Advection

• Question: During the polar night, the pole receives no solar radiation – why does polar temperature not fall to near absolute zero?

• Movement of air (wind) will carry air of different temperature around, in the process transporting energy
  – This is the main process that keeps the pole relatively warm during the polar night
Radiation behaves both as waves and particles (photons). Photons that correspond to shorter waves carry more energy.

All objects above 0 K release radiation, and its total radiative energy increases as the 4th power of its temperature.
Properties of electromagnetic radiation (Stull pp. 29-30)

- Speed of light in vacuum: $c_0 = 3 \times 10^8$ m/s
- Wavelength $\lambda$ (m/cycle)
- Frequency $\nu$ (Hz = cycles/s)
  $$\lambda \nu = c_0$$
- Angular frequency $\omega = 2\pi \nu$
- Wavenumber $\sigma = 1/\lambda$
- Period $T = 1/\nu = 2\pi/\omega$
• **Visible light**
  - $\lambda \sim 0.4\text{-}0.7\ \mu\text{m}$
    - $1\ \mu\text{m} = 10^{-6}\ \text{m}$
  - Short wave – solar radiation peaks in this range

• **Infrared radiation**
  - $\lambda \sim 0.7\ \mu\text{m} – 1\ \text{mm}$
  - Long wave – Earth’s radiation peaks in this range
Blackbody radiation

• A perfect absorber and emitter of radiation is called a “blackbody” – the sun is close to being a blackbody; the Earth is also a blackbody at infrared wavelengths

• **Planck’s law** – blackbody monochromatic irradiance at wavelength $\lambda$ depends on its temperature

$$E_\lambda = \frac{c_1}{\lambda^5 \left[ \exp\left( \frac{c_2}{\lambda T} \right) - 1 \right]} \quad \text{Stull (2.15)}$$

– $c_1$ and $c_2$ as given in Stull
$T = 5780\text{K}$

$T = 255\text{K}$
• The following two laws can be deduced from Planck’s law
  – Wien’s Law: the wavelength of the peak emission is given by
  \[ \lambda_{\text{max}} = \frac{a}{T} \]  \hspace{0.5cm} \text{Stull (2.17)}
  • Where \( a = 2897 \ \mu\text{m K} \)
  – The total amount of emission per unit area (or total emitted irradiance) is given by the Stefan-Boltzmann law:
  \[ E_{\text{tot}} = \sigma_{SB} T^4 \]  \hspace{0.5cm} \text{Stull (2.18)}
  • Where \( \sigma_{SB} = 5.67 \times 10^{-8} \ \text{W/m}^2/\text{K}^4 \)
Numerical example

- Viewed from space, the Earth’s effective temperature is 255 K.
  - What is the wavelength of peak emission?
    - Use Wien’s law:
      \[ \lambda_{\text{max}} = \frac{a}{T} = \frac{2897}{255} = 11.4 \ \mu \text{m} = 11.4 \times 10^{-6} \text{ m} \]
  - What is its wavenumber, frequency, and angular frequency?
    - Wavenumber = \( \frac{1}{\lambda} = \frac{1}{11.4 \times 10^{-6}} = 87700/\text{m} \)
    - Frequency \( \nu = \frac{c_0}{\lambda} = \frac{3 \times 10^8}{11.4 \times 10^{-6}} = 2.6 \times 10^{13} \text{ Hz} \)
    - Angular frequency \( \omega = 2\pi \nu = 1.7 \times 10^{14} \text{ radian/s} \)
  - What is the total emitted irradiance?
    - Use Stefan Boltzmann’s law:
      \[ E_{\text{tot}} = \sigma_{\text{SB}} T^4 = 5.67 \times 10^{-8} \times (255)^4 = 240 \text{ W/m}^2 \]
Classwork example

• We saw that at an effective temperature of 255 K, the earth’s radiation peaks at a wavelength of 11.4 µm.
  – A hypothetical planet farther away from the sun has an effective temperature of 127.5 K. Without looking up the value of \( \alpha \), find the wavelength of peak emission for the planet.

