Lecture 25
Anthropogenic Effects on the Carbon Cycle and Global Climate

Today – big packet, some is background reading
a. Global Climate Controls, including paleo-records.
b. The role of the Carbon Cycle
c. Anthropogenic Forcing of Greenhouse Gasses
d. Changing Global Conditions
e. The Future.

Earth’s dynamic atmosphere/hydrosphere play critical roles in determining the retention and geographical distribution of solar heat fluxes to Earth

(Recall the importance of oceanic and atmospheric circulation to flow within the hydrologic cycle)
Atmospheric gasses modulating the planet's temperature through the absorption of IR radiation that would otherwise be reflected to space from Earth's surface.

H₂O absorption bands dominate atmospheric IR transparency.

Other gasses play a secondary role, but are impacted by human activities:
• CO₂
• followed by CH₄, O₃, N₂O and CFC’s.

abundances of all but CFCs have varied for natural reasons over Earth history (CFCs are a human invention)
Past Climates on Earth
Mean global temperature has varied remarkably little (~25°C or so) over Earth history but it has been enough to allow periods of ice accumulation at the poles and times where there was little or no ice there.

**extensive glaciation**
- The Pleistocene (10ka - 2 Ma)
- The Permian through Devonian periods (240 x 10^6 to 400 x 10^6 yrs ago)
- Parts of the early Proterozoic through mid Archaen (2100 x 10^6 to 2500x 10^6)

**No Glaciation**
- The Cretaceous (65 x 10^6 to 136 x 10^6).

The Earth has glaciers today so we are in a glacial epoch. However, within the Quaternary periods of more or less glaciation have occurred frequently. Relatively warm periods like today are known as **interglacials**.

True glacial periods are much colder.

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How do we know this?
We learn this from:

a. the distribution and abundance in marine and terrestrial sedimentary records of:
   - aquatic fossils
   - pollens
   - sediment types

b. Ice core records (only back to 200 ka)

c. the distribution of glacial deposits and landforms (see plot of ice distribution now and during the last glaciation)

These types of indicate paleo temperatures swings of 5°C or so between recent glacial and interglacial times on Earth.

Stable isotopic O and H records for the hydrosphere (ice caps, marine and freshwater CaCO_3 fossils have proven to be very valuable high fidelity records of past temperature fluctuations and volume changes in the hydrosphere because isotopic fractionation is sensitive to such changes.
Cryosphere today, for comparison

Figure 4.1: The cryosphere in the Northern and Southern Hemispheres in polar projection. The map of the Northern Hemisphere shows the sea ice cover during minimum summer extent (13th September 2012). The yellow line is the average location of the ice edge (15% ice concentration) for the yearly minima from 1979 to 2012. Areas of continuous permafrost (see Glossary) are shown in dark pink, discontinuous permafrost in light pink. The green line along the southern border of the map shows the maximum snow extent while the black line across North America, Europe and Asia shows the contour for the 50% snow extent. The Greenland ice sheet (blue/grey) and locations of glaciers (small golden dots) are also shown. The map of the Southern Hemisphere shows approximately the maximum sea ice cover during an austral winter (13th September 2012). The yellow line shows the average ice edge (15% ice concentration) during maximum extent of the sea ice cover from 1979 to 2012. Some of the elements (e.g., some glaciers and snow) located at low latitudes are not visible in this projection (see Figure 4.8). The source of the data for sea ice, permafrost, snow and ice sheet are datasets held at the National Snow and Ice Data Center (NSIDC), University of Colorado, on behalf of the North American Atlas, Instituto Nacional de Estadística, Geografía e Informática (Mexico), Natural Resources Canada, U.S. Geological Survey, Government of Canada, Canada Centre for Remote Sensing and The Atlas of Canada. Glacier locations were derived from the multiple datasets compiled in the Randolph Glacier Inventory (Arendt et al., 2012).

The O and H isotopic composition of Ice Cores track climate. The oceans show a complimentary isotopic shift. Marine sediments, particularly fossils, take on isotopic compositions that reflect changes in the water with time and represent a second, straight-forward proxy record.

