Physical Meteorology 1

Lecture 4

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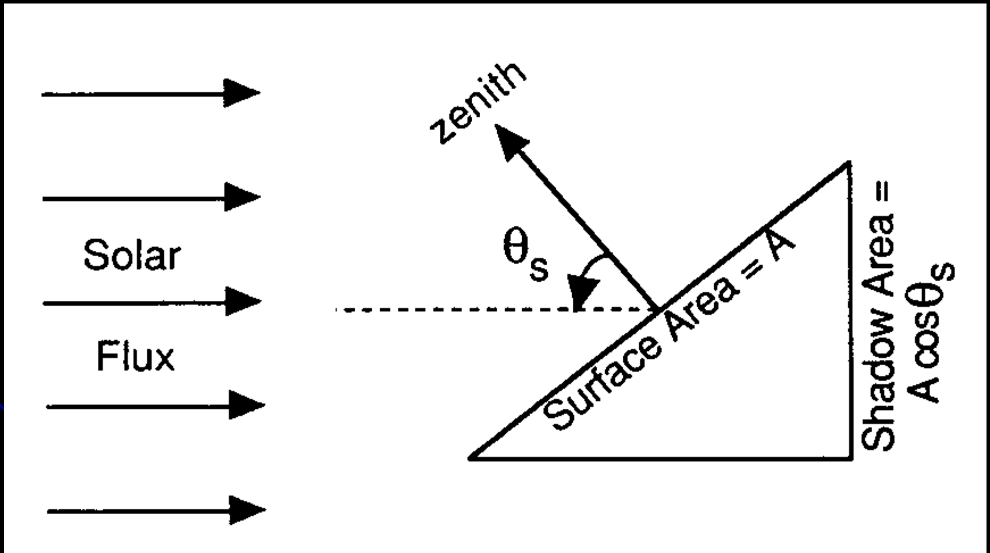
Distribution of radiation

Radiation depends on latitude, season, time of day

solar zenith angle θ_s: angle between normal to earth's surface and line between earth and sun.

Solar flux per unit area

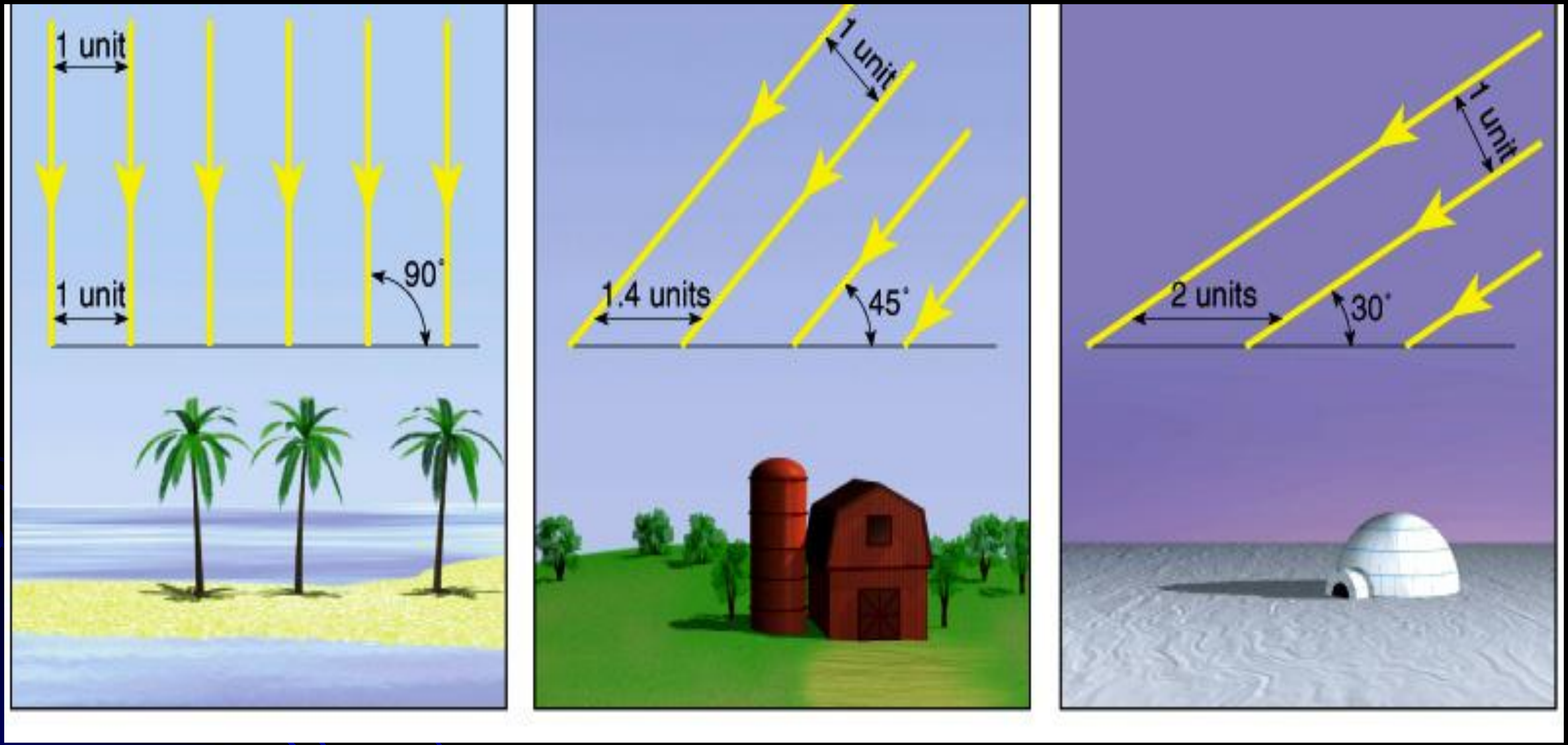


Solar zenith angle is calculated from:

Latitude (angle -90 to 90 degrees)

Angle of the sun

Most Energy | **Less Energy** | **Least Energy**



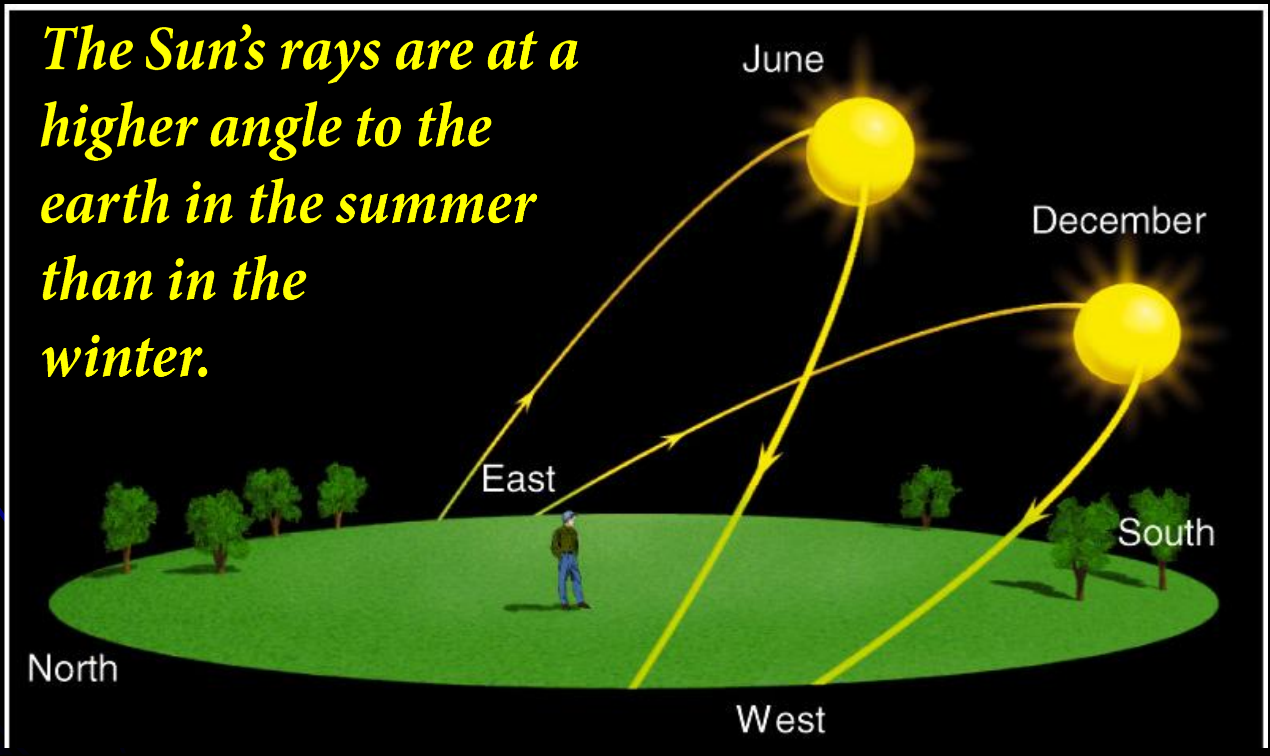
The Seasons

Three things to keep in mind when trying to understand the seasons:

1. ***The higher the angle of the sun, the more intense (concentrated) the sun's rays.***
2. ***The angle of the sun determines the thickness of the atmosphere that the sun must penetrate.***

3. The length of day determines the amount of energy that the earth is Receiving.

The Sun's rays are at a higher angle to the earth in the summer than in the winter.



Time of day

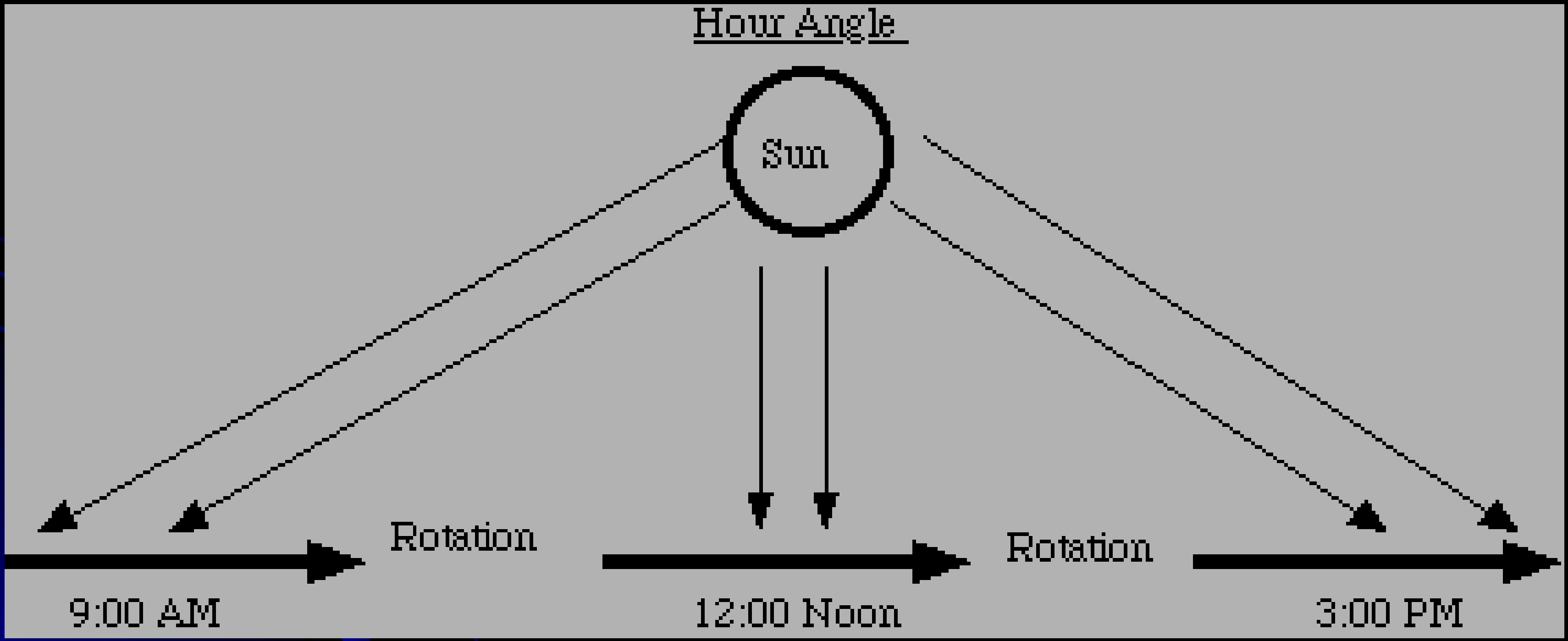
hour angle h, defined as the longitude of the subsolar point relative to its position at noon)

The earth is a sphere (360^o) that rotates 15^o with respect to the sun each hour.

These changes in solar radiation contribute to cyclic daily changes in weather.

The hour angle (h) is the angle that the earth has rotated since solar noon.

