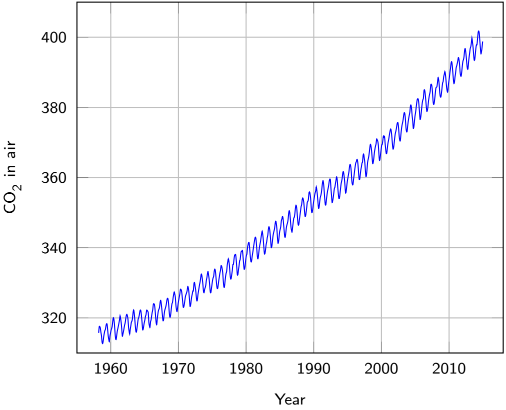
Global Climate Change

Greenhouse Gases and Earth's Energy Balance

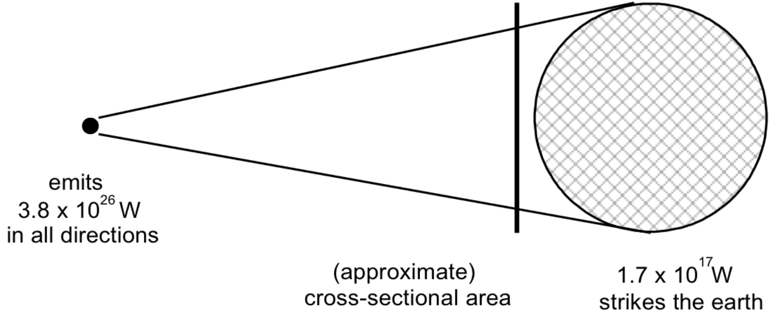


Outline of Topics

1. The Natural Earth System
   - Earth's Energy Balance
   - The Greenhouse Effect
2. Radiative Forcing
   - The Carbon Cycle
   - Other GHGs
   - Energy Balance Effects
3. Climate Change
   - Temperature
   - Models and Predictions

Solar Energy Input

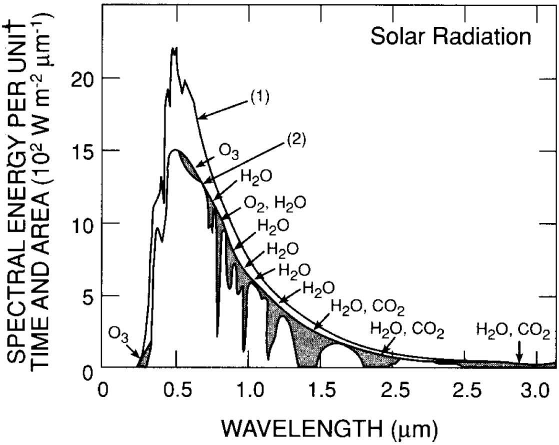
How much energy does the earth receive from the sun?



- To maintain balance, Earth must also emit at the same rate of 1.7×10^{17} J/s
- Divide by surface area: $342\,\mathrm{W/m^2}$.
- The **solar constant**, a long-term annual average.

Lecture Question

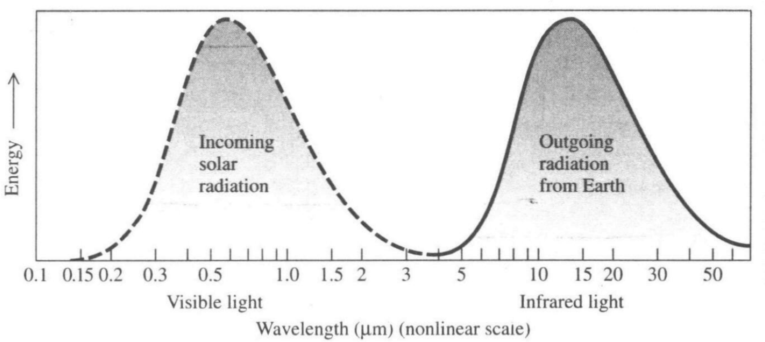
How much of this sunlight is (a) reflected immediately, (b) absorbed by the atmosphere, or (c) absorbed by Earth's surface?



