Human (mainly industrial-era) activity changing the global climate now and over the next several centuries

1. Burning fossil fuels (primarily)
2. Land use changes (mostly local impacts)

The primary index of change is rising global-mean temperature

Is Global Warming real? (the science)
- Is the energy balance theory of climate change correct?
- Are we forcing the climate system?
- Has the warming already been detected?
- How well can we forecast what comes next?

Global warming

<table>
<thead>
<tr>
<th>BIG questions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Is it real? (science) - Mon &amp; Tues</td>
</tr>
<tr>
<td>2. Is it serious? (impacts) - Weds</td>
</tr>
<tr>
<td>3. What should we do about it? (response) - Fri+</td>
</tr>
</tbody>
</table>

Energy Balance Theory

\[ \Delta T_{EQ} = \lambda \Delta F \]

\( \Delta F \) = Forcing (energy imbalance)
\( \Delta T_{EQ} \) = Response at Equilibrium
\( \lambda \) = Climate sensitivity

How it works:
1. Measure initial temp of the planet
2. Instantly turn on forcing and measure \( \Delta F = F_{IN} - F_{OUT} \) at the tropopause
3. Wait forever for temperature to warm, while waiting \( \Delta F \) decreases
4. After forever measure \( \Delta T_{EQ} \) (at this time \( \Delta F = 0 \))

Where are we today?
1. initial temp = pre-industrial
2. Instantly turn on forcing?
   1. We didn’t, it’s been slowly coming on
   2. So we have to estimate \( \Delta F \)
3. Wait forever?
   So the theory needs some refinement

What else?
\( \Delta T_{transient} = \text{transient warming, actual warming before equilibrium is achieved} \)

If \( \Delta T_{transient} < \Delta T_{EQ} \) then there is more warming in the “pipeline” or we are “committed” to more warming

Alternatively we know it is coming because \( \Delta F \) isn’t zero

Much debate about detecting warming

But another issue is what is \( \Delta F \)?

How are we forcing the climate?

* \( \Delta F \) is instantly measured at the tropopause, before any change to the climate system
Carbon Cycle
- fundamental basis of concern for future
- lessons from the past
- critical part of climate forecasts
- Is there a “missing sink”? 
  - atmosphere, ocean, biota all involved
  - many different timescales are involved

Other topics
- other forcing agents (GHGs and aerosols)
- climate response (global and regional)
- testing the theory (detection and attribution)

Methane clathrate hydrates
18,000 Gt C (4X Gt C in fossil fuel reservoir)
Methane caught in a cage of ice! Naturally occurring in ocean sediments and in permafrost
Form under high pressure and somewhat cold temperatures - may melt if they exist close to phase transition
Possible wild card

Fate of Anthropogenic Carbon
Total anthropogenic source is ~8 Gt C/yr
Only about 3 Gt C/yr is currently accumulating in the atmosphere
Where does 5 Gt C/yr go?
Land and ocean each take up about 2.5 Gt C/yr
(used to be a mystery)
Land-ocean-atmosphere (LOA) as a single reservoir:

1. atmosphere is a small reservoir (760 Gt C) but tightly tied to
2. land biota (2200 Gt C) via photosynthesis and respiration
3. surface ocean (1020 Gt C) via gas exchange

Thus entire LOA reservoir is receiving 8 Gt C/yr of anthro CO2

Changes to Land Reservoir

1) CO2 fertilizes plants. Stomata (pores) let in CO2 and let out moisture. Shrink when CO2 is increased, so the plant loses less moisture and can tolerate higher temperatures. Plants thrive.

2) Forest expansion
   - Some acid rain damage to forests are mending from CO2 fertilization
   - Reforestation from logging
   - New habitat towards poles and regions with more moisture

But does this change the planet’s albedo???

Late 21st century forest expansion caused by increasing CO2 and climate change

Results from climate model

Changes to Upper-Ocean Reservoir

Discussed in chap 8

1) CO2 Gas dissolves in ocn, reacts with H2O and acidifies ocean
2) Higher rates of weathering deposits more bicarbonate ion to upper ocean

Removal from the atmosphere

(consider fluxes that respond to change in CO2 level or climate)
- grow trees and fertilize plants: temporary
- dissolve CO2 gas into surface: can be longer term, but acidifies ocn
- carbonate weathering moves CO2 from air to upper ocn: can be longer term, but small flux and acidifies ocn
- silicate weathering (see below)

Removal from the LOA

- mix with deep ocean: Can remove C from upper ocean until the deep ocean chemistry changes ~1000’s of years (still temporary)
- form new carbonate sediments via silicate weathering: PERMANENT loss, but small flux (for our purposes)

Box Fig 16-2: Long-term CO2 projections

recall we run out of oil in ~100yrs but coal lasts a lot longer

Require mixing between surface and deep ocn
Fig 16-3
IPCC Emissions scenarios

Based on humans - e.g., politics, economics, technology

Involves the carbon cycle, given the emissions above

20th century trends observations and models

How successful are models?
How can we use models and observations together to advance understanding?

