

Climate Studies

introduction to climate science

Chapter 6

Global Atmospheric Circulation

Ch. 6: Global Atmospheric Circulation

Essential Questions

- What forces cause the initiation, magnitude and direction of wind?
- How is the pressure gradient force established?
- What is the principle cause of the Coriolis force?
- How does friction play a role in affecting the wind?
- What is the role of gravity in air circulations?
- What types of instruments are utilized in monitoring wind?
- What are the principle circulation zones in planetary wind patterns?
- Why is the wave-like pattern of upper-air circulation critical to defining climatic characteristics?
- How are surface conditions affected by blocking patterns in the upper-air flow?
- Why are certain geographic regions prone to cyclogenesis?
- Why are extra-tropical cyclone paths favored in certain areas, but not others?

Introduction

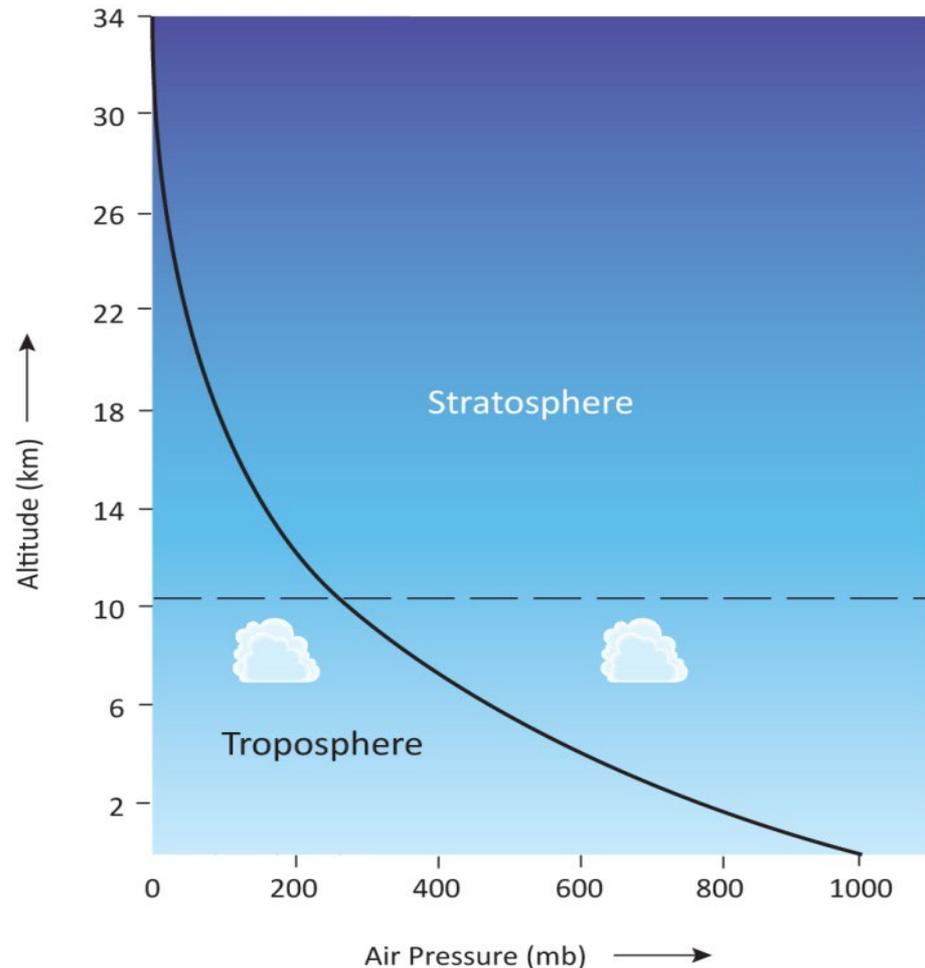
- Climate and the physical forces can explain
 - Why air masses move
 - How winds and storms are generated
 - How large scale patterns of circulation may be affected by a changing climate
- Planetary circulation, including vertical and horizontal motions that shift north and south with the Sun and the seasons, impose distinct signatures on regional climates
 - Departures from the prevailing flow patterns across the middle latitudes bring about stressful conditions, such as drought, flood or excessive temperatures
- In this chapter, the principal forces of atmospheric circulation are described
 - Pressure gradient force
 - Centripetal force
 - Coriolis force
 - Friction
 - Gravity

Forces that Act on Atmospheric Circulation

- The atmosphere and all points on Earth's surface complete a circular path every 24 hours
- The atmosphere circulates in response to temperature gradients within the planetary system
 - Gradients due to differences in rates of radiational heating and radiational cooling between Earth's surface and atmosphere, and the tropics and high latitudes
 - Circulation of the atmosphere and ocean transports heat from warmer to colder locations
- *Wind*
 - Horizontal component of moving air
 - Local motion of air measured relative to the surface of Earth
 - Tangible ECV and potentially destructive
 - Consistency (or lack) defines the climatic character of a region

Pressure Gradient Force

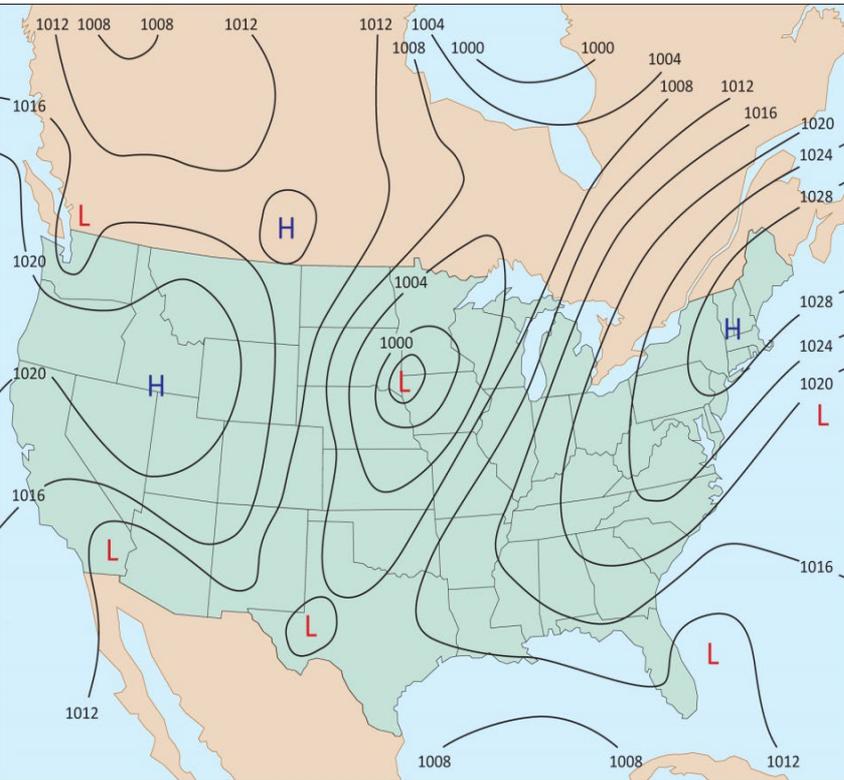
- **Force** - push or pull on an object with a vector quantity both in magnitude and direction
- **Pressure** - measure of force acting on a unit area
- The weight, a force, of the above air compresses the atmosphere so the maximum air density and pressure are at Earth's surface
 - Air density and pressure decrease rapidly with increasing altitude
 - Average air pressure at sea level is 1013.25 millibars (mb)



Pressure Gradient Force

- Air density in the atmosphere varies inversely with both temperature and humidity
 - Air density increases with falling temperature and decreasing humidity
 - Cold, dry air masses are denser and produce higher surface pressures than warm, humid air masses
 - Warm, dry air masses exert higher surface pressures than equally warm, but more humid air masses
- **Pressure gradient** - change in air pressure over a distance, can occur both vertically and horizontally
 - Falling air pressure often signals a turn to stormy weather
 - Rising air pressure indicates clearing skies or continued fair weather

Pressure Gradient Force



• Weather Maps

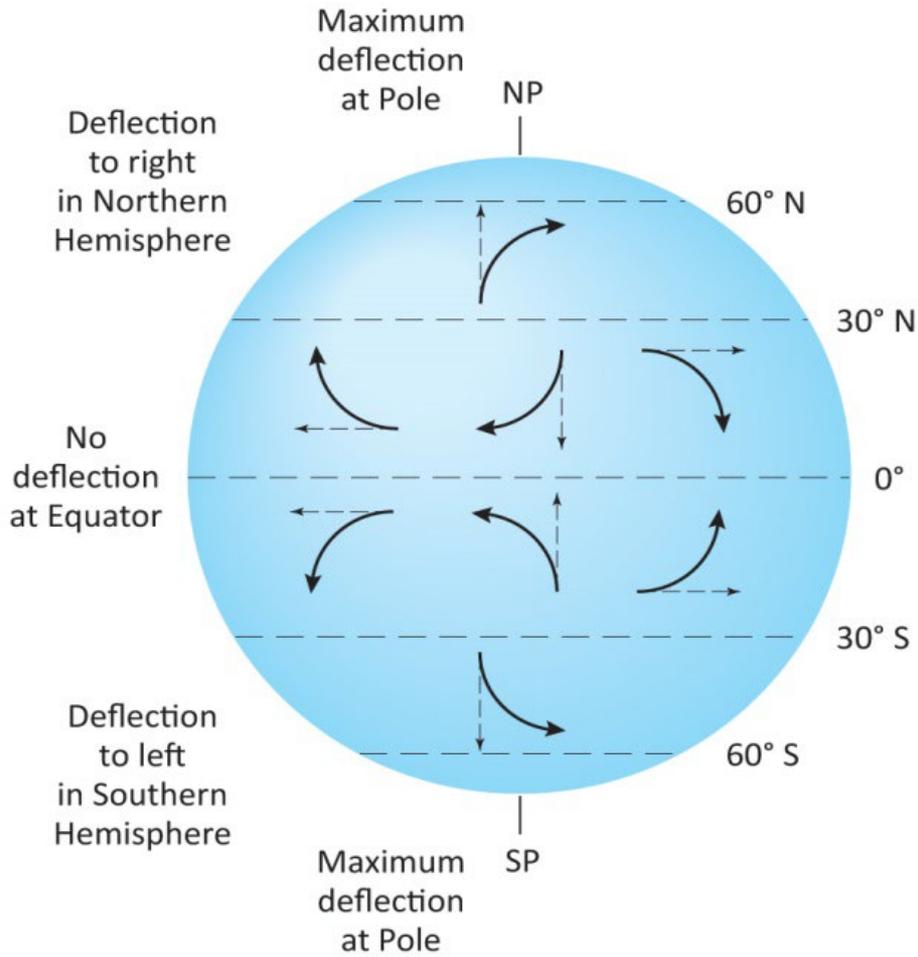
- H - High pressure system, anticyclone, brings fair weather
- L - Low pressure system, cyclone, brings stormy weather
- Isobars - lines that join areas with the same air pressure (drawn at 4-mb intervals)
 - Used to determine horizontal air pressure gradients
 - Weather stations located at altitudes adjust their air pressure readings upward to approximate sea level

Pressure Gradient Force

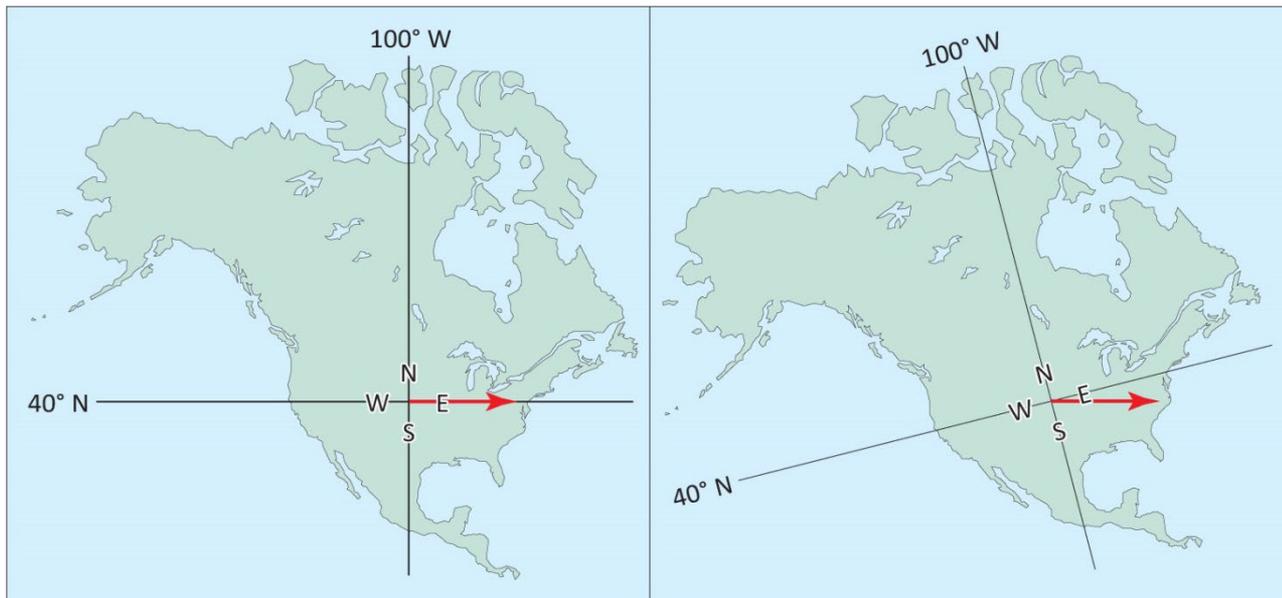
- **Pressure gradient force** - response to horizontal air pressure gradients, the wind blows from high pressure toward low pressure, orienting perpendicular to isobars
 - Wind is relatively strong where the pressure gradient is steep (closely spaced isobars)
 - Wind is light where the pressure gradient is weak (widely spaced isobars)

