Lecture 27

The Carbon Cycle and Earth's Climate

Reading for today: Ch 20 Langmuir/Broecker, "How to Build a Habitable Planet"

Turn in Journals on Friday Nov. 1

Previously

1. Stable Isotopes
2. Paleoclimate records

Today

3. Future Climate in the near term: *Big notes packet – read some on your own*
   a. Anthropogenic Effects on the Carbon Cycle and Global Climate.
   b. Greenhouse Gasses and Changing Global Conditions
   c. The Future.

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 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 CO_2: 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 CO_2 at levels we could detect, based on the rate of CO_2 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.

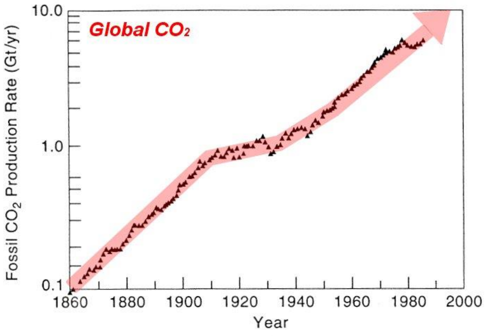


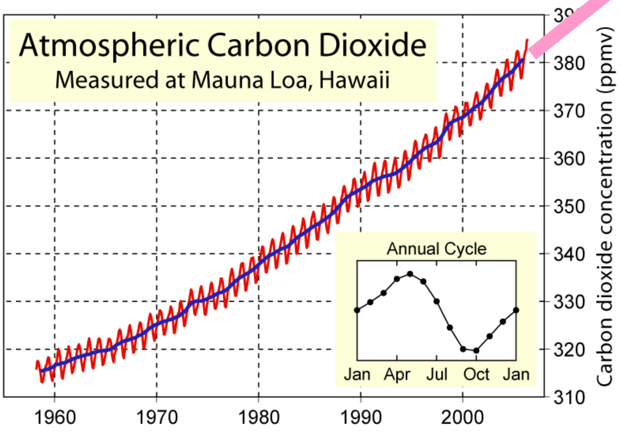
Figure 2.2. Global annual emissions of CO_2 from fossil fuel combustion and cement production in gigatons of carbon per year (plotted on a log scale). Gt = 10^9 tons. [After Watson et al. (1990), Greenhouse gases and aerosols. In *Climate change: The IPCC scientific assessment,* ed. J. T. Houghton et al., p. 10, copyright World Meteorological Organization, from Rotty and Marland (1986) and Marland (1989).]

400 ppm
(3/2013)

In 1958, Revelle persuaded one of his junior colleagues at Scripps, Charles Keeling, to begin making continuous measurements of atmospheric CO_2. The site chosen as ideal for the measurements was near the top of Mauna Loa Volcano.

By 1964, Keeling's record showed that atmospheric CO_2 had risen by almost 10%.

As of March 2012, the value was 394 ppm, another 10% higher than in 1994 (monitor it yourself, at co2now.org)



CO_2 was measured at Mauna Loa (and still is today) 5 to 10 times per year, and that the concentration oscillates. This is due to seasonal variations in the carbon cycle, such as variations in atmosphere-biosphere exchange (from the seasonal nature 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.

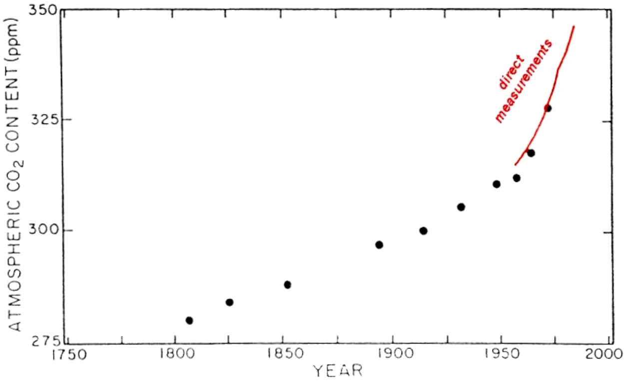


Figure 9-1. Variation in the atmospheric CO_2 content over the past 200 years: The dark line represents the results of a continuous measurement series extending from 1958 to the present made by Charles Keeling of Scripps Institution for Oceanography and his co-workers. The circles represent measurements 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 *<u>abundances</u>* of non CO_2 greenhouse gasses are much **lower**, yet their *<u>rates of increase</u>* are **greater** because of **higher relative production rates**.

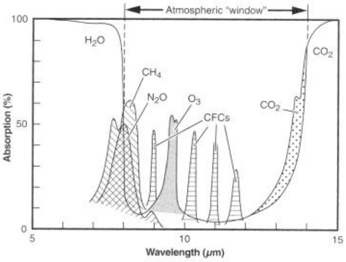


Figure 11.12 The absorption spectrum of the atmosphere in the "atmospheric window" region. The principal absorbing molecules and the relative sizes of their absorption bands are illustrated.

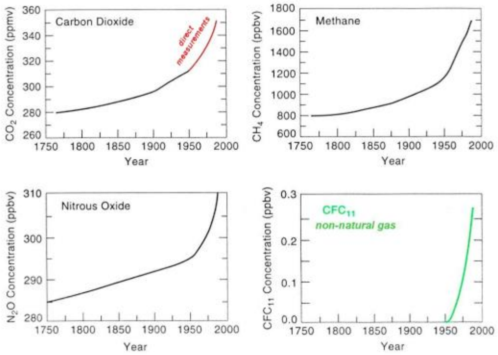


Figure 2.5. Increases in concentrations of greenhouse gases since 1750. Concentrations of CO_2 and methane, which were relatively constant up until the 1700s, have increased steeply since then due to human activities. Nitrous oxide concentrations have risen since about 1750, with the steepest increases after 1950. CFCs, which are entirely anthropogenic in origin, appeared initially in the 1930s and have increased steeply since 1950. (*Source:* IPCC 1990, *Climate change: The IPCC scientific assessment*, ed. J. T. Houghton et al., Executive summary p. xvi. Fig. 3, copyright World Meteorolgical Organization.)

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

CH_4	**20x as effective as CO_2**
N_2O	**300x as effective as CO_2**
CFCs	**10,000x as effective as CO_2**

These **approximate atmospheric lifetimes** are relevant

Gas	Lifetime	Dispensation
CO_2	variable (years	flux to oceans and biomass
N_2O	120 years	destroyed in stratosphere
CFCs	> 50 years	"
Halons (H-1301)	> 20 years	"
HCFCs	months - years	destroyed by tropospheric OH
HFCs	years	"
CH_4	8 - 10 years	"
NMHCs	hours - years	"
PFCs	1000s years	destroyed above mesosphere
NO_x	hours - days	OH, O_3
CO	month	"
SO_2	weeks	OH

NMHC non-methane hydrocarbons
HCFC hydrochlorofluorocarbon
PFC perfluorocarbon

CFC chlorofluorocarbon
HFC hydrofluorocarbon

Because of the atmospheric lifetimes, CO_2 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.

