EC1340 Topic #1

Introduction
and
Accounting for Carbon

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Outline

Stabilizing atmospheric CO_2

- World emissions of C in 2013 (most recent IPCC report) were about 13 Gt. Stabilizing atmospheric concentrations (not temp) requires cutting this about in half to 6.5Gt.
- There are about 7.4 bn people in the world as of 2015. Stabilization requires reducing emissions to 6.5Gt/7.5bn $<$ 1t C emissions per person.
- Current per capita emissions/incomes are about: US/CA/AU, 4.6t/55000$; China is 1.8/7600$; India is 0.5/1500$.
- The US needs between a 50% and 80% reduction to hope to reach this target.

This appears difficult to accomplish without reducing the number of people, their consumption, or being very clever. Being clever looks attractive here.

Some questions

- The Green New Deal proposes meeting 100% of US power demand with renewables. Is this a good idea?
- Given that the RGGI (Regional Greenhouse Gas Initiative) is in place, is the state carbon tax Aaron Regunberg proposed a good idea? RGGI website is here, https://www.rggi.org/. As of Q2 2019 the allowance auction cleared at $5.62 per allowance. An allowance allows emission of 1 short ton of CO2 by New England power plant $>$ 25MW.(short ton $=$ 2000lb $<$2200lb $=$1000kg$=$ 1 metric ton).
- How scary is this animation? https:/matthewturner.org/ec1340/lectures/pnas.1512482112.sm01.avi (personal correspondence, Anders Leverrmann, Sept. 2018).

Contents of the course

We would like to think carefully about the questions that climate change raises. For example,

- How fast should we approach CO_2 stabilization?
- What are the trade-offs between economic welfare and climate?
- What policies should we use to achieve CO_2 reductions?

To think about these questions, it would be helpful to have a model in which the tradeoffs between consumption, emissions and climate at one time and another can be explicitly calculated and examined.

The model developed in ‘A Question of Balance’ does exactly this, and one of the main objectives of the course is to allow you to read this book and to understand what it does.

As a preview, here is some of the Nordhaus, DICE (Dynamic Integrated Climate Economy) model:

$$W = \sum_{t=0}^{24} L(t) \frac{c(t)^{1-\alpha}}{1-\alpha} \left(\frac{1}{1+\rho} \right)^{t} \tag{1}$$

$$Q(t) = \Omega(t) \left[1 - \Lambda(t)\right] A(t) K(t)^{\gamma} L(t)^{1-\gamma} \tag{2}$$

$$Q(t) = C(t) + I(t) \tag{3}$$

$$K(t) = I(t) + (1 - \delta_K) K(t-1) \tag{4}$$

$$E(t) = \sigma(t) \left[1 - \mu(t)\right] A(t) K(t)^{\gamma} L(t)^{1-\gamma} \tag{5}$$

$$\Lambda(t) = \pi(t) \theta_1(t) \mu(t)^{\theta_2} \tag{6}$$

plus a description of the way climate, carbon, population and technology evolve.

The DICE model has more stuff in it than we need to start thinking about the problem (and it's a bit hard).

What is the minimum amount of hardware that we need to discuss this problem? We need to describe (at least),

- how CO_2 affects climate (a climate model).
- the carbon cycle.
- how CO_2 comes from consumption.
- how climate affects consumption (and/or utility).
- how we can use resources to reduce CO_2 , i.e., a mitigation equation.
- how we are willing to make tradeoffs across time.

Notice several of these items describe physical science surrounding climate change. These are covered in the other main reading for the course, 'Storms of my grandchildren'.

Here is the math that goes with the list we just generated. It looks a lot like the 'consumer problem' you know, but with more complicated budget constraints. This will help us to organize ideas and keep track of our progress. Once we have worked our way through this problem, we'll be ready to tackle Nordhaus.