Coriolis Force

- **Coriolis Effect** - caused by a rotating Earth, everything moving freely over the planet's surface, including air and water, is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, relative to Earth's surface

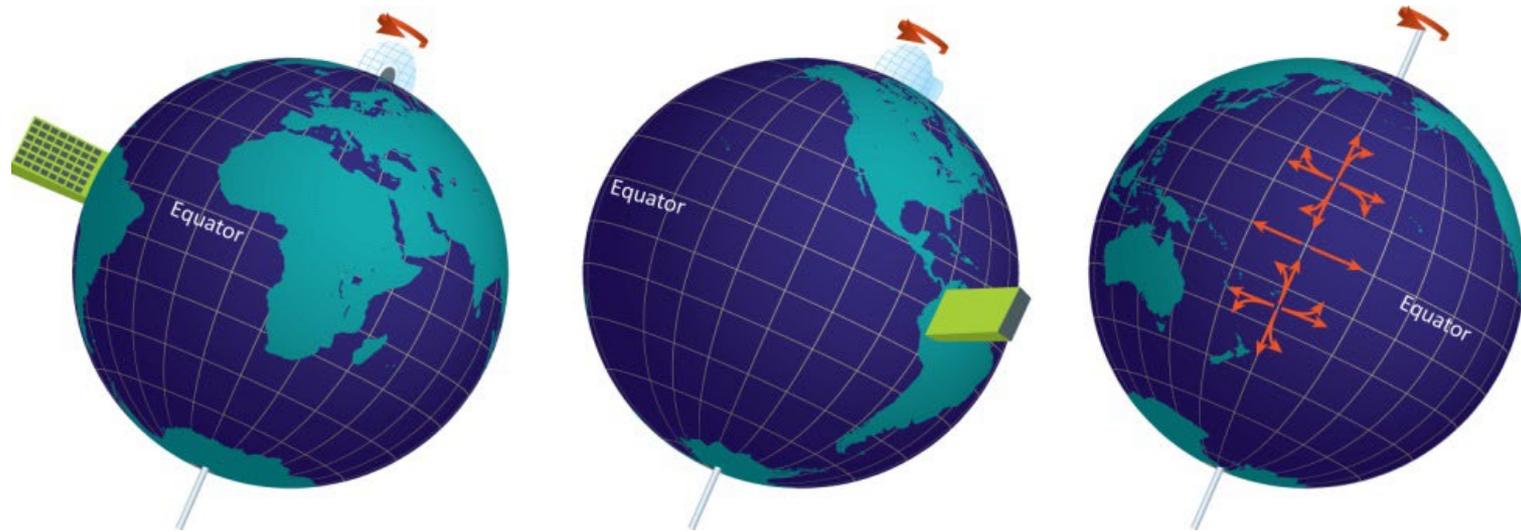


Coriolis Force



- Newton's first law of motion - a moving object remains in constant, straight-line motion unless acted upon
- Both air and water move horizontally in a straight line while Earth rotates beneath the moving air and water
- Wind is displaced from a straight-line path when measured with respect to the underlying rotating Earth's surface
- **Coriolis force** - apparent force derived to describe the Coriolis Effect's magnitude and direction

Coriolis Force



- In a 24-hr day, Earth completes one rotation, as would towers located at the North Pole and South Pole
 - A tower at the equator would not rotate at all about its vertical axis because of its orientation perpendicular to Earth's axis of rotation
 - At any latitude in between, some rotation of a tower occurs but not as much as at the poles

Friction

- **Friction** - resistance that an object or medium encounters as it moves in contact with another object or medium
- **Molecular viscosity** - the random motion of molecules composing a liquid or gas, a type of fluid friction
- **Eddy viscosity** - fluid friction that arises from eddies, large irregular motions, that develop within fluids

Friction



- **Eddies** - visible as swirls, tap the stream's kinetic energy so that the stream slows
- **Boundary layer** - atmospheric zone where frictional resistance (eddy viscosity) arising from surface effects is confined, below an average altitude of 1000 m (3300 ft.)

Gravity

- **Gravity** - force of attraction between Earth and another object, with a magnitude directly proportional to the product of the masses of Earth and the object, but inversely proportional to the square of the distance between their centers of mass
 - Accelerates at 9.8 m/s^2 (32.2 ft./sec.^2)
- Gravity always acts directly downward
 - Does not greatly affect the horizontal wind
 - Influences vertical air, including ascending and descending air
 - Such as the updrafts and downdrafts in convection currents (e.g., thunderstorms)
 - Responsible for the downhill drainage of cold, dense air

Forces that Act on Atmospheric Circulation

- The horizontal pressure gradient force
 - Responsible for initiating essentially all air motion
 - Acts on air parcels perpendicular to isobars away from regions of high air pressure and toward regions of low air pressure
 - The magnitude is directly proportional to the pressure gradient
 - The closer the spacing of isobars, the greater the magnitude of the pressure gradient force
- The Coriolis force arises from the rotation of Earth on its axis
 - Deflects large-scale winds to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere
 - Increases with latitude from zero at the equator to a maximum at the poles
- Friction always opposes motion
 - Acts opposite to the motion of the wind and increasing with increasing surface roughness
 - Slows horizontal winds blowing within 1000 m (3300 ft.) of Earth's surface
- Gravity pulls air vertically downward, not modifying the horizontal wind

Synergistic Forcing on Large Scale Wind Circulation

- Forces operating in the atmosphere act together in governing both wind speed and direction
 - From Newton's first law of motion, when the forces acting on an air parcel are balanced, no net force operates and the parcel either remains stationary or continues to move along a straight path at constant speed
 - When forces are balanced, the net acceleration is zero
- These interactions are responsible for winds typically found in the upper-atmosphere near the tropopause, called geostrophic and gradient winds

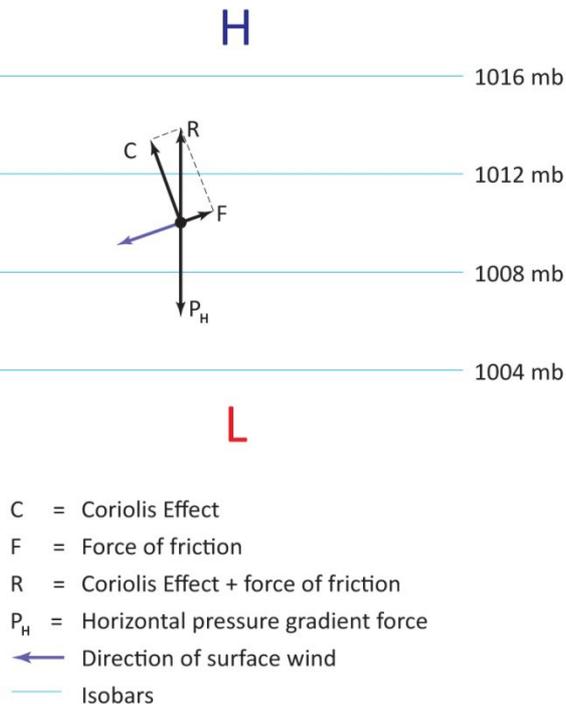
Geostrophic Wind

- **Geostrophic wind** - un-accelerated, horizontal movement of air that follows a straight path at altitudes above the atmospheric boundary layer, resulting from a balance between the horizontal pressure gradient force and the Coriolis force
- Because the Coriolis force is significant only in larger-scale circulations, the geostrophic wind develops only in large-scale weather systems

Gradient Winds

- **Gradient wind** - a large-scale, horizontal and frictionless wind blowing parallel to isobars with a curved path, because a net centripetal force constrains air parcels to a curved trajectory, forces are not balanced
 - The horizontal pressure gradient force, the Coriolis force and the centripetal force influence the gradient wind
- While the geostrophic and gradient wind models only approximate the behavior of horizontal winds above the atmospheric boundary layer, they allow atmospheric scientists to analyze maps of atmospheric wind flow

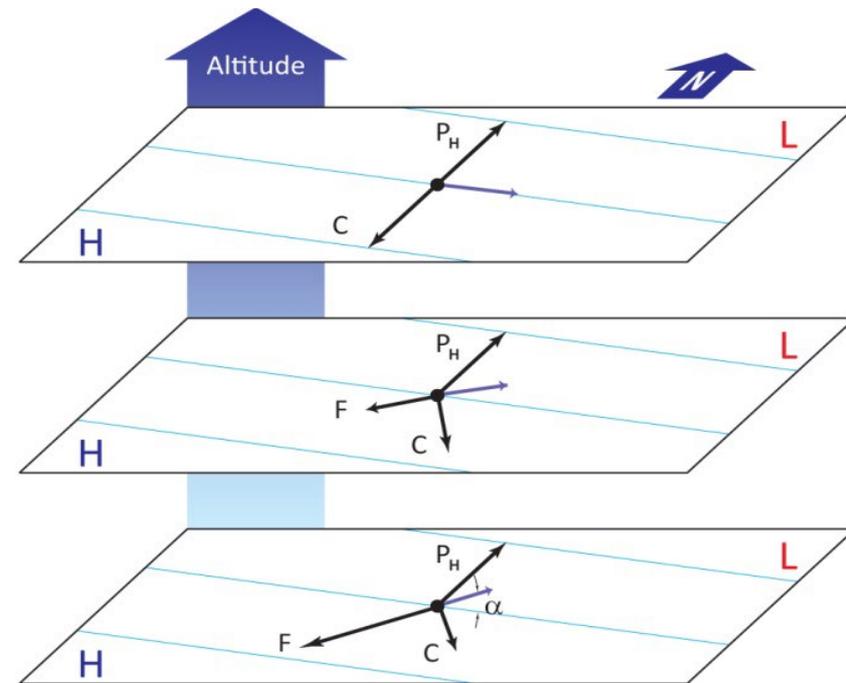
Surface Winds in Cyclones and Anticyclones



- For large-scale Northern Hemisphere air motion along a straight path, frictional force (F) combines with the Coriolis force (C) to balance the horizontal pressure gradient force (P_H)
 - Friction acts directly opposite the wind flow
 - Coriolis force acts at a right angle and to the right of the direction toward which the air moves
- Friction slows the wind, weakening the Coriolis force
 - Coriolis no longer balances the horizontal pressure gradient force
- The horizontal pressure gradient force (P_H) is balanced by the resultant (R)
 - $R = C + F$
- Due to the roughness of Earth's surface, friction slows the horizontal wind and shifts the wind direction obliquely across isobars and toward lower pressure

