Atmospheric Measurements and Observations

EAS 535

Solar Radiation Measurements

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Globally averaged energy balance
THE ELECTROMAGNETIC SPECTRUM

Wavelength (in meters)

- Longer: Soccer Field, House, Baseball, This Period, Cell, Bacteria, Virus, Protein, Water Molecule
- Shorter: Radio Waves, Infrared, Ultraviolet, "Hard" X Rays, Gamma Rays

Common name of wave

- Radio Waves, Infrared, Ultraviolet, "Soft" X Rays, Gamma Rays

Sources

- AM Radio, FM Radio, Microwave Oven, Radar, People, Light Bulb, The ALS, X-Ray Machines, Radioactive Elements

Frequency (waves per second)

- Lower: Radio Waves, FM Radio, Microwave Oven, Radar
- Higher: People, Light Bulb, The ALS, X-Ray Machines, Radioactive Elements

Energy of one photon (electron volts)

- Lower: Radio Waves, FM Radio, Microwave Oven, Radar
- Higher: People, Light Bulb, The ALS, X-Ray Machines, Radioactive Elements

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Blackbody radiation
MAWS radiation sensors - What do they measure?

QMN101 net radiation, 0 to 100 µm

QMS102 global radiation, 0.3 to 2.8 µm

“Short wave” “Long wave”

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The surface exerts strong influence on the atmosphere.
It is quantified in terms of the fluxes of energy involved.
The surface energy budget means all energy inflow is equal to the energy outflow.
Surface energy budget

\[ H + G + L \cdot E - R_n = 0 \]
Energy budget

\[ H + G + L \cdot E - R_n = 0 \]

- \( H \) depends on the temperature difference between the surface and the atmosphere, and the wind speed.
- If surface warmer than air, heat flux is warmer towards colder, sign is positive.
- \( G \) is conduction, is quite slow, proportional to the temperature difference between the surface and underlying material, flow from surface into the earth is positive.

\( E \) is water vapor mass flux \( \text{kg} / \text{m}^2 \text{s} \)

\( L \) is the latent heat of vaporization

Flux in units of \( \text{W} / \text{m}^2 \) or \( \text{J} / \text{m}^2 \text{s} \)
Latent heat

- L*E is latent heat transported by water movement, depends on availability of water for evaporation.
- Dew condensing on the surface, or ice melting on the surface, but principally evaporation for water from the soil.
- Evaporating 1 gm of water converts to 142.7 joules of latent heat in water vapor
- Flow of water from surface to atmosphere is positive
- On a bright sunny day with light winds over a grassy surface with good soil moisture H, G and L*E will be positive, therefore Rn is positive to maintain balance.
- H and L*E will be a few hundred W/m², G will be several tens of W/m².
Net Radiation

- $R_n$ is the net movement of energy by electromagnetic radiation to or from a horizontal surface.

- The most important in terms of the energy balance of the Earth-ocean-atmosphere system are:
  - UV: 0.001 to 0.4 $\mu$m
  - Solar/visible: 0.4 to 0.8 $\mu$m
  - Near Infrared (NIR): 0.8 to 4 $\mu$m
  - Far Infrared (FIR): 4 to 100 $\mu$m (emission from Earth is almost all FIR)
Radiation Budget

\[ R_n = (F_D + F_d)(1 - a) + I_d + I_u \]

- \( F_D \) = incoming direct solar (visible) radiation (energy) flux
- or Direct Solar Irradiance
- \( F_d \) = incoming indirect solar (visible) radiation (energy) flux
- or Diffuse Solar Irradiance
- \( a \) = Surface albedo
- \( I_d \) = net downwelling long wave radiation (energy) flux
- \( I_u \) = upwelling long wave radiation (energy) flux

- \( R_n \) is the total net radiant energy through a horizontal surface per unit area per unit time.
- If \( R_n = 0 \), the surface is in radiative equilibrium.
- If \( R_n \) is not \( 0 \), there is conversion between radiant energy and other energy forms at the surface, especially H and L*E.
\[ R_n = (F_D + F_d)(1-a) + I_d + I_u \]
• Global solar irradiance is the sum of the short wavelength contributions incident on the surface $F_s = F_D + F_d$
• Present shortly before sunrise until shortly after sunset
• Albedo is the fraction reflected by the surface. $F_{up} = (F_D + F_d)a$ is the reflected solar radiance
• Hence $(1-a)$ is the fraction absorbed by the surface.
• $(F_D + F_d)(1-a)$ is the net solar irradiance.
• $a$ depends on surface type, and season.
Long wave part

