GEOG 401
Climate Change
Energy Balance
Atmospheric Effects on Solar Radiation

- Atmospheric absorption: gases and aerosols
- Atmospheric reflection: scattering
- Reflection and absorption by clouds

![Diagram showing the percentage of solar radiation reflected, scattered, and absorbed by clouds, atmosphere, ground, and surface.]

- Reflection by clouds: 19%
- Scattering by atmosphere: 6%
- Reflection by ground: 5%
- Absorption by surface: 45%
- Absorption: 25%
Atmospheric Absorption of Solar Radiation

Spectral Irradiance (W/m²/nm)

Wavelength (nm)

Sunlight at Top of the Atmosphere

5250°C Blackbody Spectrum

Radiation at Sea Level

Absorption Bands

O₃, O₂, H₂O, H₂O, H₂O, H₂O, CO₂
Disposion of Solar Radiation Reaching Earth’s Surface

Reflected

Absorbed

Reflection by clouds 19%

Scattering by atmosphere 6%

Reflection by ground 5%

Absorption 25%

Absorption by surface 45%
Disposition of Solar Radiation Reaching Earth’s Surface

• Reflection: **Albedo** is a key property of surfaces controlling the surface energy balance

• **Absorbed radiation**: used to
  – **Heat the soil**: soil heat flux (G)
  – **Heat the air**: sensible heat flux (H)
  – **Evaporation water**: latent heat flux (LE)
ALBEDO

\[ \alpha = \frac{K \uparrow}{K \downarrow} \]

where:

\[ \alpha = \text{albedo} \]

\[ K \uparrow = \text{reflected shortwave radiation} \]

\[ K \downarrow = \text{downward shortwave radiation} \]
Influences on Albedo

- Density, LAI, and height of vegetation
- Soil color and moisture content
- Sun angle and slope/aspect of land surface
- Relative amount of direct and diffuse light
Albedo vs. LAI

Fig. 2. Annual average observed LAI (ISLSCP, initiative 2) vs observed surface albedo (ERBE: black, open circles) and reconstructed albedo (gray dots) from Eq. (5).

## Typical Albedo

<table>
<thead>
<tr>
<th>Land cover type</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.12 - 0.14</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.16 - 0.25</td>
</tr>
<tr>
<td>Crops</td>
<td>0.16 - 0.22</td>
</tr>
<tr>
<td>Bare soil (wet)</td>
<td>0.08 - 0.10</td>
</tr>
<tr>
<td>Bare soil (dry)</td>
<td>0.15 - 0.25</td>
</tr>
<tr>
<td>Burned vegetation</td>
<td>0.06 - 0.10</td>
</tr>
<tr>
<td>Snow</td>
<td>0.80 - 0.90</td>
</tr>
<tr>
<td>Ocean (calm; high zenith angle)</td>
<td>0.08</td>
</tr>
<tr>
<td>Planet Earth</td>
<td>0.30</td>
</tr>
</tbody>
</table>
GLOBAL ALBEDO PATTERN
Longwave Radiation

• Surface emits longwave radiation as a function of its temperature and emissivity (Stefan-Boltzmann Equation)

• Atmosphere absorbs most longwave radiation from the surface: Greenhouse Effect

• Surface also receives longwave radiation from the atmosphere
Atmospheric Absorption Spectra
Atmospheric Absorption Spectra

Much stronger absorption of longwave radiation than shortwave.

Solar peak intensity

Most of solar spectrum

Most of earth spectrum

Earth peak intensity
Greenhouse Effect

(a) Energy vs. Wavelength (μm)

(b) Absorption spectrum of various gases:
- Ultraviolet (UV)
- Visible (VIS)
- Infrared (IR)
- O₂, O₃, H₂O, CO₂, H₂O
Greenhouse Effect

![Diagram showing absorption of different gases at various wavelengths](image)

- Solar window
- Atmospheric window
- Gases: O$_2$, O$_3$, H$_2$O, CO$_2$, H$_2$O
Greenhouse Effect
Exchange of Radiation Between the Surface and the Atmosphere

• Of the shortwave radiation reaching the surface, a certain amount is reflected, depending on the albedo of the surface, the rest is absorbed. Once absorbed, that energy is converted to other forms.