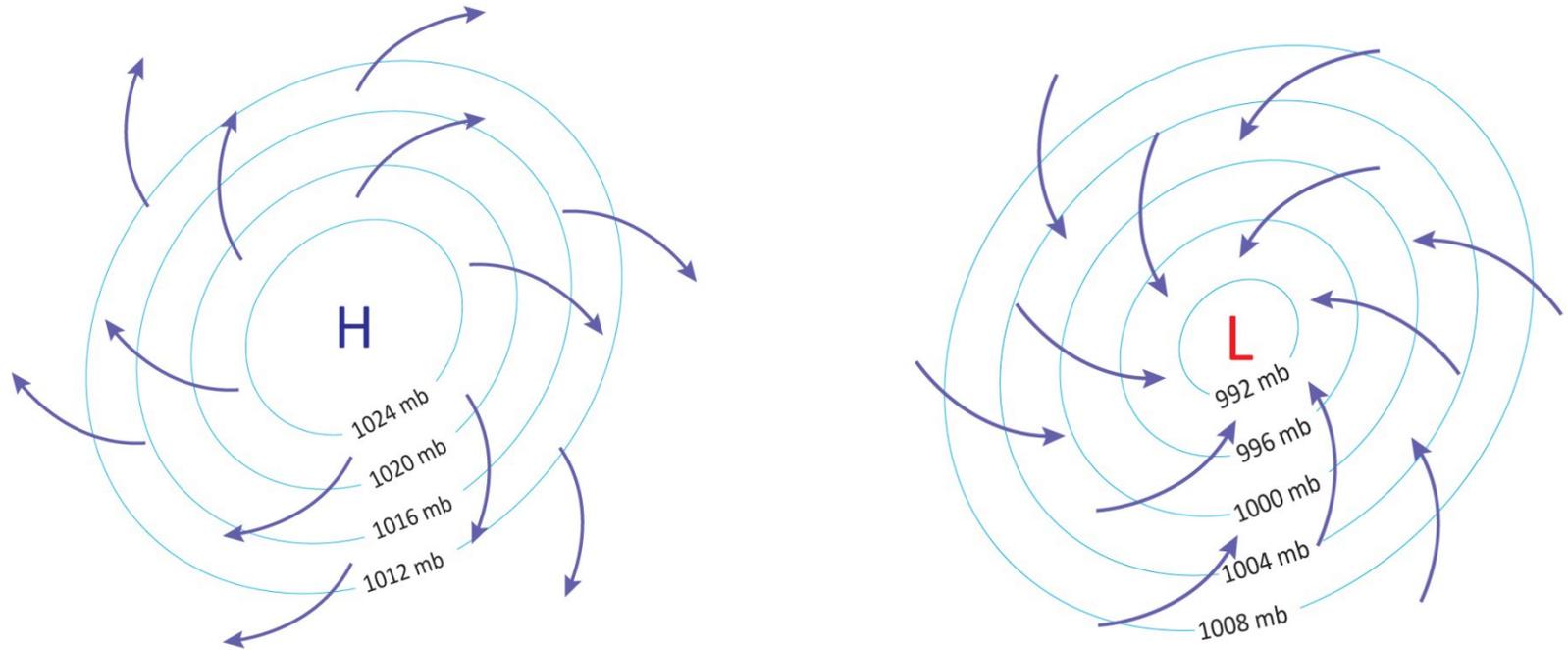
Surface Winds in Cyclones and Anticyclones

- Friction's influence on the horizontal wind diminishes with altitude
 - Where it becomes negligibly small marks the top of the atmospheric boundary layer
- Horizontal winds strengthen with altitude through the atmospheric boundary layer
- The angle between wind direction and isobars is greatest near Earth's surface
 - It decreases with altitude until essentially zero at the top of the atmospheric boundary layer



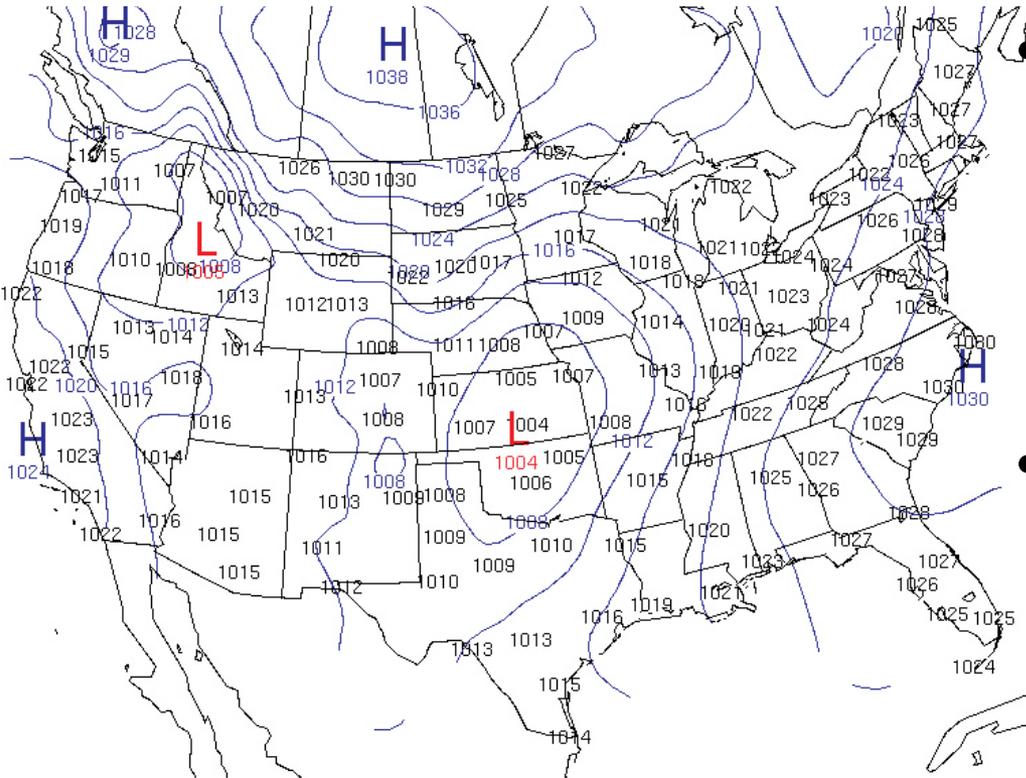
- C = Coriolis Effect
- F = Force of friction
- P_H = Horizontal pressure gradient force
- α = Angle between wind direction and isobars
- Direction of surface wind
- Isobars

Surface Winds in Cyclones and Anticyclones



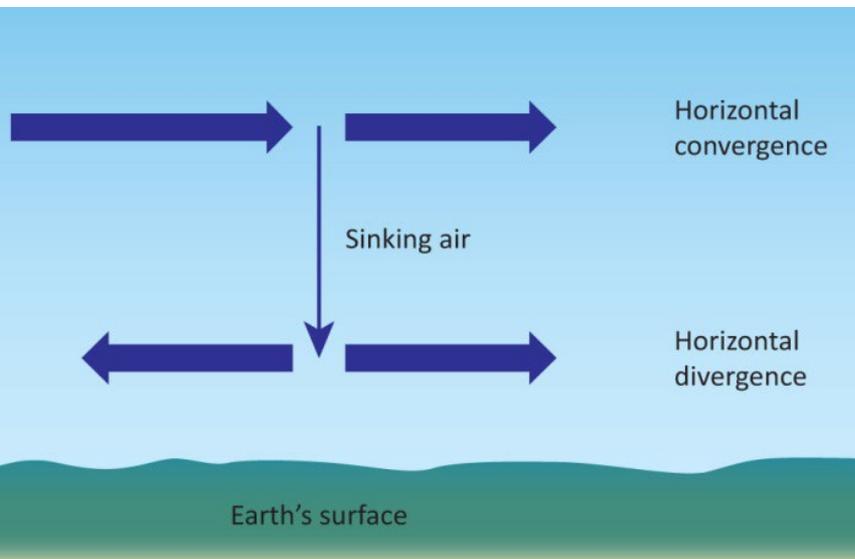
- Surface winds in a Northern Hemisphere anticyclone blow clockwise and spiral outward
- Surface winds in a Northern Hemisphere cyclone blow counterclockwise and spiral inward

Surface Winds in Cyclones and Anticyclones



- Isobars form complicated patterns
 - Ridges for anticyclonic curves
 - Troughs for cyclonic curves
- In ridges and troughs
 - Winds parallel isobars above the atmospheric boundary layer
 - Winds cross isobars toward low pressure near Earth's surface

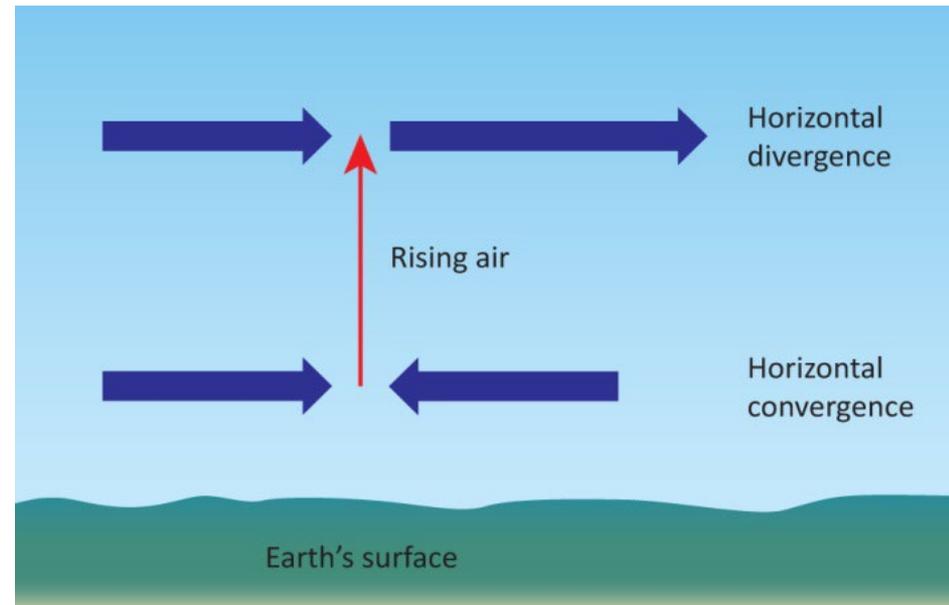
Surface Winds in Cyclones and Anticyclones



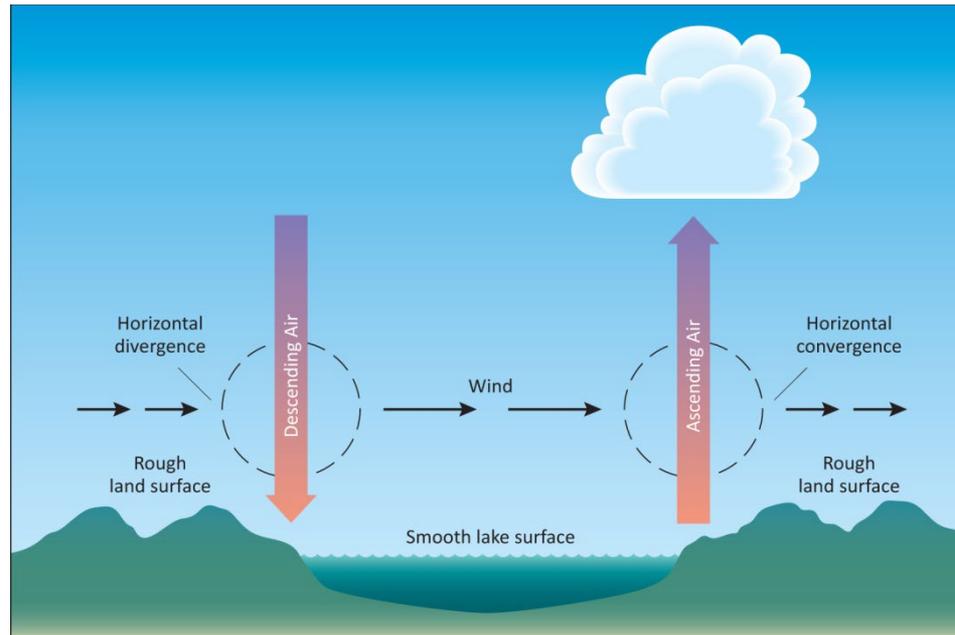
- In an anticyclone
 - Descending air causes temperature and saturation vapor pressure to increase
 - Lowers the relative humidity
 - Clouds vaporize
 - Clear skies, fair weather
 - Favors intense nocturnal radiational cooling
- Horizontal air pressure gradient is very weak over a broad area around the center of the system
- Air adjacent to the ground may be chilled to saturation so that nighttime dew, frost or fog may develop
- Air masses develop under these large, slow moving high pressure systems

Surface Winds in Cyclones and Anticyclones

- In a cyclone
 - Ascending air causes temperature and saturation vapor pressure to decrease
 - Increases the relative humidity of unsaturated air
 - Clouds and precipitation may eventually develop
 - Typically stormy weather
- Air flows into a low pressure system from all directions, at middle and high latitudes
 - Brings together different air masses, separated by fronts



Surface Winds in Cyclones and Anticyclones



- When the horizontal wind blows from a rough surface to a relatively smooth surface, as when it blows from land to sea, the wind accelerates
 - Acceleration causes the wind to diverge, inducing downward motion of air
- When the horizontal wind blows from a smooth to a rough surface, the wind slows and converges, inducing upward air motion
- Along a coastline, cumulus clouds develop with an onshore wind (from sea to land) and dissipate with an offshore wind (from land to sea)