IPCC fig 2-9 observations
(c) Annual temperature trends, 1946 to 1975

Observations of Surface air temperature

IPCC Fig 2-25 observations
Trends (%/century) in DJF Precipitation

Model Validation
With amplitude of the seasonal cycle

observed
modeled

1901-2000
1946-1975
1976-2000
How models help us learn about the climate system...

Model “hindcast” - validate models with past

2m Temperature Change (deg C) 1980 - 1999 minus 1860 - 1880

“Detection and Attribution”
Obs and model used together

How long does it take for the climate to come to an equilibrium?

Models used for future prediction

2040-2060 minus 1980-2000 temperature change (A1B Scenario)

If we eliminated anthro CO2 emissions today:

How long will it take for the Earth system to reach a new equilibrium?

It will take many centuries to thousands of years

What are the factors?
Deep ocean heat uptake

CO2 and CH4 cycles

Because climate models don’t predict carbon cycle well yet - Instead fix CO2 levels

What are the factors?
Deep ocean heat uptake (ONLY)

See next slide:
**Question on Heat Uptake**

How long to heat surface by 1K for doubling CO2?

1) Take into account atmosphere only
2) Add to it the surface ocean (~100 m)
3) With entire ocean (~4000 m deep)

Note: 4 W/m² is forcing for doubled CO₂ (Ignore carbon uptake)

**Specific heat capacity, C**

Energy per unit mass does to warm a substance by one degree Kelvin

\[ E = C \cdot M \cdot \Delta T \]

\[ \text{Energy in Joules} \]

\[ \text{Required to raise temperature by } \Delta T \]

**Time (s) = Energy Required (J) / Energy Flux (W)**

Consider mass of 1 m³ Earth "column" so M is in kg/m²

\[ \text{Time (s)} = \frac{E (\text{J/m}^3 \text{W}^{-1})}{4 \text{ (W/m}^2)} = \frac{C \cdot M \cdot \Delta T}{4 \text{ (W/m}^2)} \]

<table>
<thead>
<tr>
<th>Reservoir</th>
<th><strong>C</strong> (J/kg/K)</th>
<th><strong>M</strong> (kg/m²)</th>
<th><strong>Time</strong> to heat by 1K with 4 W/m² flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>1000</td>
<td>10⁴</td>
<td>30 days</td>
</tr>
<tr>
<td>Surface Ocean</td>
<td>4000</td>
<td>10³</td>
<td>3 years</td>
</tr>
<tr>
<td>Entire Ocean*</td>
<td>4000</td>
<td>4x10⁴</td>
<td>130 years</td>
</tr>
</tbody>
</table>

*assuming perfect mixing - which is unrealistic

**Conclude about heat uptake**

- Surface ocean provides thermal inertia on time scale of several years
- Deep ocean provides thermal inertia on time scale of many centuries (our estimate is even shorter than reality due to perfect mixing assumption)
- Oceans have a very strong stabilizing effect on climate

**Ocean heat uptake - warming in the ocean mid 21st century (deg C) (not perfectly mixed)**

**Motivation for simpler warming “scenario”**

Ocean heat uptake is complex and leads to major differences among models

At equilibrium the deep heat content is constant so no further heat “uptake”

Uncertainty about future emissions scenario is source of future uncertainty in the climate

**Solution:**

1. Run models without deep ocean - replace ocean component with shallow mixed layer only
2. Instantly double CO₂
3. Wait about 10 yrs to get equilibrium response
Transient versus Equilibrium warming

- Transient warming is smaller
- Transient warming is asymmetric across hemispheres
- Transient warming is modest in the northern North Atlantic

Equilibrium warming from 2XCO2

All the virtues described two slides ago

Used to compare models
\[ \Delta T_{EQ} \text{ ranges from 1.5-4.5 C} \]

- The range is awfully large (factor of three!)
- Hasn’t narrowed in 30 years - makes scientists look bad
- Are predictions even useful for policy-making purposes?

Why do models disagree?

At Equilibrium
- Clouds, clouds, clouds - either positive or negative feedback depending on height and thickness
- Magnitude of Ice-albedo feedback

In Transient run
- Ocean heat uptake

What else? Emissions scenario including aerosols

The problem of aerosols

direct effect: reflect sunlight back to space
indirect effect: modify clouds (more droplets) causing increase in cloud albedo

- Cooling effects are LOCALIZED near big cities
- Improved match between models and 20th century climate change
- Problem: forcing estimates of aerosols is -3 to 0 W/m² over the last century!!!

HAVE WE REALLY ATTRIBUTED 20TH CENTURY CLIMATE CHANGE TO HUMANS?

Transient temperature projections with uncertainty in emissions and ocean heat uptake

IPCC 2001 projections: 1.5 to 5.8 K

IPCC explanation:
"The higher projected temperatures... are due primarily to the lower projected sulfur dioxide emissions."

translation:
Aerosols don’t offset GHG as much in future projection due to human feedback: people won’t tolerate deadly pollution

Aerosols forcing remains uncertain in the future BUT the forcing from GHG eventually exceeds the aerosol uncertainty