- 30% reflected back to space
- 25% absorbed by atmosphere (see figure)
- 45% absorbed by surface land and water

Earth's Energy Balance: Blackbody Radiation

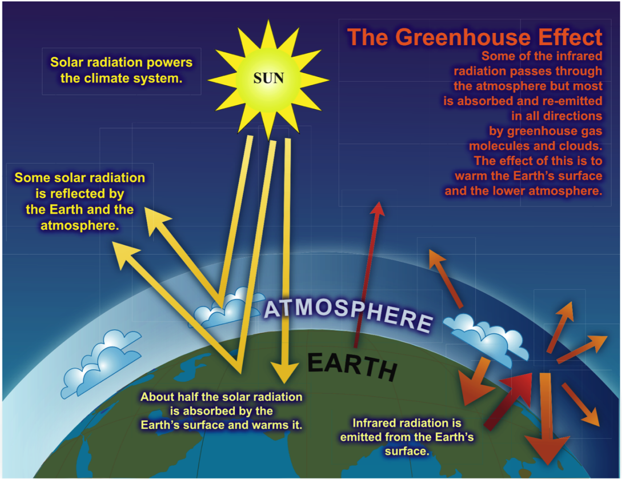
Contrast Earth's incoming and outgoing radiation.



- The sun and the earth are reasonable *blackbody radiators*
- Blackbody radiator: light emitted is determined almost entirely by temperature of the radiator
- See figure: hotter sun emits 10% uv, 40% vis, 50% near-IR, while Earth emits entirely in the mid-IR at 5–50 μm.

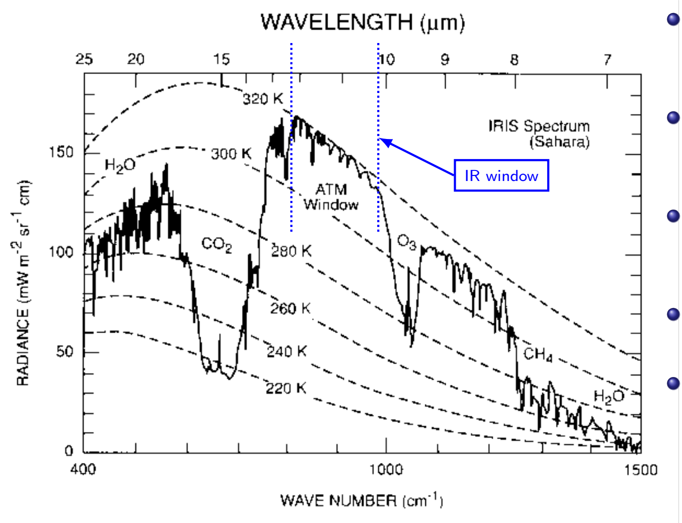
Lecture Question

What is the greenhouse effect?



- 90% of IR light emitted by the surface/clouds is re-absorbed by GHGs
- GHGs re-emit some IR light back to the surface

Is there direct evidence of the greenhouse effect?



- 90% (avg) emitted light is absorbed and re-emitted
- But some light escapes without heating air through an **IR Window**
- IR window is dynamic, depends on composition (esp water vapor)
- main window is 8–14 μm
- more windows in 0.2–5.5 μm

Lecture Questions

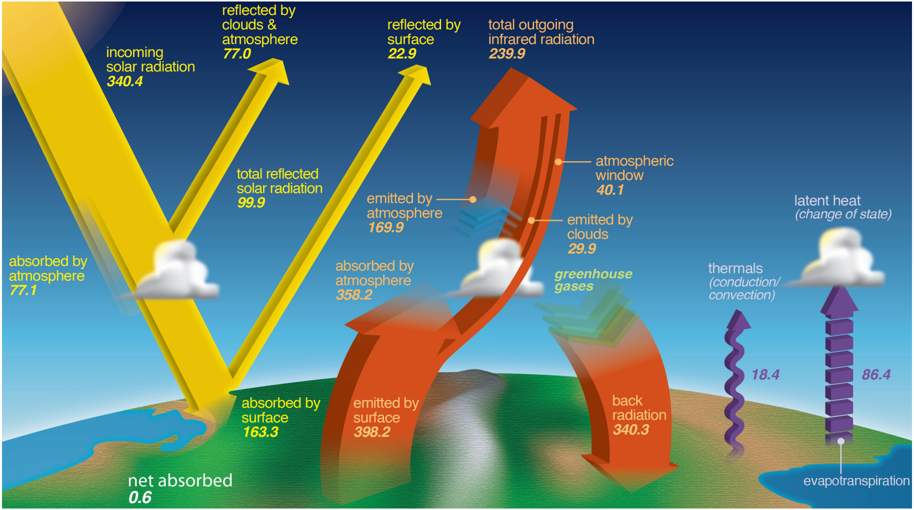
What are *greenhouse gases*, GHGs? Name the five most important GHGs present naturally in the atmosphere.

