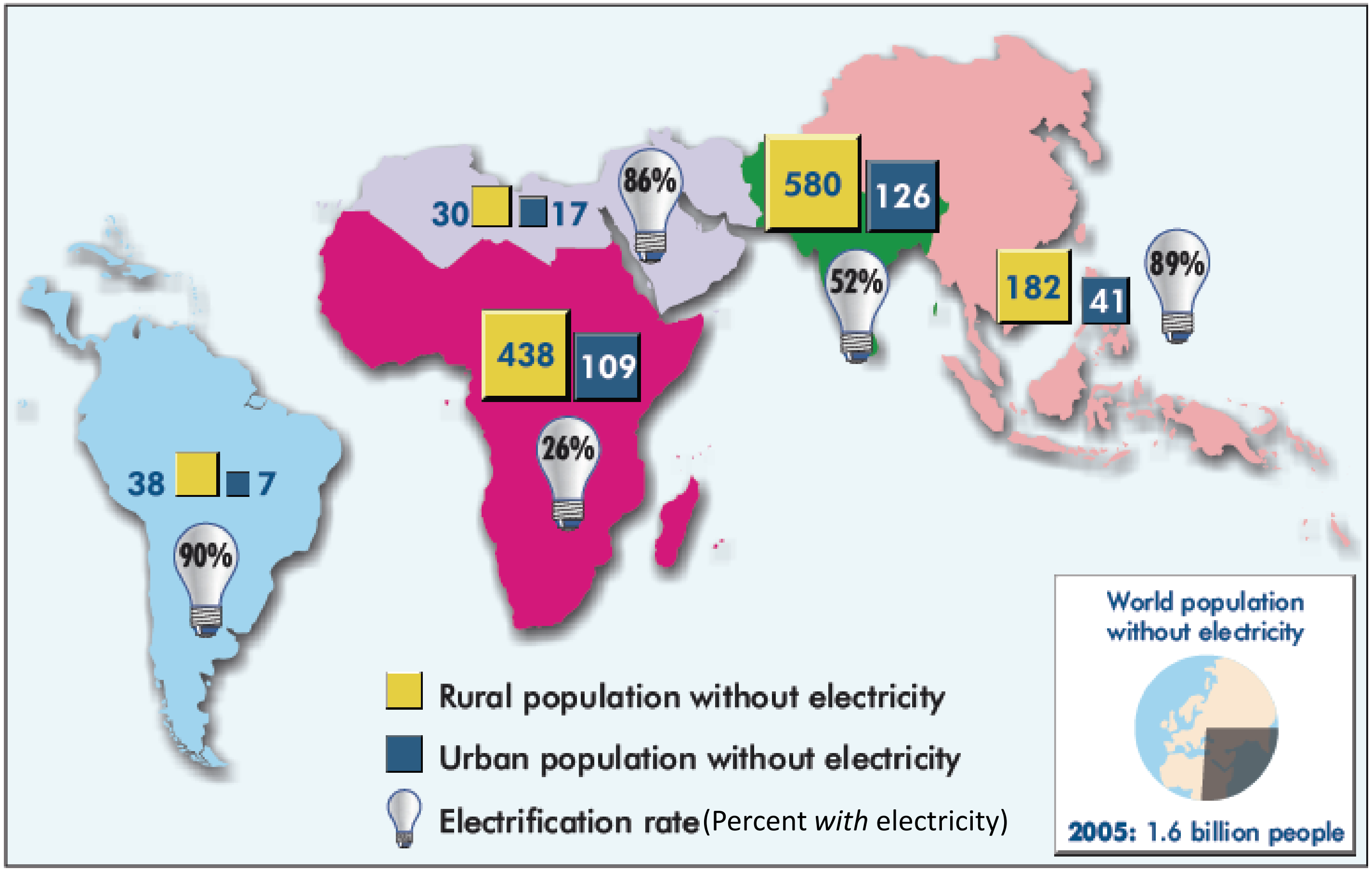
People Relying on Traditional Biomass for Cooking



The population relying on traditional biomass is set to increase from 2.5 billion today to 2.7 billion in 2030

Source: International Energy Agency, *World Energy Outlook 2006*

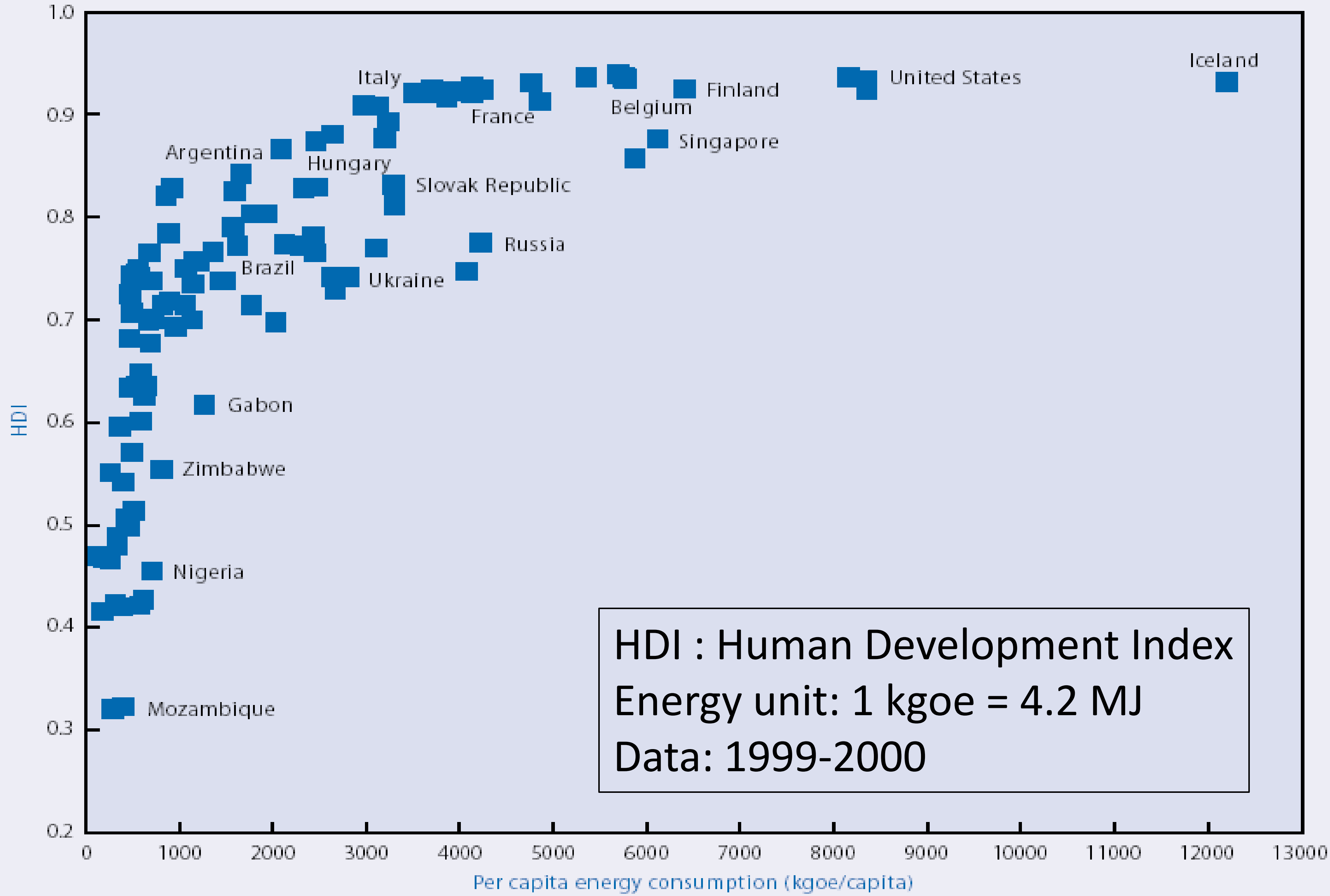
Population without electricity, 2005



To achieve the Millenium Development Goals, the number of people without access to electricity would need to fall to under a billion by 2015

