Class 1
What Determines Earth’s Temperature?

OLLI
L80X Climate Change
July 2013
QUESTIONS
Your Questions

• Clarification: anytime

• Substantive – disagreement, implications: question break and beginning of next class

• Comments on outside sources: raise at question break or by e-mail – generally posted response
Some Yes/No Questions

• Is average global temperature higher today than in 1900?

• Is the atmospheric concentration of carbon dioxide (CO₂) higher today than in 1900?

• Has more atmospheric CO₂ “contributed” to higher temperatures?
Kinds of Questions

• Yes/no questions

• Quantitative questions

• Major climate science issues
  – Yes/no: generally little (but not zero) uncertainty
  – Quantitative: often much greater uncertainty
Comparing Temperature and CO$_2$

• Issue: Can we measure 1900 and current temperature and CO$_2$ with enough accuracy?

• Temperature: Global instrument readings

• CO$_2$: Instrument reading and ice cores
Role of CO$_2$

• Issue: Can we infer a causal relationship between CO$_2$ rise and temperature rise?

• Science: CO$_2$ traps thermal radiation

• Observation:
  – General correlation between temperature and CO$_2$
  – We can (mostly) explain exceptions

• Conclusion: Very high probability that CO$_2$ contributed to temperature rise
A Quantitative Question: How Warm Will It Get?

- Behavioral issue: Future CO$_2$ emissions

- Scientific issue: CO$_2$ absorption by ocean and biosphere

- Behavioral issue: Sequestration of CO$_2$

- Scientific issue: Quantitative CO$_2$-temperature relationship (climate sensitivity)
The Causal Chain
(without radiation management)

- Anthropogenic emissions
- Carbon sequestration
- Changes in natural carbon reservoirs

Change in atmospheric concentration

Climate sensitivity: $T$ increase for doubling CO2

Change in Temperature

Human behavior

Science
IPCC 2007 Projections
What Should We Do?
Three Climate Policy Questions

• A moral question: How much should we sacrifice for the future?

• An economic and technological question: What form of sacrifice will do the most good?

• A political question: What amount and form of sacrifice is politically feasible?
WHAT DETERMINES EARTH’S TEMPERATURE?
Basic Principles

• A system’s temperature measures its atom’s average kinetic energy (energy of movement)

• Implications
  – Average temperature changes when there is an imbalance between energy added and energy lost
  – Equal energy additions and losses $\rightarrow$ unchanging average temperature
Applying the Principles to a Planet

• Planets receive and lose energy only through radiation – like perfect vacuum bottles

• Radiation
  – Incoming from their sun
  – Outgoing thermal and reflected solar

• **Radiative forcing:** Imbalance between incoming and outgoing radiation
Radiative Forcing: Long ago in a galaxy far far way

- Planet Keeling ejected from its system

- Characteristics
  - Heat from home star lost during interstellar journey
  - Geologically dead – no internal source of heat
  - Dull black – reflects nothing
  - No atmosphere
Keeling Arrives

• Captured by Sun-like star in near-circular orbit of 150 million km radius

• Incoming solar radiation:
  – Cross-section perpendicular to sun’s rays: 1366 watts/meter$^2$
  – Average for Keeling’s surface: 342 watts/meter$^2$

• Initial outgoing radiation: ~none

• Radiative forcing: 342 watts/meter$^2$
Now What?
The Path to Equilibrium

• Radiative forcing adds energy to the planet → temperature rises

• Higher temperature → more outgoing thermal radiation*

• More outgoing radiation → shrinking radiative forcing

• No radiative forcing or temperature change when thermal radiation equals incoming solar radiation: 279° K = 6° C

* For the curious, radiation = σT⁴ where radiation is in w/m², temperature is in degrees Kelvin (centigrade + 273) and σ = 5.67 x 10⁻⁸ watts
The Path to Equilibrium
Equilibrium for Planet Keeling
Planet Keeling Mark II: Add Albedo

• Albedo (reflectivity) = 0.3 (Earth’s average)
  – 30% of incoming solar radiation reflected
  – Doesn’t add energy to planet

• Solar radiation now balanced by:
  – Keeling’s own thermal radiation plus
  – Reflected solar radiation

• Equilibrium requires less thermal radiation \( \rightarrow \)
  reached at lower temperature
The New Path to Equilibrium

Graph showing the relationship between watts per square meter and temperature changes.

Key:
- **Incoming solar**
- **Solar net of albedo**
- **Outgoing thermal**

Temperature markers at -18°C and 6°C.
Equilibrium for Planet Keeling II

$\text{Incoming Solar} \quad \text{Outgoing Thermal} \quad \text{Outgoing Reflected} \quad = \quad +$
Review: Processes

• Temperature of planetary system changes if and only if there is radiative forcing.

• Other factors relevant only through effect on incoming or outgoing radiation.