At solar noon the hour angle = 0º.



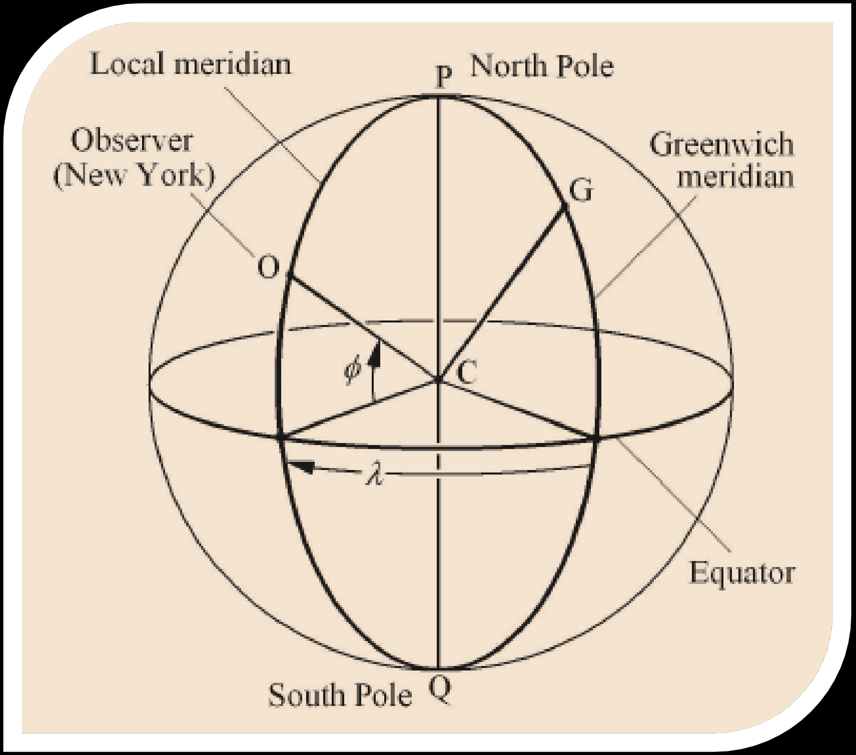
توزیع جغرافیایی و فصلی تابش خورشیدی

آفتابگیری:عبارت است از مقدار تابش خورشیدی وارد بر واحد مساحت افقی در ارتفاعی معین است.

آفتابگیری کاسته نشده خورشید در جو زیرین:

سطحی افقی که به طور قراردادی در ارتفاع 1000 کیلومتری قرار دارد در نظر می گیریم.

در اینجا تابش تحت تاثیر برهم کنش با اجزای تشکیل دهنده جو قرار نمی گیرد.

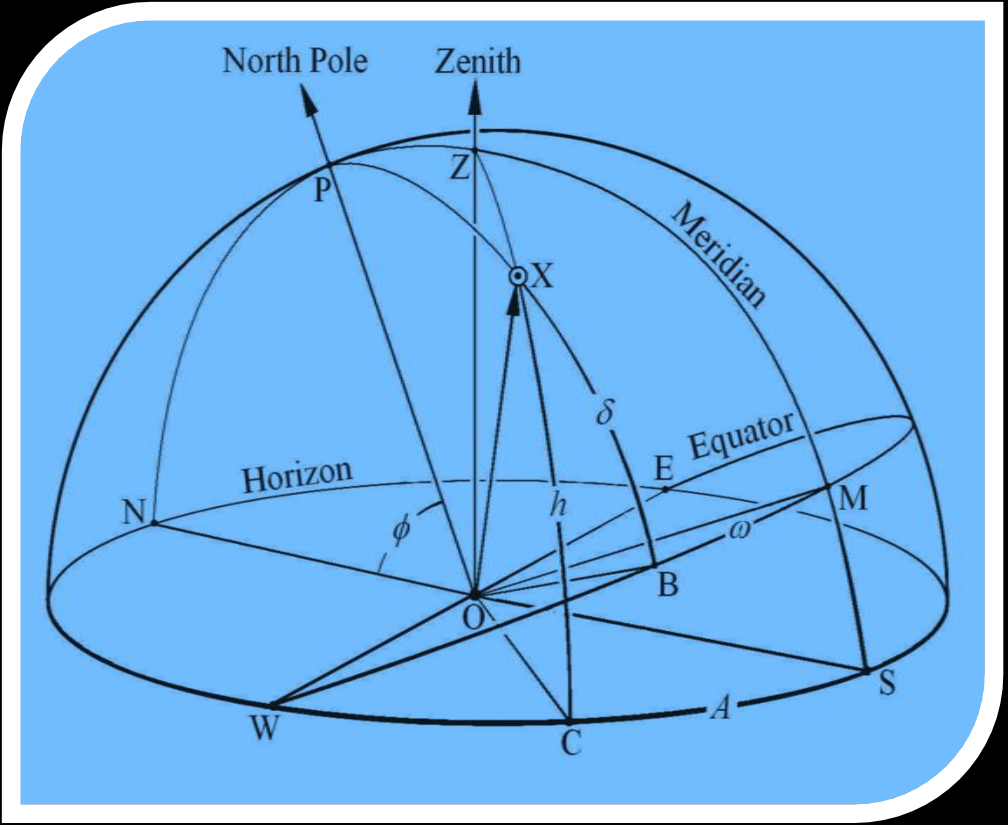


Latitude and longitude. The zero point of latitude, the prime meridian, is defined as the meridian passing through the Royal Greenwich Observatory. East of the prime meridian is the Eastern Hemisphere, and in the west is the Western Hemisphere. Similarly, north of the equator is the Northern Hemisphere, and south of the equator is the Southern Hemisphere. The position of the observer is identified by its *latitude φ and longitude λ, as marked on the map, and can be determined* using GPS. The conversion of sign is eastward is positive and westward is negative. For example, the latitude of New York City is *φ = 40◦47 N, or +0.712 rad, and its longitude is λ = 73◦58 W, or -1.29* rad.

Celestial Sphere

From the point of view of an observer on Earth, the Sun, as well as any star, is located on a sphere of a large but undefined radius.
The imaginary sphere is the *celestial sphere.*

There are two commonly used coordinate systems to describe the position of an astronomical object on the celestial sphere, the horizon system and the equatorial system.



The horizon system defines the position of a celestial body *X as directly perceived by the observer.*

The angular distance of a celestial body *X to the horizon is its height h, also called altitude or elevation.*

The other coordinate is *azimuth A. The zero point of the azimuth is defined as the south point of the horizon.*

Coordinate Transformation: Spherical Trigonometry

The coordinate transformation formulas can be easily obtained using formulas in spherical trigonometry;

We should focus our attention on the spherical triangle PZX,

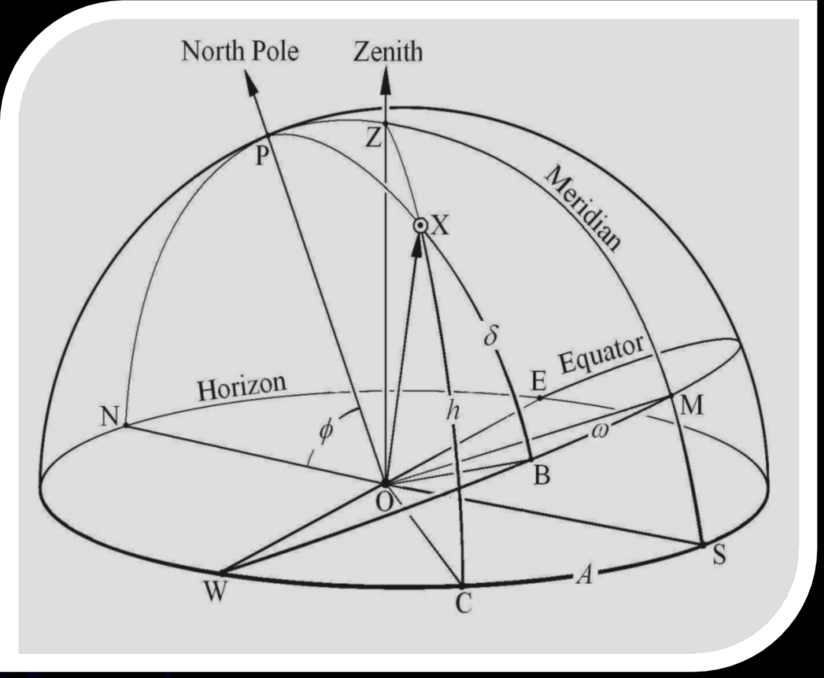
$$p = \widehat{ZX},\ z = \widehat{XP},\ \text{and}\ x = \widehat{PZ}$$

- **As seen from Fig. the relations between the elements of the spherical triangle and the quantities of interest are**

$$\begin{aligned} P &= \omega, \\ Z &= 180^\circ - A, \\ p &= 90^\circ - h, \\ z &= 90^\circ - \delta, \\ x &= 90^\circ - \phi. \end{aligned}$$

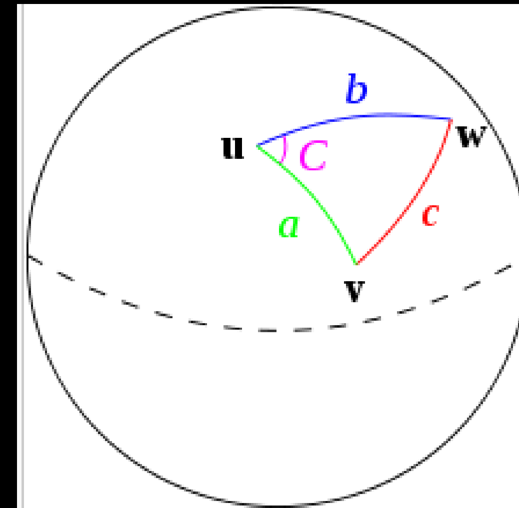
First, consider the case of given declination *δ and hour angle ω in the equatorial* system to find height *h and azimuth A in the horizon coordinate system. The latitude of* the observer's location *φ is obviously a necessary parameter. Using the cosine formu*

$$\cos p = \cos x \ \cos z + \sin x \ \sin z \ \cos P,$$



$\cos(c) = \cos(a)\cos(b) + \sin(a)\sin(b)\cos(C).$

Spherical law of cosines



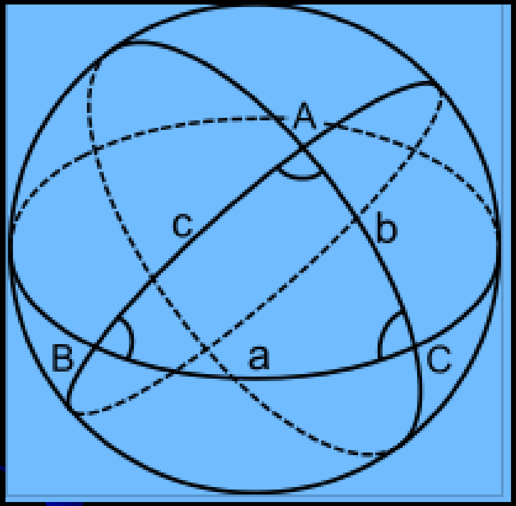
In spherical trigonometry, the **law of cosines** (also called the **cosine rule for sides**) is a theorem relating the sides and angles of spherical triangles, analogous to the ordinary law of cosines from plane trigonometry.

Given a unit sphere, a "spherical triangle" on the surface of the sphere is defined by the great circles connecting three points **u**, **v**, and **w** on the sphere (shown at right). If the lengths of these three sides are *a* (from **u** to **v**), *b* (from **u** to **w**), and *c* (from **v** to **w**), and the angle of the corner opposite *c* is *C*, then the (first) spherical law of cosines states

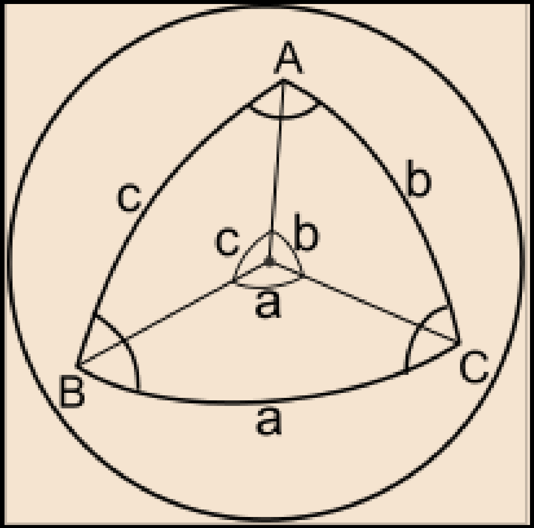
$$\cos(c) = \cos(a)\cos(b) + \sin(a)\sin(b)\cos(C)$$

Spherical polygons

A spherical polygon on the surface of the sphere is defined by a number of great circle arcs which are the intersection of the surface with planes through the centre of the sphere. Such polygons may have any number of sides.



