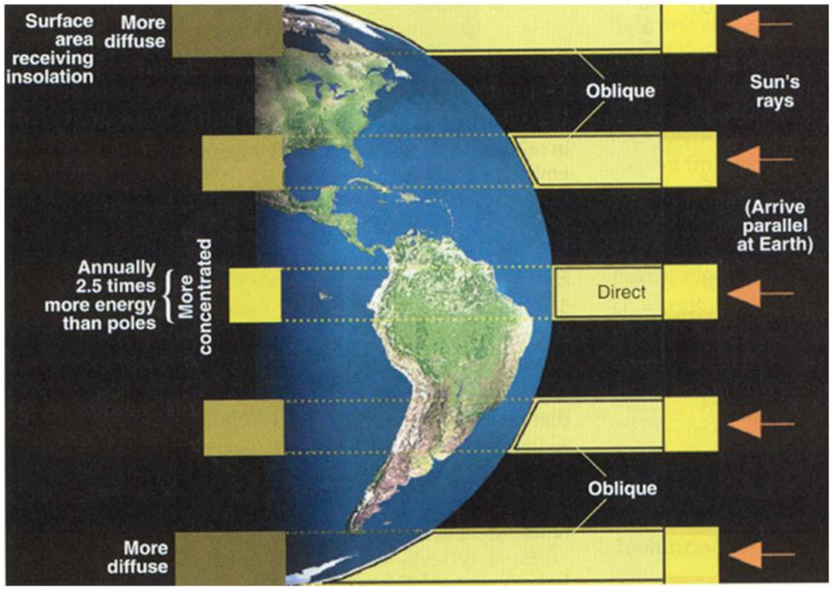
Reasons for variations in insolation with time and place on Earth

- Earth's Revolution: revolves around the sun (365.24 days for annual revolution)
- Earth's Rotation: 24 hrs; west to east; determines daylength (circle of illumination)
- Tilt of Earth's axis: 23.5° from plane of ecliptic (seasons)
- Earth's Sphericity: produces the uneven receipt of insolation from pole to pole

Insolation on a curved surface



Christopherson Fig. 2.9

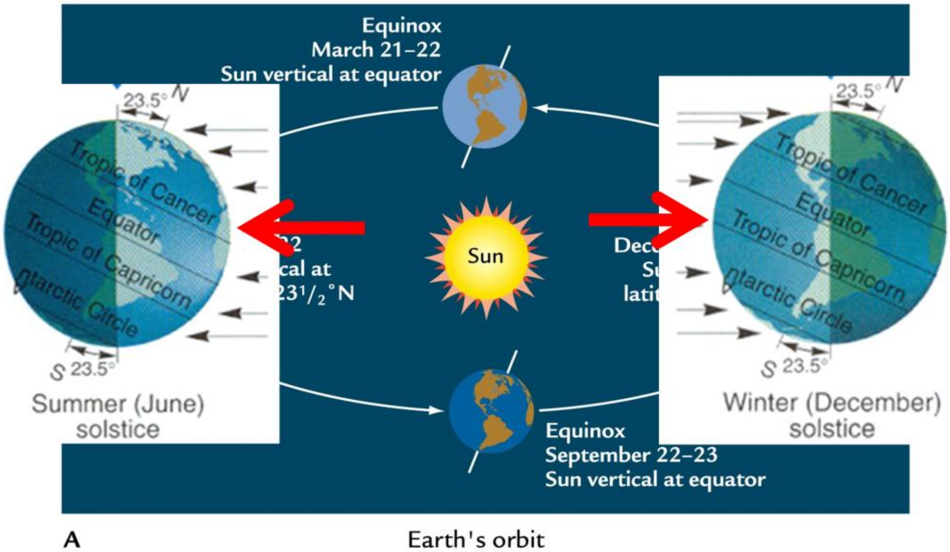
Seasonality

- Affects both:

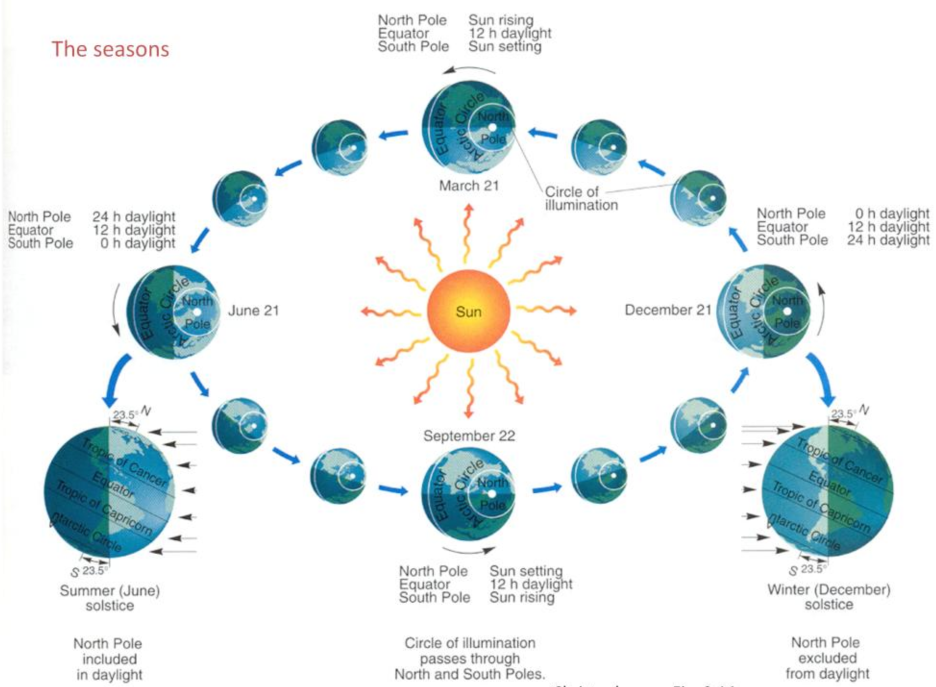
1. amount of solar radiation (angle of rays received)
2. day length

- Related to the tilt of the earth's axis
  - Equinox (Sun over Equator):
    - Vernal March 20-21
    - Autumnal September 22-23
  - Solstice (Sun over 23.5°):
    - Winter December 21-22 (23.5°S)
    - Summer June 20-21 (23.5° N)

Equinoxes and Solstices



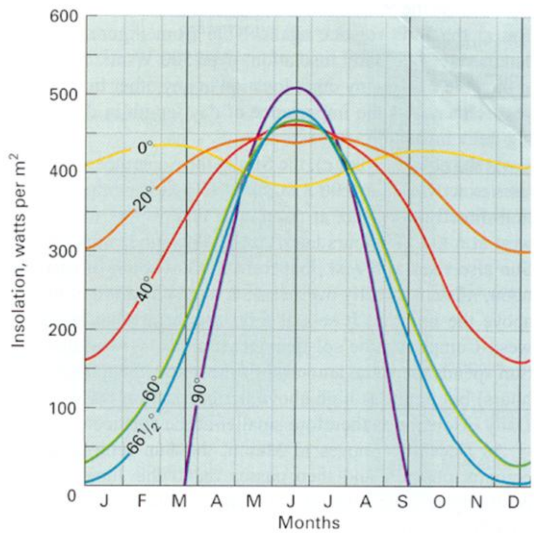
The seasons

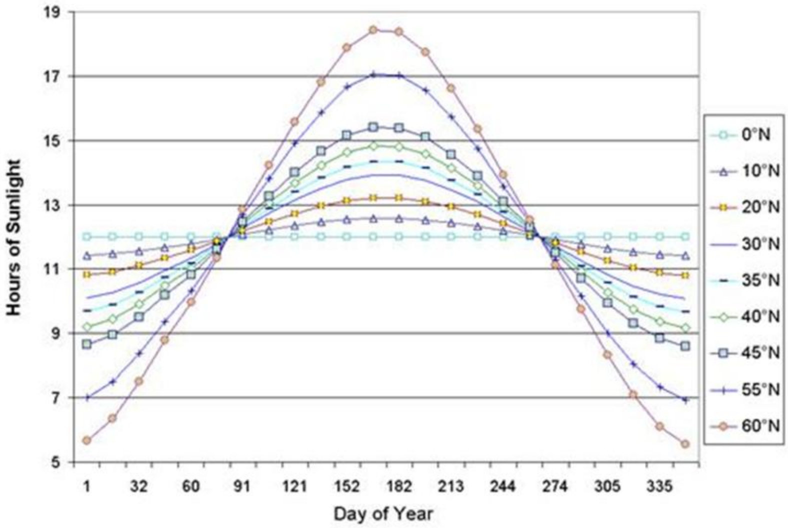


Christopherson Fig. 2.14

Insolation variations by latitude and season
at the upper atmosphere

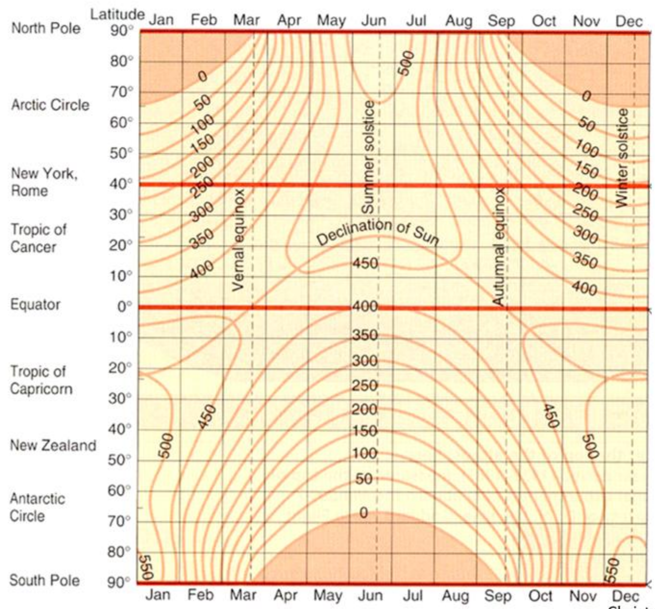
24 hour average values at given season and latitude



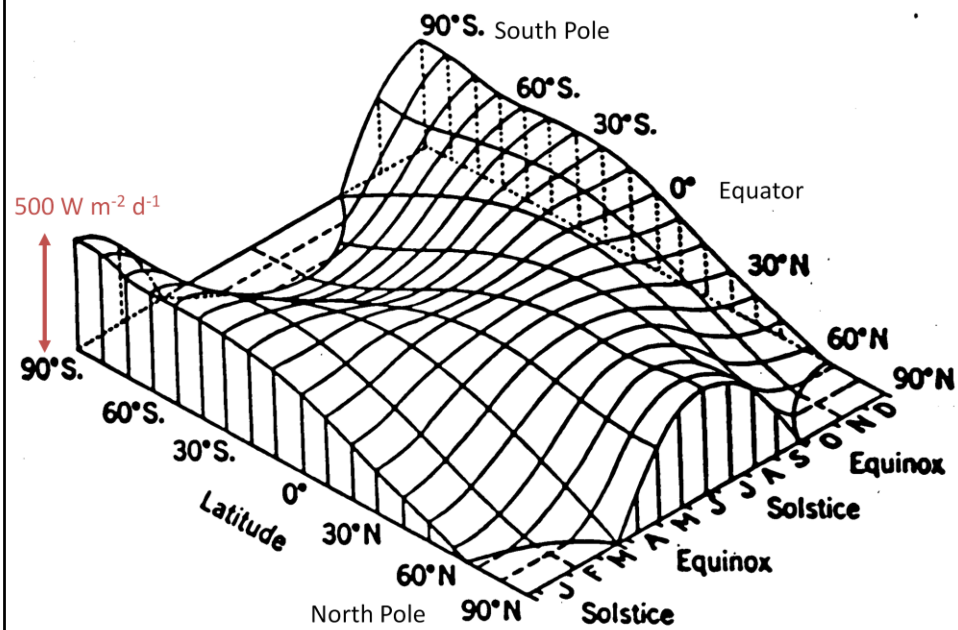


www.isws.illinois.edu/data/altcrops/giclim.asp

Radiation received in the upper atmosphere, by latitude and date



Christopherson Fig. 2.10



Solar radiation receipt at the upper atmosphere

So what are the implications of this uneven receipt of solar radiation with latitude?