Ice Cores and Marine Sediments
The simplest proxy record is locked in the polar ice caps, because the ice caps are the second largest hydrospheric reservoir (2.05% of the hydrosphere today) and their growth/reduction happens primarily at the expense of the oceans.

As more H$_2$O is stored in the polar ice caps and less is in the oceans, the surface.

The O and H isotopic composition of Ice Cores track climate.
Quaternary climate variations can be simplistically thought of as variations in the temperature gradient between the poles and the equator.

Cold and warm periods in earth’s history have most effect upon polar climate and little effect on equatorial climate.

These global temperature swings reflect a change in Earthly heat budget from:

- the amount of incident sunlight to the Earth
- the amounts of light reflected to space (both albedo and IR via heat trapping of heat by the hydrosphere/atmosphere system, which is related to atmospheric greenhouse gas composition).

**external** controls on climate:
- solar intensity
- Earth’s orbital fluctuations
- meteor/comet impacts

**internal** controls on climate:
- global tectonism
- volcanism
- the biosphere

Temporal aspects of these phenomena (some of which are shown in the figure):

**Long term controls:**
- $\text{CO}_2$ consumption and release via silicate rock weathering: Variable proportions of $\text{CO}_2$ in the atmosphere and in the hydrosphere + carbonate rocks over geological time has resulted during Earth’s history from changes in plate tectonic parameters.

**Shorter term controls:**
- amount of photosynthesis and respiration
- oceanic circulation.
- Variations in global volcanism (for both greenhouse gasses and in albedo from stratospheric particulates).
Another look at Carbon Turnover Timescales

FAQ 6.1, Figure 1: Simplified schematic of the global carbon cycle showing the typical turnover time scales for carbon transfers through the major reservoirs.

FAQ 6.1, Figure 2: Decay of a CO₂ excess amount of 5000 PgC emitted at time zero into the atmosphere, and its subsequent redistribution into land and ocean as a function of time, computed by coupled carbon-cycle climate models. The size of the color bands indicate the carbon uptake by the respective reservoir. The first two panels show the multi-model mean from a model intercomparison project (Joos et al., 2013). The last panel shows the longer term redistribution including ocean dissolution of carbonate sediments as computed with an Earth System Model of Intermediate Complexity (after Archer et al., 2009a).
The slowness at which the oceans circulate (in their current configuration they complete one “cycle in about 2000 yrs”), means that most of the oceans are isolated from the atmosphere on decade to century time scales and are thus not able to immediately exchange gases with the atmosphere.

Rates in the Marine Carbon Cycle

Central to carbon cycling is the role of the ocean biosphere and the rates of oceanic currents in distributing water masses around the globe.

The primary cause of geologically recent (Pleistocene to present) global T fluctuations

Earth’s orbital parameter’s about the sun vary regularly and on the right time scale to explain most observed phenomena.

James Croll first suggested that solar irradiance variations affected global climate in 1870. Milankovich quantified the variability in Earth’s orbital parameters in 1930. For this reason, the theory that orbital cyclicity dominates global climate is known as Milankovich theory.

Combining all of the predicted solar insolation effects arising from the various orbital fluctuations gives a curve of relative insolation into the past that matches numerous proxy records.
This periodicity shows up in various climate proxy records due to insolation alone and as they fall, they enhance the magnitude of temperature decrease. These records "wiggle" in the same places but magnitudes of temperature changes are not always the same. This is because many forces work together to "set" Earth's thermostat and the feedbacks between systems are affected in ways that alter the magnitudes of their effects.

Other internal factors such as sudden changes in volcanic or biogenic input of S to the atmosphere can also alter the system.
One way to think of the forcing mechanisms in the recent geological past is that the warm "interglacial" periods represent "normal" times and their high CO$_2$ and CH$_4$ reflect "fully-functioning" biogeochemical exchanges.

When insolation goes down, the planet cools, starts to grow ice caps, lowers sea level, changes the carbon cycle, and pulls CO$_2$ and CH$_4$ from the atmosphere.

The planet then grows ice caps.

Orbital fluctuations then progress and the system relaxes to an interglacial.

A detailed summary of the possible chain of events that occurs as Earth enters a glacial stage appears on the next slide. It includes many of the feedbacks we have discussed in class and a few we haven't.
Past, Present and Future Global Climate:

Now we understand from last lecture something of what drives global climate fluctuations and the geochemical signatures it leaves behind.

