Fundamentals of Climate Change (PCC 587): Carbon Cycle

DARGAN M. W. FRIERSON
DEPARTMENT OF ATMOSPHERIC SCIENCES

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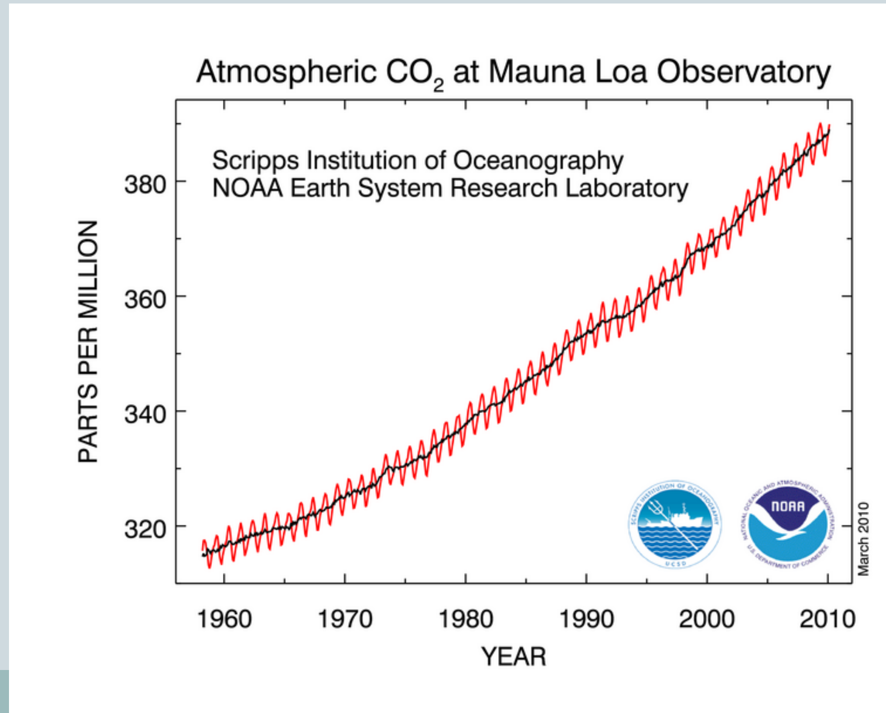
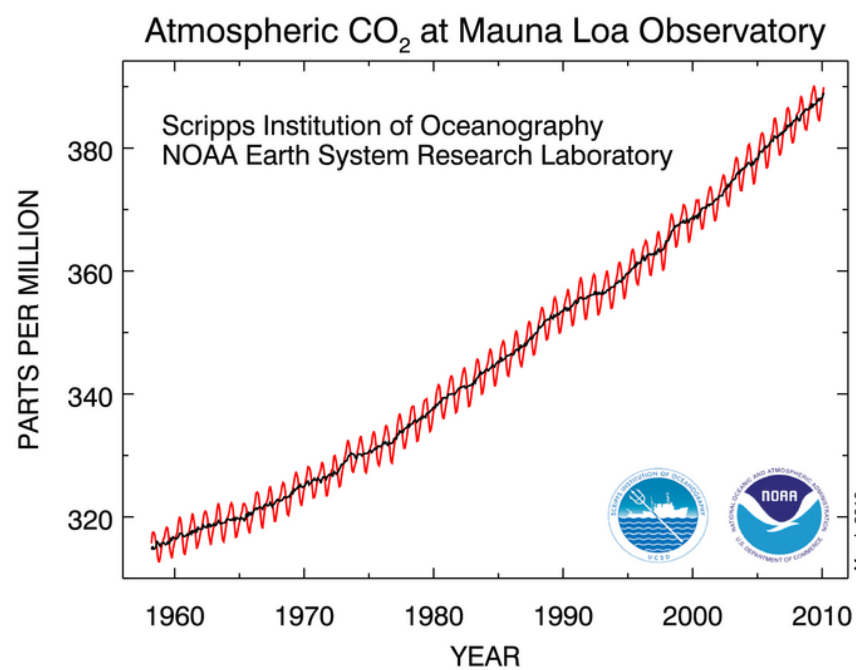
One More Important Record: CO_2

- A final important climate record: **carbon dioxide** levels
  - That CO_2 is rising rapidly due to human activity is **equally important** as the temperature rise in the whole big picture of global warming
  - Monitored accurately at **Mauna Loa** Observatory, Hawaii since 1958



The Mauna Loa Carbon Dioxide Record

- First reading in 1958: **316 ppm**
  - Most recent reading (last week): **391 ppm** (25% increase)
- Why Mauna Loa?
  - High mountains are away from **near-surface variations**
  - Hawaii gets clean ocean air most of the time

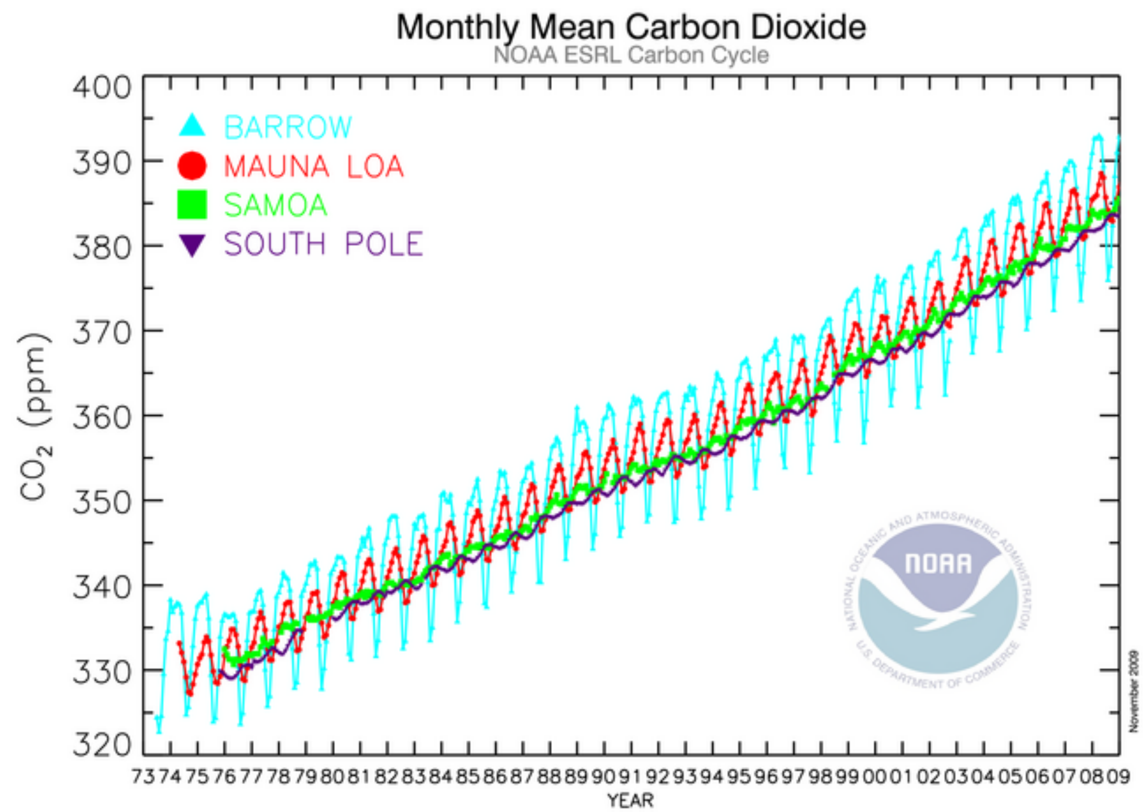


Carbon Dioxide at Other Sites

- Other sites agree with Mauna Loa, but with different seasonality

Seasonality is due to the growth of **vegetation** during summer, decay during winter

(May has the highest CO2 concentration in the NH)



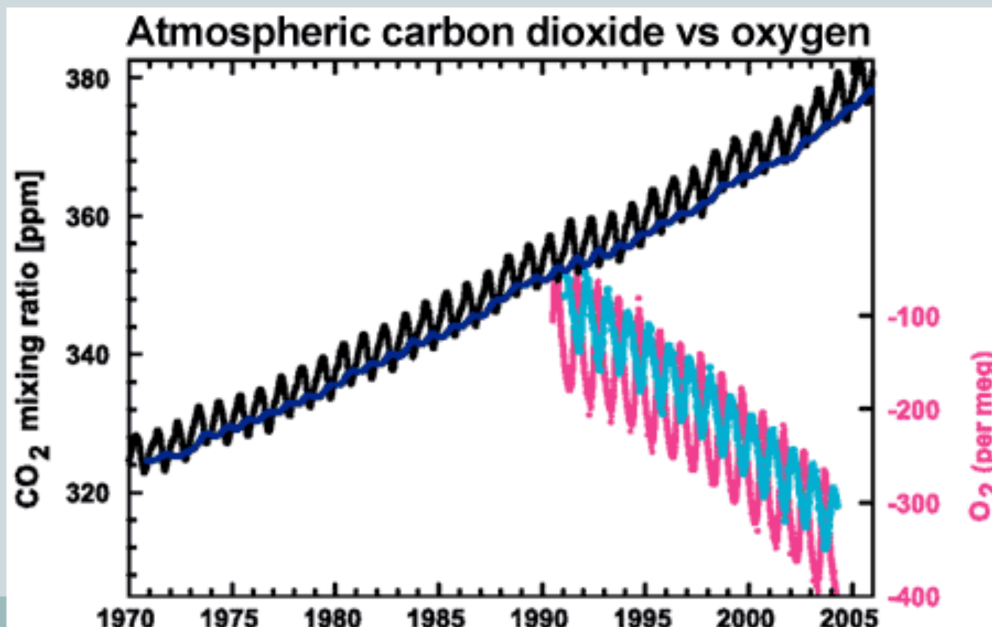
Atmospheric carbon dioxide mixing ratios determined from the continuous monitoring programs at the 4 Baseline Observatories. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Evidence of Anthropogenic Rise

- Comparisons with industrial fossil fuel usage and deforestation rates show **emissions** are larger than atmospheric increase
  - 55% of emissions goes into the ocean or terrestrial biosphere, 45% stays in the atmosphere
- As with the temperature record, there is **complementary evidence** for anthropogenic causes of carbon dioxide rise as well…

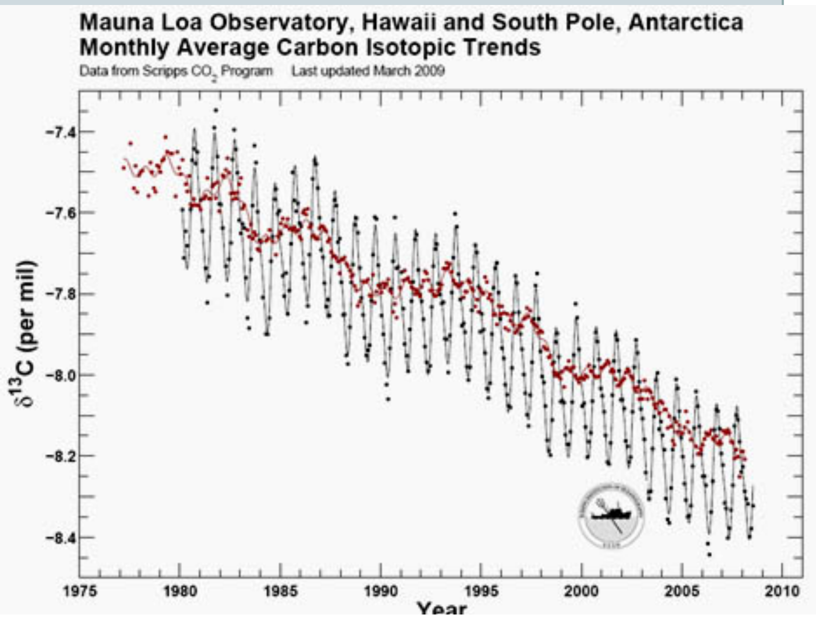
Evidence of Anthropogenic Rise

- Concentrations of **oxygen** have also been **decreasing**
  - Oxygen is used up when fossil fuels/forests are burned
  - If exchange with the ocean was the culprit, oxygen levels would stay the same