• One result of absorbing solar radiation is that the surface becomes warmer. This increases the emission of longwave radiation by the surface (Stefan-Boltzmann Eq.).
LONGWAVE EXCHANGE

• Longwave radiation by the surface is strongly absorbed by greenhouse gases in the atmosphere.

• The atmosphere is warmed as a result of absorbing longwave radiation, and hence emits more radiation. Atmospheric radiation goes in all directions, some warming the layers of air above, and some warming the surface. This re-radiation by the atmosphere to the surface is responsible for the greenhouse effect.
Longwave Radiation Balance

Atmosphere
- LW absorption: 100 units
- Net LW loss: 54 units
- LW radiation: 154 units

Surface
- LW radiation from surface: 104 units
- Net LW loss: 16 units
- LW radiation from atmosphere: 88 units

Lost to space from surface: 4 units
Lost to space from atmosphere: 66 units
SURFACE NET RADIATION

\[ R_{net} = K \downarrow - K \uparrow + A \downarrow - L \uparrow \]

where:

\( R_{net} \) = net radiation

\( A \downarrow \) = downward longwave radiation absorbed by the surface

\( L \uparrow \) = upward longwave radiation emitted by the surface
SURFACE NET RADIATION

\[ R_{\text{net}} = K \downarrow - K \uparrow + A \downarrow - L \uparrow \]

\[ R_{\text{net}} = (1 - \alpha)K \downarrow + A \downarrow - \varepsilon_s \sigma T_s^4 \]

\[ R_{\text{net}} = (1 - \alpha)K \downarrow + \varepsilon_s (L \downarrow - \sigma T_s^4) \]

where

\( \alpha = \) albedo

\( \varepsilon_s = \) surface emissivity

\( T_s = \) surface temperature

\( L \downarrow = \) downward longwave radiation from atmosphere
Radiation Measurement

- Shortwave radiation
  - Eppley 8-48 “black & white”
  - Eppley PSP: precision spectral pyranometer
  - Kipp & Zonen CM11
Radiation Measurement

• Direct shortwave radiation
  – NIP: Normal incidence pyrheliometer

• Diffuse
  – shade band
  – shade disk
Radiation Measurement

- Surface temperature (upward LW): **infrared thermometer**
  - Apogee IRTS-P
Radiation Measurement

- Net radiation: net radiometer
  - REBS Q*7.1
Radiation Measurement

• Net radiation: **net radiometer**
  – Kipp & Zonen CNR1
Radiation Balance of Earth

- **Shortwave Radiation**
  - Reflection by clouds: 19%
  - Scattering by atmosphere: 6%
  - Absorption by surface: 45%

- **Longwave Radiation**
  - Absorption 25%
  - Reflection by ground 5%

- **All-Wave Radiation**
  - Lost to space from surface: 4 units
  - Lost to space from atmosphere: 66 units

### Atmosphere
- LW absorption: 100 units
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### Surface
- LW radiation from surface: 104 units
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- LW radiation from atmosphere: 88 units

### Input of SW radiation
- Input of SW radiation = 100 units

### SW reflection
- SW reflection by atmosphere and surface = 30 units

### Net radiation for atmosphere
- Net radiation = 25–54 units
- Net LW loss = 54 units

### Net radiation for surface
- Net radiation = 45–16 units
- Net LW loss = 16 units
Energy Balance of Earth

Solar constant: 1367 W m\(^{-2}\)

Area intercepting radiation (disk area): \(\pi R^2\)

Surface area of earth (surface of sphere): \(4\pi R^2\)

Solar constant per unit surface area of earth:

\[
= 1367 \text{ W m}^{-2} \times \frac{\pi R^2}{4\pi R^2} = 1367/4
\]

\[
= 341.75 \text{ W m}^{-2}
\]
Energy Balance of Earth

- Assume earth maintains energy equilibrium
- Assume exchanges of energy into and out of the earth’s planetary system are only in the form of radiation
- Earth receives 341.75 W m\(^{-2}\) of solar energy
- To maintain energy equilibrium, Earth must give up 341.75 W m\(^{-2}\)
- Planetary albedo: 30%
- Therefore, the earth absorbs 70% of 341.75 W m\(^{-2}\) = 239.23 W m\(^{-2}\)
- To maintain balance earth must emit 239.23 W m\(^{-2}\)
Energy Balance of Earth

