Renewable Energy Systems (12210588)

6. Solar Radiation

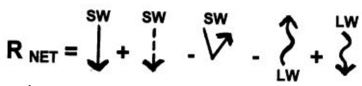
Fathi Anayah, PhD

Lecture 6

Earth Energy Budget

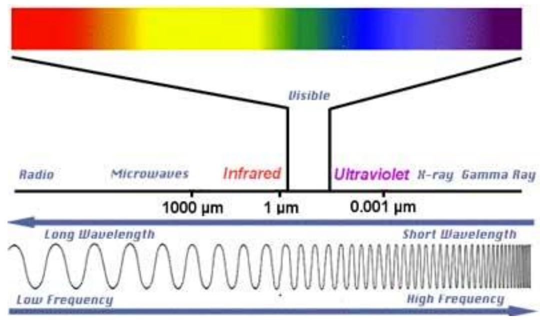
Net Radiation

Net R= net SW – net LW



where

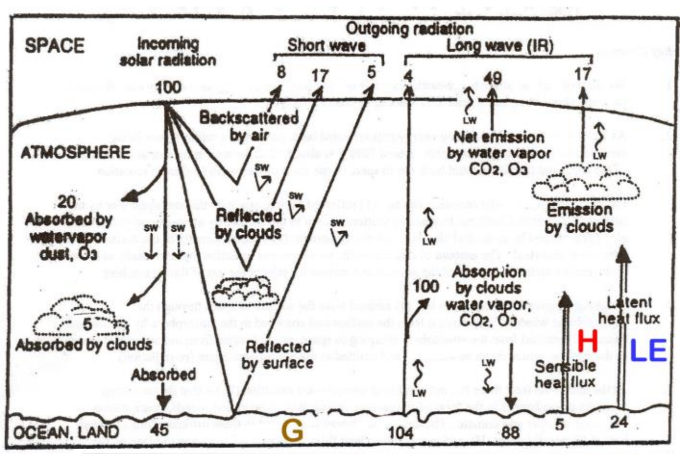
SW = direct SW + diffuse SW



Shortwave and Longwave Radiation

- Visible light and ultraviolet radiation are commonly called shortwave radiation, while infrared radiation is referred to as longwave radiation.
- The Sun radiates energy mainly in the form of **visible light**, with small amounts of ultraviolet and infrared radiation.
- For this reason, solar radiation is usually considered **shortwave** radiation.