Greenhouse gases are those that absorb in the region, 5–50 μm, emitted by the earth's surface. The most important natural GHGs are:

- water, H_2O
- carbon dioxide, CO_2
- ozone, O_3
- methane, CH_4
- nitrous oxide, N_2O

The Greenhouse Effect

Give a more detailed description of Earth's current energy balance.



The Greenhouse Effect

Compare the heat inputs of the atmosphere and surface.

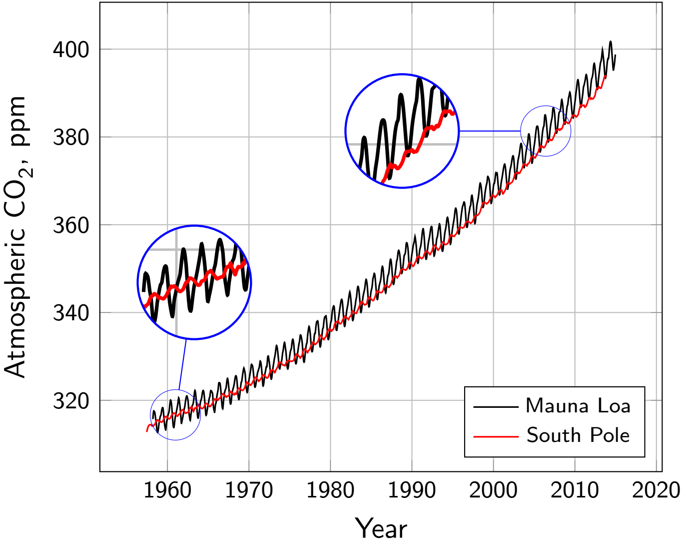
The atmosphere receives: 540 W/m^2:

- sunlight (14%)
- 'thermals' (3%)
- latent heat (16%)
- absorption of IR light by GHGs (66%)

The surface receives: 504 W/m^2:

- sunlight (32%)
- re-emitted IR light from GHGs (68%). *This is the greenhouse effect.*

What is a Keeling Curve? Explain the trends and fluctuations.



- Regular oscillations, with 1-yr period
- NH and SH 180° out of phase
- Oscillation amplitude greater at ML
- General increase in CO_2
- ML increasing faster than SP

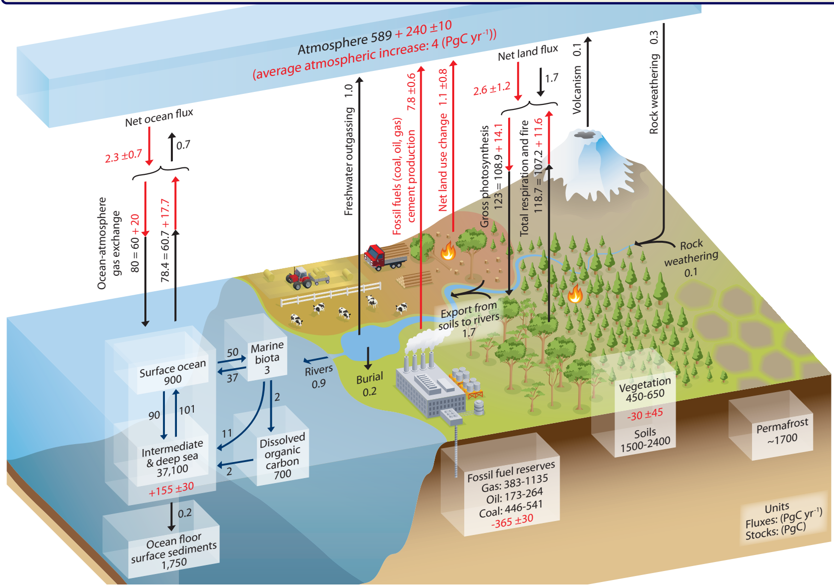
The Global Carbon Cycle

What is a **biogeochemical cycle**?

