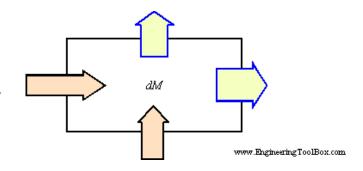


Geography 370: Climate Change and Society



Mass and volume flux conservation

- In any fluid (gas or liquid), mass is conserved.
- Final mass of a volume = initial mass + mass added – mass removed
- There can be transient changes in fluid mass in a particular region, but there is a tendency for the mass removal rate to approach the mass addition rate and for the final mass to be close to the initial mass
- For most fluids (which have densities that vary slowly over space), this mass conservation principle implies a conservation of volume flux (i.e. the volume of fluid entering a region per unit time is compensated by the volume of fluid leaving the same region in the same unit time)





Pressure and the hydrostatic equation

- Pressure is force/area
- The force is the mass*g (g is the gravitational constant 9.8 m/s²)
- Hydrostatic equation of fluid balance
- $\Delta p = -gp\Delta z$ (where p is pressure, p is the density, z is elevation and Δ represents "change")
- Sea level atmospheric pressure is about 1 bar or 1000 millibars (mb) (1 atm~ 1 bar = 100,000 Pa or 100,000 kg/m/s²~ 15 psi)
- Atmospheric pressure decreases exponentially with elevation, as does density
- The pressure at 5.5 km above sea level averages around 500 mb and the summit of Mt. Everest (8.8 km) has a pressure of 1/3 atmosphere
- Ocean water is almost 1000 times the density of air and is far less compressible (i.e., density does not change much with pressure)
- Descending about 10 meters in the ocean is tantamount to adding another atmosphere of pressure



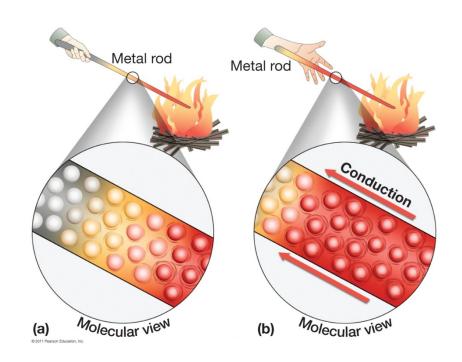
Ideal Gas Law

- Ideal gas law
- pV = nRT (where p is pressure, V is volume, n is the number of moles of gas, R is a constant and T is the absolute temperature (K))
- The ideal gas law implies that if pressure does not vary greatly, volume increases with increasing temperature
- Interestingly, this volumetric expansion accompanying elevated temperatures at the surface causes rising motion and lower molecular density which slightly decreases pressure



Modes of Heating: Conduction

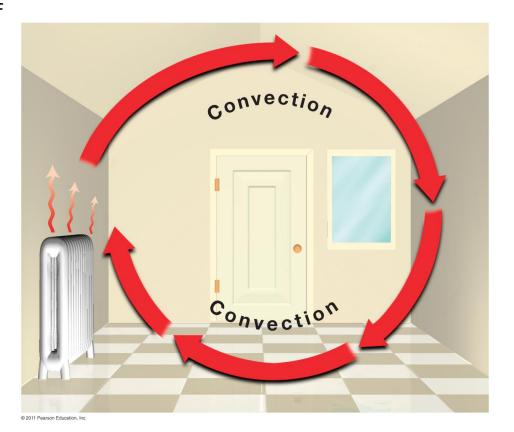
- Transfer of heat energy across a medium
- Results from molecular collision
- The ability to conduct heat varies among substances
- Most metals are great conductors
- Air is a poor conductor
- The earth transfers some of the absorbed solar radiation deeper into the ground with conduction.





Convection

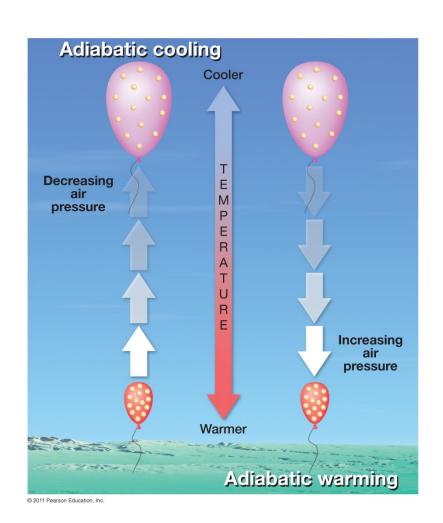
- Convection is the vertical motion of a fluid (liquid or gas) induced by heating and expansion
- Surface warming causes air to expand and therefore rise – this process slightly suppresses surface pressure
- In order to preserve mass/fluid balance, the air that has risen must sink elsewhere – this process slightly increases surface pressure
- Convection is vital to atmospheric dynamics: differences in surface temperature induce pressure differences that induce vertical and horizontal motions that are vital to creating weather and steady circulation in the atmosphere





Adiabatic Processes

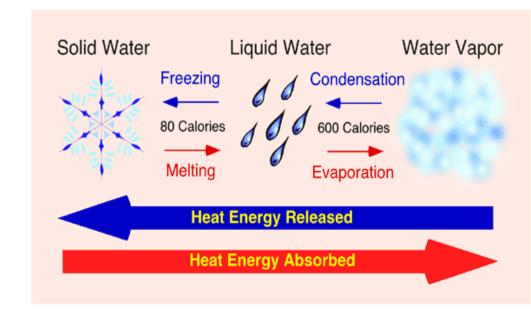
- An adiabatic process is one that does no thermodynamic work (pV^I is fixed, where I is a constant)
- Adiabatic cooling
 - Air rises and expands, molecular collisions decrease, so temperature decreases
- Adiabatic warming
 - Air sinks and compresses, collisions increase so temperatures increase





Latent Heat Exchange

- Phase Change
 - The physical state of water changes in the earth system, i.e., it changes between ice, water and water vapor
 - During a phase change energy is released or absorbed





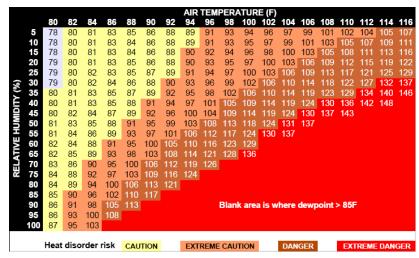
Pressure gradients and advection

- Advection is horizontal fluid motion (in water or air)
- Advection strength (wind or current strength) is a function of the pressure gradient
- u α Δp/Δx
- ν α Δρ/Δγ
- $w \alpha \Delta p/\Delta z$
- u is the zonal (east-west) velocity, v is the meridional (north-south) velocity, w is the vertical velocity, x is the zonal position, y is the meridional position, z is the vertical position and α means "directly proportional to"

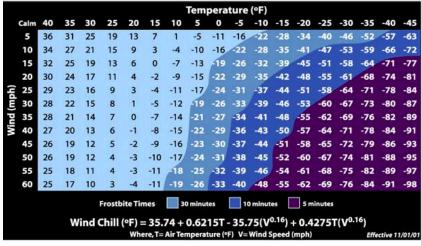


Apparent temperature

- Heat index: on muggy humid summer days, the air feels hotter because the air is close to saturation and cannot easily remove sweat from the skin, thereby limiting the effect of the latent cooling from that evaporation (heat cramps and heat stroke)
- Dry heat: on hot, dry summer days, especially with high wind, it is very easy to get dehydrated and to not even realize the danger you might face because hot dry air will quickly evaporate sweat from your skin
- Wind chill: in the winter, the air immediately adjacent to the body is warmed by body heat, and warm clothing helps to insulate this warm layer, but when winds are strong, this protective layer of warm air can be compromised by wind (frostbite and hypothermia)



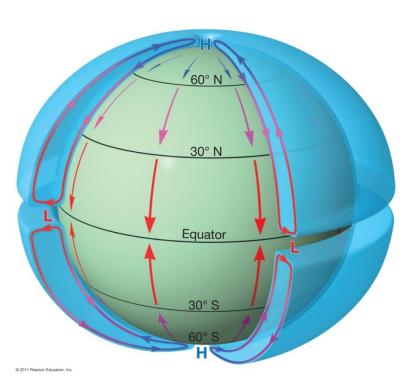






Fluid motion on a non-rotating planet

- If the earth did not rotate, convection established by surface heating differences would drive vertical atmospheric motion, and advective motion between areas of differing temperature and pressure would drive horizontal atmospheric motion
- Strong solar heating at equator
- Little heating at poles
- Thermal low pressure forms over equator
- Thermal high forms over poles
- Ascending air over equator
- Descending air over poles
- Winds blow equatorward at surface, poleward aloft





The Coriolis "force"

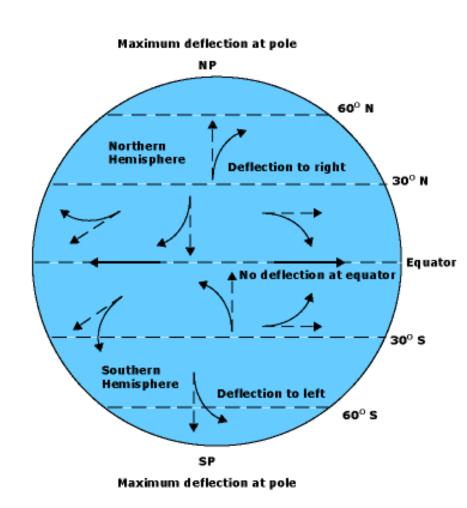
- The Coriolis "force" is an "apparent" force which acts on fluids on a rotating sphere; the earth rotates from west to east
- In physics, there are the principles of conservation of linear momentum (mass* velocity) and conservation of angular momentum (mass*angular velocity)
- At rest with respect to a rotating sphere, all points on the rotating sphere have the same rotational momentum but linear momentum is a function of latitude
- Eastward fluid motions (in the same directions of the earth's rotation) tend to impart an equatorward velocity
- Westward fluid motions (in the direction opposite to the earth's rotation) tend to impart a poleward velocity