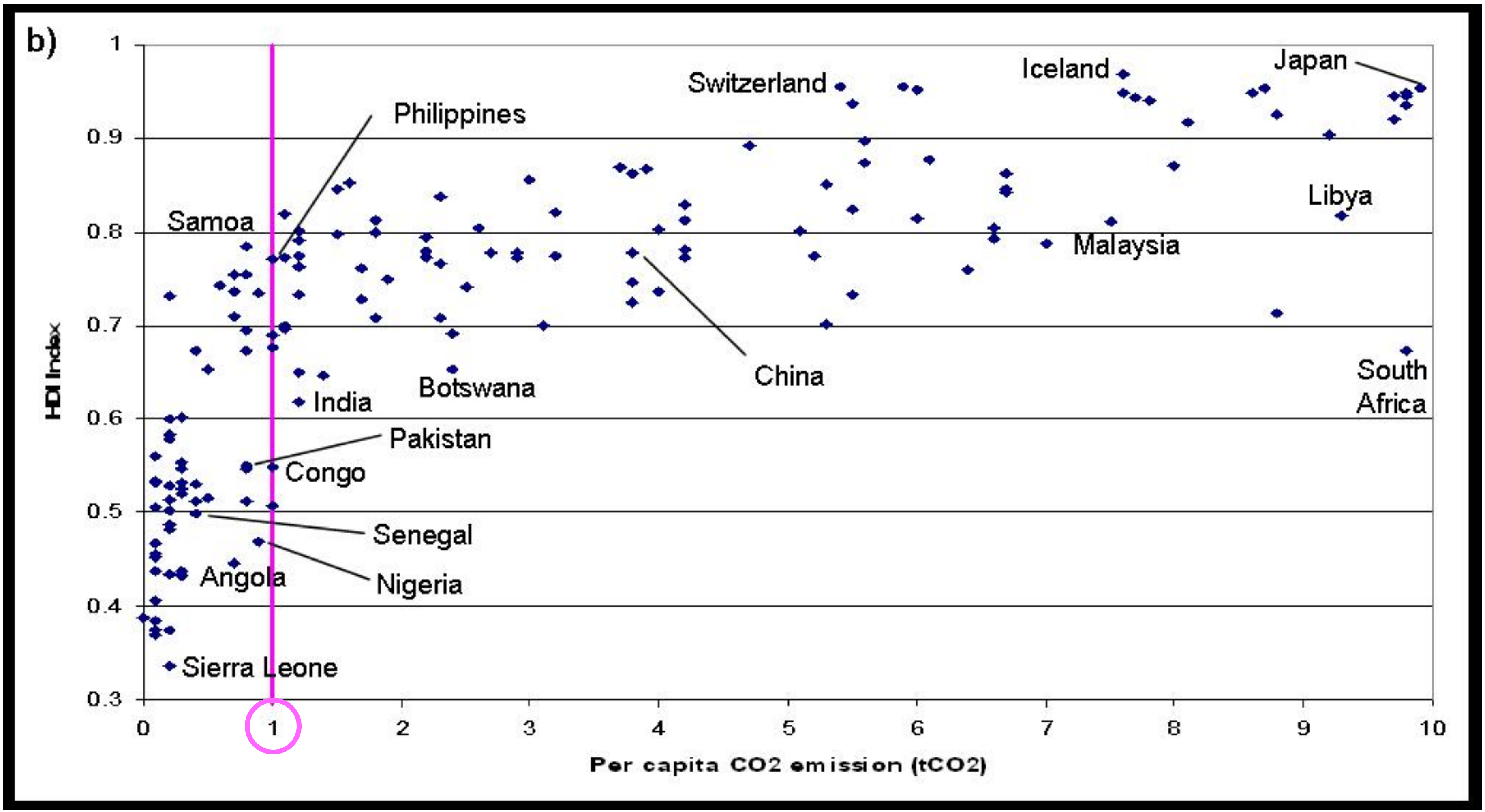
Source: International Energy Agency, *World Energy Outlook 2006, p. 156*

FIGURE 3. RELATIONSHIP BETWEEN HDI AND PER CAPITA ENERGY USE, 1999/2000



HDI : Human Development Index
Energy unit: 1 kgoe = 4.2 MJ
Data: 1999-2000

Per capita CO_2 vs the U.N.'s Human Development Index



What does 1 tCO_2/person-yr allow?

Direct Energy Use	*Household rate of use (4.5 people)*	*Individual emissions ($kgCO_2$/yr)*
Cooking	1 LPG canister per month	120
Transport	70 km by bus, car, motorbike per day	220
Electricity	800 kWh per year	160
Total		*500*

1 tCO_2/yr: Double the "direct" emissions to account for "indirect" emissions.

1 tCO_2/person-yr exceeds the emissions of two billion people!

“ONE BILLION HIGH EMITTERS”:

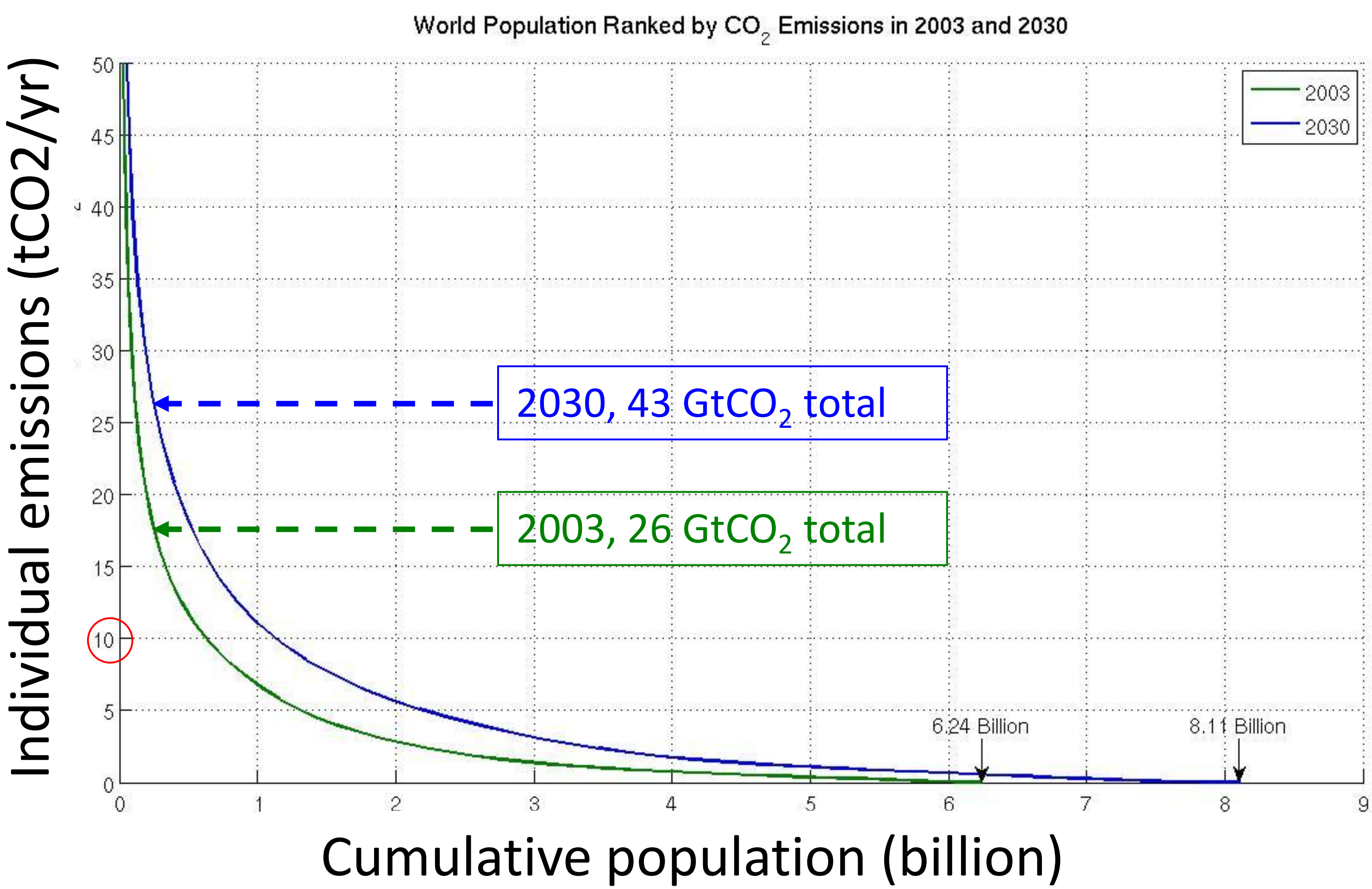
A SCHEME TO ALLOCATE NATIONAL EMISSIONS REDUCTIONS BASED ON INDIVIDUAL EMISSIONS

A new definition of fairness

In the international agreements about climate change established in 1992, "*common but differentiated responsibilities*" is the key phrase. Industrialized countries ("Annex One countries") are differentiated from developing countries. Annex One countries are required to reduce emissions. Developing countries get an indefinite pass.

