Introduction to the Earth’s Climate System and its Evolution

EAS302
Lecture 32

Climate and Energy Balance

• Earth’s surface is heated by:
  – Energy from the Sun
  – Geothermal Energy
    • Heat being conductively lost from the Earth’s interior
      – Radioactive decay plus initial gravitational energy
    • As we will see, geothermal energy is trivial and has been so since very, very early in Earth’s history.
• Earth’s surface is cooled by energy radiated to space.
Wein’s Law

- Wavelength of maximum spectral emittance, \( \lambda_m \), is inversely related to temperature:

\[ \lambda_m = \frac{Y}{T} \]

- Where T is absolute temperature (Kelvins) and Y is a constant equal to 2987\(\mu\)m-K

Solar and Terrestrial Radiation

- For the Sun, \( T \approx 6000 \) K; \( \lambda_m \approx 0.5 \mu\)m (visible light)
- For the Earth, \( T \approx 300 \) K; \( \lambda_m \approx 10 \mu\)m (infrared)
Radiation in the Atmosphere

- Earth’s atmosphere is transparent to visible radiation
  - This, after all, is why we can see the Sun, the stars, and each other for that matter.
  - Therefore, incoming radiation from the Sun does little to heat the atmosphere.
    • (Exception: ozone in stratosphere does adsorb some of the Sun’s radiation, which is why temperature increases upward in stratosphere.)
    • Dust, water vapor, droplets, etc. also absorb some radiation.
- Atmosphere is much less transparent to infrared radiation
  - Infrared radiation from Earth’s surface does not go directly to space, but is adsorbed by the atmosphere.
  - Atmosphere is heated by Earth’s surface (by radiation, conduction, and evaporation).

Incoming Energy flux

- Solar Constant, $S_O$:
  Energy incident on 1 sq. meter perpendicular to incident ray at top of atmosphere
  - $S_O = 1368 \text{ W/m}^2$
  - This times Earth’s cross-sectional area is the solar energy flux to the Earth: $S_O \times \pi R^2$ (where $R$ is radius of the Earth)
- This radiation is spread (on average) over the spherical surface of the Earth, so energy per unit surface area is:
  - $S_O \times \pi R^2 / (4 \pi R^2) = S_O / 4$
Reflected Solar Energy

- Some of incoming energy is reflected back to space. The fraction reflected is called the albedo ($\alpha$).
- Albedo for:
  - Seawater: 0.1
  - Bare land: 0.3
  - Sea ice: 0.6
  - Fresh snow: 0.9
  - Clouds: 0.4-0.9
- Average albedo for the whole Earth at present is 0.31.
- Energy gained by the Earth is thus:
  \[ \frac{S \pi R^2 (1-\alpha)}{4 \pi R^2} = 236 \text{ W/m}^2. \]
- By comparison, geothermal energy is about 0.1W/m$^2$. Therefore, geothermal energy is trivial compared to solar energy, at least with respect to surface temperature.

Outgoing Energy Flux and Effective Surface Temperature

- Stephan’s Law relates the energy radiated by a black body to its temperature:
  \[ E = \sigma T_e^4 \]
  - where $T_e$ is the effective temperature and $\sigma$ is the Stephan-Boltzmann constant ($= 5.67 \times 10^{-8}$ W/m$^2$K$^4$)
- For the total Earth
  \[ E_{\text{outgoing}} = \sigma T_e^4 \times 4\pi R^2 \]
Steady-State and Radiation Balance

- On human-time scales (10-100 yrs), Earth’s surface temperature changes little, despite daily energy gain from the Sun.
- Earth must therefore lose (very nearly) as much heat as it gains.
  \[ E_{\text{outgoing}} = E_{\text{incoming}} \]
- Therefore:
  \[ S_0 \times \pi R^2 (1-\alpha) = \sigma T_e^4 \times 4\pi R^2 \]
  - Rearranging:
    \[ T_e = (S_0(1-\alpha)/4\sigma)^{1/4} \]
- From this we calculate an effective temperature of 254K = -19°C.
- Actual average surface temperature \( T_s \) is 286.5K (= 13.3°C).

The Greenhouse Effect

- The difference between \( T_s \) and \( T_e \) reflects the effects of greenhouse gases:
  - Greenhouse gases keep the Earth’s surface 32.5°C (56°F) warmer than it would be if:
    - The Earth had no atmosphere or
    - The atmosphere contained no \( \text{H}_2\text{O}, \text{CO}_2, \) or \( \text{CH}_4 \).
- (Hmm, maybe the greenhouse effect is not such a bad thing after all.)
Greenhouse Gases

- Three Greenhouse Gases
  - $\text{H}_2\text{O}$
  - $\text{CO}_2$
  - $\text{CH}_4$
  - known as “greenhouse gases” because they act just like the glass of a greenhouse – transmitting visible and adsorbing infrared radiation