The Coriolis "force"

- If an object or air parcel moves to higher latitude, the linear velocity would decrease, so to conserve linear momentum, an eastward velocity is imparted
- If an object or air parcel moves to lower latitude, the linear velocity would increase, so to conserve linear momentum, a westward velocity is imparted
- In the Northern Hemisphere, the Coriolis force displaces fluid motions to the right of their initial path
- In the Southern Hemisphere, the Coriolis force displaces fluid motions to the left of their initial path
- The Coriolis parameter, f is defined by $\mathbf{f} = \mathbf{2}\Omega \mathbf{sin}\theta$, where Ω is the rotational rate, θ is latitude defined as North Pole +90 degrees, equator as 0 degrees and South Pole as -90 degrees
- The Coriolis parameter vanishes at the equator and has its largest magnitude values in the high latitudes of both hemispheres



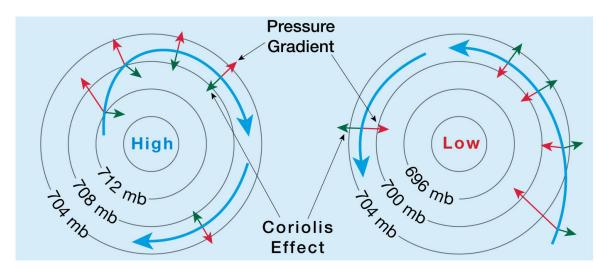


Geostrophic balance

• In the absence of friction, fluid motions on the geophysical scale would be strictly geostrophic (meaning there would be an exact balance between the pressure gradient and Coriolis forces)

$$fu = -\frac{1}{\rho} \frac{\Delta p}{\Delta y}$$
 $fv = \frac{1}{\rho} \frac{\Delta p}{\Delta x}$

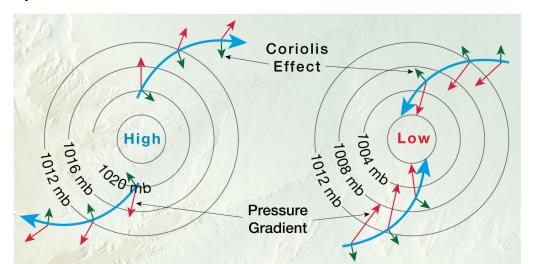
- f is the Coriolis parameter
- In purely geostrophic motion, wind vectors are along isobars





Friction and Quasi-Geostrophy

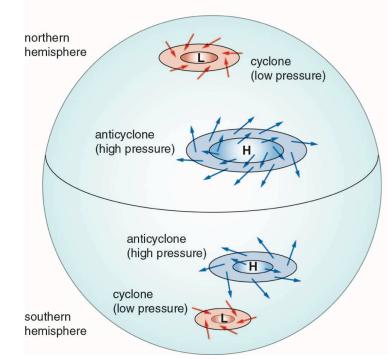
- Of course in reality, there is friction between the ground or ocean and the atmosphere
- This friction acts against the direction of motion and effectively alters the balances of forces
- The balance between pressure gradient, Coriolis and frictional forces is known as quasi-geostrophy and is the dynamic balance for most geophysical scale fluid motions
- In quasi-geostrophic flow, fluid motion is still down the pressure gradient while still being deflected by the Coriolis force

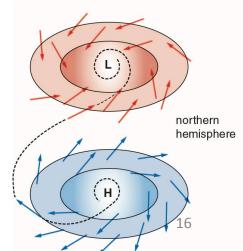




Motions around low and high pressure systems

- in the Northern Hemisphere, surface high pressure centers have divergent clockwise flow, while surface low pressure centers have convergent counterclockwise flow
- in the Southern Hemisphere, surface high pressure centers have divergent counterclockwise flow, while surface low pressure center have convergent clockwise flow
- At high elevation, pressure anomalies and corresponding wind fields tend to be the opposite of the surface (i.e., surface convergence and low pressure corresponds to high pressure and divergence aloft)

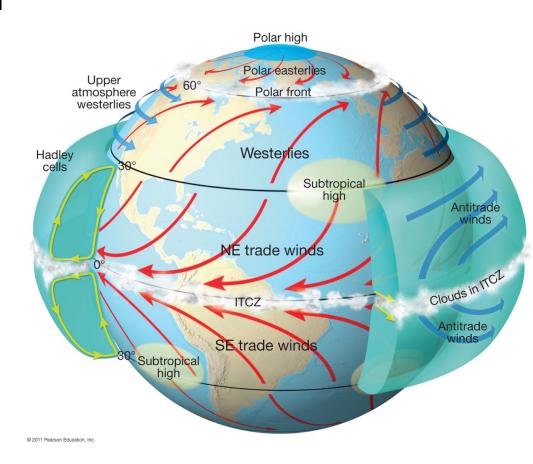






The observed atmospheric circulation

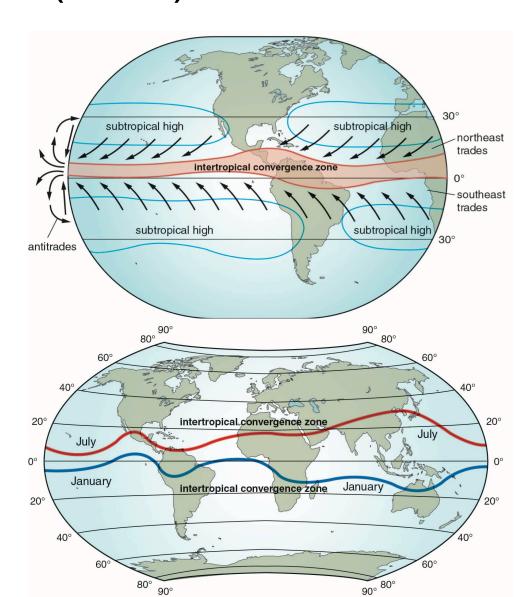
- Features of the observed general circulation
 - Hadley cells
 - Subtropical high
 - Trade winds
 - Intertropical Convergence
 Zone
 - midlatitude westerlies
 - Jet streams
 - Rossby waves
 - Polar highs
 - Polar easterlies
 - Polar front





Intertropical Convergence Zone (ITCZ)

- Region of convergence of the trade winds
- Form a belt around the equator, most clear over the ocean.
- Calm surface winds, constant rising motion and storminess in this region
- Position seasonally shifts (more over land than water)
- Doldrums trapping sailing ships for days

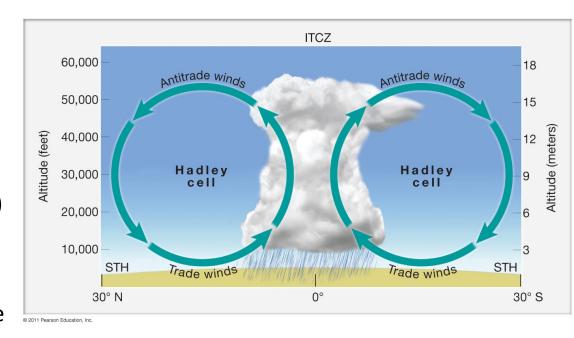




The Hadley cell refers to the cell of atmospheric circulation from the equator to the subtropics in both the North and South hemispheres: air rises near the equator (intertropical convergence zone) and sinks in the subtropics (subtropical highs) because of convection

- There is equatorward surface wind and poleward winds aloft
- The equatorward trade winds are deflected to the west (east to west winds are called easterlies by meteorologists)
- The antitrade winds aloft are deflected to the east (thereby becoming westerly)
- Generally from 0 to 30 degrees latitude

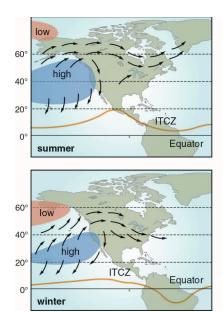
Hadley cells

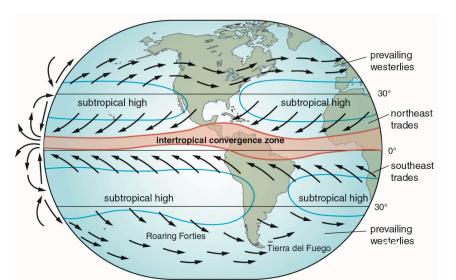




Subtropical Highs

- Persistent zones of high pressure near 30° latitude in both hemispheres
- Result from descending air in Hadley cells
- Subsidence of dry air is common over these regions
- Regions of world's major deserts
- Sinking air, horse latitudes
- Seasonal shifting of position with ITCZ position