http://www.kidsgeo.com/geography-for-kids/0060-shortwave-longwave-radiation.php

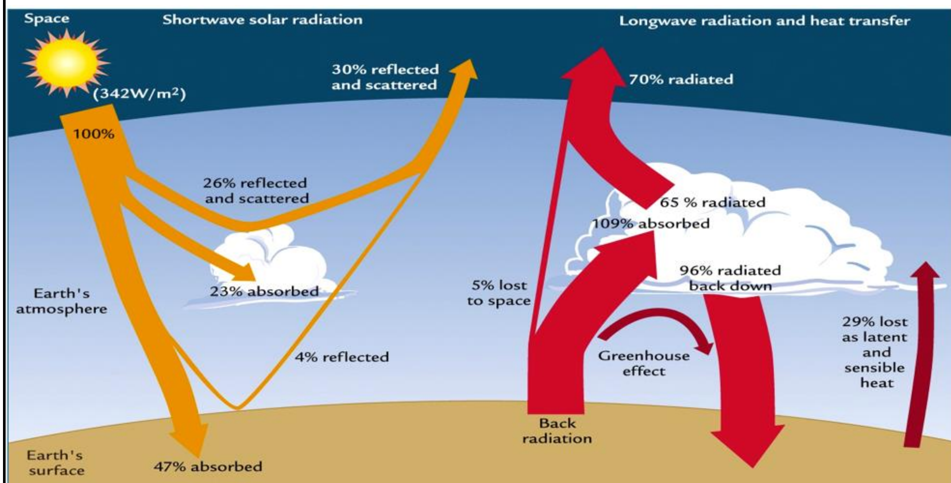


Solar energy budget

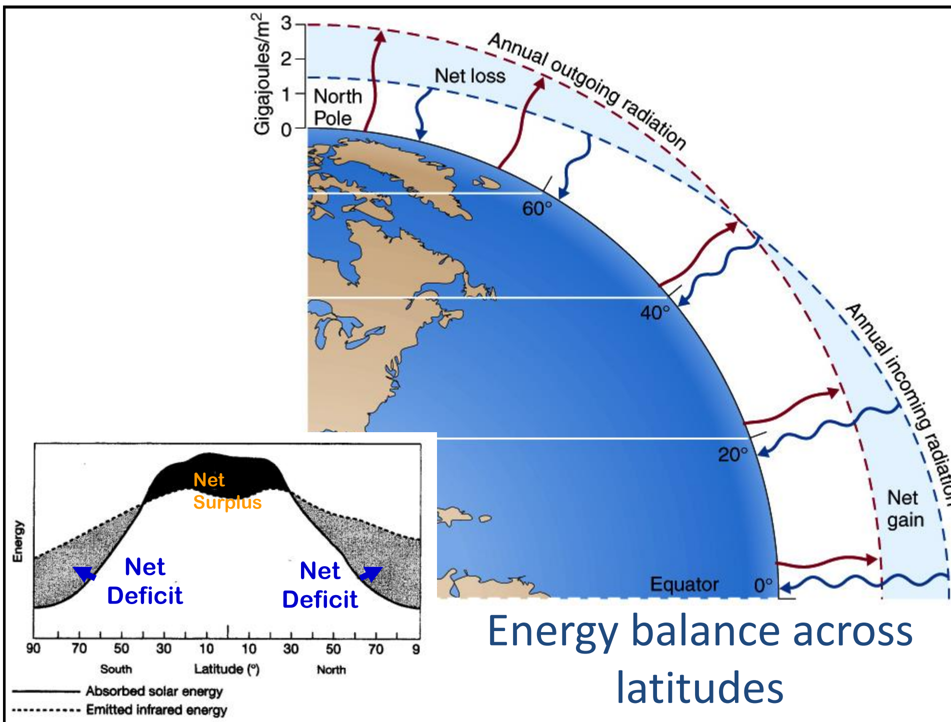
	IN		OUT		R_{NET}
	SW	LW	SW	LW	IN - OUT
Balance at top of atmosphere	100	0	8 + 17 + 5 = 30	4 + 49 + 17 = 70	0
Balance within atmosphere	20 + 5 = 25	100	0	88 + 49 + 17 = 154	- 29
Balance at Earth's surface	45	88	0	104	+ 29

R_{NET} = 0 at the top of the atmosphere
R_{NET} = + 29 at the Earth's surface, but these surplus units go into H + LE fluxes to atmosphere (G = 0)
R_{NET} = - 29 within the atmosphere, but this deficit is balanced by H + LE fluxes from Earth's surface

Earth's energy balance

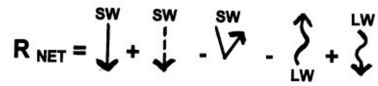


http://www.sonoma.edu/users/f/freidel/global/207lec1images.htm



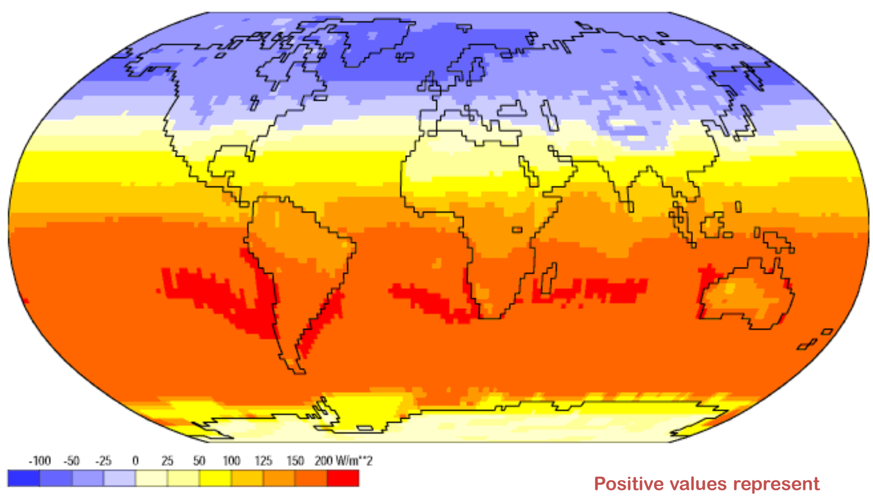
Energy balance across latitudes

Net Radiation =



Net Radiation

Dec

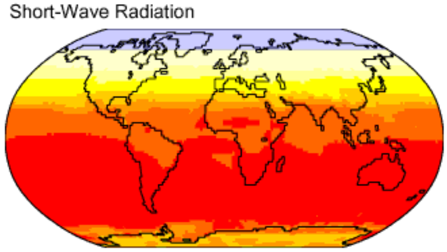


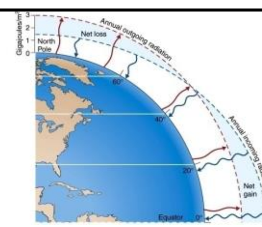
Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

Positive values represent energy moving towards the surface, negative values represent energy moving away from the surface.