...why do we care?

Seasonal observations at a temperate bog

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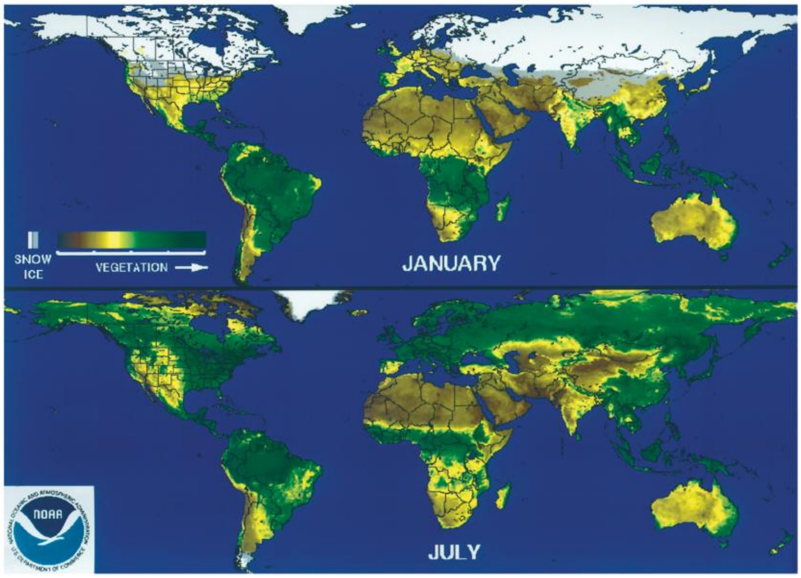
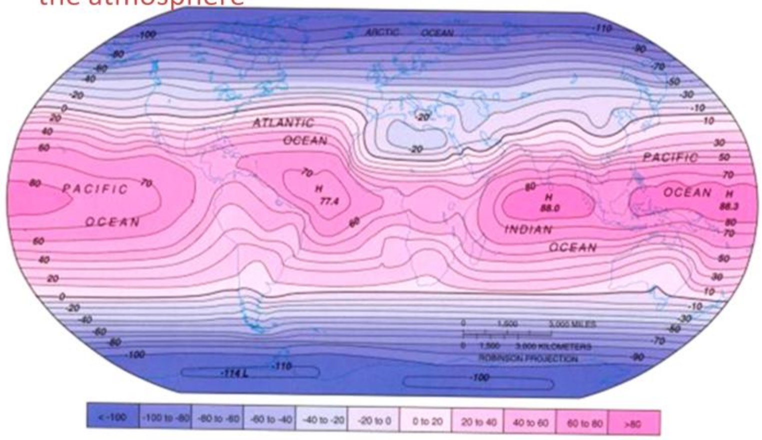


FIGURE 2.18 Seasonal change from orbit.
Seasonal change is monitored and measured by sensors aboard polar-orbiting satellites. Compare and contrast similar regions for January and July: central Canada, China, Argentina, and Europe. Orbital remote sensing is tracking an earlier spring season worldwide. [Images courtesy of Garik Gutman, NOAA, National Environmental Satellite, Data, and Information Service.]

Net radiation imbalance with latitude

Daily net radiation (W/m^2) patterns at the top of the atmosphere



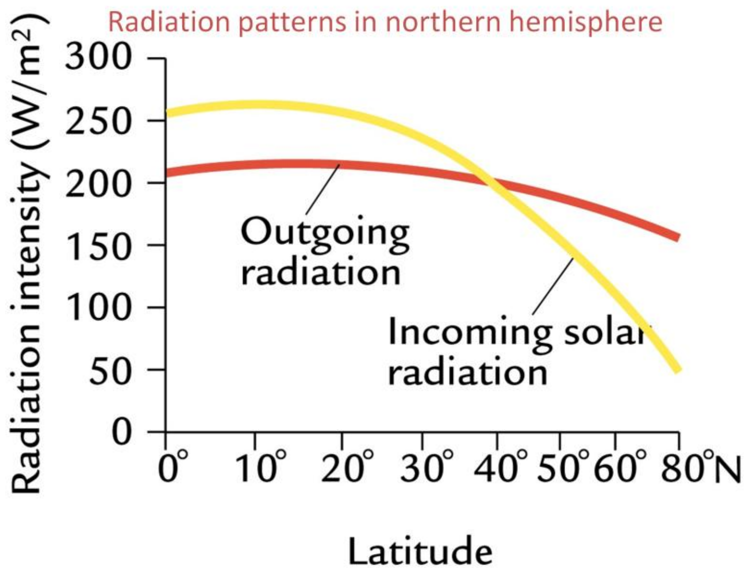
Net radiation = all incoming – all outgoing radiation

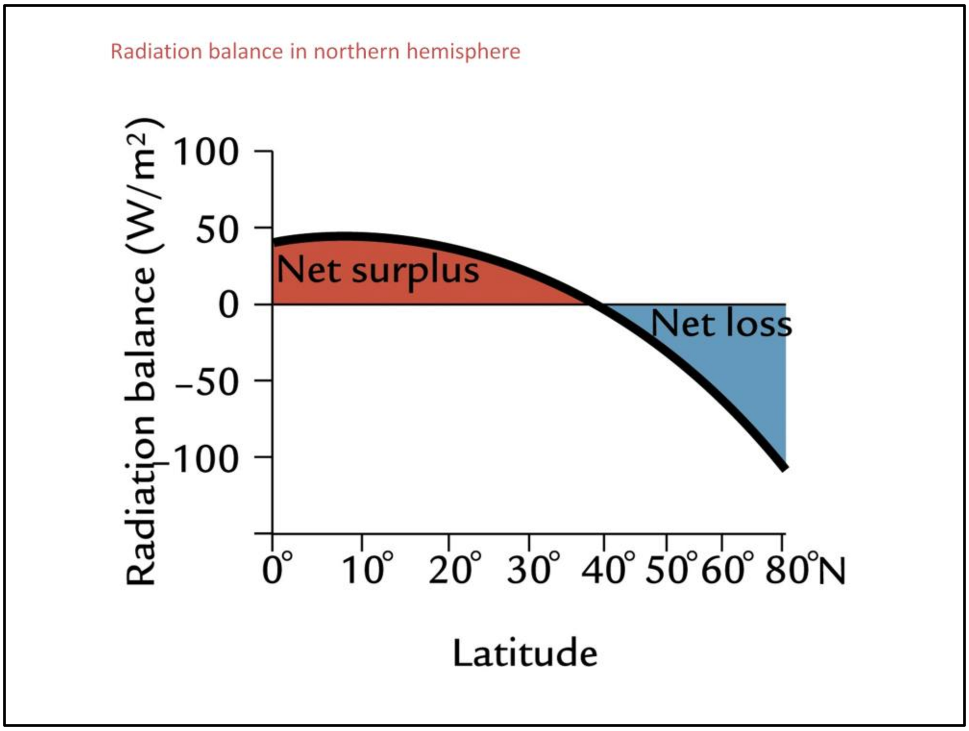
Positive at Tropics

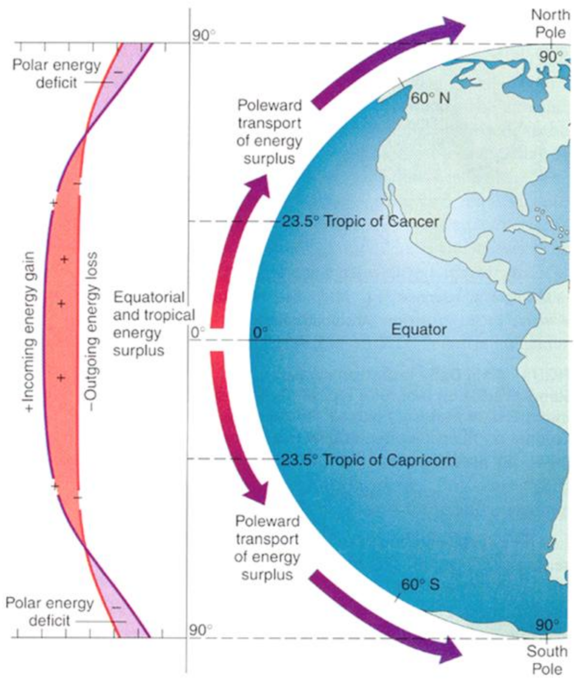
Negative at Poles

Christopherson Fig. 2.11

Net radiation imbalance driven by differences in incoming solar radiation



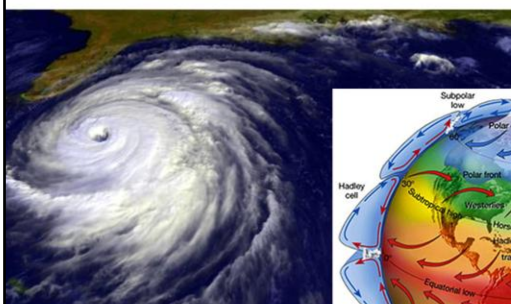

Radiation balance in northern hemisphere
Radiation balance (W/m²)
100
50
0
−50
−100
Net surplus
Net loss
0° 10° 20° 30° 40° 50° 60° 80°N
Latitude

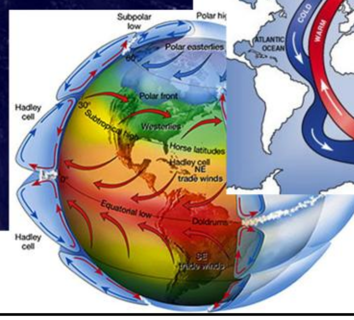


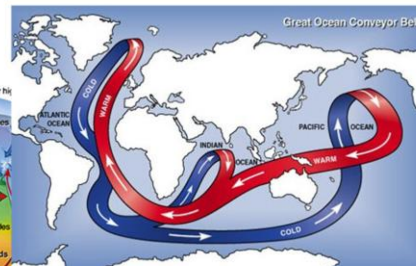
Energy transfer by latitude, through atmospheric and oceanic circulation

Chrisopherson Fig. 4.14)

This net energy imbalance between tropics and poles drives global circulation patterns





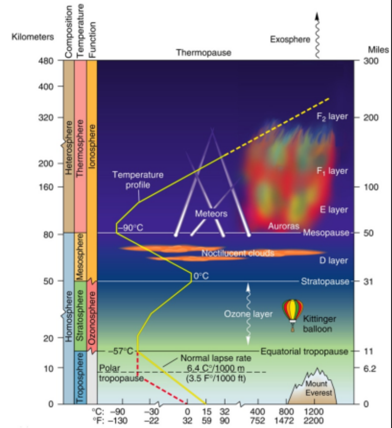



The Atmosphere:
Earth's security blanket!
Earth's Modern Atmosphere
•Composition
•Temperature
•Function
Readings: Chapter 3 (pp. 63 – 75)

Atmospheric Profile

- Atmosphere extends ~480 km from the surface

- Beyond that the atmosphere is rarified (nearly a vacuum) – known as the ***exosphere*** extending outwards as far as 32,000 km
    - contains scarce helium and hydrogen atoms weakly bound by gravity



Atmospheric Profile

- The atmosphere can be divided into shells (layers) by
  - Composition
  - Temperature
  - Function
- Different layers called spheres
  - E.g. troposphere
- Top boundary of each layer called –pause
  - E.e. tropopause