Eight spherical triangles defined by the intersection of three great circles



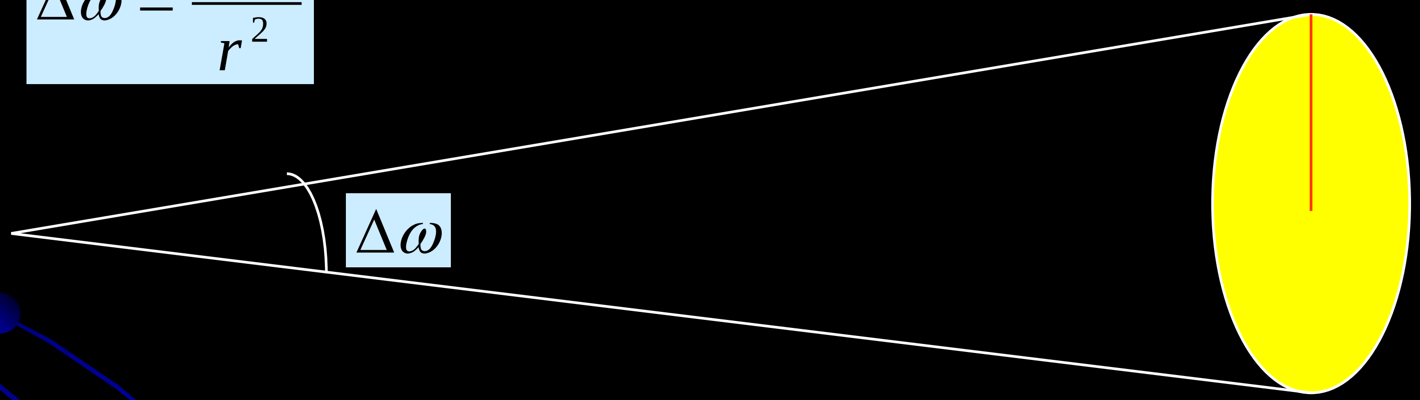
The basic triangle on a unit sphere

The theory for the **distribution of solar radiation at the top of the atmosphere** concerns how the solar irradiance (the power of solar radiation per unit area) at the top of the atmosphere is determined by the sphericity and orbital parameters of Earth. The theory could be applied to any monodirectional beam of radiation incident onto a rotating sphere, but is most usually applied to sunlight, and in particular for application in numerical weather prediction, and theory for the seasons and the ice ages.

امتداد خورشید و زاویه ای که نسبت به یک عنصر گیرنده در هر جایی در جو تشکیل می دهد اصولا با همان زاویه ای که از مرکز زمین اندازه گیری می شود برابر است.

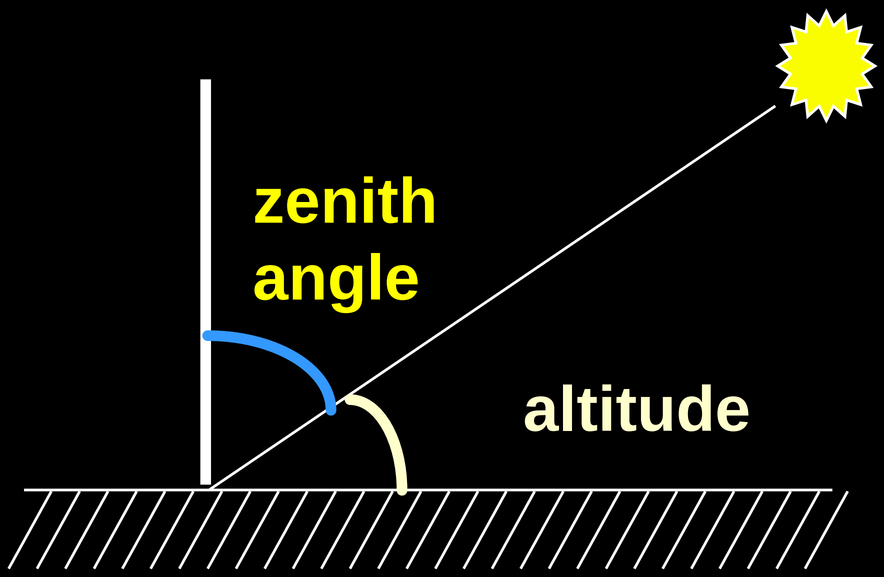
زاویه فضایی که توسط خورشید در مرکز زمین تشکیل شده چنین است:

$$\Delta\omega = \frac{\pi R^2}{r^2}$$



که در اینجا R شعاع خورشید و r فاصله بین مراکز زمین و خورشید است.

Zenith angle--is the angle between the sun and the vertical at the earth's surface.



Radiation Flux

$$F_\nu = \frac{dE_\nu}{dA\ dt\ d\nu}$$

Radiation Intensity

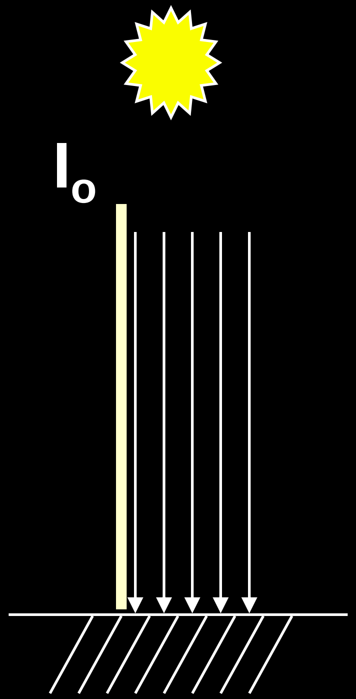
$$I_\nu = \frac{dE_\nu}{dA\ dt\ d\nu\ d\omega}$$

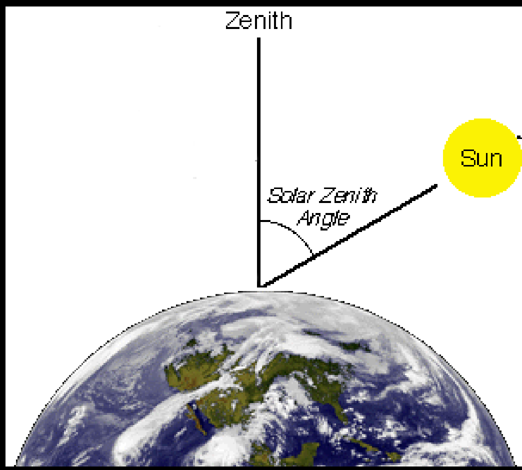
اگر خورشید در زاویه سرسو θ باشد
شاری که از واحد سطح افقی در قله جو می گذرد چنین بدست می آید

$$F_0 = I_0 \cos\theta \Delta\omega$$

$$F_0 = \frac{I_0 \cos\theta \pi R^2}{r^2}$$

$$S = \frac{I_0 \pi R^2}{r_M^2}$$





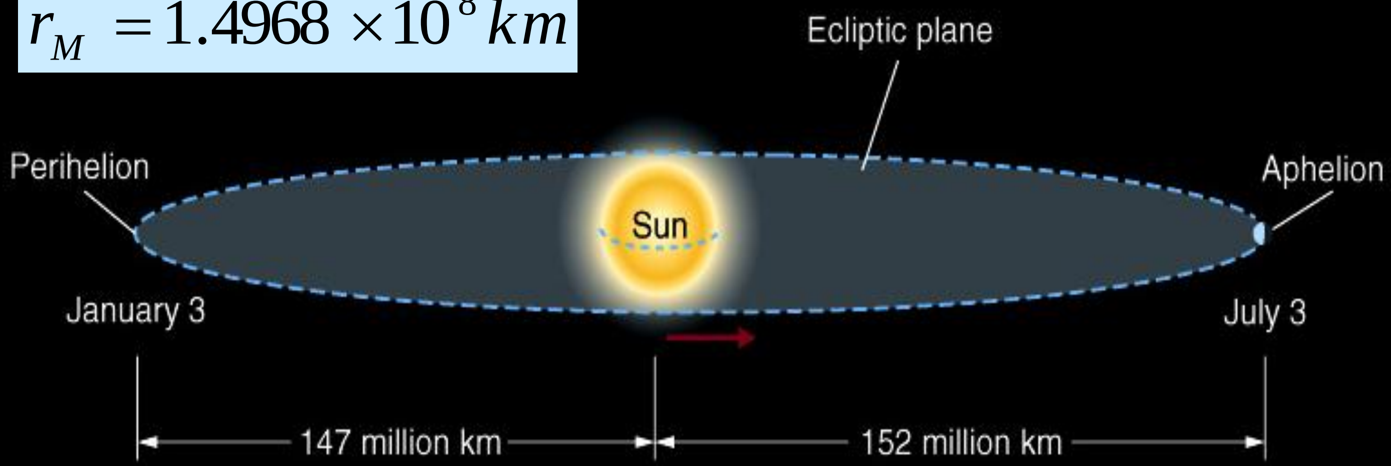
فرض می شود که I_0 داخل زاویه فضایی کوچک $\Delta\omega$ ثابت باشد با جا نشانی

وقتی $\theta=0$ و $r=r_M$ این عبارت به ثابت خورشیدی تبدیل می شود.

$$F_0 = S\frac{r_M^2}{r^2}\cos\theta$$

بنابراین آفتابگیری ناکاسته (F_0) نه تنها تابع فاصله زمین از خورشید(r) بلکه تابع زاویه سرسوی (θ) خورشید هم است.

$$r_M = 1.4968 \times 10^8 \, km$$



1) آفتابگیری ناکاسته در اوایل ژانویه (11 دی) 7% بیشتر از اوایل ژوئیه (10 تیر) است.

زاویه سرسوی (θ) خورشید تغییرات بیشتری را در آفتابگیری ناکاسته پدید می آورد. زاویه برخورد پرتوهای خورشید با یک سطح افقی به عرض جغرافیایی – فصل و طول روز بستگی دارد.

از آنجا که طول روز با عرض جغرافیایی و فصل تغییر میکند مقدار انرژی خورشیدی ناکاسته که واحد سطح افقی در یک روز دریافت می کند فقط به فصل و عرض جغرافیایی بستگی دارد. (Q_0)

$$Q_0 = S \frac{r_M^{\;2}}{r^2} \int_{dawn}^{sunset} \cos\theta dt$$

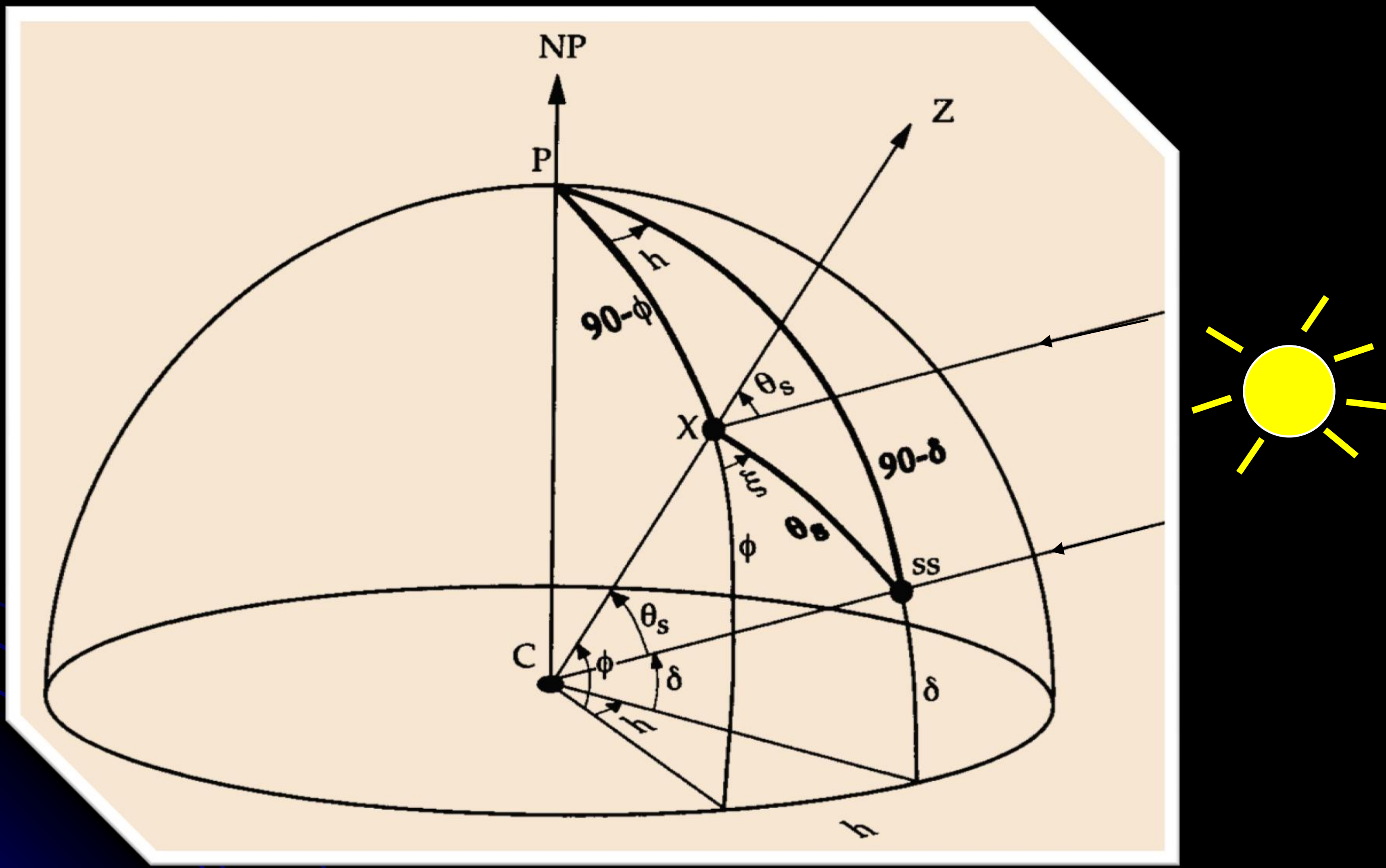
$$Q_0 = \frac{24S \; r_M^{\;2}}{\pi r^2} \sin\phi \sin\delta (H - \tan H)$$

