EC1340 Topic #2

Carbon cycle, emissions and consumption, and emissions levels and trends

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Outline

Last time, we...

described our endowment of climate and atmospheric CO_2 and discussed climate models that allow us to link current climate and CO_2 to future climate.

- The world has warmed by about 1 degree Celsius since preindustrial times.
  - This warming is not uniform. Poles are warming faster.
  - Possible changes to regional weather patterns.
  - Other aspects of climate are also changing; rainfall, sea level, snow/glacier cover, ocean ph.
  - Proxy record suggests the world is warm relative to the last 6-800k years.

- Atmospheric CO_2 concentrations are very high relative to their levels over the past 6-800k years.
  - measured CO_2 has increased monotonically to 412 ppm at Mauna Loa observatory (July 2019).
  - ice core record suggests we are at or above atmospheric CO_2 concentrations observed over past 6-800k years.

- Atmospheric CO_2 almost certainly causes global warming and climate change.
  - The physics relating atmospheric CO_2 to warming is elementary and uncontroversial. Earth's radiation spectrum confirms the theory.
  - The ice core record confirms the theoretical relationship between CO_2 and climate.
  - Aerosols are probably unprecedented as is the rate of increase of atmospheric CO_2 and mean that we should not expect the historical record to predict the path of future climate.
  - We use climate models to make these guesses. There is a lot of uncertainty.

We also introduced the BDICE model:

$$\max_{I,M} u(c_1, c_2) \tag{1}$$

$$\text{s.t. } W = c_1 + I + M \tag{2}$$

$$c_2 = (1 + r)I - \gamma(T_2 - T_1)I \tag{3}$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{4}$$

$$P_2 = \rho_0 E + P_1 \tag{5}$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \tag{6}$$

Last time we talked about the red parts.

- The last equation is a climate model. We discussed all of the pieces of this model last time; our endowment of temperature and atmospheric CO_2 , along with climate models relating atmospheric CO_2 to climate.

- The next to last equation is a model of the atmospheric carbon cycle. We discussed our endowment and projected atmospheric CO_2 last time.
- This time, we want to talk about Emissions, E, ρ_0 the relationship between emissions and concentration, and ρ_5 the relationship between consumption and emissions.

Emissions and concentration of CO_2

What is the relationship between emissions and atmospheric concentration?

- Each ppm of atmospheric concentration is about 2.12 Gt C . This is a standard conversion factor, both IPCC and Hansen use it. (gigatons = billion tons).
- A molecule of CO_2 , is about 44/12 as heavy as a molecule of C . Thus, each ppm of atmospheric concentration of C is about $2.12 GtC \times (44/12) = 7.77 GtCO_2$.
- *Hansen* and *IPCC 2007/2013 Physical Science Basis* measure emissions in terms of Gt C , but *Stern*, *IPCC 2007/2013 Mitigation of Climate Change* measure emissions in terms of Gt CO_2 .
- Social scientists often measure Green house gases in terms of CO_2 equivalent emissions:

In July 2019, the concentration of CO_2 in the atmosphere was 412 ppm. This is equal to 873 Gt C and 3201 Gt CO_2 .

CO_2 is not the only GHG I

Table 8.1 Characteristics of Kyoto Greenhouse Gases

Despite the higher GWP of other greenhouse gases over a 100-year time horizon, carbon dioxide constitutes around three-quarters of the total GWP of emissions. This is because the vast majority of emissions, by weight, are carbon dioxide. HFCs and PFCs include many individual gases; the data shown are approximate ranges across these gases.

	Lifetime in the atmosphere (years)	100-year Global Warming Potential (GWP)	Percentage of 2000 emissions in CO_2e
Carbon dioxide	5-200	1	77%
Methane	10	23	14%
Nitrous Oxide	115	296	8%
Hydrofluorocarbons (HFCs)	1 – 250	10 – 12,000	0.5%
Perfluorocarbons (PFCs)	>2500	>5,500	0.2%
Sulphur Hexafluoride (SF_6)	3,200	22,200	1%

Source: Ramaswamy et al. (2001)[8] and emissions data from the WRI CAIT database[9].