To start, we'll need some notation,

- $c_1, c_2 =$ per capita consumption now and in 100 years
- $W =$ per capita wealth/income today
- $I =$ investment today
- $M =$ expenditure on mitigation today
- $E_1 = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) =$ Emission of CO_2 today increases in I, c_1 and decreases in M
- $P_1, P_2 =$ Atmospheric concentration of CO_2 now and in 100 years
- $T_1, T_2 =$ climate now and in 100 years

Using this notation, we can state the 'baby DICE ' model (BDICE) as

$$
\begin{aligned}
&\max_{I,M}\ u(c_1, c_2) && \text{utility} && (7)\\
&\text{s.t. } W = c_1 + I + M && \text{budget} && (8)\\
&\quad c_2 = (1+r)I - \gamma(T_2 - T_1)I && \text{production} && (9)\\
&\quad E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) && \text{emissions} && (10)\\
&\quad P_2 = \rho_0 E + P_1 && \text{carbon cycle} && (11)\\
&\quad T_2 = \rho_1(P_2 - P_1) + T_1 && \text{climate model} && (12)
\end{aligned}
$$

- Choose savings and mitigation to maximizes welfare u. $\Longrightarrow$ carbon concentration path. These are the IPCC's 'Representative Concentration Pathways(RCPs)'
- Physical quantities like climate or the relationship between CO_2 concentration and climate are like prices and endowments.

We're going to work towards an understanding this problem, one parameter and equation at a time. To do this, we'll need to study the following topics

- Emissions and endowment of atmospheric carbon, E, ρ_5, P_1 and P_2.
- The endowment of climate, T_1.
- The link between atmospheric CO_2 and future climate, ρ_1, T_1.(climate model)
- The link between emissions and atmospheric CO_2 , ρ_0(Carbon cycle)
- Cost of climate change, γ.
- Cost of mitigation (reduction of emissions), ρ_4.
- What should u look like (discounting and uncertainty)

Once we understand this, we'll be able to think about solving the global warming problem, and we'll be ready to tackle the Nordhaus model.

Other things we'll want to think about that aren't in the basic global warming problem (but are in the Nordhaus model)

- Population growth
- Economic growth
- Dynamics – this is a dynamic problem, so c, T are consumption paths and climate paths. A wise regulatory program will reflect the fact that investments in climate and economic growth have different returns at different times. This will turn out to suggest a 'ramping up' of mitigation expenditures.
- There is LOTS of uncertainty. This makes everything more difficult.

These are just generalizations of the basic model.
With the model in hand, we'll be able to think about policies to manage CO_2 . This will be the last third of the course.

Units for measuring Greenhouse gases(GHG) I

We need to be careful about the units we use to track carbon.

- A Ton is 1000kg(about 2200lb). A Megaton (Mt) is 1000 tons. A Gigaton(Gt) is a billion tons or 1000Mt.
- A molecule of CO_2 , is about 44/12 as heavy as a molecule of C . Each ton of C is 44/12 tons of CO_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 .
- Each ppm of atmospheric C is about 2.12 Gt C or $2.12 \times (44/12) = 7.77 GtCO_2$. This is a standard conversion factor, both IPCC and Hansen use it. (gigatons = billion tons).

Units for measuring Greenhouse gases(GHG) II

In April 2021, the concentration of CO_2 in the atmosphere was 419 ppm. This is equal to 888 Gt C and 3257 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

- Aggregate all GHGs using conversion factors based on their 'global warming potential(GWP)'. This gives us measurements in terms of 'CO_2 equivalent' (CO_2e).
- April 2021 concentration of CO_2 was 419 ppm. Using the numbers above, current CO_2e is $419ppm/0.77 = 544ppm$ CO_2e .
- GWP combines the ability of a molecule to reflect radiation and its lifetime in the atmosphere. More on this later, it's pretty made up.
- Social scientists usually measure Green house gases in terms of CO_2 equivalent emissions:

Units, again

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.

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 .

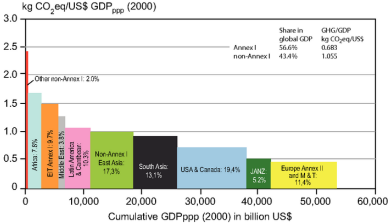
Recall the third equation from our global warming model:

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{13}$$

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

Emissions per unit of consumption by country

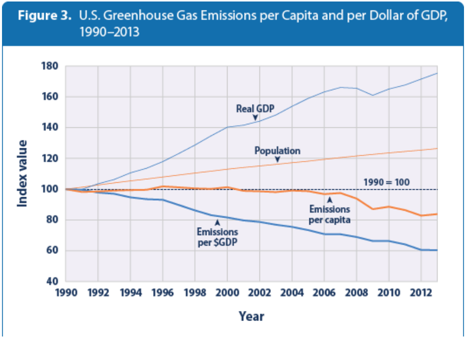
- It's also interesting to look at the country by country breakdown.(ca. 2004) The US and Canada make a lot of stuff per ton of emissions.



