The Five C's of Climate Change

October 24, 2013
Causes - Continued

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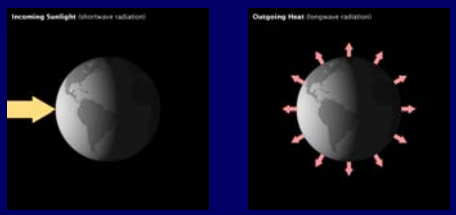
To have a stable temperature Earth must be in thermal equilibrium.

Earth's Climate Is a Solar Powered System

- Our climate system is driven by the energy derived from the sun.
- The sun heats equatorial regions more than the poles.
- Coupled atmospheric and oceanic circulations work to even out the solar heating imbalances. This is one task of "Earth's heat engine."
- The other task is to radiate heat to space. Earth's average temperature will be constant only when outgoing energy equals incoming energy.



NASA illustration by Robert Simmon, http://earthobservatory.nasa.gov/Features/EnergyBalance/page1.php

Electromagnetic Spectrum

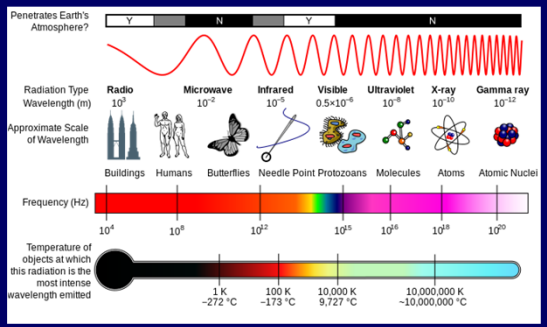
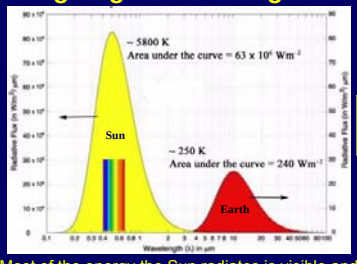


Figure from Wikipedia, http://en.wikipedia.org/wiki/File:EM_Spectrum_Properties_edit.svg. Original from NASA.

Incoming Sunlight = Short-wave Radiation
Outgoing Heat = Long-wave Radiation

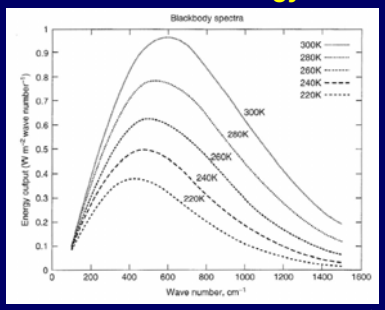


Note that the wavelength scale is reversed from the previous figure.

- Most of the energy the Sun radiates is visible and near-infrared light. This is referred to as short-wave radiation.
- Because Earth is cooler it radiates in the near- and mid-infrared range. This is referred to as long-wave radiation.

Figure from American Chemical Society, Climate Science Toolkit; drawn by Jerry Bell; http://www.acs.org/content/acs/en/climatescience/energybalance.html

In the Absence of an Atmosphere, Earth Would Emit Energy as a Blackbody



K = 273 + °C

- The area under the curve is the emission rate in Wm^{-2}.
- The higher the surface temperature, the greater the emission rate.

Wave number = 1/wavelength; units = cycles/cm or cm^{-1}

Figure from D. Archer, *Global Warming: Understanding the Forecast*, 2nd Edition, John Wiley & Sons, Inc., 2012, p14

Certain gases affect the climate by altering the outgoing radiation.

Planetary Energy Balance

- To maintain a constant average temperature, the amount of energy a planet radiates must equal the amount of solar energy radiation it absorbs.
- Concept developed by Joseph Fourier in the early 19th century.
- Can be used to estimate the temperature of a planet in the absence of an atmosphere.