From Stern 2008, table 8.1

CO_2 is not the only GHG II

- July 2019 concentration of CO_2 was 412 ppm. Using the numbers above, current CO_2e is $412/0.77 = 535CO_2e$
- From the forcing tables we see that non-CO_2 is has about half the forcing capacity of CO_2 . However, non-CO_2 is less persistent, so it makes a smaller total contribution to warming than this share suggests.

What is 'Global Warming Potential'? I

- We would like to calculate the rate at which we are willing to trade CH_4 for CO_2 . To do this, define α_t as the change in radiative forcing from one unit of concentration of the gas at t, i.e. $\frac{\frac{W}{m2}}{PPM}$. Define GWP as warming potential relative to CO_2 ,

$$GWP(CH_4) = \frac{\int_0^T \alpha^{CH_4}(t)dt}{\int_0^T \alpha^{CO_2}(t)dt}$$

- Example, suppose $t = 1, 2, 3$ and for CO_2 , $(\alpha^{CO_2}(1), \alpha^{CO_2}(2), \alpha^{CO_2}(3)) = (1, 1, 1)$ and for CH_4 , $(\alpha^{CH_4}(1), \alpha^{CH_4}(2), \alpha^{CH_4}(3)) = (2, 0, 0)$.
  Then $GWP(CH_4) = \frac{2+0+0}{1+1+1}$

What is 'Global Warming Potential'? II

Issues:

- T is completely arbitrary. GWP of CH_4 for $T = 20, 100, 500$ is about 63, 21, 9.
- We care about damage, not radiative forcing (see Schmalensee, The Energy Journal (1993)) . To see this consider,
  - If we anticipate that the world will end in 20 years, then neither CO_2 nor CH_4 is very harmful, but CH_4 causes a lot more warming over that time than CO_2
  - If we plan to spend the next 20 years as we do now, but then to permanently convert to an economy based on penguin farming, then CH_4 emissions now are not very harmful, but CO_2 is (because it is persistent).

We can't really assign relative values to CO_2 and CH_4 until we solve for the whole optimal path of emissions for both gases, so any definition of GWP is going to be unsatisfactory.

Units!

Stern 2007 p193 gives CO_2e emissions for 2000 as 42Gt CO_2e .
Hansen has 8.5 Gt C from fossil fuel.
Can we reconcile these numbers?(Yes)

- About .77 of CO_2e is CO_2 .
- About .18 of CO_2 is non fossil fuel (more on this later)
- Stern reports CO_2 , Hansen C

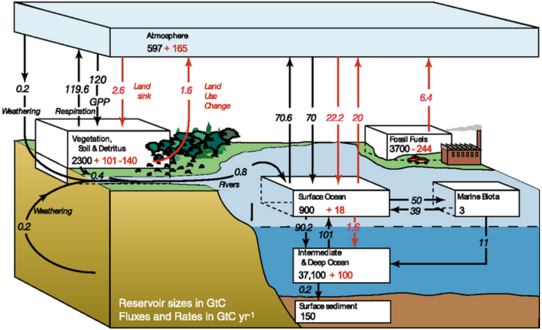
so, Stern's 42 Gt CO_2e becomes:
$42 \times (.77(1 - .18)) \times (12/44) = 7.2$ Gt of atmospheric C .
It would be closer, but Stern uses 2000 numbers and Hansen's 8.5 is for about 2008.