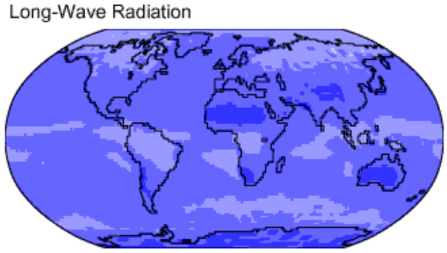
Short-Wave Radiation

Dec

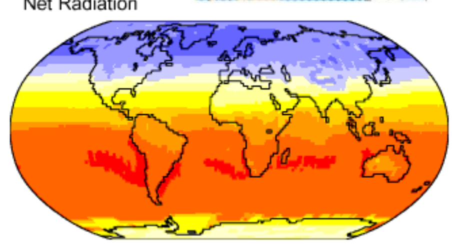


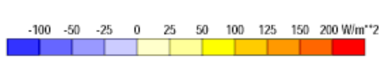


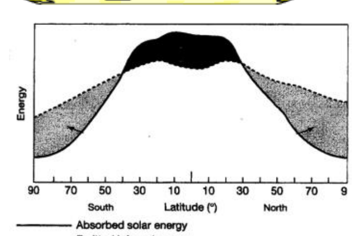
Long-Wave Radiation



Net Radiation

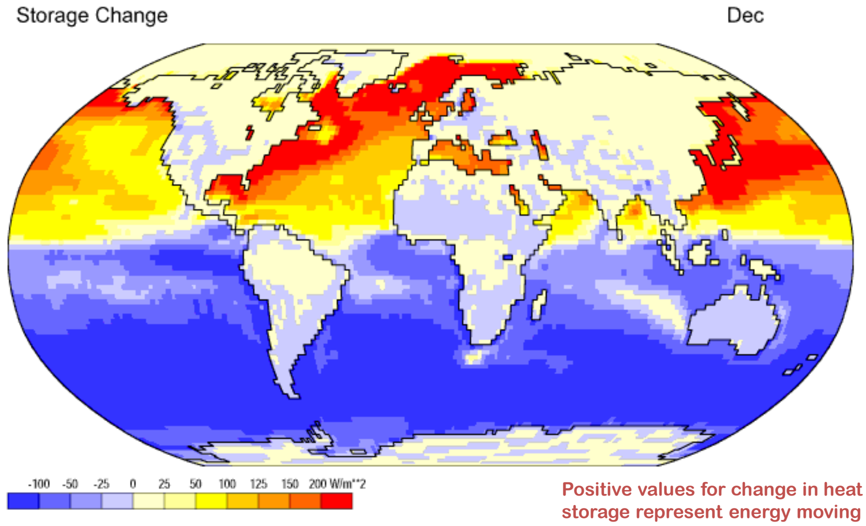






Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

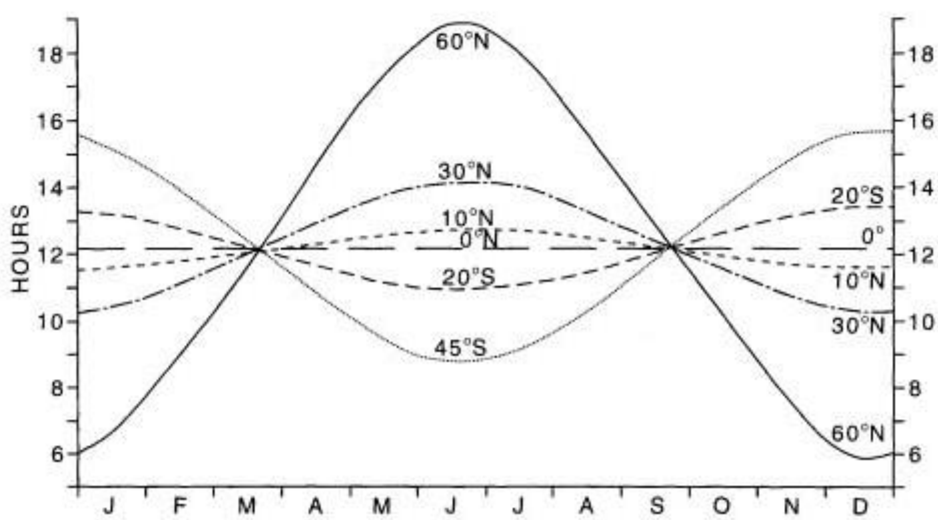
Change in Heat Storage ($\Delta G = G_1 - G_2$)



Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

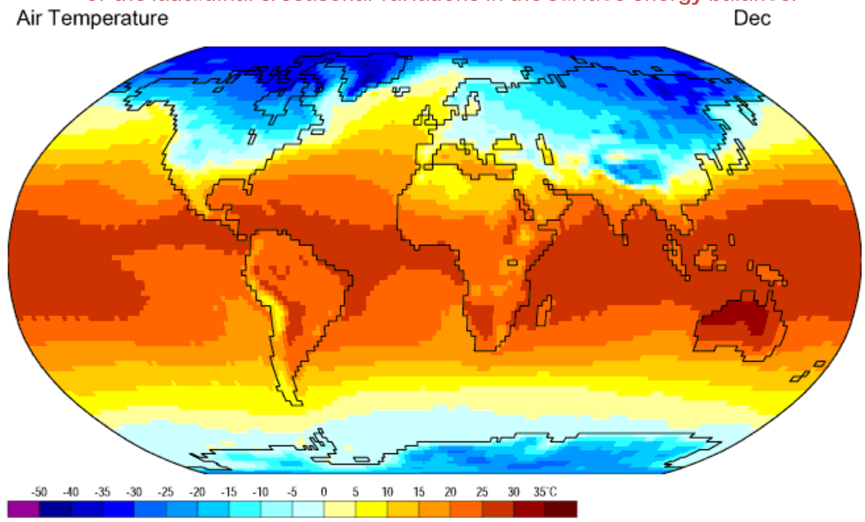
Positive values for change in heat storage represent energy moving out of storage, negative values represent energy moving into storage.

Seasonal day length at various latitudes



Air Temperature (at the surface) = T (°C)

Seasonal temperature variations can be explained in terms of the latitudinal & seasonal variations in the surface energy balance.



Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

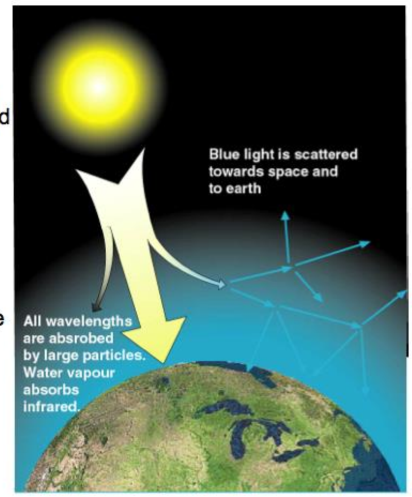
The pattern of temperatures is a function of net short-wave radiation, net long-wave radiation, sensible heat flux, latent heat flux and change in heat storage.

Solar radiation and position of the sun

Terrestrial Radiation

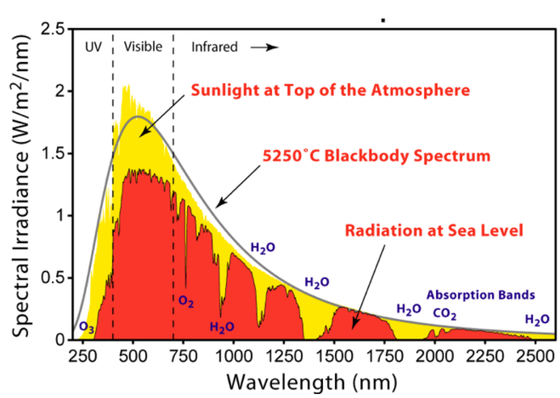
Atmosphere has several different effects on radiation: 1. scattering, 2. absorption, and 3. reflection.

- Earth's atmosphere has several impacts on radiation:
  - Scattering of ~10% of light causes this light to hit earth's surface at a wide range of angles and coming from anywhere in the sky. It is most effective for higher energy photons.
    - Direct light is the light from the sun which reaches the earth without scattering.
    - Diffuse light is scattered by the atmosphere.
  - Absorption in the atmosphere changes both the power density and the spectral distribution of terrestrial solar spectrum.
    - Ozone absorbs at high photon energies.
    - Water vapor, CO_2, absorb in infra-red.
  - Clouds, other local variation in atmosphere introduce variability (both locally and temporally) into terrestrial solar radiation.



