Assignment 8

There are two main methods of pricing carbon,

- Carbon Tax

- Cap-and-Trade

Briefly discuss the merits (2) and problems with each (2).

Your opinion?

Due on March 30
Driving Factors of Global Climate

- Radiation budget review
- Drivers of change
- Feedbacks to change
- “The climate machine”
Box model for energy

- For steady state, energy in must equal energy out
- Amount of heat in the system directly affects sink
  - $E_{out}$ is related to $Q$

- $E_{in} = E_{out} + \Delta Q$
  - At equilibrium, $\Delta Q = 0$

Turco: Figure 11.8
Stefan-Boltzmann Law

- All matter emits radiation
- Intensity of radiation in W/m² is proportional to $T^4$

\[ I = \varepsilon \sigma T^4 \]

- $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴
- $\varepsilon$ is the emissivity of the object, ranging from 0 to 1.
Solar constant

- Energy received by the Earth from the sun: 1367 Wm$^{-2}$
  - 30% reflected, rest is absorbed

- Roughly 1000 Wm$^{-2}$ is absorbed
  - Over the sunlit area

- To balance this, roughly 250 Wm$^{-2}$ must be emitted
  - Over the entire area

- Leads to $T = 255$ K
Incoming radiative balance

Ahrens: Fig. 2.17
Outgoing radiative balance

Ahrens: Fig. 2.18
The Greenhouse Effect

Ahrens, Fig. 2.12
Lecture outline

- Radiation budget review
- **Driving factors**
  - Solar forcing
  - Albedo
  - Greenhouse gases
- Feedbacks
- “The climate machine”
Solar constant

- Energy received by the Earth from the Sun
  - Determines $E_{in}$
- 1367 Wm-2
  - 30% is reflected (albedo)
  - Rest is absorbed either by the atmosphere or the surface
  - Must be matched by outgoing energy

- Solar strength has increased on geologic time scales
Solar flares

- Explosions in the sun’s atmosphere
- Large amounts of radiation over all wavelengths
  - Radio waves may disrupt communications
  - X-rays and UV rays enhance auroras
  - Directly hazardous to astronauts
- More frequent during sunspot cycle peaks
Sunspots

Magnetic structures inhibiting local convection in the solar atmosphere

Image: NASA
Not really ‘constant’

- Sunspots: $\pm 0.1\%$ to $E_{in}$
- Long term cycles and changes

Image: 400 Years of Sunspot Observations, Global Warming Art Project
Solar cycles

- Maunder minimum roughly coincides with the “Little Ice Age”
  - Colder temperatures in Europe; possibly global

- Only 40 years of direct observations of solar strength
  - Magnitude of long-term cycles is unknown
  - Very long-term cycles may also exist
  - Constrained; not large on time scale of decades
Solar cycles

- Only 40 years of direct observations of solar strength
  - Magnitude of long-term cycles is unknown
  - Constrained; not large on time scale of decades

Ahrens: Fig. 16.16
Albedo

- Reduces $E_{in}$
- Reflection of radiation back into space
  - Earth’s albedo is 30%
  - Majority by clouds and backscatter from the atmosphere
Aerosols

- Tiny particles suspended in the atmosphere
- Many are reflective (increase albedo)
  - $\text{SO}_x$ and $\text{NO}_x$
- Also act as cloud condensation nuclei
  - Encourage cloud formation
  - Enhance cloud reflectivity
- Some aerosols absorb sunlight (reduce albedo)
  - Black carbon (soot)
Volcanic eruptions may inject sulfate aerosols into the stratosphere. They remain for a year or more. Mt Pinatubo, June 15, 1991: 18 MtSO$_2$. Ahrens: Fig. 16.13
Volcanoes

- But this is short term
  - Aerosols reach troposphere eventually
  - Temperature recovers

Ahrens: Fig. 16.15
Air pollution

- $\text{NO}_x$ emissions
  - Lightning: 5 MtN/year
  - Fossil fuels: 22 MtN/year
  - Agriculture: 28 MtN/year
- $\text{SO}_x$ emissions
  - Volcanoes: 20 MtS/year
  - Oceans: 30 MtS/year
  - Anthropogenic: 90 MtS/year
Air pollution

- Aerosol residence times are very short
- Concentration closely tied to source
  - Constant emission \(\rightarrow\) constant loading
  - Trend?
Land surface cover

- Urban heat islands
- Deforestation
- Agriculture
- Desertification

- Net effect is real but small cooling

Table 2.3  Typical Albedo of Various Surfaces

<table>
<thead>
<tr>
<th>SURFACE</th>
<th>ALBEDO (PERCENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh snow</td>
<td>75 to 95</td>
</tr>
<tr>
<td>Ice</td>
<td>30 to 40</td>
</tr>
<tr>
<td>Sand</td>
<td>15 to 45</td>
</tr>
<tr>
<td>Grassy field</td>
<td>10 to 30</td>
</tr>
<tr>
<td>Dry, ploughed field</td>
<td>5 to 20</td>
</tr>
<tr>
<td>Water</td>
<td>10*</td>
</tr>
<tr>
<td>Forest</td>
<td>3 to 10</td>
</tr>
<tr>
<td>Clouds (thick)</td>
<td>60 to 90</td>
</tr>
<tr>
<td>Clouds (thin)</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Earth and atmosphere</td>
<td>30</td>
</tr>
<tr>
<td>Moon</td>
<td>7</td>
</tr>
<tr>
<td>Venus</td>
<td>78</td>
</tr>
<tr>
<td>Mars</td>
<td>17</td>
</tr>
</tbody>
</table>

*Daily average.