Planet	Mercury	Venus	Earth	Mars
S_{ave}, W·m^{-2}	2290	662	342	145
α	0.10	0.75	0.30	0.25
T_P, K (°C)	437 (163)	232 (-41)	255 (-18)(~0°F)	209 (-64)

Fourier image from Wikipedia: http://en.wikipedia.org/wiki/File:Fourier2.jpg
Table adapted from American Chemical Society, Climate Science Toolkit, http://www.acs.org/content/acs/en/climatescience/energybalance/predictedplanetarytemperatures.html

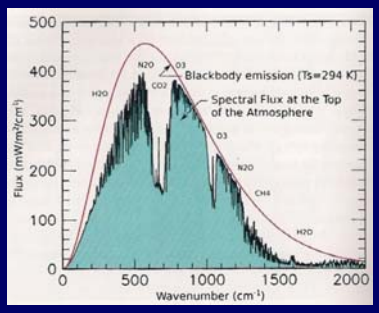
An Atmosphere Can Strongly Affect a Planet's Surface Temperature

Planet	Mercury	Venus	Earth	Mars
T_P, K (°C)	437 (163)	232 (-41)	255 (-18)(~0°F)	209 (-64)
T_{obs}, K (°C)	~440 (167)	735 (462)	288 (15)(59°F)	215 (-58)
Atmosphere: Pressure, kPa composition [trace gases]	none	9300 CO_2(0.965), N_2(0.035), [SO_2, Ar]	101 N_2(0.78), O_2(0.21), Ar(0.009), [CO_2, H_2O]	0.64 CO_2(0.95), N_2(0.03), Ar(0.02), [O_2, CO]

- Although Fourier did not calculate Earth's temperature, he recognized that Earth's warmth was due to the presence of its atmosphere.
- Although he did not coin the term "greenhouse," he used an analogy similar to the greenhouse analogy in an 1827 paper.

Table from American Chemical Society, Climate Science Toolkit, http://www.acs.org/content/acs/en/climatescience/energybalance/planetarytemperatures.html

Earth's Atmosphere Affects Its Outgoing Radiation



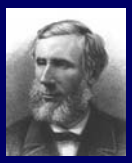
Certain gases in the atmosphere decrease the amount of outgoing radiation. They are called "greenhouse gases". The most important ones are:

- Water vapor, H_2O
- Carbon dioxide, CO_2
- Nitrous oxide, N_2O
- Ozone, O_3
- Methane, CH_4

Note that nitrogen, N_2, and oxygen, O_2, the major components of Earth's atmosphere, are not greenhouse gases.

Figure from G. T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis, Vol. 1 – The Physical Climate*, Springer, New York, 2013, p.94; Data NASA/GISS, Public Domain

John Tyndall Was the First to Measure the Absorption of Infrared Radiation by Gases



- John Tyndall was a 19th century British Physicist.
- In 1859 Tyndall showed experimentally that water vapor, carbon dioxide, ozone, and methane absorb infrared radiation.
- He concluded that water vapor is the most important absorber of infrared radiation in the atmosphere.
- He also concluded that the atmosphere is warmed by the presence of the greenhouse gases, which absorb infrared radiation from Earth and emit it at a different wavelength. Thus, he was the first to prove that the atmosphere has a greenhouse effect.
- Beer's law (1852) – Absorption increases with concentration.

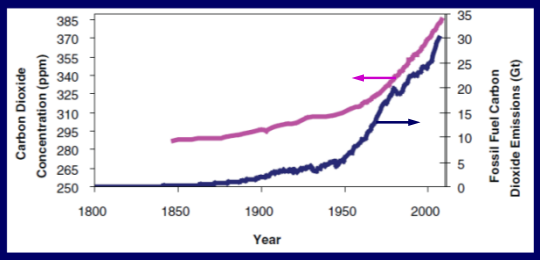
Figure from http://en.wikipedia.org/wiki/File:JohnTyndall(1820-1893).Engraving.SIL14-T003-09a_cropped.jpg

Svante Arrhenius Was the First to Recognize the Interaction Between CO_2 and Water Vapor