Carbon cycle

Carbon is cycled back and forth between the atmosphere, ocean and land by biological and chemical processes. This means that emissions don't translate immediately into atmospheric concentrations. Stocks/annual flows of C (not CO_2) are:

- Atmosphere 800/+4.5Gt
- Ocean 40,000/+3Gt
- Volcanos –/-0.1Gt
- Forests 600/-1.6 Gt
- Fossil fuels 5000/-8.5
- Sediments –/-.1Gt

Fossil fuel emissions and deforestation put about 10Gt C in the atmosphere (ca. 2007). Atmospheric C increased by about 4.5Gt. About 3Gt are absorbed by the ocean. The remaining 2.5Gt are thought to be absorbed by plants (N.B: old numbers to go with figure). Numbers from Hansen 2009, about the same as in Jacob 1999



Black = natural, Red=Anthropogenic. AOGCM models of carbon cycle are complicated. IPCC 2007 Physical Science basis

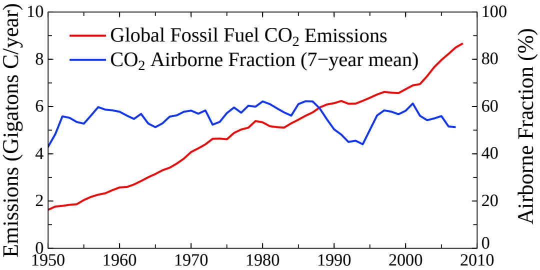
figure 7.3

Atmospheric CO_2 cycle, data I

Another way to see this is to look at the relationship between emissions and concentration directly

- Calculate annual change in C ppm from Mauna Loa (e.g.)
- Calculate annual emissions using emissions rates and consumption data (more below).
- Calculate ratio $\frac{\Delta CO_2 \text{ppm}}{\text{Fossil Fuel emissions}} =$ concentration yield of emissions.

Atmospheric CO_2 cycle, data II



Hansen 2009 figure 16

Atmospheric CO_2 cycle, data III

So, concentration yield of emissions is about .55. Thus,

- (1/0.55)= 1.8 Gt C emissions gives 1 Gt ton of atmospheric C .
- 2.12 Gt atmospheric C to gives 1ppm atmospheric C (or CO_2).
- Multiplying, $1.8 \times 2.12 = 3.8$Gt C of emissions to get 1ppm of atmospheric concentration.

Recall the carbon cycle equation from our model:

$$P_2 = \rho_0 E + P_1.$$

We have just calculated that $\rho_0 = \frac{1}{3.8} = 0.26 \frac{ppm\ \mathrm{C}\ (\mathrm{or}\ \mathrm{CO_2}\ )}{Gt\ \mathrm{C}}$.

What is ρ_0 if we denominate emissions in terms of CO_2 ?

Atmospheric CO_2 cycle, data IV

In Hansen's graph, the fraction of emissions retained in the atmosphere is CONSTANT as emissions are increasing. This is thought to reflect increased absorbtion by plant, 'carbon fertilization' or increased 'net primary productivity'.

In AOGCM's the carbon cycle is modelled very carefully. We really want to deal with the possibility that absorbtion varies with temperature or CO_2 (it probably does) and there is a lot of uncertainty about this relationship.

Emissions for particular activities I

- CO_2 from gasoline, 2.3 kg/liter = 19.4 pounds/gallon. So, 1000 kg of CO_2 emission results from 435 liters or 114 gallons of gas. (about 1% not burned is mostly N_2O so CO_2e is higher).
- CO_2 from diesel 2.7 kg/liter = 22.2 pounds/gallon 1000 kg of CO_2 emission results from 370 liters or 97 gallons of diesel.

  http://www.epa.gov/otaq/climate/420f05001.htm#calculating
- BBQ propane tank, about 18 pounds propane = 24kg = 53 lb CO_2 . (NB Gasoline weighs 6.3 pounds/gallon so 18 pounds of gas gives about 54 pounds CO_2 . Propane has more hydrogen per carbon atom than gasoline).

Emissions for particular activities II

- CO_2 sequestration by 1 acre 90 year old pine forest in Southeastern US is about 100 tons C, about 1 ton/acre/year. So burning this acre releases about 100 tons C or 367 tons CO_2. http://www.epa.gov/sequestration/faq.html For tropical forests, about 1.8 times as much not reliable source.
- CO_2 from coal, about 2.00 tons CO_2 per ton (a lot of the stuff in coal is not burned – I think), or 2100lb CO_2 per 1000 KWH from non-baseload coal burning electricity generation. CO_2e is higher. Baseload will usually be lower (often nuclear or hydro) `http:\/\/www.eia.gov/tools/faqs/faq.cfm?id=74&t=11`.