What is the radiative equilibrium temperature of earth (temp. necessary to emit 239.23 W m\(^{-2}\))?  
Use the Stefan-Boltzmann equation:

Rearranging \( I = \sigma T^4 \) we get:

\[
T = \left(\frac{I}{\sigma}\right)^{0.25}
\]

\[
T = \left(\frac{239.23}{5.67 \times 10^{-8}}\right)^{0.25}
\]

= 254.86 K

= -18.3°C  \( \leftarrow \) Radiative Equilibrium Temperature of Earth
Energy Balance of Earth
Radiative Equilibrium Temperature of Earth = -18.3°C

Actual mean surface temperature of earth:

- 20th Century Mean: **13.90°C (57.02°F)**
- 2014 Mean: **14.59°C (58.26°F)**
- 2015 Mean: **14.80°C (58.64°F)**
- 2016 Mean: **14.84°C (58.71°F)**
- 2017 Mean: **14.74°C (58.53°F)**

**Question 1:** Why is the actual surface temperature currently 33.14°C higher than the radiative equilibrium temperature?

**Question 2:** Is the radiative equilibrium temperature of the earth changing due to increasing greenhouse gases?

**Question 3:** Why is the surface temperature of the earth increasing?
Radiative Equilibrium Temperature

<table>
<thead>
<tr>
<th>Planet</th>
<th>Atmos. CO2</th>
<th>Sfc Pressure</th>
<th>Equil Temp</th>
<th>Actual Sfc Temp</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.04%</td>
<td>1 atmos</td>
<td>-18.3°C</td>
<td>14.8°C</td>
<td>33.1°C</td>
</tr>
<tr>
<td>Venus</td>
<td>97%</td>
<td>90 atmos</td>
<td>-26°C</td>
<td>470°C</td>
<td>496°C</td>
</tr>
<tr>
<td>Mars</td>
<td>95%</td>
<td>0.006 atmos</td>
<td>-62°C</td>
<td>-55°C</td>
<td>7°C</td>
</tr>
</tbody>
</table>
Energy Balance of Earth System Components

Planetary System: $R_{\text{net}}$ for planetary system = 0
Atmosphere: $R_{\text{net}}$ for planetary system < 0
Surface: $R_{\text{net}}$ for planetary system > 0

Why no radiative equilibrium for atmosphere or surface?
Why no radiative equilibrium for atmosphere or surface?

• Because of other (non-radiation) energy exchanges between surface and atmosphere

• Sensible and latent energy flux moves energy derived from radiation surplus at surface to make up the radiation deficit in the atmosphere
Surface Energy Balance

- Energy balance equation:
  \[ R_{\text{net}} = LE + H + G + P \]
  where: \( LE \) = latent energy flux to the atmosphere, \( H \) = sensible energy flux to the atmosphere, \( G \) = sensible energy conduction into the soil, and \( P \) = photosynthesis

- \( G \) is positive during the day and negative at night; on a 24-hour basis \( G \) can be ignored

- \( P \) is small relative to other energy balance terms and can also be ignored

- Simplified Energy Balance Equation
  \[ R_{\text{net}} = LE + H \]

- This says that the energy derived from net radiation at the surface goes primarily into things: energy for evaporation of water and energy for heating the air.

- Surface characteristics control the partitioning of net radiation into \( LE \) and \( H \).
Temperature

Fundamental Influences on Air Temperature

- net radiation: latitude, time of year, time of day, cloudiness, surface characteristics
Temperature

Fundamental Influences on Air Temperature

- net radiation: latitude, time of year, time of day, cloudiness, surface characteristics
- partitioning of net radiation: surface characteristics (vegetation cover, moisture availability) \( R_{\text{net}} = LE + H \)
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• land or ocean: specific heat, evaporation, mixing, transparency
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• energy advection: horizontal transfer of energy via ocean currents and atmospheric circulation

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• altitude-elevation: air is primarily heated by the surface—distance from the source; reduced downward longwave radiation with elevation; rising air cools by expansion.
Global Temperature Distribution
Continentality