عرض جغرافیایی

زاویه میل خورشید

زاویه ساعتی

زاویه ساعتی تابع عرض جغرافیایی و زمان سال است بنابراین آفتابگیری ناکاسته روزانه بر حسب یکاهای $Jm^{-2}day^{-1}$ فقط به عرض جغرافیایی و فصل سال بستگی دارد.



NP
P
Z
h
90-ϕ
θs
X
ω
90-δ
θs
ϕ
SS
θs
C
ϕ
δ
h
δ
h

انرژی خورشیدی روزانه

$$Q_0 = S\frac{r_M^2}{r^2}\int_{dawn}^{sunset}\cos\theta dt$$

$$\int_{dawn}^{sunset}\cos\theta dt = 2\int_{noon}^{sunset}\cos\theta dt$$

با نظر گرفتن مثلث کروی در شکل فوق

$$\cos\theta = \cos(\frac{\pi}{2}-\varphi)\cos(\frac{\pi}{2}-\delta)+\sin(\frac{\pi}{2}-\varphi)\sin(\frac{\pi}{2}-\delta)\cosh$$

$$\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cosh$$

$$dh = \Omega dt = (\pi/12)dt$$

$$Q = 2S\frac{r_M^2}{r^2}\int_0^H \cos\theta dt$$

$$Q = \frac{24}{\pi}S(\frac{r_M}{r})^2\int_0^H (\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos h)dh$$

$$Q = \frac{24}{\pi}S(\frac{r_M}{r})^2\left[\sin\varphi\sin\delta H + \cos\varphi\cos\delta\sin H\right]$$

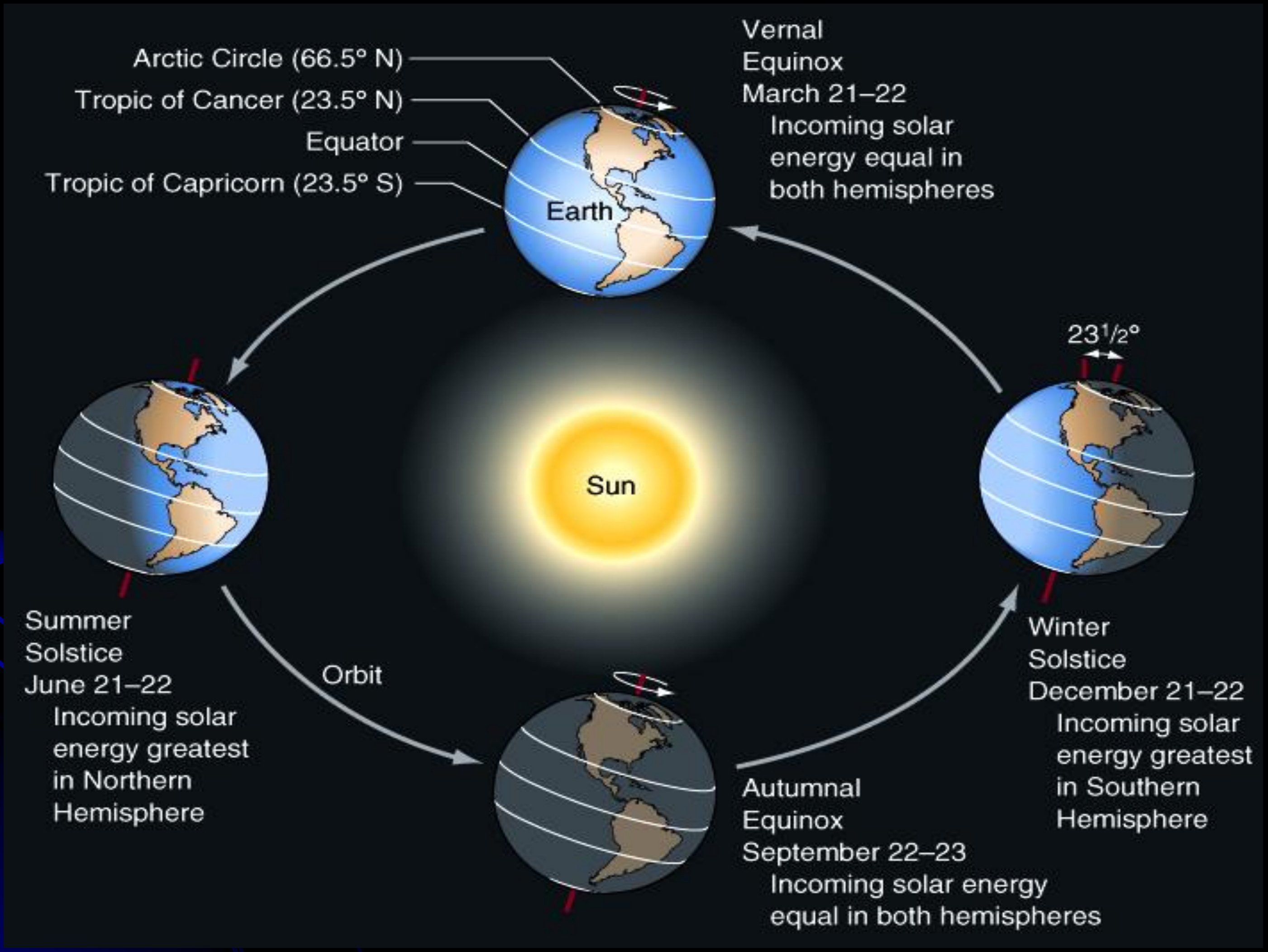
$$\cos H = -tg\varphi tg\delta$$

$$Q_0 = \frac{24}{\pi}S(\frac{r_M}{r})^2\sin\varphi\sin\delta(H - \tan H)$$

در صورت عدم وجود جو جنبه های اصلی توزیع انرژی خورشیدی از معادله فوق تعیین می شود.

1) تغییرات فصلی تابش خورشیدی دریافتی از جانب استوا نسبتا ناچیز است. علت این امر آن است که خورشید در نیمروز هرگز بیشتر از 23/5 درجه از زاویه سرسو دور نمی شود و دوام نور خورشید همیشه دوازده ساعت است.

2) ماکزیمم تغییرات روزانه آفتابگیری در قطبها روی می دهد.



3) دومین ماکزیمم آفتابگیری روزانه در نزدیکی عرض 45^0 و در انقلاب تابستان هر نیمکره روی می دهد.

با افزایش عرض جغرافیایی آهنگ دریافت انرژی کاهش می یابد اما دوام آفتابگیری افزایش می یابد.

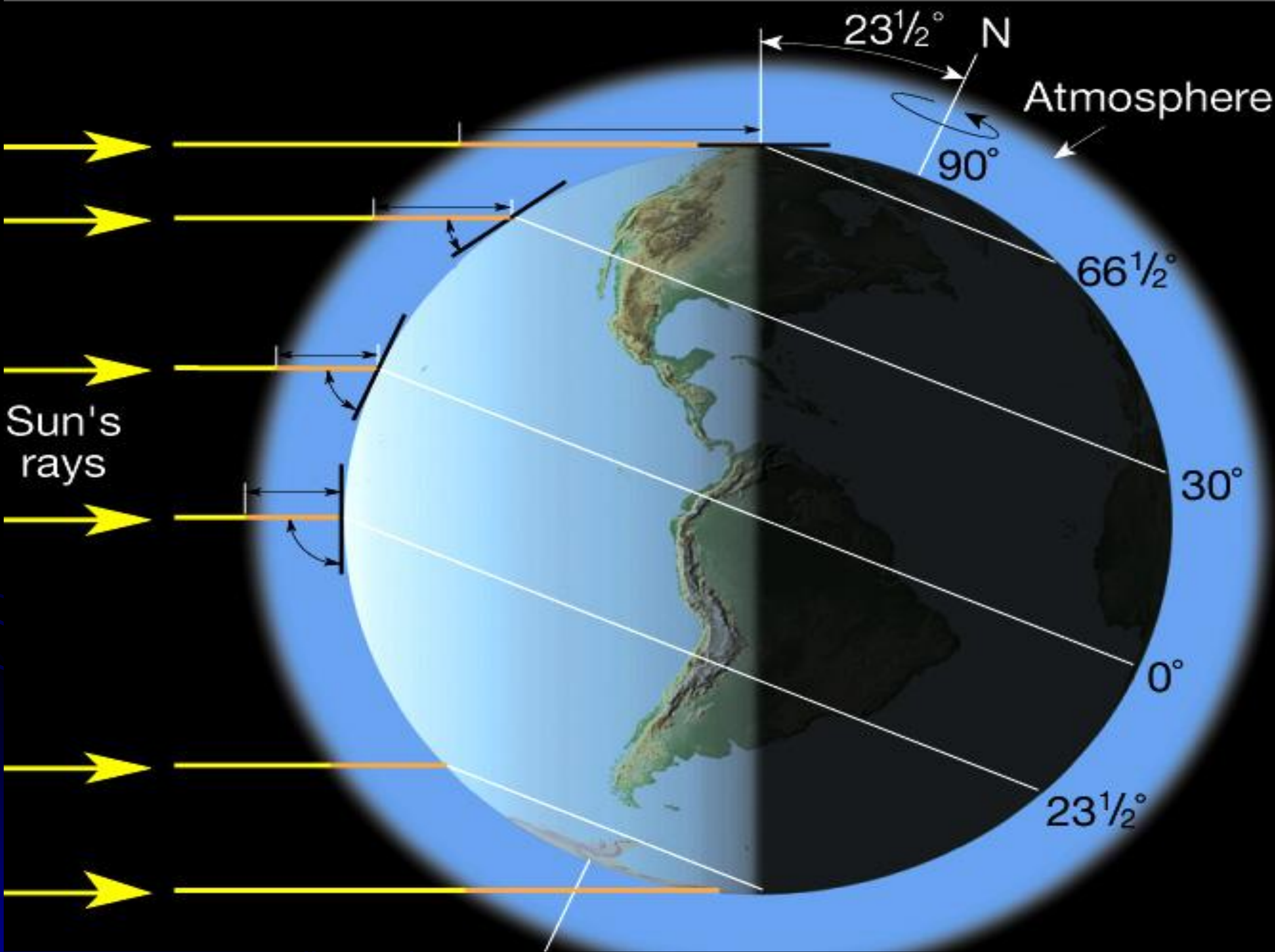
4) مقدار آفتابگیری برای هر عرض جغرافیایی در تابستان نیمکره جنوبی بیشتر از مقدار متناظر آن برای عرضهای نمیکره شمالی در تابستان است.

The Fate of Incoming Radiation

کاستی تابش خورشیدی

کاهش انرژی خورشیدی در عرضهای بالاتر بیشترین مقدار است. زیرا در آنجا طولانیترین مسیر را در جو می پیماتد.

در نتیجه ناحیه آفتابگیری ماکزیمم در سطح زمین در تابستان در قطب نخواهد بود



23½°
N
Atmosphere
90°
66½°
Sun's rays
30°
0°
23½°

تابش خورشیدی که به سطح زمین می رسد از راه جذب وپراکندگی در جو تعدیل پیدا می کند.