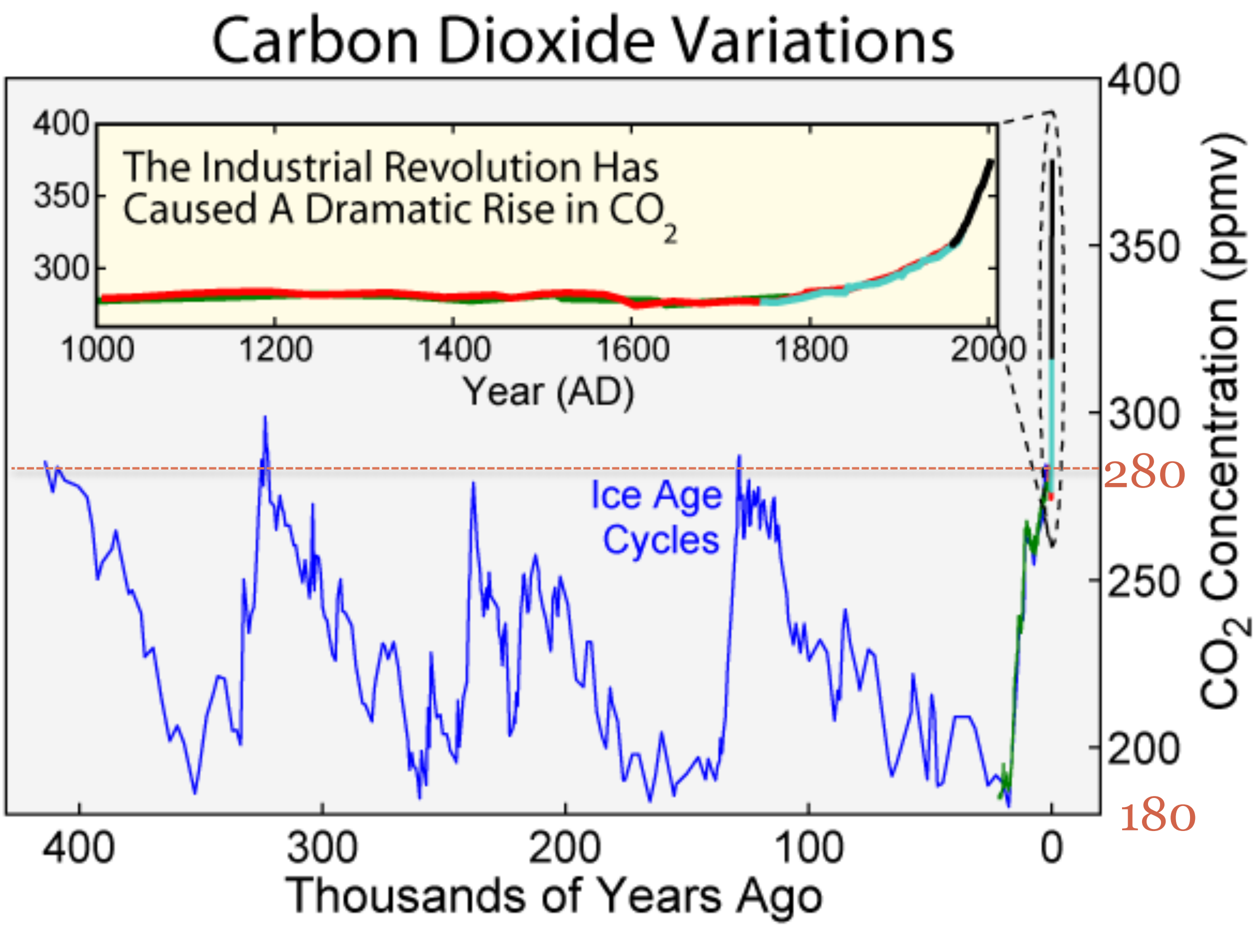
Evidence of Anthropogenic Rise

- Anthropogenic emissions also have different **isotope** concentrations
  - **Isotope**: have different number of neutrons in the atom, so different weight
  - Carbon isotopes: carbon-12, carbon-13, and carbon-14
  - **Plants** use **more carbon-12** than carbon-13 as compared with the atmosphere
  - Carbon-13 fraction has been decreasing (indicating burning of former plant/animal material is the culprit)



Connection to Paleoclimate

- We also know carbon dioxide levels are higher than they've been in several *hundred thousand years*



Natural variation over Ice Age Cycles: **180-280 ppm**

The Carbon Cycle

- Let's discuss the various reservoirs of carbon and the fluxes among them
- The **atmosphere** holds around 700 gigatons of carbon
  - 1 Gton = 1 billion (metric) tons = 10^12 kg
  - If it were all put into a layer of pure gas at surface pressure, would be about 10 feet deep
- Note sometimes these figures are quoted for *carbon dioxide* instead of *carbon* (multiply by 3.67 to convert from C to CO_2)
  - Especially companies who claim they're reducing their emissions use CO_2 (the *bigger* number)

Terrestrial Carbon Reservoir

- 500 Gtons carbon in living carbon on land
  - The "terrestrial biosphere"
  - Seasonal cycle in the terrestrial biosphere causes atmospheric CO_2 seasonal cycle
- 1500 Gtons carbon in dead carbon in soils

Ocean Carbon Reservoir

- **38,000** Gton inorganic carbon in the ocean
  - Dissolved CO_2, carbonic acid, etc
- 600 Gton of dead organic carbon (mostly old plant material)
- 1 Gton of living organic carbon
- Takes centuries for ocean to completely get in equilibrium with the atmosphere
  - Water must come in contact with the surface to dissolve atmospheric carbon into it

Solid Earth Carbon Reservoir

- Even bigger! But breathes even more slowly
- 1,200,000 Gton carbon in sedimentary rocks (mostly limestones)
- 5000 Gton carbon in fossil fuels
- How does carbon get into the earth? **Chemical weathering**
  - Changing *silicate* rocks into *sedimentary* rocks – very slow
  - Involves dissolving rocks via rainfall
  - Metamorphic decarbonation is the opposite – formation of CO_2 within metamorphic rocks

Silicate Weathering-CO_2 Thermostat

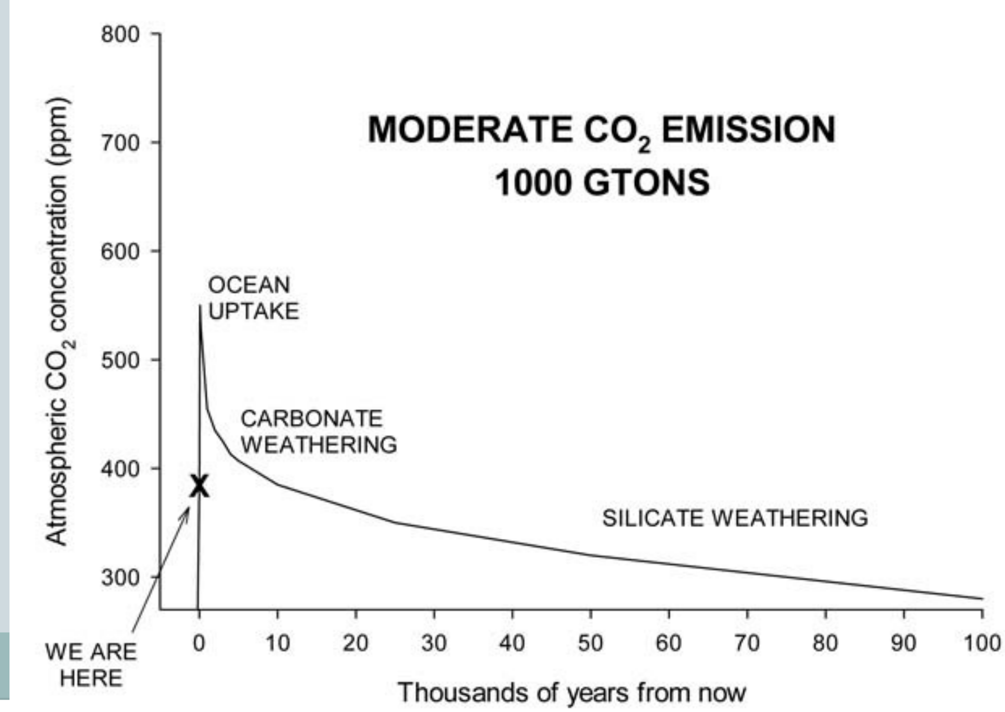
- Weathering is thought to be the primary stabilizer over very long periods of time
- More rainfall & weathering w/ high CO_2, leading to more CO_2 taken out of the atmosphere
  - Safety valve on climate
- Unfortunately dissolving of rocks takes a long time!

Anthropogenic Emissions

- Of CO_2 emissions, around 25% goes into the ocean immediately
  - Not necessarily a good thing -- causes ocean acidification
- 25% goes into the land currently
  - This fraction could change…
- 50% stays in the atmosphere
  - This is called the “airborne fraction”

What if we immediately stopped emitting?

- Some carbon would likely stay in the atmosphere for **thousands** of years!
- Ocean uptake happens "quickly" (300 yrs)
  - A few years for surface ocean to 300 yrs for deep ocean
- Carbonate weathering: as ocean pH recovers, more carbonate is formed & buried in deep ocean
  - Takes 5000 yrs
- Silicate weathering takes 100,000 yrs



Next: Who's Responsible?

- How much are average emissions for:
  - Citizen of the world
  - Average American
  - Nations of the world
- Which sectors do emissions come from?
  - Transportation
  - Electricity generation
  - Industry
- "Carbon efficiency"

How Much Carbon Dioxide Is There?

- Total amount of carbon dioxide in the atmosphere: 3000 gigatonnes
- World emissions: over 30 gigatonnes per year
  - 1 gigatonne = 1 billion metric tons
    - And one metric ton is a little more than a regular ton (2000 pounds)