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Profile of the Atmosphere

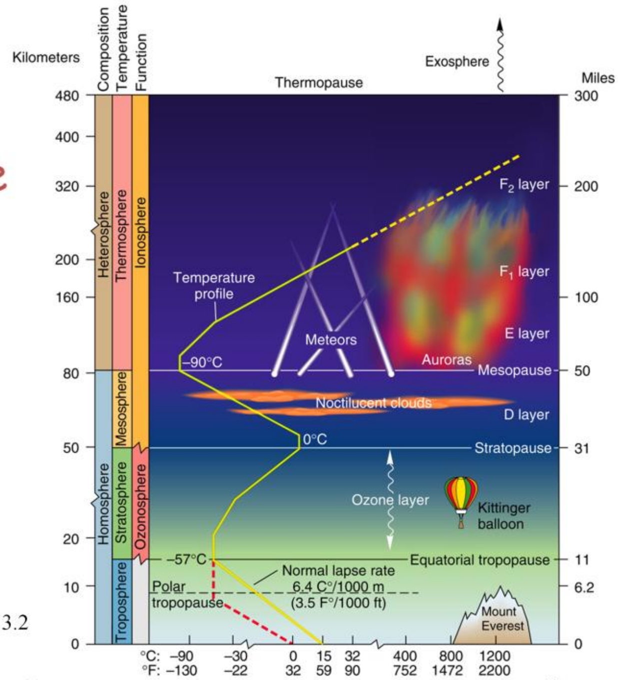

Figure 3.2

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Atmospheric Pressure

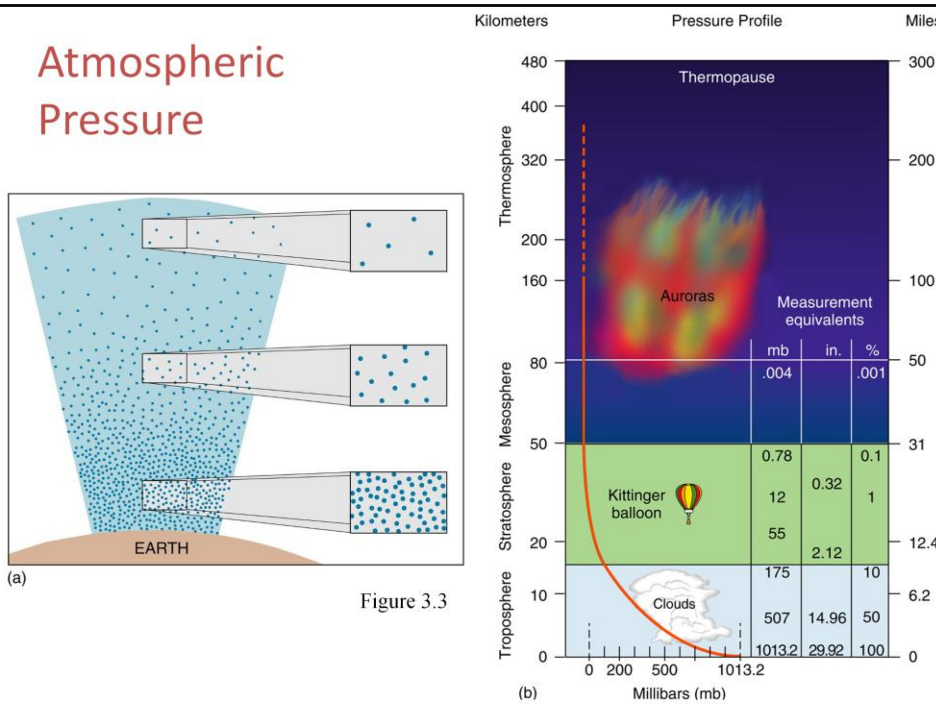


Figure 3.3

Experiencing the stratosphere

1960: 31 km

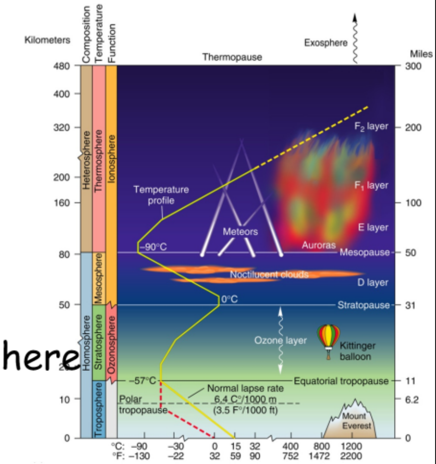
FIGURE 1 Stratospheric leap into history.
Moments into Captain Joseph Kittinger's historic exploration of the atmosphere, captured by a remotely triggered camera. The lanyard cord is attached to his parachute pack and snaps to set a timer that opens a small stabilization chute 16 seconds into the free fall. The clouds are more than 26,000 m (85,000 ft) below him. He carries an instrument pack on his seat, his main chute, and pure oxygen for his breathing mask. [Volkmar Wentzel/NGS Image Collection, used by permission from the National Geographic Society, *National Geographic Magazine*, Dec. 1960, p. 855. All rights reserved.]

2012: 39 km

Felix Baumgartner jumps out of his capsule from more than 24 miles above the earth on Oct. 15, 2012. Baumgartner shattered the sound barrier Sunday while making the highest jump ever — a tumbling, death-defying plunge from a balloon to a safe landing in the New Mexico desert. Here's a look at how Baumgartner prepared for his feat. (Red Bull Stratos/AP)

Atmospheric Composition

- **Heterosphere** – outer atmosphere
  - gases are not mixed
  - H & He in outer layer
  - O & N in lower layers
  - > 80 km
- **Homosphere** – inner atmosphere
  - gases blended (mostly)
  - 0 – 80 km
  - ~99.999% of the atmosphere



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Composition of the Earth's Atmosphere

Constituent	Formula	Content	Role
Nitrogen	N_2	78.1 %	Inert
Oxygen	O_2	21.0 %	Absorbs U-V radiation
Argon	Ar	0.9 %	Inert
Carbon dioxide	CO_2	370 ppm	Absorbs IR radiation
Neon	Ne	18 ppm	Inert
Helium	He	5 ppm	Inert
Methane	CH_4	1.8 ppm	Absorbs IR radiation
Nitrous oxide	N_2O	0.3 ppm	Absorbs IR
Carbon monoxide	CO	0.01 ppm	Reactive gas
Ozone	O_3	0.01 ppm	Reactive gas, absorbs U-V and IR radiation
CFCs	Various	< 0.001 ppm	Absorbs IR, destroys O_3
Water vapour	H_2O	0.01 - 4 %	Absorbs IR radiation

"Greenhouse" gases

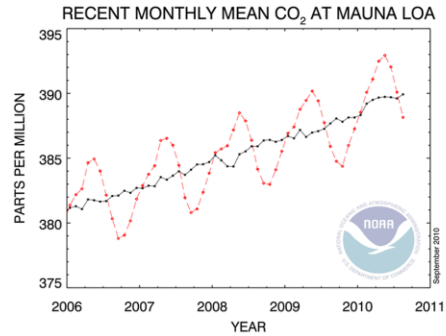
Variability in CO_2 concentration
1) over the past few years…

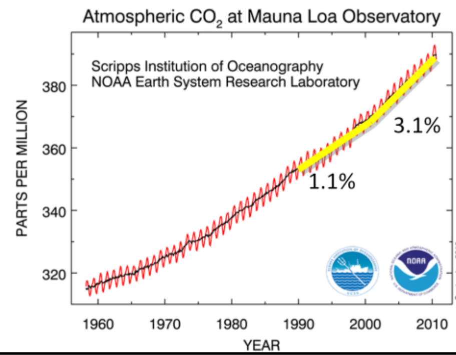
What causes the pattern?

2) over the past 50 years

Scenario → 1390 ppm by 2100

http://www.esrl.noaa.gov/gmd/ccgg/trends/

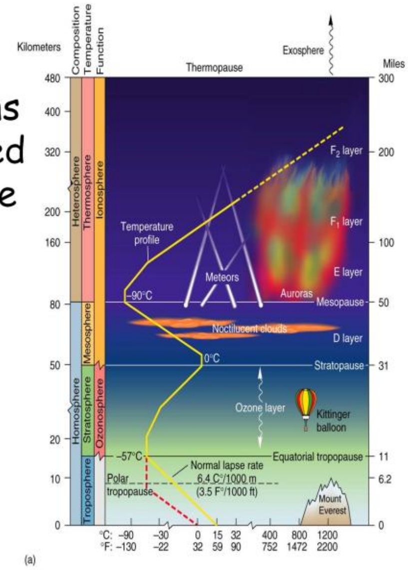




Atmospheric Profile - Temperature

- Earth's atmosphere contains four different layers defined according to air temperature

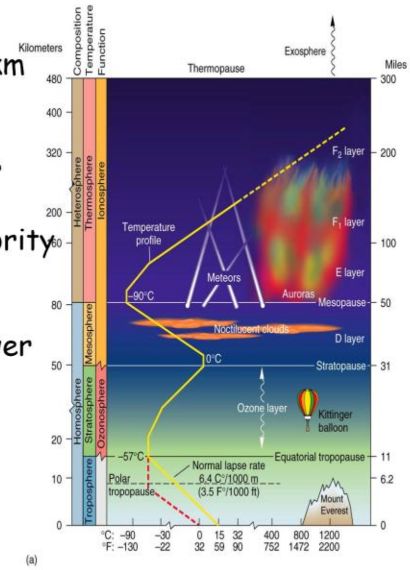
- Troposphere
- Stratosphere
- Mesosphere
- Thermosphere



Atmospheric Profile - Temperature

Troposphere

- extends from the surface to ~ 18 km
- ~ 90 % of the total mass of the atmosphere is contained in this layer
- Unstable: the layer where the majority of our weather occurs
- maximum air temperature in the lower atmosphere occurs in this layer
- with increasing height, air temperature dec. at a rate of ~6.4 °C/1000 m (<u>normal lapse rate</u>)



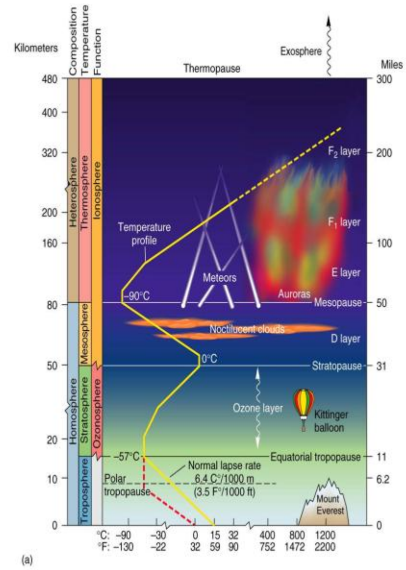
Atmospheric Profile - Temperature

Tropopause

•extending from 8 to 18 km

•an <u>isothermal layer</u>
- temperature remains constant

•the layer where the jet stream occurs

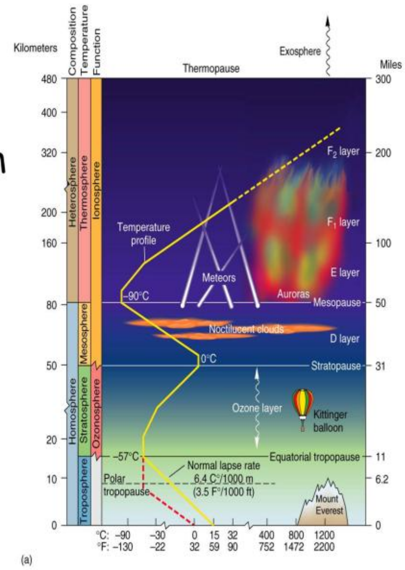


Atmospheric Profile - Temperature

Stratosphere

•extends from 18 to 50 km

•temperature inc. with altitude
- why?
- ozone layer



Ozone layer

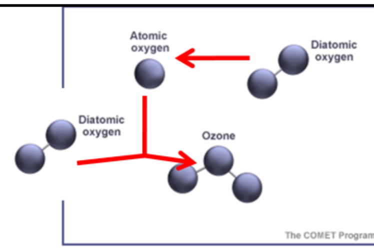
Ozone – molecule made up of three oxygen atoms joined together (O_3)

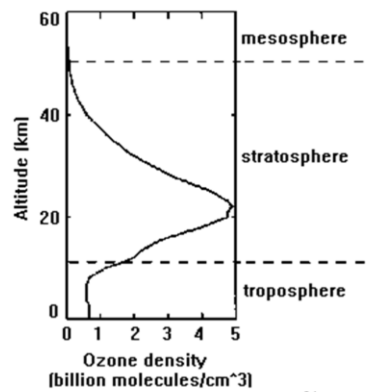
•concentrated in a layer of the stratosphere called the ozone layer, lies between 15-48 km above the Earth's surface

Why is ozone important?