- Arrhenius was a Swedish physicist who also became known as a chemist.
- In 1896 he made the first calculations of the warming power of excess CO_2 in the atmosphere.
- In his calculations he included the interaction between CO_2 and water vapor – as the atmosphere warms because of CO_2 increases, it can hold more water vapor, which also warms the atmosphere. Without water vapor, doubling the CO_2 concentration causes the temperature to rise 1°C. With it, the temperature rises more.
- Arrhenius was also the first to recognize that the burning of fossil fuels would lead to an increase in CO_2 in the atmosphere, raising Earth's temperature, although he thought this would be beneficial.
  - It would delay the next ice age.
  - It would allow agriculture in cold climates.

Figure from http://en.wikipedia.org/wiki/File:Arrhenius2.jpg

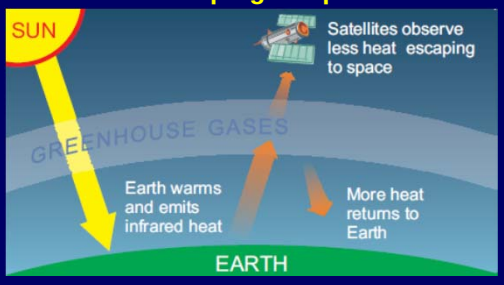
The Burning of Fossil Fuels Is Increasing the Concentration of Atmospheric CO_2



We know that the increased CO_2 is from fossil fuels because the ratio of C-13 to C-12 in the atmosphere is decreasing. This is also happening in corals and sea sponges.

Figure from *Advancing the Science of Climate Change*, National Academies Press, Washington, DC, page 34, 2010

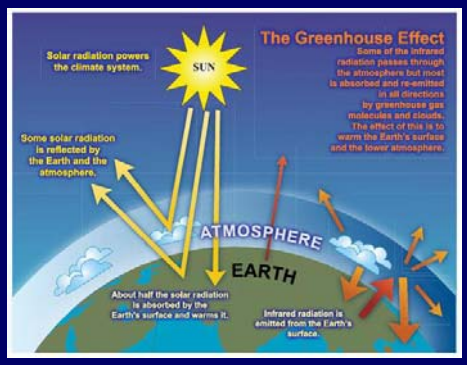
Satellite Data Show that Less Infrared Heat Is Escaping to Space



A comparison of satellite data from 2003 to that from 1970 found a decrease in the amount of infrared heat escaping to space at the wavelengths that greenhouse gases absorb.

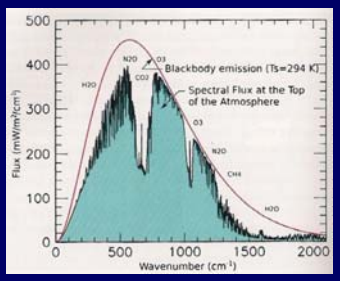
Figure from John Cook, The Scientific Guide to Global Warming Skepticism, www.skepticalscience.com

How Does the Greenhouse Effect Work?



Source: http://www.global-greenhouse-warming.com/effect-green-house.html

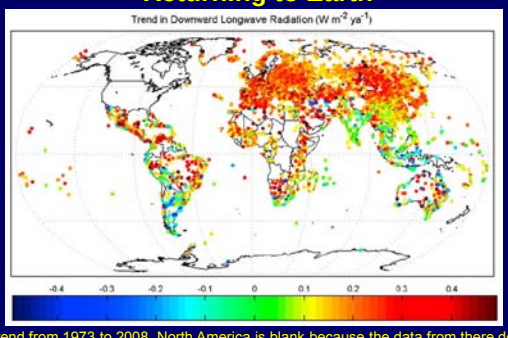
How Does the Greenhouse Effect Work?



- The atmosphere warms to a temperature where it emits sufficient heat to balance the incoming heat from the sun.
- The greenhouse gases emit in all directions so part of their energy is returned to Earth's surface, further warming it, which causes it to emit more infrared radiation.
- The system will eventually stabilize at a temperature that allows outgoing energy to equal incoming energy.