Emissions for particular activities III

- For natural gas, about 1200lb CO_2 per 1000 KWH. So, fracking is fantastic, unless too much methane leaks before it's burnt. With 1 ton of methane worth 23 tons of CO_2, about 4.3% leakage makes coal and natural gas even (unless there is methane leakage from coal mines). The rate of leakage is currently contested, EPA current estimate is about 0.6%, but 0.5% is probably better (Allen et al. PNAS 2013).
- For reference: Avg household in RI = 500KWH/mo; Avg household in TX = 1000KWH/mo. https://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3 (Feb 2016). Or, average household in Providence $\sim$ 8000kwh/year in 2001, Dallas $\sim$ 18,500kwh/year (Glaeser and Kahn, JUE 2010).

Emissions for particular activities IV

- For thinking about fracking, also consider the following:


Global emissions per unit of consumption, ca. 2013

Using these sorts of particular numbers, together with information about aggregate consumption, one can calculate world emissions.

- Global annual emissions ca 2013 are about 49Gt $\mathrm{CO_2}$e or $49 \times \frac{12}{44} \sim 13.3$ Gt C (more on this later).
- World GDP in 2013 is about 77 trillion USD. (NB: this is W in our model).
- Dividing,we have $\frac{13.3\times 10^9 \text{ tons C}}{77\times 10^{12}000 USD} = \frac{13.3}{7700}\frac{\text{ton C}}{\text{USD}} \sim 0.17\frac{\text{kg C}}{\text{USD}}$ (1 ton = 1000 kg). Multiply by 44/12 for $\mathrm{CO_2}$ instead of C .

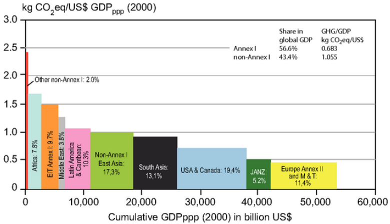
Recall the third equation from our global warming model:

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{7}$$

We've just calculated ρ_5. Why is this sloppy?

Emissions per unit of consumption by country

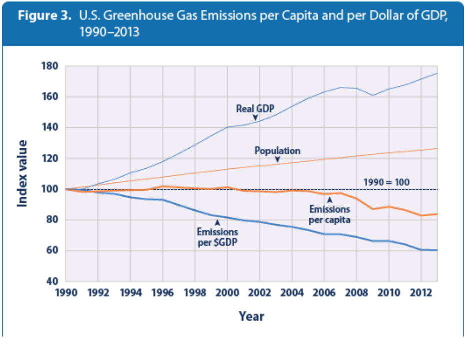
- It's also interesting to look at the country by country breakdown.(ca. 2004) The US and Canada make a lot of stuff per ton of emissions.



IPCC 2007 Mitigation fig SPM.3b

- What if China and Africa made same output at US/CA emission rates? This is why technology transfer is important.
- Compare 0.68 kg CO_2e per dollar ca. 2004 to my calculation of 0.17 kg C per dollar 2013. How important is technical progress?

Technological progress I



http://www3.epa.gov/climatechange/science/indicators/ghg/us-ghg-emissions.html, January 2016

Technological progress II

Nordhaus does this calculation every year, country by country

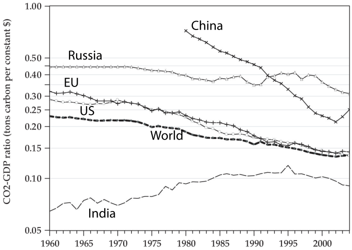


Figure 3-1. Historical ratios of CO_2 emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of CO_2 emissions to GDP for five major regions and the global total. We call the decline in this rate "decarbonization." Most major economies have had significant decarbonization since 1960. The rates of decarbonization have slowed or reversed in the last few years and appear to have reversed for China. With the changing composition of output by region, the world CO_2-GDP ratio has remained stable since 2000. Note that "W C Eur" is Western and central Europe and includes several formerly centrally planned countries with high CO_2-GDP ratios.