How is ozone formed and destroyed?

What is the Montreal Protocol?





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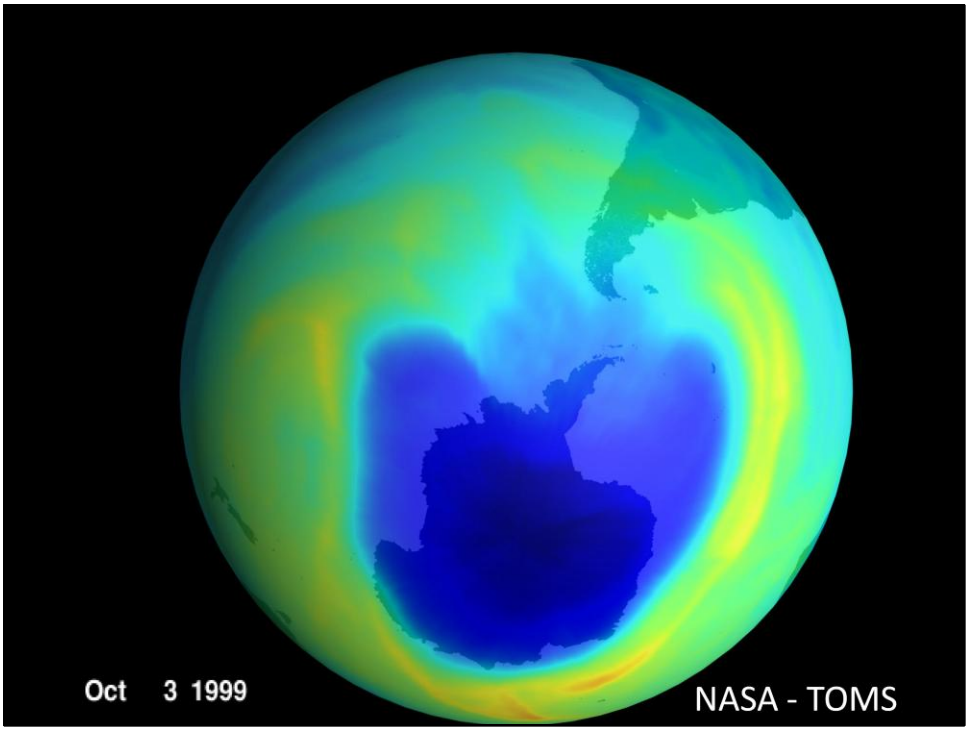
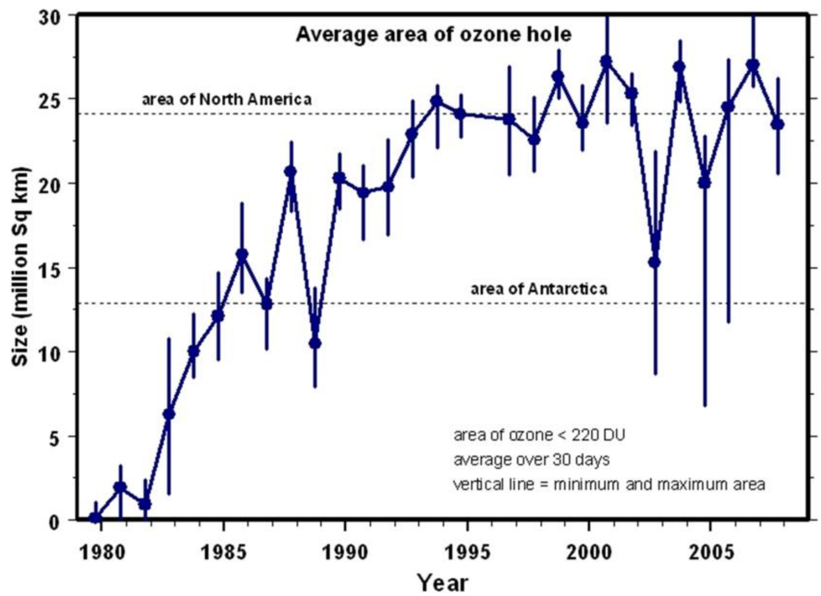
Hair spray + 80s =
Mega rock star + environmental degradation
32


Oct 3 1999
NASA - TOMS



http://jwocky.gsfc.nasa.gov/eptoms/dataqual/ozone.html

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NOAA HOME WEATHER OCEANS FISHERIES CHARTING SATELLITES CLIMATE RESEARCH COASTS CAREERS

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» NOAA's South Pole Ozone
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Media Contact
» Katy Human (NOAA) 303-497-4747
» Steve Cole (NASA) 202-358-0918

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NOAA, NASA: Antarctic ozone hole second smallest in 20 years

October 24, 2012

Warmer air temperatures high above the Antarctic led to the second smallest seasonal ozone hole in 20 years, according to NOAA and NASA satellite measurements. This year, the average size of the ozone hole was 6.9 million square miles (17.9 million square kilometers). The ozone layer helps shield life on Earth from potentially harmful ultraviolet (UV) radiation that can cause skin cancer and damage plants.

Staff at the South Pole get ready to release a balloon that will carry an ozone instrument up to 20 miles in the atmosphere, measuring ozone levels all along the way. NOAA image from 2011.

Download here. (Credit: NOAA.)

The Antarctic ozone hole forms in September and October, and this year, the hole reached its maximum size for the season on Sept. 22, stretching to 8.2 million square miles (21.2 million square kilometers), roughly the area of the United States, Canada and Mexico combined. In comparison, the largest ozone hole recorded to date was in 2000 at 11.5 million square miles (29.9 million square kilometers).

The Antarctic ozone hole began making a yearly appearance in the early 1980s, caused by chlorine released by manmade chemicals called chlorofluorocarbons or CFCs. The chlorine can rapidly break apart ozone molecules in certain conditions, and the temperature of the lower stratosphere plays an important role.

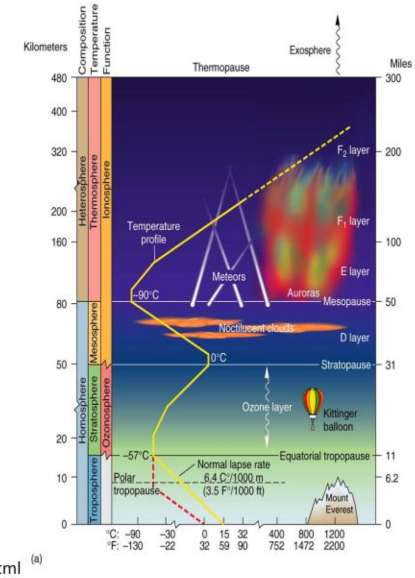
"It happened to be a bit warmer this year high in the atmosphere above Antarctica, and that meant we didn't see quite as much ozone depletion as we saw last year, when it was colder," said Jim Butler with NOAA's Earth System Research Laboratory in Boulder, Colo.

Even 25 years after an international agreement was signed to regulate production of ozone-depleting chemicals, the ozone hole still forms each year. In fact, it could be another decade before scientists can detect early signs of Antarctic ozone layer recovery, according to a paper by NOAA researchers and colleagues published last year. The ozone layer above Antarctica likely will not return to its early 1980s state

Atmospheric Profile - Temperature

Mesophere

•50 – 80 km
•atmosphere reaches its coldest temperatures (~-90°C) at a height of ~80 km

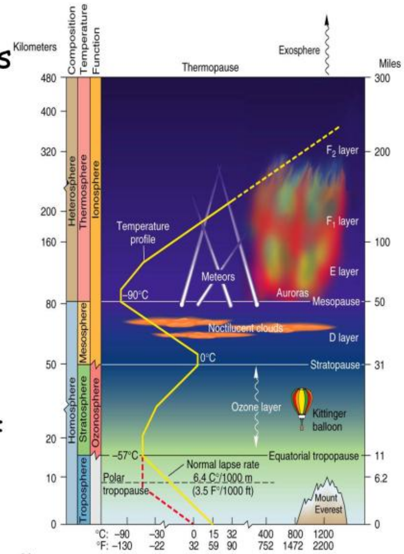


http://science.nasa.gov/spaceweather/nlcs/gallery2004_page1.html

Atmospheric Profile - Temperature

Thermosphere

- last atmospheric layer - altitudes greater than 80 km
- intense solar radiation excites individual molecules to high levels of vibration – vibration is the energy of motion (kinetic energy) measured as **temperature** which rises to 1200 °C
- however, few molecules – v. low transfer of **sensible heat** (flow of kinetic energy from one molecule to another)



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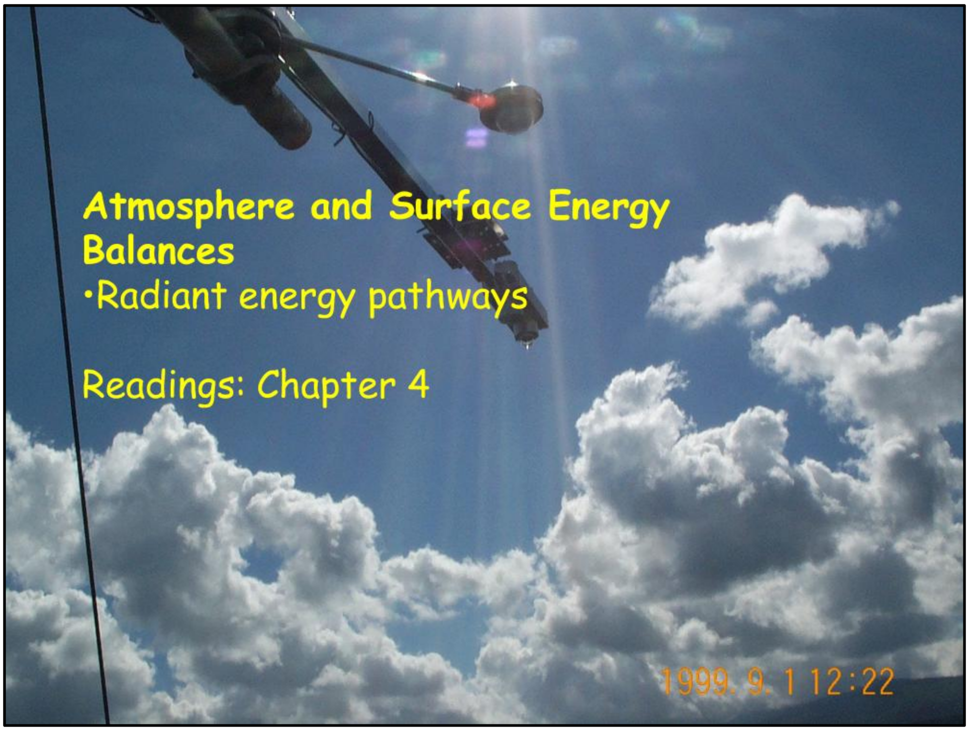
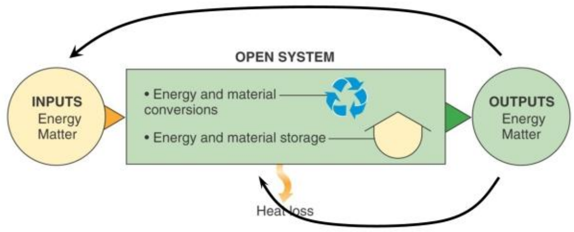

Atmosphere and Surface Energy Balances
•Radiant energy pathways
Readings: Chapter 4
1999. 9. 1 12:22