Over the last 1 to 2 million years of Earth history, greenhouse gasses have naturally risen and fallen in response to biosphere-land-sea interactions, ... and this enhances the climate variations caused by orbital forcing.

Anthropogenic Forcing of Present/Future Global Climate:

How do gasses being added by human activities perturb the natural balance between global temperature, solar insolation and atmospheric greenhouse gas concentration?"

Anthropogenic Forcing of Present/Future Global Climate:

This is a complicated and not entirely understood topic. It has scientific, social and political ramifications.

The hard data:
The accumulation rates of atmospheric greenhouse gasses since the start of the industrial revolution and global climate data over the corresponding time period.

The predictions:
*How this might alter our global climate in the future*

Models make predictions, which is not the same thing as data. Nevertheless climate system models are now very sophisticated, and can accurately reproduce past trends, lending confidence to their predictive power.
Greenhouse gas emissions of industrialized society:

**Loading the atmosphere with CO2: the record.**

During the “boom” years of oceanography and global geochemical studies (the 1940’s and 50’s), Roger Revelle proposed that industrialization of the planet should lead to increased atmospheric CO2 at levels we could detect, based on the rate of CO2 input to the atmosphere due to fossil fuel burning and cement production (cement accounts for ~ 6% of the total). These values are known from production and usage records of the mining and construction industries.

![Graph showing global CO2 emissions](image)

**Figure 2.2.** Global annual emissions of CO2 from fossil fuel combustion and cement production in giga-tons of carbon per year (plotted on a log scale), Gt = 10^9 tons. [After Watson et al. (1990), Greenhouse gases and aerosols. In Climate change: The IPCC scientific assessment, ed. J. T. Houghton et al., p. 10, copyright World Meteorological Organization, from Rotty and Marland (1986) and Marland (1993).]

In 1958, Revelle persuaded a junior colleague at Scripps, Charles Keeling, to begin making continuous measurements of atmospheric CO2. The site chosen as ideal for the measurements was near the top of Mauna Loa.

By 1964, Keeling’s record showed that atmospheric CO2 had risen by almost 10%.

Last month it was 408 ppm, in March 2012, it was 394 ppm, 3.6% higher than 5 yrs prior and 93% higher than 1958 (monitor it yourself, at https://www.co2.earth/)

CO2 is measured at Mauna Loa 5 to 10 times per year and the concentration oscillates. This is due to seasonal variations in the carbon cycle, such as variations in atmosphere-biosphere exchange (from the seasonality of photosynthesis and respiration) and to a lesser extent, ocean-atmosphere exchange variations.
This time series record was later extended into the past with ice core measurements to just before the start of the industrial revolution.

Figure 9.1. Variation in the atmospheric CO₂ content over the past 200 years: The dark line represents the results of a continuous measurement series extending from 1958 to the present made by Charles Keeling of Scripps Institution for Oceanography and his co-workers. The circles represent measurements made by Oeschger and his colleagues at the University of Bern on air bubbles trapped in ice from Antarctica.

Since then, scientists have examined the changes in other important greenhouse gasses in the atmosphere with time since just before the start of the industrial revolution largely by examining the gas content of layers in Greenland and Antarctic ice cores.

The atmospheric abundances of non CO₂ greenhouse gasses are much lower, yet their rates of increase are greater because of higher relative production rates.

Greenhouse gasses effectiveness as IR light absorbers are also much higher:

- CH₄ 20x as effective as CO₂
- N₂O 300x as effective as CO₂
- CFCs 10,000x as effective as CO₂
Recall these **approximate atmospheric lifetimes** from lecture 24