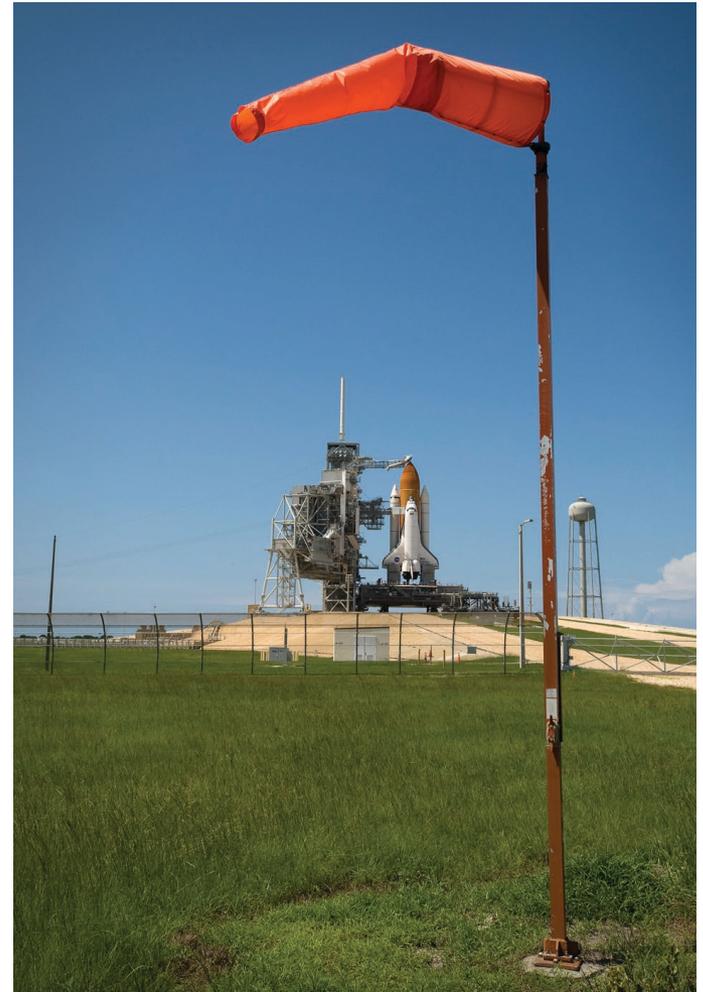
Monitoring Wind Circulations



- Common wind-monitoring instruments measure only the horizontal component of wind
- **Wind vane** - a free-swinging horizontal shaft with a vertical plate at one end and a counterweight (arrowhead) at the other end, which always points directly into the wind, or a windsock, a cone-shaped cloth sleeve open at both ends

Monitoring Wind Circulation

- Airport windsock
 - Cone-shaped cloth sleeve open at both ends
 - Larger end of the sock is held open by a metal ring, which is attached to a pole and is free to rotate
 - Air enters the larger opening and stretches the sleeve downwind



Wind Direction

- Wind direction is always designated and reported as the direction from which the wind blows
 - Wind blowing from the east toward the west is described as an east wind
- A wind vane may be linked electronically or mechanically to a dial that is calibrated to read and record in points of the compass or in degrees measured clockwise from true north
- These observations, taken over a long period of time, help define the wind climatology for a location

Wind Speed



- **Cup anemometer** - 3 or 4 open hemispheric or conical-shaped cups mounted to spin horizontally on a vertical shaft
- Sonic anemometer - 3 or 4 arms that send and receive ultrasonic pulses
 - The travel times of sound waves with and against the wind are translated into wind speed and direction
- Sonic anemometers replaced cup anemometers as the standard wind sensor in the NWS's ASOS

Wind Speed



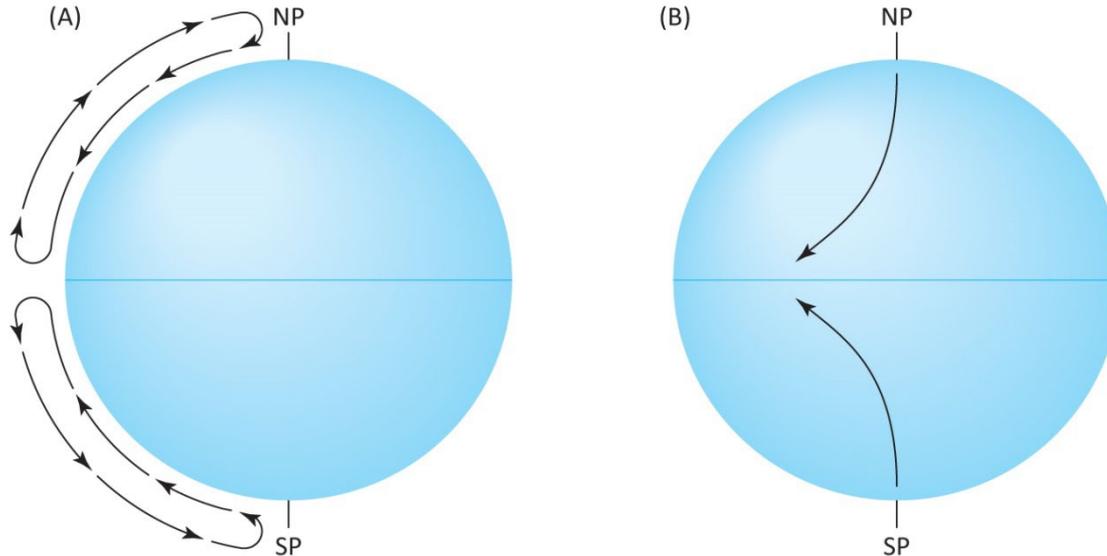
- **Scatterometer** - radar system mounted on satellites to monitor near-surface ocean wind speed and direction
 - They emit pulses of microwave energy to the sea surface and waves backscatter some of the energy to the instrument as an echo.
 - Stronger wind results in higher waves, and greater backscattering as a result

Winds Aloft

Circulation	Space Scale (km)	Time Scale
Planetary scale	10,000 – 40,000	Weeks to months
Synoptic scale	100 – 10,000	Days to a week
Mesoscale	1 – 100	Hours to a day
Microscale	0.001 – 1	Seconds to hours

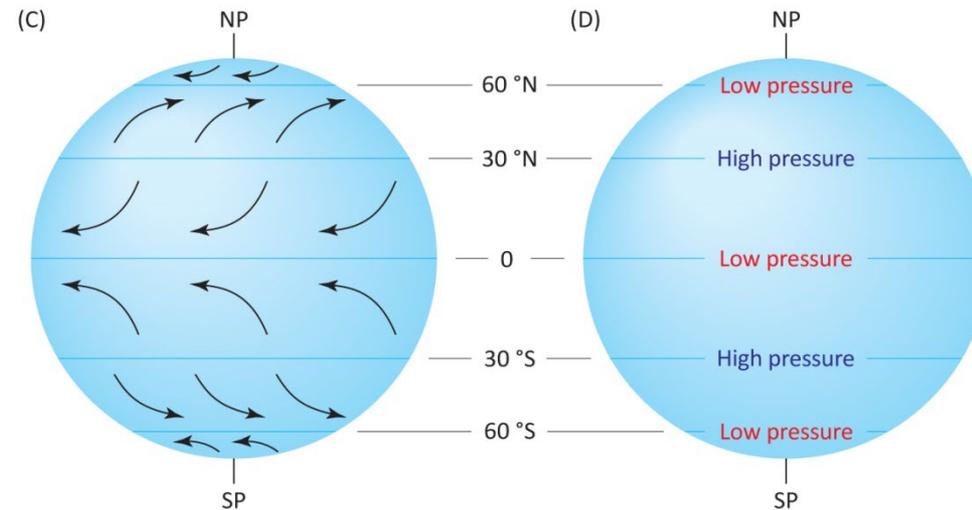
- The Doppler Effect used in wind profilers to monitor winds up to an altitude of about 16,000 m (52,500 ft.)
- **Synoptic scale** - continental or oceanic weather systems, such as extratropical cyclones, hurricanes, and air masses, 100 – 10,100 km in size, lasting weeks to months
- **Mesoscale** - weather systems that are so small they influence only a portion of a county or large city, such as thunderstorms and sea and lake breezes, 1 – 100 km in size, lasting hours to days
- **Microscale** - weather system that covers a very small area, such as several city blocks or a small town, such as a tornado, 0.001 – 1 km in size, lasting seconds to hours

Boundary Conditions



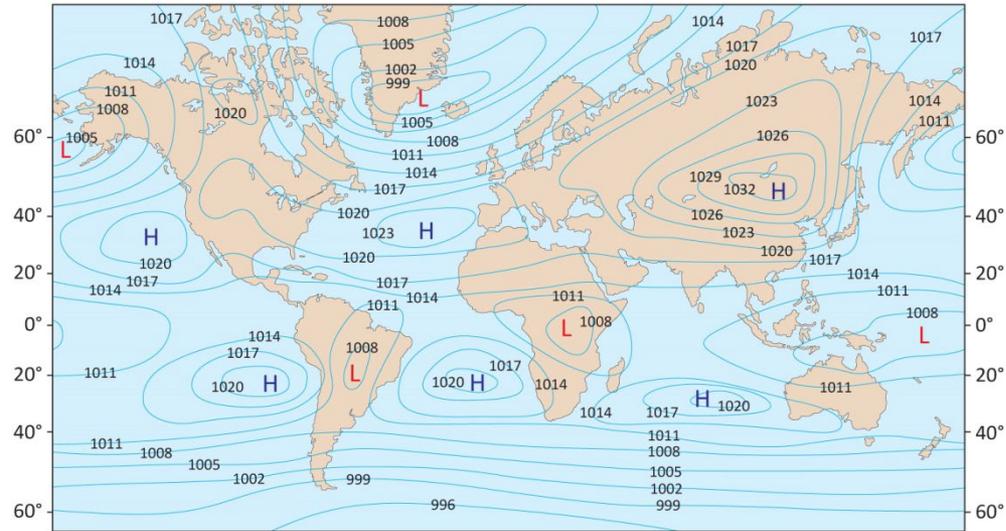
- **A: Non-rotating Sphere**
 - Temperature gradient develops between the equator and poles on the side facing the Sun
 - A huge convection cell forms in each hemisphere
 - Cold, dense air at the poles sinks and flows at the surface toward the equator, forcing warm, less dense air to rise
 - Aloft, the equatorial air flows toward the poles, completing the convective circulation
- **B: Rotating Sphere**
 - Surface winds in the higher latitudes blow counter to the planet's direction of rotation, which is from west to east

Boundary Conditions

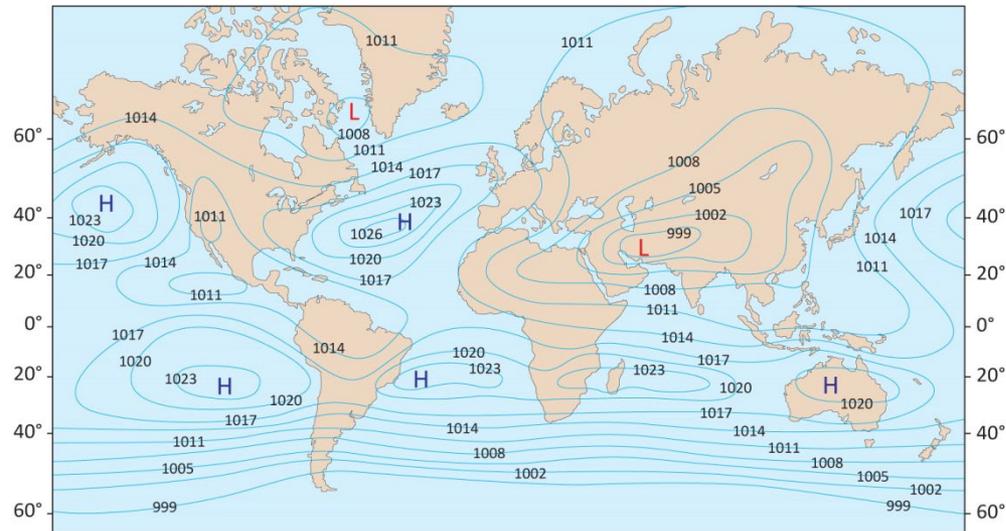


- C: 6 Wind Belts
 - Atmospheric circulation is maintained because the planetary-scale winds split into three belts in each hemisphere
 - Winds blow with and against the planet's rotational direction
- D: Convergence/Divergence Zones
 - Convergence leads to ascending air, cooling by expansion, cloud development and precipitation
 - Convergence zones are belts of low surface air pressure
 - Where winds diverge, air descends, is compressed and warms, and the weather is generally fair
 - Divergence zones are belts of high surface air pressure