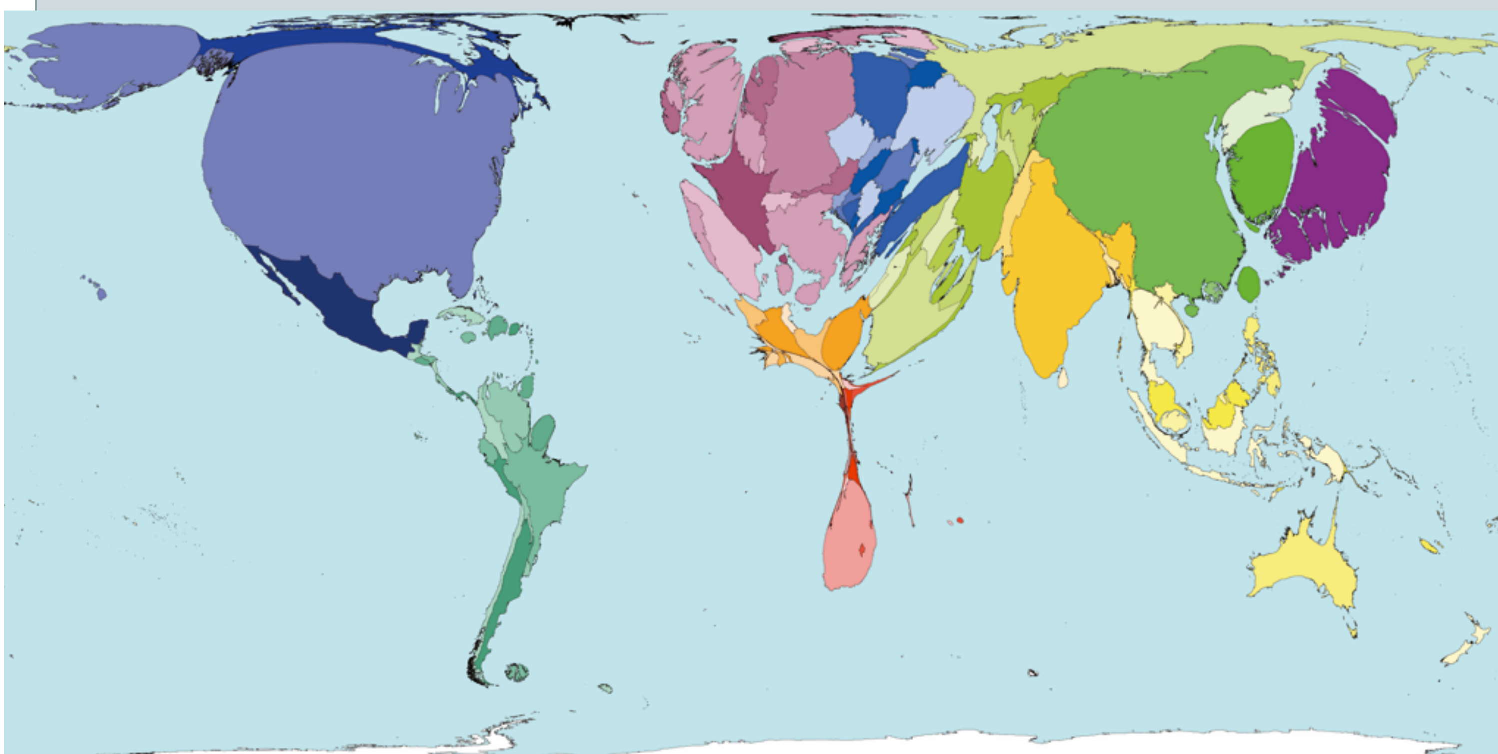
Countries by Fossil Fuel CO_2 Emissions

- China: 21%
- US: 19%
- European Union: 14%
- India: 5%
- Russia: 5%
- Japan: 4%
- All others less than 3% each

2007 data (CDIAC)

National Emissions

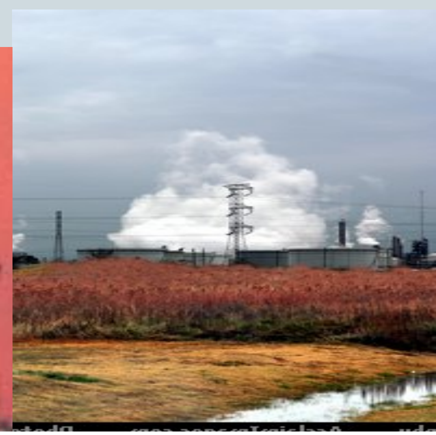
- Another way to look at national carbon dioxide emissions
  - Area of each country is made proportional to its emissions



Source of images: WorldMapper

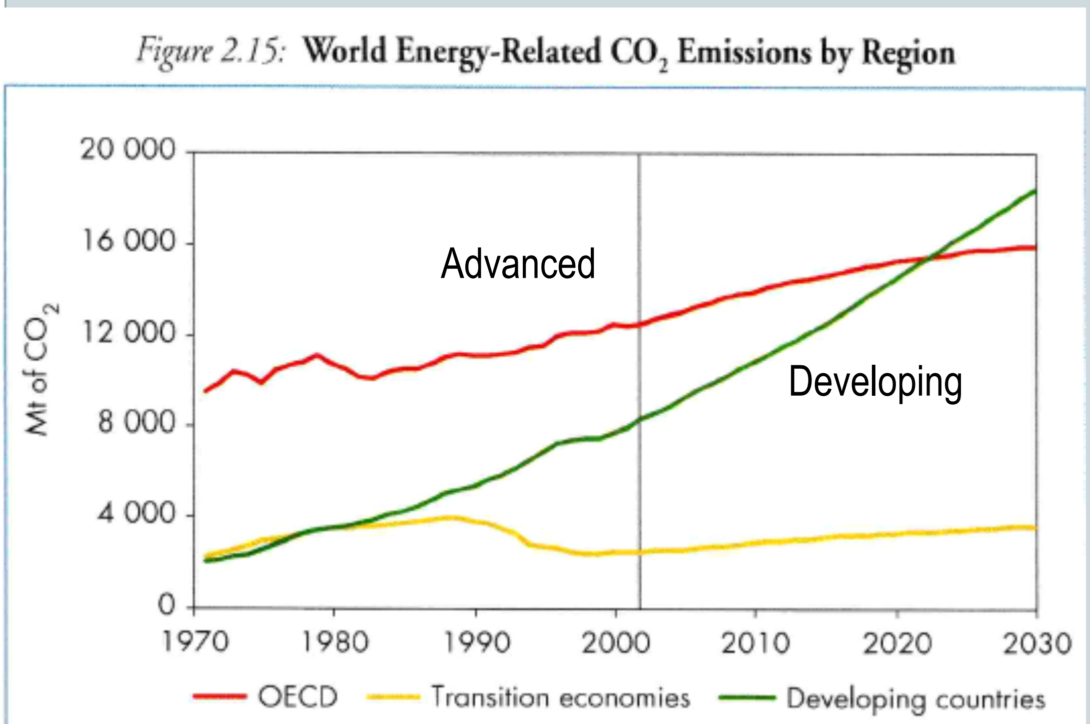
The Developing World

- Half of the people in the world live on less than $2.50/day
- 2.1 billion live without access to electricity

Future of Emissions for Developing Nations

- In around 20 years, the developing world will surpass developed countries in CO_2 emissions



Developing nations will be a massive energy market in the future…
What fuels will they use?
(this plot assumes no additional regulations)

OECD = Organization for Economic Cooperation and Development includes 30 countries, mostly industrialized

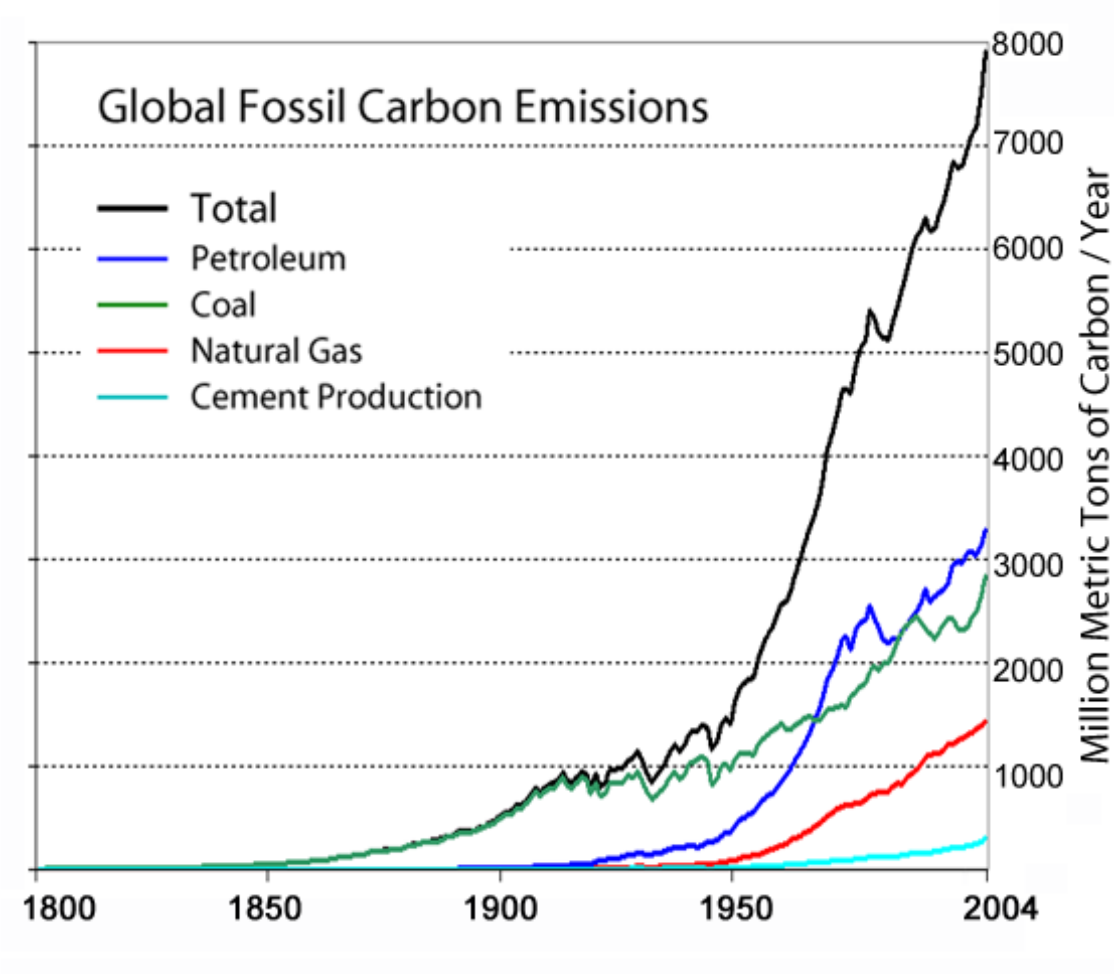
Emissions Numbers

- World average **per capita** emissions is a little less than 5 tonnes
  - World population: 7 billion → total emissions are a little more than **30 billion tonnes** (30 gigatonnes)

Countries by Per Capita CO_2 Emissions

- World average is 4.6 tonnes per year
- Highest are **oil producing** states (e.g., Qatar)
- **US** is rather high (11^{th}): 4x world average (**19** tonnes per person)
  - **Australia**, **Canada** have similar emissions as **US** per capita
- Many **EU** countries, **Russia**, **Japan**: **10** tonnes
- **Sweden**, **Switzerland**, **China**: **5** tonnes
- **India**: **1.1** tonnes

What Makes Up the Emissions?



80% fossil fuel burning, 20% deforestation

Coal and oil makes up 80% of worldwide fossil fuel emissions

Oil for transportation, coal for electricity

What Makes Up the Emissions?