Absorption

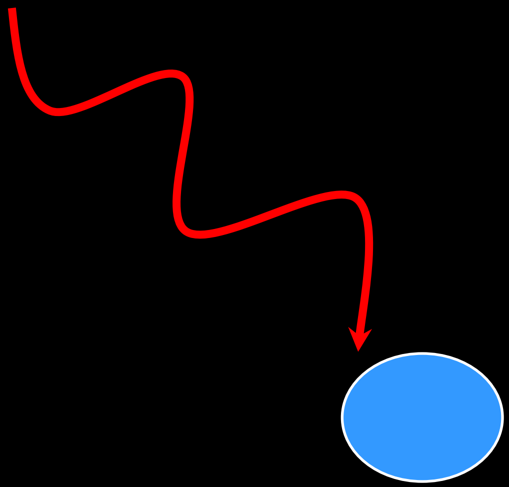
Scattering

Absorption

69% of top-of-atmosphere solar radiation is absorbed

Earth's surfaces (45%)

Atmosphere (24%)

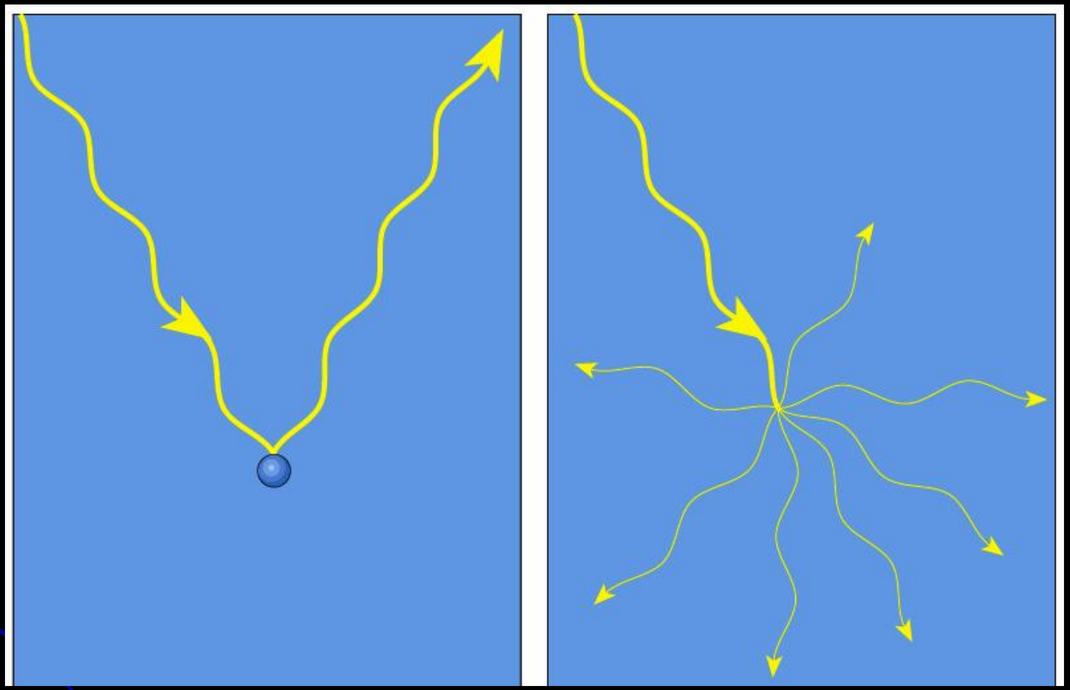


Energy consumed by molecule

- Ozone absorbs UV radiation
- Water Vapor, CO_2 absorb IR Radiation

Scattering

Gas molecules, dust particles, pollutants, ice and cloud droplets scatter incoming solar radiation.



Reflected light:

bounces back at the same angle at which it strikes the surface and with the same intensity.

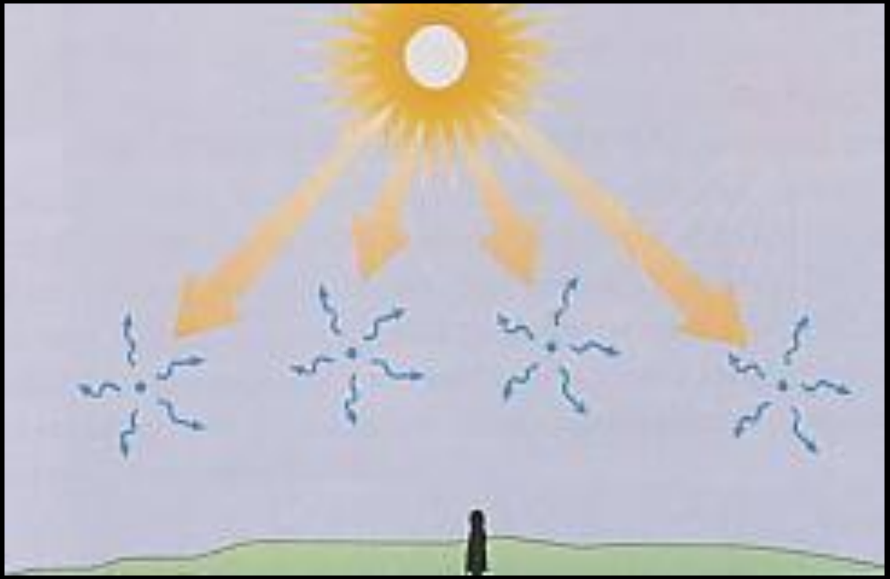
Scattered light:

a larger number of weaker Rays all traveling in different directions.

Why is the Sky Blue? Sunset Sky Red?

Why is the day sky blue?

- Sunlight is scattered by air molecules
- Air molecules are much smaller than the light's l
- Shorter wavelengths (green, blue, violet) scattered more efficiently
- So the color we see is dominated by short visible wavelengths



Our eyes are remote sensors that are sensitive to light with wavelengths between approximately 0.4-0.7 microns (one micron is a millionth of a meter or one one-hundredth the diameter of a human hair).

Color	Wavelength in microns
Violet	0.390- 0.455
Blue	0.455- 0.492
Green	0.492- 0.577
Yellow	0.577- 0.597
Orange	0.597- 0.622
Red	0.622- 0.780

Why not violet?

While all colors are scattered by air molecules, violet and blue are scattered most. The sky looks blue, not violet, because our eyes are more sensitive to blue light (the sun also emits more energy as blue light than as violet).

Why are sunsets red?

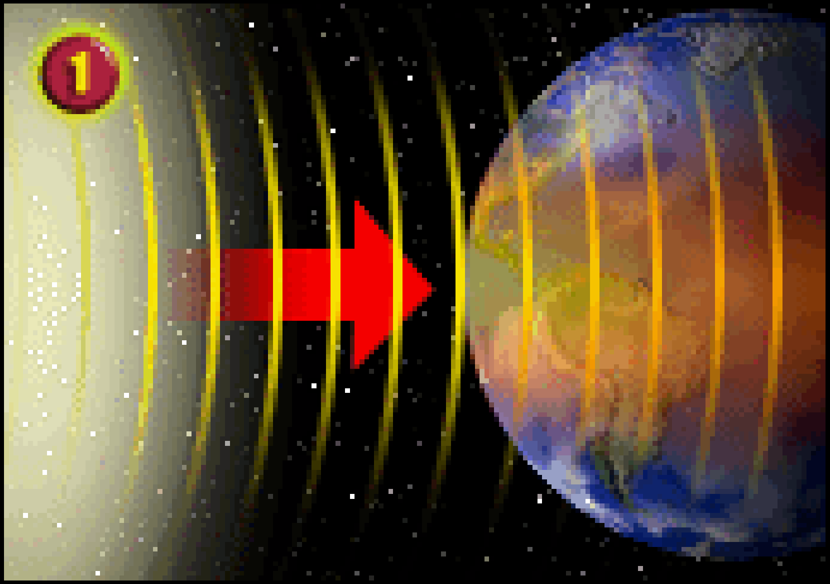
At sunset and sunrise, the sunlight passes through more atmosphere than during the day when the sun is higher in the sky.

More atmosphere means more molecules to scatter the violet and blue light.

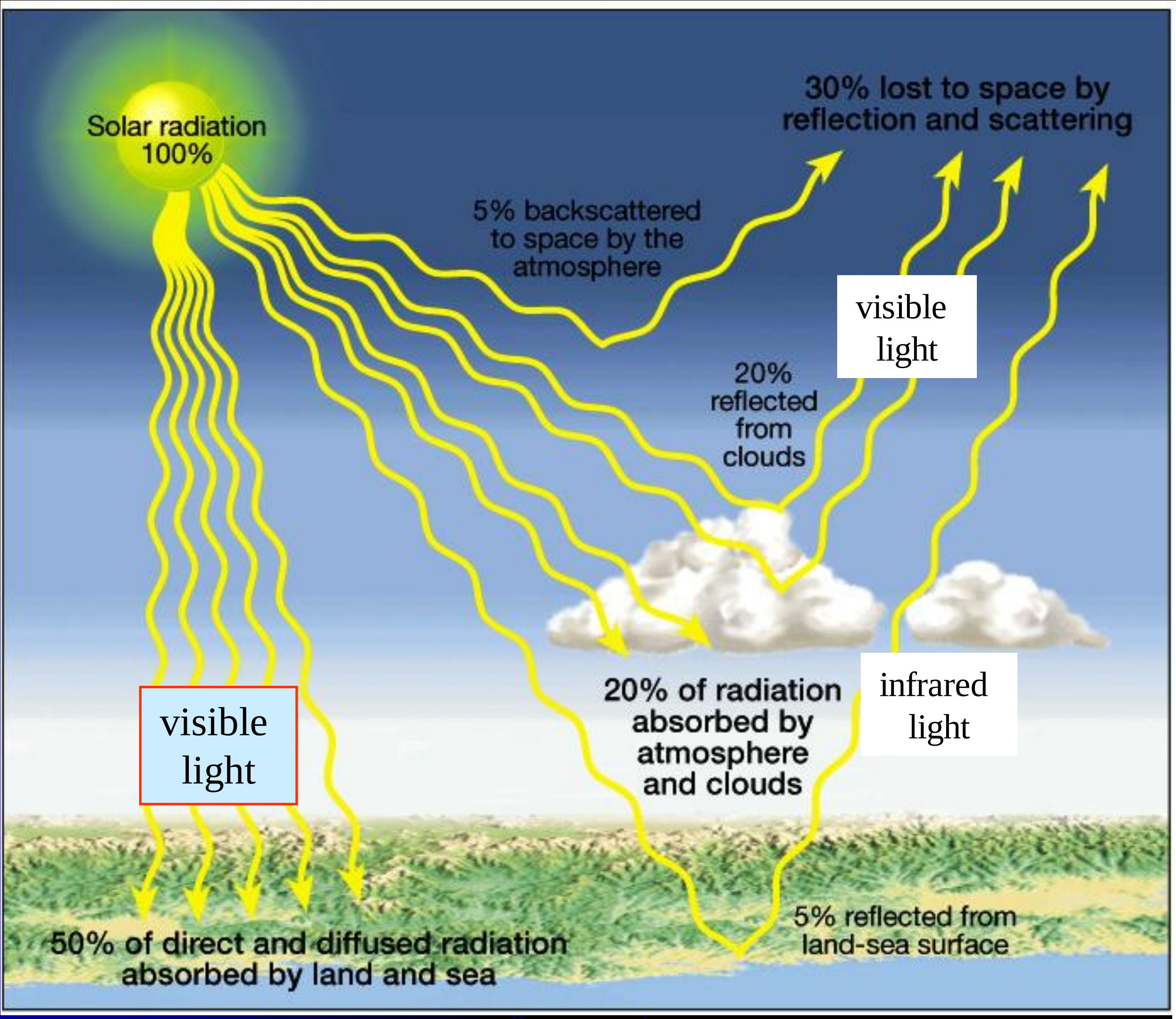
If the path is long enough all of the blue and violet light gets redirected out of your line of sight, while much of the yellow, orange and red colors continue along the undeviated path between your eye and the sun.

This is why sunsets often are composed of yellow, orange and red colors.

