ESCI 340 – Physical Meteorology
Radiation Lesson 6 – The Sun
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References: *The Sun*, Nicholson
An Introduction to Atmospheric Radiation, Liou

THE SUN

- **The sun is a star of average mass.**
- **The sun is composed mostly of hydrogen (75% by mass) and helium (25% by mass), with traces of iron, silicon, neon, and carbon.**
- **The sun produces radiation in its high density core, via thermonuclear fusion, the result of which is**

$$4p \Rightarrow He^4 + 2e^+ + 2\nu + 2\,photons$$

where *p* is a proton, e^+ is a positron, and ν is a neutrino.

THE STRUCTURE OF THE SUN

- **Sun has several layers**
  - **Core**
    - **Temperatures of 15 million K**
    - **Density as high as 160,000 kg/m^3**
    - **Extends to about ¼ of the radius of sun**
    - **Thermonuclear reactions generate gamma- and x-rays**
  - **Radiative zone**
    - **Temperatures on the order of 100,000 K**
    - **Extends to about 0.85 of solar radius**
    - **Photons are continually absorbed and emitted**
    - **Photons are of longer and longer wavelengths**
    - **Takes 100,000 years for energy to make its way from the core to the surface**
  - **Convective zone**
    - **Outermost 15%**
    - **Very opaque to radiation**

        - **Large radial temperature gradient**
        - **Convective currents carry energy from radiative zone to surface**
    - **Photosphere**
        - **The visible part of the sun**
        - **Very thin (~500 km)**
        - **Where most of suns radiation is emitted.**
        - **Temperature of about 6000 K**
        - **Granular in appearance (because of convection)**
- **The solar atmosphere**
    - **Chromosphere**
        - **Rarified (low density) layer**
        - **A couple of thousand km thick.**
    - **Corona**
        - **Very rarified**
        - **Very high temperature (up to 5 million K)**
    - **Above the corona is the magnetosphere.**
    - **The solar wind is a flow of atomic particles into space from the sun**

SUN SPOTS

- **Sun spots are cool regions on the surface of the sun.**
    - **Temperatures are ~4000 K, as compared with the normal 6000 K**
- **Sun spots are associated with a magnetic field disturbance.**
- **Sunspots vary according to the sunspot cycle.**
    - **11-year cycle – maximum in number of spots every 11 years or so, with spots having the opposite polarity from the previous maximum**
    - **22-year cycle – this is the average time between maxima having the same polarity**
- **When sunspots are present, the sun is very active in terms of solar flares.**

THE EARTH'S ORBIT AROUND THE SUN

- **All of the planets of the solar system revolve in elliptic orbits around the Sun, which is at one of the foci of the ellipses.**
- **All of the planets except Mercury and Pluto orbit nearly in the same plane, known as the *ecliptic*.**
- **The eccentricity of the Earth's orbit is currently about 0.0167, so it is very close to being a circle.**
  - **The average Earth-Sun distance (d_m) is defined as an *astronomical unit* (AU), and has a value of 149,597,870 km.**
  - **The Earth is farthest from the Sun (1.0167 AU) at *aphelion*, which occurs near July 4.**
  - **The Earth is closest to the sun (0.9833 AU) at *perihelion*, which occurs near January 2.**
  - **The distance to the Sun can be found from**

$$\frac{d}{d_m} = \frac{1-\varepsilon^2}{1-\varepsilon\cos(\alpha n)}$$

    where ε is the eccentricity of the Earth's orbit, n is the number of days from aphelion, and α is the orbital rate of the Earth (~0.9863°/day).
  - **The eccentricity varies within a range of about 0.05 in 100,000 years.**
- **The rotational axis of the Earth is tilted at an angle of 23.5° relative to the normal to the plane of the ecliptic.**
  - **The inclination angle varies in a range of 1.5° over about 41,000 years.**
- **The Earth "wobbles" on its axis due to precession.**
  - **This precession changes the position in the orbit where the equinoxes and solstices occur.**
  - **They get earlier by about 25 minutes each year.**
  - **The period of this precession is about 21,000 years.**
- **The precession of the equinoxes, the changing eccentricity of the orbit, and the changing tilt of the rotational axis all affect the climate of the Earth.**