- Electricity generation: 25%
- Deforestation: 18%
- Transportation: 14%
  - Rising rapidly
- Industry: 14%
  - Getting **more efficient** & dropping in importance
  - More and more shifting to developing countries like China, India
    - Another equity concern: "carbon leakage"
- Other fuel-related emissions: 14%
  - Coal, oil, and gas production
- Agriculture: 14%

From textbook & World Resource Institute

US Emissions Sources

- Electricity: 42%
- Transportation: 32%
- Industry: 15%
- Residential: 6%
- Commercial: 4%

- 2008 data, EPA

US Emissions Sources

- If you distribute electricity use into the other sectors:
- Transportation: 32%
- Industry: 27%
- Residential: 21%
- Commercial: 19%

- 2008 data, EPA

U.S. Energy Sources

U.S. **energy** sources (2007):

- Oil 40%,
- Coal 23%,
- Natural gas 22%,
- Nuclear 8%,
- Renewables:7%

Oil for transportation, coal for electricity

(U.S. **electricity** sources: coal, nuclear and renewables dominate)

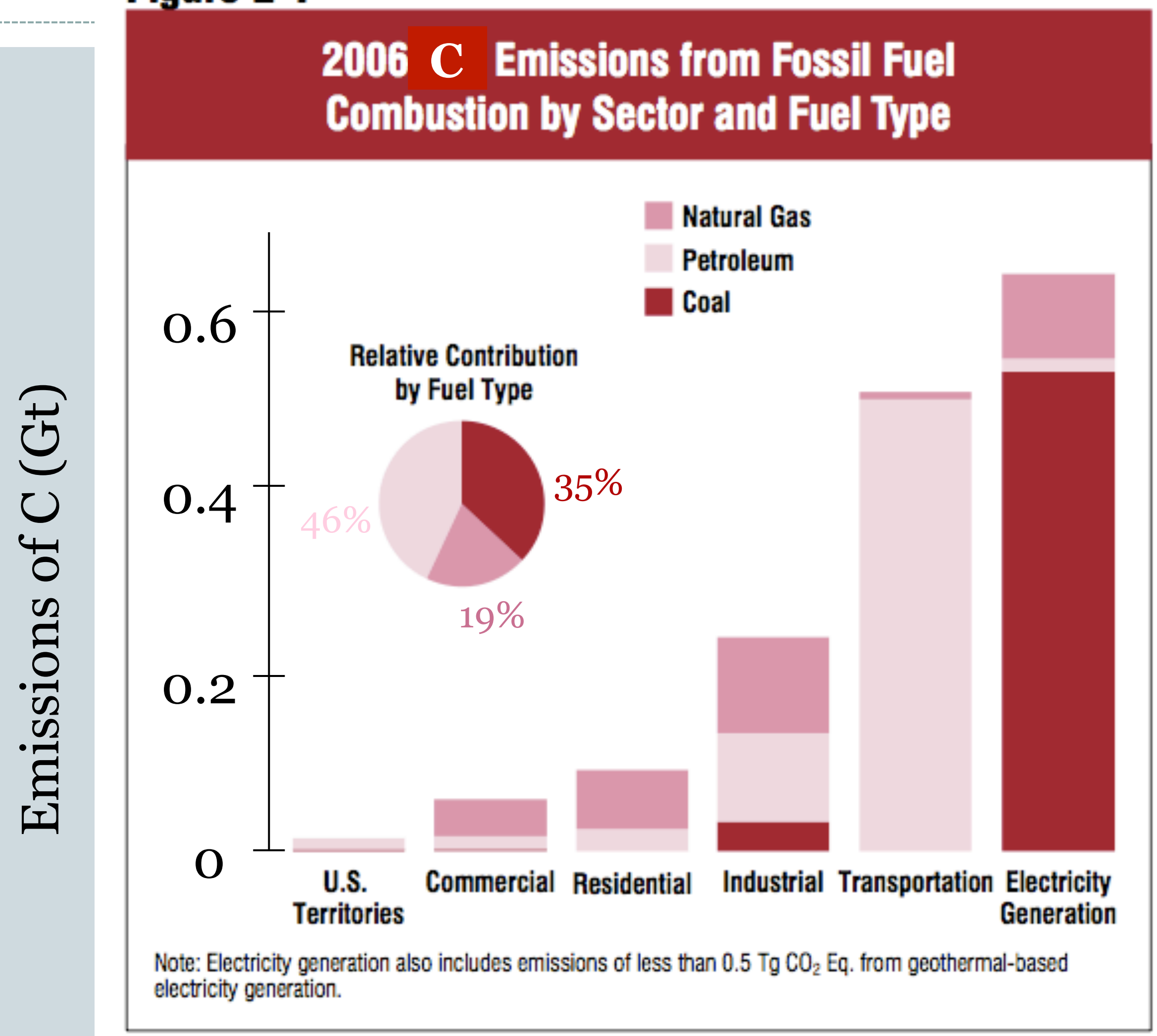
Useful Facts about CO2

- CO_2 per unit energy emitted:
  - Coal emits 67% more CO2 than natural gas
  - Coal emits 30% more CO2 than oil
  - Coal is a 'dirty fuel'

- U.S. CO_2 emissions by energy sources (2007):
  - Oil 46%,
  - Coal 35%,
  - Gas 19%,
  - Renewables and nuclear ~0%

US Emissions 2006

Figure 2-7



Emissions of C (Gt)

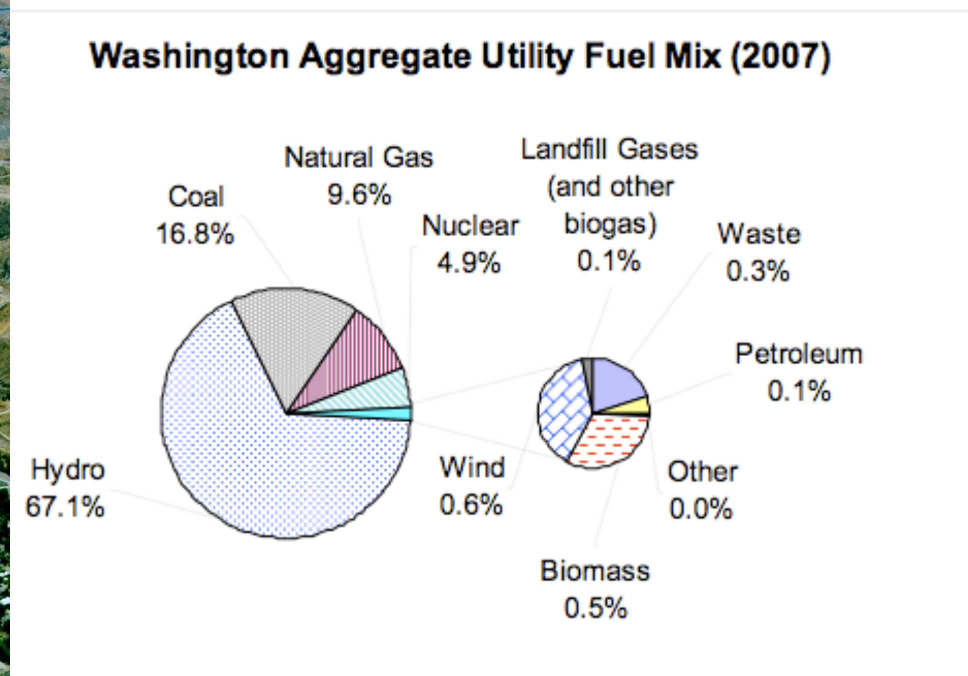
CO_2	
Electricity	0.63
Transport	0.51
Industry	0.24
Residential	0.09
Commercial	0.06
Other	0.10
Subtotal	1.63
CO_2 equiv	
CH_4	0.15
N_2O	0.10
HFC, etc	0.04
Total	1.93

(for reference: global emission is ~10 Gt C/yr)

Source EPA #430-R-08-005 (April 2008)

In Washington we have Hydro Power

- About 7% of the U.S. *electricity* comes from hydropower
    - 67% of Washington's electricity
- Extremely expensive to build new facilities
- Possible extreme environmental damage to flooded area and fish migration
- Not likely to see more dams built in the U.S.



How About in Seattle?

- Recent study by Brookings Institution says Seattle is 6th best in the country (5.7 tons CO_2 each per year)
  - Hydroelectric power means small electricity emissions
  - Relatively mild climate means small home heating
  - Surprisingly, Los Angeles was #2 in this study
- Study did not include industrial emissions, or airplane travel (which constitutes most of my personal footprint)
  - Also only CO_2, no methane, etc
  - No emissions associated with where we get food & goods either

Summary

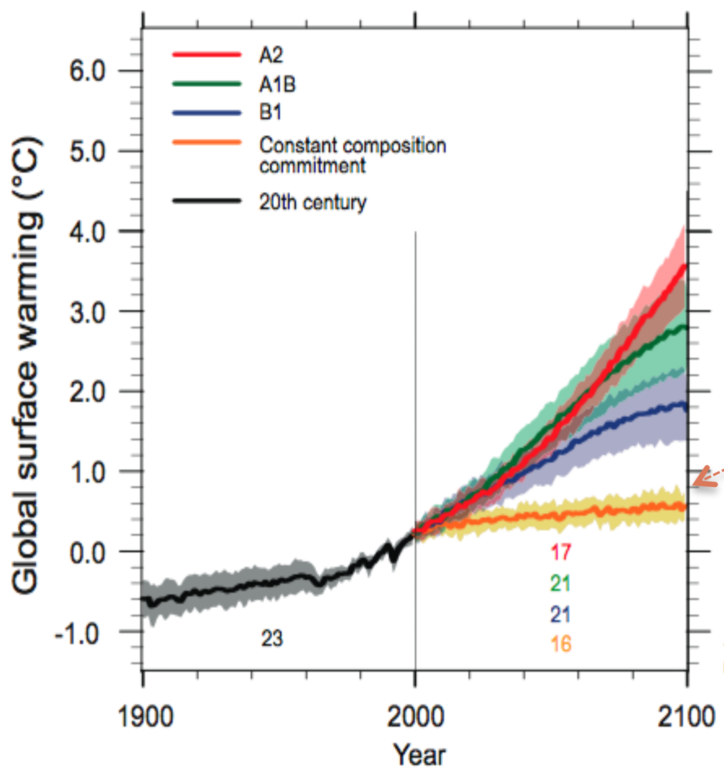
- Big problem spanning lots of different sectors
  - Can’t blame just one type of energy use
- Trends in energy use
  - Industry is getting more efficient
  - Residential is getting worse
    - Partially due to significantly larger home sizes
  - Transportation is getting worse
    - More cars on the roads, longer driving distances

Next: Solutions

- First, the bad news
  - How much we will have to cut emissions to make a difference
- Then, the good news
  - What changes we can make to get this done: we can fix it!
  - And many of the changes we'll need to make will be beneficial in other ways

Goals for Fixing the Problem

- One goal: minimize temperature increase
- But recall that some warming is **locked in** even if we keep CO_2 concentrations *exactly at today's levels*

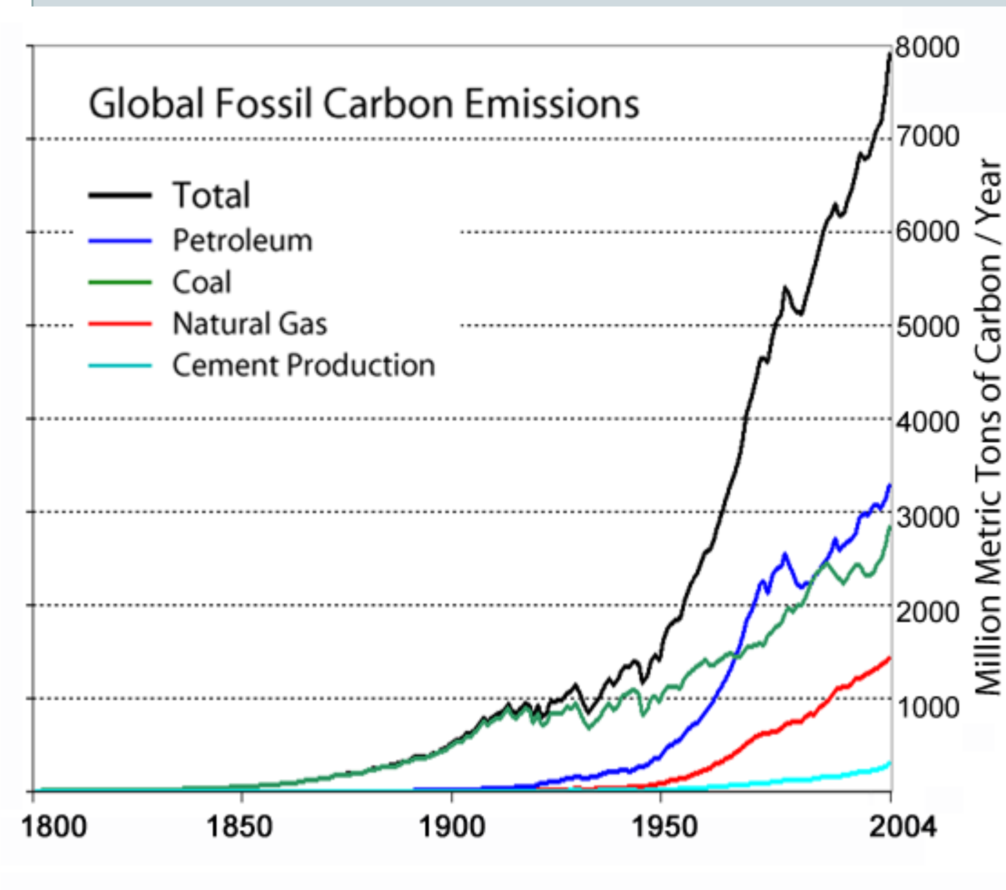


The yellow experiments assume concentrations are held constant at year 2000 values

Temperatures still increase by **0.5° C** (because the ocean takes time to warm)

How to Prevent Higher CO_2 Concentrations

- Higher CO2 levels mean higher temperatures eventually: how to avoid?