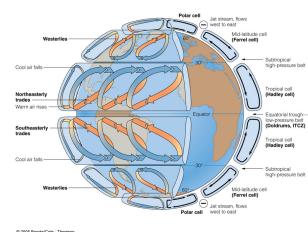






Midlatitude Ferrell cells

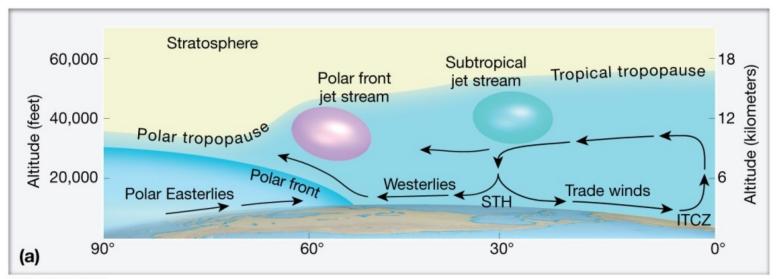
- In the mid-latitudes, the descending air from the subtropics tends to flow poleward at the surface to the polar front which induces rising motion
- There is equatorward return flow aloft
- This being said, the south/north wind direction is seasonally variable in the midlatitudes as is the position of the Ferrell cell
- Prevailing Westerlies
- Winds flowing from west to east in the midlatitudes in both hemispheres
- Midlatitude Winds are not as consistent in direction as the trade winds
- From ~30 degrees to ~60 degrees latitude





Polar Front

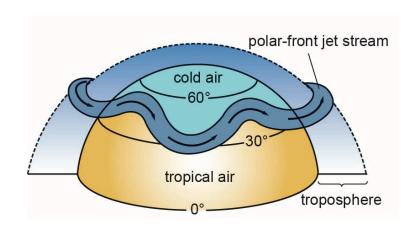
- Low pressure area between polar high and westerlies
- Air mass conflict between warm westerlies and cold polar easterlies
- Rising motion and precipitation
- Polar jet stream position typically coincident with the polar front – varies seasonally, but average position is about 60 degrees latitude

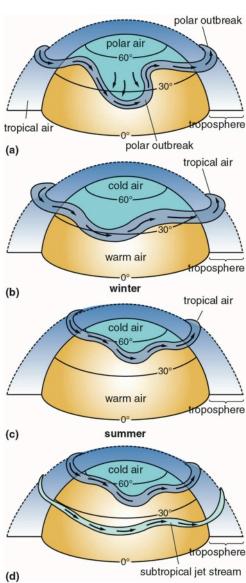




Rossby Waves

- Pattern of waves along the polar front jet stream
- Particularly prominent in winter and associated with subpolar lows
- Subtropical jet develops in warmer months
- General direction of polar jet stream is west to east, but the path meanders
- These meandering motions are called Rossby waves
- The Rossby waves separate cold polar air from warm tropical air and can influence surface climate.
- The subtropical jet stream does not have as much impact on surface climate

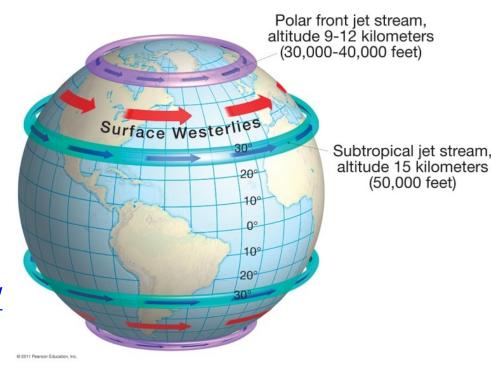






Jet Streams

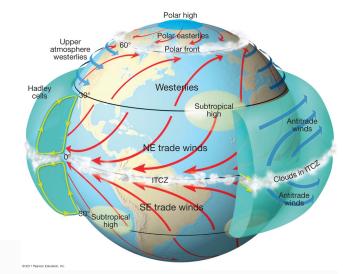
- Although the surface westerlies are variable, the jet streams in the upper atmosphere are more constant
- Zone of strong winds in the upper troposphere
- Polar jet stream at 9-12 km altitude.
- Subtropical jet stream at 15 km altitude
- http://whs.moodledo.co.uk/file.php/ 1365/Atmospheric Systems/Polar Jet Stream.swf

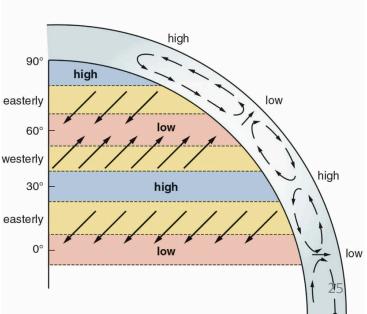




Polar Cells

- Sinking air at the poles (thermal high pressure) is especially strong over Antarctica
- Air flows equatorward at the surface towards the polar front in both hemispheres
- Returning poleward air aloft
- Polar easterlies from poles to subpolar regions
- Winds are anticyclonic; strong subsidence, clockwise surface flow in NH, counter-clockwise flow in SH.
- Regions north of 60°N and south of 60°S
- Air is very cold and dry

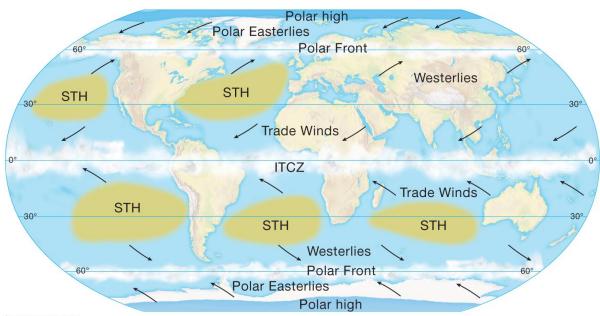


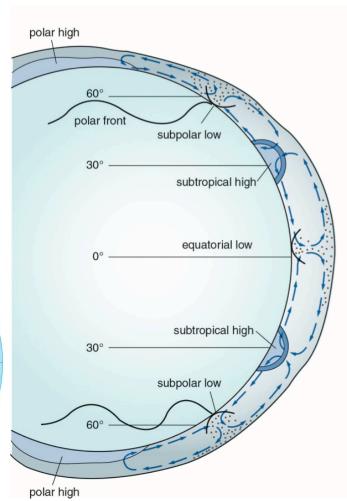




The General Circulation of the Atmosphere

- The seven components of the general circulation
- Thermal low pressure at the equator, thermal high pressure at the poles, dynamic high pressure at the subtropics, dynamic low pressure at the polar front
- Rising air at equator and polar fronts, sinking air at poles and subtropics
- Equatorward and easterly surface flow in the low latitudes and high latitudes, poleward and westerly flow in the middle latitudes

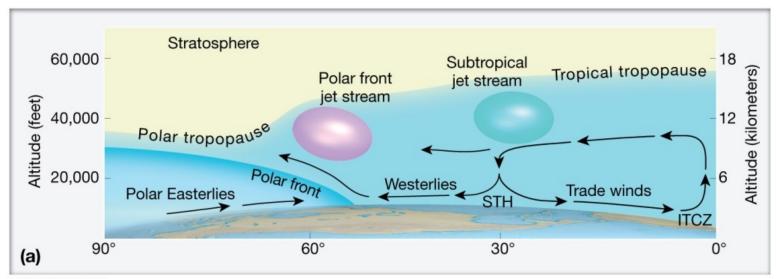






More on jet streams

- The jet streams are high level, fast moving winds which play an important role in steering weather patterns
- They form between circulation cells in areas where the tropopause height varies rapidly with latitude





Thermal wind

- The troposphere is thicker at low latitudes because warm air expands
- Thermal scale height, H = RT/g
- The strength of the jet stream depends on the gradient of troposphere thickness and relates to the thermal wind equation (derived from the ideal gas law, geostrophic balance and hydrostatic balance)

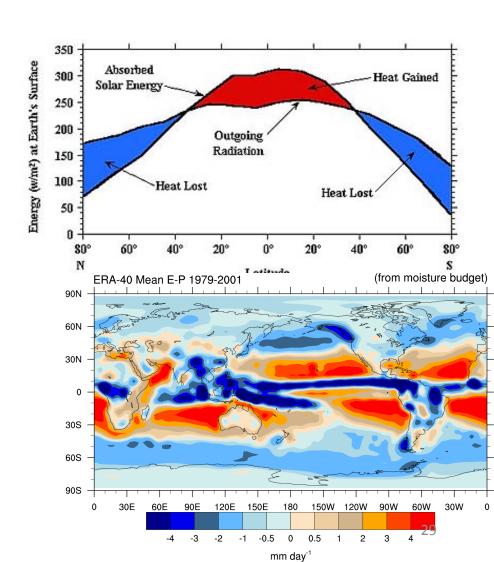
$$\frac{\Delta u}{\Delta z} = \frac{R}{fH} \frac{\Delta T}{\Delta y} = \frac{g\Delta T}{fT\Delta y}$$

 As meridional temperature gradient increases, so does jet stream strength, but as meridional temperature gradient decreases, so does jet stream strength



Atmospheric budget of heat and moisture

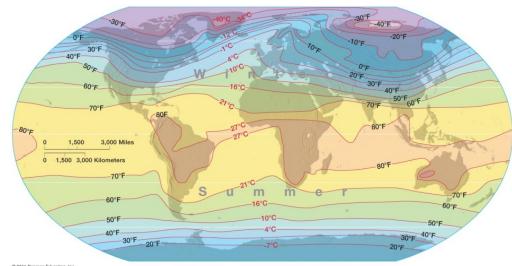
- In sum total, meridional differences in direct solar heating are much greater than differences in apparent temperature
- The atmosphere acts to export heat from the tropics to the high latitudes
- Moisture advection is more complex and is partly reflected by climatological precipitation, but in sum total, there is also some export of moisture from the low latitudes to the high latitudes

