EC1340 Topic #2

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

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Outline

1. Review
2. Carbon cycle
3. Atmospheric carbon cycle
4. Consumption and emissions
5. Emissions
6. Peak oil?
7. Conclusion
Last time, we...
described our endowment of climate and atmospheric $\text{CO}_2$ and discussed climate models that allow us to link current climate and $\text{CO}_2$ 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 CO₂ concentrations are very high relative to their levels over the past 6-800k years.

- measured CO₂ has increased monotonically to 407 ppm at Mauna Loa observatory.
- ice core record suggests we are at or above atmospheric CO₂ 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.
Review

We also introduced the BDICE model:

\[
\text{max } u(c_1, c_2) \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (1)
\]

\[
s.t. \ W = c_1 + s + M \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (2)
\]

\[
c_2 = (1 + r)s - \gamma(T_2 - T_1)s \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (3)
\]

\[
E = \left(1 - \rho_4 \frac{M}{W}\right)(\rho_5(c_1 + s)) \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (4)
\]

\[
P_2 = \rho_0 E + P_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (5)
\]

\[
T_2 = \rho_1(P_2 - P_1) + T_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad (6)
\]

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 CO₂ last time.

This time, we want to talk about Emissions, \( E \), \( \rho_0 \) the relationship between emissions and concentration, and \( \rho_5 \) 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 $2.12 \times \frac{44}{12} = 7.77$ 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:

The concentration of CO$_2$ in the atmosphere is now about 407 ppm. This is equal to 863 Gt C and 3162 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.

<table>
<thead>
<tr>
<th></th>
<th>Lifetime in the atmosphere (years)</th>
<th>100-year Global Warming Potential (GWP)</th>
<th>Percentage of 2000 emissions in CO$_2$e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>5-200</td>
<td>1</td>
<td>77%</td>
</tr>
<tr>
<td>Methane</td>
<td>10</td>
<td>23</td>
<td>14%</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>115</td>
<td>296</td>
<td>8%</td>
</tr>
<tr>
<td>Hydrofluorocarbons (HFCs)</td>
<td>1 – 250</td>
<td>10 – 12,000</td>
<td>0.5%</td>
</tr>
<tr>
<td>Perfluorocarbons (PFCs)</td>
<td>&gt;2500</td>
<td>&gt;5,500</td>
<td>0.2%</td>
</tr>
<tr>
<td>Sulphur Hexafluoride (SF$_6$)</td>
<td>3,200</td>
<td>22,200</td>
<td>1%</td>
</tr>
</tbody>
</table>


From Stern 2008, table 8.1
**CO₂ is not the only GHG II**

- Current atmospheric concentration of CO₂ is about 407 ppm. Using the numbers above, current CO₂e is \( \frac{407}{0.77} = 529 \text{CO₂e} \)

- From the forcing tables we see that non-CO₂ has about half the forcing capacity of CO₂. However, non-CO₂ 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 $\text{CH}_4$ for $\text{CO}_2$. To do this, define $\alpha_t$ as the change in radiative forcing from one unit of emissions of the gas at $t$, i.e. $\frac{\text{W}}{\text{m}^2 \text{ton}}$. Define GWP as warming potential relative to $\text{CO}_2$,

$$GWP(\text{CH}_4) = \frac{\int_0^T \alpha_{\text{CH}_4}(t) \, dt}{\int_0^T \alpha_{\text{CO}_2}(t) \, dt}$$

- Example, suppose $t = 1, 2, 3$ and for $\text{CO}_2$,
  $$(\alpha_{\text{CO}_2}(1), \alpha_{\text{CO}_2}(2), \alpha_{\text{CO}_2}(3)) = (1, 1, 1)$$
  and for $\text{CH}_4$,
  $$(\alpha_{\text{CH}_4}(1), \alpha_{\text{CH}_4}(2), \alpha_{\text{CH}_4}(3)) = (2, 0, 0).$$
  Then $GWP(\text{CH}_4) = \frac{2+0+0}{1+1+1}$
What is ‘Global Warming Potential’? II