Changes in CO_2, input to the atmosphere reflect these 3 main parameters (left) and regional inputs (right):

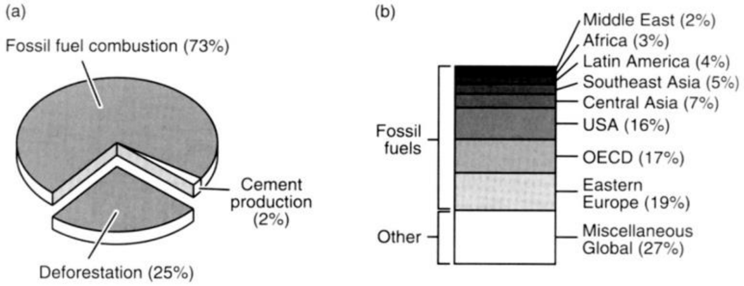


Figure 12.4 Relative sources of global carbon dioxide emissions according to (a) cause and (b) region. The relative magnitudes of the emissions are given as a percentage of the total. (Data from U. S. Environmental Protection Agency)

And within the US,

CO_2 and CFC inputs by source are:

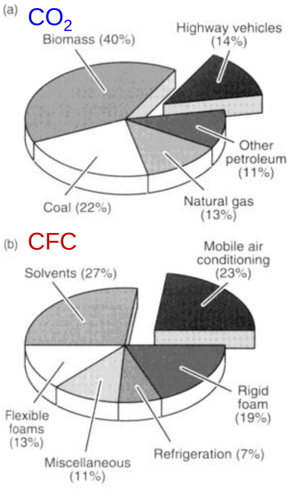


Figure 12.5 Relative sources of the greenhouse gases (a) carbon dioxide and (b) chlorofluorocarbons for the United States. Sources are specified as a percentage of the total in each case. The components associated with motor vehicles are highlighted. (Data from Hammerle, R. H., J. W. Shiller, and M. J. Schwartz, “Global Warming,” Ford Research Technology Assessment Series, September, 1988. Adopted from Figure 7.)

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:

a. greenhouse gas contents of the atmosphere

b. rates of continental erosion

c. 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 <u>atmosphere</u> rose by ~20%

☹ <u>Fossil Fuels</u>: Both exploitable and "dispersed" = unrecoverable reserves, diminished by 0.3%.

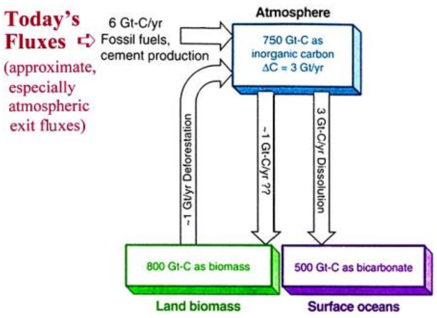
☹ <u>Terrestrial plant biomass</u> and <u>oceanic concentrations</u> changed but in difficult to pinpoint ways, because annual fluctuations and other anthropogenic activities (such as deforestation) are also part of the signal. But the data point to a slight increases to the oceans and land biosphere.

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.

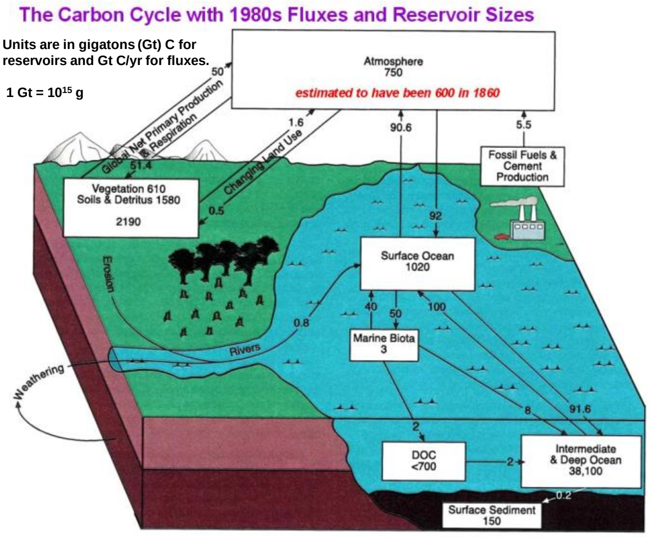
Table 1

Net Annual Changes in Global Carbon Reservoirs (1990's) (Houghton et al, 2001)

	Gt C/year
Fossil fuel and cement production emissions	6.3 ± 0.4
Net terrestrial uptake	1.4 ± 0.7
Net oceanic uptake	1.7 ± 0.5
Net atmospheric storage	3.2 ± 0.1


Today's Fluxes ⇨ (approximate, especially atmospheric exit fluxes)

Present-day carbon cycle showing anthropogenic contributions.



Units are in gigatons (Gt) C for reservoirs and Gt C/yr for fluxes.

1 Gt = 10^{15} g

The principal anthropogenic carbon fluxes, against the background of some of the main 'background' natural fluxes. The results are updated from the 1995 IPCC report and Schimel (1995) with updates from Sarmiento and Sundquist (1992) and Hansell and Carlson (1998). Fluxes shown are estimated averages for the decade of the 1980s. Where unbalanced fluxes are indicated (global primary production and respiration, land use and air-sea gas exchange) the imbalance reflects the anthropogenic fluxes. Note that this figure shows decadal average fluxes and we now know these fluxes to be quite variable from year to year.

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

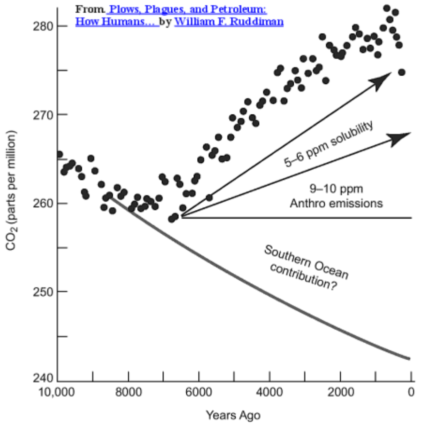
then the modern one is far out of equilibrium because the other reservoirs can't accept C fast enough from the atmosphere to avoid it's build up there.

We find about 50% of the "known" anthropogenic CO_2 output presently residing in the atmosphere.

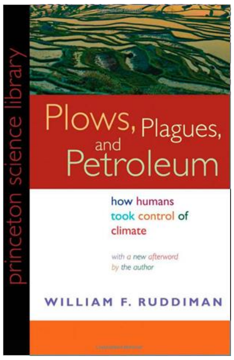
The other 50% is often referred to as the "missing" carbon and is in some combination of the oceans, land biosphere and perhaps some unknown inorganic form, such as in soils.

A world out of Equilibrium

An aside: some, such as Bill Rudiman, argue 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.


From Plows, Plagues, and Petroleum: How Humans… by William F. Ruddiman

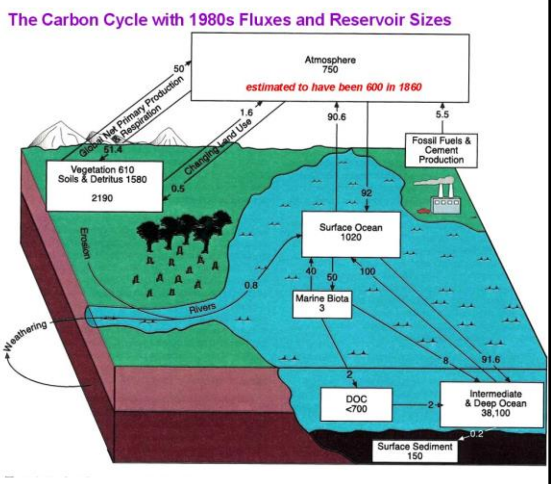
A.6. A "pie-chart" representation of possible contributions to the anomalous CO$_2$ trend during the last 7,000 years from: warming of the deep ocean (resulting in decreased CO$_2$ solubility), direct anthropogenic emissions, and maintenance of anomalous warmth in the Southern Ocean.