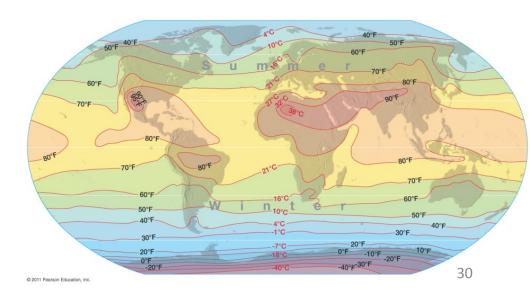




Properties of water and marine climates

- Water has a high heat capacity (it takes a lot of heat to change the temperature of water compared to air)
- Consequently, water temperatures do not oscillate through as large a range as do air temperatures
- Peak and minimum water temperatures also tend to lag peak and minimum air temperatures (e.g., in the NH, air temperatures usually peak in late July, while water temperatures usually peak in late August/early September)
- Likewise, marine climates which are constantly influenced by a sea breeze tend to have more muted temperature contrasts than continental interiors at the same latitude

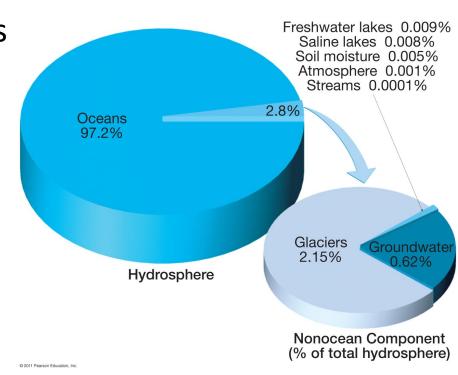






Hydrosphere

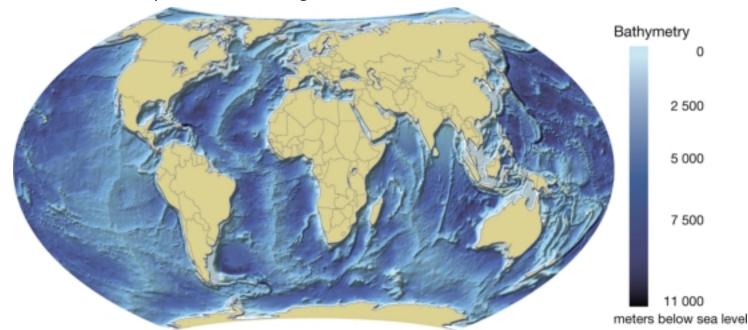
- The vast majority of the world's water (97%) is in the oceans; this is followed by the glaciers and ice caps (2.2%), ground water, surface water (rivers, lakes, etc.) and atmospheric water)
- Over land, precipitation evaporation is positive, while over the ocean precipitationevaporation is negative; the difference is made up by river runoff





Marine Geology

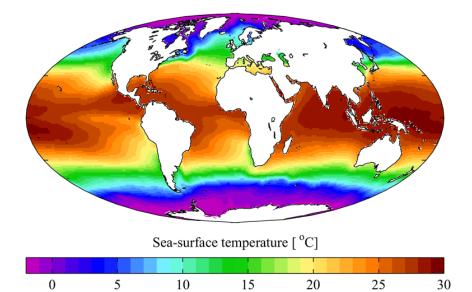
- The ocean cover 70% of the surface area of the Earth and contains 97% of the water
- Continental shelf Along the margins of the world's continents; shallow (lower limit usually defined as several hundred meters), relatively gently sloping
- Continental slope a little further away from shore than the continental shelves; steeply sloping transition to the abyss
- Abyssal plain most of the area of the world ocean is underlain by abyss, largely flat (although some parts of the abyss have very striking features) and deep (4-5 km)
- mid-ocean ridges massive volcanically created undersea mountain systems that rise a few kilometers above the surrounding abyssal plains; these are the product of divergent tectonic motion
- Trenches deep depressions in the ocean bottom the deepest are around 10-11 km below sea level; these are the product of convergent tectonic motions





Global ocean temperature

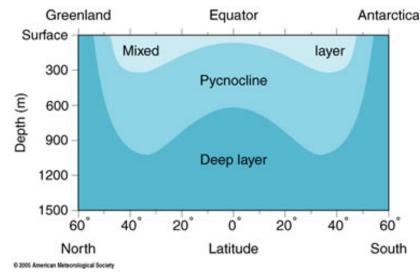
- Temperatures depend on latitude, season, currents and depth
- Upwelling regions and equatorward currents are unusually cool for their latitude while shallow waters and poleward currents tend to be warm
- Deep waters even in the tropics are very cold because very little light penetrates 1 km
- SST (sea surface temperature)

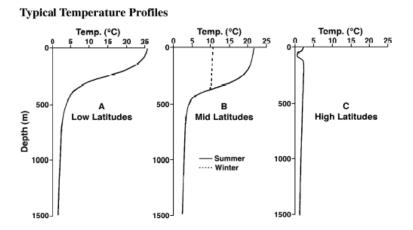




Characteristics of ocean waters

- Surface waters (also known as mixed layer) generally 50-200 m depth depending on wind strength and other factors; relatively warm (anywhere from 0-35 °C depending on latitude and season), light waters relatively rapid chemical and physical interaction between mixed layer and lower atmosphere, the vast majority of the light in the ocean is in the mixed layer, most marine life lives here
- Thermocline/pycnocline zone of rapid temperature decline with depth and increasing density below mixed layer but above deep ocean, limited light, limited marine life
- Thermocline position and gradient varies with latitude and season
- Deep ocean in many regions the "top" of the deep ocean is around 1 km depth, water is very cold (average temperatures range from 0 to 4 °C) and dense, high pressure, complete dark, limited but very specialized life
- Light attenuates exponentially with depth







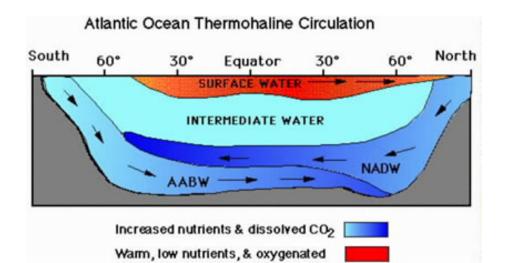
Vertical motions and density contrasts in the ocean

- Salt water density is a function of both temperature and salinity: cold, salty water is most dense; warm, fresh water is the lightest
- Equation of state: $\rho = \rho_0 (1 \alpha_t T + \beta S)$
- Where ρ_0 is a reference density, α_t is a thermal expansion coefficient, β is a salinity density coefficient and S is salinity



Deep water formation

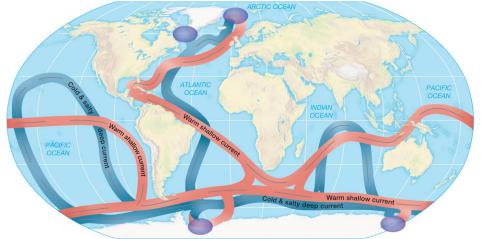
- Surface water sinks and forms "deep water" where surface water densities are high
- "deep water" then finds its level of neutral buoyancy in relation to "deep water" from other sources
- In the current state of the world oceans, this process is dominated by the temperature effect on density, so deep water forms in cold regions (i.e. the North Atlantic and around Antarctica)
- Three distinct deep waters are formed Antarctic bottom water (AABW), Antarctic Intermediate
 Water (AAIW) and North Atlantic deep water (NADW): these are the dominant deep and
 intermediate waters
- Some intermediate water is formed in the Mediterranean Sea (MIW) because of the salinity effect,
 although the density of this water is only large enough to bring it down to about 1-2km depth





Thermohaline Circulation

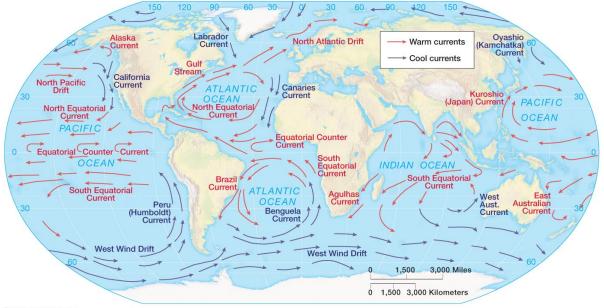
- Once deep water is formed and spreads out through its level of neutral buoyancy in the deep ocean, deep water slowly upwells in all regions of the world ocean except the deep water formation regions
- As the deep water rises through thermocline and into the mixed layer, it is moved through the surface currents by wind driven circulation
- The wind driven circulation ultimately returns surface water to areas of deep water formation
- This very long, slow circulation is called the thermohaline circulation and the rate of upwelling and deep water formation is controlled by the thermally and salinity induced density differences
- On very long time scales, this has important ramifications for the world's climate system





Role of wind stress on surface motions in the ocean

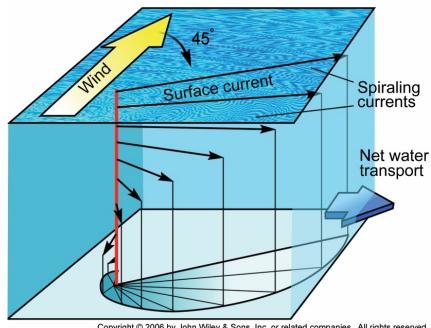
- The primary driver of both lateral and vertical motions in the surface ocean mixed layer is wind stress
- The surface winds shape the surface ocean currents, which in turn affect areas of convergence and divergence setting up areas of upwelling and downwelling





Ekman Transport

- Contrary to what one might assume, motions in the surface ocean on geophysical scales are not in the same direction as the surface wind (although on small scales they are)
- On geophysical scales, the Coriolis force acts to deflect surface waters to the right (left) of prevailing wind in the Northern (Southern) hemisphere
- As one further descends through the water column of the mixed layer, each successive layer is deflected further
- In sum total, the Ekman transport of the surface water is 90 degrees to the right (left) of the winds in the Northern (Southern) hemisphere