Figure from G. T. Farmer and J. Cook, *Climate Change Science: A Modern Synthesis, Vol. 1 – The Physical Climate*, Springer, New York, 2013, p.94; Data NASA/GISS, Public Domain

Instruments Show that More Infrared Heat Is Returning to Earth



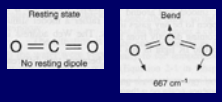
Trend from 1973 to 2008. North America is blank because the data from there do not cover the entire period.

From K. Wang and S. Liang, *Journal of Geophysical Research*, **114**, D19101, doi:10.1029/2009JD011800, 2009

Why Do Greenhouse Gases Absorb and Emit Infrared Radiation while N_2 and O_2 Don't?

- Greenhouse gases all contain at least 3 atoms: H_2O, CO_2, N_2O, O_3, and CH_4
- When they absorb infrared energy their shape is altered, so as they absorb and emit energy they vibrate.

For CO_2 the most important vibration is bending:



Bending is also the most important vibration for water vapor:

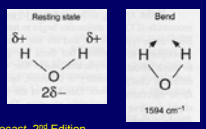
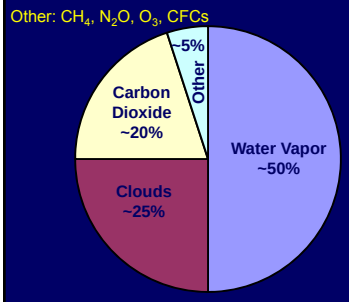


Figure from D. Archer, *Global Warming: Understanding the Forecast*, 2nd Edition, John Wiley & Sons, Inc., 2012, pp 31 & 32

Contributions of Clouds and Various Gases to the Greenhouse Effect



The effect of clouds depends on their type:

- Cirrus clouds warm Earth.
  - Transparent to solar radiation
  - Absorb outgoing infrared radiation
- Dense, low-lying clouds have two counteracting effects:
  - Cool Earth by reflecting sunlight
  - Warm Earth by absorbing outgoing infrared radiation

Data from G. A. Schmidt et al., Journal of Geophysical Research, **115**, D20106, doi:10.1029/2010JD014287, 2010

Global Warming Potential (GWP) of Greenhouse Gases

		GWP Time Horizon, yr		
Gas	Lifetime, yr	20	100	500
Carbon Dioxide, CO_2	See text	1	1	1
Methane, CH_4	12	72	25	7.6
Nitrous Oxide, N_2O	114	289	298	153
CFC-12, CCl_2F_2	100	11,000	10,900	5,200
HFC-23, CHF_3	270	12,000	14,800	12,200
HFC-134a, CH_2FCF_3	14	3,830	1,430	435
Sulfur Hexaflouride, SF_6	3,200	16,300	22,800	32,600

GWP depends on:

- The wavelength where the molecule absorbs
- The strength of its absorption
- Its atmospheric lifetime

About half of a CO_2 sample emitted today will be gone in a century, but a portion will persist for 1000s of years.

Table from American Chemical Society, Climate Science Toolkit, http://www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html

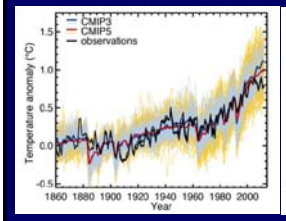
CO_2 Acts as the Temperature Control Knob for Earth by Influencing the Amount of Water Vapor in the Atmosphere

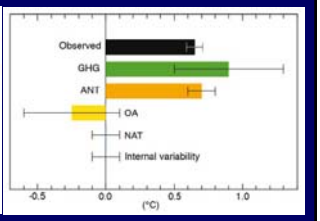
CO_2 ↑ Water Vapor ↑

CO_2 ↓ Water Vapor ↓

- CO_2 remains in the atmosphere for a very long time, whereas water vapor has a short lifetime.
- CO_2 is well mixed throughout the atmosphere, water vapor is not.
- CO_2 does not condense at the temperatures in our atmosphere, whereas water vapor does.
- Without CO_2 the greenhouse would collapse.