• Known: \( T_1 = 255K \), \( \lambda_1 = 11.4 \) µm
  \[ T_2 = 127.5K, \quad \lambda_2 = ? \]

• Using Wien’s Law
  – \( \lambda = \alpha / T \) \( \Rightarrow \) \( \lambda \times T = \alpha = \text{constant} \)
  – Therefore \( \lambda_1 T_1 = \lambda_2 T_2 \) \( \Rightarrow \) \( \lambda_2 = \lambda_1 T_1 / T_2 = 11.4 \times 255 / 127.5 \)
  \[ = 22.8 \text{ µm} \]
Radiative balance at top of Earth’s atmosphere

• Total emission at solar surface
  \[ E_1 = \sigma_{SB} T^4 = 5.67 \times 10^{-8} \times (5780)^4 \]
  \[ = 6.3 \times 10^7 \text{ W/m}^2 \]

• Intensity of solar radiation at Earth’s orbit
  \[ E_2 = E_1 \left(\frac{R_1}{R_2}\right)^2 = E_1 \times 2.167 \times 10^{-5} \]
  \[ (R_1 = \text{radius of sun} \sim 7\times10^8 \text{ m}, R_2 = \text{distance between sun and earth} \sim 1.5\times10^{11} \text{ m}) \]
  \[ = 1368 \text{ W/m}^2 \quad \text{-- the solar constant} \]
  \[ \text{-- Average downward solar flux at top of Earth’s atmosphere} = \frac{E_2}{4} = 342 \text{ W/m}^2 \]
  \[ (\text{Radiation over a disk is spread over the surface of a sphere}) \]
• Earth’s average albedo = 0.3
  – Hence average upward (reflected) short wave flux = 0.3×342 = 103 W/m²

• Radiative equilibrium
  – requires average upward long wave flux equals net downward short wave flux (=342-103 = 239 W/m²)
  – hence upward long wave flux = 239 W/m²
  – 239 W/m² implies a blackbody temperature of 255 K (from numerical example above)
  – Without an atmosphere, Earth’s average surface temperature would be as low as 255 K

• Why is the Earth’s surface so much warmer than this?
Atmospheric Absorption

Atmospheric gases emit (and absorb) at selective wavelengths. Ozone absorbs UV radiation, whereas water vapor and CO$_2$ absorbs strongly at IR wavelengths. Other greenhouse gases (N$_2$O, CH$_4$) also absorb at selective IR wavelengths.

Short waves pass relatively freely through the atmosphere. Long waves are largely absorbed, except in the so-called IR window.

-Absorption by gases
Earth's energy balance requires that absorbed solar radiation is emitted to maintain a constant temperature. Without natural levels of greenhouse gases absorbing and emitting, this surface temperature would be as low as 255 K (-18 °C), about 33°C cooler than the observed temperature.
Without atmosphere:

- Earth’s surface is only warmed by solar radiation
- Incoming radiation is balanced by outgoing longwave (IR) radiation
- This implies a temperature of 255K or -18C
What are the key ingredients giving rise to the atmospheric greenhouse effect?
With Atmosphere:

- Atmospheric gases are selective absorbers: they absorb longwaves but not shortwaves
- Solar radiation can pass through atmosphere to warm earth’s surface
- Earth’s surface emits IR
- IR absorbed by atmosphere
- Atmosphere reemits this energy as IR radiation
- Part of this energy is directed downwards and absorbed by Earth’s surface
- Hence Earth’s surface is warmed both by incoming solar radiation and IR emitted by the atmosphere
Review of equations covered in Chapter 2

- Radiation
  - Relationships between \( c_0, \lambda, \nu, \omega, \sigma, \) and \( P \)
  - Planck’s Law
    \[
    E_\lambda = \frac{c_1}{\lambda^5 \left[ \exp\left( \frac{c_2}{\lambda T} \right) - 1 \right]}
    \]
  - Wien’s Law
    \[
    \lambda_{\text{max}} = \frac{a}{T}
    \]
  - Stefan-Boltzmann Law
    \[
    E_{\text{tot}} = \sigma_{SB} T^4
    \]