Solar energy passes through the troposphere to the Earth's surface

-**Input**: insolation

-**Output**: reflected shortwave radiation and emitted longwave radiation

-The difference is **net radiation**, the energy used to drive many of Earth's abiotic and biotic systems

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At the surface …

$$K\downarrow - K\uparrow + L\downarrow - L\uparrow = R_n = H + LE + G + \Delta S$$

Radiation balance

energy balance

$K\downarrow (SW\downarrow)$

$K\uparrow (SW\uparrow)$

$L\downarrow (LW\downarrow)$

$L\uparrow (LW\uparrow)$

$R_n (NET\ R)$

K = shortwave radiation
L = Longwave radiation
Rn = net radiation

H= Sensible heat
LE= latent heat (evaporation)
G= ground heating and cooling

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$K\downarrow$ at the surface (insolation) is much less than the solar constant…

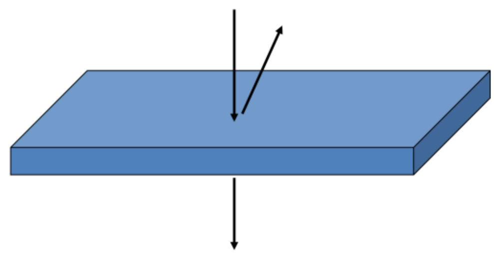
Solar radiation has many fates/pathways as it travels to the surface:

- Transmission
- Reflection
- Absorption
- Scattering
- Refraction

- Transmission, Absorption, Reflection of Solar Radiation
  - -Transmission: passage through the atmosphere, etc
  - -Absorption: assimilation by molecules & its conversion from one form of energy to another
  - -Reflection: energy that bounces back into space without being absorbed or changed in any way

Energy that is not transmitted (T) is either reflected (R) or absorbed (A)

100% = A + R + T



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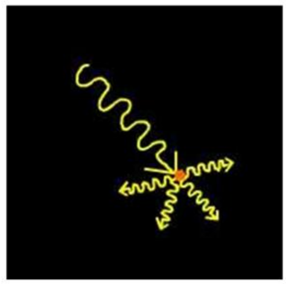
- Scattering
  - Changing direction of light's movement, without altering its wavelengths
  - Produces diffuse radiation (vs. direct)



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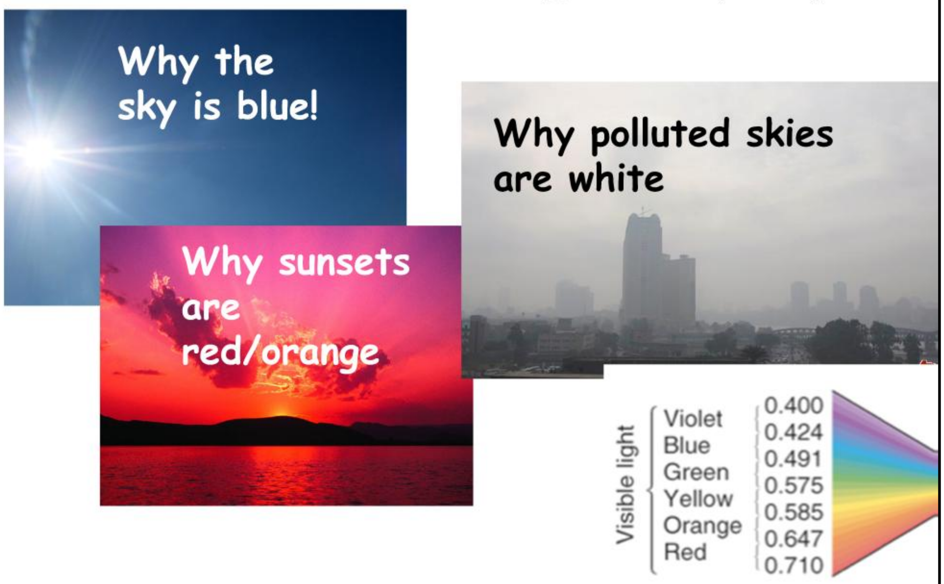
You see scattering everyday!



- Refraction
  - -Change in speed and direction of light

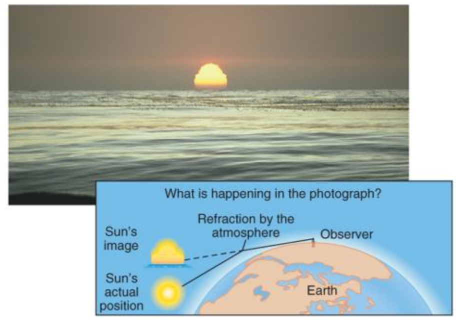
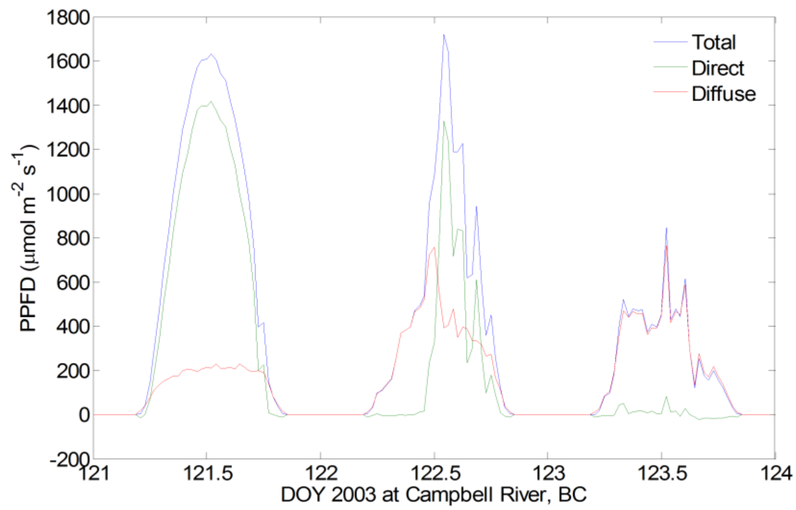


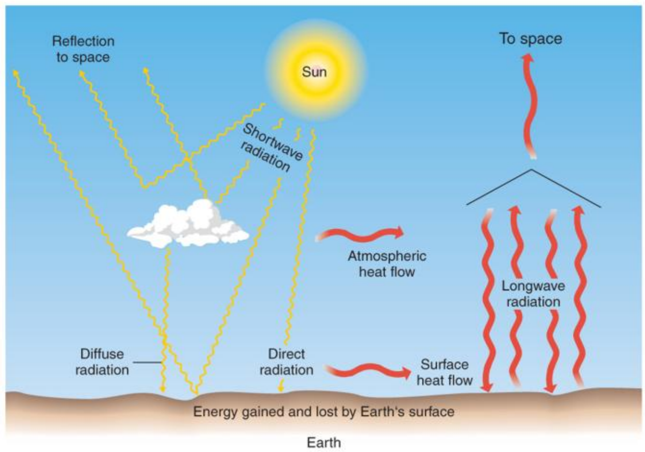
FIGURE 4.3 Sun refraction.
The distorted appearance of the Sun nearing sunset over the ocean is produced by refraction of the Sun's image in the atmosphere. Have you ever noticed this effect? [Photo by Robert W. Christopherson.]

Can you tell what type of weather occurred during these three days art Campbell River, BC?



Radiant energy pathways & principles

Shortwave energy Longwave energy



- **Insolation input ($K\downarrow$):** All radiation received at Earth's surface – direct and indirect

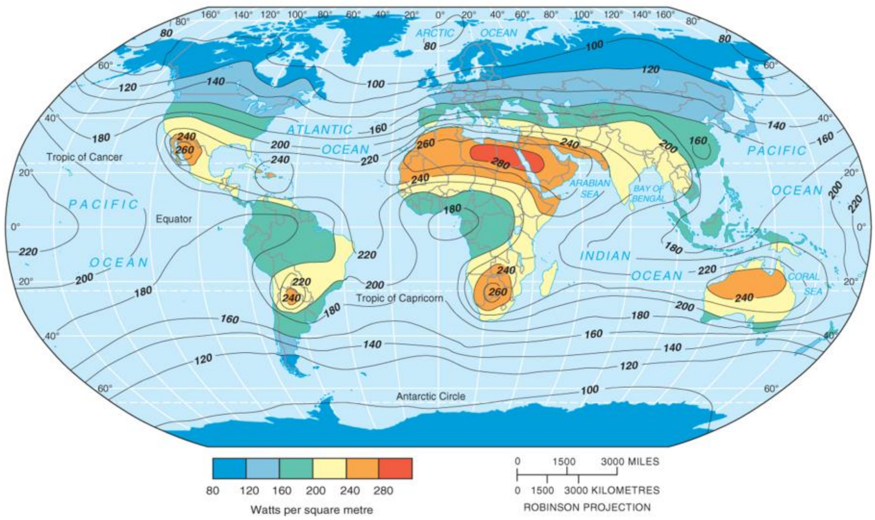
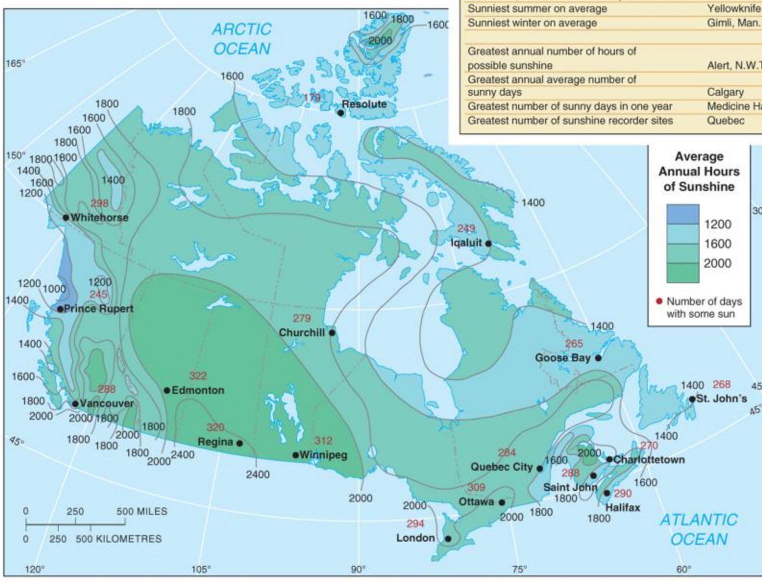


FIGURE 4.4 Insolation at Earth's surface.
Average annual solar radiation received on a horizontal surface at ground level in watts per square metre (100 W/m^2 = 75 kcal/cm^2/year). [After M. I. Budyko, *The Heat Balance of the*

Sunshine Hours in Canada

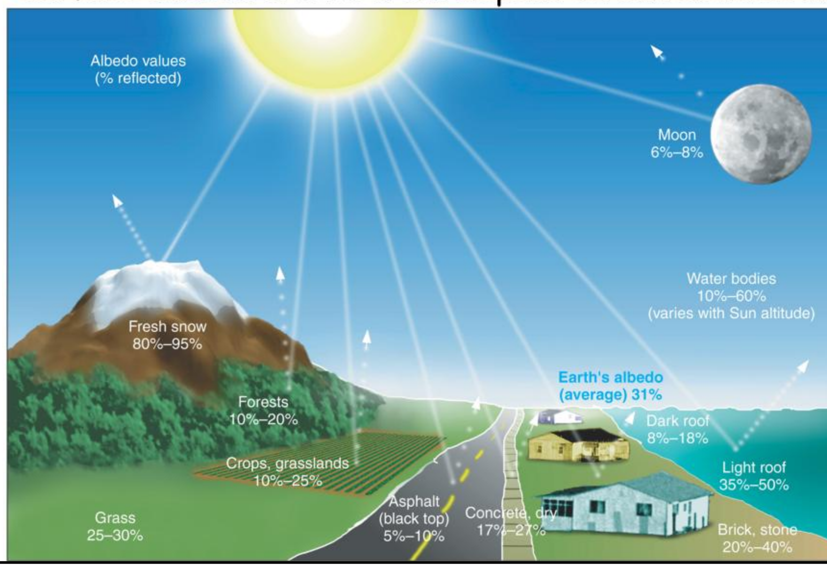
Sunniest Places in Canada

Sunniest month	Eureka, N.W.T.	621 hours	May 1973
Greatest average annual number of sunny hours	Estevan, Sask.	2537	
Major city with greatest annual average number of sunny hours	Saskatoon	2450	
Sunniest small town under 10,000 population	Coronation, Alta.	2490	
Sunniest provincial capital	Regina	2331	
Sunniest year on record	Manyberries, Alta.	2785	1976
Shortest spell of consecutive days without sun	Charlottetown	10 days	
Sunniest summer on average	Yellowknife	1065 hours	June, July, Augus
Sunniest winter on average	Gimli, Man.	376 hours	December, Janua February
Greatest annual number of hours of possible sunshine	Alert, N.W.T.	4580	
Greatest annual average number of sunny days	Calgary	329	
Greatest number of sunny days in one year	Medicine Hat	346	1976
Greatest number of sunshine recorder sites	Quebec	84	