Modern Temperature Increases Can Only Be Explained by Including Greenhouse Gases



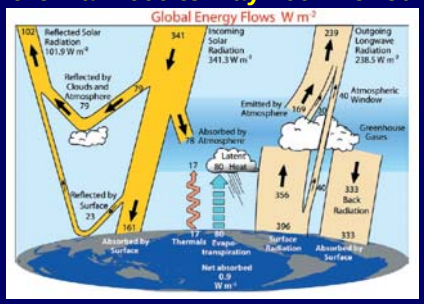


Observations and simulations of Earth's temperature. Simulations included both natural and man-made causes.

Impacts of various factors on Earth's warming over the 1951-2010 period.

Left figure adapted from Figure TS.9, IPCC 5th Assessment Report, Technical Summary, 2013
Right figure is Figure TS.10, IPCC 5th Assessment Report, Technical Summary, 2013

Global Annual Mean Energy Balance for the Mar 2000 to May 2004 Period



Incoming (341.3 – 101.9) = Outgoing (238.5) + Net absorbed (0.9) = 239.4 W·m^{-2}

Figure from K. E. Trenberth et al., "Earth's Global Energy Budget, *Bull. Amer. Meteor. Soc.* **90** 311 2009

All Factors Acting to Heat or Cool Earth Are Expressed as Radiative Forcing (W m^{-2})

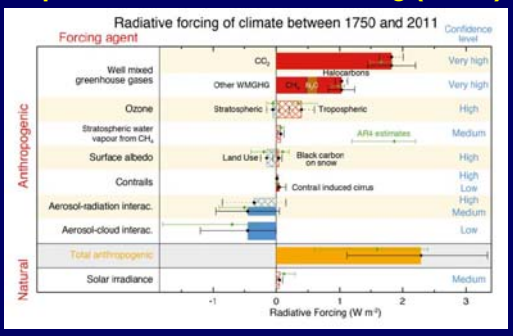
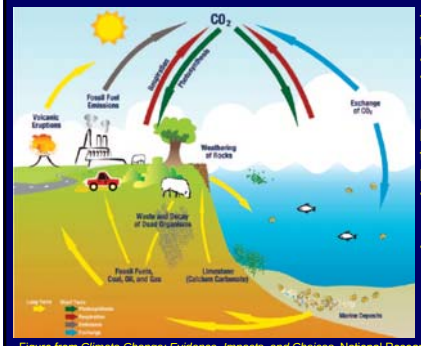


Figure adapted from Figure TS.6, IPCC 5th Assessment Report, Technical Summary, 2013

Human activities have disrupted the carbon cycle by increasing the rate at which CO_2 enters the atmosphere.

The Carbon Cycle

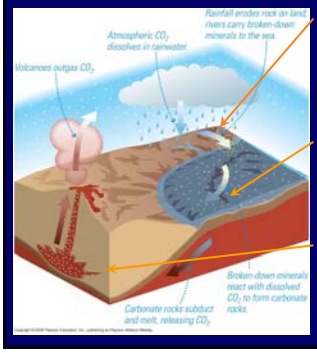


Two components of the carbon cycle:
- Short term (fast)
- Long term (slow)

Until we started burning fossil fuels, the cycles were in balance.
- Volcanic eruptions emit ~0.2 gigatons CO_2/yr.
- Humans cause ~38 gigatons CO_2/yr to be emitted.