Read this fascinating book if you want to learn more.

The reservoirs in this figure ARE the major holders of exogenic cycle 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.


The Carbon Cycle with 1980s Fluxes and Reservoir Sizes

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

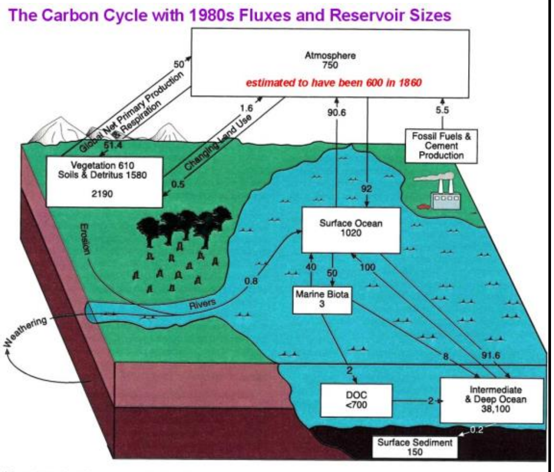
To estimate these timescales, assume:

(1) the pre-industrial revolution atmosphere was close to static equilibrium for CO_2

(2) the integrated mean CO_2 input rate since has been constant (it hasn't)

(3) roughly half the added CO_2 was removed to other reservoirs,

then the effective chemical half-life of atmospheric CO_2 is currently about 150 years in our out of equilibrium condition.


The Carbon Cycle with 1980s Fluxes and Reservoir Sizes

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:

Consider ocean-atmosphere gas exchange a la Henry's Law: There should be equilibrium between the well-mixed surface layer of the oceans and the atmosphere over less than a 100 yr time scale. However, this~100m deep section is only 1/40th of the ocean's volume. The rest of the oceans don't "see" the atmosphere to participate in exchange but once every 2000 years or so (the present marine overturn rate).

Ocean circulation imposes these "effective" gas exchange efficiencies:

☼ CO_2
~~~~~~~↕~~~~~~~~~~~~~~~~~~~
a
↕ 100% a. 100% x 100m =100m
-- 100 meters
b
↕ 25% b. 25% x 900 m =225m
-- 1000 meters

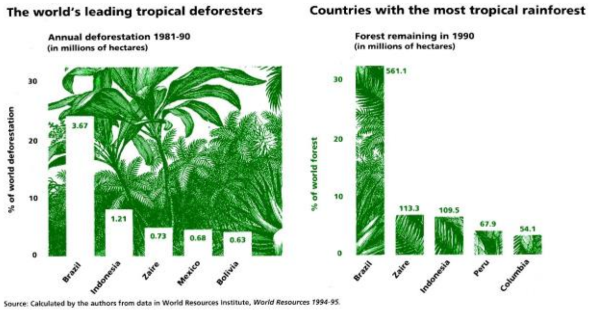
c
↕ 2.5% c. 2.5% x 3000 m =<u>75m</u>
-- 4000 meters
Sum = 400m

For short-term removal of CO_2 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 turnaround rates.

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



Source: Calculated by the authors from data in World Resources Institute, *World Resources 1994-95*.

It could be absorbing some of the extra CO_2 input, but the effect of CO_2 "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 CO_2 on a short time scale.

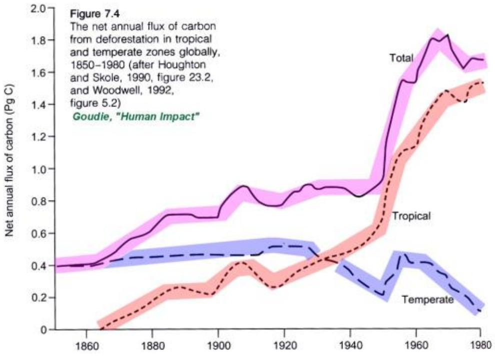
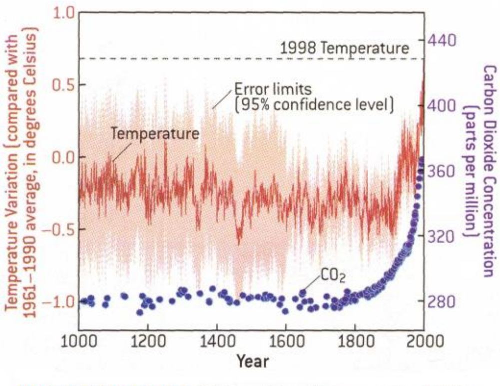


Figure 7.4
The net annual flux of carbon from deforestation in tropical and temperate zones globally, 1850–1980 (after Houghton and Skole, 1990, figure 23.2, and Woodwell, 1992, figure 5.2)
Goudie, "Human Impact"

Global Warming:

The uniqueness of our present situation is that we are loading the atmosphere with greenhouse gasses in amounts greater than occur in response to solar insolation fluctuations. This has put the system out of equilibrium. This was clear before 2000.



WARMEST DECADE of the millennium was the 1990s, researchers now say with a fairly high degree of confidence, based on direct and indirect temperature readings (*red*). Scientists also say with the same degree of confidence that carbon dioxide levels, measured in ice cores (*blue*), are the highest in 20 million years.

from: Scientific American, Oct. 2001

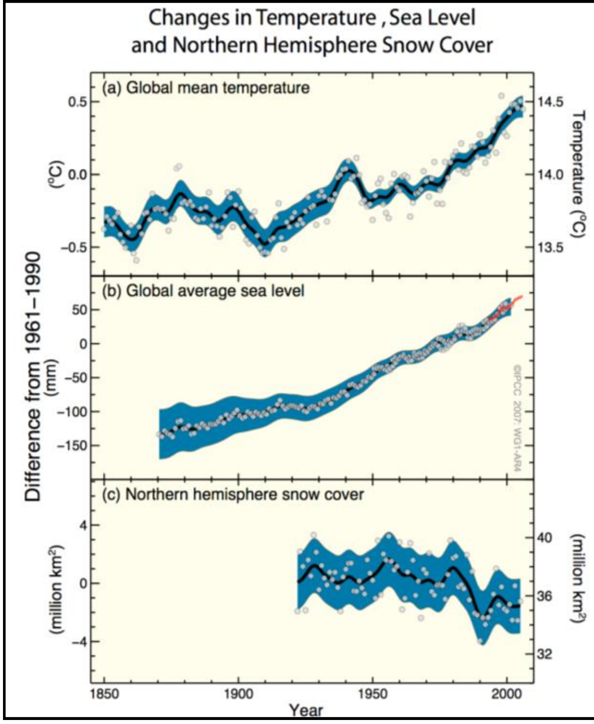
Temperature and sea level have risen over the past century.

The scientific community has known this since the 1980s.

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

There is a strong correlation of global temperature and CO_2 (plot 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

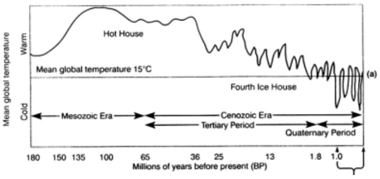
IPCC-IV-2007
FIGURE SPM-3.
Observed changes in (a) global average surface temperature; (b) global average sea level rise from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April.

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 durng the last interglacial maximum.
- ✓ The last time CO_2 was > 375 ppm was in the last "hothouse" period on Earth (Oligocene, @ 6^o 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.

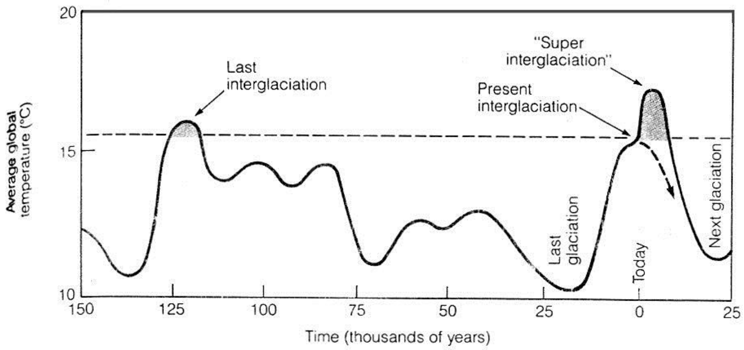
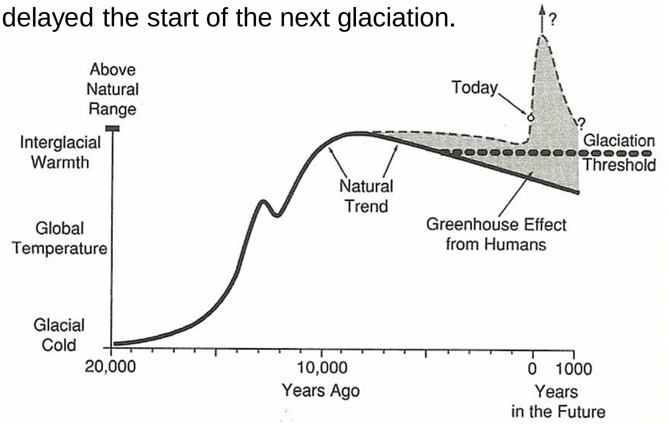


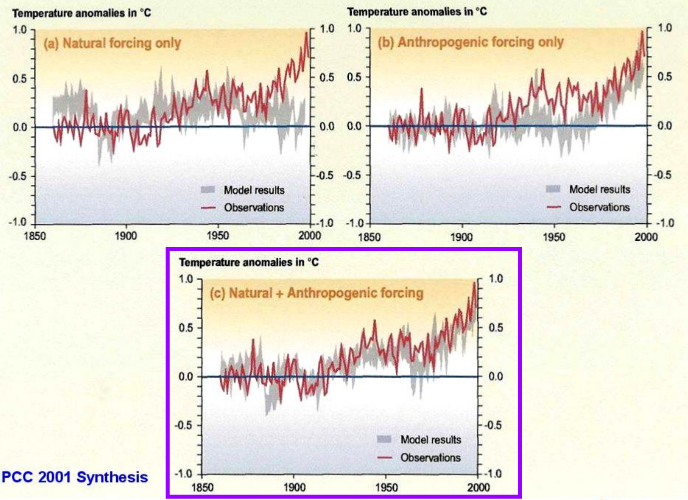