Pressure Systems and Wind Belts

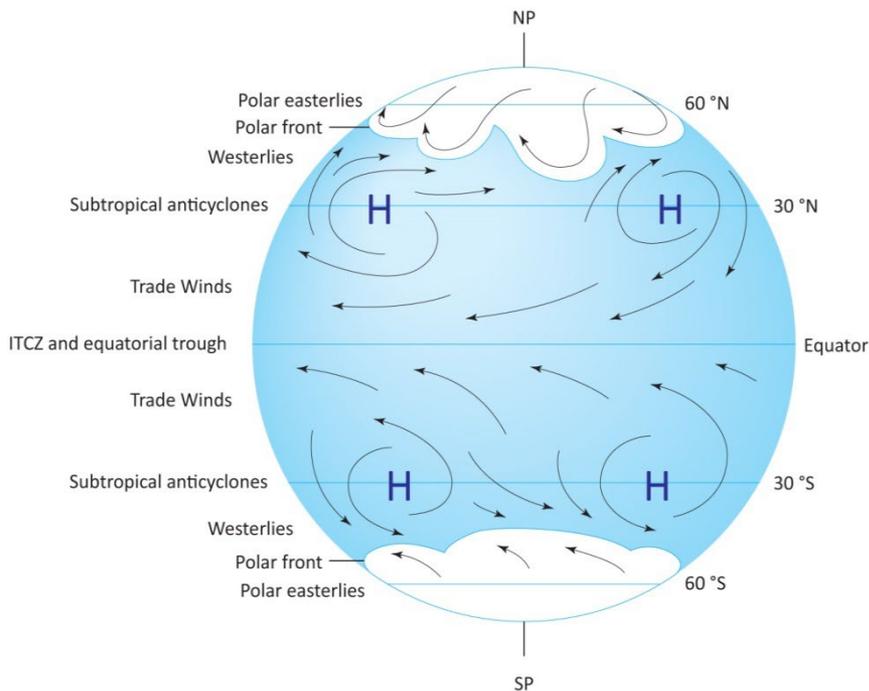


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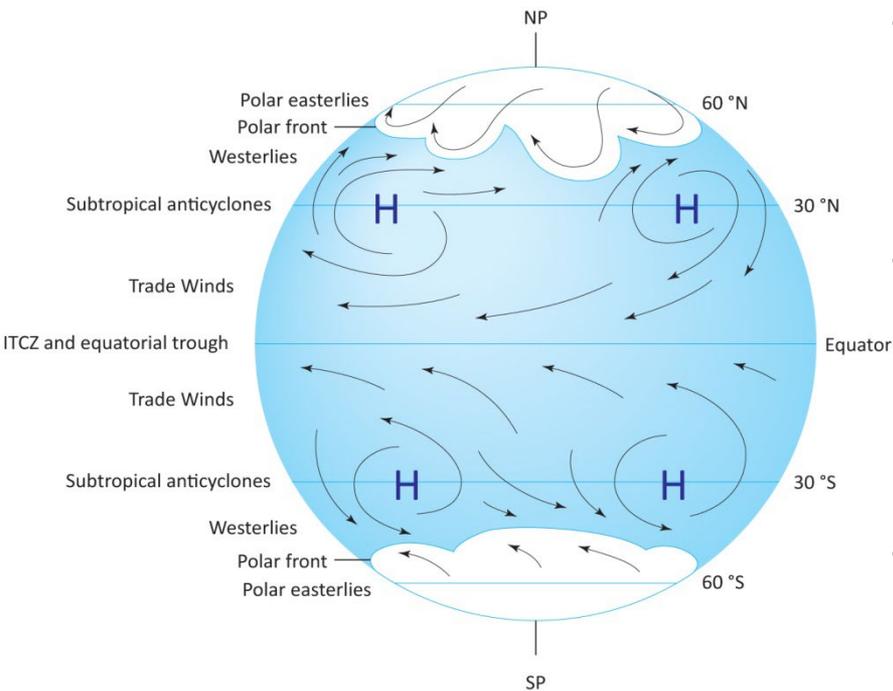
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Pressure Systems and Wind Belts



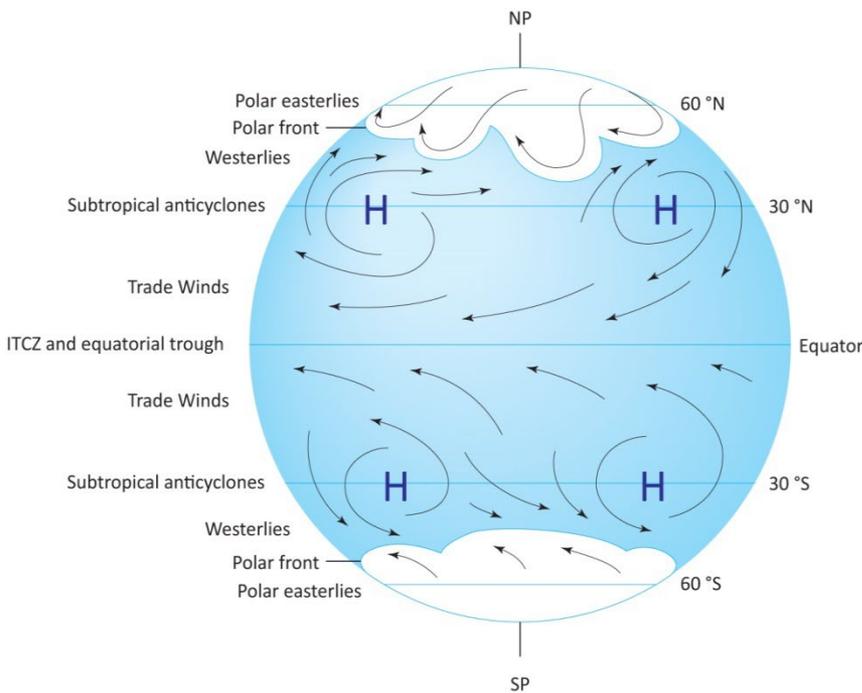
- **Circumpolar vortex** - an upper-air eastward flowing jet stream encircling the Antarctic produced by the midlatitude northwesterlies and the polar southeasterlies converging along a nearly continuous belt of low pressure around the Antarctic continent
- **Polar front** - where discontinuous, dense, cold air masses flowing toward the equator meet milder, less dense air masses moving toward the pole
 - **Front** - a narrow zone of transition between air masses that differ in temperature, humidity or both

Pressure Systems and Wind Belts



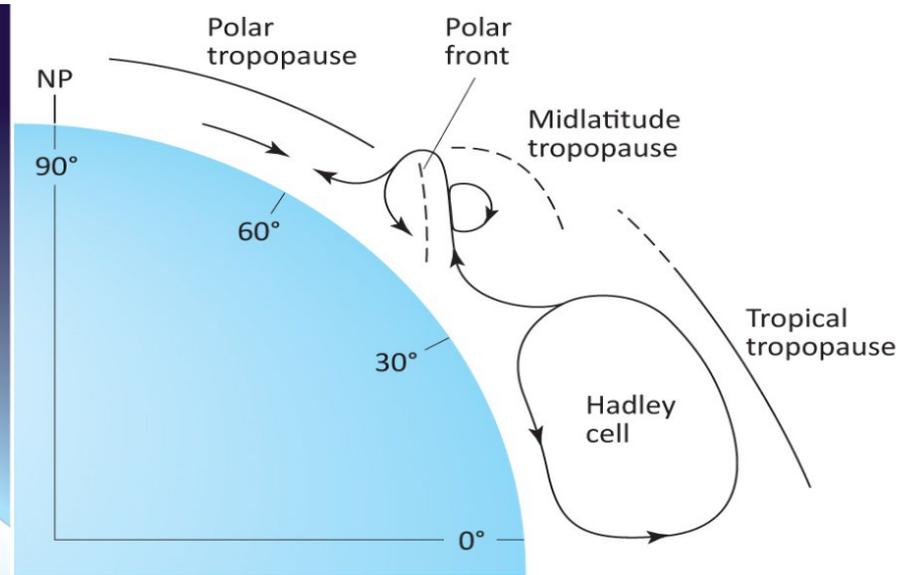
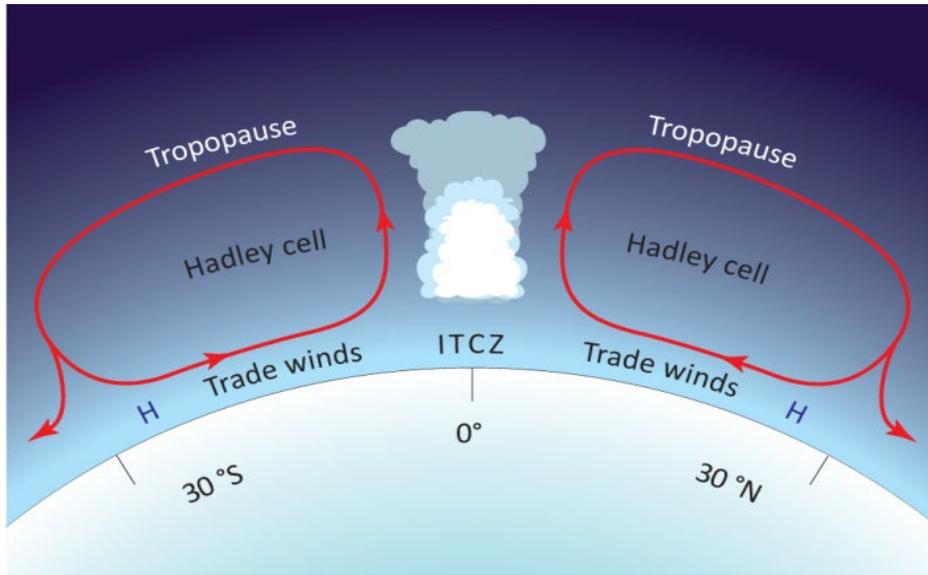
- **Westerlies** - highly variable mid-latitude surface winds north of the horse latitudes that blow from the southwest
- **Horse latitudes** - weak horizontal air pressure gradient with light surface winds or calm air, at all latitudes between about 30 and 35 °N and S under subtropical highs
- **Subtropical high** - extending from the ocean surface up to the tropopause, planetary-scale circulation centered over subtropical latitudes, near 30 °N and S of the North and South Atlantic, the North and South Pacific, and the Indian Ocean

Pressure Systems and Wind Belts



- **Trade winds** - persistent surface winds blowing from the northeast out of the southern flanks of the anticyclones
- **Intertropical convergence zone (ITCZ)** - discontinuous low-pressure belt with thunderstorms paralleling the equator, located along the heat equator

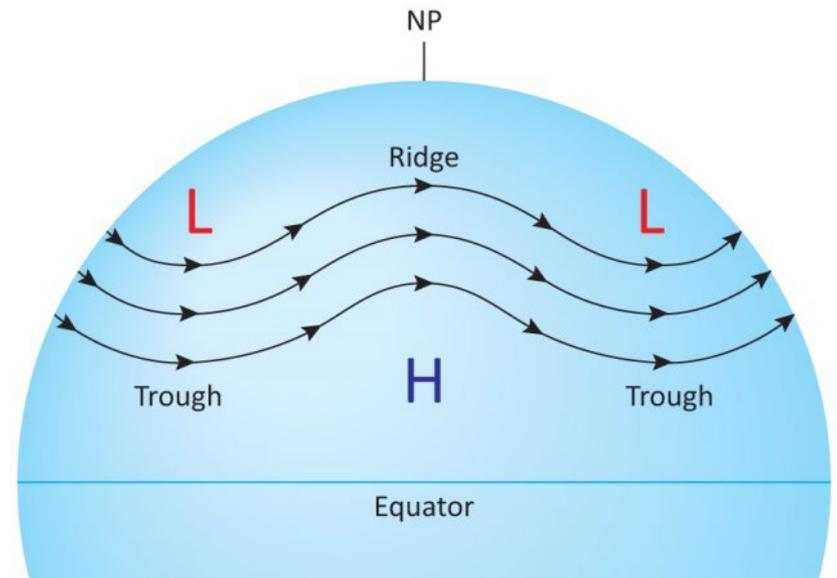
Winds Aloft



- **Hadley cell** - a north-south vertical profile of low-latitude circulation resembling a huge convection current located on either side of the ITCZ and extending to the subtropical highs
- Similar cells do not occur in middle or polar latitudes

Winds Aloft

- Aloft in middle latitudes, winds blow from west to east in a wavelike pattern of ridges and troughs
 - Responsible for the development and movement of the synoptic-scale weather systems, such as cyclones and anticyclones
 - North-south components contribute to poleward heat transport