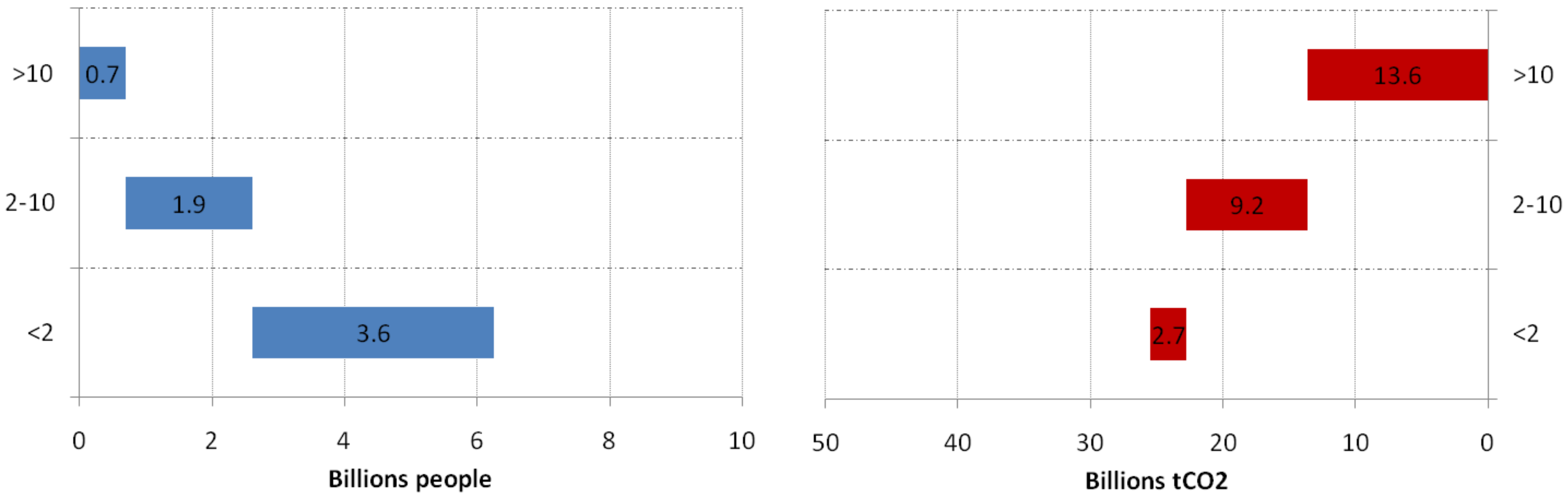
What if "common but differentiated responsibilities" were to refer to *individuals*, instead of nations? Wealthy *individuals* are required to reduce emissions, wherever they live.

CO_2 emissions distribution across the world's individuals



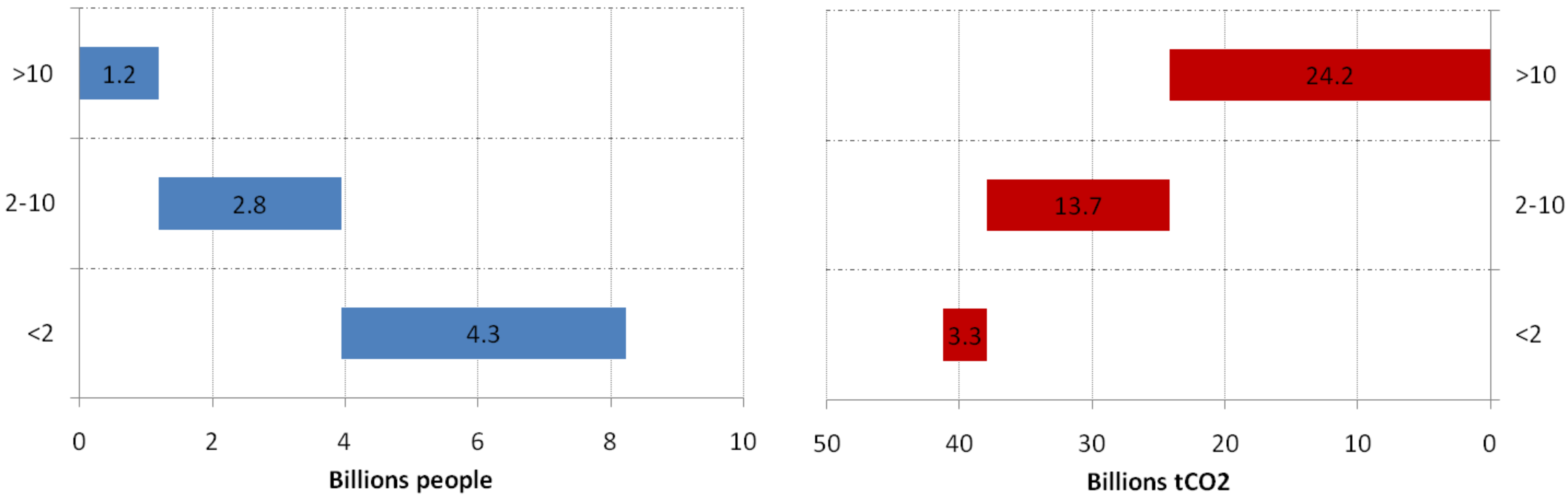
"One-billion high emitters," ***PNAS,*** **2009.** ***Co-authors*****: Shoibal Chakravarty, Ananth Chikkatur, Heleen de Coninck, Steve Pacala, Massimo Tavoni.**

Global population and emission distribution in 2003...



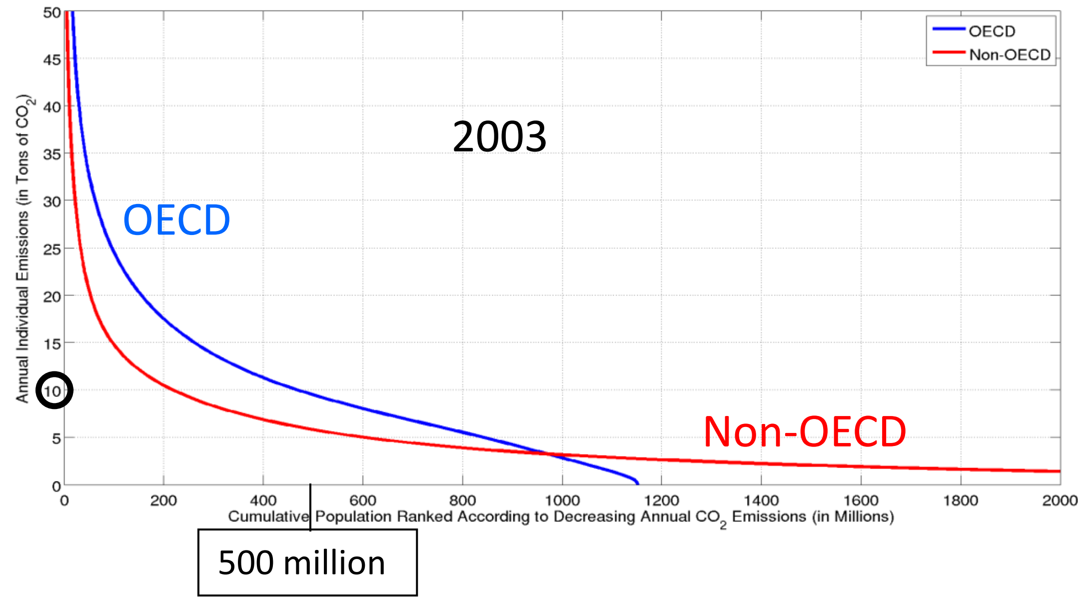
Source: Shoibal Chakravarty, private communication