Emissions - Summary

- We've now calculated ρ_5, emissions per GDP at about 0.17kg C per dollar ca. 2013.
- Looking at the data a little more carefully highlights two deficiencies on our model:
  - Technological progress is at work, so this ratio changes over time.
  - There are huge difference across places in this ratio

  This highlights the importance of technological progress and technology transfer in solving the problem of climate change.
- We'll address this when we get to the Nordhaus model.

Emissions trends and levels

Recall,

$$\max_{I,M} u(c_1, c_2) \tag{8}$$

$$\text{s.t. } W = c_1 + I + M \tag{9}$$

$$c_2 = (1+r)I - \gamma(T_2 - T_1)I \tag{10}$$

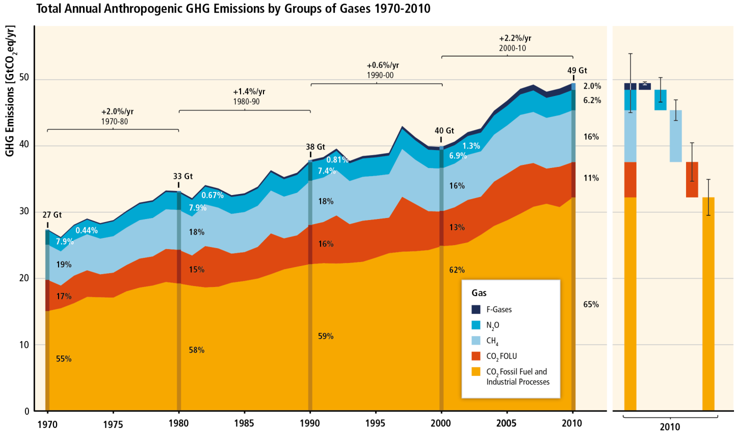
$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{11}$$

$$P_2 = \rho_0 E + P_1 \tag{12}$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \tag{13}$$

We've filled in a bit more. The next step is to look at E. This means looking at trends and levels in CO_2 emissions.

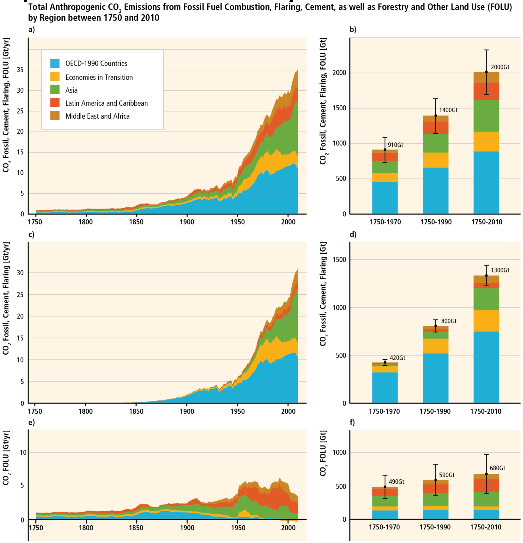
CO_2e 1970-2010



IPCC 2013 WG3 fig TS.1

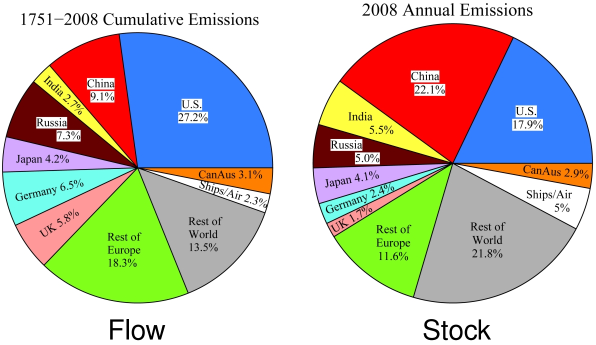
Right panel gives confidence bounds for 2010. 49Gt CO_2e in 2010.