• Path to equilibrium with constant solar radiation and albedo: radiative forcing produces temperature change that reduces forcing.
THE GREENHOUSE EFFECT
Something’s Missing

• Calculated temperature is too low:
  – Solar radiation and albedo match Earth
  – But Earth is not a snowball
• Fourier (1824): Atmosphere must trap heat
• Tyndall (1859): Determines what part of atmosphere does this
  – Oxygen and nitrogen (99% of atmosphere) are transparent to infrared radiation
  – Water, CO$_2$ and methane (CH$_4$) are not
Tyndall Experiment: Modern Version

CO$_2$ → Glass tube

Infrared Camera → Reduced infrared component

Person → Full-spectrum radiation
Infrared Image of Face with Normal Atmosphere
Add $\text{CO}_2$ to Tube
– And More, and More
What’s Happening I
Electromagnetic Radiation

• Includes visible light, X-rays, radio waves and others

• Behaves as particles (photons) and waves

• High/low-energy photons = short/long wavelength
Shorter wavelength = More energetic photons
Sun and Earth

• Photon energy/radiation wavelength determined by temperature of source

• Incoming solar radiation: high energy photons/short wavelength

• Outgoing thermal radiation: low energy photons/long wavelength
Solar Radiation
And Earth’s Thermal Radiation

The sun: 6000 K

earth: −278 K
What’s Happening II
Molecules and Greenhouse Gases

• Molecules can only occupy certain energy states – like guitar strings and pitch

• Molecules absorb a photon if its energy matches an energy interval of the molecule

• Greenhouse gases absorb photons from Earth’s thermal radiation
The Process Continues

• Molecule drops back to original energy level
• Emits photon
  – Same energy as before
  – But in random direction
• Further collisions repeat process
• Ends when photon escapes into space or strikes Earth’s surface
From Photon to Photon: Nothing Lost and Nothing Gained

Molecule moves to (available) higher energy state

Photon transfers (appropriate) energy to molecule

Molecule reverts to ground energy state

Reduction in molecule’s energy embodied in photon
Molecular Bumper Cars
Planet Keeling Mark III (preliminary edition)

• Add CO$_2$ to atmosphere

• Part of outgoing radiation re-radiated back to surface

• Higher surface temperature

• But not enough higher
Just Add Water

• Water vapor is a greenhouse gas
• But atmospheric content determined by temperature
• \( \text{CO}_2 \): the control knob
• Water vapor: positive feedback
  – \( \text{CO}_2 \) causes temperature rise
  – Higher temperature adds water vapor to atmosphere
  – Roughly doubles effect of \( \text{CO}_2 \)
Planet Keeling Mark III
The New Equilibrium

• Radiation into space now consists of:
  – Reflected solar radiation
  – **Part** of thermal radiation from Earth’s surface

• Equilibrium requires making up thermal radiation trapped by greenhouse gases:
  – Thermal radiation from surface must increase
  – Requires higher temperature

• Equilibrium: 18° C or 65° F
Planet Keeling Mark III

Incoming Solar + Absorbed Thermal = Net Outgoing Thermal + Outgoing Reflected
A Tale of Two Houses

• Two houses on dark side of Mercury identical except House A is insulated and House B is not.
• Heated by identical electric heaters, which run continuously
• At end of year, thermal radiation from each house is measured.
• What is the relation between the thermal radiation from the two houses? A is greater? B is greater? They are equal?
THE DISCOVERY OF GLOBAL WARMING
Determinants of Earth’s Temperature: Implications

• Earth’s temperature is determined by solar radiation, albedo and greenhouse gases

• Temperature will rise if solar radiation or greenhouse gases increase or albedo declines
A Global Warming Issue?

• Points wouldn’t have surprised Tyndall

• But prevailing view: these factors would not change (uniformitarianism)

• View challenged by discovery of traces of past glaciation

• World could change, but would it warm?
How It Could Warm:
Svante Arrhenius

• 1896 analysis: Perhaps fewer volcanic eruptions caused ice age $\rightarrow$ less CO$_2$ $\rightarrow$ cooler $\rightarrow$ less water vapor $\rightarrow$ more cooling

• To be complete, let's look at the reverse
  – More eruptions $\rightarrow$ more CO$_2$ $\rightarrow$ more water vapor $\rightarrow$ warmer world
  – Burning fossil fuels also could serve – but not for centuries
Quantifying the Impact

• Considers CO$_2$ and water vapor feedback

• Tools: pen and paper

• Result: 5°-6° C warming for doubled CO$_2$ – within range of modern calculations

• Moral: Basic idea of global warming isn’t complicated
But is there a problem?

- Arr$\text{CO}_2$ will not double anytime soon
- A large increase in emissions is far in the future
- Oceans will absorb the $\text{CO}_2$
Roger Revelle

• Grant to study ocean chemistry (1957)
  – Expects to find that ocean absorb CO$_2$
  – It does but (surprise) most pops back out again

• Disproves one reasons for putting problem far into the future

• But other reason remains: expected slow growth in emissions
The Issue Around 1960

• Basic science is settled
  – Tyndall
  – Arrhenius
  – Revelle

• What is lacking: measurements
  – Is CO$_2$ concentration increasing
  – Are global temperatures increasing