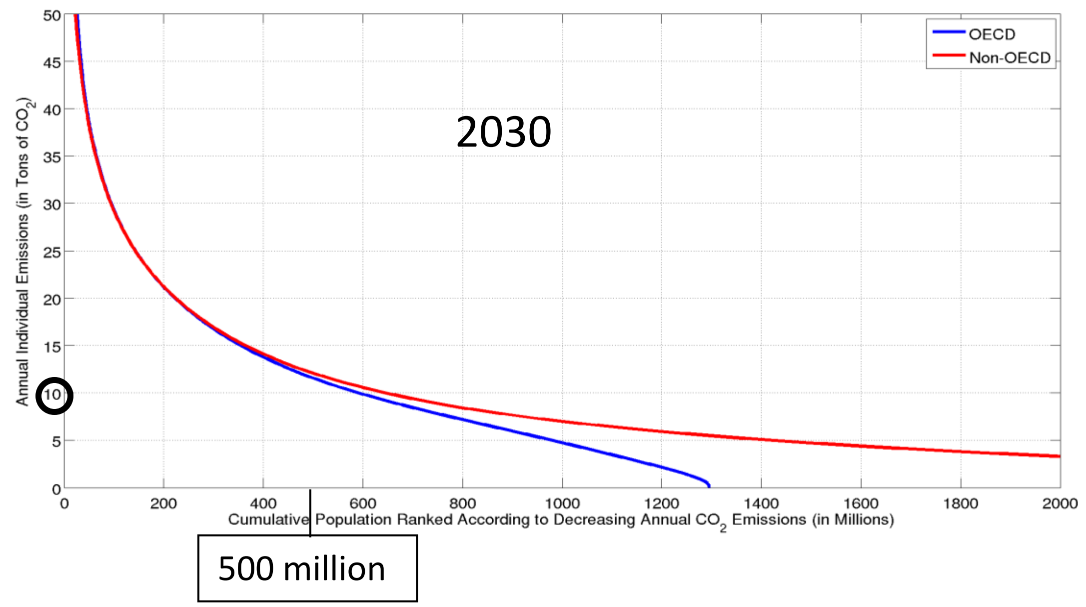
… and 2030



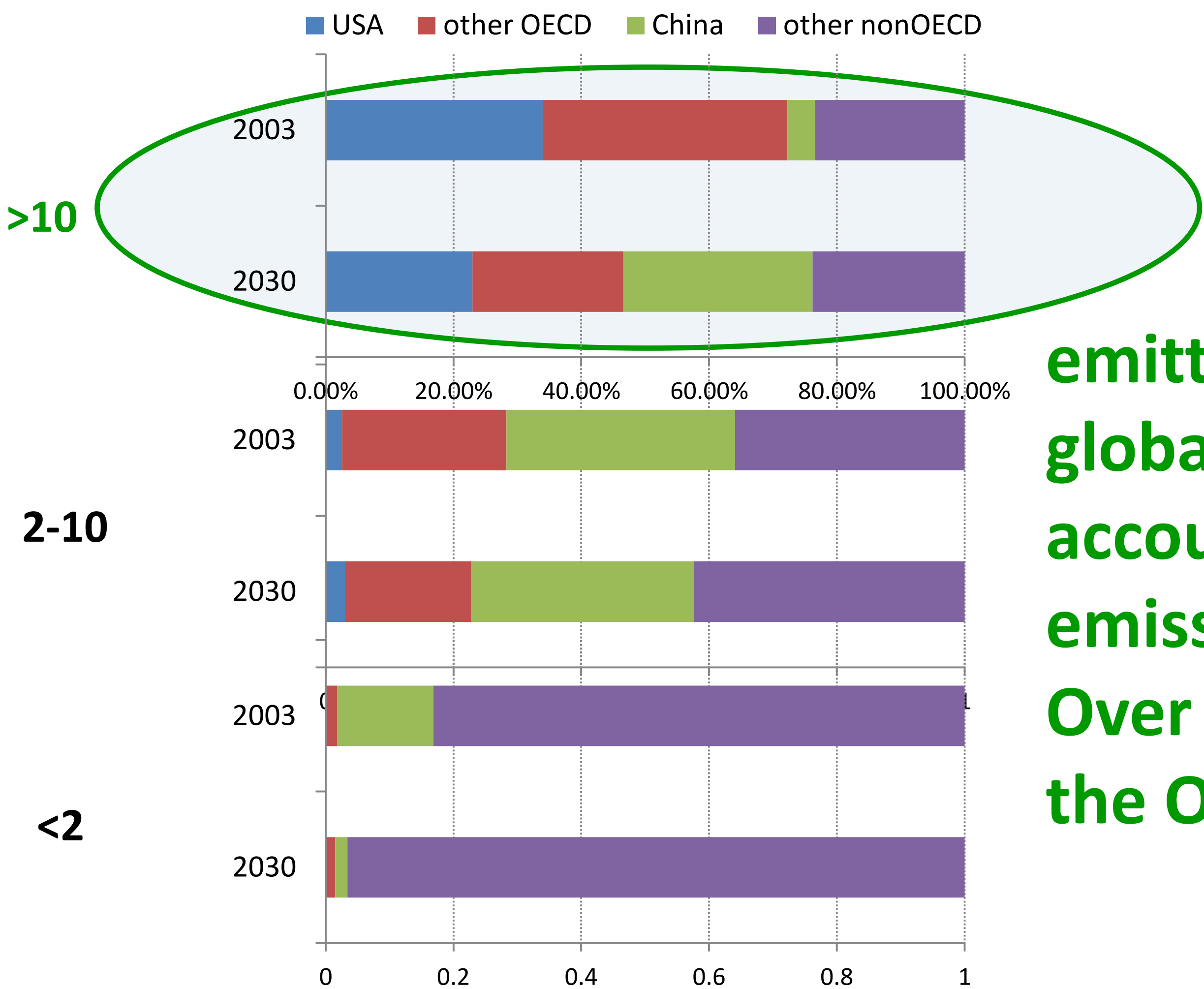
Source: Shoibal Chakravarty, private communication

Ever more high emitters outside the OECD





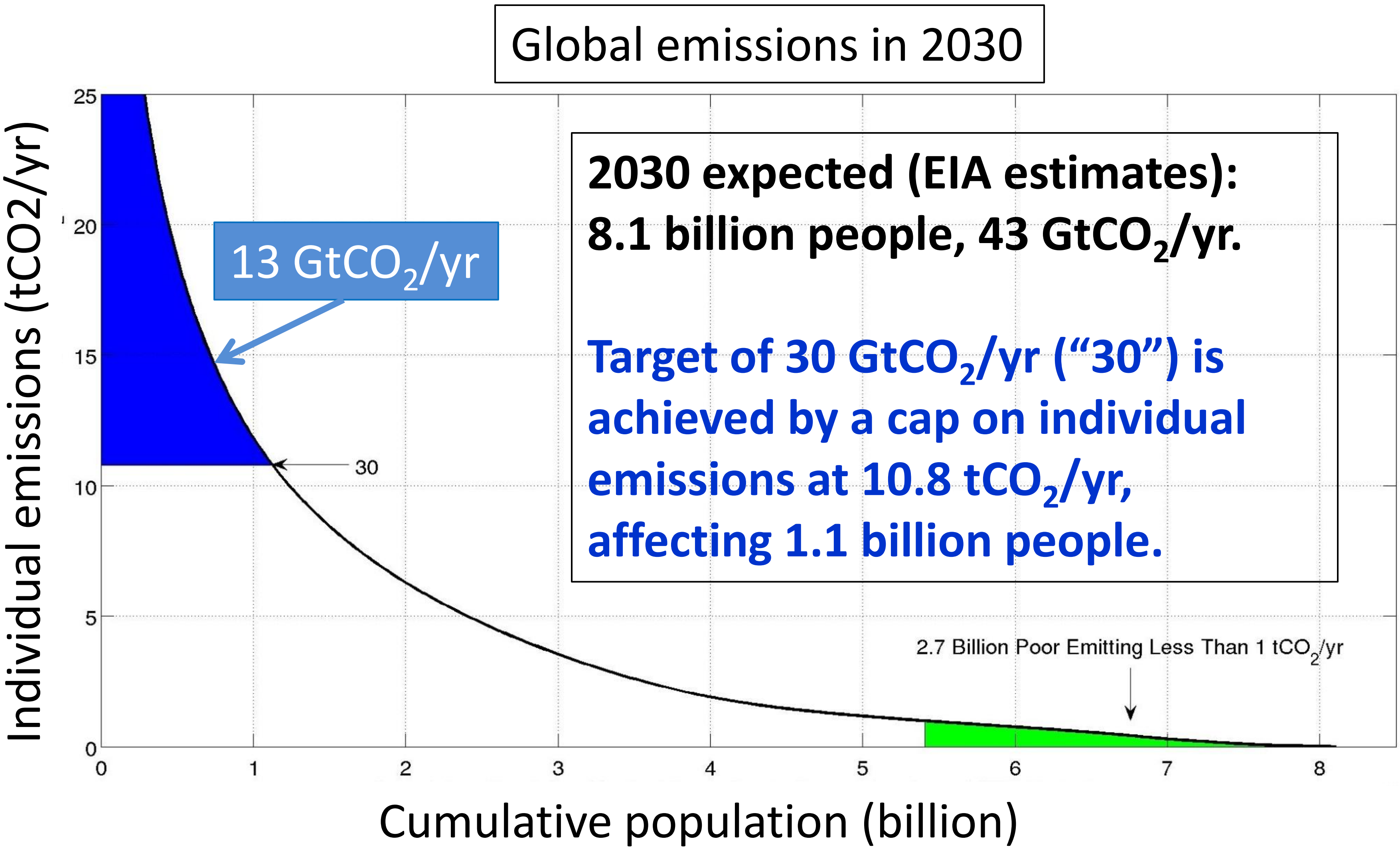
One billion "high-emitters"