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lifetime</th>
<th>Dispensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>variable (years)</td>
<td>flux to oceans and biomass</td>
</tr>
<tr>
<td>N₂O</td>
<td>120 years</td>
<td>destroyed in stratosphere</td>
</tr>
<tr>
<td>CFCs</td>
<td>&gt; 50 years</td>
<td>&quot;</td>
</tr>
<tr>
<td>Halons (H-1301)</td>
<td>&gt; 20 years</td>
<td>&quot;</td>
</tr>
<tr>
<td>HCFCs</td>
<td>months - years</td>
<td>destroyed by tropospheric OH</td>
</tr>
<tr>
<td>HFCs</td>
<td>years</td>
<td>&quot;</td>
</tr>
<tr>
<td>CH₄</td>
<td>8 - 10 years</td>
<td>&quot;</td>
</tr>
<tr>
<td>NMHCs</td>
<td>hours - years</td>
<td>&quot;</td>
</tr>
<tr>
<td>PFCs</td>
<td>1000s years</td>
<td>destroyed above mesosphere</td>
</tr>
<tr>
<td>NOₓ</td>
<td>hours - days</td>
<td>OH, O₃</td>
</tr>
<tr>
<td>CO</td>
<td>month</td>
<td>&quot;</td>
</tr>
<tr>
<td>SO₂</td>
<td>weeks</td>
<td>OH</td>
</tr>
</tbody>
</table>

**NMHC** non-methane hydrocarbons  
**HCFC** hydrochlorofluorocarbon  
**CFC** chlorofluorocarbon  
**HFC** hydrofluorocarbon  

Because of the atmospheric lifetimes, CO₂ is the **biggest concern** for the long term (1000 yr) vector of the climate system from human activities.

Gas increases reflect direct anthropogenic inputs as well more indirect changes to the carbon and nitrogen biogeochemical cycles.

Recall the near doubling terrestrial N and P cycles from human activities that we discussed earlier this semester. This "cranks up" the rates of biological cycling of DOC/POC and biogenic gasses.

For CO₂, input changes to the atmosphere reflect these 3 main parameters (left) and regional inputs (right):
And within the US, CO$_2$ and CFC inputs by source are:

The Role of the Carbon (and Nitrogen) Cycles

Chemical exchanges between living organisms, the hydrosphere, the atmosphere, and the geosphere impacts global climate by regulating:

- greenhouse gas contents of the atmosphere
- rates of continental erosion
- albedo (e.g., forests absorb light and deserts reflect)

The rate of change of carbon (and other gasses) in the exogenic C cycle is variable between various reservoirs. The mass balance for carbon in the exogenic cycle has changed between the 1860s and the 1980s:

- CO$_2$ in the atmosphere rose by ~20%
- Fossil Fuels: Both exploitable and "dispersed" = unrecoverable reserves, diminished by 0.3%.
- Terrestrial plant biomass and oceanic concentrations changed but in difficult to pinpoint ways, because annual fluctuations and other anthropogenic activities (such as deforestation) are also part of the signal. But the data point to a slight increases to the oceans and land biosphere.
Human impacts on the rates, magnitude and types of exchanges within the carbon cycle and nitrogen cycle have been very large, and for carbon can be broken down into an anthropogenic source function and 3 main short-term holding areas.

### Table 1

<table>
<thead>
<tr>
<th>Source Function</th>
<th>Gt C/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel and cement production</td>
<td>6.3 ± 0.4</td>
</tr>
<tr>
<td>Net terrestrial uptake</td>
<td>1.4 ± 0.7</td>
</tr>
<tr>
<td>Net oceanic uptake</td>
<td>1.7 ± 0.5</td>
</tr>
<tr>
<td>Net atmospheric storage</td>
<td>3.2 ± 0.1</td>
</tr>
</tbody>
</table>

**Today’s Fluxes**

- **Gt C/yr from reservoirs**
- **Gt C/yr for atmospheric exit fluxes**

**Present-day (late 90s) carbon cycle showing anthropogenic contributions.**

Why is so much carbon loading into the atmosphere when (1) the oceans have 39,000 Gt/600 Gt = 65x more carbon than the atmosphere…

AND when (2) all marine sediments have 1600x more carbon than the oceans (only surface sediments are shown in this plot)?
A world out of Equilibrium

Carbon is accumulating in the atmosphere because of the RATES of processes within the exogenic carbon cycle.

If the 1860 system was closer to equilibrium

then the modern one is far out of equilibrium because the other reservoirs can’t accept C fast enough from the atmosphere to avoid it’s build up there.