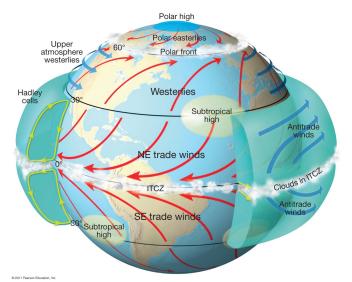


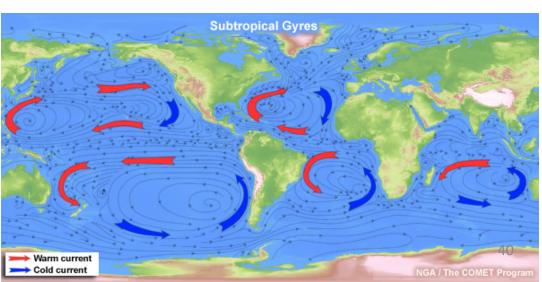
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Subtropical Gyres

- Because of the prevailing westerlies in the mid-latitudes and the prevailing easterly trade winds in the low latitudes and the Ekman transport effect, surface ocean water tends to move towards the subtropics
- This surface water is then deflected around the "mound" of water in the subtropics by the Coriolis force creating a gyre with clockwise (counterclockwise) motion in the Northern (Southern) hemisphere
- In most of the area of the subtropical gyres, the meridional water transport is equatorward and the currents on the eastern boundaries of the oceans tend to be cold currents

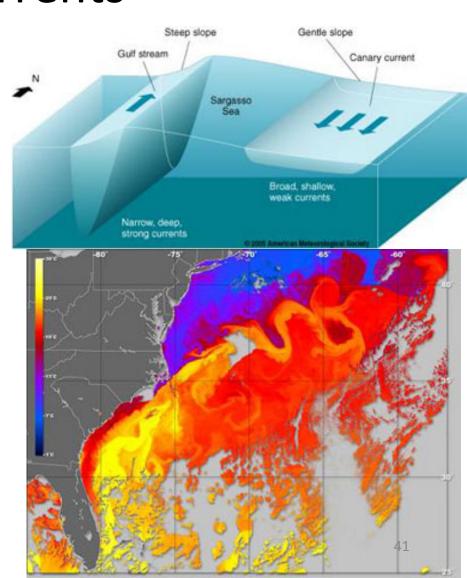






friction and western boundary currents

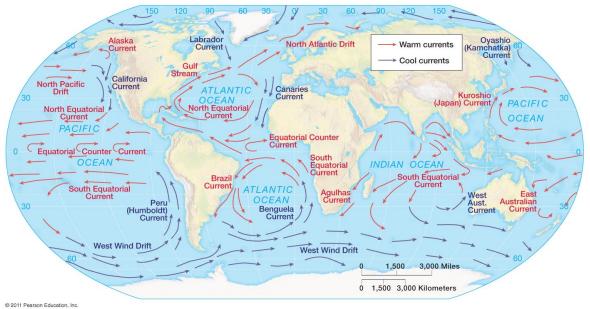
- Friction with the continents on the western side of the ocean basins (eastern coast of the Americas, Africa, Australia and Asia) causes intensification of the western boundary currents around the subtropical gyres (Gulf Stream in the North Atlantic, Kuroshio current in the North Pacific, Brazil current in South Atlantic, EAC in the South Pacific and Mozambique/Agulhas in the Southern Indian)
- Western boundary currents are narrow, fast, flow towards the poles and export a great deal of heat from low to high latitudes and have important impacts on local climates





High Latitude Currents

- In the southern hemisphere high latitudes, the dominant current is the Antarctic circumpolar current from west to east: very powerful and stormy (sometimes, there are 100 ft tall waves), although there are some east to west currents right near the Antarctic continent
- In the north Atlantic, the Gulf Stream evolves into the North Atlantic drift and then the Norwegian current conveying warmth to Europe, while the East Greenland and Labrador currents convey cold surface water equatorward and facilitate the formation of deep water
- In the north Pacific, the Kuroshio evolves into the North Pacific current and then the Alaska current, conveying warmth to BC and SE Alaska, while the Oyashio current conveys cold surface water equatorward







Near equatorial zonal currents

- Because the Coriolis force is very weak near the equator, oceanic motion is dominated by strictly zonal transport near the equator
- The dominant equatorial jets go from east to west and there are subsurface countercurrents that preserve mass balance and transport water at depth from west to east
- In part because of coastal upwelling along the eastern margins of the ocean basins and the equatorial currents, the Atlantic and Pacific tend to have warmer sea surface temperatures in the west than in the East

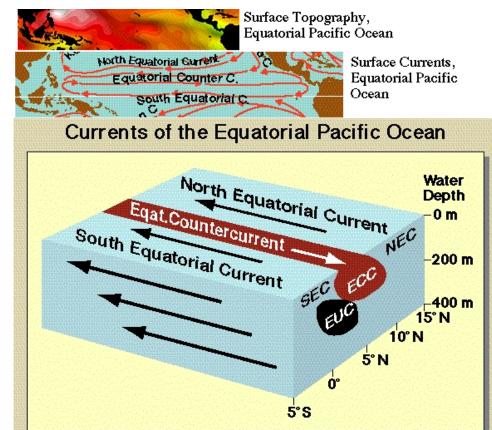


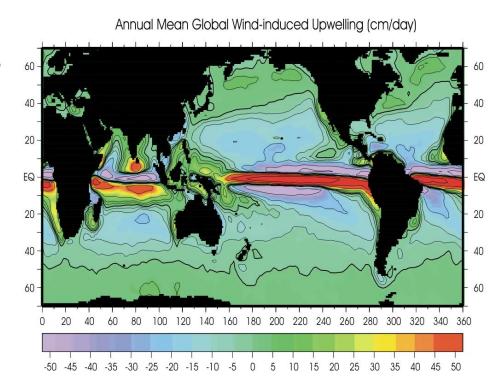
Diagram showing the complex currents in the Equatorial belt of the Pacific Ocean. Northern and Southern Equatorial Currents flow westward; the Equatorial Countercurrent and the Equatorial Undercurrent (EUC) flow in an easterly direction in the region between the other currents. The jet flow of the Equatorial Undercurrent, reaching velocities as great as 1.2 m/sec, considerably exceeds the speed of the other currents.

43



Upwelling regions

- The equatorward easterly winds in the tropical latitudes induce surface Ekman transport away from the Americas, Africa and Australia
- This surface divergence is compensated by upwelling in these coastal regions
- The convergence of surface winds near the equator and the polar fronts of each hemisphere establishes a divergence of surface ocean currents, which is compensated by upwelling along the equator and the polar fronts



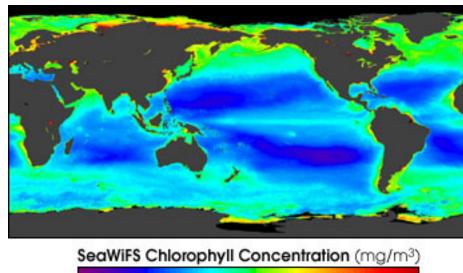


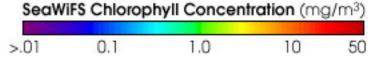
Chlorophyll distribution

- Proxy for biological productivity
- Most productive areas at high latitude, upwelling regions, shallow seas and near equator
- Surface oceans of gyres tend to have more limited productivity
- Seasonality:

 http://

 earthobservatory.nasa.gov/
 GlobalMaps/view.php?
 d1=MY1DMM CHLORA

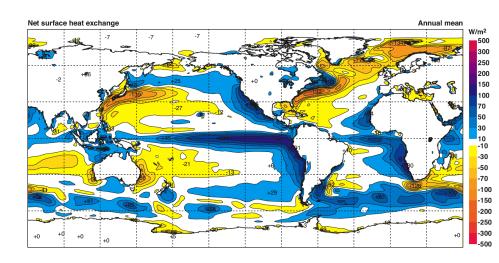


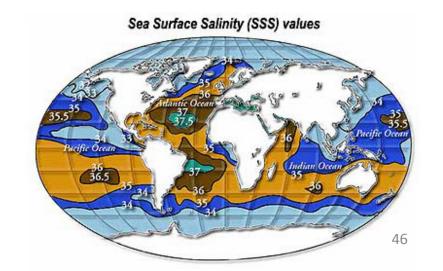




Heat and salinity

- As with the atmosphere, the world's oceans act on balance, to export heat from low latitudes to high latitudes, but heat exchange with the atmosphere depends on whether the current is warm or cold
- the story on salinity is a bit more complicated; surface salinity in the ocean is largely driven by the difference in precipitation and evaporation – areas with excess precipitation are fresh and areas with excess evaporation are salty
- But advection then plays a role in transporting high salinity water from the subtropics to the high latitudes where deep water forms







Precipitation: lapse rate

- Conceptually, a lapse rate is the rate of change of a variable with altitude and can be defined for a number of different variables
- In meteorology, when trying to understand precipitation, generally the lapse rate of greatest interest is the rate of temperature change with altitude $\Delta T/\Delta z$
- from the hydrostatic balance and the ideal gas law, the dry adiabatic* lapse rate is

$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p} = -9.8^{\circ} C / km$$

where c_p is the specific heat for a constant pressure

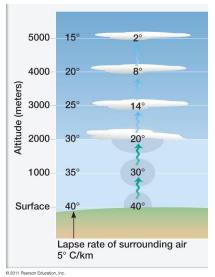
- If there is water vapor in the air, the lapse rate equation is more complex and is temperature dependent, but a typical saturated adiabatic lapse rate is -5.5 °C/km
- The environmental lapse rate is the observed rate of temperature change with elevation (typical lapse rate values are on the order of –(5 to 8) °C/km
- As mentioned earlier, lapse rates in the troposphere are generally negative and in the stratosphere become positive
- If an environmental lapse rate is positive (temperature increases with increasing altitude), this is called an **inversion**