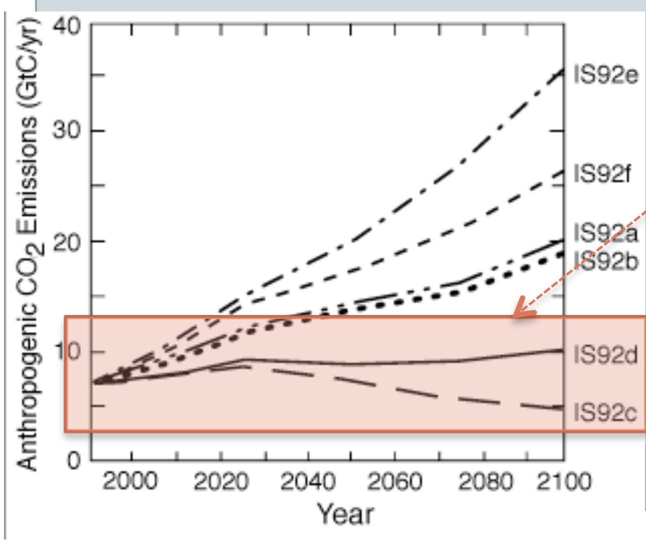
Emissions are increasing rapidly

Is flattening out emissions enough?

Is Stabilizing Emissions Enough?

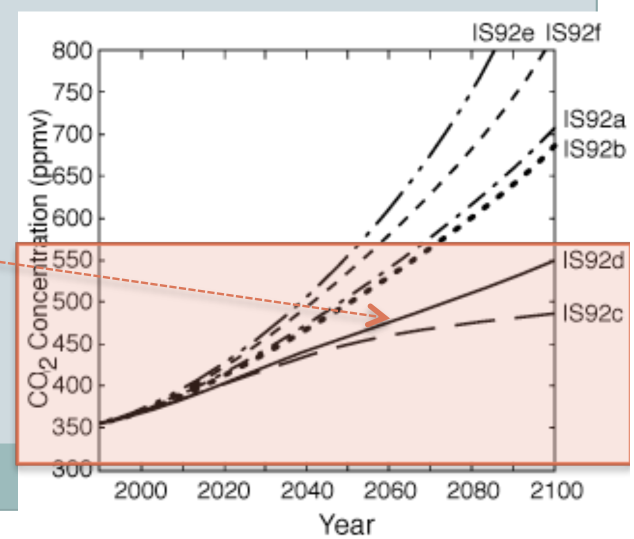
- **No!** Flattening out CO_2 emissions still leads to large increases in CO_2 concentrations
  - Imagining blowing air into a balloon: you have to **stop blowing** into it to stop it from getting bigger!
    - (The real system is a little less extreme than this, as the **ocean** can take up a small amount of emissions)

Emissions



Flat **emissions** lead to **concentrations** that increase…

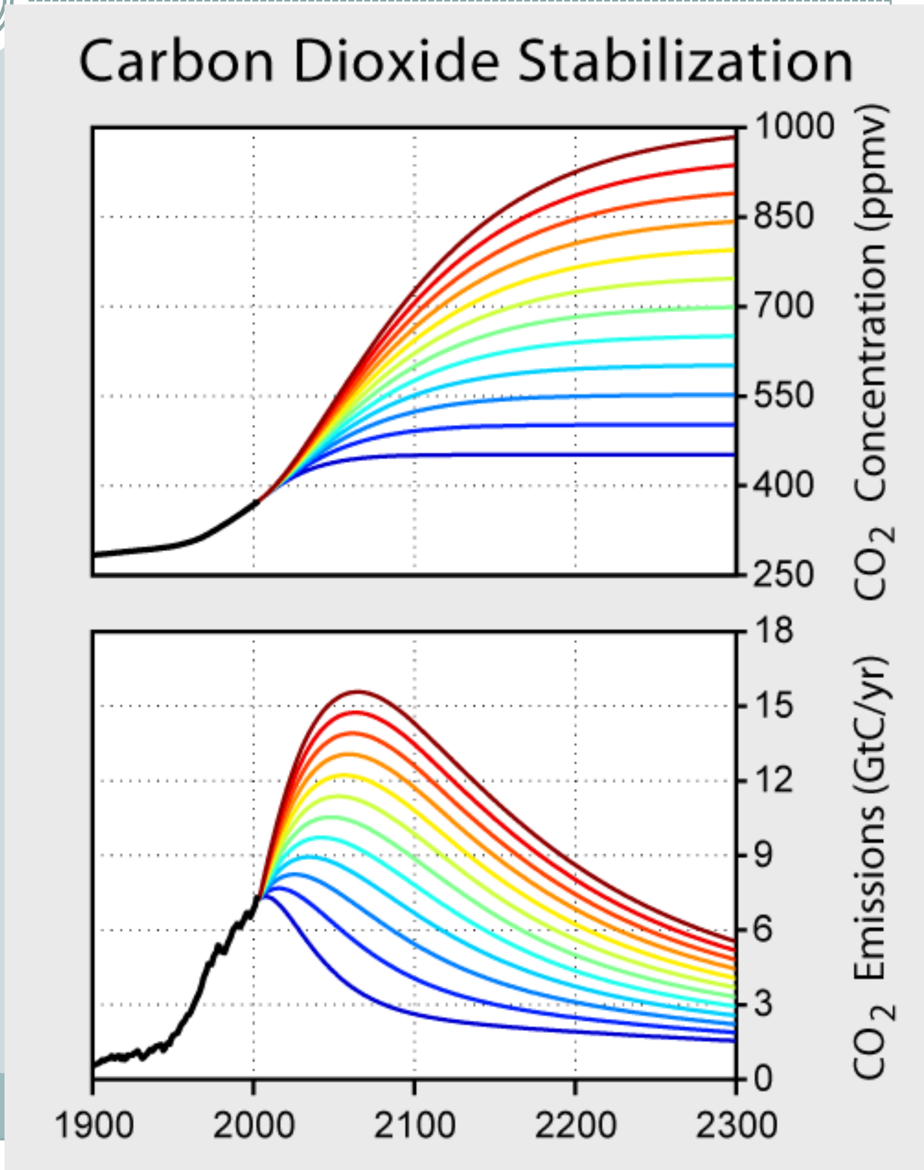
Concentrations



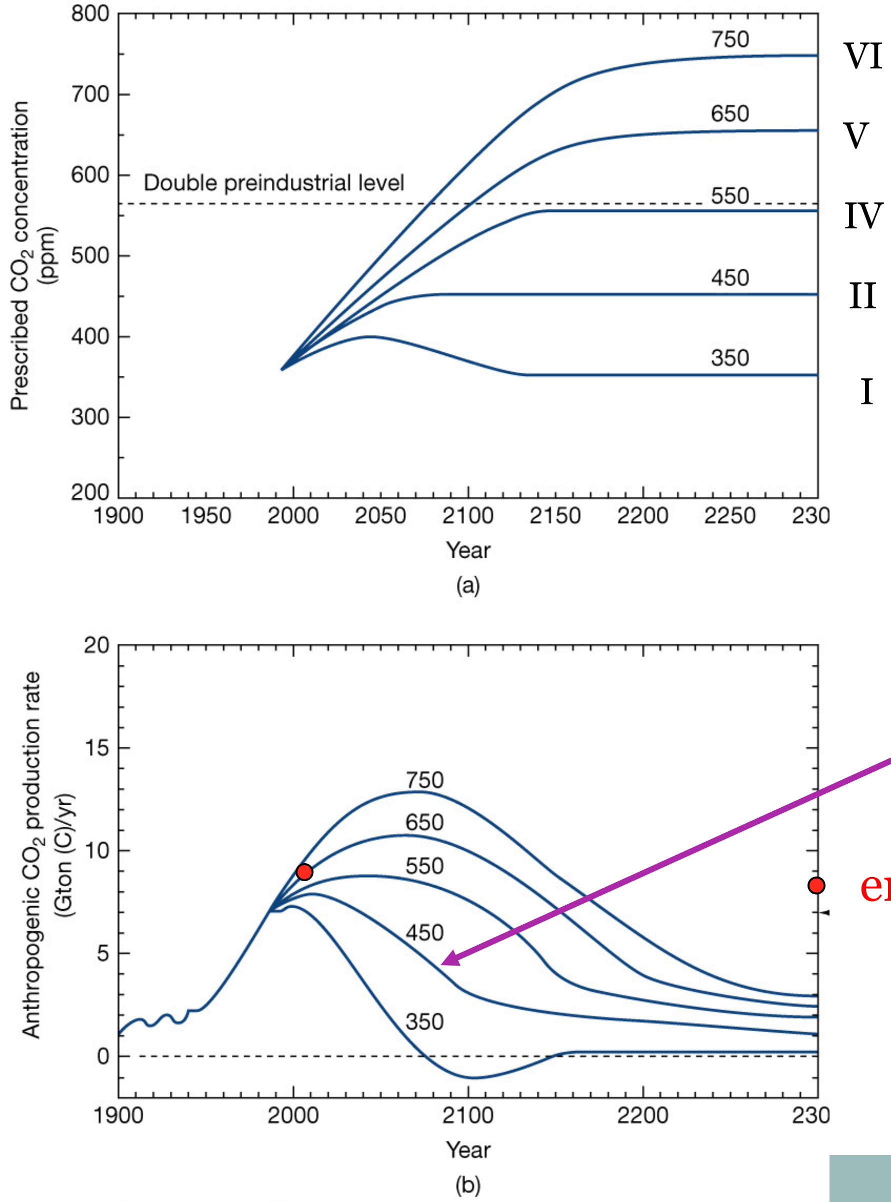
How To Stabilize Concentrations

- Stabilization at these **concentrations**…. →

- …requires these cuts in **emissions** →



Paths to CO_2 stabilization

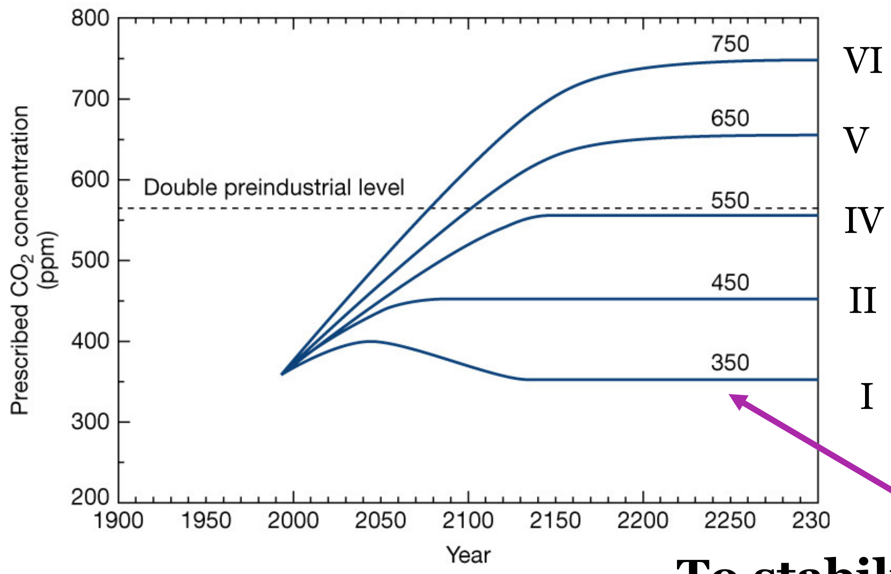


To stabilize at 450 ppm..