The Importance of Greenhouse Gases

- Too much greenhouse gas is why Venus is so hot.
- Too little greenhouse gas is why Mars is so cold.
Terrestrial Energy balance with the greenhouse effect

• Because of greenhouse gases, the effective temperature is lower than the surface temperature.
• To account for this, we can modify our equation for outgoing energy to be:

\[ E_{\text{outgoing}} = \sigma f T_s^4 \times 4\pi R^2 \]

• Where \( f \) is the effective infrared transmission factor, such that \( T_e^4 = f T_s^4 \)

Factors Controlling Earth’s Surface Temperature

• We can write our energy balance equation as:

\[ T_s = (S_o(1-\alpha)/4f\sigma)^{1/4} \]

• From this we see that the Earth’s surface temperature depends on just 3 variables:
  - \( S_o \): solar constant
    • Function of Sun’s surface temperature and Earth’s orbital radius
  - \( A \): albedo
    • Function of the relative amounts of clouds, snow, ice, land and sea.
    • Amounts of land and sea are functions of geologic processes like plate tectonics; clouds, snow and ice are functions of climate.
  - \( f \): effective infrared transmission factor
    • Function of greenhouse gas concentrations; the concentration of the dominant greenhouse gas, \( \text{H}_2\text{O} \) will in some way be a function of surface temperature.
Complexities: Heat Budget of the Atmosphere

Ignoring the complexities for a moment, we can say that Earth’s climate history will reflect variation in these three variables: $S_o$, the solar constant, $\alpha$, the albedo, and $f$, the greenhouse gas constant.

We know that climate has varied considerably over Earth’s history.
- Changes in climate are likely to reflect changes in these variables.

Climate History
Unraveling Climate History

• Climate proxies
  – Fossils
    • By comparing ancient forms to modern ones, we can make reasonable guesses as to the climate in which ancient organisms lived (e.g., reef-building corals require water temperatures between 18 and 30°C).
  – Erosive and depositional effects of glaciers and icebergs
  – Physical, chemical, and isotopic “fingerprints” in sediments (including ice!).
Isotopes as climate proxies

3 million year climate record from oxygen isotope ratios in carbonates of North Atlantic sediment.
Physical Fingerprints in Sediments

A Deposition by ice

Mixed grain sizes

Bedrock

Gouges on bedrock

B Deposition by wind

Cross-bedding

C Deposition by water (good archive)

Horizontal layering

D Deposition by water (poor archive)

Ripple marks

Graded beds

Evidence of ancient glaciations

Early Proterozoic Tillite

Paleozoic Striations
Why has climate changed?

• Possibilities
  – Solar ‘constant’
  – Albedo
  – Greenhouse gases
  – Other (e.g., ocean-atmosphere circulation)

Is the Solar Constant really constant?

• NO!
  – Stars get brighter as they age!
Faint Young Sun Paradox

• Sun’s luminosity has increased about 30% over its life time.
  – Energy flux at top of atmosphere would have been only 263 W/m$^2$ 3.8 Ga ago.
  – Assuming the same albedo, energy adsorbed would be only 182 W/m$^2$.
  – $T_e$ would be only 238 K (16°C cooler).
  – All else being equal, average surface temperature would have been 270 K = -3°C.

• But, water-laid sediments of this age exist, so surface must have been above freezing (hence the paradox).

What is the solution?

• Indeed, despite intermittent glacial episodes (such as the present), there is evidence for liquid water on the Earth throughout its history.
• “Geothermal heat”?
  – No, Even 3.8 Ga ago, geothermal heat is trivial
• Higher greenhouse gas content of atmosphere?
  – Consistent with what we suspect about atmospheric evolution, i.e., CO$_2$ has been removed by photosynthesis (and subsequent burial of remains) and rock weathering.
  – How much more CO$_2$?
    • A lot! Doubling atmospheric CO$_2$ increases downward radiative flux by only 4W/m$^2$; need to make up 54 W/m$^2$.
    • No problem! There’s plenty of carbon in sediments (as sedimentary organic matter and carbonate minerals) that was once in the atmosphere.
  – A role for methane too? (Methane is 25 times more effective as a greenhouse gas than CO$_2$).
Cold Periods in Earth’s History

- Using the climate proxies mentioned about, a number of particularly cold periods have been identified in Earth’s history.
  - Quaternary (now)
  - Late Paleozoic
  - Neoproterozoic
  - Early Proterozoic
- How cold was it?
  - Snowball Earth?
    - Some think that oceans were completely covered with ice in Proterozoic
    - Results from changes in albedo and greenhouse gases.

Take Home Message

- Earth’s climate has varied.
- Chemical and physical record in the rocks allows us to determine past climates.
- Climate is affected by a number of factors:
  - Plate tectonics (location and size of landmasses)
  - Chemical cycling (particularly carbon cycle)
  - Climate!
    - There are built-in feedbacks that can limit or accelerate climate change.
  - Life
    - Life has an effect both on greenhouse gases and on albedo.
- Climate may have been an important factor in organic evolution.