- A biogeochemical cycle is a description of the major reservoirs of a substance, and the processes that exchange that substance between the reservoirs.
- Each reservoir has a *stock* of substance in it, and each exchange process causes a *flow* of substance from one reservoir to another.
- Processes are biological/chemical/geological, and can operate on greatly different time scales
- Biogeochemical cycles can be local or global

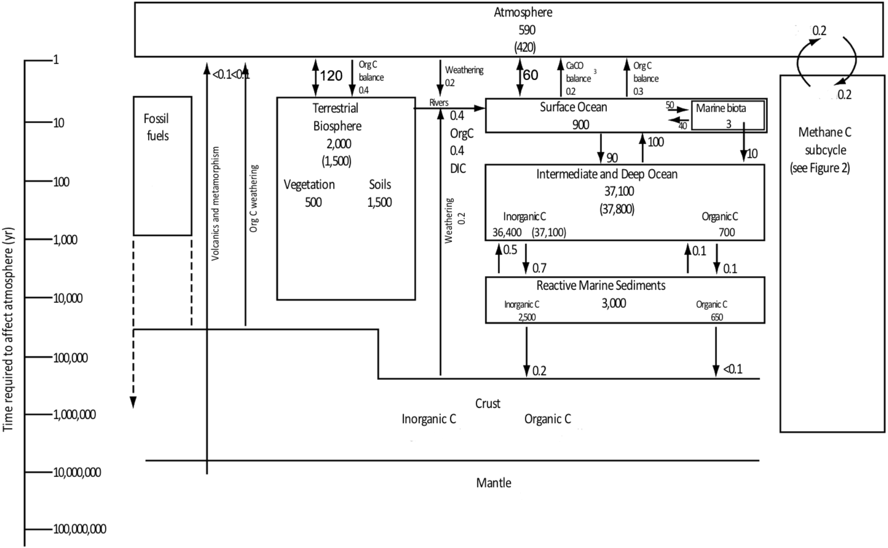
Lecture Question

Describe the carbon cycle and how we have affected it.



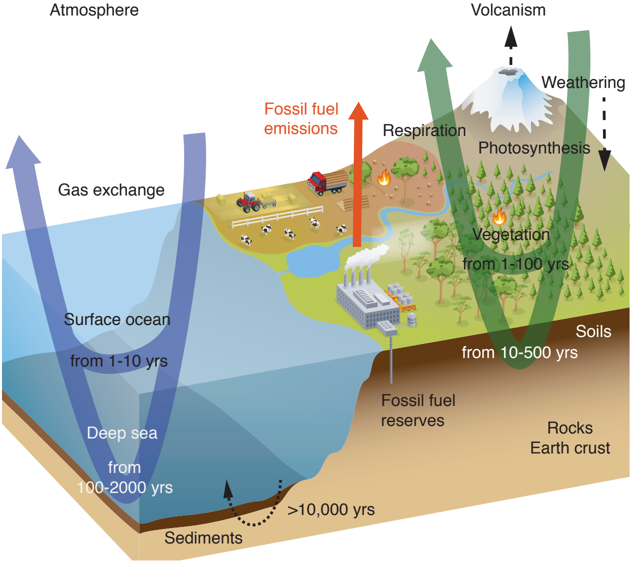
The Global Carbon Cycle: Fast and Slow Carbon Pools

Explain the difference between ‘fast’ and ‘slow’ carbon cycles.



The Global Carbon Cycle

Explain what happens to the CO_2 humans emit.



- The 'old' carbon we emit re-distributes between the three 'fast' pools
- Uptake by dissolution into surface ocean and by fast-growing plans is pretty rapid (avg 4.5 yr)
- But most of this is re-emitted back into the atmosphere (still in 'fast' C pool)

The Global Carbon Cycle

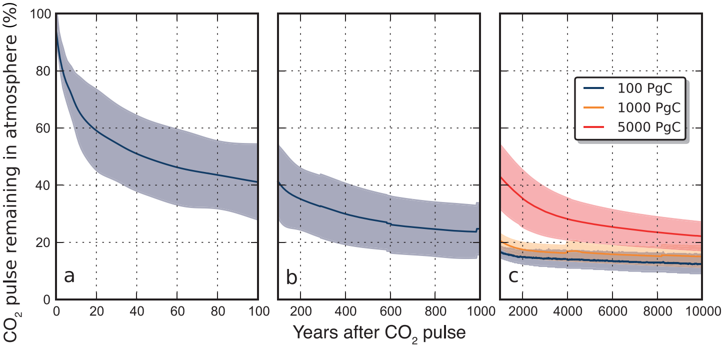
How about some numbers this time?