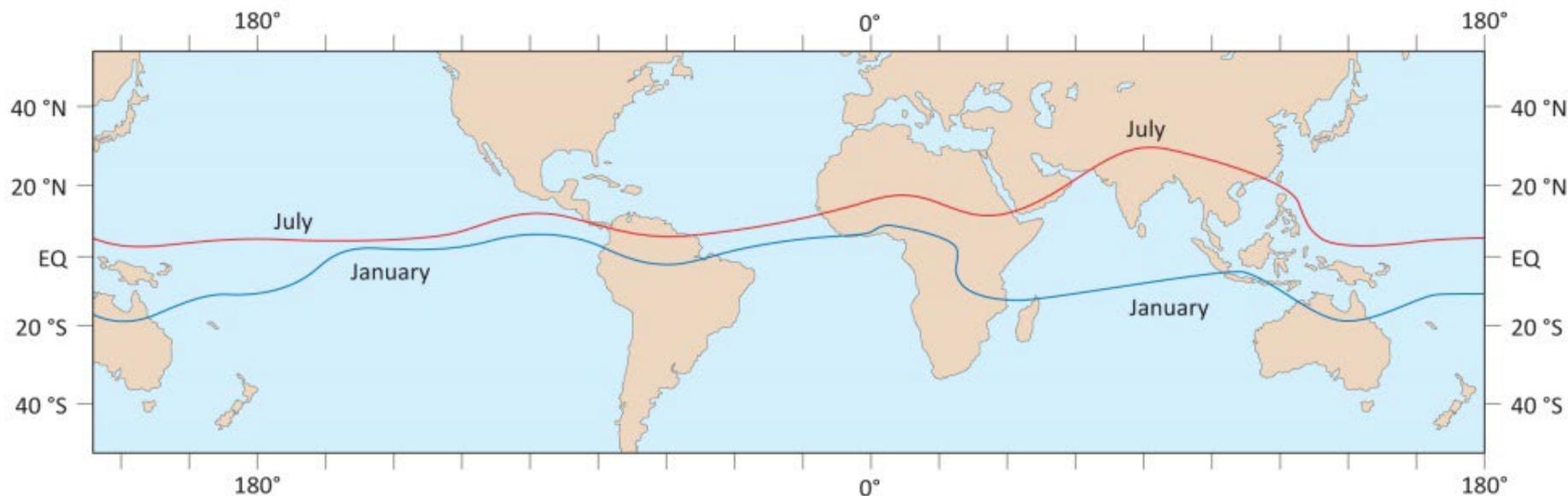
Trade Wind Inversion

- **Trade wind inversion** - persistent feature of the planetary-scale circulation over the eastern portions of tropical ocean basins, caused by the circulation on the eastern flank of subtropical anticyclones
- Subsiding air in the subtropical highs as part of the Hadley circulation, it is warmed by compression and its relative humidity decreases
- Descending air encounters the marine air layer
 - Where SSTs are low, the marine air layer is cool, humid and stable
 - Where SSTs are high, the marine air layer is warm, more humid, less stable and well mixed by convection
- Its extreme stability
 - Limits the vertical development of convective clouds and rainfall
 - Inhibits formation of tropical storms and hurricanes
 - Limits orographic precipitation

Trade Wind Inversion

- Ocean surface exhibits smaller temperature variations over the course of a year than does land
 - Causes seasonal reversal in surface air pressure
 - Continents at middle and high latitudes dominated by high pressure in winter and low pressure in summer
 - In winter, due to extreme radiational cooling, cold anticyclones develop over northwestern North America and interior of Asia
 - In summer, in response to intense solar heating, a belt of low pressure forms across North Africa and stretches from the Arabian Peninsula eastward into Southeast Asia

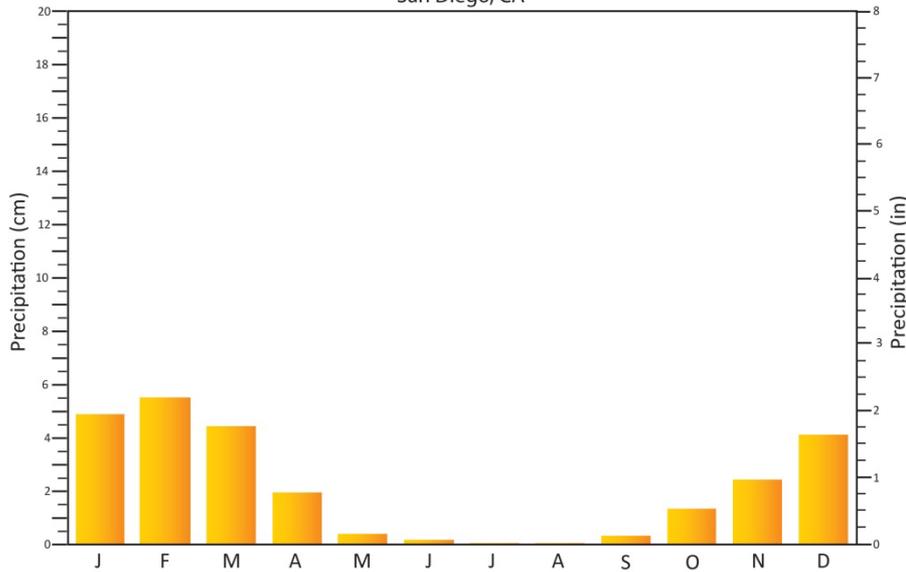
Trade Wind Inversion



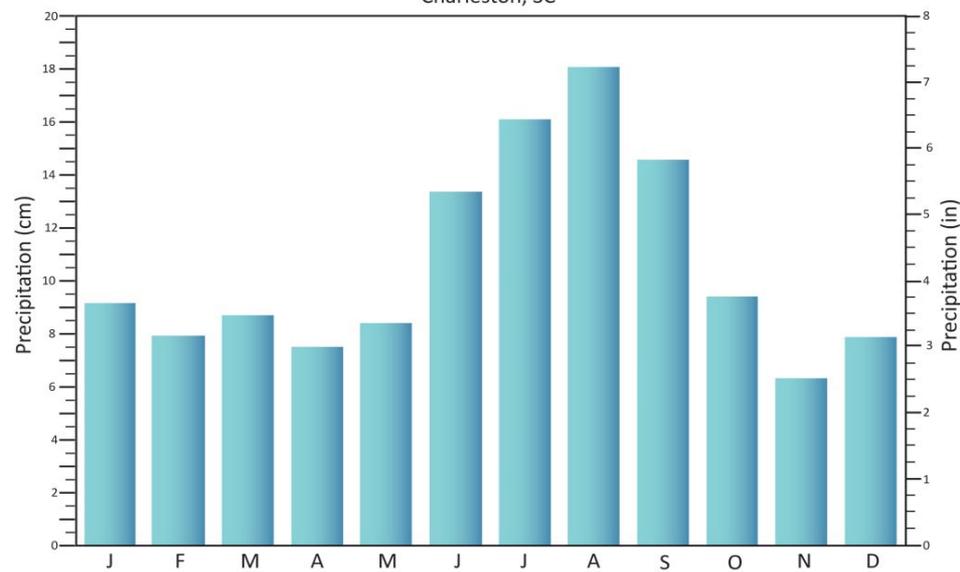
- Seasonal shifts in the planetary-scale wind belts, pressure systems and ITCZ mark regional climate character
- Northward migration of the ITCZ triggers summer monsoon rains in Central America, North Africa, India and Southeast Asia

Trade Wind Inversion

San Diego, CA



Charleston, SC



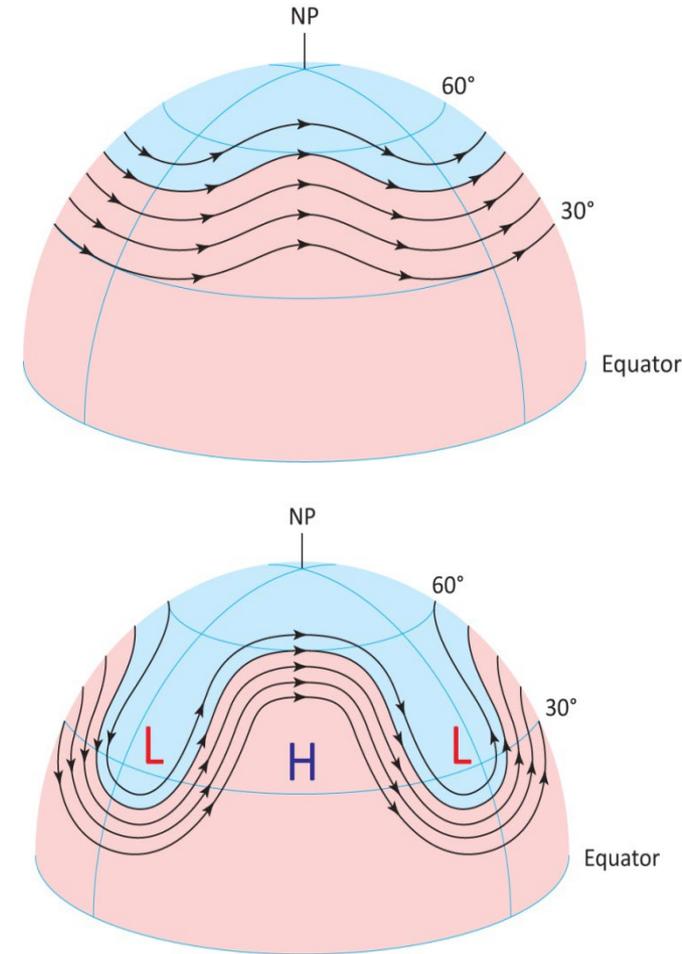
- The influence of the subtropical anticyclones on precipitation regimes on two cities at about the same latitude
 - In summer, San Diego is under the dry eastern flank of the Hawaiian high, while Charleston is on the receiving end of the humid airflow on the western flank of the Bermuda-Azores high
 - In autumn, after the subtropical highs shift toward the equator, both cities receive widespread precipitation associated with the west-to-east moving extratropical cyclones, so that winters are wet in both places

Trade Wind Inversion

- **Rossby waves** - the west to east wavelike patterns of clockwise, anticyclonic curvature in ridges and counterclockwise, cyclonic curvature in troughs of the westerlies above the 500-mb level, where the atmospheric pressure is 500 mb, typically with two to five waves
- Atmospheric scientists describe the upper-air westerlies in terms of
 - Rossby wavelength, the distance between troughs (or ridges)
 - Amplitude (north-south extent)
 - Number of waves encircling the hemisphere
- In winter, they strengthen and exhibit fewer waves of longer length and greater amplitude
- In summer, north-south temperature differences shift poleward, weakening and displacing horizontal air pressure gradients and westerlies poleward

Zonal and Meridional Flow

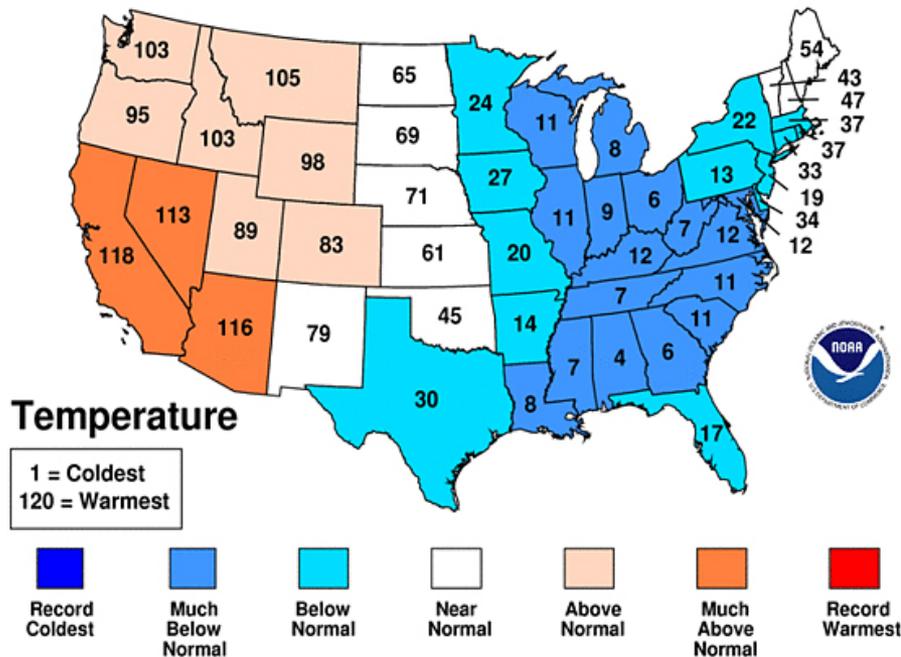
- The weaving westerlies have two components of motion
 - **Meridional flow** - north-south airflow
 - **Zonal flow** - west-to-east airflow
- A weak meridional component (top)
 - Cold air masses stay to the north while warm air masses remain in the south
- Strong meridional component (bottom)
 - Contrasting air masses collide, warm air overrides cold air, and encourages development of extratropical cyclones