Ahrens: Table 2.3
The greenhouse effect

- Reduces $E_{out}$
- Selective absorbers
  - Most substances absorb only certain wavelengths of radiation
  - E.g. Glass absorbs ultraviolet and infrared radiation, but not visible radiation
- *Greenhouse gases* are transparent to visible radiation, but absorb infrared radiation
  - Therefore they have no effect on $E_{in}$ but reduce $E_{out}$
Greenhouse gases

- The action of greenhouse gases is to trap heat
  - Prevent radiation into space

- Natural greenhouse effect
  - Global average temperature 33°C warmer than it would be otherwise (15°C instead of -18°C)
  - Most important gas is H$_2$O
  - Also significant are CO$_2$, CH$_4$, N$_2$O, O$_3$

- Enhanced greenhouse effect
  - CO$_2$, CH$_4$, Halocarbons, O$_3$, N$_2$O, others
Forcings

- Insolation
- Albedo changes
  - Volcanoes
  - Aerosols
  - Land cover
- Greenhouse gases
Ahrens: Fig. 16.18
Feedbacks

- A feedback is a response to an initial change that influences that same change
  - A cause-and-effect chain with a loop
  - A positive feedback reinforces the initial change
  - A negative feedback counteracts the initial change
- E.g. thermostat
Water vapour

- Saturation vapour pressure depends on temperature
- Higher temperatures lead directly to increased water vapour
- Water vapour is a greenhouse gas
- Positive feedback
Ice and snow

- Ice and snow are very reflective
- Albedos:
  - Open water: 0.1
  - Ice: 0.3 – 0.4
- Sensitive to changes in temperature
- Also a positive feedback

Ahrens: Fig. 2.13
The Many Roles of Clouds

- Reflect shortwave (solar) radiation
  - Cover 50% of surface, albedo of 50%
- Absorb longwave (terrestrial) radiation
- Emit radiation to space and back down to the surface

- Changes in the extent of clouds increases all three
Cloud height

- Altitude affects temperature
  - High clouds are colder
  - Colder clouds emit less radiation

- An increase in high clouds has a heating effect
- An increase in low clouds has a cooling effect
Cloud particles

- Water droplets are more reflective than ice crystals
- Clouds with many smaller droplets are more reflective than those with fewer, larger ones
- Thicker clouds are more reflective than thin ones
Summary: Cloud feedbacks

Net effect of the cloud feedback is uncertain.

Magnitude could be significant for future climatic change.

Turco: Figure 11.13
Driving climate change

- Driving factors:
  - Solar change
  - Albedo
  - Greenhouse gases

- Climate Feedbacks
  - Water vapour (positive)
  - Snow cover (positive)
  - Clouds (uncertain)
The climate flywheel?

- A flywheel is a device for storing mechanical energy
  - Rotating device resists changes to rotational speed
  - E.g. Bicycle wheel

- By “climate flywheel” Turco refers to elements of the climate system that are resistant to change
  - Residence time of heat in the land surface is less than a year
  - Residence time of heat in the surface ocean is in decades
  - Residence time of heat in the deep ocean is in centuries
Oceans

- Surface (100 m or less)
  - Well-mixed (winds)
  - Photosynthesis only in top few metres
  - Takes part in surface energy balance

- Deep ocean (average nearly 4 km deep)
  - Thermohaline: very slow circulation
  - Heat that enters the deep ocean delays surface equilibrium
  - Response to changes in forcing occur over decades
Ice cover (cryosphere)

- Also stores a considerable amount of energy
- More important is the energy required to freeze or thaw the ice
  - Delays temperature change
Other influences: General circulation

- Atmospheric and oceanic circulations transfer heat from tropics to poles
  - Oceanic transfer is half that of the atmosphere

- Changes in circulations affect the internal transfers of the energy budget
  - Very significant on timescales of decades-centuries
Other influences: Internal variability

- El Niño / Southern Oscillation (ENSO)
- Pacific Decadal Oscillation (PDO)
- Other long and short cycles
Pacific Decadal Oscillation

(a) Warm (positive) phase

(b) Cool (negative) phase

Ahrens: Fig. 10.25
Pacific Decadal Oscillation
Other potential feedbacks

- Carbon dioxide dissolves in the ocean
  - Solubility decreases as temperature increases

- Carbon dioxide, methane, nitrous oxide are all influenced by the biosphere
  - Drier soils
  - Dying forests
  - Melting permafrost
Next lecture

- Global Warming