…drastic & immediate emissions cuts are necessary

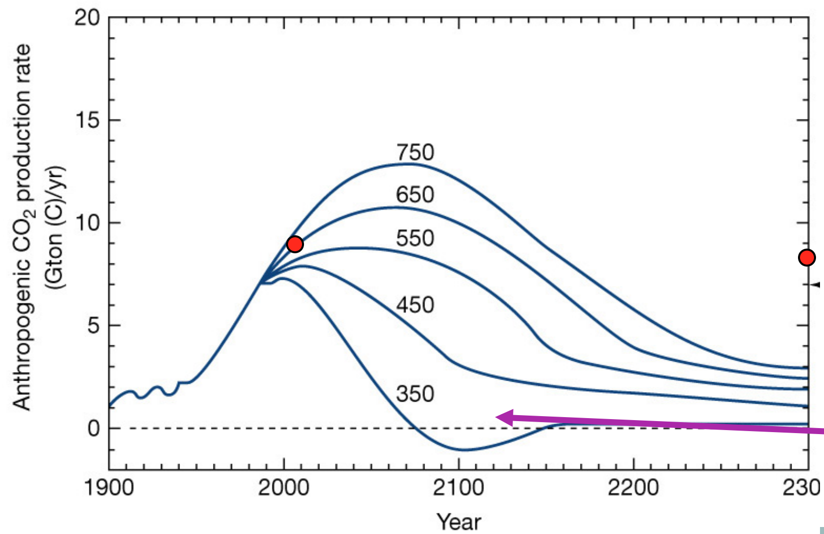
emissions today

Path to 350 ppm CO_2 concentration



(a)

To stabilize at 350 ppm…



(b)

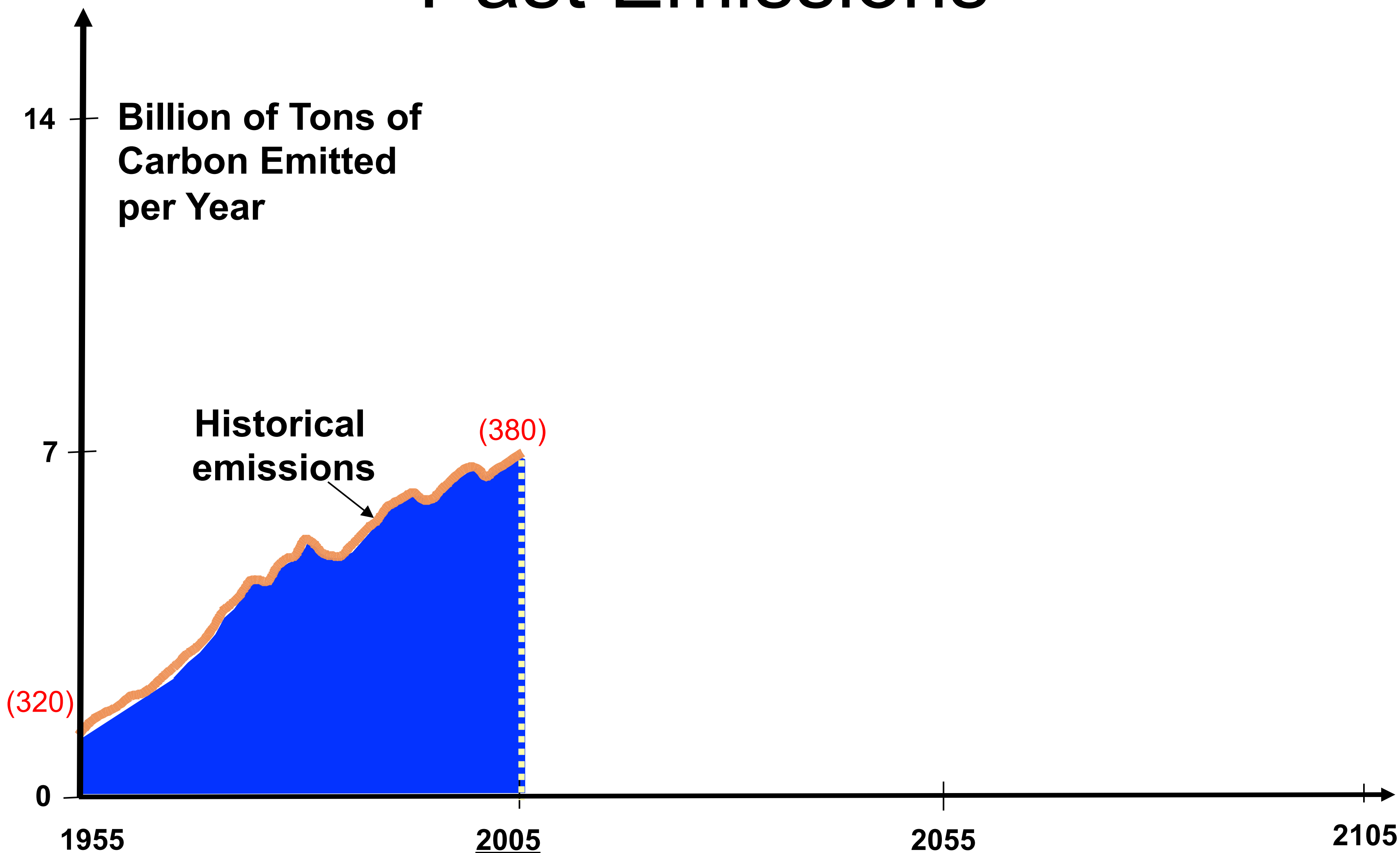
emissions today

…emissions must *plummet* & we probably have to take some CO_2 *out* of the atmosphere

Stabilizing atmospheric CO_2 at ~ 500ppm

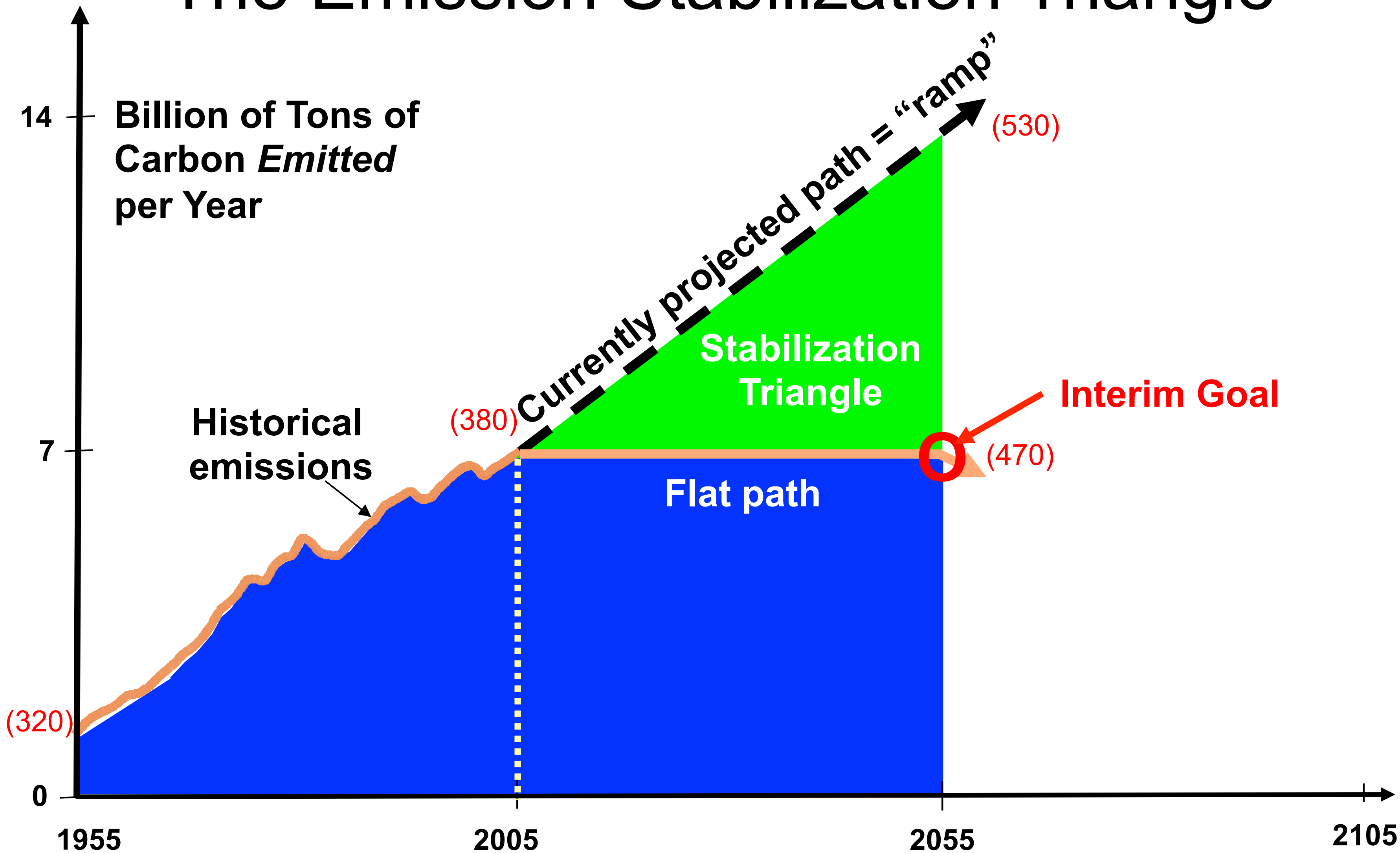
- In 2004, Pacala and Socolow proposed a scheme to achieve this goal
  - **Phase 1**: **No further increase** in emissions until 2054, with energy production still increasing rapidly. Ramping up existing technologies to do this.
  - **Phase 2**: After 2054, **rapid reductions** in global emissions. Final emissions of all GHGs must level off by ~2100 to ~ 1.5 Gt/yr, or ~20% of present global emissions.