Figure from *Climate Change: Evidence, Impacts, and Choices*, National Research Council of the National Academies, 2012

Slow Carbon Cycle – Silicate Weathering Thermostat

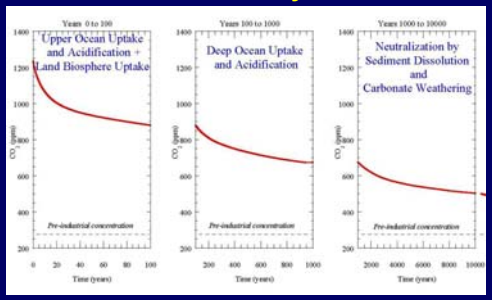


Erosion of rocks is called weathering: $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$
$CaCO_3$ and SiO_2 are dissolved in acidic rainwater resulting from CO_2.
$CaSiO_3$ represents silicate rock. Actual silicate rock is more complex.

In the oceans, solid $CaCO_3$ and SiO_2 are formed by precipitation or by coral and shell-forming plankton, which die and fall to the ocean floor. Solid $CaCO_3$ and SiO_2 represent typical sedimentary rock.

After subduction, sedimentary rocks undergo metamorphic decarbonation, $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$.
Volcanoes release the CO_2. Cycle regulates atmospheric CO_2 concentrations on geologic time scales.

CO_2 Removal Is Slow, Causing Inertia in the Climate System



Carbonate weathering involves the dissolution of carbonate sediments and limestone. After 10,000 years, only silicate weathering will cause removal of the CO_2. This will take more than 100,000 years.

Figure adapted from Box 2.2 in *Climate Stabilization Targets*, National Academy of Science, 2011, p75.

The Global Rate of Carbon Dioxide Emissions Is Increasing

Current emission rate is 9.5 Pg C/yr = 38 gigatons CO_2/yr.

Emission rate is following RCP8.5, which is the worst case considered by the IPCC in the new report.

The emission rate is growing at 2.6% per year.

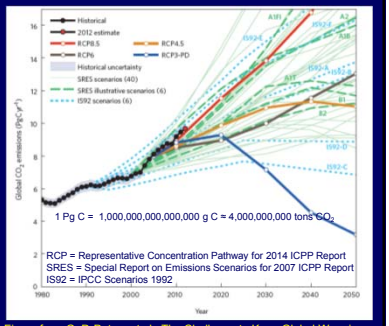


Figure from G. P. Peters et al., The Challenge to Keep Global Warming below 2°C, *Nature Climate Change* 3: 4-6, 2013

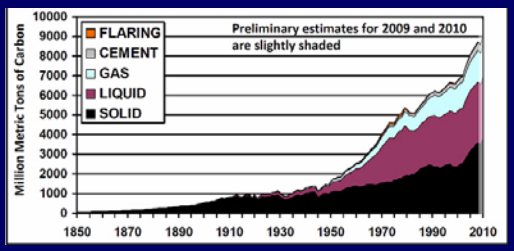
Emissions of CO_2 come from diverse sources all over Earth.

Fossil Fuels Differ in the Amount of CO_2 Emitted per Unit of Energy Obtained

CO_2 Emission Factors, Lbs CO_2/Million Btu		
Fuel	Emission Factor	Relative to Nat. Gas
Natural Gas	117.1	1.00
Propane Gas	139.2	1.19
Jet Fuel	156.3	1.33
Kerosene	159.5	1.36
Distillate Fuel Oil	161.4	1.38
Residual Fuel Oil	173.9	1.49
Bituminous Coal	205.3	1.75
Sub-bituminous Coal	212.7	1.82
Lignite Coal	215.4	1.84

Source: Adapted from US Energy Information Administration: http://www.eia.gov/electricity/annual/html/epa_a_03.html

Global Carbon Emissions 1 Ton Carbon = 3.67 Tons CO_2



These figures do not reflect the recent increase in the use of natural gas in the USA.