We find about 50% of the "known" anthropogenic CO₂ output presently residing in the atmosphere.

The other 50% is often referred to as the "missing" carbon and is in some combination of the oceans, land biosphere and perhaps some unknown inorganic form, such as in soils.

A world out of Equilibrium

An aside: some, such as Bill Rudiman, have argued that humans have been affecting climate by land-use and greenhouse gas production for 8000 yrs (albeit on a much lesser scale before the start of the industrial revolution).

Read this fascinating book if you want to learn more.
The reservoirs in this figure ARE the major holders of exogenic carbon in the past, and should continue in this role.

So there is also no reason not to believe that eventually, if the rate of carbon input diminishes, the carbon cycle will reach a more familiar chemical steady-state and the atmospheric excess will be diminished.

But, this could take many hundreds to thousands of years to stabilize, which is of greatest concern to human society.

To estimate these timescales, assume:

1. the pre-industrial revolution atmosphere was close to static equilibrium for CO₂
2. the integrated mean CO₂ input rate since has been constant (it hasn’t)
3. roughly half the added CO₂ was removed to other reservoirs,

then the effective chemical half-life of atmospheric CO₂ is currently about 150 years in our out of equilibrium condition.

The simplistic calculation suggests it would take 150 yrs to cut our excess in half again if we dramatically cut back our input rate – unfortunately, this is of by 10-100x because of other interactions, such as from warming.
The Oceans:
For ocean-atmosphere gas exchange via Henry's Law, equilibrium between the well-mixed surface layer of the oceans and the atmosphere should occur over <100 yr time scale. However, this ~100m deep section is only 1/40th of the ocean’s volume. The rest of the oceans only “see” the atmosphere to participate in exchange once every 1500 years or so (the present marine overturn rate).

Ocean circulation imposes these “effective” gas exchange efficiencies:

- **a.** 100% x 100m = 100m
- **b.** 25% x 900m = 225m
- **c.** 2.5% x 3000m = 75m

Sum = 400m

For short-term removal of CO₂ from the atmosphere, the oceans act as though they are only 10% of their real size, reducing the carbon differential from 65x to about 6.5x

The terrestrial biosphere:
This is the other known major reservoir with relatively quick turnover rates.

Living global biomass has changed over the past century, but not by huge amounts.

It could be absorbing some of the extra CO₂ input, but the effect of CO₂ “fertilization” is competing with deforestation. Also, the roles of soils and microbial fauna on TOC storage and re-mineralization rates are not that well-known.

As the pace of deforestation quickens, it further diminishes the exogenic cycle’s ability to modulate atmospheric CO₂ on a short time scale.
Global Warming:

The uniqueness of our present situation is that we are loading the atmosphere with greenhouse gases in amounts greater than occur in response to solar insolation fluctuations and this has put the system out of equilibrium.

Temperature and sea level have risen over the past century.

The scientific community has known this since the 1980s.

The quality of the assessments have improved as the size of the changes have increased.

There is a strong correlation of global temperature and CO$_2$ (the plot is from 2001). The mean global temperature rise of 1°C and associated sea level rise of almost 8 cm over the past century portend ominous things for the future since they are due mostly to greenhouse gas loading, which we have had difficulty curtailing.

Intergovernmental Panel on Climate Change reports provide unbiased scientific, data on greenhouse gasses and climate.

http://www.ipcc.ch

FIGURE SPM-3. Observed changes in (a) global average surface temperature; (b) global average sea level rise from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April.

All changes are relative to corresponding averages for the period 1961-1990.

Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c).
Coupling this to our knowledge of the geologic record...

✓ Atmospheric CO$_2$ was 280 ppm during the last interglacial and fell to 180 ppm during the last glacial maximum. CO$_2$ was also about 280 ppm in 1750.

✓ We have now taken it up to about ~394 ppm, or about 30% above the last interglacial.

✓ Earth was a degree or two warmer than now during the last interglacial maximum.

✓ The last time CO$_2$ was > 375 ppm was in the last "hothouse" period on Earth (Oligocene, @ 6° C warmer). Thus, it will likely get a lot warmer before it cools down.

Well back into the 1970s these observations led to predictions of an impending super interglacial (warmer than "normal"), due to anthropogenic forcing of Pleistocene to recent climate change.