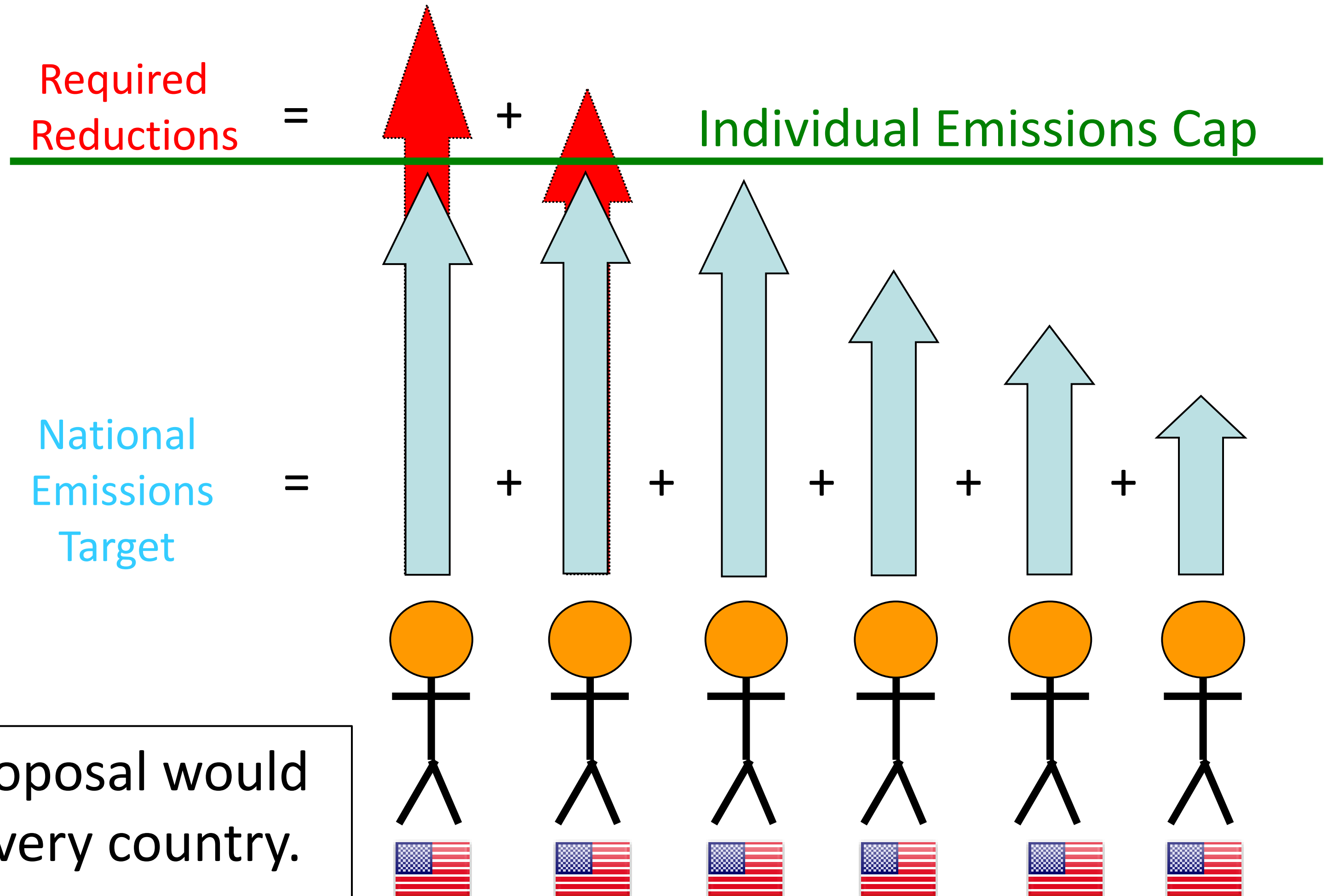
In 2030, "high-emitters" (15% of global population) account for 60% of emissions.
Over half live outside the OECD.

Estimated emissions of individuals in 2030, in tons CO_2/year

Allocation via a CO_2 emissions cap



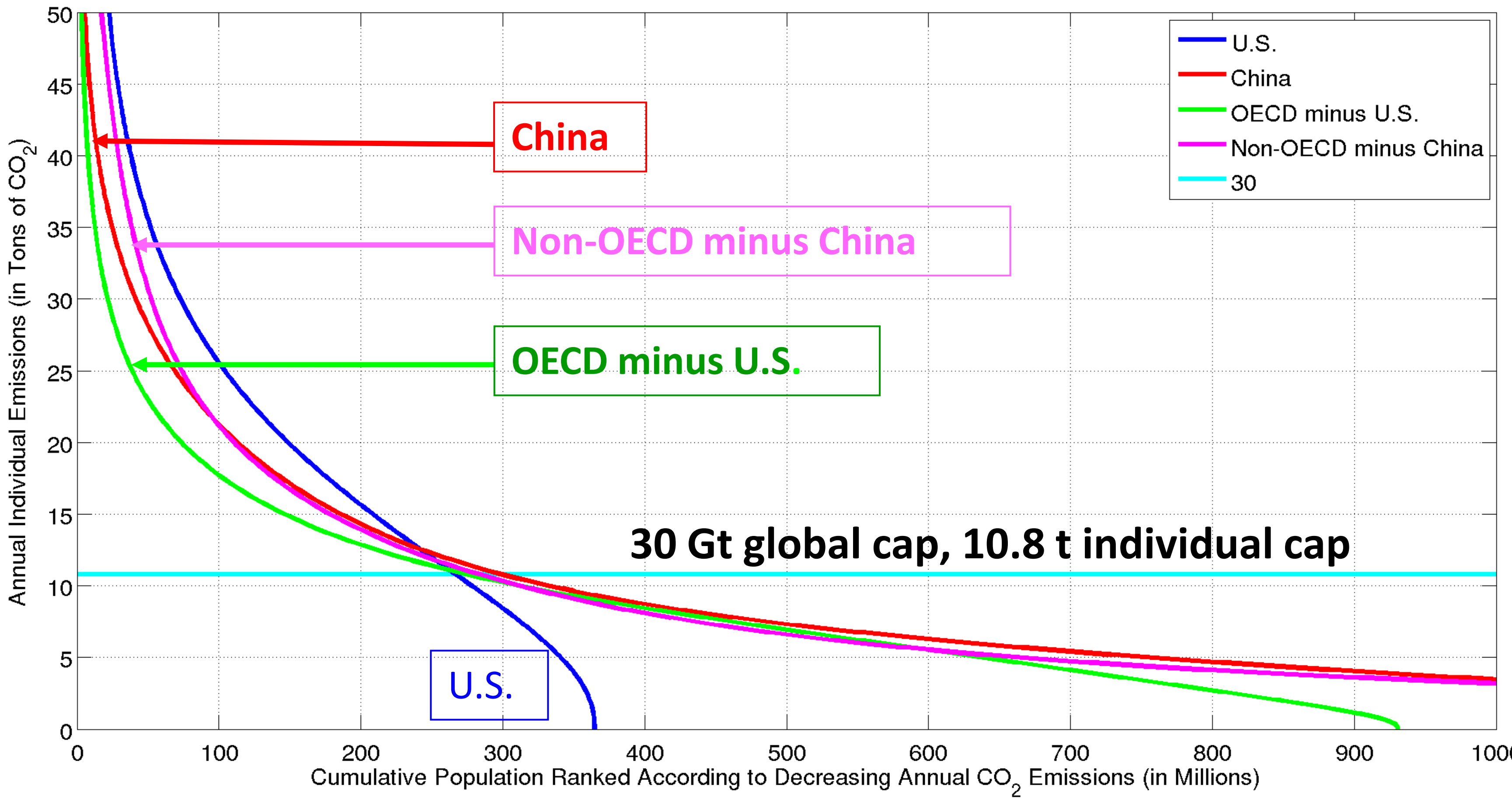
National accounting



The proposal would be to every country.