FIGURE 20.30 Course of climate during the last 150,000 years and 25,000 years into the future. Natural course of future climate (dashed line) would involve declining temperatures until the next glacial maximum, about 23,000 years from now. With CO_2-induced greenhouse effect, continued warming may lead to a super interglaciation within the next several hundred years. During such an interval, temperature may rise above that of the last interglaciation. The decline toward the next glaciation would thereby be delayed by several millennia. (*Source:* After Imbrie and Imbrie, 1979.)

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.



17.1. Greenhouse-gas emissions from farming have offset part of a natural cooling since 8,000, years ago and probably prevented a new glaciation. The rapid changes caused by modern industrialization will eventually reach levels of warmth not attained on Earth for many millions of years. Once the supply of fossil fuels is depleted in a few centuries, climate will gradually cool toward natural levels. ***Ruddiman, P^3, 2005***

Comparison between modeled and observations of temperature rise since the year 1860



IPCC 2001 Synthesis

Figure 2-4: Simulating the Earth's temperature variations and comparing the results to the measured changes can provide insight into the underlying causes of the major changes. A climate model can be used to simulate the temperature changes that occur from both natural and anthropogenic causes. The simulations represented by the band in (a) were done with only natural forcings: solar variation and volcanic activity. Those encompassed by the band in (b) were done with anthropogenic forcings: greenhouse gases and an estimate of sulfate aerosols. Those encompassed by the band in (c) were done with both natural and anthropogenic forcings included. From (b), it can be seen that the inclusion of anthropogenic forcings provides a plausible explanation for a substantial part of the observed temperature changes over the past century, but the best match with observations is obtained in (c) when both natural and anthropogenic factors are included. These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed. Similar results to those in (b) are obtained with other models with anthropogenic forcing.

WGI TAR Figure 12-7

Naysayers question the reliability of predictive models for

- gas buildups
- reservoir/flux changes

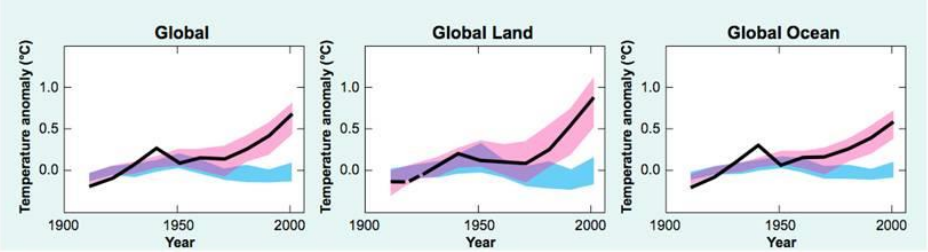
and

- associated temperature increases,

but modeling as far back as 2001 of existing data convincingly demonstrated the anthropogenic effect thus far

---

More recent Global Temperature Change Models



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.

Global and Continental Temperature Change

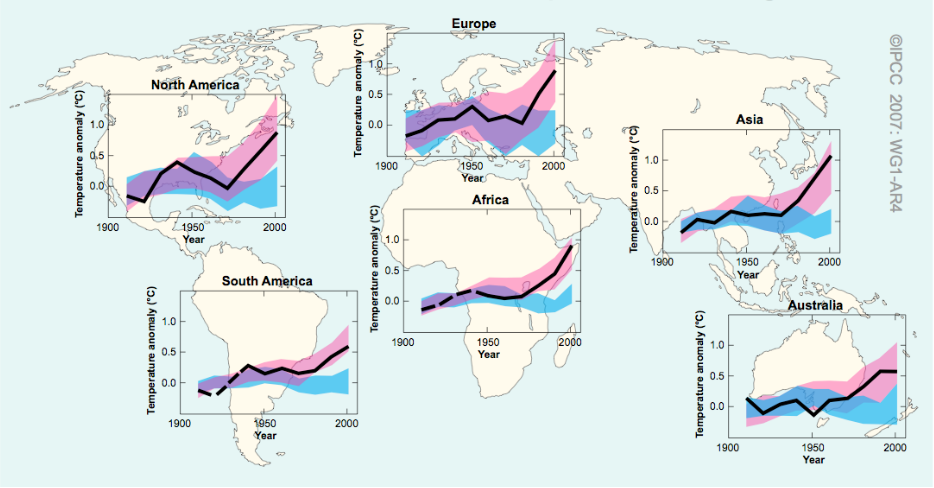
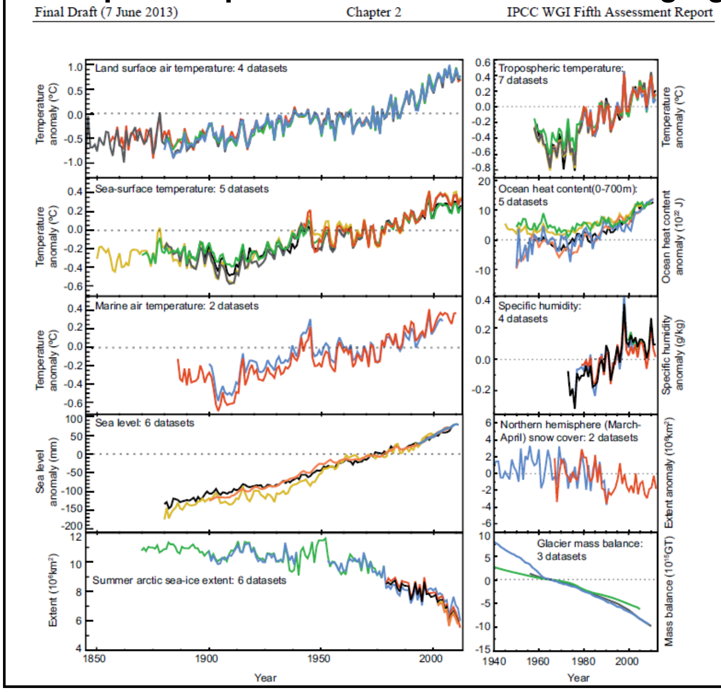


FIGURE SPM-4. Continued…

Every continent shows measurable anthropogenic temperature changes since roughly 1980.

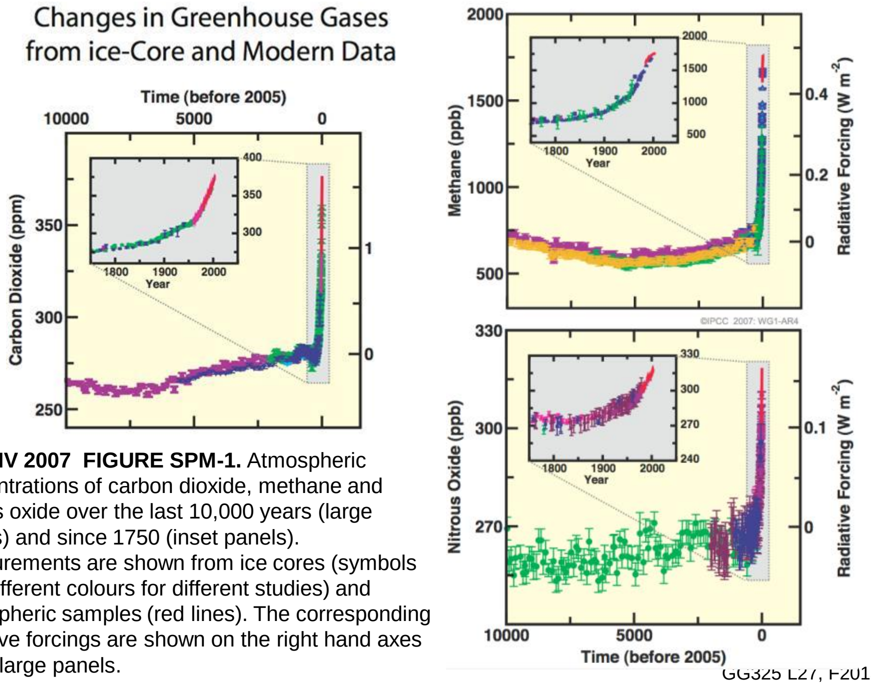