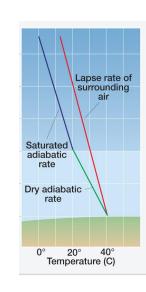
*an adiabatic process is one in which the air parcel does no thermodynamic work (i.e. PV remains constant, where I is a special constant)

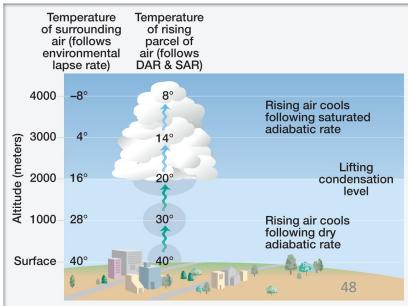


Stability and condensation level

- If the lapse rate of a parcel of air is steeper than the environmental rate (i.e., the temperature of the parcel decreases more rapidly with height than the surroundings), the parcel will tend to be stable and sink relative to surroundings
- If the lapse rate of a parcel of air is shallower than the environmental rate (i.e., the temperature of the parcel decreases more slowly with height than the surroundings), the parcel will tend to be unstable and rise relative to surroundings
- If the lapse rate of the parcel matches the lapse rate of the surroundings, the parcel will be in equilibrium
- The lifting condensation level (LCL) is the level of the atmosphere at which a given parcel of air will have full water vapor saturation – this is the level at which precipitation can start to form because the air parcel will have reached its dew point temperature
- **Condensation nuclei** solid or liquid particles onto which water vapor can condense
- In the complete absence of condensation nuclei (which is very rare), precipitation may not form even at full saturation, but one may wind up with "supercooled water"



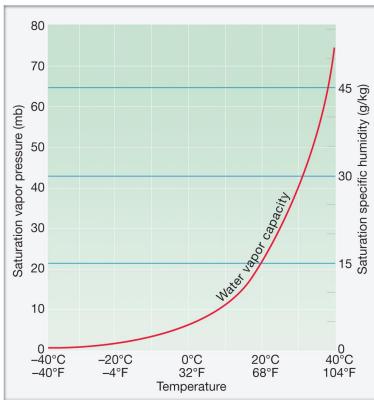






Humidity and saturation

- Absolute humidity: the mass of water vapor per volume of air (kg/m³) (moderately temperature dependent)
- Specific humidity/mixing ratio: the mass of water vapor per mass of air (kg/kg) (not temperature dependent)
- Relative humidity: the concentration of water vapor/ the saturation concentration of water vapor at the same temperature % (strongly temperature dependent)
- dew point temperature is the temperature at which there is 100% RH for a given SH
- Dew point temperatures tend to be low in cold and dry climates and high in warm and moist climates, although dew point temperatures tend to vary more with temperature than with climatological precipitation – the highest dew point temperatures ever recorded (around 95 °F/35 °C) were actually near the Persian Gulf rather than the Amazon rainforest
- The amount of water the atmosphere can hold is strongly temperature dependent





Clausius-Clapeyron equation

- Is derived from the ideal gas law and principles of thermodynamics
- Quantifies the relationship between saturation water vapor pressure and temperature

$$\frac{\dot{\Delta}p_{sw}}{\Delta T} = \frac{L_v(T)p_{sw}}{R_v T^2}$$

- where p_{sw} is the saturation vapor pressure of water, L_v is the specific latent heat of vaporization, R_v is the vapor gas constant and T is the temperature in degrees Celsius
- because this is a nonlinear differential equation, there is a useful approximation

$$p_{sw}(T) = 6.11e^{\left(\frac{17.625T}{243+T}\right)}$$

 This implies that with a 1 °C rise in temperature, there is an approximately 6-8% increase in the amount of water vapor the air can hold (at typical atmospheric temperatures)



Precipitation basics: types of precipitation

- Rain liquid water at surface (may have started as snow or hail initially)
- Freezing rain falls as a liquid, but becomes frozen on contact with cold ground; creates very hazardous conditions "black ice" for walking and driving, can endanger trees and powerlines
- Sleet falls as small ice pellets, implying that it went through a layer of above freezing air, became liquid and then refroze before hitting the ground; also very hazardous, although generally not quite as hazardous as freezing rain
- Snow falls in frozen form and was below freezing at every point on its descent to the ground, snow is typically much less dense than water or ice
- Hail falls in frozen form, but often in the summer months because very strong convective updrafts enabled formation of large chunks of ice







Cloud types

- There are many types of clouds, but the simple version is as follows
- Cumulus "puffy" clouds; when small to moderate, tend to indicate fair weather, when large tend to indicate convective storm and rather intense weather, positive radiative forcing
- Stratus relatively flat, vertically undeveloped, tend to produce steady, drizzling kind of precipitation, negative radiative forcing
- Cirrus thin, wispy clouds (usually fairly high – near tropopause), tend to precede storms, but do not produce precipitation directly, positive radiative forcing
- Nimbo or nimbus precipitating and often vertically developed









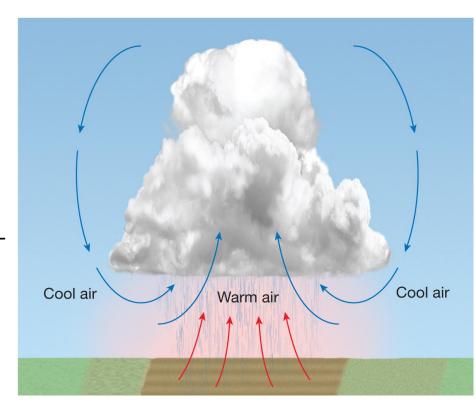
Precipitation genesis

- Convective/convergent precipitation that forms from convective motions induced by differential heating
- Frontal precipitation that forms from one air mass colliding with another air mass with different properties
- Orographic precipitation that forms from an air parcel encountering a topographic barrier and being forced to higher elevation and lower temperature



Convective/convergent precipitation

- Can be from small scale (isolated thunderstorms only a few miles wide) to very large scale (massive hurricanes/typhoons that are hundreds of miles in diameter)
- Responsible for almost all of the precipitation in the tropics, much of the summer precipitation in the midlatitudes and even some summer precipitation in the high latitudes
- Can be responsible for extremely violent weather –
 both hurricanes and tornadoes are a product of
 convective precipitation from warm, moist air,
 although not all convective precipitation is
 extremely violent
- Can produce extremely tall clouds (cumulonimbus clouds) which extend as high as 70,000 feet – well into the stratosphere
- Convective precipitation produces the majority of the world's hail

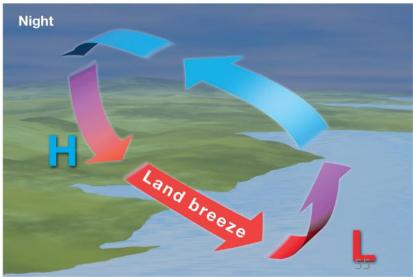




Land-sea breezes

- Because of the high heat capacity of water, water temperatures tend to vary less pronouncedly than air temperatures both on seasonal and daily time scales
- During the cooler times (night and winter), there is thermal convection over the water while during the warmer times (day and summer) there is thermal convection over the land
- The onshore flow of air from the sea to the convection over land is called the sea breeze, while the offshore flow of air from the land to the sea convection is called the land breeze
- Land-sea breezes usually refer to relatively small scale processes

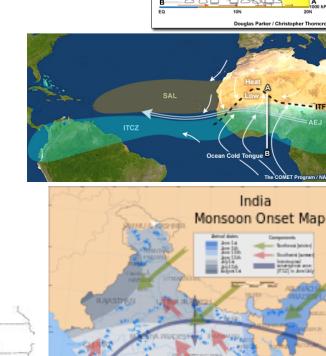






Wet-dry monsoons

- Monsoonal climates (typical in the tropics and subtropics) are a product of differential heating between a continental interior and the surrounding ocean
- In a simplistic way, monsoons can be thought of as giant land-sea breezes on a continental and seasonal scale
- In the summer a thermal low pressure system develops in a continental interior drawing in moisture advection from the surrounding ocean and creating intense, seasonal convective precipitation
- Monsoons respond to and contribute to the seasonal displacement of the ITCZ
- There are monsoonal climates in Africa, Asia, Australia and the Americas



Large-scale Features of the West African Monsoon and the Tropical Atlantic



Bimodal rains climates

- In the low latitudes, near the equator, the intertropical convergence zone arrives twice a year, causing two rainy seasons and two dry seasons
- Bimodal rain patterns can be seen in a range of climatologies from almost rainforest to desert

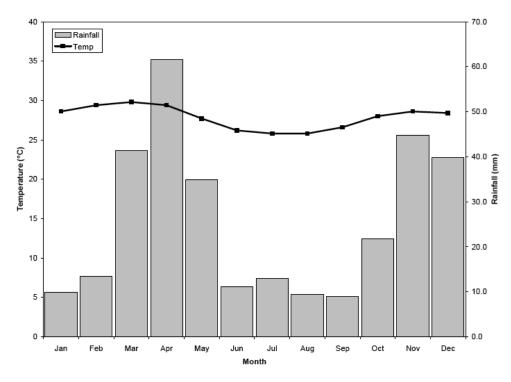


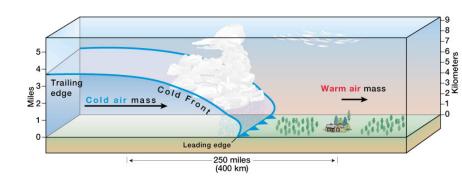
Figure 3. Climograph for the study area based on climate records for Hola for the period 1966–1985.