Solar radiation spectrum

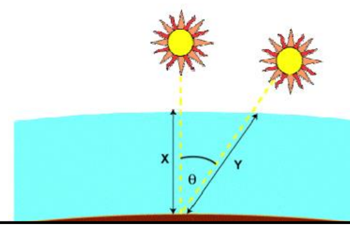
- As the sunlight travels through the atmosphere, chemicals **interact** with the sunlight and **absorb** certain wavelengths
- Example: O_3 strips UV light
- Atmospheric **scattering** plays a role, removing higher frequencies from direct sunlight and scattering it about the sky
- This is why the **sky** appears **blue** and the **sun yellow**
- The greater the distance in the atmosphere through which the sunlight travels, the greater this effect
- This is why the **sun** looks **orange** or **red** at dawn and sundown



http://en.wikipedia.org/wiki/File:Solar_Spectrum.png

Air Mass (AM)

- AM defines the direct optical path length through the Earth's atmosphere, expressed as a ratio relative to the path length vertically upwards, i.e. at the zenith
- AM is defined as $$AM = \frac{1}{\cos(\theta)}$$
- It is used to characterize the performance of solar cells under standardized conditions, and is often referred to using the syntax "**AM**" followed by a number
- **AM1.5**: is almost universal (standard) when characterizing terrestrial power-generating panels
- **AM1.5G**: G stands for global, or direct and diffuse radiation
- The solar radiation outside the Earth's atmosphere is called **AM0**

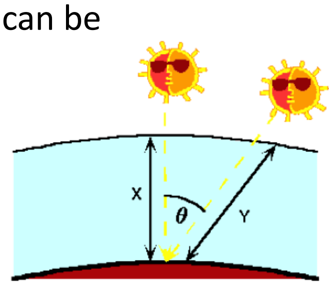


Direct and global irradiance

- Absorption in incident light is approximated by the concept of Air Mass (**AM**)
- Power density in space is called **AM0**
- Standard conditions **AM1.5**
- Direct and indirect radiative power can be approximated from AM value

$$I_D = 1.353 \times \left(0.7^{AM}\right)^{0.678}$$

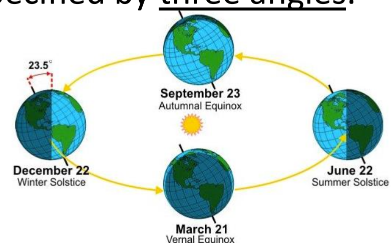
$$I_G = 1.1 \times I_D$$



where I_D is direct irradiance, I_G is global irradiance (direct + indirect (diffuse))

Angular dependence of solar radiation

- The **angle** between the **sun** and the **earth's surface** is continually changing because of the rotation of the earth about the sun and the rotation of the earth on its axis
- Determining the **angle** between the sunlight and a surface is critical in finding the **usable sunlight** since only the component of the incident sunlight which is normal to a surface can be used by the surface
- The **position** of the **sun** is specified by three angles:
  - **Declination angle (δ)**
  - **Elevation angle (α)**
  - **Azimuth angle (Θ)**



http://www.businessinsider.com/standing-an-egg-on-its-head-has-nothing-to-do-with-the-spring-equinox-2013-3

Angular dependence II

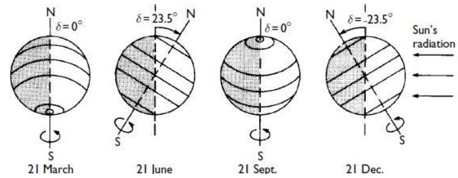
- When calculating solar angles, it is more convenient to express the **day of the year (d)** as the number of degrees which the earth has rotated around the sun – denoted by **Ω**

Daily: $\Omega = \frac{360^\circ}{365}(d-81)$ Hourly: $\Omega = \frac{360^\circ}{365}\left(d-81+\frac{hour-12}{24}\right)$

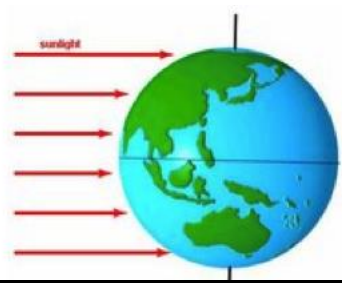
- Angular dependence has a **daily** and **seasonal** component
- **Tilt of the Earth's axis** and **rotation around the sun** causes a variation in the **angle** at which the sun strikes the earth
- **Declination** angle represents this **tilt**
- **Maximum** value of the **declination angle** is **23.45°**