Zonal and Meridional Flow

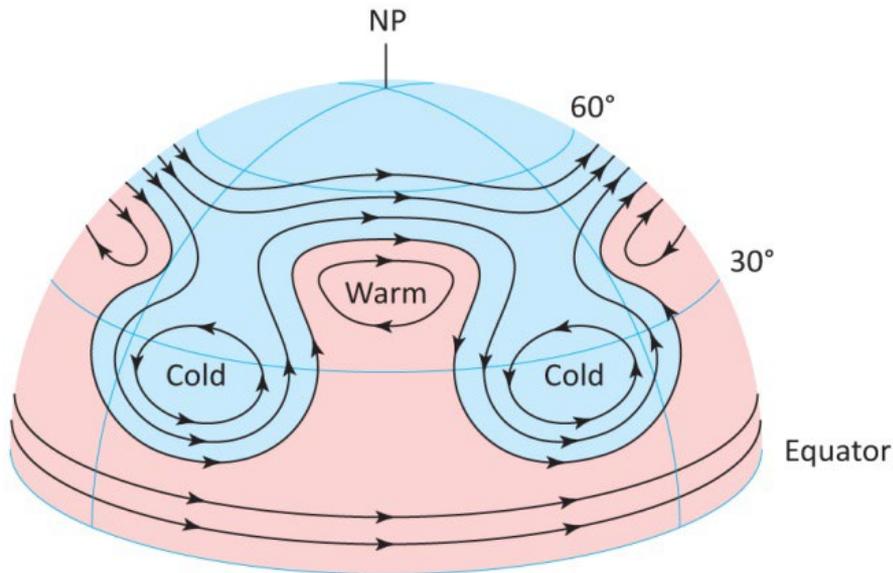
January 2014 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



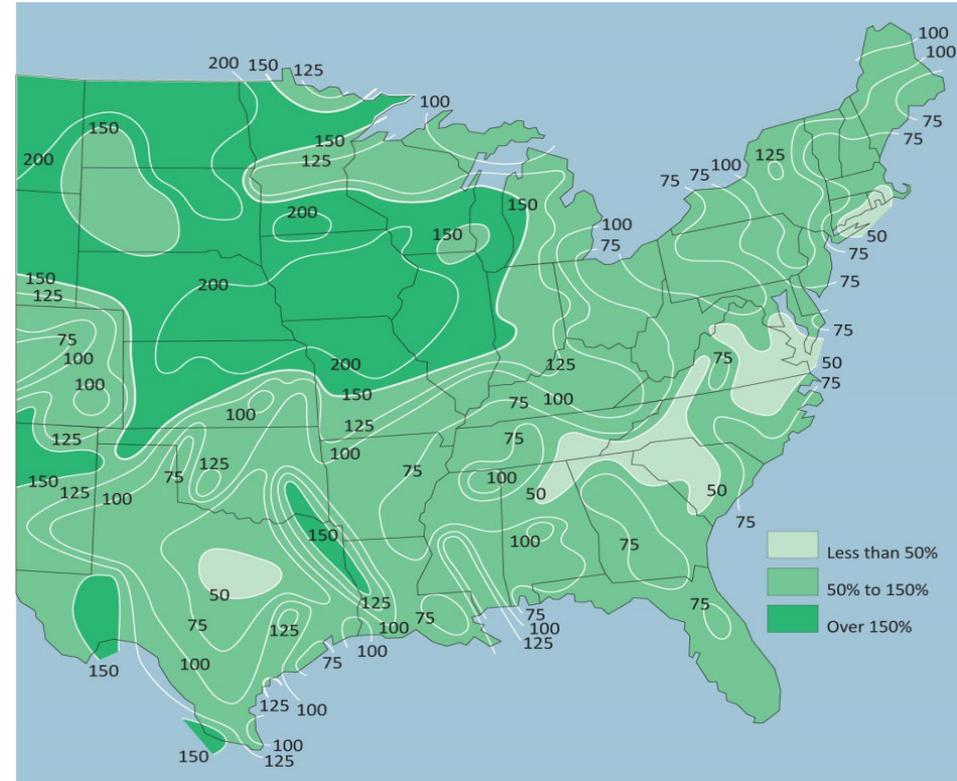
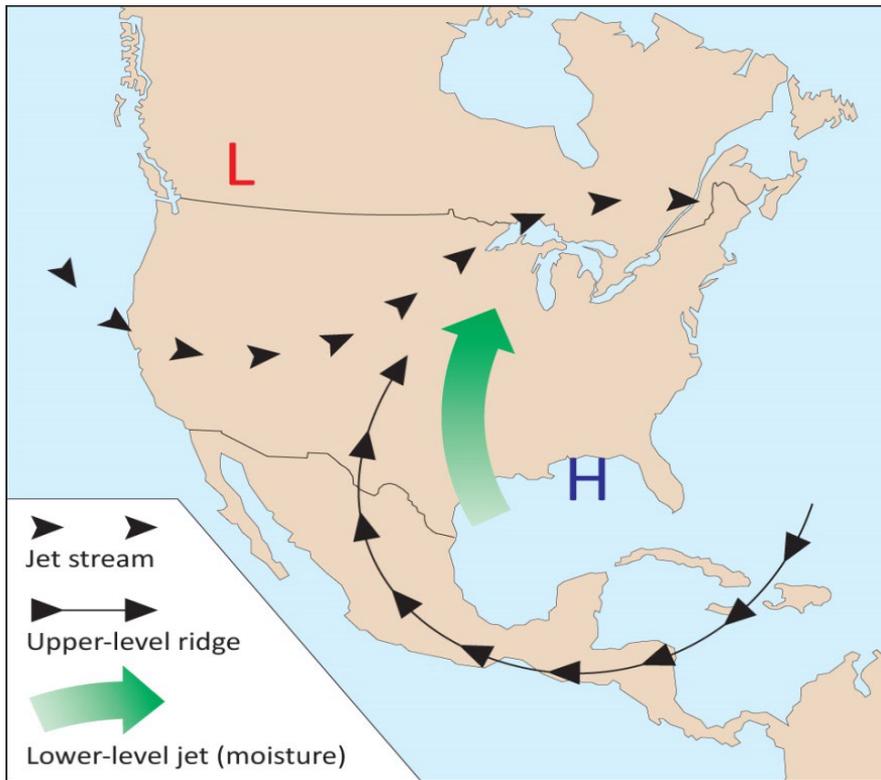
- A strong meridional wave pattern during the winter of 2013-14
 - Northwestern winds brought bitterly cold arctic air into the upper Midwest and Northeast
 - One of the coldest winters in decades
 - Southwesterly winds aloft brought unseasonably mild air to far-western North America, especially the West Coast

Blocking Patterns and Their Effects



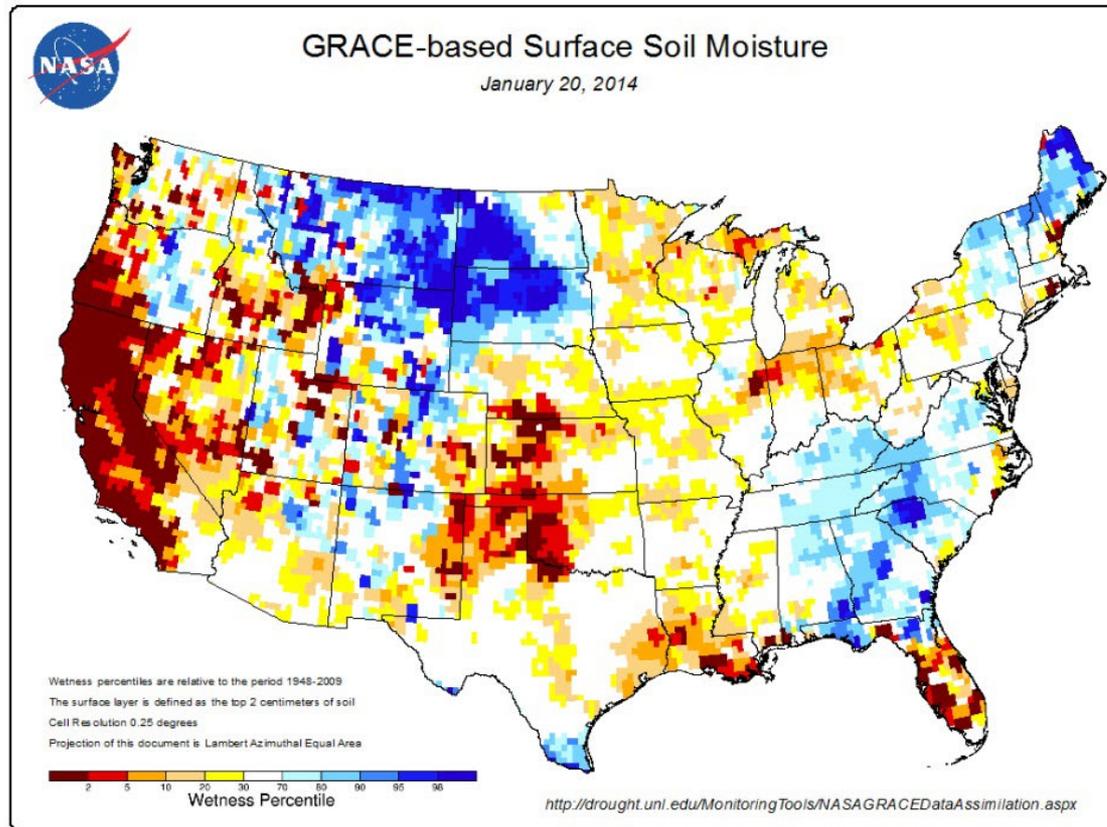
- **Blocking pattern** - a cutoff low or a cutoff high that prevents the usual west-to-east movement of weather systems
 - Often persisting for several weeks or longer
 - Cause drought, flooding or excessive heat or cold

Blocking Patterns and Their Effects



- A blocking circulation pattern during the summer of 1993
 - Record flooding in the Midwest and drought over the Southeast
 - Some parts of the Midwest received more than twice the long-term average seasonal rainfall
 - Some localities in the Southeast received less than half of their long-term average seasonal rainfall

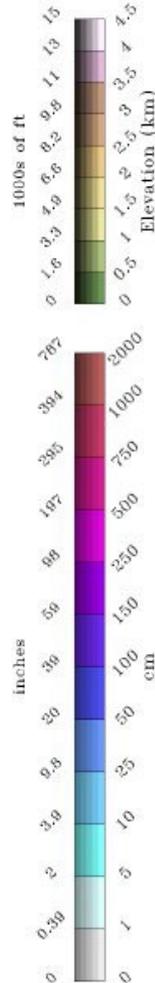
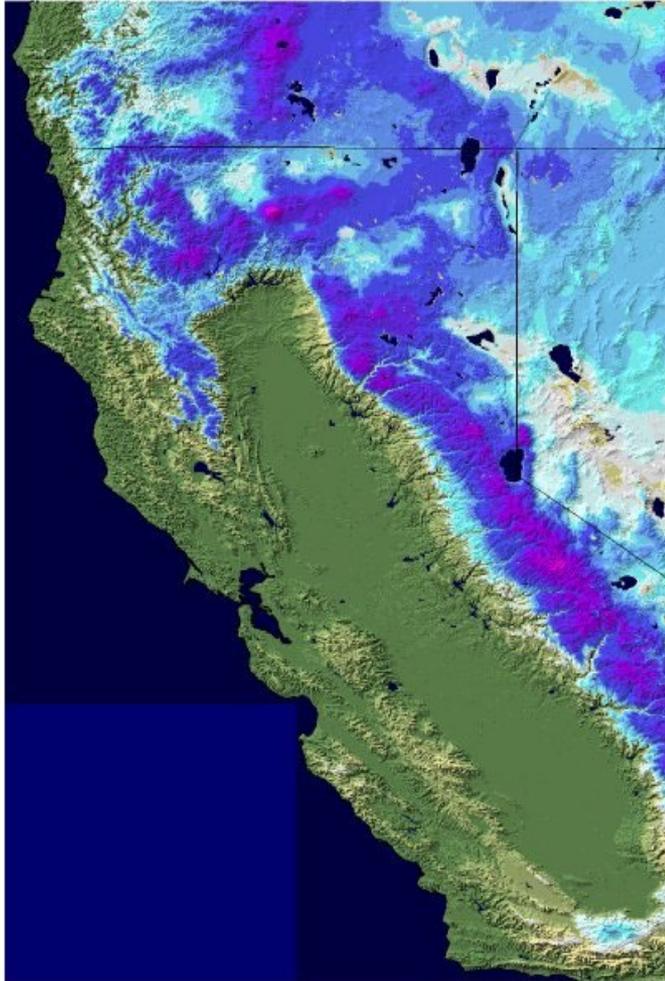
Blocking Patterns and Their Effects



- Relative to the period 1948-2009, drought indicators describe wet or dry conditions by the probability of occurrence. Lower values (warm colors) are for dryer than normal and high values (cool colors) mean wetter than normal