Past Emissions



Values in parentheses are ppm of CO_2

The Emission Stabilization Triangle

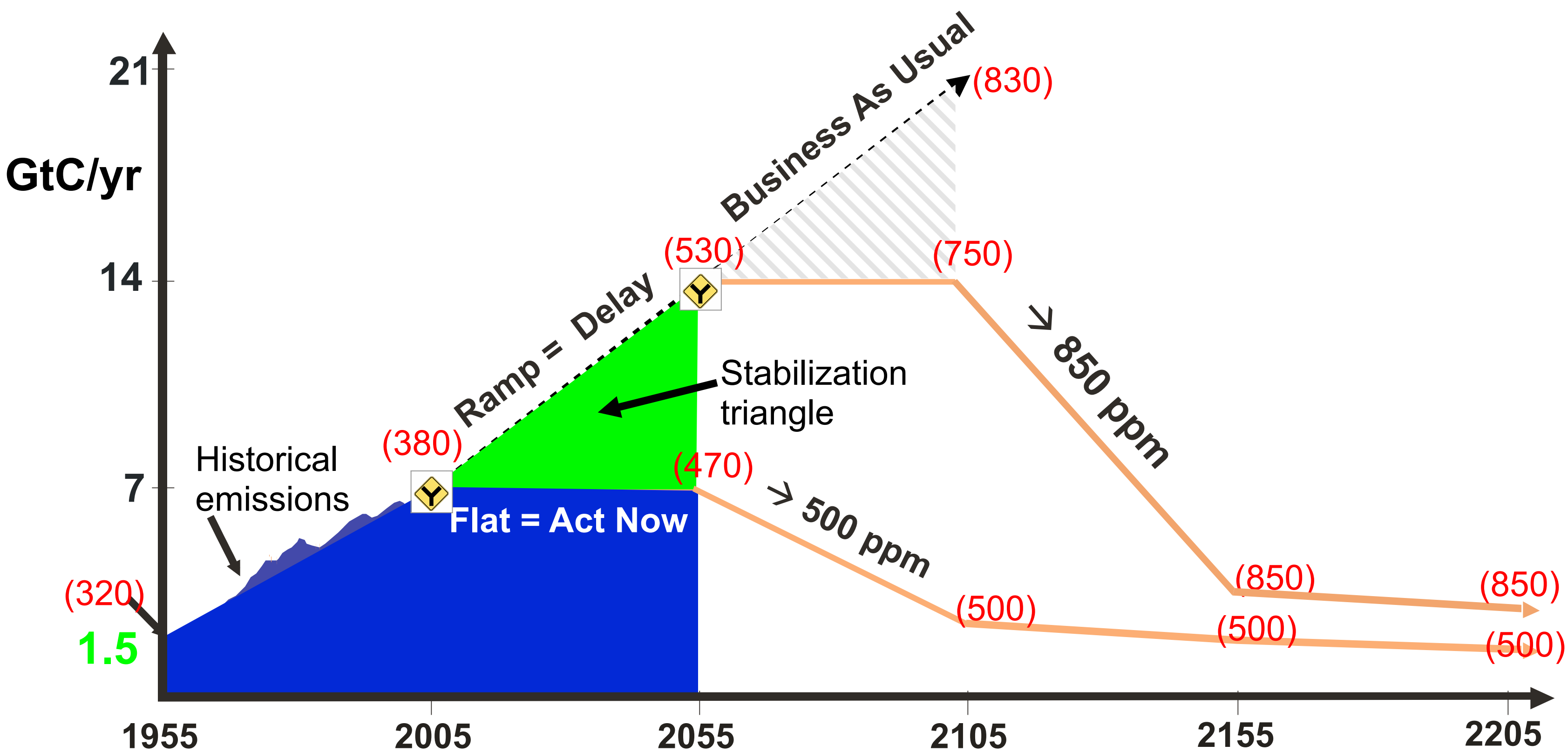


Interim 2054 goal: **stabilize emissions** immediately (yet increase energy by ~70% in 2054) and invest in technology to have much more energy with reduced emissions after that

Pacala and Socolow (2004)

The Stabilization Triangle:

settle for **double** (560) or **triple** (840) pre-industrial CO_2? Or more???

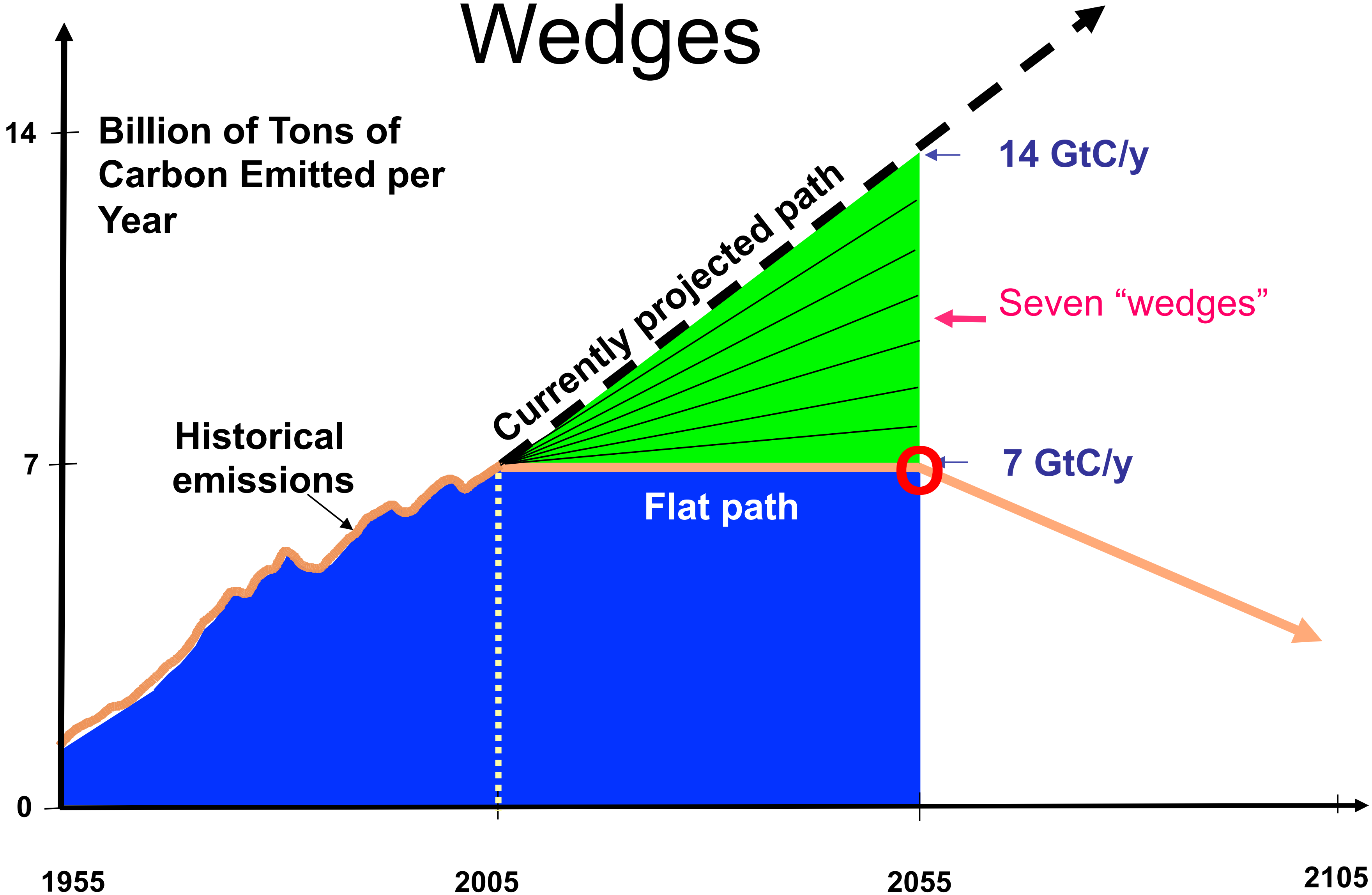


Values in parentheses are ppm (1 ppm = 2.1 GtC).

Stabilizing at 500ppm requires the global emission be 1.5 Gt/yr by 2100

Pacala and Socolow (2004)

Wedges

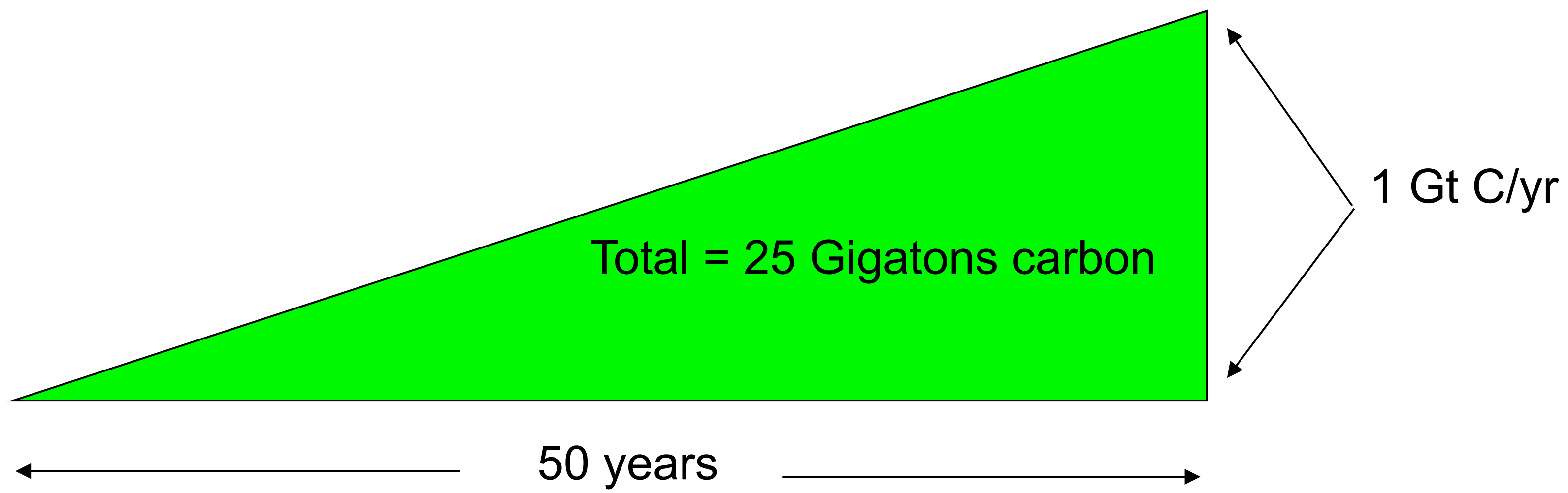


How do we meet the *increase* in energy demand (projected to increase by 70% by 2050 and 200+% by 2100) without increasing emissions of CO_2?

Pacala and Socolow (2004)

What is a “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr.

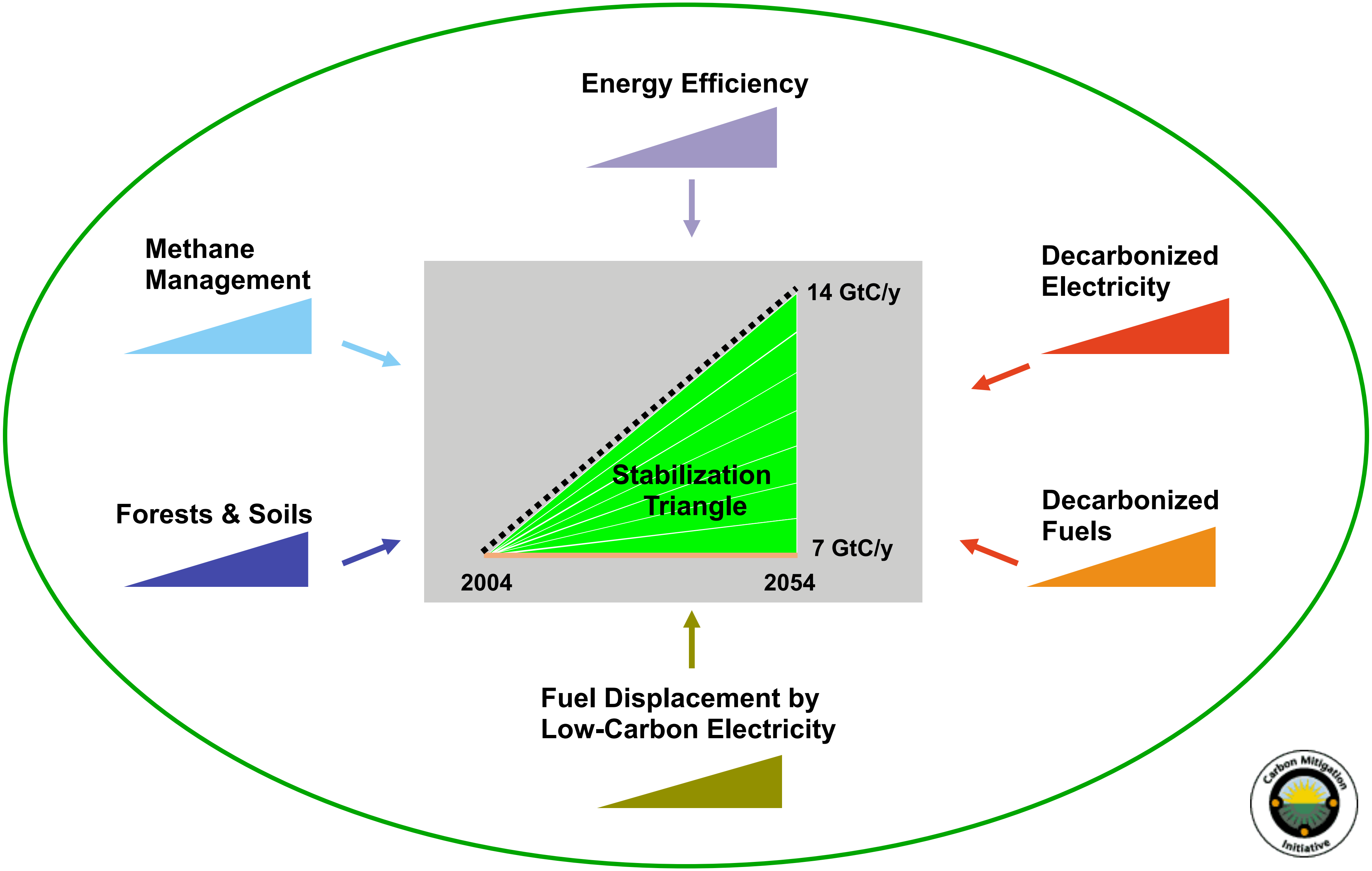


Cumulatively, a wedge redirects the flow of 25 Gt C in its first 50 years.