Multiple independent indicators of a changing global climate



IPCC-V 2013

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.

recent greenhouse gas estimates (notice the relative “radiative forcing” scales on the right hand y-axes):



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.

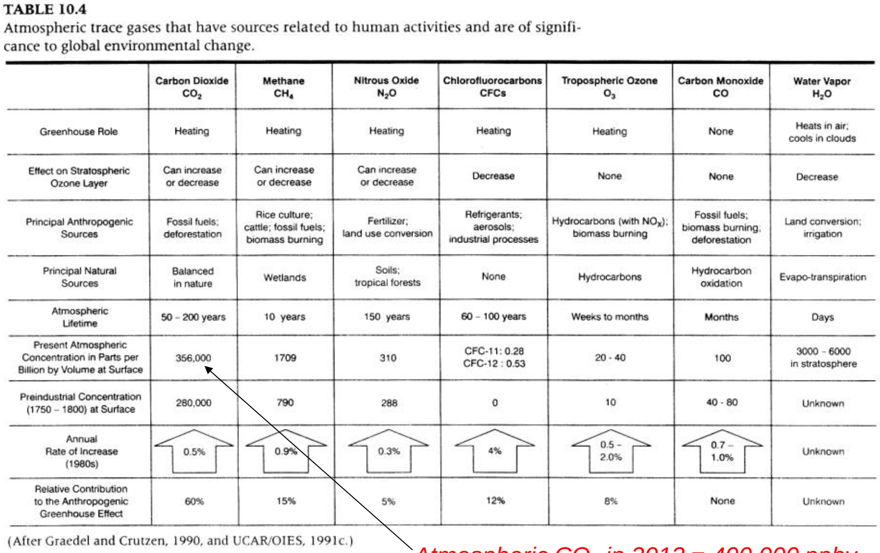


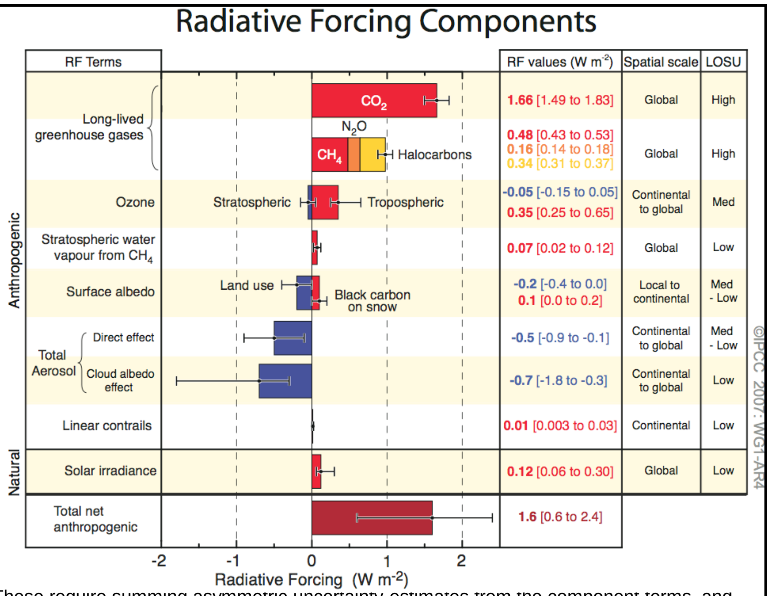
TABLE 10.4
Atmospheric trace gases that have sources related to human activities and are of significance to global environmental change.

	Carbon Dioxide CO_2	Methane CH_4	Nitrous Oxide N_2O	Chlorofluorocarbons CFCs	Tropospheric Ozone O_3	Carbon Monoxide CO	Water Vapor H_2O
Greenhouse Role	Heating	Heating	Heating	Heating	Heating	None	Heats in air; cools in clouds
Effect on Stratospheric Ozone Layer	Can increase or decrease	Can increase or decrease	Can increase or decrease	Decrease	None	None	Decrease
Principal Anthropogenic Sources	Fossil fuels; deforestation	Rice culture; cattle; fossil fuels; biomass burning	Fertilizer; land use conversion	Refrigerants; aerosols; industrial processes	Hydrocarbons (with NO_X); biomass burning	Fossil fuels; biomass burning; deforestation	Land conversion; irrigation
Principal Natural Sources	Balanced in nature	Wetlands	Soils; tropical forests	None	Hydrocarbons	Hydrocarbon oxidation	Evapo-transpiration
Atmospheric Lifetime	50 – 200 years	10 years	150 years	60 – 100 years	Weeks to months	Months	Days
Present Atmospheric Concentration in Parts per Billion by Volume at Surface	356,000	1709	310	CFC-11: 0.28 CFC-12 : 0.53	20 - 40	100	3000 - 6000 in stratosphere
Preindustrial Concentration (1750 – 1800) at Surface	280,000	790	288	0	10	40 - 80	Unknown
Annual Rate of Increase (1980s)	0.5%	0.9%	0.3%	4%	0.5 – 2.0%	0.7 – 1.0%	Unknown
Relative Contribution to the Anthropogenic Greenhouse Effect	60%	15%	5%	12%	8%	None	Unknown

(After Graedel and Crutzen, 1990, and UCAR/OIES, 1991c.)

Atmospheric CO_2 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

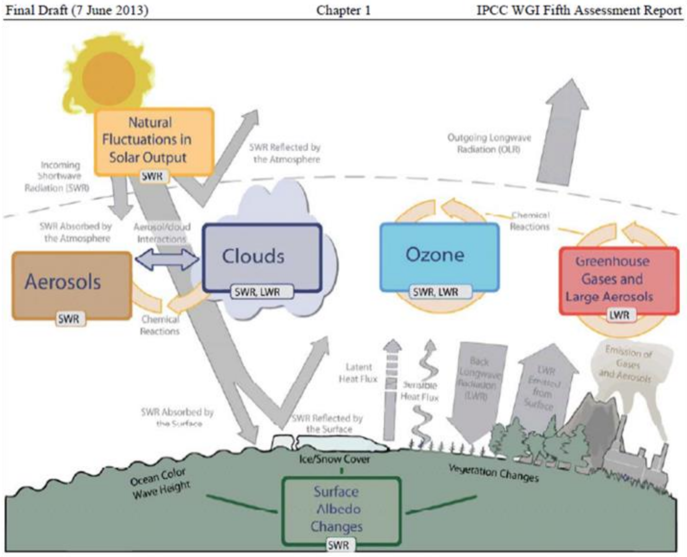
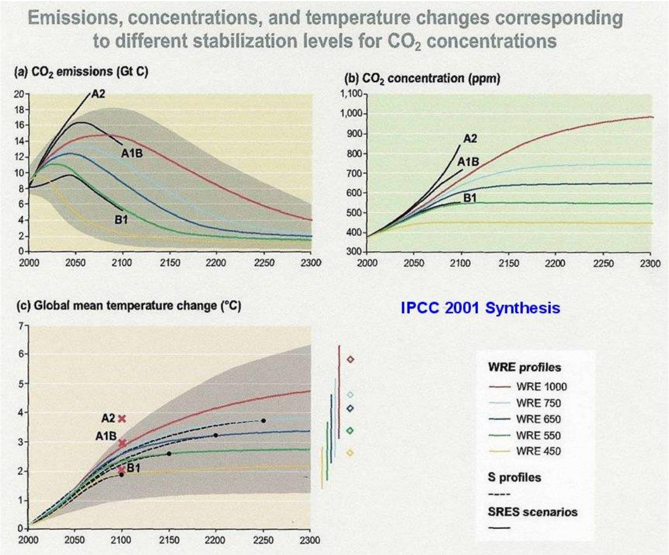
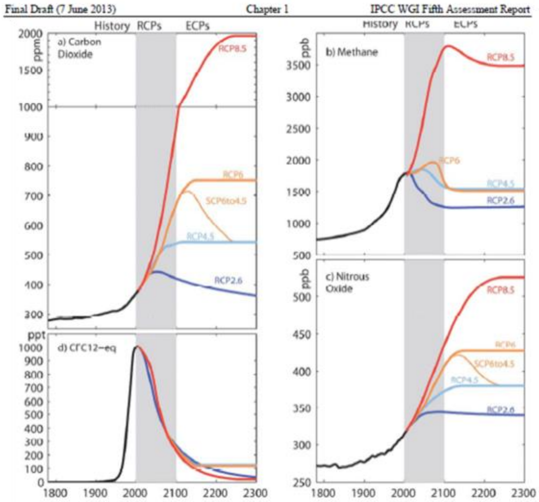


Figure 1.1: Main drivers of climate change. The radiative balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (LWR) is influenced by global climate “drivers”. Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (through fluctuations 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 outgoing LWR 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 CO_2 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*.



Box 1.1, Figure 2: Concentrations of GHG following the 4 RCPs and their extensions (ECP) to 2300. (Reproduced from Figure 5 in Meinshausen et al., 2011). Also see Annex II Table AII.4.1 for CO_2, Table AII.4.2 for CH_4, Table AII.4.3 for N_2O.