![Diagram of climate changes](image)
A related hypothesis by Ruddiman and colleagues is that human's began changing global climate due to greenhouse gas loading via land use and agricultural practices at early as 10,000 years ago. He also predicts an impending super interglacial, but goes farther to say that humans have already delayed the start of the next glaciation.

Naysayers question the reliability of predictive models for:
- gas buildups
- reservoir/flux changes
- associated temperature increases,
but modeling of existing data convincingly demonstrates the anthropogenic effect thus far.
IPCC-IV 2007 FIGURE SPM-4. Comparison of observed continental- (next slide) and global-scale (this slide) changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.

Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

FIGURE SPM-4. Continued…

Every continent shows measurable anthropogenic temperature changes since roughly 1980.
Multiple independent indicators of a changing global climate

FAQ 2.1, Figure 2: Multiple independent indicators of a changing global climate. Each line represents an independently-derived estimate of change in the climate element. In each panel all datasets have been normalized to a common period of record. A full detailing of which source datasets go into which panel is given in the Supplementary Material 2.SM.5.

IPCC-V 2013

Changes in Greenhouse Gases from ice-Core and Modern Data

IPCC-IV 2007 FIGURE SPM-1. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels.
The relative role in warming for each gas is difficult to estimate because of all of the feedbacks.

TABLE 10.4
Atmospheric trace gases that have sources related to human activities and are of significance to global environmental change.

<table>
<thead>
<tr>
<th>Carbon Dioxide CO₂</th>
<th>Methane CH₄</th>
<th>Nitrous Oxide N₂O</th>
<th>Chlorofluorocarbons CF₃</th>
<th>Tropospheric O₃</th>
<th>Carbon Monoxide CO</th>
<th>Water Vapor H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse Role:</td>
<td>Heating</td>
<td>Heating</td>
<td>Heating</td>
<td>Heating</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Effect on Stratospheric Ozone Layer:</td>
<td>Can increase or decrease</td>
<td>Can increase or decrease</td>
<td>Can increase or decrease</td>
<td>None</td>
<td>None</td>
<td>Decrease</td>
</tr>
<tr>
<td>Principal Anthropogenic Source:</td>
<td>Food, fuel, deforestation</td>
<td>Photochemical, fossil fuels, biomass burning</td>
<td>Methane, land use conversion</td>
<td>Methane, ammonia, industrial processes</td>
<td>Methane, biomass burning</td>
<td>Methane, biomass burning, deforestation</td>
</tr>
<tr>
<td>Principal Natural Source:</td>
<td>Balanced in natural ecosystems</td>
<td>Volcanic, biomass, land use conversion</td>
<td>None</td>
<td>Hydrogen, hydrogen, oxidation, deposition</td>
<td>Emissions, transportation</td>
<td></td>
</tr>
<tr>
<td>Atmospheric lifetime:</td>
<td>30 - 300 years</td>
<td>15 years</td>
<td>160 years</td>
<td>60 - 150 years</td>
<td>Weeks to months</td>
<td>Months</td>
</tr>
<tr>
<td>Present Atmospheric Concentration:</td>
<td>389,000</td>
<td>1700</td>
<td>310</td>
<td>CFC-11: 0.28</td>
<td>90 - 40</td>
<td>100</td>
</tr>
<tr>
<td>Projected Concentration:</td>
<td>1900</td>
<td>289</td>
<td>0</td>
<td>CFC-12: 0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Rate of Increase:</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.0%</td>
<td>0.7%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Relative Contribution to Anthropogenic Greenhouse Effect:</td>
<td>50%</td>
<td>15%</td>
<td>5%</td>
<td>12%</td>
<td>0%</td>
<td>None</td>
</tr>
</tbody>
</table>

(After Grubb and Crutzen, 1999, and UCAR/NCAR, 1994a.)

Atmospheric CO₂ in 2013 = 400,000 ppbv

IPCC-IV-2007
FIGURE SPM-2.
Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic CO₂, CH₄, N₂O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown.