- $I_d$ is the net flux of downwelling long wave (infrared or IR) radiation.
- 2 parts: NIR originating at the sun (small), and FIR originating in the atmosphere (large).
- FIR depends on the vertical distribution of temperature and water vapor in the overlying atmosphere.
- All IR is absorbed at the surface (no equivalent albedo)
- $I_u$ is the net flux of upwelling FIR radiation from the surface to the atmosphere.
- $I_u$ is never 0, it is proportional to 4th power of $T$
- Stefan Boltzman’s Law (area under blackbody curve):
  \[ E^* = \sigma_{SB} \cdot T^4 \]
  $E^*$ is total irradiance
  \[ \sigma_{SB} = 5.67 \times 10^{-8} \, W / m^2 / K^4 \]
  $T$ is temperature in K
## Shortwave and longwave measurement devices

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<th>Long Wave</th>
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<td>0.3 – 3.0 µm</td>
<td>4 – 50 µm</td>
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<tr>
<td>( F_D \downarrow )</td>
<td>direct downwelling shortwave solar radiation</td>
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<td>( F_d \downarrow )</td>
<td>diffuse horizontal sky radiation</td>
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<td>( F_{S}=F_D+F_d \downarrow )</td>
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<td>( F_{\text{up}}=(F_D+F_d)\ast a \uparrow )</td>
<td>upwelling reflected shortwave radiation</td>
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<td>Pyrheliometer 5.7 deg FOV solar tracker</td>
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<td>Pyranometer hemispherical view uplooking, shaded</td>
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MAWS radiation sensors -
What do they measure?

Global radiation sensor:
\[ F_s = F_D + F_d \]

Net radiation sensor (daytime)
\[ F_s - F_{up} = F_D + F_d - (F_D + F_d)a \]
\[ = (F_D + F_d)(1-a) \]

Fraction absorbed by surface

Net radiation sensor (night time)
\[ I_u + I_d \]
\[ (I_u \text{ is negative}) \]
Pyranometer (shortwave)  Pyrgeometer (longwave)
Pyrheliometer deployed with a pyranometer and pyrgeometer
Typical clear sky irradiance

What is the direct normal (downwelling) shortwave irradiance at solar noon?

What is the max global irradiance?

What is the max reflected shortwave irradiance?

What is the max diffuse shortwave irradiance?

Why doesn’t the diffuse irradiance change much over the day?

What is the albedo?

Southern Great Plains, Fall, local time = GMT – 6 hrs
Typical clear sky irradiance

When does the longwave upward irradiance peak?

What is the longwave upward irradiance at night?

What is the longwave downward irradiance at night?

What is the net longwave radiation?

Southern Great Plains, Fall, local time = GMT – 6 hrs
Typical clear sky irradiance

What component of the irradiance is measured by a pyrheliometer?

What feature in the data is likely due to cleaning of dust off the glass cover of the pyrheliometer?

About how much of an error did the dust produce?

Southern Great Plains, Fall, local time = GMT – 6 hrs
Typical clear sky irradiance

- Near solar noon, the direct normal shortwave (beam) irradiance is \( \sim 1000 \text{ Wm}^{-2} \),
- the peak global (total hemispheric) irradiance is \( \sim 800 \text{ Wm}^{-2} \)
- the diffuse (sky) irradiance is \( \sim 50 \text{ Wm}^{-2} \)
- the peak reflected shortwave is \( \sim 155 \text{ Wm}^{-2} \)
- Albedo is \( \frac{155}{1000} \% \) or \( \sim 19\% \) (typical for a vegetated surface).
- The peak upwelling longwave irradiance is \( \sim 488 \text{ Wm}^{-2} \)
- The peak downwelling longwave irradiance is \( 355 \text{ Wm}^{-2} \)
- Net longwave irradiance is \( 133 \text{ Wm}^{-2} \)