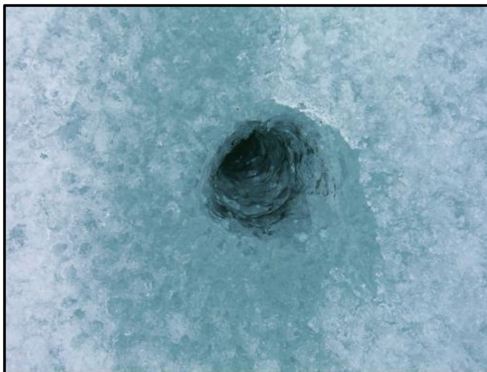
Albedo: reflected shortwave radiation/incoming shortwave radiation

- surface characteristic & can depend on sun altitude angle



Albedo

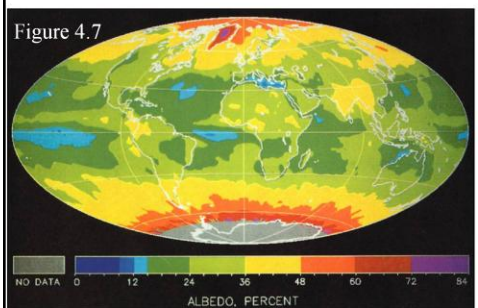
Cloudberry leaf and ptarmigan droppings on Daring Lake ice, NWT, May 2006

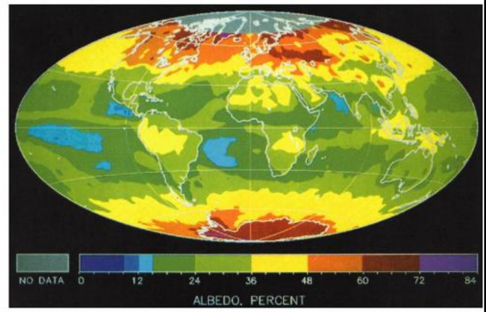


Water has a lower albedo than ice

Seasonal and Spatial Variations in Albedo

Which image is likely taken in January?

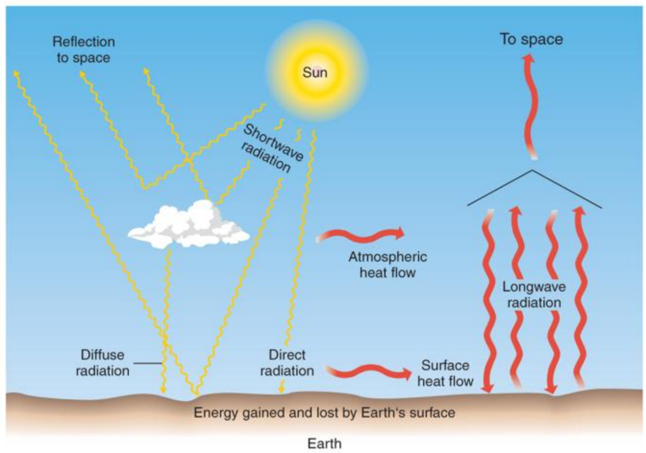




Radiant energy pathways & principles

$$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

Shortwave energy Longwave energy



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Longwave radiation

How much longwave radiation do objects emit?

- All objects above absolute zero emit radiation

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

T is temperature in Kelvin

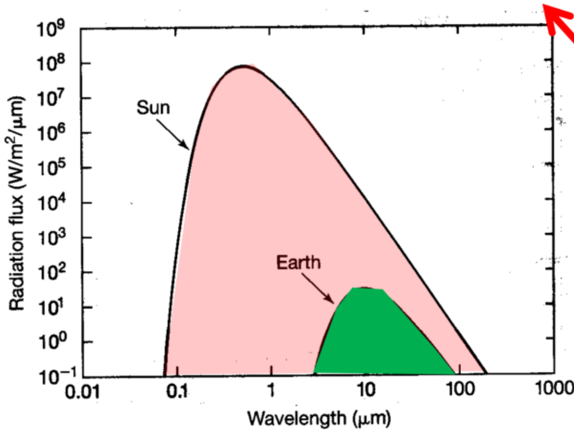
σ is the Stefan-Boltzmann constant
= 5.67×10^{-8} W m^{-2} K^{-4}

ε is the **emissivity** of the object

Radiation: the basics

Hotter objects emit more total radiation- curve for black body

Total radiation emitted = $\varepsilon \, \sigma \, T^4$



Deviation from black body

Emissivity describes how readily the object emits L
(ε = 1, object is a perfect blackbody and emits the full amount of L possible based on temp)

Surface	Emissivity
plant leaves	0.94-0.99
soil	0.93-0.96
water	0.96
animals	0.98-0.99
clear sky	0.5 - 0.75
overcast sky	~0.95

Sky emissivity depends on:
- water vapour content
- cloud cover
- air temperature

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Quinn is a pretty good black body, ε ~ 0.99

...so is Abby, ε ~ 0.99

ε does not depend on colour, skin, or fur!

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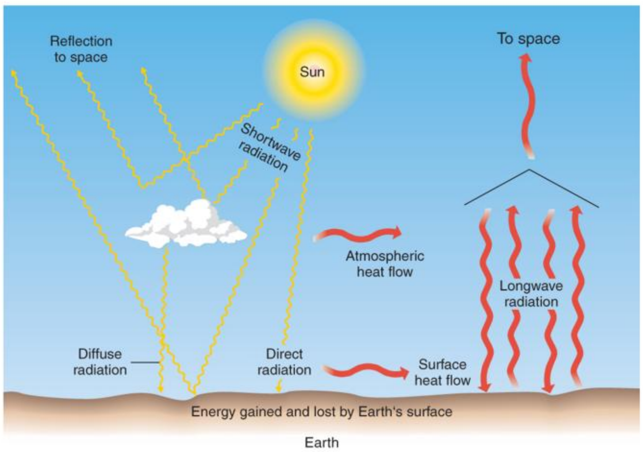
Radiant energy pathways & principles

$$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

Shortwave energy   Longwave energy



$L\downarrow$

- atmospheric gases & dust, clouds emit L in all directions (including down!)

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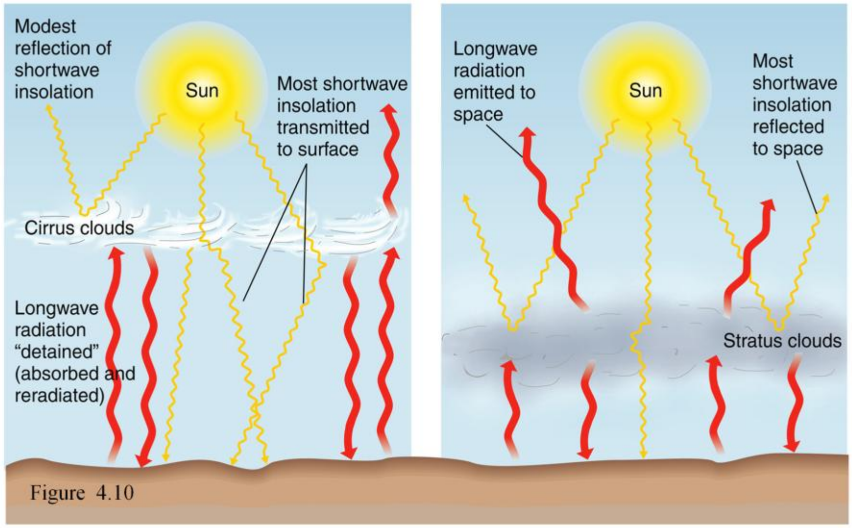


(a) High clouds: net greenhouse forcing and atmospheric warming

(b) Low clouds: net albedo forcing and atmospheric cooling

Fig 4.11

The effects of jet contrails

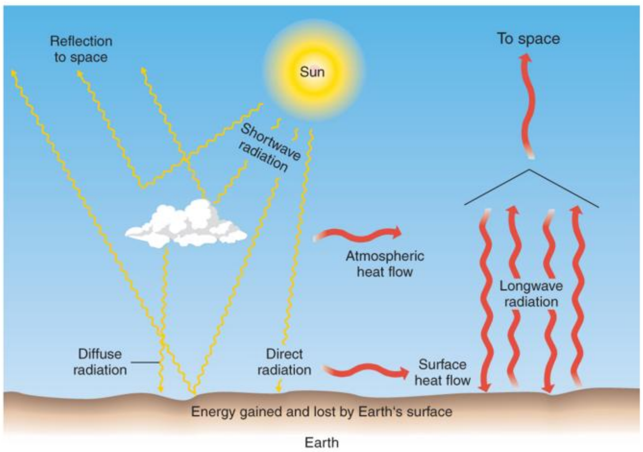
(c)

Fig 4.10c

Radiant energy pathways & principles

$$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

Shortwave energy   Longwave energy

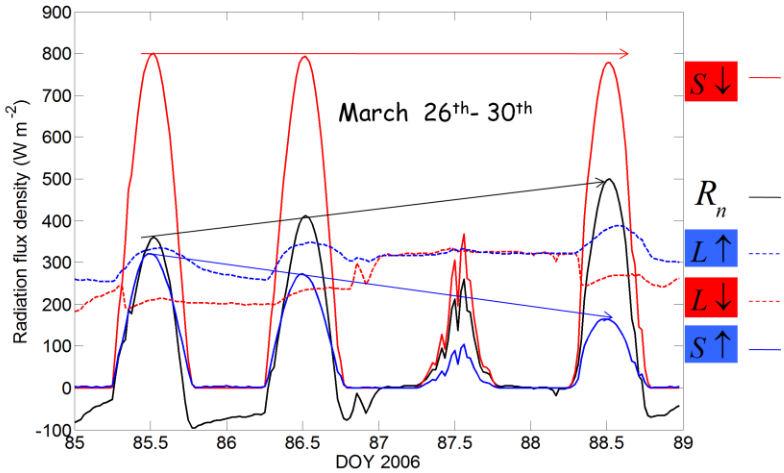


$L\uparrow$

- Surface objects emit L in all directions

Local radiation budgets at the surface (microclimatology)

Mer Bleue bog, March 26 – March 29, 2006



How do changes in the weather & in the surface affect radiation budget?

Global and local patterns of energy budgets

- **Energy Balance**
  - Radiation budget
  - Energy budget
  - Urban heat island

Readings: Chapters 4

Radiation Budget

R_n = inputs – outputs

$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$ (W m^{-2})

R_n = net radiation (NET R)
K ↓= incoming shortwave radiation (insolation, SW↓)
K↑ = outgoing shortwave radiation (SW↑)
L↓ = incoming longwave radiation (LW↓)
L↑ = outgoing longwave radiation (LW↑)

all units in W m^{-2}

Sources? Pathways?