Anthropogenic sources	fossil fuel combustion, cement production	8.3 ± 0.4 PgC/yr
	changes in land-use	1.0 ± 0.5 PgC/yr
	total emissions	***9.3 ± 0.6 PgC/yr***
Partitioning among reservoirs	net ocean uptake	2.5 ± 0.5 PgC/yr
	net land uptake	2.6 ± 0.8 PgC/yr
	net storage in atmosphere (*measured*)	***4.3 ± 0.1 PgC/yr***

- Less than half (46%) of emitted carbon stays in air
- Dissolution in ocean causes acidification: $CO_2 + H_2O \longrightarrow H_2CO_3$
- Land sink has the highest uncertainty, subject of much current research

Lecture Questions

How much has atmospheric CO_2 increased since 1750?
What is the recovery time if all anthropogenic CO_2 emissions ceased?



- CO_2: 280 → 400 ppm (and rising)
- We have emitted 555 GtC to date
- Figure shows predicted recovery after CO_2 'pulse'

IPCC: 'Depending on the [future emission] scenario, 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1000 years.'

Lecture Question

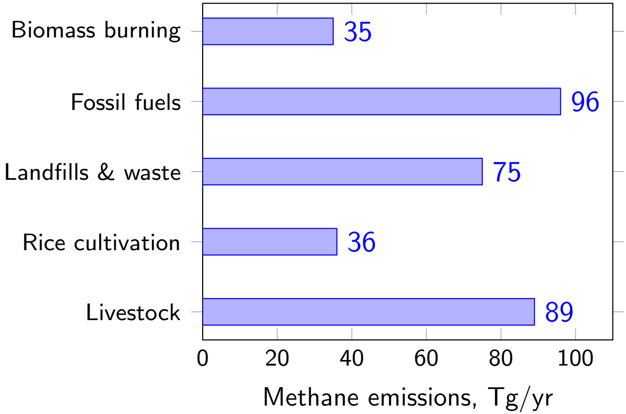
What GHGs have increased since 1750?

GHG	1750	Recent	GWP	Lifetime, yr	RF, W/m^2
CO_2	280 ppm	400 ppm	1	100-300	1.68
CH_4	722 ppb	1825 ppb	28	12	0.97
N_2O	270 ppb	325 ppb	265	121	0.17
O_3	237 ppb	337 ppb	n/a	short	*
CFC-11	0	235 pptr	4,660	45	0.18 (all)
CFC-12	0	527 pptr	10,200	100	
CFC-113	0	74 pptr	5,820	85	
HCFC-22	0	220 pptr	1,760	11.9	

- GWP is the *global warming potential* relative to CO_2 over a 100 yr period
- Lifetime is for the troposphere; it is not well defined for CO_2
- There are a number of other halogenated compounds not included in the table: HCFCs, HFCs, halons, CCl_4, SF_6

The Methane Cycle

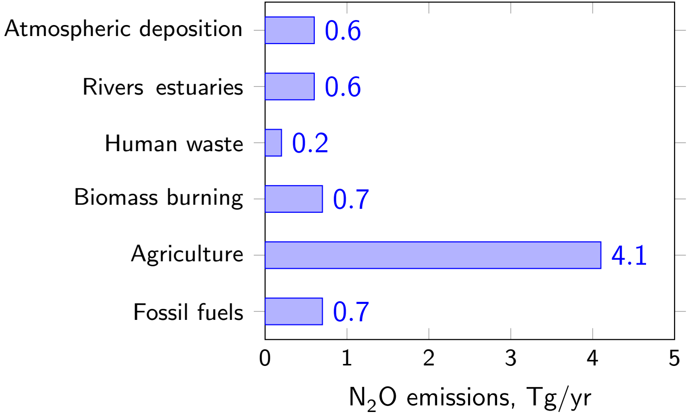
What human activities have lead to the increase in CH_4?