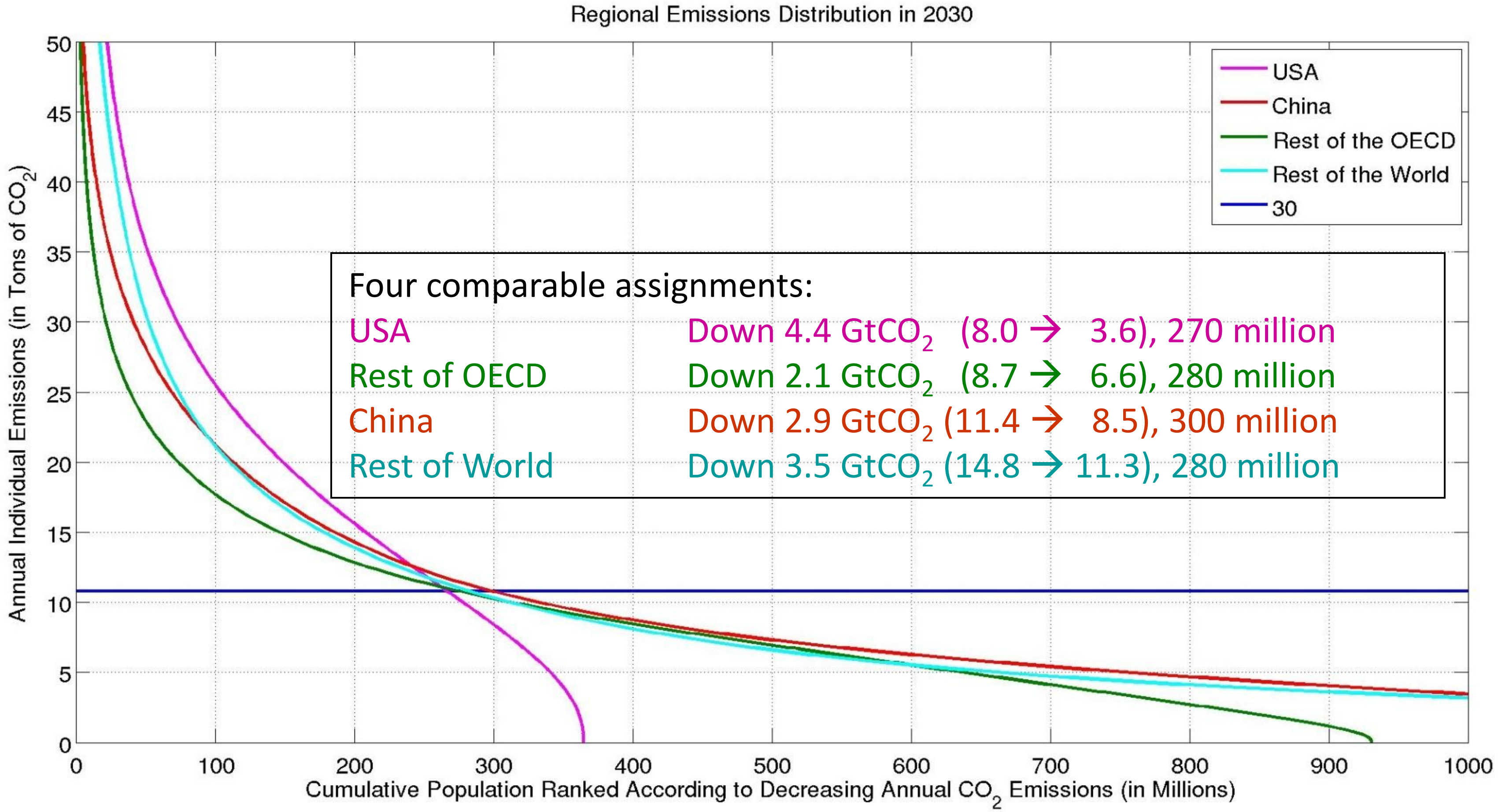
Source: Shoibal Chakravarty, private communication

Regional emissions in 2030



For a 30 $GtCO_2$ global cap in 2030, four regions have comparable assignments

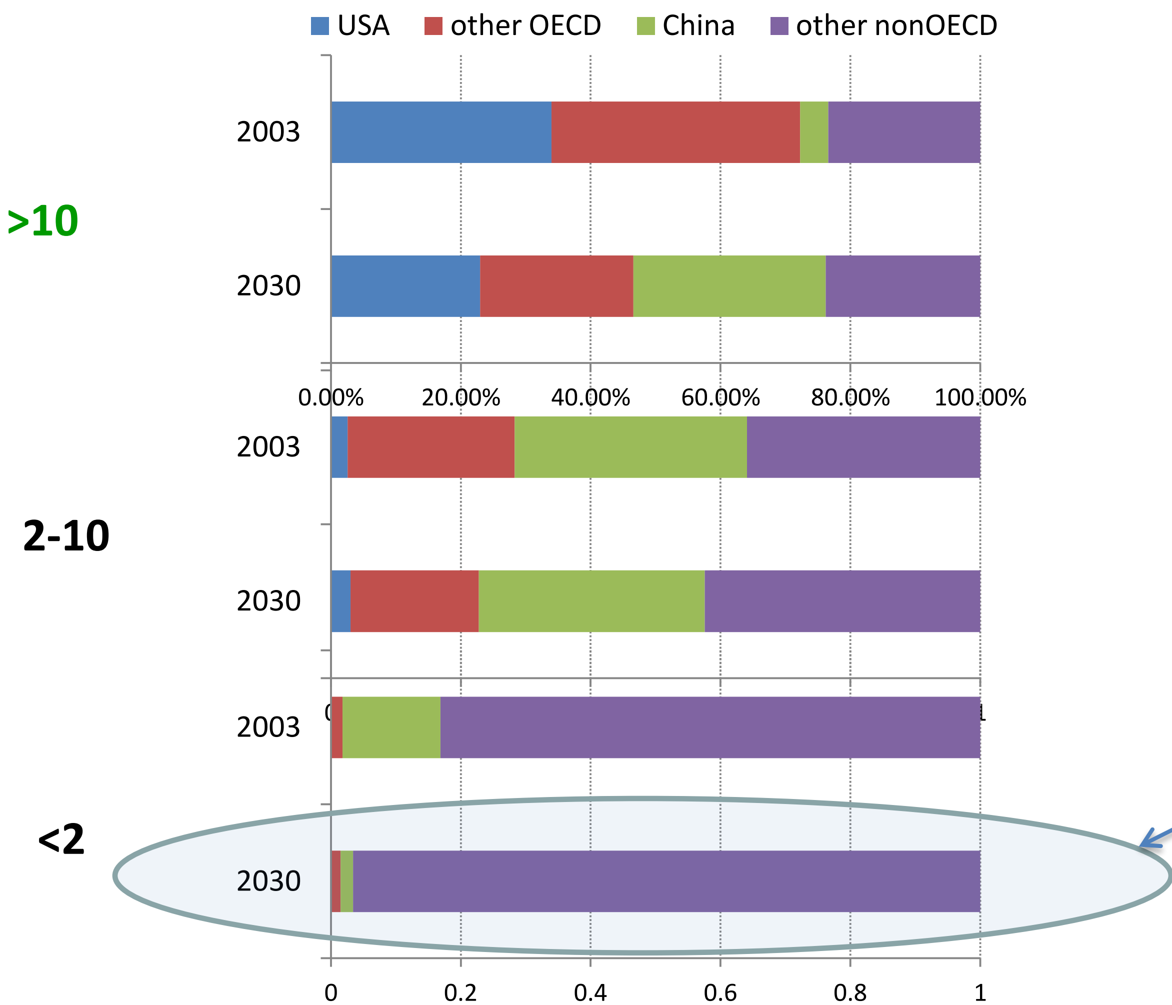
Four regions of the world have comparable assignments



Four comparable assignments:

USA	Down 4.4 $GtCO_2$ (8.0 → 3.6), 270 million
Rest of OECD	Down 2.1 $GtCO_2$ (8.7 → 6.6), 280 million
China	Down 2.9 $GtCO_2$ (11.4 → 8.5), 300 million
Rest of World	Down 3.5 $GtCO_2$ (14.8 → 11.3), 280 million

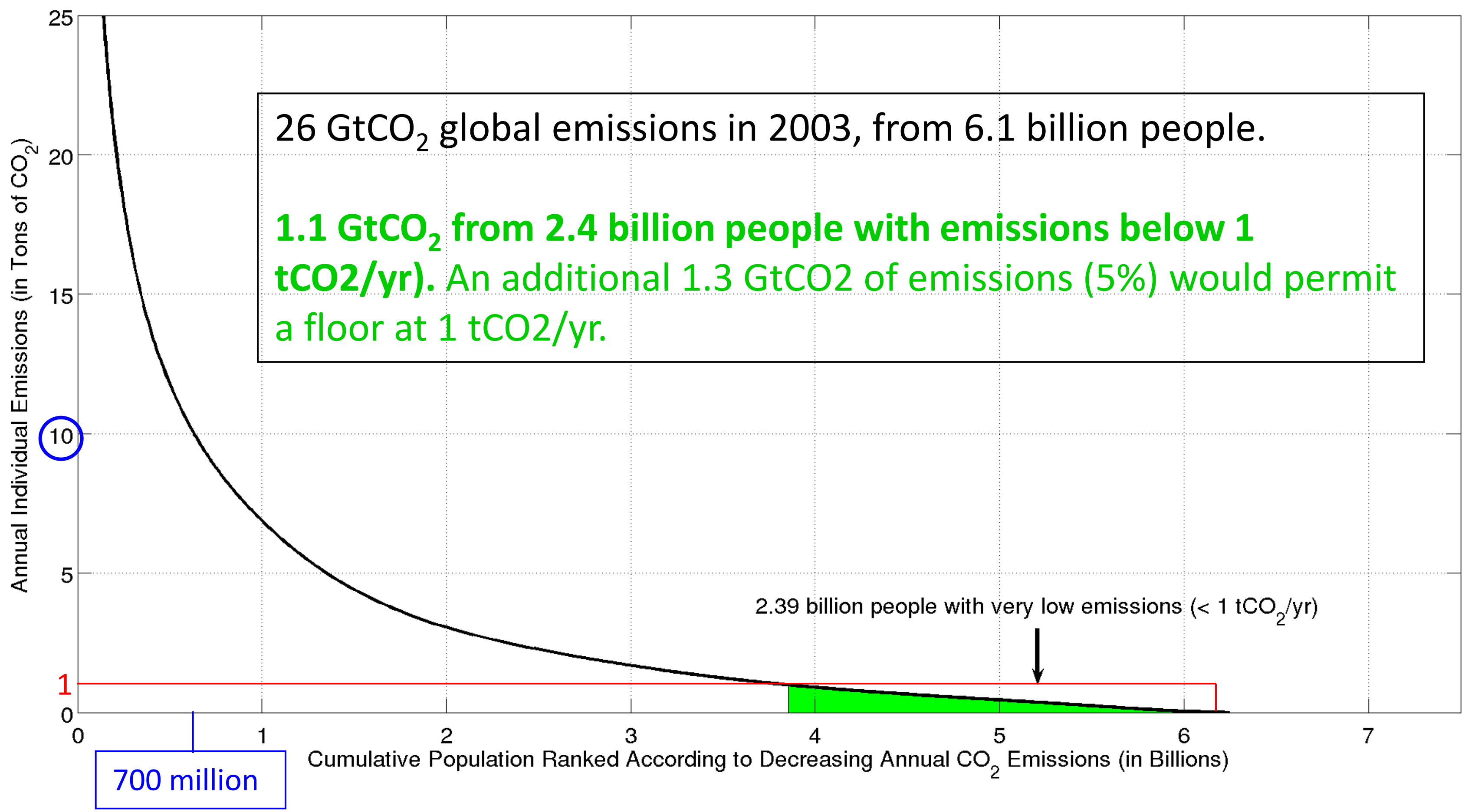
Four billion low emitters in 2030: Acceptable?