Issues:

- $T$ is completely arbitrary. GWP of $\text{CH}_4$ 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.
Carbon cycle

**Units!**

Stern 2007 p193 gives $\text{CO}_2\text{e}$ emissions for 2000 as 42Gt $\text{CO}_2\text{e}$. Hansen has 8.5 Gt C from fossil fuel. Can we reconcile these numbers?(Yes)

- About .77 of $\text{CO}_2\text{e}$ is $\text{CO}_2$.
- About .18 of $\text{CO}_2$ is non fossil fuel (more on this later)
- Stern reports $\text{CO}_2$, Hansen C

so, Stern’s 42 Gt $\text{CO}_2\text{e}$ becomes:

$$42 \times (0.77(1 - 0.18)) \times (12/44) = 7.2 \text{ Gt of atmospheric C}.$$  
It would be closer, but Stern uses 2000 numbers and Hansen’s 8.5 is for about 2008.
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 CO₂) 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
Atmospheric carbon cycle

**Atmospheric CO\textsubscript{2} cycle, data I**

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

- Calculate annual change in CO\textsubscript{2} 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 carbon cycle

Atmospheric CO₂ cycle, data II

Hansen 2009 figure 16
Atmospheric carbon cycle

Atmospheric CO₂ cycle, data III

So, concentration yield of emissions is about .55. Thus,
- \((1/0.55)= 1.8 \text{ Gt c emissions gives } 1 \text{ Gt ton of atmospheric C .}\)
- 2.12 Gt atmospheric C to gives 1ppm atmospheric C (or CO₂ ).
- Multiplying, \(1.8 \times 2.12 = 3.8\text{Gt c of emissions to get 1ppm of atmospheric concentration.}\)

Recall the carbon cycle equation from our model:

\[
P_2 = \rho_0 E + P_1.
\]

We have just calculated that \(\rho_0 = \frac{1}{3.8} = 0.26 \frac{\text{ppm C (or CO}_2\text{)}}{\text{Gt c}}.\)

What is \(\rho_0\) if we denominate emissions in terms of CO₂ ?
Atmospheric carbon cycle

Atmospheric \( \text{CO}_2 \) 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 absorption 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 absorption varies with temperature or \( \text{CO}_2 \) (it probably does) and there is a lot of uncertainty about this relationship.
Emissions for particular activities I

- \( \text{CO}_2 \) from gasoline, 2.3 kg/liter = 19.4 pounds/gallon. So, 1000 kg of \( \text{CO}_2 \) emission results from 435 liters or 114 gallons of gas. (about 1% not burned is mostly \( \text{N}_2\text{O} \) so \( \text{CO}_2 \text{e} \) is higher).

- \( \text{CO}_2 \) from diesel 2.7 kg/liter = 22.2 pounds/gallon 1000 kg of \( \text{CO}_2 \) 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 \( \text{CO}_2 \). (NB Gasoline weighs 6.3 pounds/gallon so 18 pounds of gas gives about 54 pounds \( \text{CO}_2 \). 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](http://www.epa.gov/sequestration/faq.html) For tropical forests, about 1.8 times as much [not reliable source](http://www.epa.gov/sequestration/faq.html).

- 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$_2$e is higher. Baseload will usually be lower (often nuclear or hydro) [http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11](http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11).
Emissions for particular activities III

- For natural gas, about 1200lb $\text{CO}_2$ 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 $\text{CO}_2$, 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 CO\textsubscript{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 \(\frac{13.3 \times 10^9}{77 \times 10^{12}}\) tons c USD = \(\frac{13.3}{7700}\) ton c USD \(\sim 0.17\) kg c USD (1 ton = 1000 kg). Multiply by 44/12 for CO\textsubscript{2} instead of c.

Recall the third equation from our global warming model:

\[ E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + s)) \] (7)

We’ve just calculated \(\rho_5\). Why is this sloppy?
Consumption and emissions

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.