- Note unit change compared to CO_2 emissions
- Total anthropogenic flux: 330 Tg/yr (50–65% of total flux from all sources)
- Main natural source: wetlands (about 200 Tg/yr)

Part of the Nitrogen Cycle

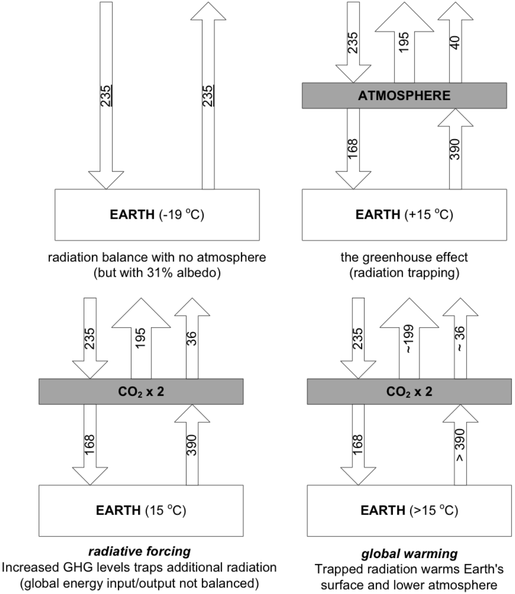
What human activities have lead to the increase in N_2O?



- Current anthropogenic flux: 7 Tg/yr (35–40% of total from all sources)
- Main natural sources: soils (6.6 Tg/yr) and oceans (3.8 Tg/yr)

Lecture Question

What is *radiative forcing*?



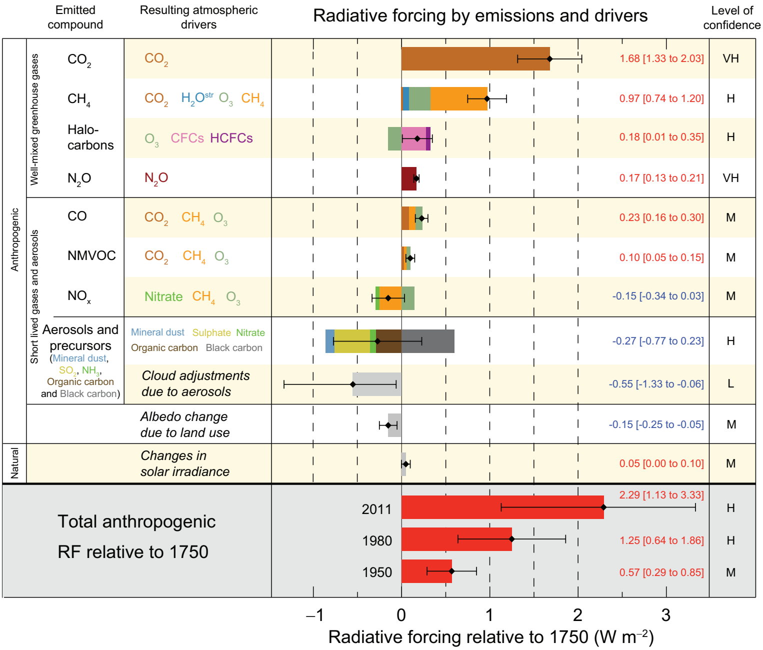
- 2nd panel adds an atmosphere with GHGs (some flows omitted)
- 3rd panel shows an imbalance of $4\,\mathrm{W/m^2}$ due to a doubling of CO_2 concentration

  Radiative forcing, RF, is this quantitative measure of the radiative energy imbalance

  $$\mathrm{RF} = \text{incoming} - \text{outgoing}$$

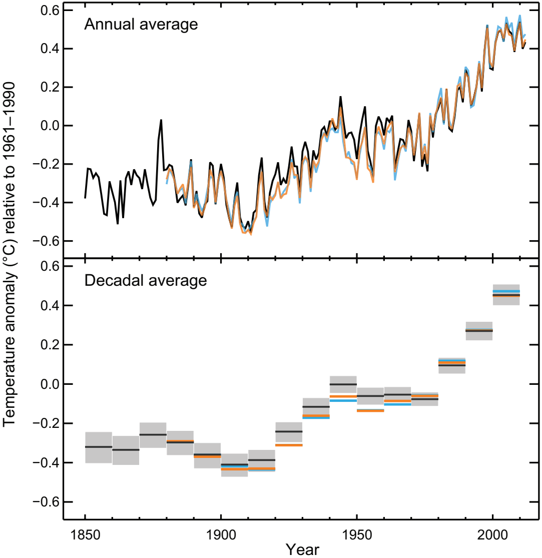
- 4th panel shows a restored energy balance after global warming has occurred

What factors are currently causing radiative forcing?