These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness.
**Main drivers of climate change**

Figure 1.1: Main drivers of climate change. The radiative balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (LWR) is influenced by global climate "drivers". Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (through fluctuations in the amount of incoming SWR) (Section 2.3). Human activity changes the emissions of gases and aerosols, which are involved in atmospheric chemical reactions, resulting in modified O3 and aerosol amounts (Section 2.2). O3 and aerosol particles absorb, scatter and reflect SWR, changing the energy balance. Some aerosols act as cloud condensation nuclei modifying the properties of cloud droplets and possibly affecting precipitation (Section 7.4). Since cloud interactions with SWR and LWR are large, small changes in the properties of clouds have important implications for the radiative budget (Section 7.4). Anthropogenic changes in greenhouse gases (e.g., CO2, CH4, N2O, O3, CFCs), and large aerosols (>2.5 µm in size) modify the amount of outgoing LWR by absorbing and re-emitting less energy at a lower temperature (Section 2.2). Surface albedo is changed by changes in vegetation or land surface properties, snow or ice cover and ocean colour (Section 2.3). These changes are driven by natural seasonal and diurnal changes (e.g., snow cover), as well as human influence (e.g., changes in vegetation types) (Forster et al., 2007).

As early as 2001, most models predicted that maximum CO2 wouldn’t be reached until 2050 to 2100, even if we had stopped increasing the rate of greenhouse gas production at that time.
The global greenhouse gas production rate is still rising quickly. The most "extreme" global treaty proposals have global greenhouse gas emissions levels being diminished to 1990 levels, and this still results a dramatic net reduction over time.

Different production and stabilization scenarios for CO$_2$ and other GHG (Green Hous Gas) emissions

The best and worst cases take us to roughly 50% or 800% of the PRE-INDUSTRIAL REVOLUTION CO$_2$ VALUE by the year 2300.

IPCC2013 synthesis

Some Scenarios have CO2 going to 500 ppm (almost 2x the pre-industrial value).

Figure 1.5: Observed globally and annually averaged CO2 concentrations in parts per million (ppm) since 1950 compared with projections from the previous IPCC assessments. Observed global annual CO2 concentrations are shown in dark blue. The shading shows the largest model projected range of global annual CO2 concentrations from 1950 to 2035 from FAR (Figure A.3 in the Summary for Policymakers (SPM) of IPCC, 1990), SAR (Figure 5b in the TS of IPCC, 1996), TAR (Appendix II of IPCC, 2001), and from the A2, A1B and B1 scenarios presented in the AR4 (Figure 10.26 in Meehl et al., 2007). The bars at the right hand side of the graph show the full range given for 2035 for each assessment report. The publication years of the assessment reports are shown. See Appendix 1.A for details on the data and calculations used to create this figure.
Other gases for various scenarios.

Figure 8.5: Time evolution of global-averaged mixing ratio of long-lived species 1850–2100 following each RCP; blue (RCP2.6), light blue (RCP4.5), orange (RCP6.0) and red (RCP8.5). Based on Meinshausen et al. (2011b).

Figure 1.4: Estimated changes in the observed globally and annually averaged surface temperature anomaly relative to 1961–1990 (in °C) since 1950 compared with the range of projections from the previous IPCC assessments. Values are harmonized to start from the same value in 1990. Observed global annual mean surface air temperature anomaly, relative to 1961–1990, is shown as squares and smoothed time series as solid lines (NASA (dark blue), NOAA (warm mustard), and the UK Hadley Centre (bright green) reanalyses). The coloured shading shows the projected range of global annual mean surface air temperature change from 1990 to 2035 for models used in FAR (Figure 6.11 in Brohmann et al., 1990), SAR (Figure 19 in the TS of IPCC, 1996), TAR (full range of TAR Figure 9.13(b) in Cubasch et al., 2001). TAR results are based on the simple climate model analyses presented and not on the individual full threedimensional climate model simulations. For the AR4 results are presented as single model runs of the CMIP3 ensemble for the historical period from 1950 to 2000 (light grey lines) and for three scenarios (A2, A1B and B1) from 2001 to 2035. The bars at the right hand side of the graph show the full range given for 2035 for each assessment report. For the three SRES scenarios the bars show the CMIP3 ensemble mean and the likely range given by –40% to +60% of the mean as assessed in Meehl et al. (2007). The publication years of the assessment reports are shown. See Appendix 1.A for details on the data and calculations used to create this figure.