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_2VALUE** by the year 2300.

IPCC2013 synthesis

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

Final Draft (7 June 2013) Chapter 1 IPCC WGI Fifth Assessment Report

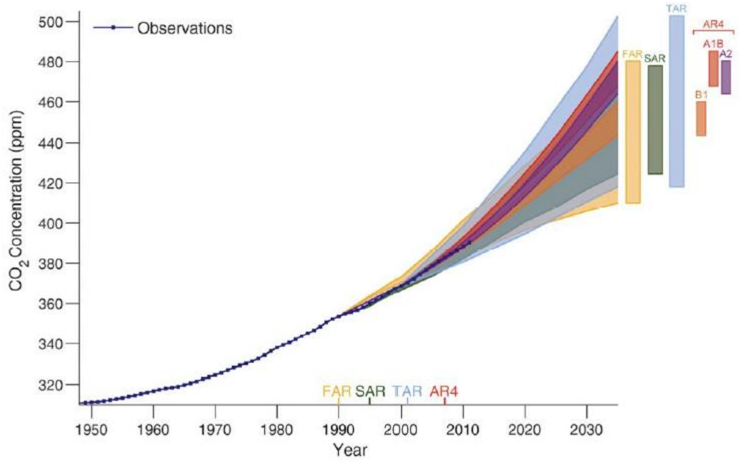


Figure 1.5: Figure 1.5: Observed globally and annually averaged CO2 concentrations in parts per million (ppm) since 1950 compared with projections from the previous IPCC assessments. Observed global annual CO2 concentrations are shown in dark blue. The shading shows the largest model projected range 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 gasses for various scenarios.

Final Draft (7 June 2013) Chapter 8 IPCC WGI Fifth Assessment Report

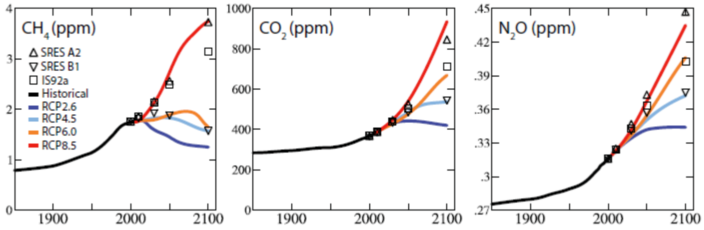
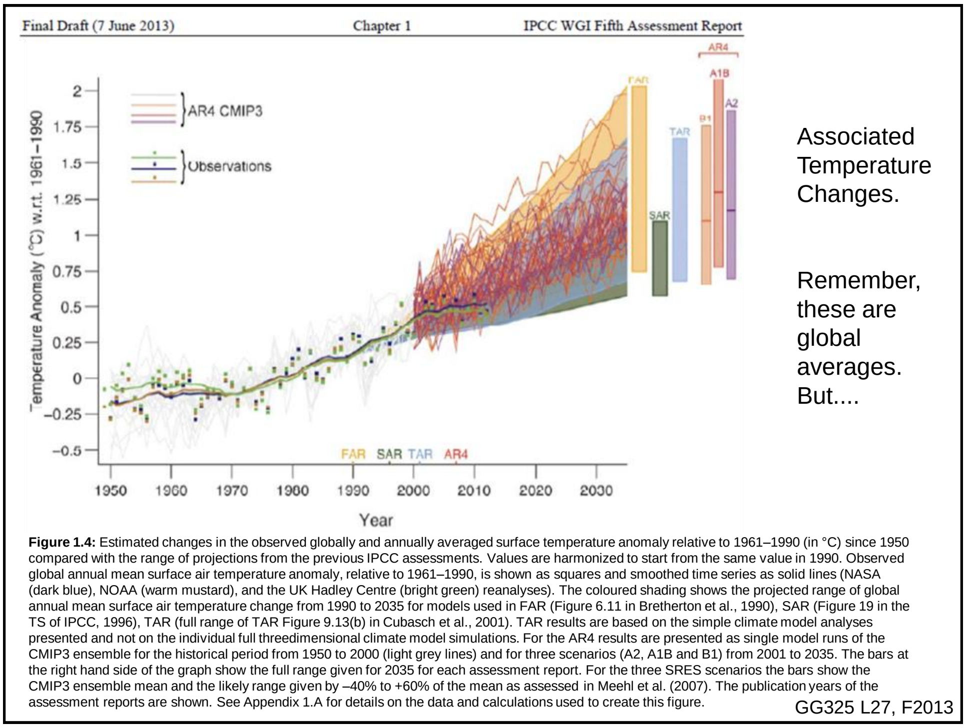


Figure 8.5: Time evolution of global-averaged mixing ratio of long-lived species1850–2100 following each RCP; blue (RCP2.6), light blue (RCP4.5), orange (RCP6.0) and red (RCP8.5). Based on Meinshausen et al. (2011b).



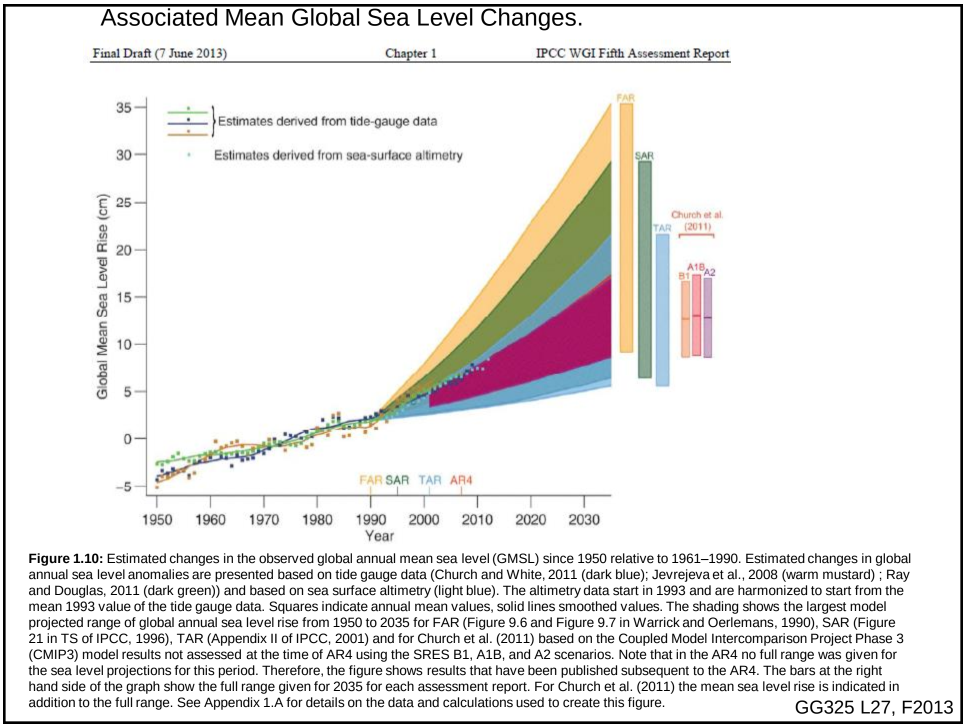
Final Draft (7 June 2013) Chapter 1 IPCC WGI Fifth Assessment Report

Associated Temperature Changes.

Remember, these are global averages. But....

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 Bretherton 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.

GG325 L27, F2013



Associated Mean Global Sea Level Changes.

Final Draft (7 June 2013) Chapter 1 IPCC WGI Fifth Assessment Report

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 White, 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.

GG325 L27, F2013

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.

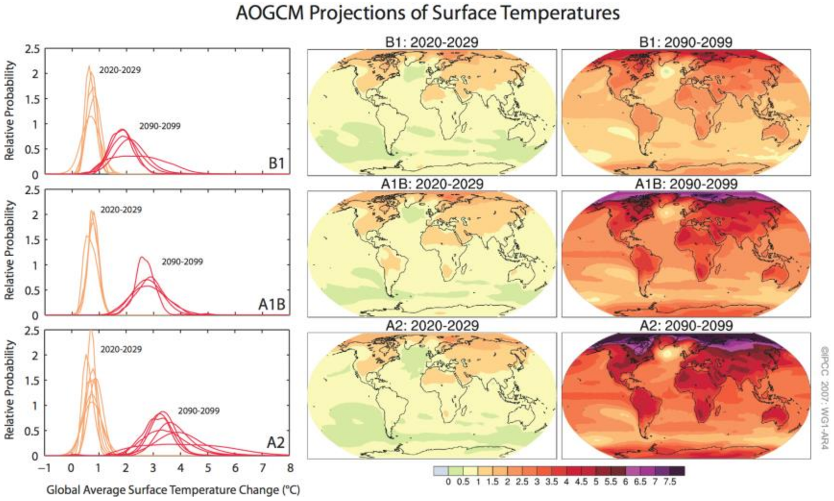
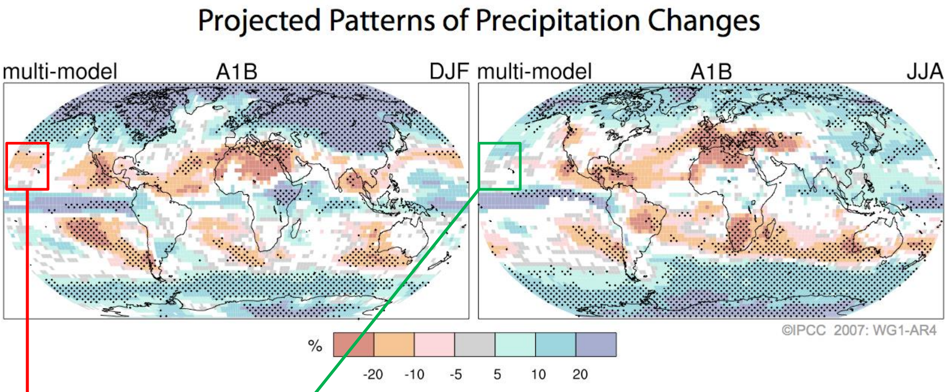


FIGURE SPM-5. Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the Atmosphere-Ocean General Circulation multi-Model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over decades 2020–2029 (center) and 2090–2099 (right). The left panel shows corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and EMICs studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves, shown in the left-hand panels, is due only to differences in the availability of results.



Hawaii Zoom ins

FIGURE SPM-6. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.

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

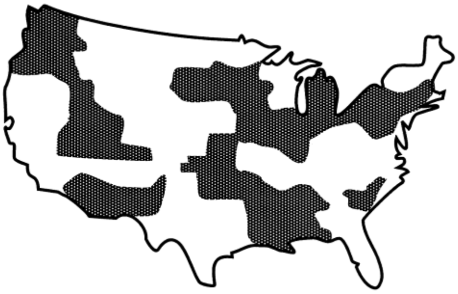
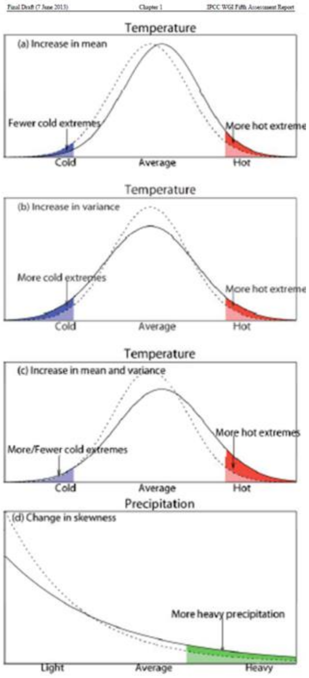


Figure 14.3. Sections of the lower 48 United States in which precipitation levels have increased by 10-20% since about 1900 (shown as shaded regions). Some areas, particularly North Dakota, eastern Montana, Wyoming, and California have experienced decreases in precipitation of a similar magnitude. This map is based on data gathered by the National Oceanic and Atmospheric Administration's National Climatic Data Center.