- **The climate changes noted due to these factors are called *Milankovitch* cycles after the astronomer who studied these climate oscillations.**

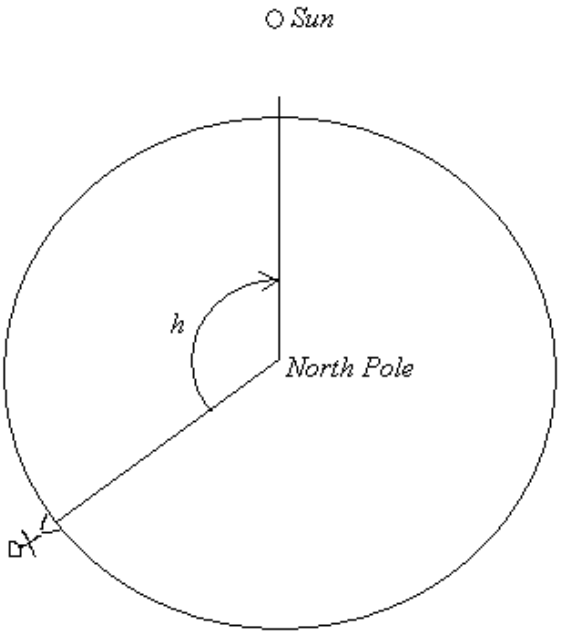
THE SEASONS

- **The fact that the Earth's rotational axis is tilted causes the noon sun angle to change from day-to-day throughout the year.**
- **Some definitions**
  - **Declination (δ) – the latitude over which the Sun is directly overhead**
    - **The declination varies from +23.5° to –23.5° over the course of one year.**
    - **Declination for a given day can be found from**

$$|\delta| = 23.5° \sin N$$

where *N* is the number of days to the closest equinox. *N* is positive for dates between the Vernal and Autumnal Equinoxes, and negative for dates between the Autumnal and Vernal Equinoxes.

  - **Hour angle (*h*) – the angle between your meridian and the meridian of the Sun (see diagram).**



    - **Hour angle is always measured westward.**
    - **Hour angle is zero at local noon, and increases with time.**

- **Since the Earth rotates approximately 360° every 24 hours, that means the hour angle increases by roughly 15° every hour. The table below gives the hour angle at various local times.**

Time	noon	3 p.m.	6 p.m.	9 p.m.	12 p.m.	3 a.m.	6 a.m.	9 a.m.
h	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**

- **The change in hour angle with time is simply the angular velocity of the Earth ($dh/dt = \Omega$).**

o **Solar zenith angle (θ) – the angle that the Sun makes with the local vertical.**

- **The solar zenith angle can be found at any time by knowing the sun's declination and hour angle, via the formula**

$$\cos\theta = \sin\lambda\sin\delta + \cos\lambda\cos\delta\cos h$$

where λ is your latitude (south latitudes and declinations are negative).

o **Sun angle (Θ) – the angle that the sun makes with the horizon.**

$$\Theta = 90° - \theta$$

- **Local noon is defined as the time that the sun crosses the local longitude ($h = 0$).**
- **Since the declination is never greater than +23.5° or less than –23.5°, *the sun can only ever be directly overhead in latitudes ranging from* 23.5S *to* 23.5N.**
- **The changing declination throughout the year is the cause of the seasons. This changing sun angle has three effects:**
  - **It spreads the suns energy over a larger area when the sun angle is small.**
  - **It causes the rays to pass through more atmosphere (greater optical depth) when the sun angle is small.**
  - **It causes varying lengths of daylight and darkness throughout the year.**

EXERCISES

1. Show that at local noon, $\Theta = 90° - \lambda + \delta$

2. Calculate the sun angle for the following times and places:

a. Millersville (latitude 40N) at 7 a.m. local on July 1.

b. Keflavik, Iceland (latitude 64N) at 3 a.m. local on June 21.

c. Thule, Greenland (76N) at 2 p.m. local on December 25.

3. A 1000 W flashlight shines directly on a floor in a parallel beam. The beam has a radius on the floor of 3 cm.

a. Find the irradiance on the floor.

b. The flashlight is tilted 30° from the vertical. Now find the irradiance. (You will need to look up the formula for the area of an ellipse).

c. The flashlight is tilted 60° from the vertical. Now find the irradiance.