Pacala and Socolow (2004)

Fill the Stabilization Triangle with Seven Wedges

There are 15 different options for this! Each **challenging** but **feasible**



Wind Electricity

Prototype of 80 m tall Nordex 2.5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

Effort needed by 2055 for 1 wedge:

One million 2-MW windmills displacing coal power.

Today we have about 50,000 MW (1/40 of this)

R. Socolow (per. comm.)

Electricity numbers

- 100 Watts: relatively bright incandendencent **lightbulb** (the non-efficient kind)
- 1000 Watts: average **household** demand (averaged over the day)

- 1 MW = 1 million Watts: average **wind turbine** (powers 1000 households)
- 1 GW = 1 billion Watts: average coal/ nuclear **power plant** (powers 1 million households)

Wind Electricity

One million 2-MW windmills displacing coal power.

Would require land space the size of Montana (but land below could be used for grazing, farmland, etc)

Wind energy would only have to increase by 8% per year to achieve this (and recent increases have been 30% per year)

Prototype of 80 m tall Nordex 2.5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

R. Socolow (per. comm.)

Pholtovoltaic (solar) Power

Effort Needed by 2055 for one wedge:

2000 GW_{peak} (700 times current capacity)

2 million hectares (about 12% the size of Washington): roofs can be used though

Would require 14% increase per year (we're currently increasing at 30% per year)

Graphics courtesy of DOE Photovoltaics Program

Nuclear Electricity

Effort needed by 2055 for 1 wedge:

700 GW displacing coal power (tripling current capacity).

Graphic courtesy of NRC

R. Socolow (per. comm.)

Fuel Switching

Photo by J.C. Willett (U.S. Geological Survey).

Effort needed by 2055 for 1 wedge:

Substitute 1400 natural gas electric plants for an equal number of coal-fired facilities

One wedge requires an amount of natural gas equal to that used for all purposes today

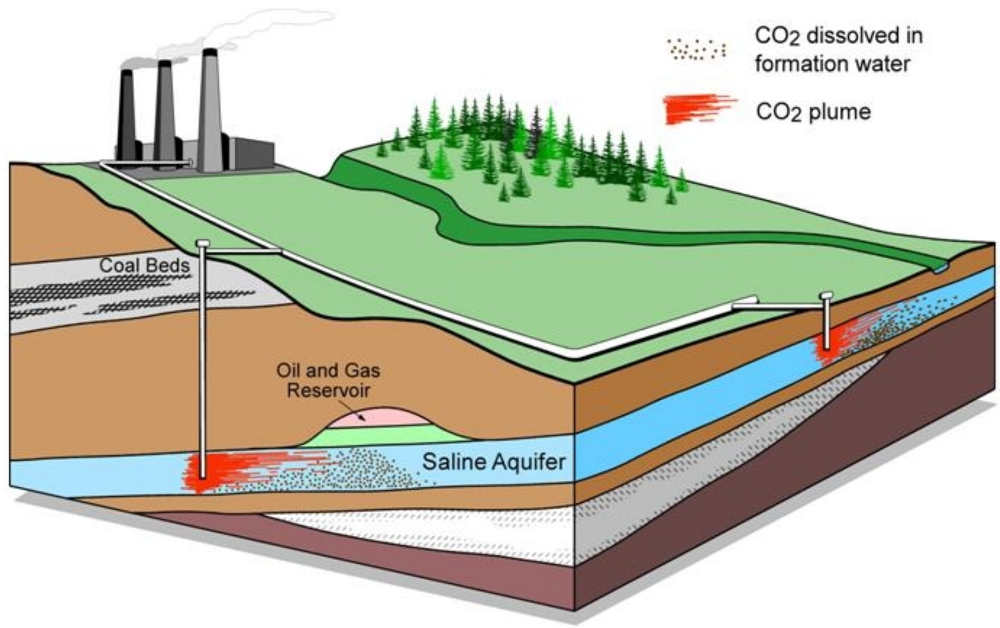
Carbon Capture & Storage

Effort needed for 1 wedge by 2055

Implement CCS at 800 GW coal electric plants

Effort needed for 1 wedge each by 2055

Implement CCS at 1600 GW natural gas electric plants

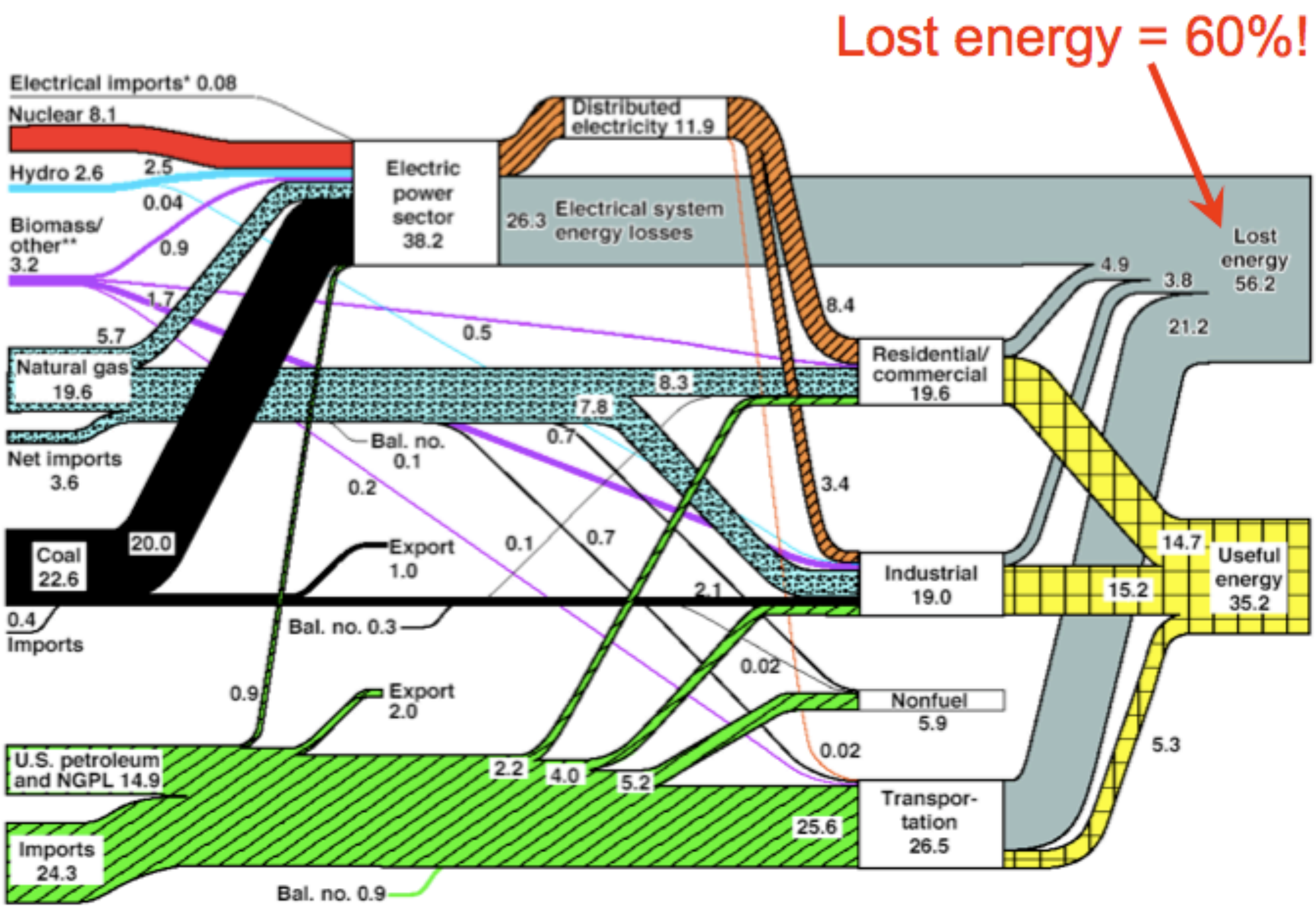


Graphic courtesy of Alberta Geological Survey

There are currently three storage projects that each inject 1 million tons of CO_2 per year – by 2055 need 3500.

Lots of potential for increased efficiency in US

example electricity production and use



Efficient Use of Electricity

industry

buildings

power

Effort needed by 2055 for 1 wedge:

Use best efficiency practices in all residential & commercial buildings

25% - 50% reduction in expected 2055 electricity use in commercial and residential buildings

Changing all light bulbs to CFL would be 1/3 of a wedge!

R. Socolow (per. comm.)

Efficient Generation of Electricity

Effort needed by 2055 for 1 wedge:

Improve the efficiency of coal power plants from 40% to 60%, and double efficiency from which we take fossil fuels from the ground.

power

R. Socolow (per. comm.)

Efficient Use of Fuel

Effort needed by 2055 for 1 wedge:

Decrease the **number of miles** driven per car: 5,000 instead of 10,000 miles per year.

Effort needed by 2055 for 1 *more* wedge:

Double **fuel efficiency** of cars: 60 mpg instead of 30 mpg.

Biofuels

Effort needed by 2055 for 1 wedge:

2 billion 60 mpg_e cars running on biofuels instead of gasoline and diesel.

To produce these biofuels: 250 million hectares of high-yield (15 t/ha) crops, one sixth of world cropland.

Challenge: To find ecologically responsible ways to grow biomass for power and fuel on hundreds of millions of hectares.

Usina Santa Elisa mill in Sertaozinho, Brazil (http://www.nrel.gov/data/pix/searchpix.cgi?getrec=5691971&display_type=verbose&search_reverse=1_

Deforestation

Eliminate all tropical deforestation

Reforestation

Plant new forests over an area the size of the continental U.S.

Conservation Tillage

Use conservation tillage on *all* cropland (1600 Mha)

Leaves at least 30% of crop residue on the surface

Stores more carbon within the soil

Conservation tillage is currently practiced on less than 10% of global cropland (and 40% of US croplands)

Do wedge strategies get used up?

Is the second wedge **easier** or **harder** to achieve than the first?

Are the first million two-megawatt wind turbines more expensive or cheaper than the second million two-megawatt wind turbines?

The first million will be built at the more favorable sites.

But the second million will benefit from the learning acquired building the first million.

The question generalizes to almost all the wedge strategies:

Geological storage capacity for CO_2, land for biomass, river valleys for hydropower, uranium ore for nuclear power, semiconductor materials for photovoltaic collectors.

Summary: What's appealing about wedges?

- The stabilization triangle
  - Does not concede doubling CO_2 is inevitable
  - Shortens the time frame to within business horizons
- The wedge
  - Decomposes a heroic challenge (the Stabilization Triangle) into a limited set of monumental tasks
  - Establishes a unit of action that permits quantitative discussion of cost, pace, risk, trade-offs, etc
- The wedge strategy
  - Does not change the fact there are winners (alternative energies) and losers (coal and oil become more expensive sources of energy), but brings many options to the table