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$K\downarrow$ From the sun – some gets absorbed & reflected before reaching the surface – includes both diffuse & direct

$K\uparrow$ Reflected off clouds & particles in atm, off ground surface objects – depends on albedo & sun angle. $K\uparrow = \alpha K\downarrow$

$L\downarrow$ Emitted from clouds & other atm constituents. At the surface, will also include L from overhead/nearby trees, buildings, etc. $L\downarrow = \varepsilon\sigma T^4$

$L\uparrow$ Emitted from surface objects. $L\uparrow = \varepsilon\sigma T^4$

Radiation Budget

Top of the atmosphere
→ is $R_n > 0$, < 0, or $= 0$?

At Earth's surface
→ is $R_n > 0$, < 0, or $= 0$?

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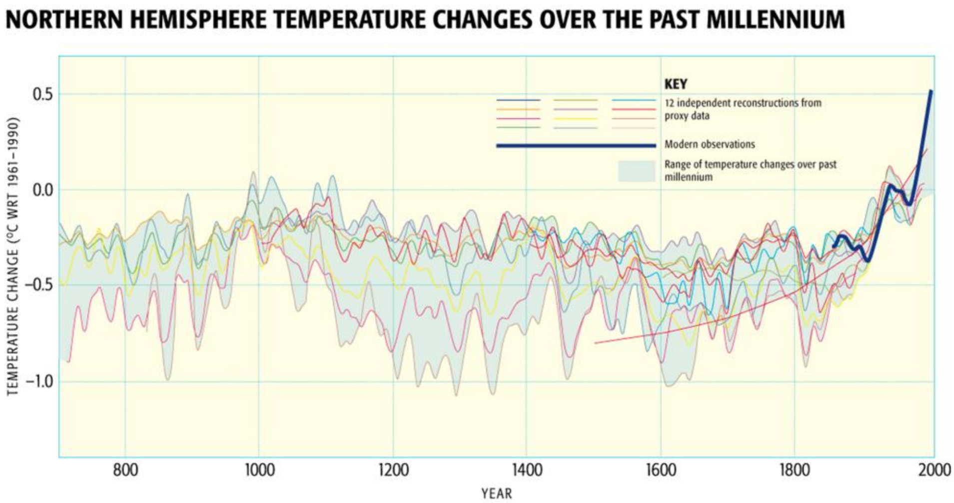
Dynamic equilibrium?



Radiation Budget

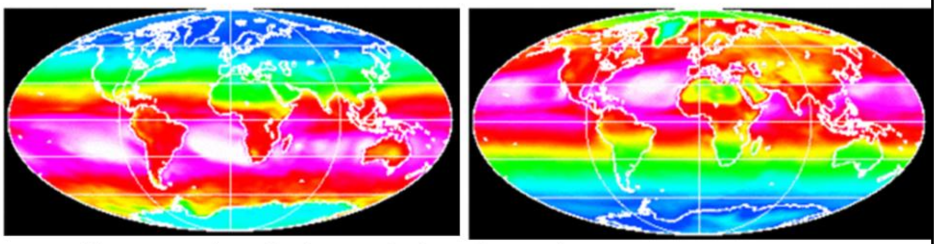
R_n = inputs – outputs

$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$

R_n = net radiation (NET R)
$K\downarrow$ = path changes in Earth's orbit around sun, etc.
$K\uparrow$ = changes in albedo in atmosphere
$L\downarrow$ = GHGs
$L\uparrow$ =

all units in $W\ m^{-2}$

R_n at earth's surface



Source: NASA Surface Radiation Budget Project)

Latitudinal differences driven by differences in shortwave solar input (sun angle)

http://www.eoearth.org/article/Energy_balance_of_Earth

What happens to R_n?

Energy is absorbed:

- Surface materials and atmosphere both **absorb energy**
- Molecules convert radiation from one form into another
- Absorbing surface re-radiates longwave radiation
- Absorbed (mostly shortwave) radiation is converted to **heat** or to chemical energy

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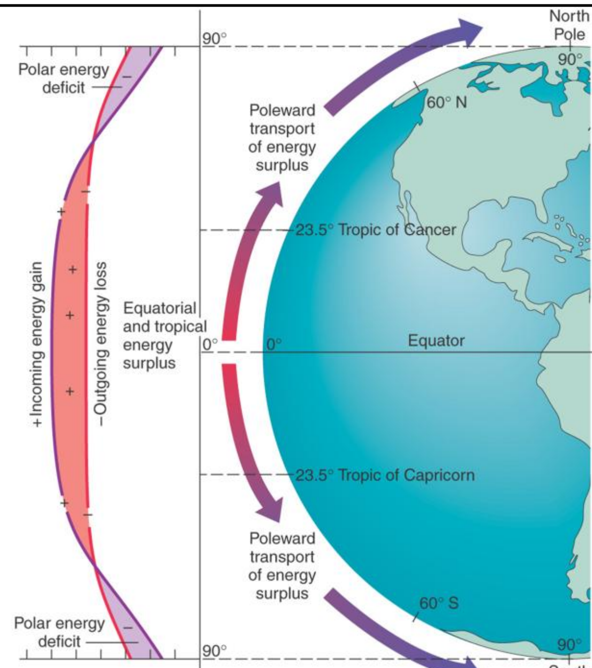
North Pole
90°
90°
Polar energy deficit
60° N
Poleward transport of energy surplus
23.5° Tropic of Cancer
+Incoming energy gain
−Outgoing energy loss
Equatorial and tropical energy surplus
0°
0°
Equator
23.5° Tropic of Capricorn
Poleward transport of energy surplus
60° S
Polar energy deficit
90°
90°
South Pole
Figure 4.14

Temperature: measure of the average kinetic energy (motion) of individual molecules in matter

Heat: Form of energy that flows from one object (system) to another along a gradient

→ we *feel* the effect of temperature due to the transfer of sensible heat to our bodies

Heat Transfer

Radiation is 1 of 3 means by which energy is transferred.

Radiation: Energy traveling through air or space (due to rapid oscillations of electromagnetic fields)

Conduction: Molecule to molecule transfer

Convection: Energy transferred by mass flow (of water, air)

Heat Transfer

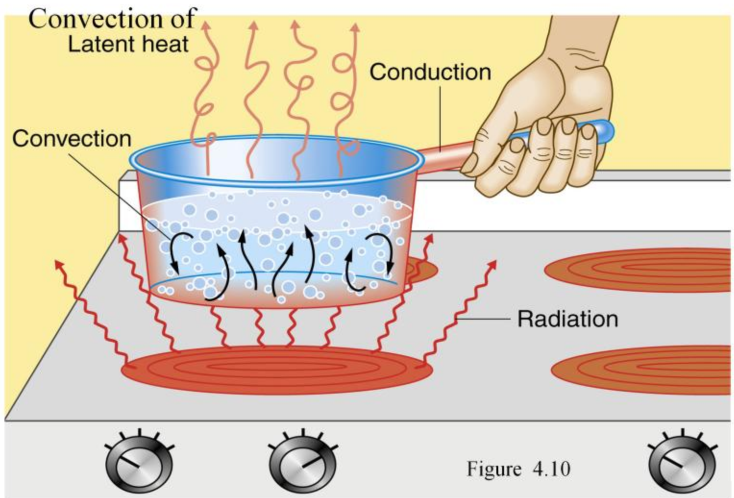

Figure 4.10

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Important elements of the surface energy budget

Convective energy transfer:

Horizontal → Advection

Vertical → Convection

- Sensible heat flux (H):
  Flow of heat between the surface & atm. by convection.
- Latent heat flux (LE):
  Flow of latent heat between the surface & atm. by convection. ie. evaporation/condensation

Conductive energy transfer:

- Ground heat flux (G):
  Flow of heat into/out of ground by conduction.

The physics of evaporation

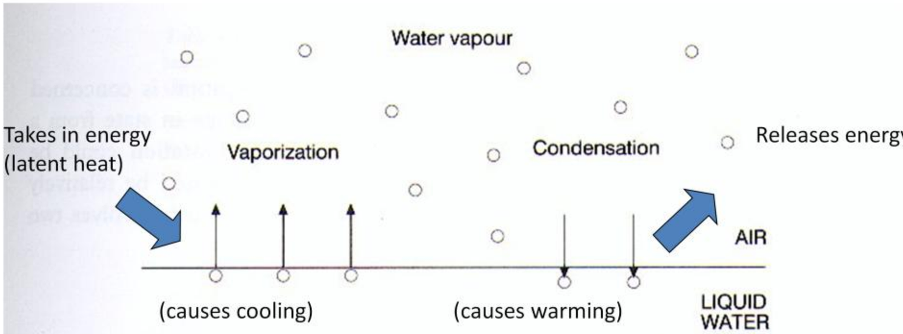

Figure 4.1 Evaporation is the net balance between the rate of vaporization of water molecules into the atmosphere, and the condensation rate of molecules from the atmosphere.

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Surface Energy Budget

$\text{Input} = \text{Outputs} + \text{Storage}$ (W m^{-2})

$R_n = H + LE + G + S$

Type of energy transfer

R_n = net radiation (NET R)

H = sensible heat flux

LE = latent heat flux

G = ground heat flux (or M)

S = change in stored energy

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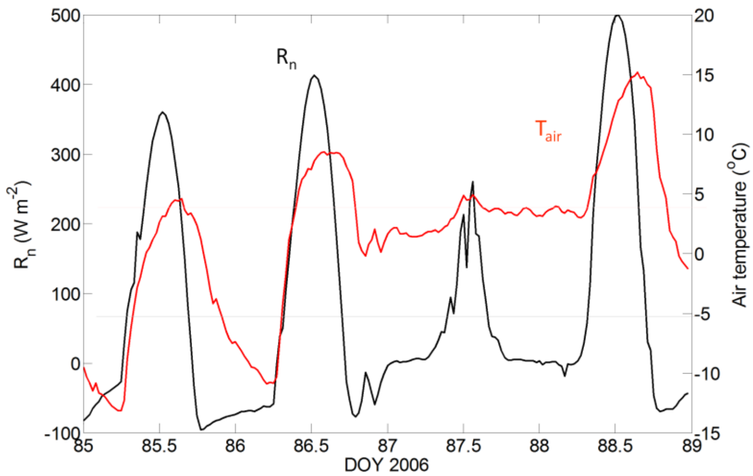
Why is there a temperature lag between peak net radiation and air temperature?