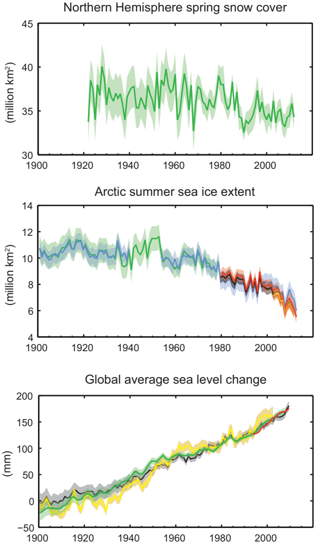
Lecture Question

What are the recent temperature trends?



- Figures show combined land & surface temps
- 1880–2012: 0.85 °C increase
- Since 1951: rate of increase is 0.12 °C per decade
- 2014 recently declared hottest year ever measured directly (and no El Niño)

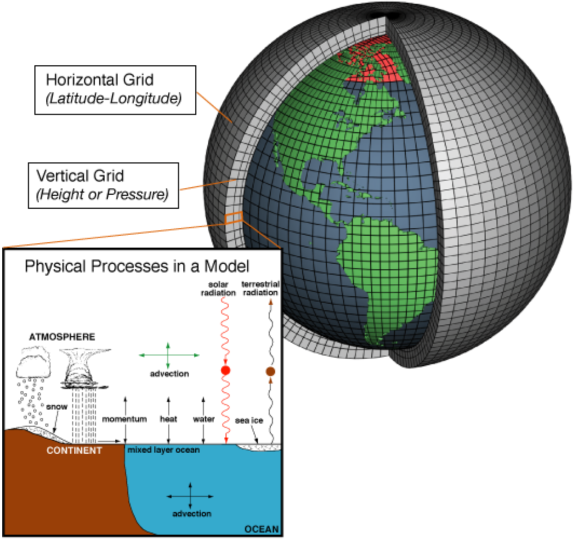
Besides the increase in global mean temperature, what other changes have been observed?



- Oceans absorbed most (90+%) of the heat dumped into the system in the last 40 yr
- Precipitation has increased (NH mid-latitude)
- Extreme events: heat waves, droughts, heavy precipitation events
- Glaciars have shrunk worldwide
- Antarctic and Greenland ice sheets have lost mass for two decades
- Arctic ice sheet and NH snow cover (see figure)
- Sea levels have risen by 0.19 m since 1901 (figure)
- Non-climate: ocean pH has decreased by 0.11 (30% increase in $[H_3O^+]$)

Climate Modeling

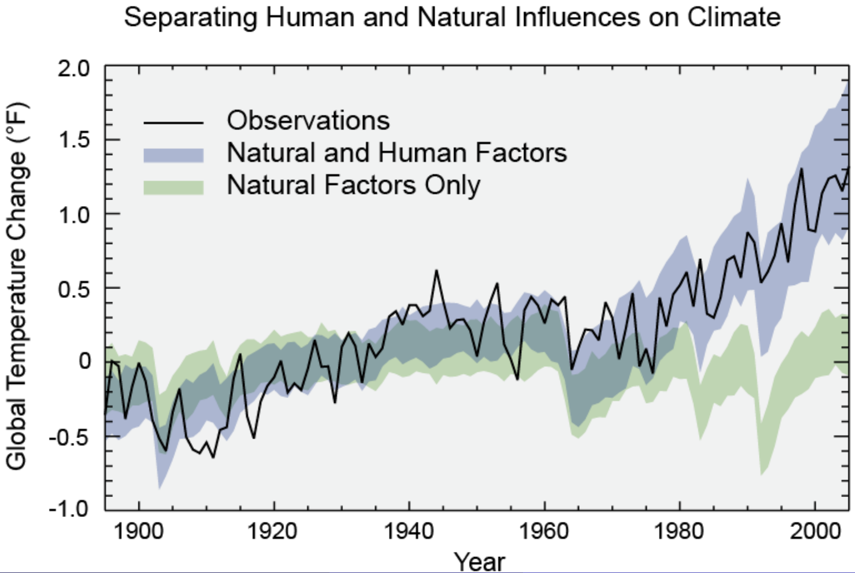
What are General Circulation Models (GCMs)?