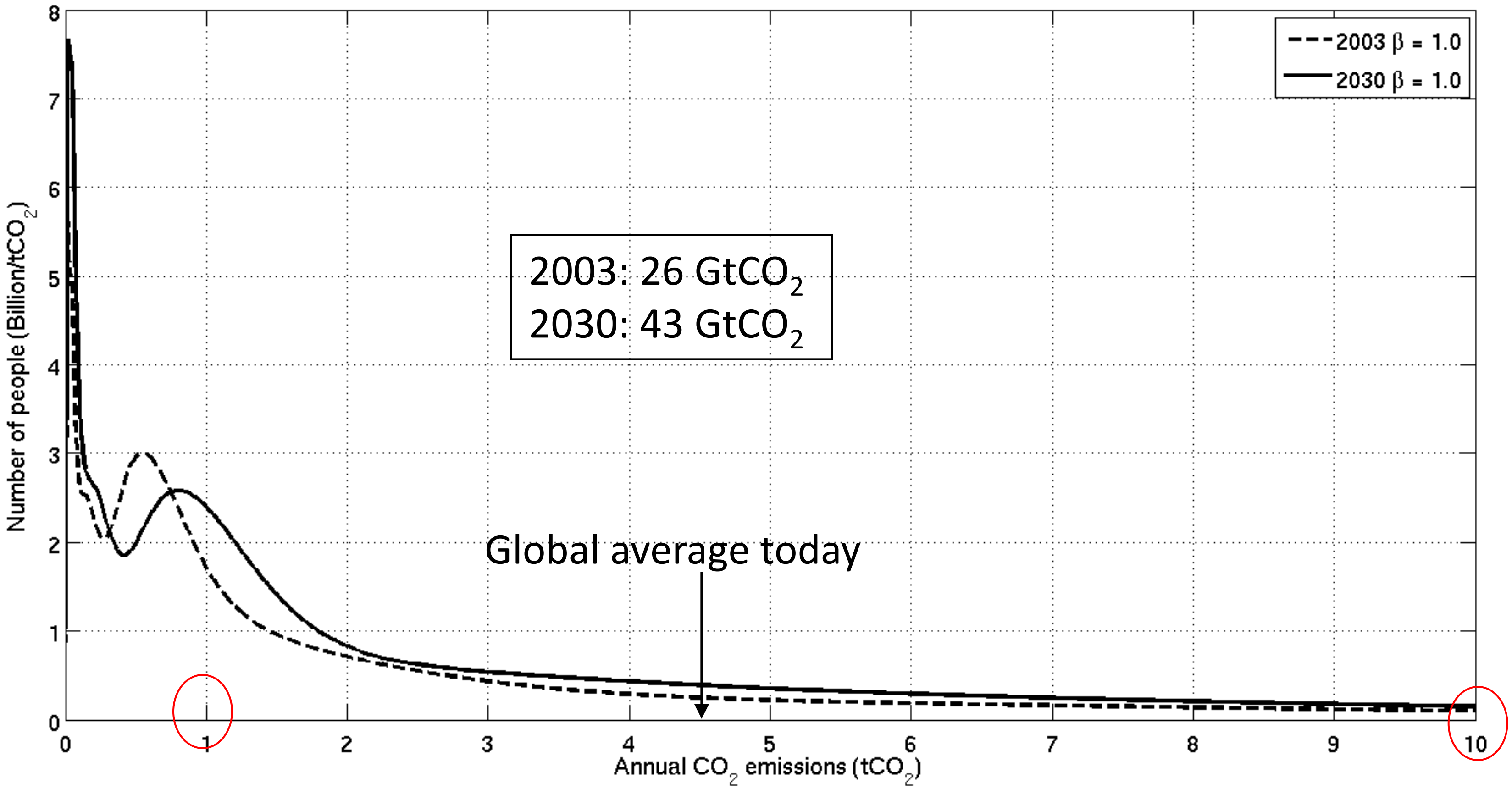
The lower half of the world's emitters in 2030, 8% of emissions.