Source of figure: http://cdiac.ornl.gov/trends/emis/prelim_2009_2010_estimates.html

The Emission Rate of CO_2 from Various Sources Has Changed over Time

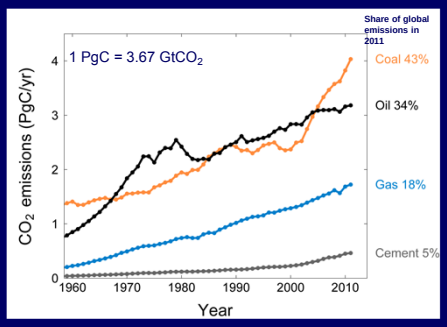
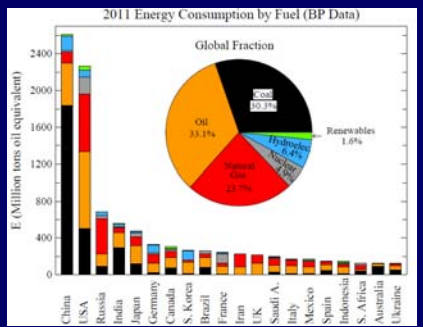


Figure from *Global Carbon Budget 2012*; http://www.globalcarbonproject.org/carbonbudget/12/presentation.htm

Fossil Fuel Use Varies in Quantity and Type



From J. Hansen, Columbia University, 2013: http://www.columbia.edu/~mhs119/EnergyConsump/Econsump.pdf

Top Four Emitters in 2011 Covered 62% of Global Emissions

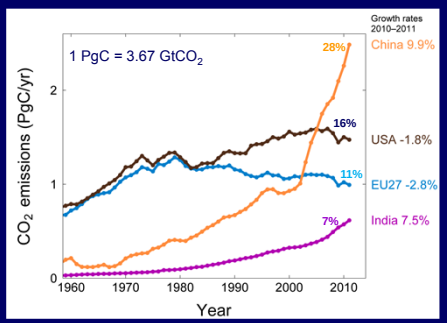


Figure from *Global Carbon Budget 2012*; http://www.globalcarbonproject.org/carbonbudget/12/presentation.htm

Average per Capita Emissions
World Average = 1.4 tC/person/yr (2011)

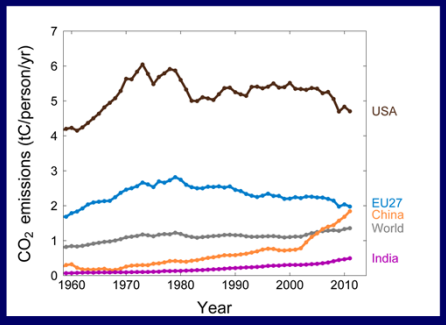


Figure from *Global Carbon Budget 2012*; http://www.globalcarbonproject.org/carbonbudget/12/presentation.htm

The Global Distribution of Emissions Has Changed since 1990

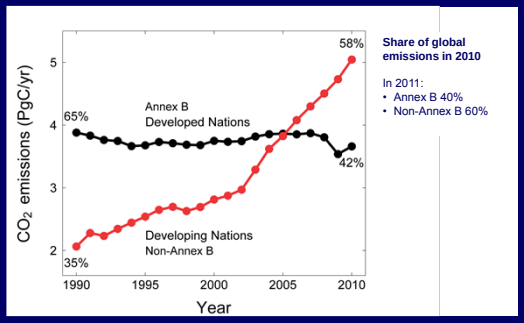
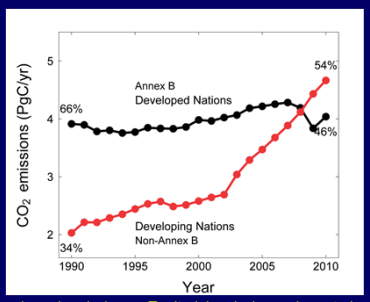


Figure from *Global Carbon Budget 2012*; http://www.globalcarbonproject.org/carbonbudget/12/presentation.htm

Consumption-Based Emissions Change the Distribution Somewhat



Consumption-based emissions = Territorial emissions + imported emissions - exported emissions

Figure from *Global Carbon Budget 2012*; http://www.globalcarbonproject.org/carbonbudget/12/presentation.htm