Associated Temperature Changes.

Remember, these are global averages. But....
Associated Mean Global Sea Level Changes.

Figure 1.10: Estimated changes in the observed global annual mean sea level (GMSL) since 1950 relative to 1961–1990. Estimated changes in global annual sea level anomalies are presented based on tide gauge data (Church and Wijns, 2011 (dark blue); Jevrejeva et al., 2008 (warm mustard); Ray and Douglas, 2011 (dark green)) and based on sea surface altimetry (light blue). The altimetry data start in 1993 and are harmonized to start from the mean 1993 value of the tide gauge data. Squares indicate annual mean values, solid lines smoothed values. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR (Figure 9.6 and Figure 9.7 in Warrick and Oerlemans, 1990), SAR (Figure 21 in TS of IPCC, 1996), TAR (Appendix II of IPCC, 2001) and for Church et al. (2011) based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) model results not assessed at the time of AR4 using the SRES B1, A1B, and A2 scenarios. Note that in the AR4 no full range was given for the sea level projections for this period. Therefore, the figure shows results that have been published subsequent to the AR4. The bars at the right-hand side of the graph show the full range given for 2035 for each assessment report. For Church et al. (2011) the mean sea level rise is indicated in addition to the full range. See Appendix 1.A for details on the data and calculations used to create this figure.

Warming will not be evenly distributed from the equator to the poles (where the ice caps currently reside). Notice for instance that temperature increases of 8° are predicted over most of the high northern latitudes in this conservative warming model.
Changes in weather patterns around the world are expected to be significant. This plot shows changes in within the continental US detected just during the 20th century.

We expect the world to enter an era of more frequent and more intense extreme weather events (very cold or warm winters, large storms and flooding, heat waves, drought).

This is likely due to more energy (as heat) being stored in the atmosphere, resulting in more seawater evaporation. This in turn increases the rate at which the hydrologic cycles, with all the attendant heat and mass exchanges.
Some of you may recall from a biology class that latitudinal shifts in climate produce biome variations moving to higher latitude from the equator.

These biome shifts occur in very similar fashion moving to higher altitude at a given latitude.

Thus one finds deciduous and temperate evergreen forests, and even tundra-like conditions (e.g., "alpine" meadows) at high elevations of equatorial mountains.

10 years ago there was already evidence that these vertical biome boundaries are shifting to higher levels, and with them, the habitat of cold-sensitive pests like mosquitoes and the diseases they carry.

Scientists have hypothesized that there will be an increase in frequency and intensity of "extreme" weather patterns in the near future.

Figure 1.8: Schematic representations of the probability density function of daily temperature, which tends to be approximately Gaussian, and daily precipitation, which has a skewed distribution. Dashed lines represent a previous distribution and solid lines a changed distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. In the case of temperature, changes in the frequencies of extremes are affected by changes a) in the mean, b) in the variance or shape, and c) in both the mean and the variance, d) in a skewed distribution such as that of precipitation, a change in the mean of the distribution generally affects its variability or spread, and thus an increase in mean precipitation would also likely imply an increase in heavy precipitation extremes, and vice-versa. In addition, the shape of the right hand tail could also change, affecting extremes. Furthermore, climate change may alter the frequency of precipitation and the duration of dry spells between precipitation events. a)-c) modified from Folland et al. (2001) and d) modified from Peterson et al. (2008) as in Zhang and Zwiers (2012).
Some people have hypothesized that there will be an increase in frequency and intensity of El Niños, and the "extreme" weather patterns that occur with them.

Although it is difficult to predict exact effects of continued global atmospheric loading of greenhouse gasses or when they will occur, one can predict the types of changes in addition to more extreme weather:

1. shifts in locations of farmable land or in crop types that can be grown there.
2. increases in habitat for cold temperature sensitive organisms.
3. increases in diseases spread by cold T sensitive pests such as mosquitoes.

Recent El Niños and associated extreme weather have brought more and more widespread outbreaks of temperature/humidity related disease, suggesting climate change may also bring other health-related changes to the planet.