- Math model of the circulation of air or ocean to describe/simulate climate
- Divides fluid up into 3-d grid
- Mathematically describes flow of energy and mass between grids using set of differential equations solved numerically
- Complete climate model requires coupled air/ocean GCMs plus other components (eg ice sheet model)

Model Validation

Can we attribute temperature increases to human activities?



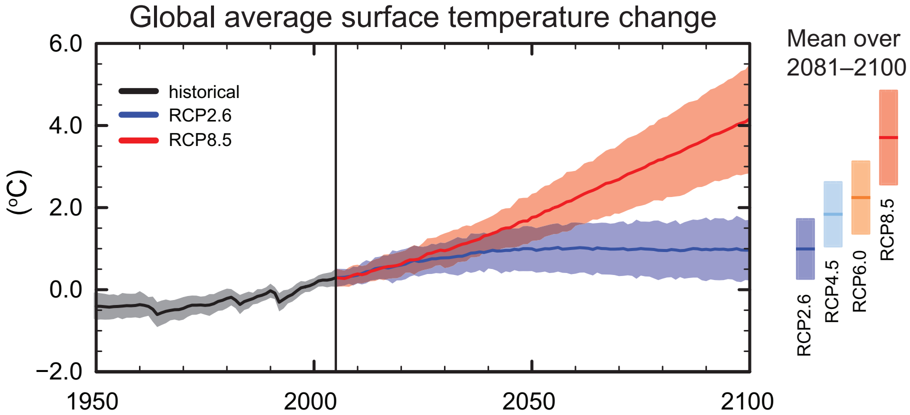
Climate Modeling

What are feedback effects? Examples?

- Response to a change that either opposes further change (negative feedback) or amplifies it (positive feedback).
- Can lead to non-linear equations that are harder to model.
- Possible carbon cycle feedbacks:
    - CO_2 solubility decreases with increasing temperature (positive)
    - carbon fertilization effect (negative)
    - increased rate of decomposition with temperature (positive)
    - melting of permafrost releases stored methane (positive)
- Hydrologic cycle feedback: water vapor pressure increases with temperature (positive)
- Earth's albedo:
    - increases due to increased cloud cover (negative)
    - decreases due to reduced snow/ice cover (positive)
- Changes in air/ocean circulation causes local feedback effects

Lecture Question

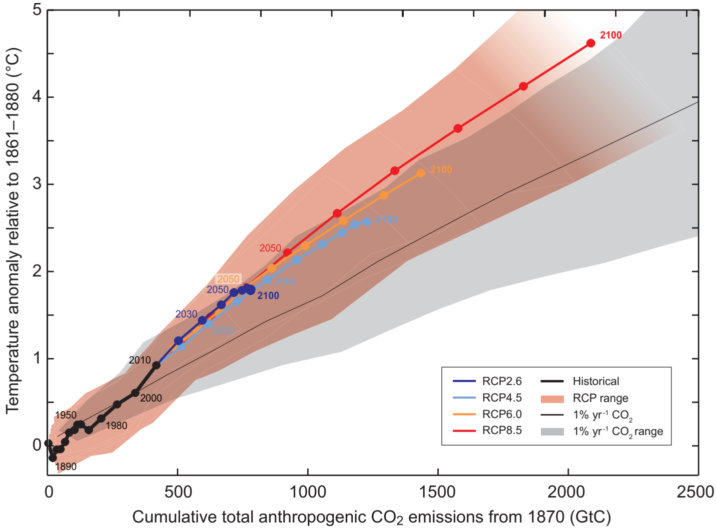
How does the IPCC use models to predict future climate effects?



- Range of values due to variability in models (scientific uncertainty)
- Range of values due to variability in emission scenario (policy response uncertainty)
- Two sources of variability roughly similar

Future Carbon Emission Scenarios

Explain the IPCC future emission scenarios.



- Projected warming is a function of cumulative emissions
- 555 GtC emitted to date
- RCP = Representative Concentration Pathway
- Number is projected forcing in 2100 relative to 1750

Lecture Question

What changes are predicted for temperature and sea level?

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range**	**Mean**	***Likely* range**
Global Mean Surface Temperature Change (°C)	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range**	**Mean**	***Likely* range**
Global Mean Sea Level Rise (m)	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

- Ranges are 90% confidence intervals