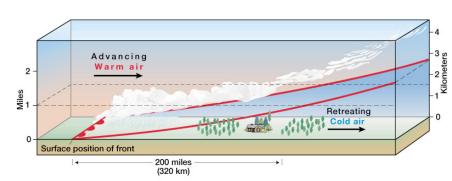
From paper by John Maingi, 2006
Referring to study area in eastern Kenya



Frontal Precipitation

- Along cold fronts (where a cold air mass displaces a warm air mass at the surface), precipitation tends to be somewhat more intense and less persistent than along warm fronts (where a warm air mass displaces a cold air mass at the surface) because cold fronts tend to have a steeper profile, thereby causing the rising and cooling to happen more rapidly
- Fronts can be over 1000 miles long bringing a swath of precipitation to much of a continent in a short time
- Most winter and a fair amount of spring and fall precipitation in the mid-latitudes and high latitudes comes from frontal systems

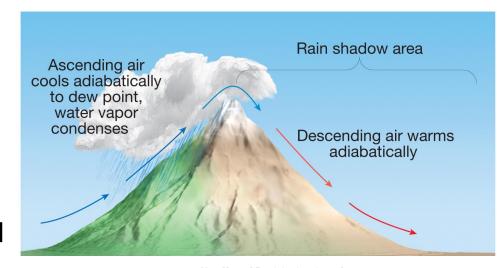


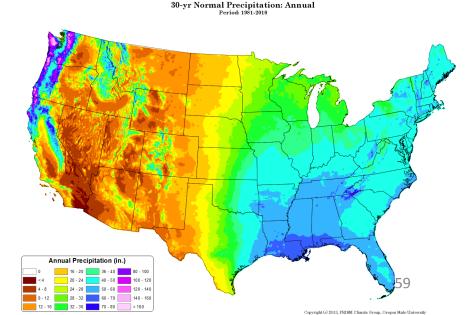




Orographic precipitation

- Precipitation that is formed by moisture laden air encountering a mountain and being forced to higher elevations and colder temperatures
- Orographic effects can have a profound impact on local precipitation on a very short spatial scale
- Example the Pacific Northwest

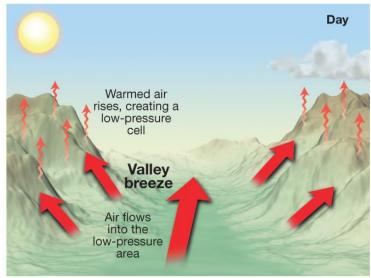




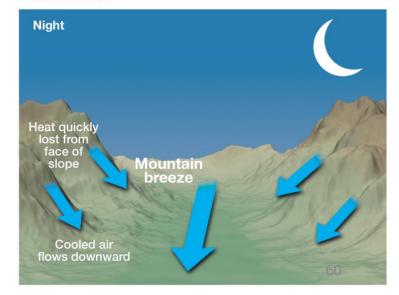


Mountain-valley breezes

- During the daytime, high peaks tend to experience more warming relative to valley floors; this induces upslope winds (valley breezes)
- During the night time, high peaks tend to experience more cooling relative to valley floors; this induces downslope winds (mountain breezes)



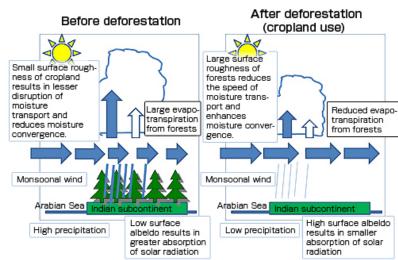
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Biophysical feedbacks on precipitation

- Plant cover effects surface roughness impacting how easily wind can act on the surface and how well water drains
- Heavy plant cover can decrease albedo, but increase shade
- Plant cover can effect precipitation significantly, especially in the tropics
- Plants store a fair amount of water which is given to the atmosphere through transpiration
- When convection then occurs, that transpired water can be returned to the plants as rain
- It's estimated that on the order of 40% of the very abundant rainfall in the Amazon rainforest had its origin in the trees of the rainforest and not the tropical ocean
- In arid climates especially, small changes to the amount of vegetation cover can have significant changes on local hydroclimatology
- Denudation tends to lead to lessened precipitation, higher runoff coefficients and more rapid erosion (although the effect on temperature is a bit more contextually dependent)

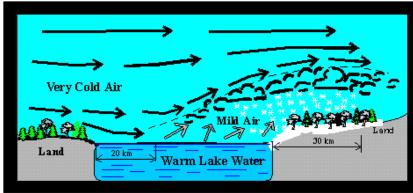


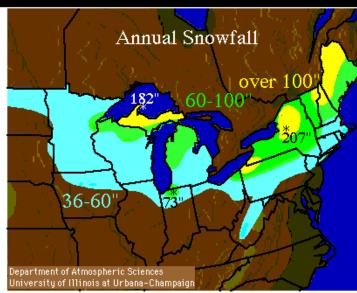




Lake/Ocean effect precipitation

- When water vapor is evaporated from a lake or ocean and that moisture laden air is then advected elsewhere to a place with a cold enough temperature to have precipitation, the precipitation can be enhanced
- This effect is often more pronounced in winter, as the water body is likely to be significantly warmer than the surrounding air enabling a great deal of moisture transfer
- The Lake effect snowfall in the Great Lakes is legendary







Hurricanes/Tropical Cyclones

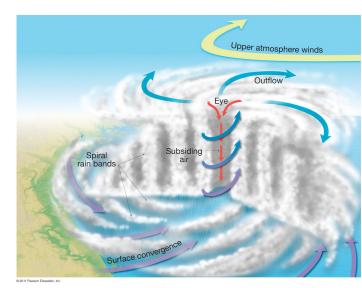
- Extreme thermal low pressure systems (sometimes below 900 mb) that originate in areas of very warm surface waters
- Export heat from low latitudes to high latitudes
- Formation
 - only over oceans with sea surface temperatures of 78°F or more
 - seldom form within 5° latitude of equator (needs Coriolis effect)
 - no one really knows how they are formed
 - often generated by African Easterly Waves
- Maintenance
 - derive energy from the latent heat of condensation





Hurricanes/ Tropical Cyclone features

- Decreasing pressure as one approaches the center
- In large hurricanes, an eye forms because surface convergence is so strong that not all the outflow can be aloft: eye is a relatively calm area of descending air and minimal wind and precipitation
- Eyes are not as prevalent in weaker hurricanes
- Cyclonic convergence at surface
- Anticyclonic divergence aloft
- Not frontal
- nearly circular isobars (closed)
- winds 75 MPH or greater (up to 200 MPH)
- Intense rainfall and winds in the center or around eyewall
- outbreaks of tornadoes in spiral arms and along eyewall
- Smaller than extratropical frontal storm: 100-600 mile diameter
- storm surge both because of intense low pressure and because of wind advection of surface waters
- winds reverse direction after passage of eye



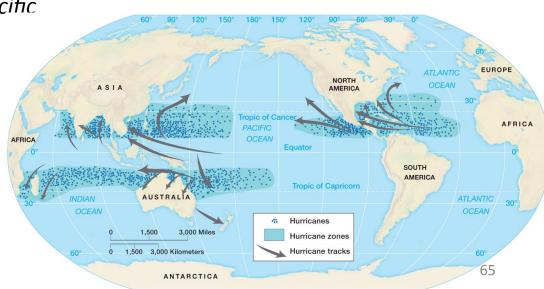


TC timing and distribution

- Most in late summer and early autumn because sea surface temperature at its maximum
- Heat export from tropics to extratropics and poles
- Dissipation
 - over colder ocean water
 - over land due to frictional effects, moisture sources cut off
 - Can cut itself off if it lingers too long in one location drawing warm water from surface ocean
 - Can also be dissipated or weakened by strong upper level wind-shear
- Track generally to west in tropics and subtropics (trades), then curve to the poleward and to the east as they encounter the mid latitude westerlies

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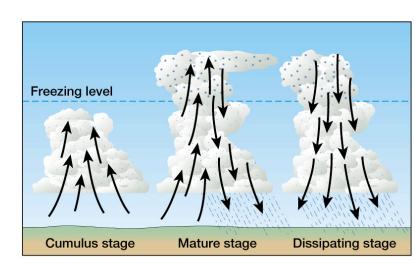
Few found in S. Atlantic, eastern S. Pacific

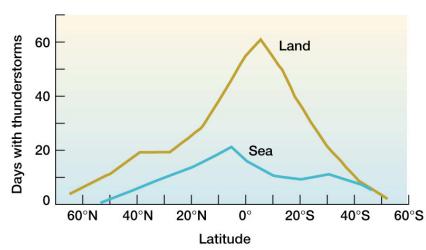




Thunderstorms

- Generally small (few 10's of miles in diameter maximum)
- Generally occur in summer or at least not winter (although thundersnow is possible)
- Can occur in meso-scale complexes, or strung along a front (squall line), or isolated
- Associated with vertical instability, high humidity
- Stages
 - cumulus: early, updrafts, precipitation formation
 - mature: precipitation falling, hail perhaps, maximum of thunder and lightning, wind (microbursts), tornadoes may occur, downdrafts and updrafts
 - dissipating: downdrafts