Mer Bleue bog, March 26 – March 29, 2006



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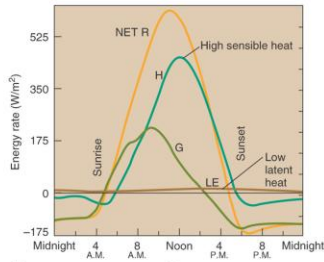
Contrasting Surface Energy Budgets

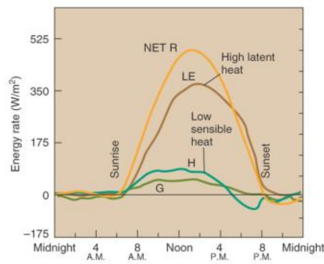
El Mirage, CA: hot, dry



(a)


(b)

Pitt Meadows, BC: moist, with moderate temperatures



(c)


(d)

Global Energy Fluxes: Latent Heat

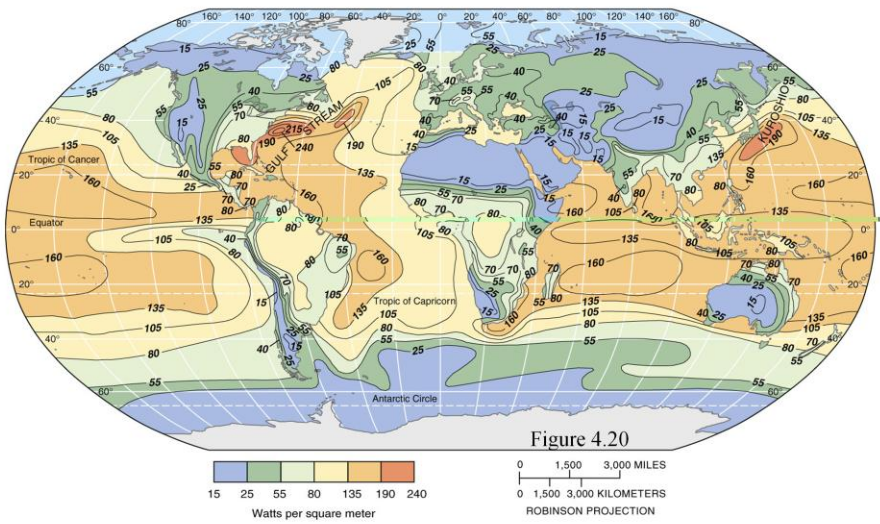


Figure 4.20

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Global Energy Fluxes: Sensible Heat

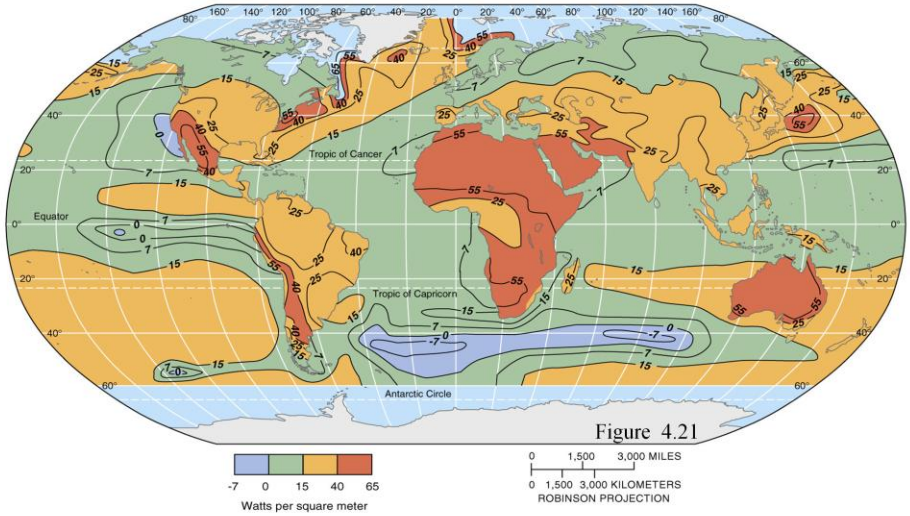
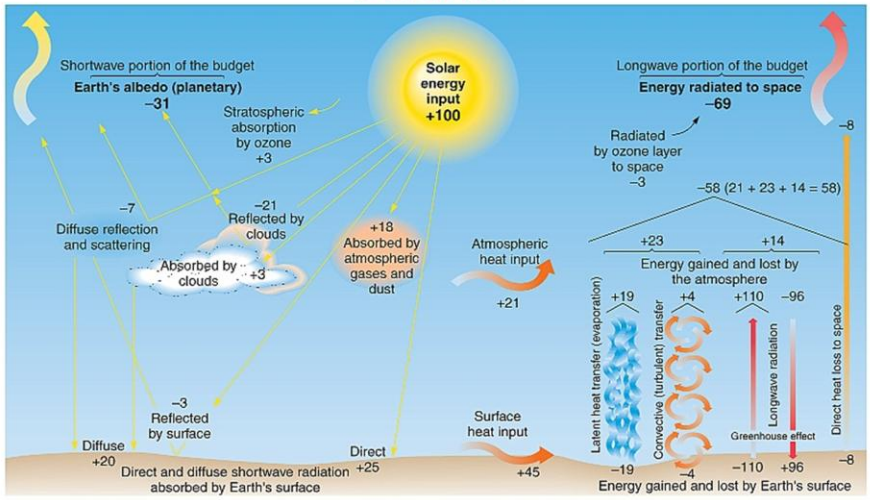


Figure 4.21

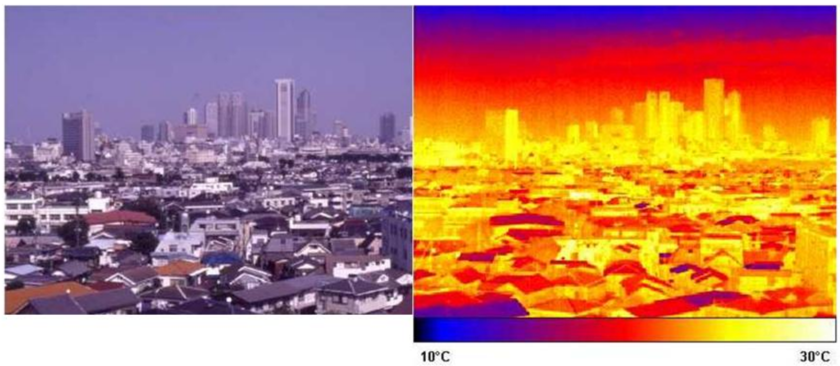
Earth–Atmosphere Radiation/Energy Balance



Inputs (K) = Outputs (K + L)

100 = 31 + 69

Urban microclimate: Urban heat island



Tokyo, Japan - M. Roth (National University of Singapore)

Cities are dramatic examples of the anthropogenic impact on terrestrial ecosystems and surface climates.

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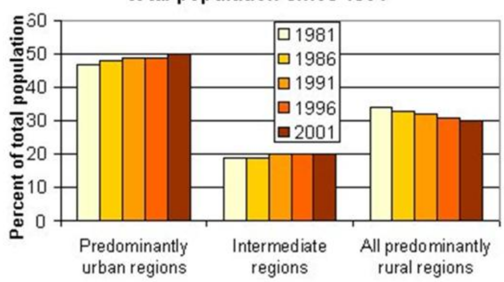
Urbanization & Microclimatology

•70% of Canadian population lives in urban areas (2011)
•50% of global population lives in urban areas (2007, where urban is city with > 20 000 inhabitants)
•By 2025, 68% of global population is expected to live in urban areas. **http://www.unhabitat.org/**

Figure 1. The population of rural regions in Canada has steadily declined as a share of total population since 1981



Source: Statistics Canada. Census of Population, 1981 - 2001.

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Urban Heat Island

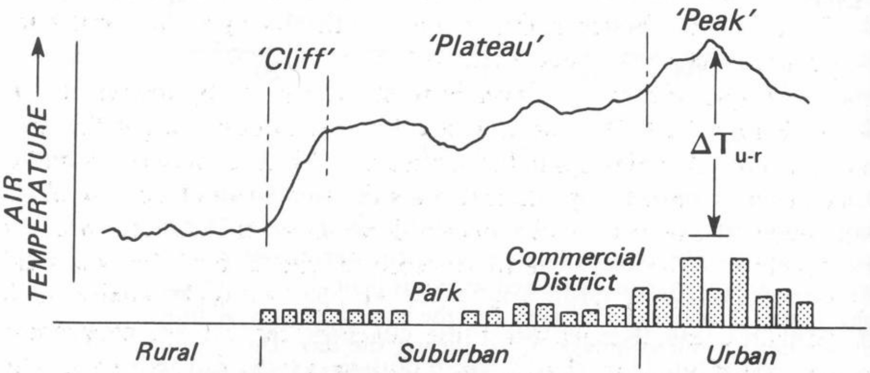
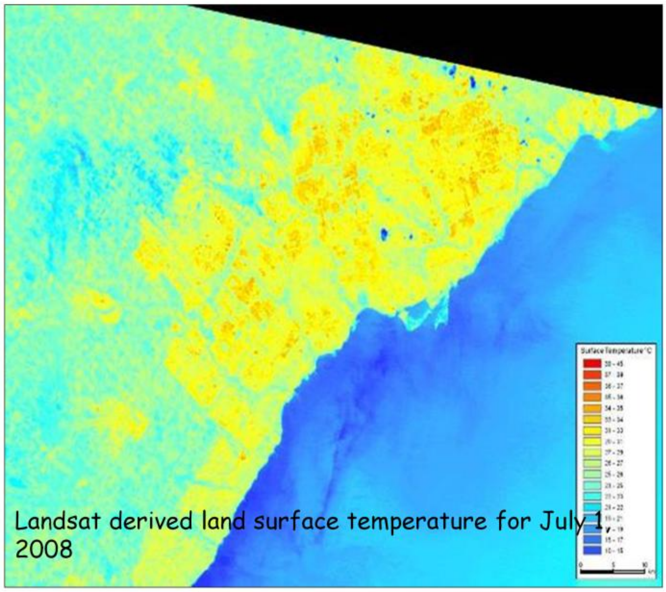


Figure 8.12 Generalized cross-section of a typical urban heat island (after Oke, 1976b).

Oke, 1987

Urban Heat Island (surface level): GTA



Landsat derived land surface temperature for July 1 2008

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M. Maloley 2010

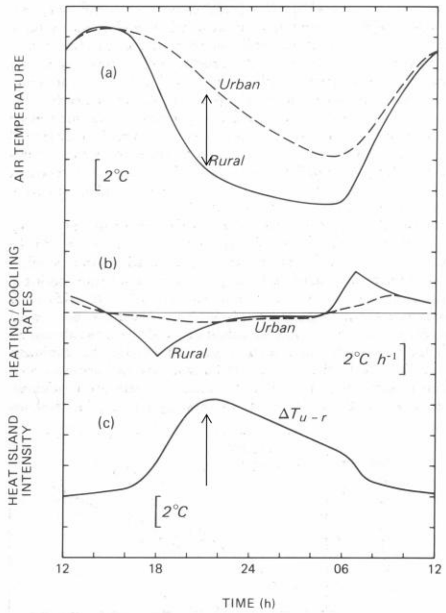

Figure 8.14 Typical temporal variation of urban and rural (a) air temperature and (b) cooling/warming rates and (c) the resulting heat island intensity (ΔT_{u-r}) under 'ideal' weather conditions (after Oke, 1982).

Oke, 1987

But, in the air, UHI is largely a nighttime phenomenon

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What causes the urban heat island effect?

What causes urban heat island effect?

Altered energy budget terms leading to +ive ΔT_{u-r}	Related features of urbanization
1. Increased absorption of short-wave radiation	Canyon geometry - increased surface area and multiple reflections
2. Increased long-wave radiation from sky	Air pollution - greater absorption and re-emission
3. Decreased long-wave radiation loss	Canyon geometry - reductions of sky view factor
	Building and traffic heat loss
	Construction materials - increased impermeability- remove H20 storage
	Construction materials - increased thermal admittance
	Canyon geometry - reduction of wind speed

Oke 1987

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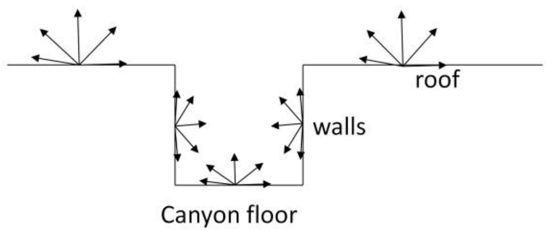
Long-wave radiation balance

Restricted <u>sky view factor</u> (the amount of sky 'seen' by the surface)

ie. much of the L emitted is absorbed & re-emitted to the surface.

Reduces total *outgoing longwave radiation*



Important factor <u>limiting</u> radiative cooling at night!

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How can we limit the urban heat island effect?

Altered energy budget terms leading to +ive ΔT_{u-r}	Related features of urbanization
1. Increased absorption of short-wave radiation	Canyon geometry - increased surface area and multiple reflections
2. Increased long-wave radiation from sky	Air pollution - greater absorption and re-emission
3. Decreased long-wave radiation loss	Canyon geometry - reductions of sky view factor
4. Anthropogenic heat source	Building and traffic heat loss
5. Decreased evapotranspiration	Construction materials - increased impermeability
6. Increased heat storage	Construction materials - increased thermal admittance
7. Decreased total turbulent heat transport	Canyon geometry - reduction of wind speed

Oke 1987

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