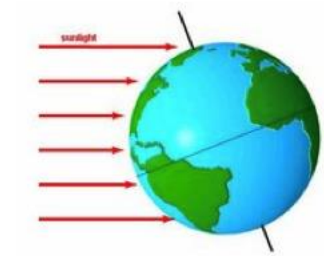
Rotation of Earth

- **Declination angle**: angle between the sun and earth



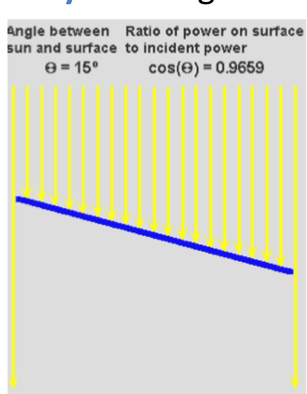
- **Declination angle**, which is the same everywhere on earth at a given time, changes with seasons

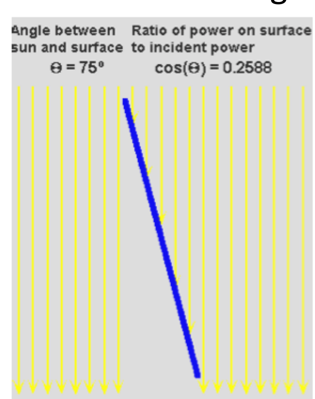




Earth surface inclination

- Rotation of the earth changes the **angle** at which the sun strikes the earth surface and though the **power density** of sunlight on the earth's surface changes





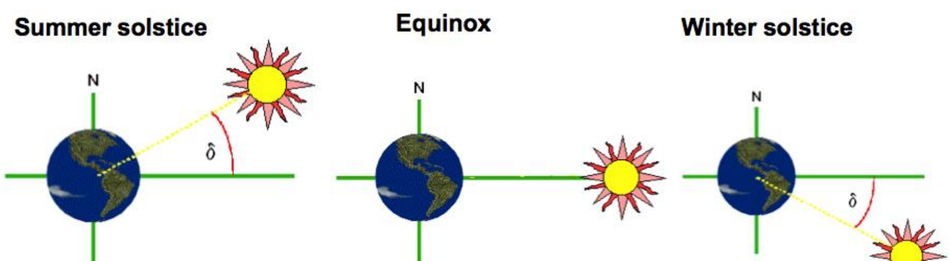
https://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Declination angle

- **Maximum** and **minimum** declination angle occur at **summer** and **winter** solstice, respectively
- **Declination** angle is **zero** at the **equinoxes**

$$\delta = \sin^{-1}\left[\sin(23.45^\circ)\sin\Omega\right] \approx 23.45^\circ \sin\Omega$$

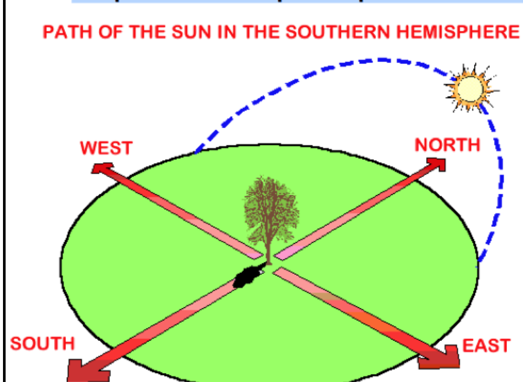
$$\delta = 23.45^\circ \sin\left[\frac{360}{365}(284 + d)\right]$$ d: day of the year (DoY)

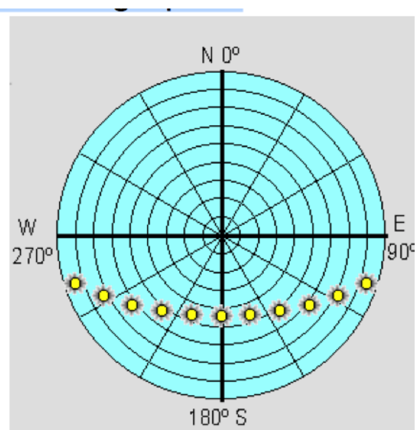


https://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Path of the sun

- Net **path** of sun throughout the day calculated based on **azimuth** and **altitude** angles
- Represent on **polar plots** or **elevation angle** plots