- What if China and Africa made the same output at US/CA emission rates? This is why technology transfer is important.

- Compare 0.68 kg $\text{CO}_2$e per dollar ca. 2004 to my calculation of 0.17 kg c per dollar 2013. How important is technical progress?

IPCC 2007 Mitigation fig SPM.3b
Technological progress I

Figure 3. U.S. Greenhouse Gas Emissions per Capita and per Dollar of GDP, 1990–2013

Technological progress II

Nordhaus does this calculation every year, country by country.

Figure 3-1. Historical ratios of CO₂ emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of CO₂ 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 CO₂-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 CO₂-GDP ratios.
Emissions - Summary

- We’ve now calculated $\rho_5$, emissions per GDP at about 0.17kg of 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 differences 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,

$$\max_{s,M} u(c_1, c_2)$$ \quad (8)

s.t. $$W = c_1 + s + M$$ \quad (9)

$$c_2 = (1 + r)s - \gamma(T_2 - T_1)s$$ \quad (10)

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

$$P_2 = \rho_0 E + P_1$$ \quad (12)

$$T_2 = \rho_1(P_2 - P_1) + T_1$$ \quad (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.
Right panel gives confidence bounds for 2010. 49Gt CO$_2$e in 2010.
CO₂ by purpose and country income 1750-2010

Emissions

IPCC 2013 WG3 fig TS.2
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$_2$e by purpose

Greenhouse Gas Emissions by Economic Sectors

- Electricity and Heat Production: 25%
- AFOLU: 24%
- Buildings: 6.4%
- Transport: 14%
- Industry: 11%
- Other Energy: 9.6%
- Energy: 1.4%
- Industry: 11%
- Transport: 0.3%
- Buildings: 12%
- AFOLU: 0.87%

49 Gt CO$_2$eq (2010)

IPCC 2013 WG3 fig TS.3
2010 CO₂e by purpose and country income

IPCC 2013 WG3 fig TS.3
Emissions

US 1990-2012 CO$_2$e

This reflects: fracking, recession, technical progress, off-shoring of manufacturing.

Emissions per person

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

As of 2012 US had 4.54 tons CO₂eq/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 CO₂

- Emissions are about 13Gt C per year.
- The ocean and biosphere absorb about 45% at current concentration of 400ppm.
- 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 CO₂ (but not climate).
- This involves a 55% decrease. For an average American 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.
Current emissions of $\text{CO}_2\text{e}$ are about 49Gt. Of this, 35Gt is $\text{CO}_2$, and of this, about 30Gt is 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 $\text{CO}_2\text{e}$ was 30Gt.

2010 $\text{CO}_2\text{e}$ : 14% transport, 18% buildings, 21% industry 24% AFOLU. We could use this to calculate refinements of $\rho_5$.

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

Source: International Energy Agency
Conclusion

Conclusion I

Here is where we stand with our model:

\[
\max_{s, M} u(c_1, c_2) \tag{14}
\]

s.t. \( W = c_1 + s + M \) \tag{15}

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

\[
E = \left(1 - \rho_4 \frac{M}{W}\right) \left(\rho_5 (c_1 + s)\right) \tag{17}
\]

\[
P_2 = \rho_0 E + P_1 \tag{18}
\]

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

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, $\gamma$, 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 greenhouse 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$_2$. 
Emissions are about 13Gt c for 2015. The rate at which atmospheric \( \text{CO}_2 \) is increasing has risen from about 1ppm/yr 1960s to 2ppm for 2000’s. Since there is lots of fuel, we should expect atmospheric \( \text{CO}_2 \) to continue to increase and at an increasing rate. ‘business as usual scenarios call for atmospheric \( \text{CO}_2 \) e > 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.
Steady state CO\textsubscript{2} emissions are probably very small, Stern suggests less than 1/3 of current. Our calculations suggest (1-0.55)\(=\)45\%. 