CO_2 by purpose and country income 1750-2010



IPCC 2013 WG3 fig TS.2

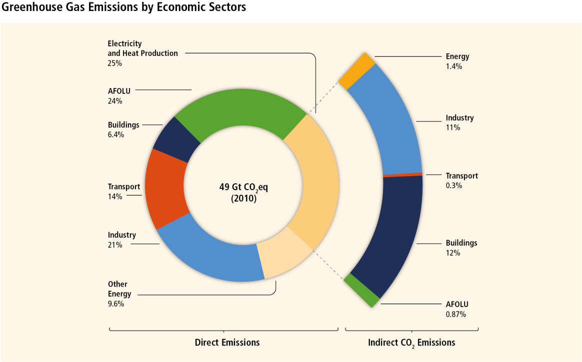
Hansen's version of the same thing...



Hansen 2009 fig 27

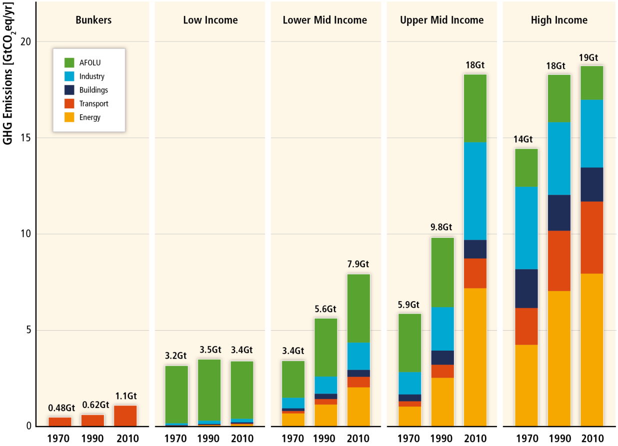
Contributions to stock and flow are very different. At the negotiating table, developing countries want the right to emit, since everyone else had their turn.

2010 CO_2e by purpose



IPCC 2013 WG3 fig TS.3

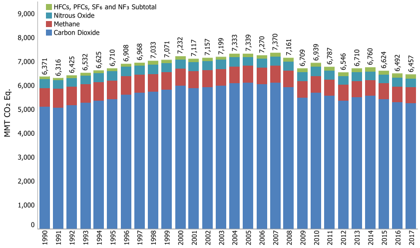
2010 CO_2e by purpose and country income



IPCC 2013 WG3 fig TS.3

US 1990-2017 CO_2e

Figure ES-1: Gross U.S. Greenhouse Gas Emissions by Gas (MMT CO_2 Eq.)

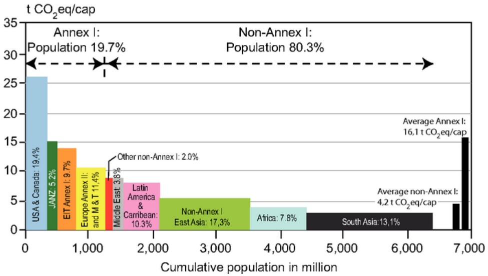


https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf, September, 2019

This reflects: fracking, recession, technical progress, off-shoring of manufacturing. Emissions are likely up since 2017.

Emissions per person

It's also interesting to look at the country by country breakdown in terms of emissions per capita:



IPCC 2007 Mitigation fig SPM.3a

As of 2012 US had 4.54 tons C /person and for India, this number was 0.46. China was 1.8.(http://cdiac.ornl.gov/trends/emis/top2011.cap)