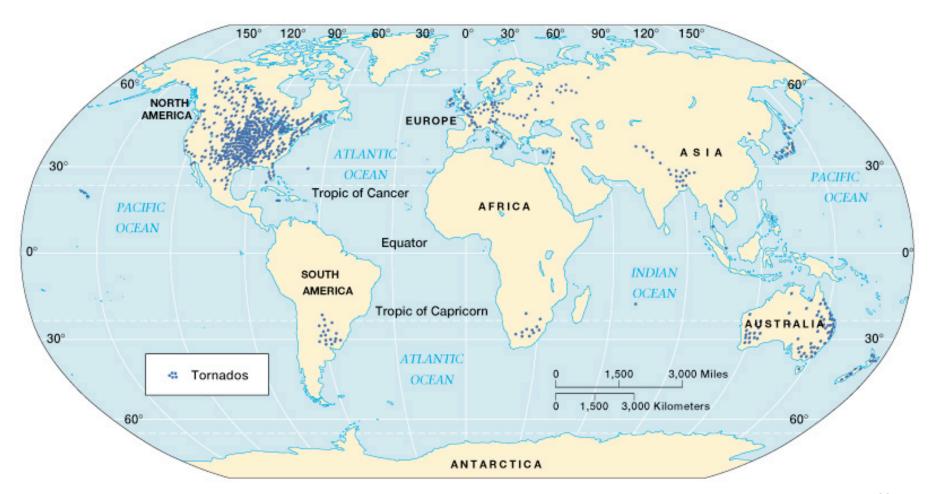
Tornadoes

- The product of collision between warm, moist air and cold dry air aloft
- Winds may exceed several hundred miles per hour, although most are much weaker (close to 100 MPH)
- Small (tenths of a mile to a mile or two wide)
- Short lived (minute to few hours on ground, move 15-30 MPH)
- Associated with severe thunderstorms, formation process quite uncertain
- Often on back end (SW) of storm
- Often have a "hook echo" radar signature
- Tornado activity tends to peak in late spring, although the temporal distribution varies regionally and tornadoes can happen at almost any time of year depending on conditions





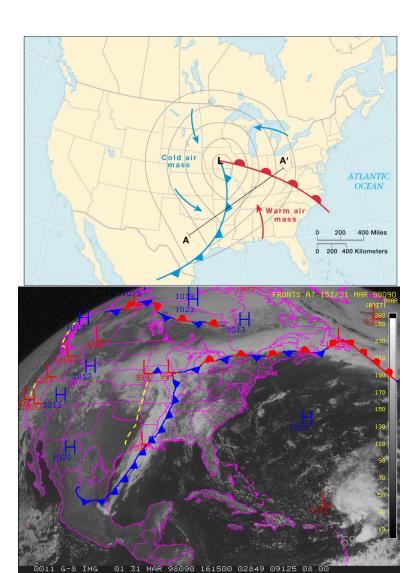
Distribution of Tornadoes





Midlatitude/Extratropical Cyclones

- Low pressure center storm in the mid-latitudes with a trailing front
- Very large scale (often on the order of 1000 miles
- stormy weather in vicinity of low, but also along associated fronts
- a fair amount of non-summer midlatitude precipitation comes from ETCs





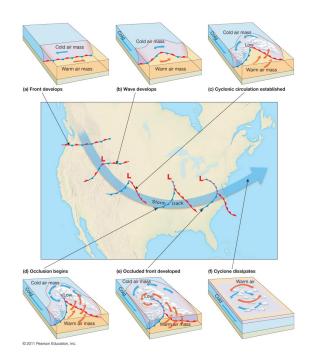
Extratropical Cyclones

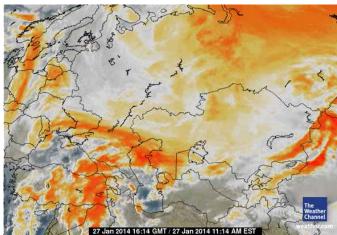
Movement

- generally west to east (although sometimes stronger meridional transport)
- 20-30 MPH (crosses US in 3-4 days)

Numbers

- 6-15 at a given time in either hemisphere
- more numerous, better organized, stronger in winter because temperature gradient is sharper and jet stream is stronger







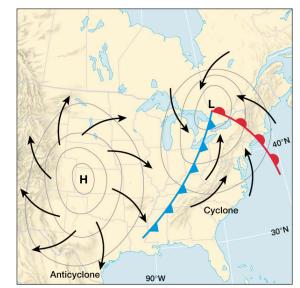
Extratropical Cyclones

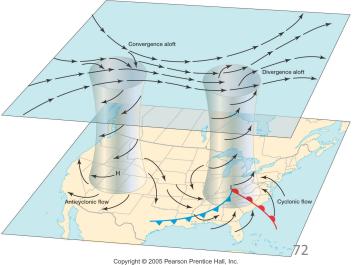
- Routes/storm tracks
 - Position varies north to south with season
 - Variations induced by the position of mountains, coastlines, jet stream
- Life cycle
 - cyclogenesis: often associated with kinks in the westerly flow pattern resulting from air passing over mountains or from land to ocean, or where a warm (cold) mass intrudes into a cold (warm) region
 - spin up to maturity takes a few days to a week
 - at maturity, a storm reaches maximum strength and warm and cold fronts are in "classic" positions
 - spin down takes a few days to a week
- Nor'Easters specific types of ETCs that effect the Eastern seaboard ETC approaches from southwest and encounters cold high pressure system in NE US and Eastern Canada: blizzard of 1993
- Sandy was a blend of tropical cyclone meets northeast blocking high and gets entrained into frontal system



Extratropical Anticyclones (highs)

- Larger than a cyclone
- High pressure abounds
- Result in generally fair weather
- No associated fronts
- Temperature depends on region of origin; often from high latitudes, although can originate in mid latitudes
- Often move along with cyclones; however can stall/ stagnate for period of days to even a week or more

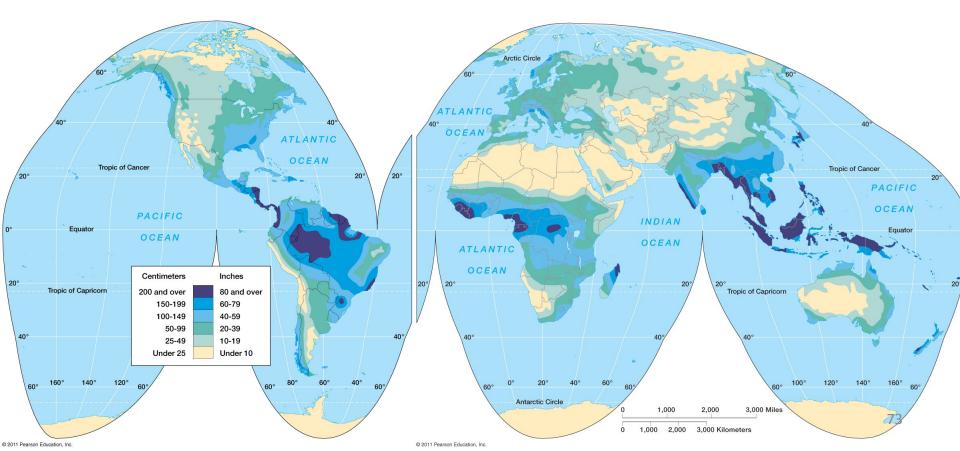






Global precipitation

 Heaviest in the tropics and near the polar front, lightest in the subtropics and high latitudes





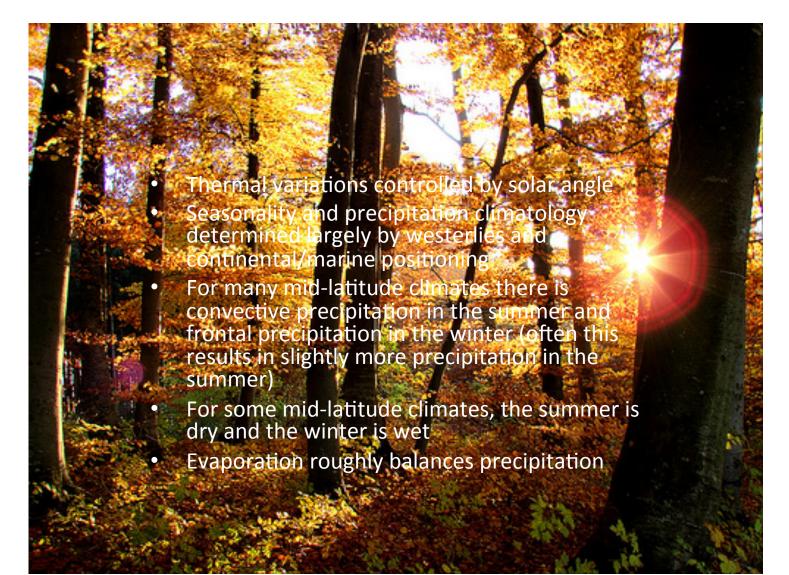
high latitudes

- Cold climate dominated by thermal high pressure and polar easterlies
- The limited precipitation that does fall generally comes from the midlatitudes and storms advected along the polar front
- The high latitude summers tend to be the wettest time of year
- (remember the relationship between water vapor concentration and air temperature)
- evaporation roughly balances precipitation





midlatitudes





Arid subtropics (and saline oceans)

- Aridity the product of sinking air/ dynamic high pressure from the descending limbs of the Hadley and Ferrell cells
- Arid conditions at low latitude can be induced by sinking air on the lee side of a mountain range
- Evaporation greatly exceeds precipitation



Tropics

- Precipitation pattern
 dominated by the seasonal
 position of the ITCZ
- Monsoonal climates in most regions of the tropics
- Very little temperature contrast from one time of the year to another
- Precipitation tends to greatly exceed evaporation