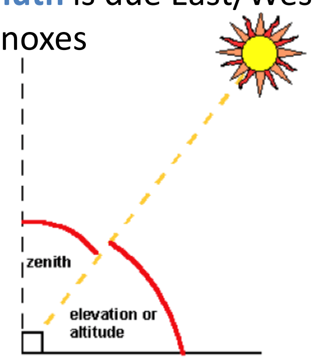


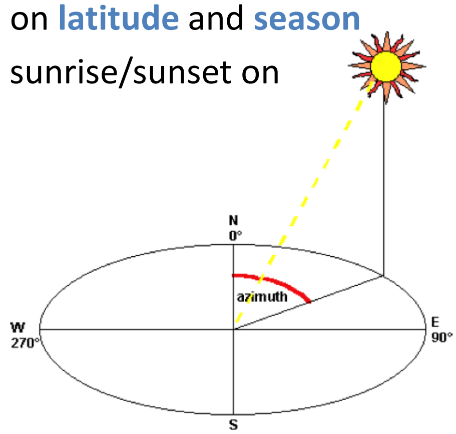


Atlanta, Feb 19th

Azimuth and elevation angles

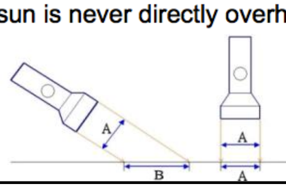
- Daily and seasonal **angular dependence** at a particular location given by **azimuth** and **elevation** (or zenith or altitude) angles
- Both **elevation** and **azimuth vary** through the day
- **Max** and **min** values depend on **latitude** and **season**
- **Azimuth** is due East/West at sunrise/sunset on equinoxes

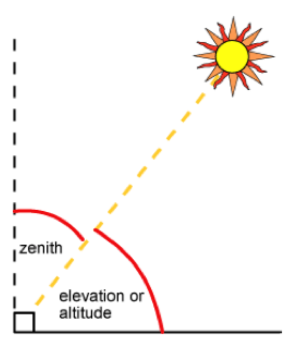




Elevation angle

- The elevation angle (used interchangeably with altitude angle) is the angular height of the sun in the sky measured from the horizontal.
  - Note: both altitude and elevation are also used to describe the height in meters above sea level – this is NOT the same parameter.
- Zenith angle is measured from vertical rather than horizontal.
- The elevation angle varies throughout the day – it is 0° at sunrise and achieves its maximum value at solar noon.
- The elevation angle at solar noon is largest at Summer Solstice (where it equals latitude plus maximum declination (23.45°)) and lowest at Winter Solstice, (where it equals latitude minus maximum declination (23.45°)) .
- For most many latitudes (greater than 23°), the sun is never directly overhead.



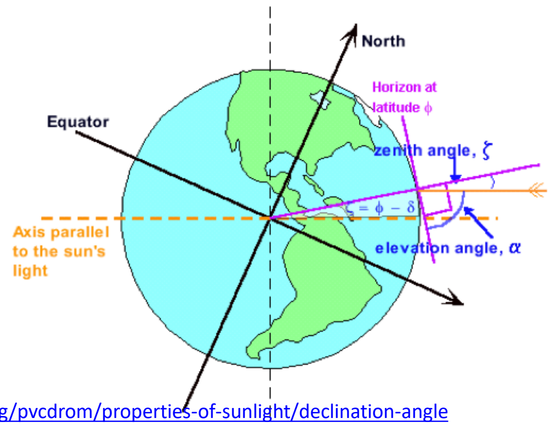


Elevation (or altitude) angle

- **Maximum** and **minimum elevation** angle depend on **latitude** and **season**
- **Maximum altitude** angle can be found from **declination** and **latitude**

$$\alpha = 90° - (\phi - \delta)$$

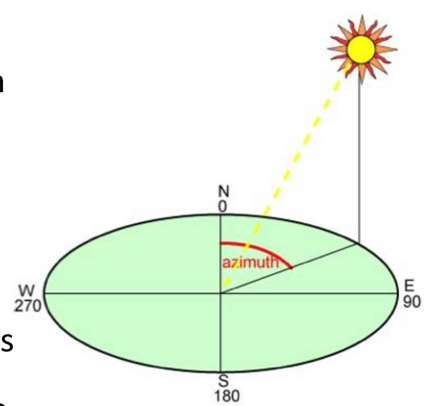
where
δ is the declination angle at a particular day of the year
ϕ is the latitude angle
α is the altitude angle