- Heating of the surface and the atmosphere is evident from the increasing longwave (infrared) irradiance measurements.
- The peak longwave irradiances occur after solar noon, demonstrating the “thermal lag” of the earth-atmosphere system response to solar heating.
- The effect of cleaning the pyrheliometer window is seen in the abrupt increase in direct normal irradiance prior to local solar noon at 17:10 GMT where removal of contamination results in an increase from 947.81 Wm-2 and 963.25 Wm-2
Typical cloudy sky conditions

- What is the longwave irradiance measured by the two SIRS pyrgeometers?
- What are the likely conditions if the exchange of infrared radiation is constant?
- What is the direct normal shortwave (beam) irradiance during a cloudy day?
- Why are there several peaks in the global radiance?
- What are the peak global (total hemispheric) and diffuse irradiance?
- What is the peak reflected shortwave?
- What is the albedo (reflected / global irradiance)? Is it the same as for a sunny day?
Typical cloudy sky conditions

- The two SIRS pyrgeometers measure ~ 415 W-2 of longwave irradiance
- The nearly constant exchange of infrared radiation suggests low clouds.
- The direct normal shortwave (beam) irradiance remains near zero all day.
- Variable cloud thickness causes several peaks
- The global (total hemispheric) and the diffuse (sky) peak at about 256 Wm-2
- The reflected shortwave reaches a peak of 45 Wm-2 (albedo of about 18%)
Atmospheric absorption

- To a first approximation, the DIRECT solar radiation at the surface is related to the incoming radiation at the top of the atmosphere by

\[ F_{dir} = \mu_o F_o \exp\left(-\frac{\tau}{\mu_o}\right) \]

- where
  - \( F_{dir} \) is the directly transmitted radiation (Wm\(^{-2}\))
  - \( F_o \) is the solar constant (Wm\(^{-2}\))
  - \( \tau \) is the atmospheric optical depth (non-dimensional)
  - \( \mu_o \) is the cosine of the solar zenith angle (non-dimensional)

- Taking natural logarithms of both sides, we have

\[ \ln\left(\frac{F_{dir}}{\mu_o}\right) = \ln(F_o) - \left(\frac{\tau}{\mu_o}\right) \]

- If we identify \( y \equiv \ln\left(\frac{F_{dir}}{\mu_o}\right) \) and \( x \equiv \frac{1}{\mu_o} \)

- then we have the form \( y = mx + c \)

- The slope, which should be negative, will yield the optical depth, \( \tau \), and the intercept will yield \( \ln(F_o) \) from which the solar constant can be calculated.
\[ \ln \left( \frac{F_{\text{dir}}}{\mu_o} \right) = \ln(F_o) - \left( \frac{\tau}{\mu_o} \right) \]

- Slope is \(-\tau\)
- Intercept is \(\ln(F_o)\)
Solar zenith angle

- Solar time = local time + solar correction

- Since Lafayette is not located at the longitude which defines Eastern Standard Time, the solar correction is not zero. By inspecting the column of DIRECT flux, estimate the SOLAR CORRECTION.

- $h = \text{hour angle} = 2\pi \left(\text{solar time} - 12\right)/24$

- The angle of declination of the sun is equal to the latitude at which the Sun is directly overhead at noon, so it varies from +23.5 to −23.5°.
The declination angle $\delta$

$$\theta_d = 2\pi \left( jda - 1 \right)/365$$

$$\delta(jda) = \sum_{j=0}^{3} an_j \cos(j\theta_d) + bn_j \sin(j\theta_d)$$

- $an_j = 0.006918, -0.399912, -0.006758, -0.002697$
- $bn_j = 0.0, 0.070257, 0.000907, 0.001480$
- $jda = \text{integer day of the year}$.

- The solar zenith angle, $\theta_o$, is given by the equation

$$\mu_o = \cos \theta_o = \sin \Phi \sin \delta + \cos \Phi \cos \delta \cos(h)$$

- where $\Phi = \text{latitude} = 40^\circ$ for Lafayette and $h$ is the hour angle (only $h$ varies with time in your calculation).