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.

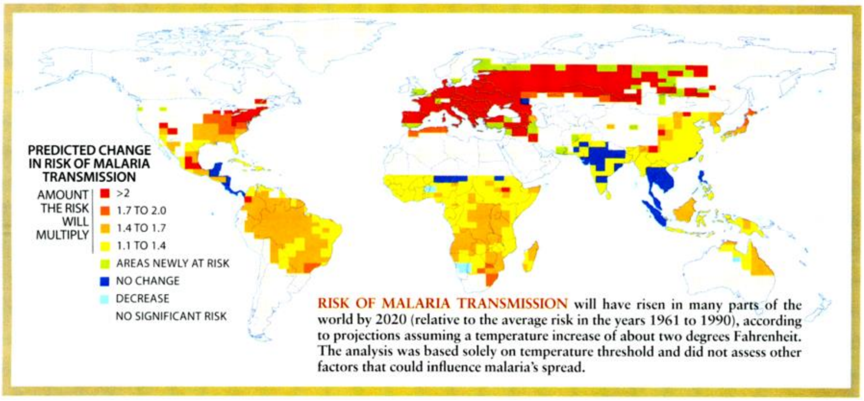


Scientists have hypothesized that there will be an increase in frequency and intensity of "extreme" weather patterns in the near future.

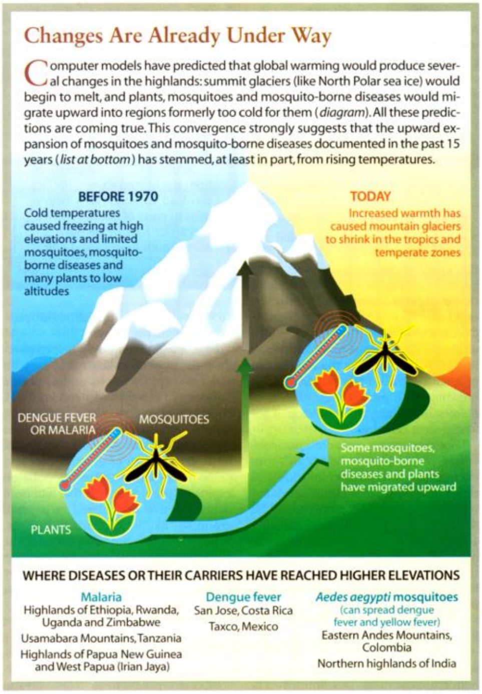
Figure 1.8: Schematic representations of the probability density function of daily temperature, which tends to be approximately Gaussian, and daily precipitation, which has a skewed distribution. Dashed lines represent a previous distribution and solid lines a changed distribution. The probability of 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).

Although it is difficult to predict exact effects of continued global atmospheric loading of greenhouse gasses in each specific location 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.



RISK OF MALARIA TRANSMISSION will have risen in many parts of the world by 2020 (relative to the average risk in the years 1961 to 1990), according to projections assuming a temperature increase of about two degrees Fahrenheit. The analysis was based solely on temperature threshold and did not assess other factors that could influence malaria's spread.



Changes Are Already Under Way

Computer models have predicted that global warming would produce several changes in the highlands: summit glaciers (like North Polar sea ice) would begin to melt, and plants, mosquitoes and mosquito-borne diseases would migrate upward into regions formerly too cold for them (*diagram*). All these predictions are coming true. This convergence strongly suggests that the upward expansion of mosquitoes and mosquito-borne diseases documented in the past 15 years (*list at bottom*) has stemmed, at least in part, from rising temperatures.

BEFORE 1970
Cold temperatures caused freezing at high elevations and limited mosquitoes, mosquito-borne diseases and many plants to low altitudes

TODAY
Increased warmth has caused mountain glaciers to shrink in the tropics and temperate zones

Some mosquitoes, mosquito-borne diseases and plants have migrated upward

WHERE DISEASES OR THEIR CARRIERS HAVE REACHED HIGHER ELEVATIONS

Malaria	Dengue fever	*Aedes aegypti* mosquitoes (can spread dengue fever and yellow fever)
Highlands of Ethiopia, Rwanda, Uganda and Zimbabwe	San Jose, Costa Rica	Eastern Andes Mountains, Colombia
Usamabara Mountains, Tanzania	Taxco, Mexico	Northern highlands of India
Highlands of Papua New Guinea and West Papua (Irian Jaya)		

SCIENTIFIC AMERICAN August 2000

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.

15 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.