https://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Azimuth angle

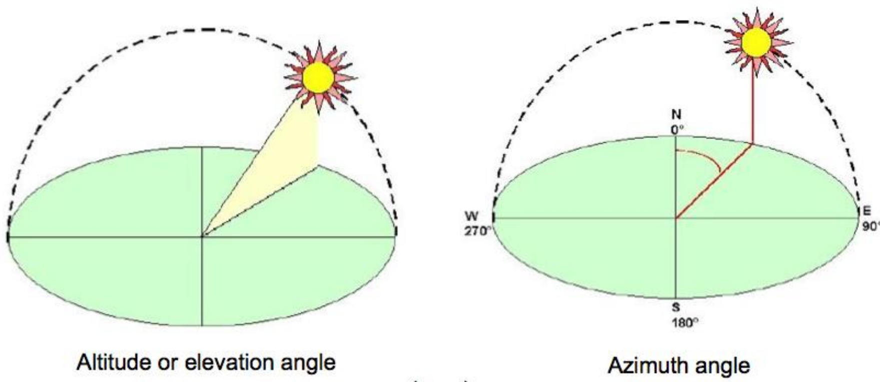
- The **azimuth** angle is the **compass** direction from which the sunlight is coming
- At **solar noon**, the **sun** is always directly **south** in the **northern** hemisphere and directly north in the southern hemisphere
- At the **equinoxes**, the **sun** rises directly **east** and sets directly **west** regardless of the latitude, thus making the **azimuth** angles **90°** at sunrise and **270°** at sunset



https://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Solar radiation for hourly calculations

- To calculate the **azimuth** and **elevation** (also called altitude or zenith (90 – elevation) angles throughout each day



$$\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos(hra)$$

$$\cos\Theta = \frac{\cos\phi\sin\delta - \sin\phi\cos\delta\cos(hra)}{\cos\alpha}$$

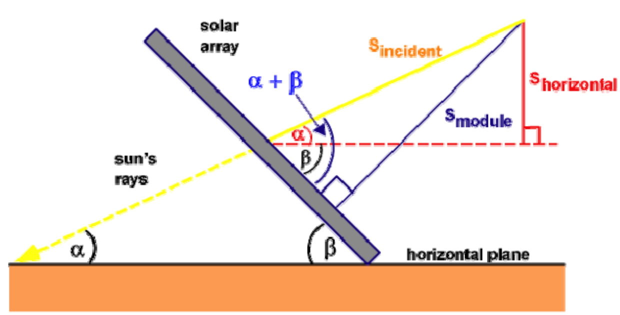
Power on a tilted surface

- The amount of **solar radiation** incident on a **tilted** module surface is the **component** of incident solar radiation which is **perpendicular** to module surface
- In solar radiation data sets, the **sunlight** is often specified as the component **normal** to a horizontal surface ($S_{horizontal}$)

$$S_{horizontal} = S_{incident}\sin(\alpha)$$

$$S_{module} = S_{incident}\sin(\alpha+\beta)$$

$$S_{module} = \frac{S_{horizontal}\sin(\alpha+\beta)}{\sin(\alpha)}$$

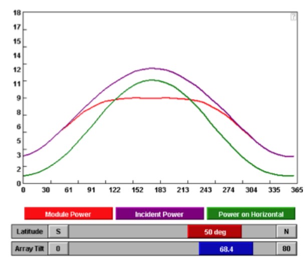


Effect of Module Tilt

- **Maximum** power into a module occurs when the **surface** is **normal** to the incident **sunlight**, but since the angle of the sun is continually changing, a module with **fixed tilt** captures only a **fraction** of the total power over a year
- **Optimum** often to set

  module tilt = latitude

but usually get equal amounts of sunlight in summer and winter



- For **maximum power**:

  module tilt = Latitude - 15°
- For more **uniform production of power**:

  module tilt = Latitude + 15°

Israel's Renewable Energy Sector at a Crossroads

RENEWABLE ENERGY WORLD.COM

- Israel transfers 290 MW renewable energy quotas to the solar PV sector as follows:
  - 70 MW of large wind power parks
  - 20 MW of small wind power installations (up to 50 kW each)
  - 200 MW of solar thermal power plants
- **Target**:
  - **10**% electricity generation from renewable energy by **2020** and this will lead to savings of more than 2 billion NIS
  - **17** – **30**% electricity generation from renewable energy by **2030**

www.renewableenergyworld.com

https://www.timesofisrael.com/israel-ups-2030-renewable-energy-target-from-17-to-30-at-cost-of-22-billion/