The End



Review of the Average Distribution of Incoming Solar Radiation



+100% from Sun

-5% backscattered to space

-50% absorbed by Earth

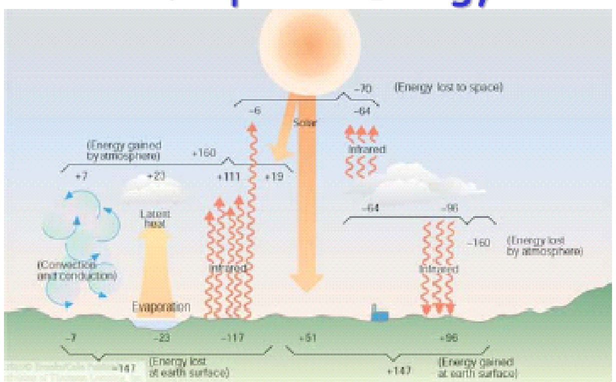
-20% absorbed by clouds

-20% reflected from clouds

-5 reflected from land-sea

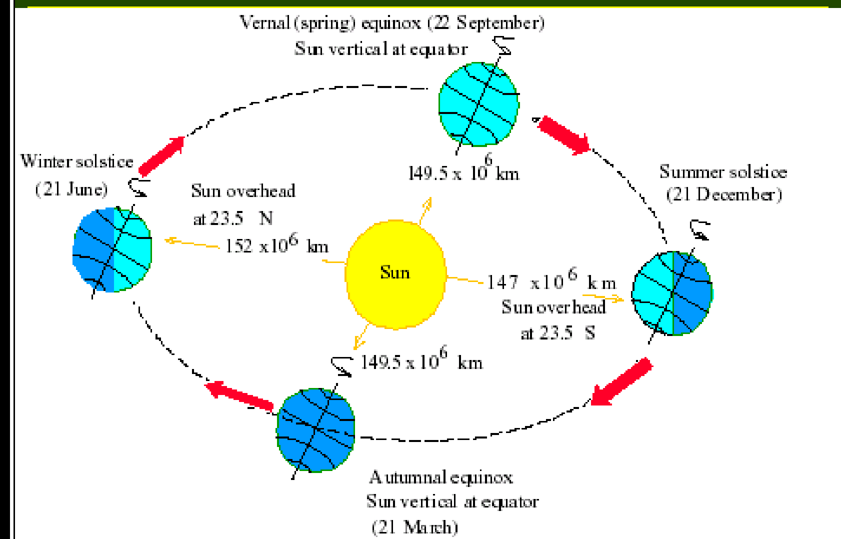
0 leftover

Earth-Atmosphere Energy Balance



Earth's surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds.
These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.
Earth's surface loses these 147 units through convection, evaporation, and radiation.

Seasonal variation on incident radiation



The Vernal & Autumnal Equinoxes

In March & September:

Axis is at *right angles* to the Earth-Sun line.

The Sun is seen on the Celestial Equator.

Day and Night are equal length (12 hours).

March: Vernal Equinox

Northern Spring & Southern Autumn.

September: Autumnal Equinox

Northern Autumn & Southern Spring.

Winter Solstice

In December:

The Earth's axis tilts *away* from the Sun.

The Sun is at its maximum southern declination

Northern Winter:

The Sun is low in the sky.

The day is shorter than the night

Southern Summer:

The Sun is high in the sky.

The day is longer than the night

Summer Solstice

In June:

The Earth's axis tilts *towards* from the Sun.

The Sun is at its maximum northern declination

Northern Summer:

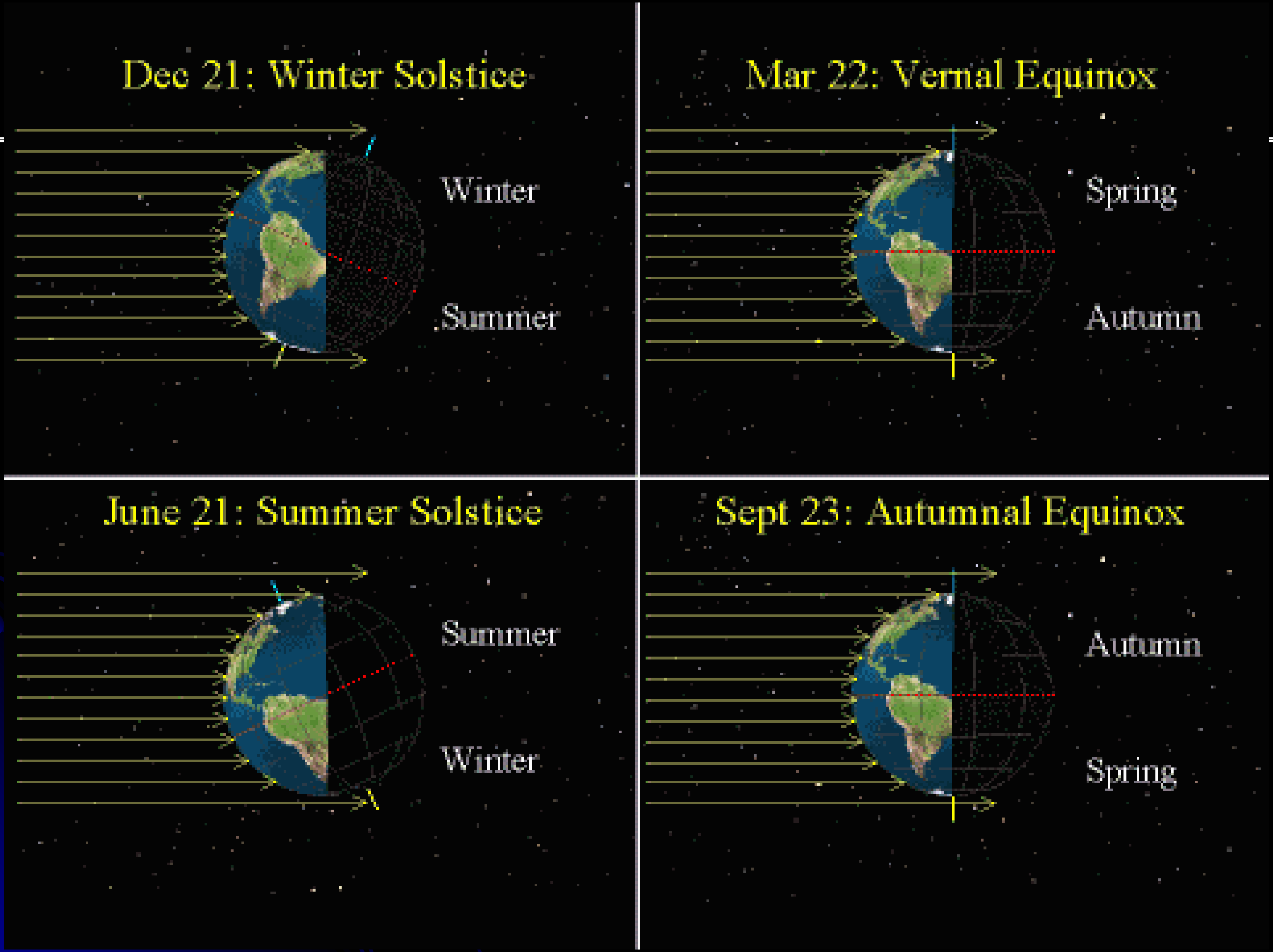
The Sun is high in the sky.

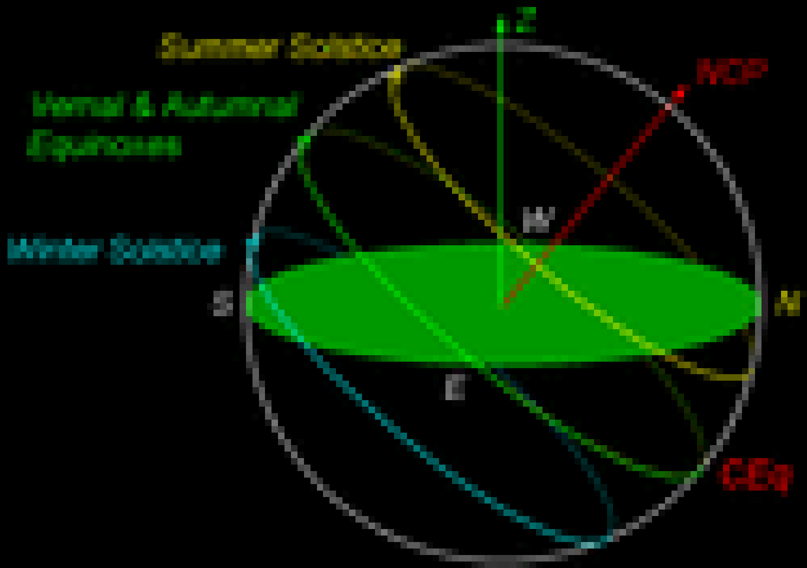
The day is longer than the night

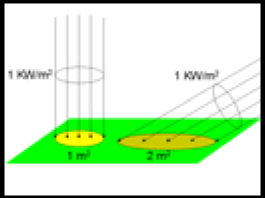
Southern Winter:

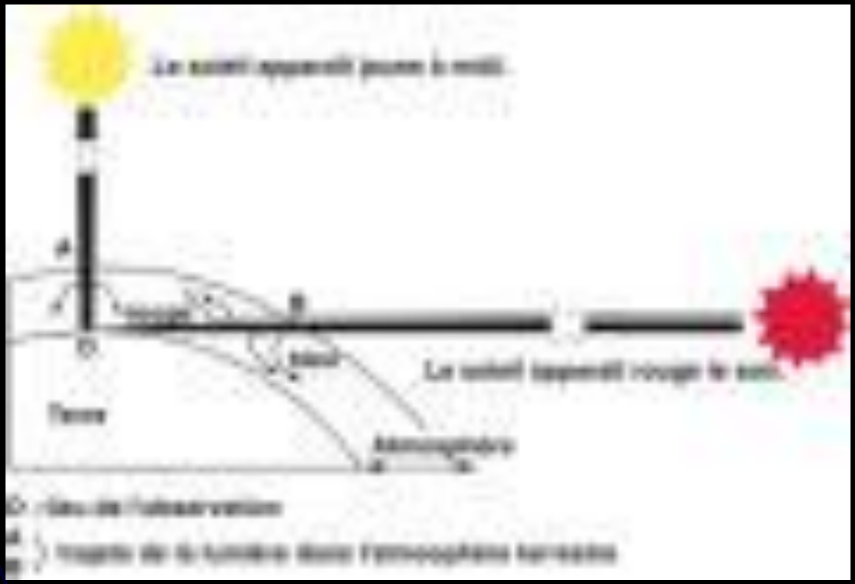
The Sun is low in the sky.

The day is shorter than the night

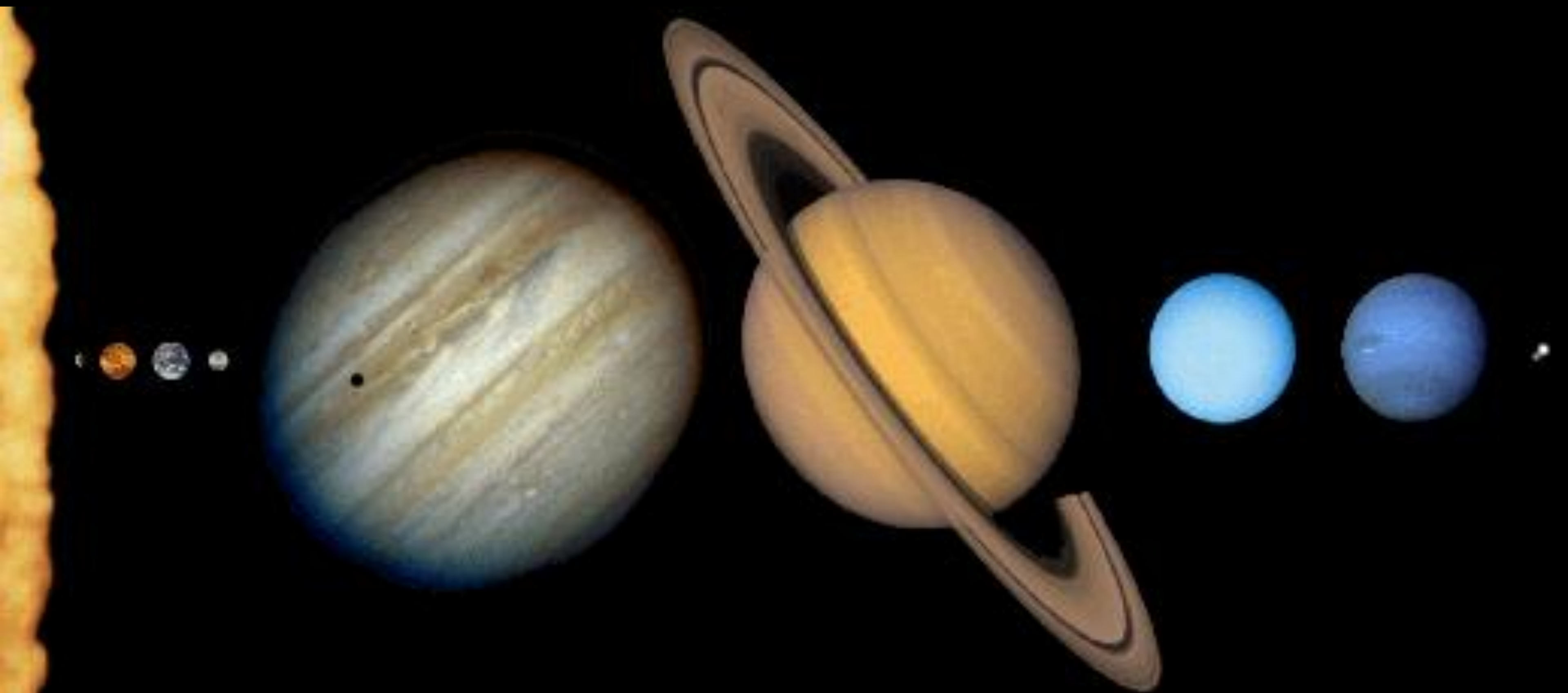

Dec 21: Winter Solstice
Winter
Summer
Mar 22: Vernal Equinox
Spring
Autumn
June 21: Summer Solstice
Summer
Winter
Sept 23: Autumnal Equinox
Autumn
Spring


Z
Summer Solstice
NCP
Vernal & Autumnal
Equinoxes
W
Winter Solstice
S
N
E
CEq


1 KW/m²
1 KW/m²
1 m²
2 m²


Terre
Atmosphère

Questions?