The problem of stabilizing atmospheric CO_2

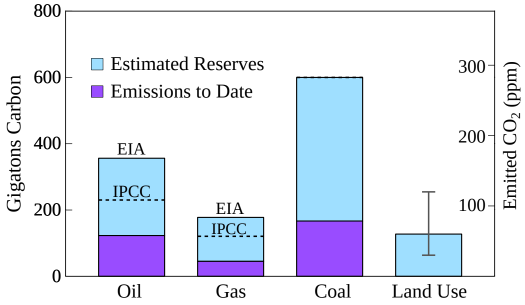
- Emissions are about 13Gt C per year.
- The ocean and biosphere absorb about 45% of emissions (so far).
- This means the ocean and biosphere absorb $13 \times 0.45 \approx 6$Gt C per year.
- As a rough guess, this means that reducing emissions to 6Gt C per year will stabilize atmospheric CO_2 (but not climate).
- This involves a 55% decrease. For an average American this means this means reducing emissions from 4.5 tons per year to about 2.0 *if US share of total emissions stays constant.* If emissions are allocated equally to each of the world's 7.4b people, then each of us gets 6Gt C /7.4b people or about 0.8 ton. This is an 82% decrease for the average American. It is also about the twice the level of the average Indian and half that of the average Chinese.

Summary

- 2013 emissions of CO_2e were about 49Gt. Of this, 35Gt was CO_2 , and of this, about 30Gt from fossil fuels and 5Gt from land use change and agriculture. This is E in our model.
- Emission are growing rapidly, about 2%/year between 2000 and 2010. 1970 CO_2e was 30Gt.
- 2010 CO_2e : 14% transport, 18% buildings, 21% industry 24% AFOLU. We could use this to calculate refinements of ρ_5.
- The countries responsible for most of the stock are not the countries responsible for most of the flow.
- Per capita emissions vary by a factor of about 10 between rich and poor countries.
- There has been a decline in US emissions since 2008 due to; fracking, recession, technical progress, off shoring.

Will we run out of fossil fuel? I

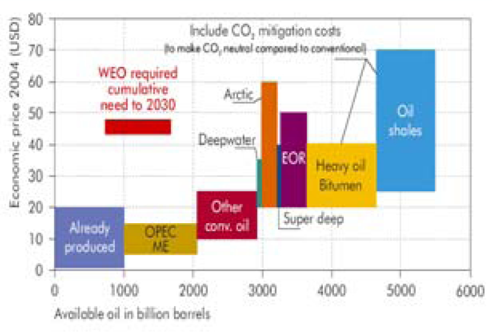
Not soon enough to matter:



We have oceans of coal and lots of oil, and these figures predate US fracking.

Will we run out of fossil fuel? II

Figure 7.6 Availability of oil by price[48]



Source: International Energy Agency

Conclusion I

Here is where we stand with our model:

$$\max_{I,M} u(c_1, c_2) \tag{14}$$

$$\text{s.t. } W = c_1 + I + M \tag{15}$$

$$c_2 = (1 + r)I - \gamma(T_2 - T_1)I \tag{16}$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{17}$$

$$P_2 = \rho_0 E + P_1 \tag{18}$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \tag{19}$$

We have enough pieces filled in to permit you to calculate the impact on future climate of particular sorts of current consumption, e.g., burning a tank of propane on your bbq. We'll next start

Conclusion II

thinking about the effect of climate change on production, γ, though we'll make an aside to talk about measurement error first.

Conclusion III

- Each ppm of atmospheric CO_2 corresponds to about 2.12 Gt C and 7.78 Gt of CO_2 . Pay attention to the units people use.
- Not all gases are equal in their green house potential. CO_2 is most common and most important, but other gases are more important per unit of emissions.
- Over the past 50 years, about 55% of each emitted Gt of C has stayed in the atmosphere. The rest has been absorbed by land or oceans. Thus, it takes about 3.8 Gt C per 1ppm of atmospheric CO_2 .

Conclusion IV

- Emissions are about 13Gt C for 2013. The rate at which atmospheric CO_2 is increasing has risen from about 1ppm/yr 1960s to 2ppm for 2000's. Since there is lots of fuel, we should expect atmospheric CO_2 to continue to increase and at an increasing rate. 'business as usual scenarios call for atmospheric CO_2e > 800 within 100 years.
- Not all countries are the same. They are responsible for different shares, have different per capita emissions, use emission more or less efficiently, and are responsible for different shares of historical emissions. These factors are very important obstacles to international agreements and also suggest the need for a richer model.

Conclusion V

- Steady state CO_2 emissions are probably very small, Stern suggests less than 1/3 of current. Our calculations suggest (1-0.55)=45%.