Estimated emissions of individuals in 2030, in tons CO_2/year

The aggregate emissions of the world's poorest people today are negligible

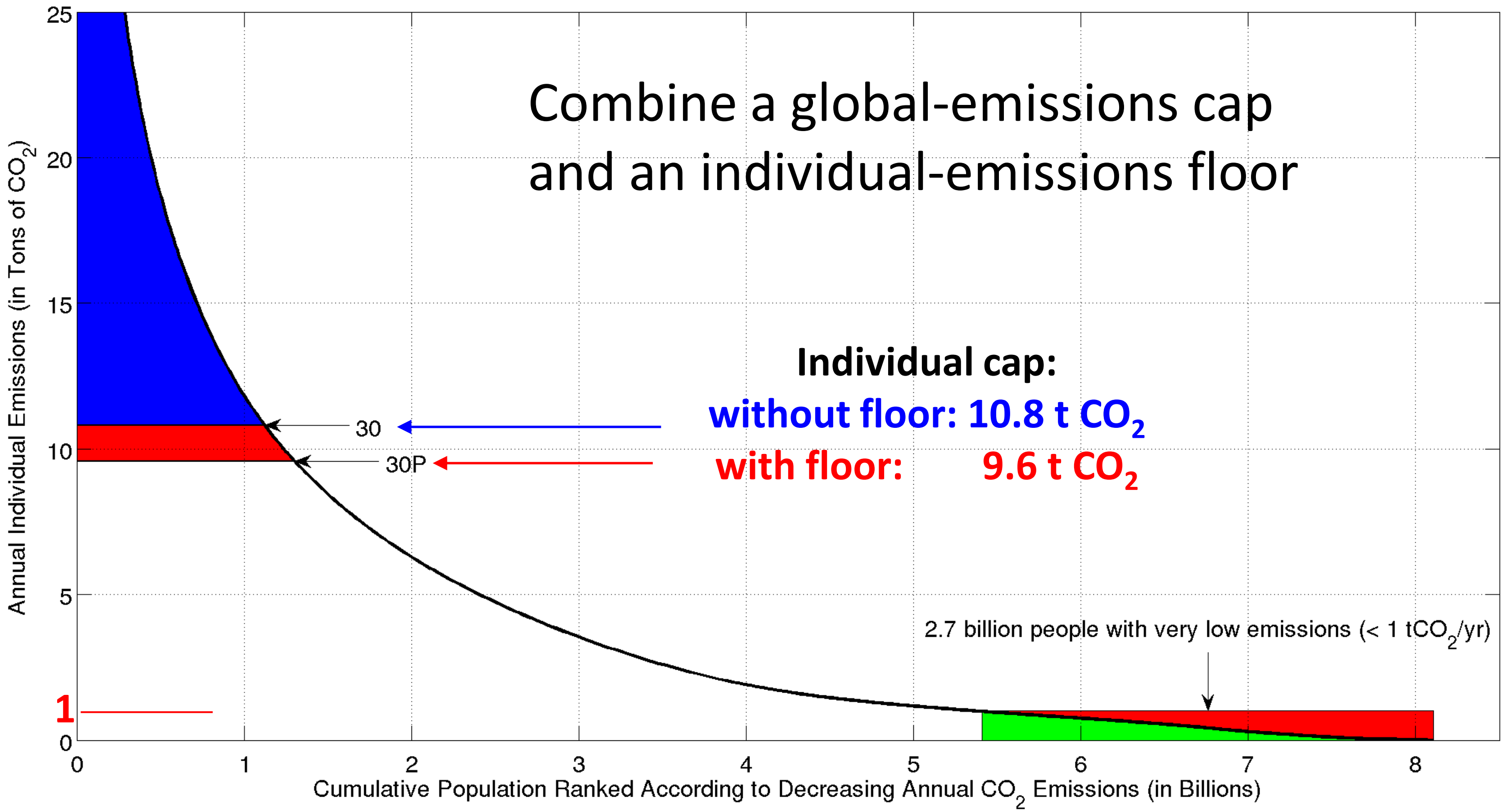


Distribution of the world's individuals with emissions below 10 tCO_2/yr

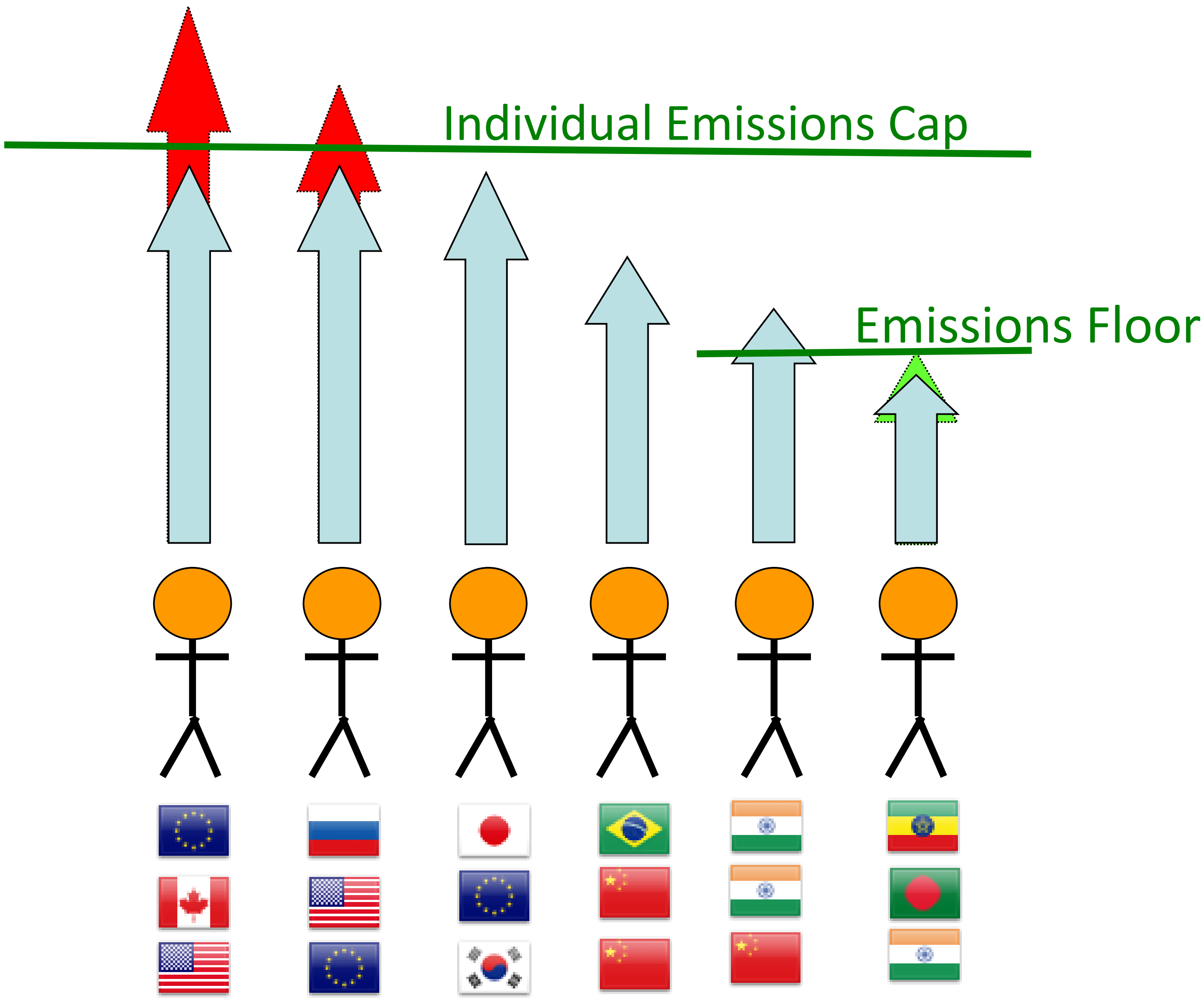


Note: linear scale. The high emitters are not in view.

The world's poor need not be denied fossil fuels.

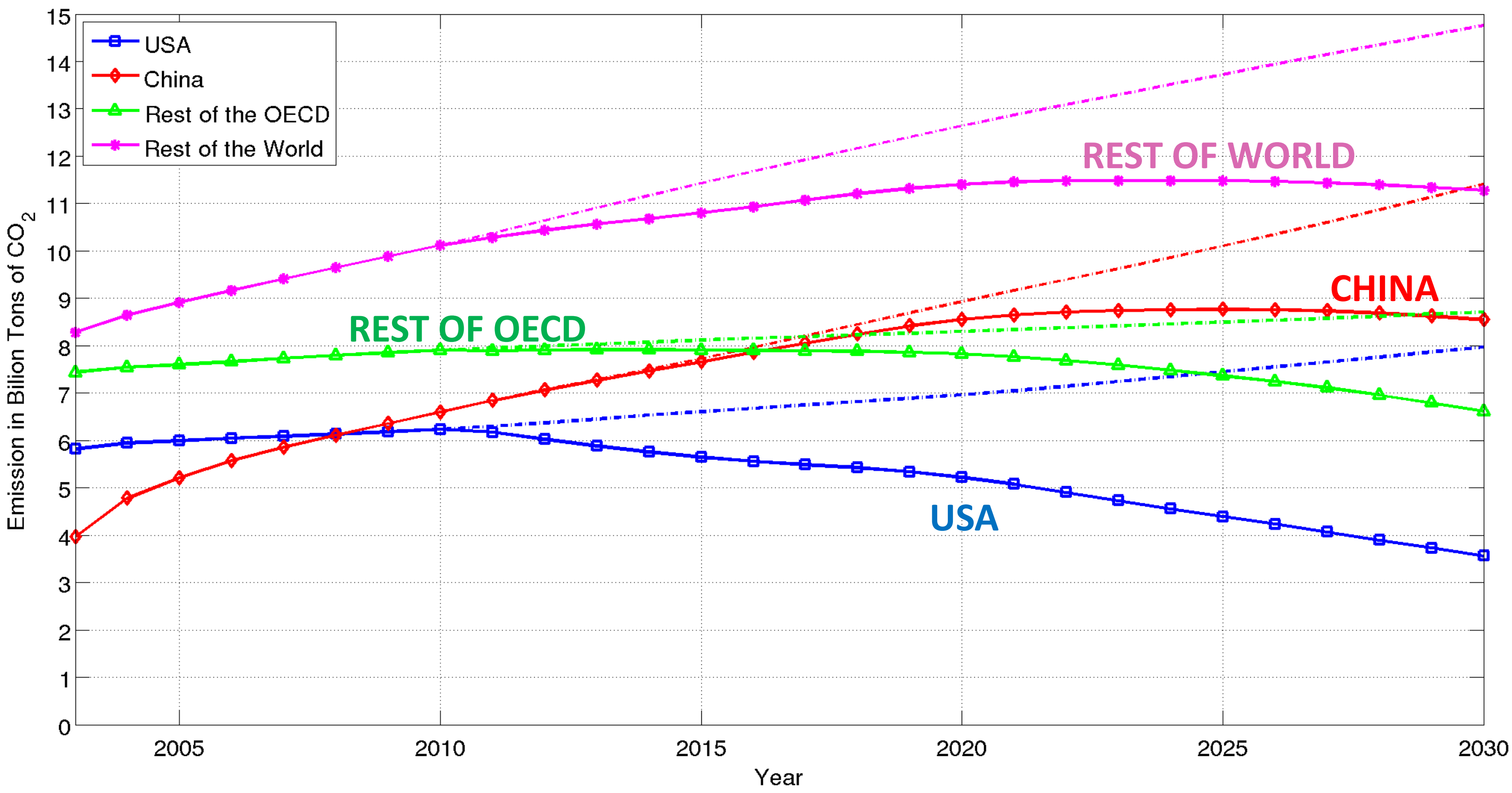


Overall proposal



Source: Shoibal Chakravarty, private communication

Emissions paths over time



Dashed lines: EIA Business As Usual
Solid lines: Global cap is 30 $GtCO_2$ in 2010, 33 $GtCO_2$ in 2020, 30 $GtCO_2$ in 2030.

BREAK (30 minutes)