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

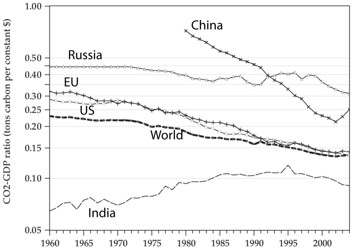


Figure 3-1. Historical ratios of CO_2 emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of CO_2 emissions to GDP for five major regions and the global total. We call the decline in this rate "decarbonization." Most major economies have had significant decarbonization since 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 I

- 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 - Summary II

Recall,

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

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

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

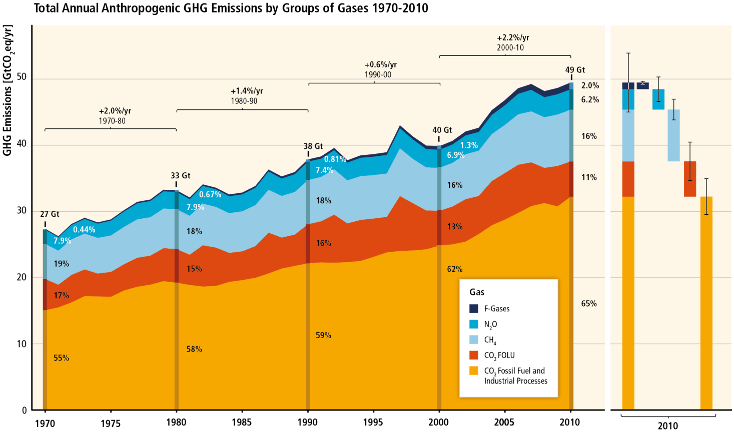
$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{17}$$

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

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

We've filled in $\rho_5 = 0.17kg/\$$. W is world GDP. If $M \approx 0$ then $W = c + I$. We actually know $E \approx$ 13GtC/year, but it's important enough to learn a little more about – coming up.

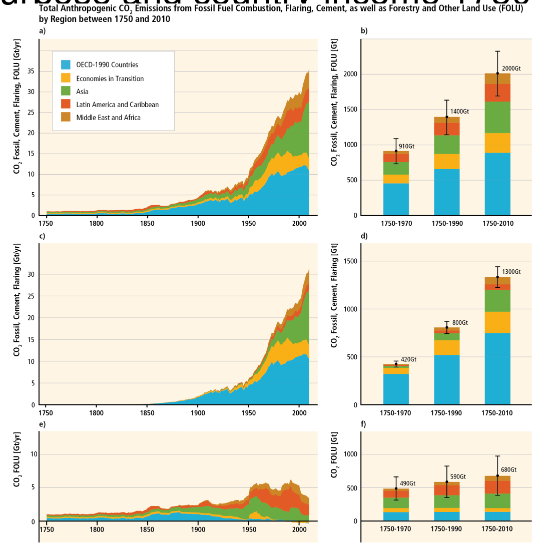
CO_2e 1970-2010



IPCC 2013 WG3 fig TS.1

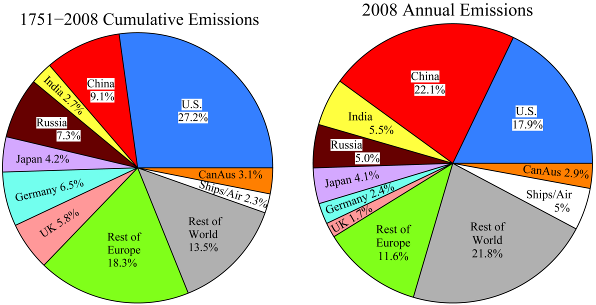
Right panel gives confidence bounds for 2010. 49Gt CO_2e in 2010.

CO_2 by purpose and country income 1750-2010



IPCC 2013 WG3 fig TS.2

Hansen's version of the same thing...