Stefan-Boltzmann Law

- the **total amount of Energy emitted is f(x) of temperature**
- hot bodies emit more energy than cold
- described as:

$$I = \sigma T^4$$

where I = intensity (W/m^2)
σ = Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2/K^4$)
T = temperature in K

Earth = 400 W/m^2
Sun = 73,000 W/m^2

e.g. Earth: avg. temp = 15^oC or 290 K
$I = (5.67 \times 10^{-8}\ W/m^2/K^4)(290\ K)^4$
$= 400\ W/m^2$

- doubling of T → 16-fold increase in emission

Stefan-Boltzmann Law (cont.)

- previous slide applies to **blackbodies**
- most solids/liquids considered **greybodies → emit percentage of max. amt of radiation at given T**
- every substance has a specific **emissivity (ε), generally > 90% (0.90)**

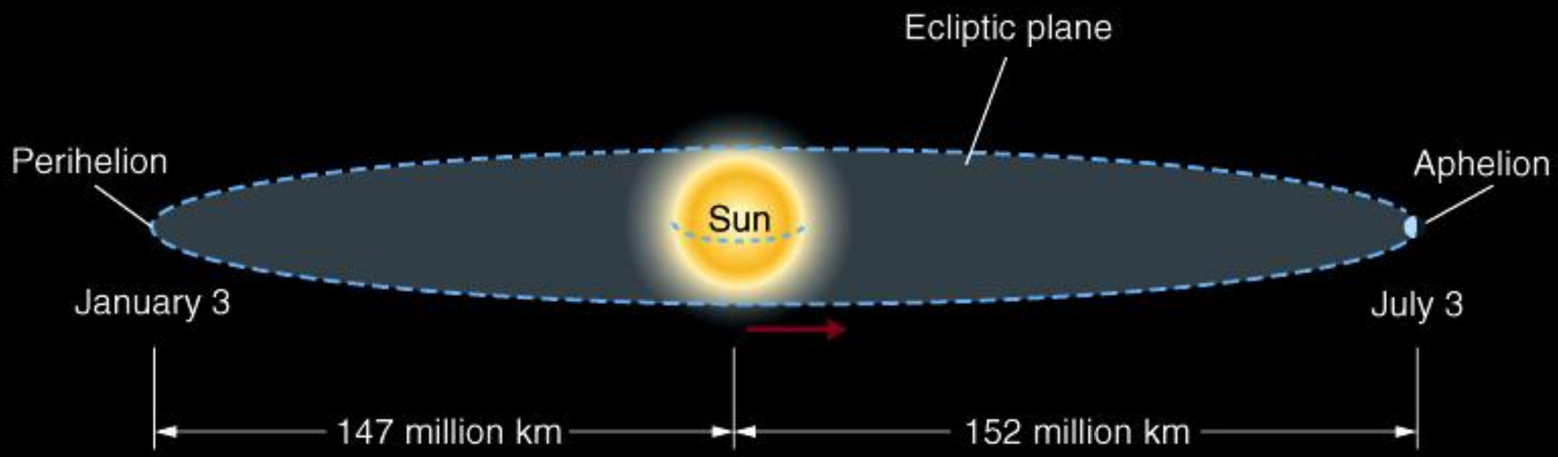
- **incorporated into equation**

$$I = \varepsilon\sigma T^4$$

I = intensity (W/m^2)
σ = Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2/K^4$)
T = temperature in K
ε = emissivity

Reasons for the Seasons

Earth's Orbit and Orientation



- complete **revolution** = 365.25 days (1 year)
- orbit is elliptical → distance from sun varies
- **perihelion:** near sun (Jan. 3), 147 million km
- **apehelion**: furthest away (July 3), 152 million km

- **NOT responsible for seasons**

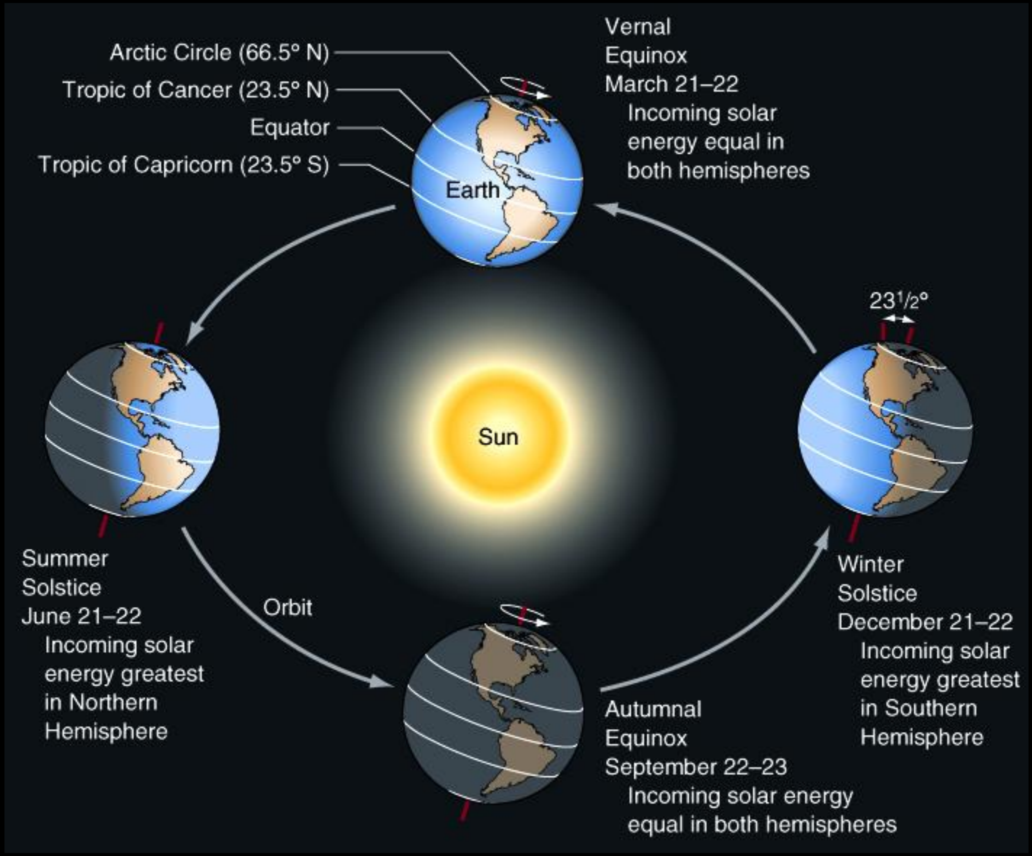
BUT

- determines the <u>length of the year</u> and <u>duration of the seasons</u>

Orientation

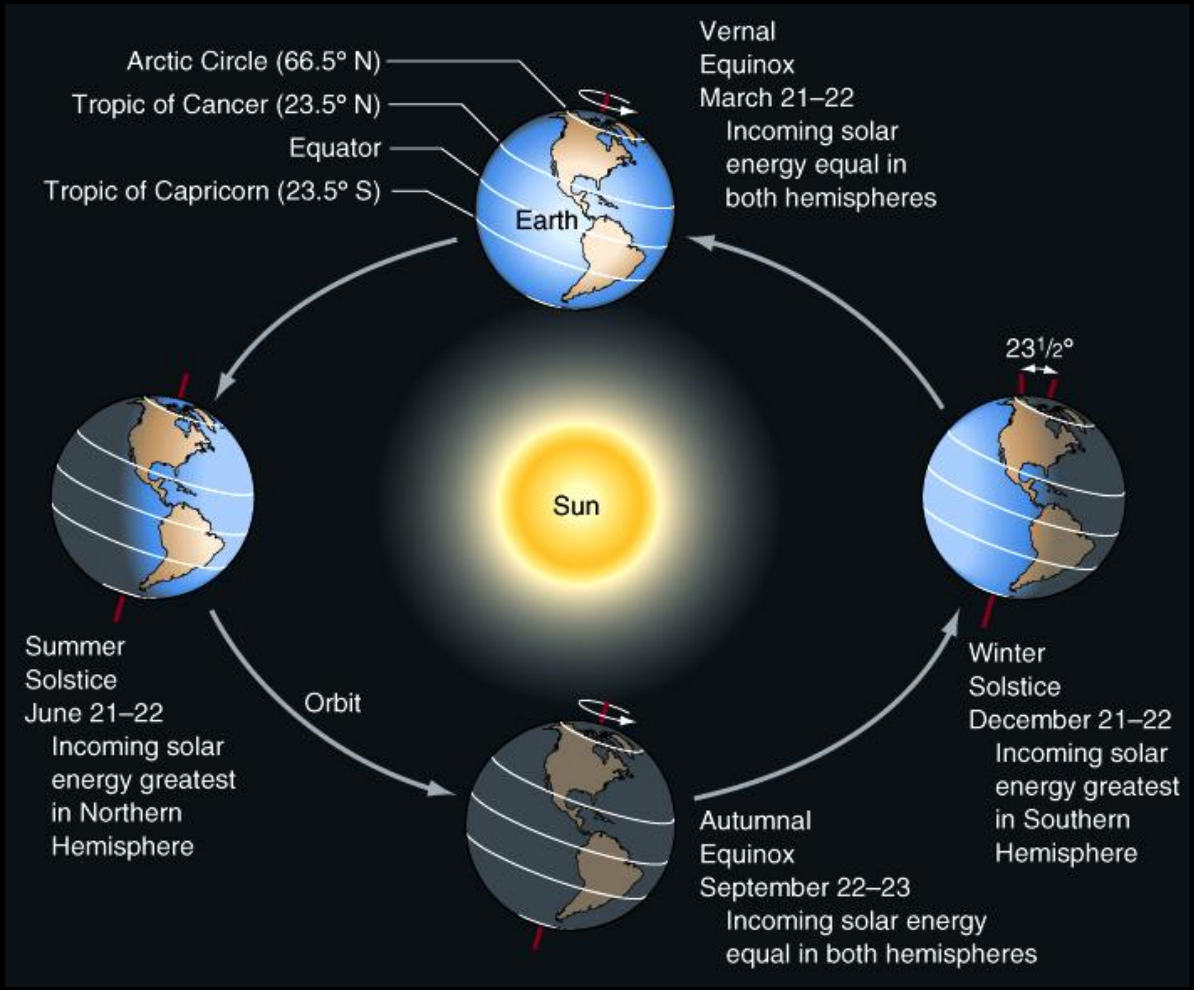
- rotation → spins on its axis
- determines day length
- axis tilted 23.5º (constant)
- pts toward *Polaris*
- N. hemisphere pts toward Sun for ½ year

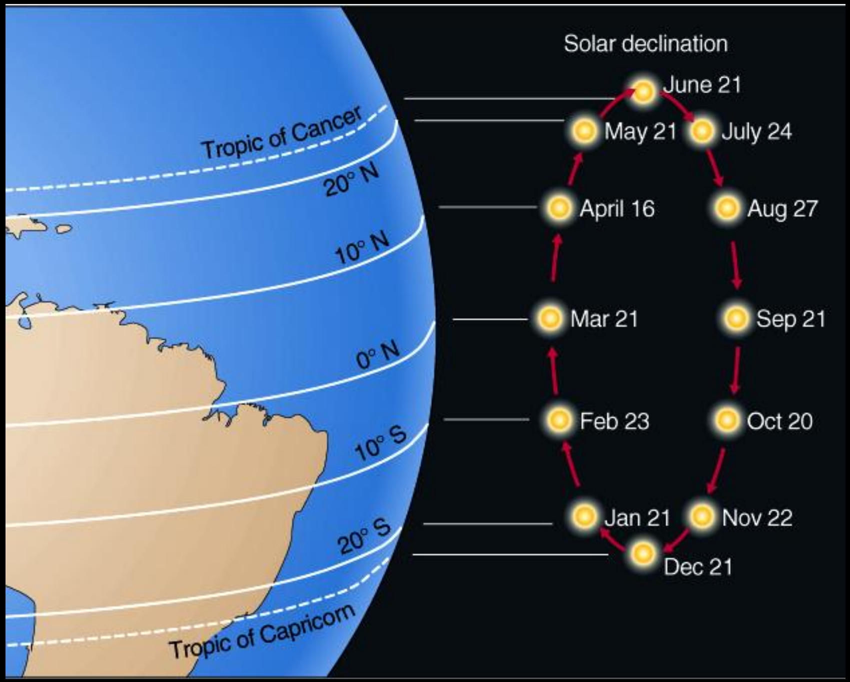
- **REASON FOR SEASONS**
- w/o tilt no seasonal change → constant Spring/Fall conditions with equal days/nights everywhere