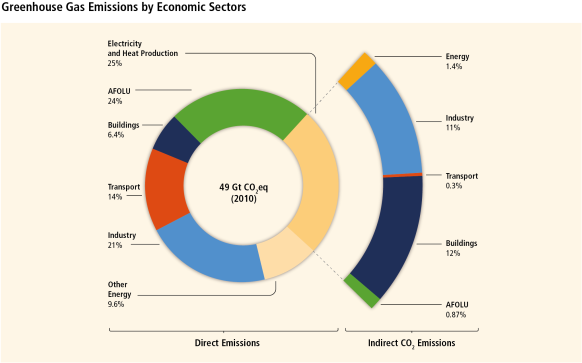


Flow Stock

Hansen 2009 fig 27

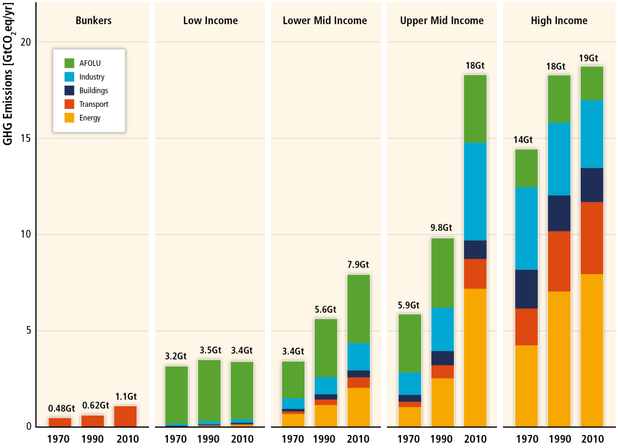
Contributions to stock and flow are very different. At the negotiating table, developing countries want the right to emit, since everyone else had their turn.

2010 CO_2e by purpose



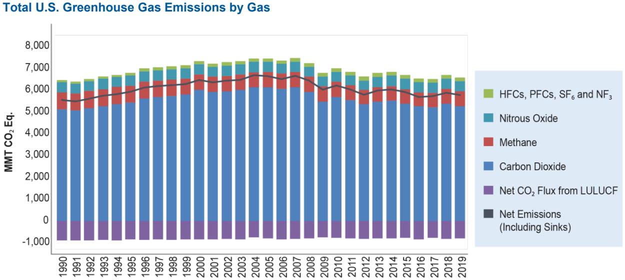
IPCC 2013 WG3 fig TS.3

2010 CO_2e by purpose and country income



IPCC 2013 WG3 fig TS.3

US 1990-2019 CO_2e

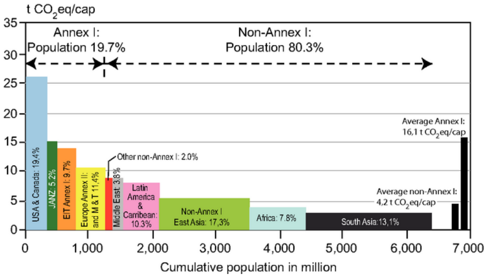


https://www.epa.gov/sites/production/files/2021-04/documents/us-ghg-inventory-1990-2019-data-highlights.pdf, May 2021

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:



IPCC 2007 Mitigation fig SPM.3a

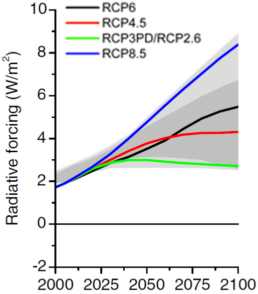
As of 2012 US had 4.54 tons C /person and for India, this number was 0.46. China was 1.8.(http://cdiac.ornl.gov/trends/emis/top2011.cap)

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.

Representative Concentration Pathways (RCPs)

The IPCC fifth assessment report is organized around RCP's. These are hypothetical future levels of CO_2 . This is what we get to choose. In BDICE, and RCP is just the future level of concentration, P_2.



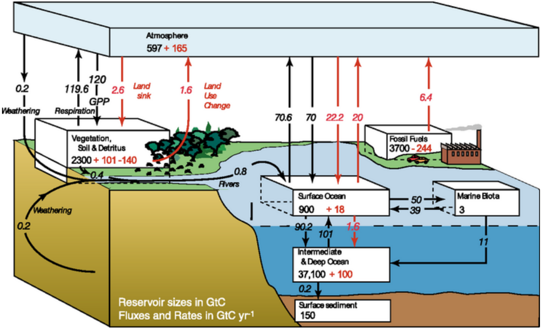
RCP 8.5 is 'business as usual' and involves CO_2 concentrations reaching 850ppm within 100 years. Other RCPs involve varying degrees of mitigation.