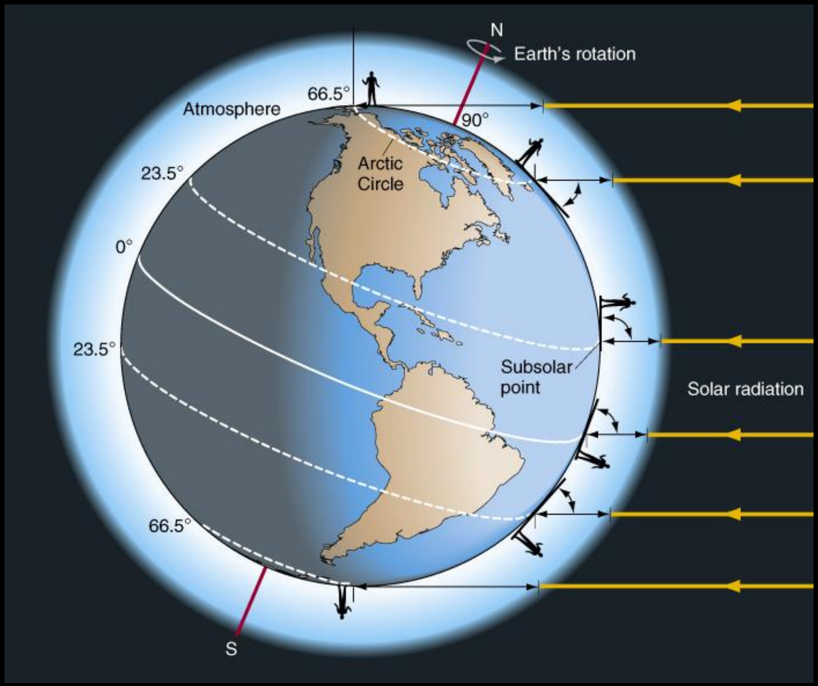


Four Cardinal Dates:

Summer Solstice (June 21st)
Fall Equinox (Sept 22nd)
Winter Solstice (Dec 21st)
Spring Equinox (March 21st)





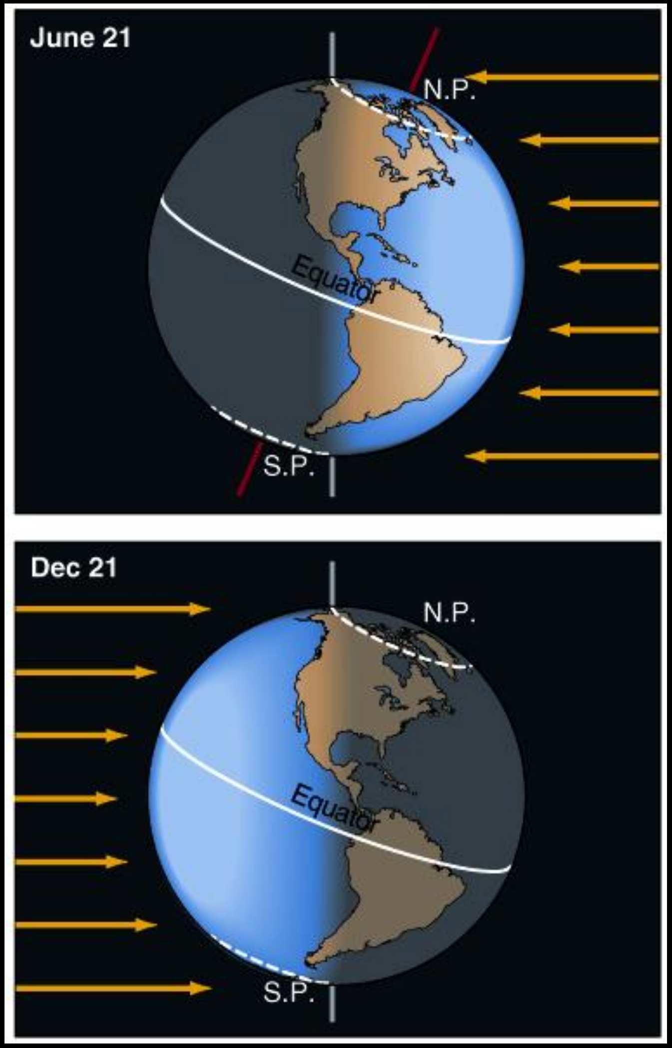


Sub-solar Point and Solar Declination

- *sub-solar point* – where Sun's rays hit Earth surface at 90°
- *solar declination* – latitude at which the SSP is found
- SSP migrates 47° every 6 months (solstice → equinox → solstice)

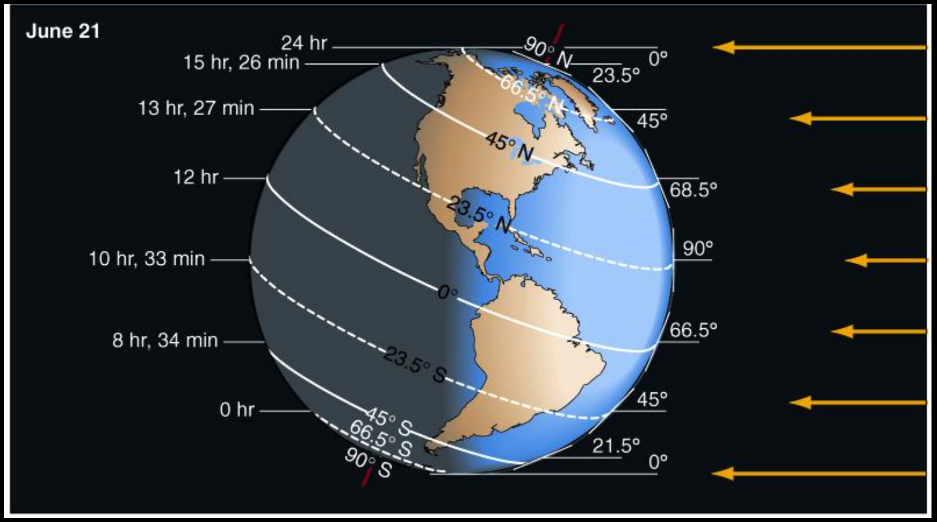
The tilt of Earth's axis affects solar rad'n receipt in 3 ways:

1) Length of daylight
2) Solar angle
3) Beam depletion

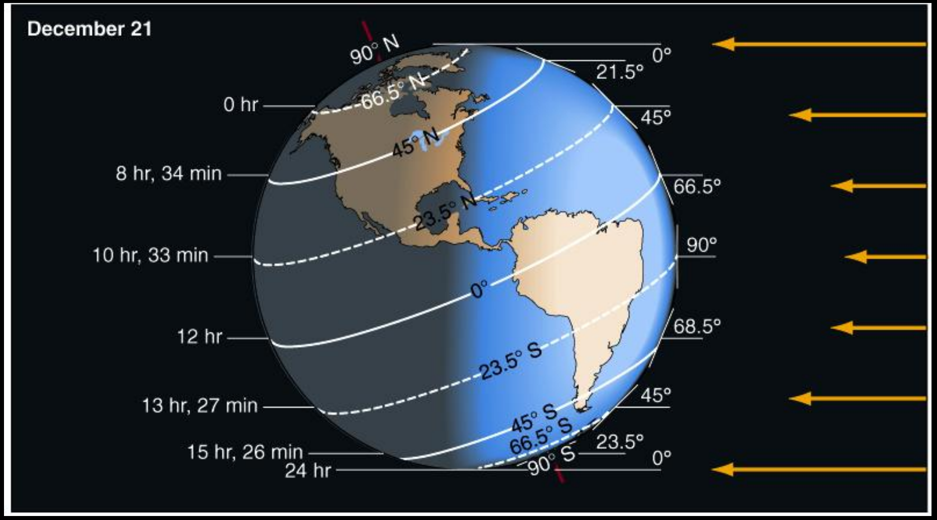


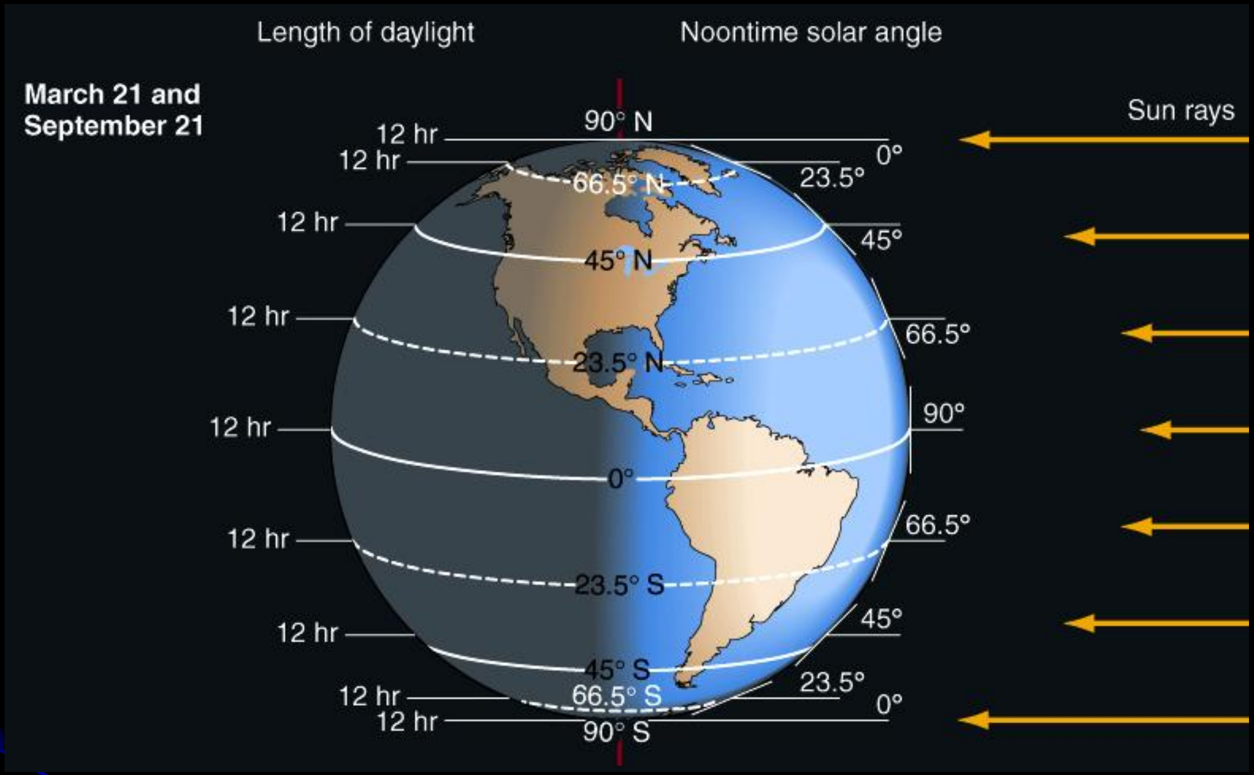
How does Day Length influence energy receipt?

June 21st
- Arctic Circle – N. pole → 24 hrs light
- Antarctic Circle – S. pole → dark
- high northern latitudes longer days
- high southern lat. shorter days



December 21st
- Arctic Circle – N. pole → dark
- Antarctic Circle – S. pole → 24 hrs light
- high northern latitudes short days
- high southern lat. long days





Length of daylight
Noontime solar angle
March 21 and
September 21
Sun rays
12 hr
12 hr
12 hr
12 hr
12 hr
12 hr
12 hr
12 hr
12 hr
90° N
66.5° N
45° N
23.5° N
0°
23.5° S
45° S
66.5° S
90° S
0°
23.5°
45°
66.5°
90°
66.5°
45°
23.5°
0°

How Does Beam Depletion Influence Energy Receipt?

- beam depletion increases with atmospheric thickness
- high sun angle less atmosphere to penetrate → limited depletion