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

Basic atmospheric chemistry

- Nitrogen 78%, 780,000 ppm
- Oxygen 21%, 210,000 ppm
- Argon 0.93% 930 ppm
- CO_2 0.0365% , 365 ppm
- Methane (CH_4) 1.7 ppm

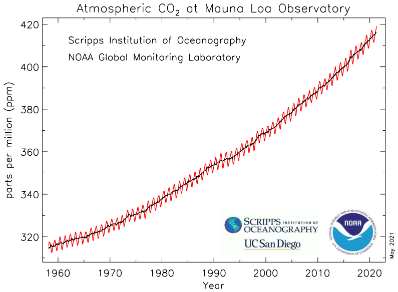
and lots of other trace gases. From: Introduction to Atmospheric Chemistry, D. J. Jacob, Princeton University press, 1999.

CO_2 concentration $=$ 409ppm in July 2018. 412ppm in July 2019. 419ppm in April 2021.

Pre-industrial norm is 280ppm. This will be P_1.

Atmospheric Carbon Measurements

Since 1959, the Mauna Loa observatory in Hawaii has measured atmospheric concentration of CO_2 daily. CO_2 disperses rapidly through the atmosphere, so a single observatory gives a good description of the whole world.



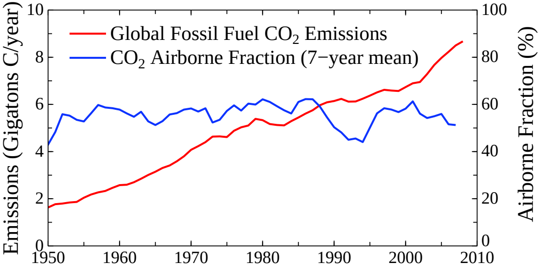
http://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.pdf

Atmospheric CO_2 cycle, data I

We can compare emissions data and concentration data for a purely empirical approach to the carbon cycle.

- 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 $\rho_0 = \frac{1}{3.8} = 0.26 \frac{ppm\ \mathrm{C}\ (\text{or } \mathrm{CO_2})}{Gt\ \mathrm{C}}$.

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'.

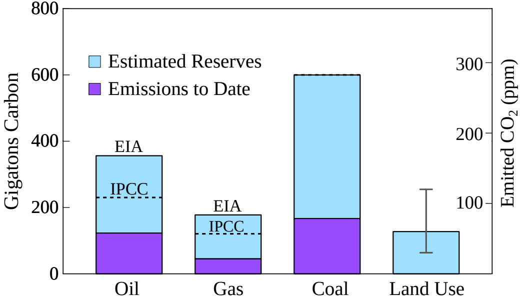
In AOGCM's the carbon cycle is modelled very carefully. We really want to deal with the possibility that absorbtion varies with temperature or CO_2 (it probably does) and there is a lot of uncertainty about this relationship.

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.

Will we run out of fossil fuel? I

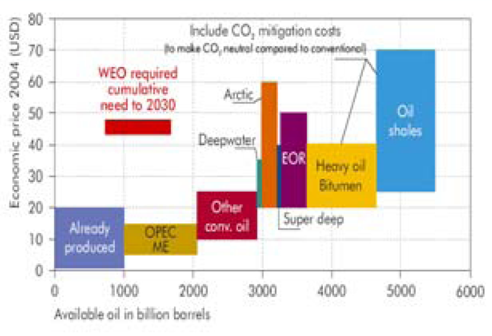
Not soon enough to matter:



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:

$$\max_{I,M} u(c_1, c_2) \tag{20}$$

$$\text{s.t. } W = c_1 + I + M \tag{21}$$

$$c_2 = (1 + r)I - \gamma(T_2 - T_1)I \tag{22}$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{23}$$

$$P_2 = \rho_0 E + P_1 \tag{24}$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \tag{25}$$

We've filled in a little more. We know E and how E is converted into P, that is ρ_0. We also know P_2. This is a policy for future concentration, or an RCP – it's something we get to choose.

Conclusion II

- Each ppm of atmospheric CO_2 corresponds to about 2.12 Gt C and 7.78 Gt of CO_2 . Pay attention to units.
- 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 emissions per 1ppm of atmospheric CO_2 .

Conclusion III

- 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 RCPs call for atmospheric CO_2e > 800 within 100 years.
- Not all countries are the same. They are responsible for different current and historical shares, have different per capita emissions, use emissions more or less efficiently. These factors are obstacles to international agreements, and suggest the need for a richer model.

Conclusion IV

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