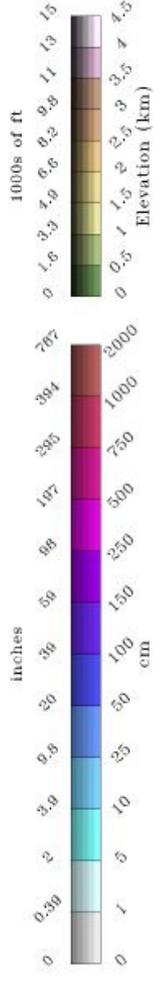
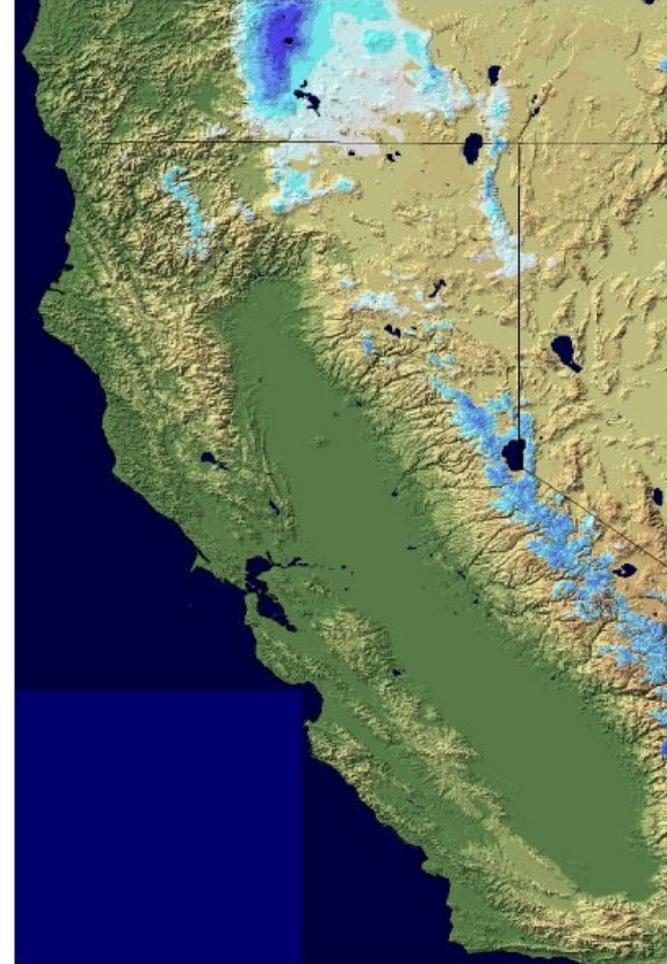
Snow Depth

2013-01-15 06



Snow Depth

2014-01-15 06 UTC



- West coast snow depth as of 15 January 2013 compared to that on the same day in 2014, when suffering from a

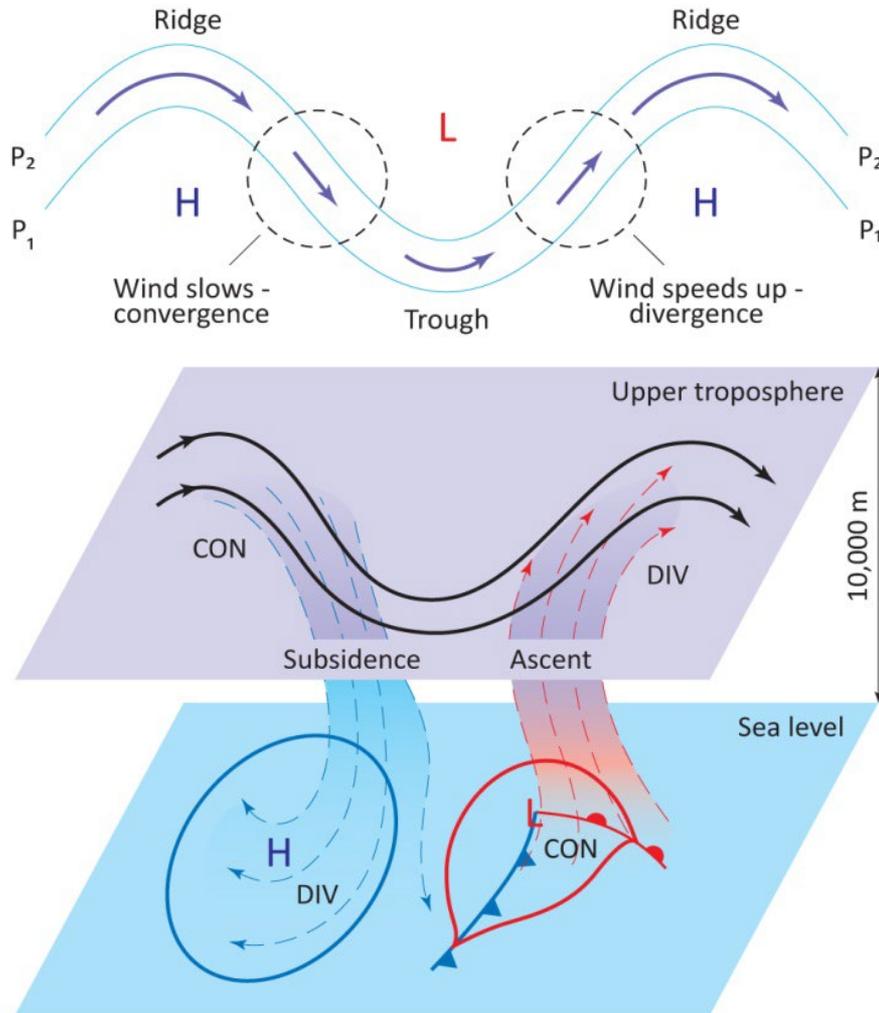
Blocking Patterns and Their Effects

- A changing climate may also be to blame for some of the highly amplified patterns that recently seem more frequent
- **Arctic amplification** - the Arctic warming nearly twice as rapidly as the entire Northern Hemisphere
 - Encourages more meridional flow regimes, which increases the probability of blocking patterns
 - Implies that anthropogenic global warming is heightening the chances that some regions in the mid-latitudes could experience both exceptionally warm and cold patterns in some seasons

Connection from Winds Aloft to the Surface

- Frontal weather occurring in combination with an extratropical cyclone is a major feature in defining the climatic character of regions in the middle and high latitudes
- **Norwegian Cyclone Model** - early model explored the variance in air mass types, fronts and cyclones, derived primarily from surface weather observations
 - Advances in atmospheric monitoring techniques, especially remote sensing by satellite, have verified its main features

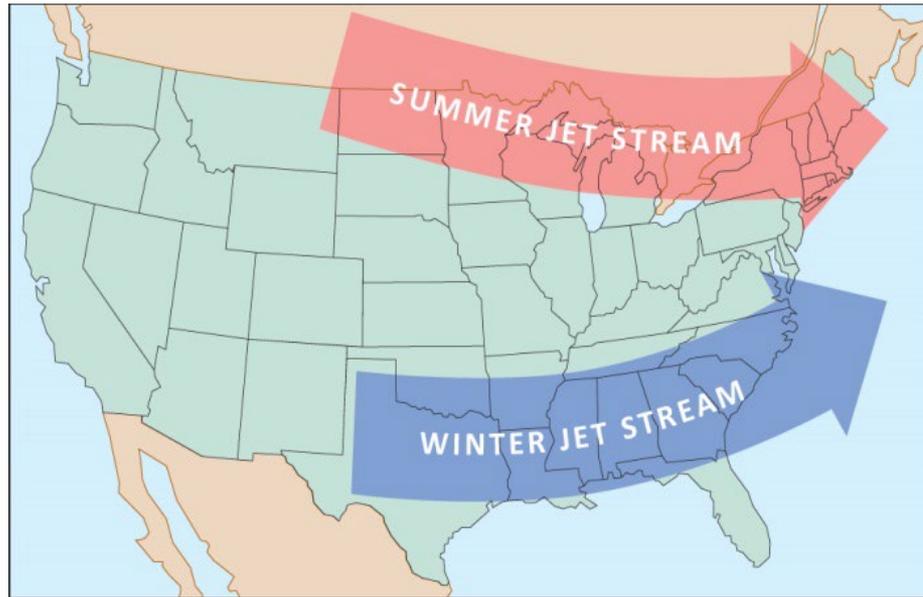
Supporting Processes



CON = Convergence
DIV = Divergence

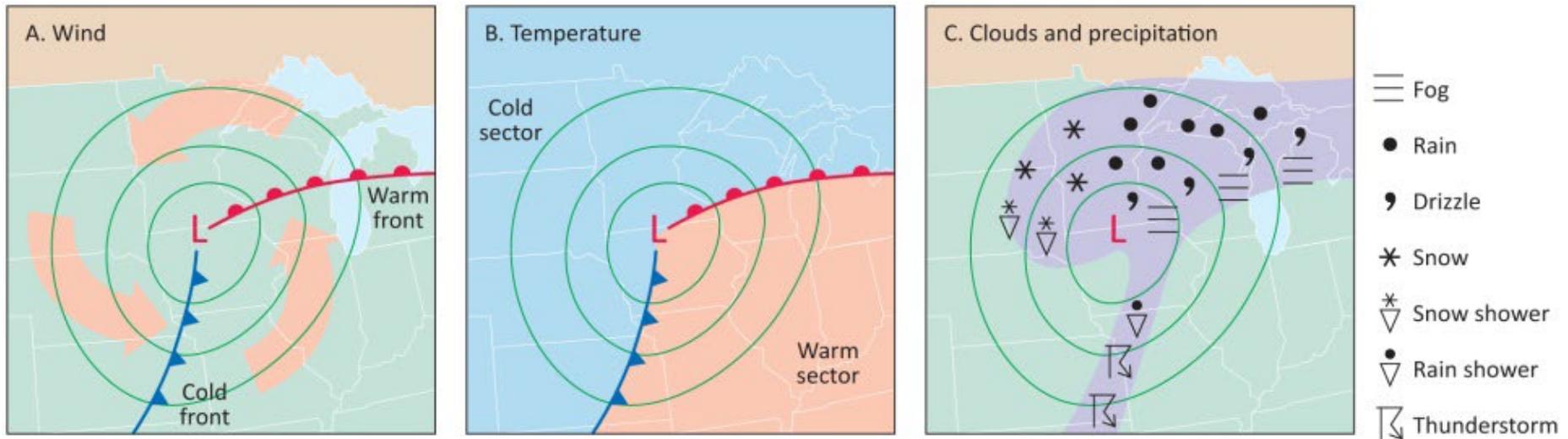
- **Cyclogenesis** - the birth of a cyclone, occurs along the polar front, directly under an area of strong horizontal divergence in the upper troposphere
 - Both short waves and long waves in the westerlies provide upper-air “lift” for the development of cyclones
- Winds speed up into a ridge and weaken before a trough
 - Resulting in horizontal divergence of mid-to-upper-tropospheric winds to the east of a trough and west of a ridge

Supporting Processes



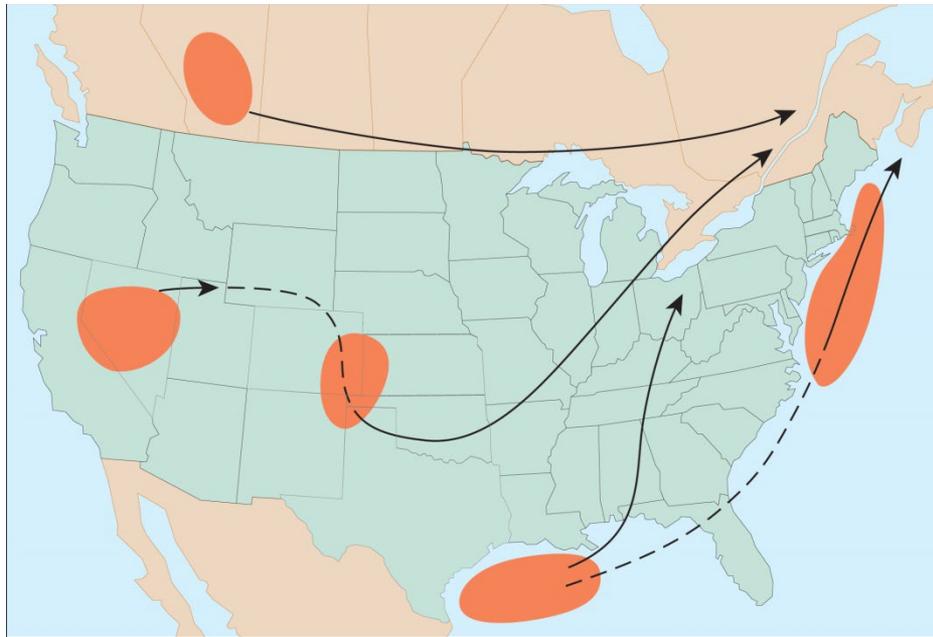
- **Jet stream** - relatively narrow corridors of very strong winds within the atmosphere
 - Strengthens in winter when the north-south air temperature contrast is greatest
 - Weakens in summer when temperature contrasts are less
- **Polar front jet stream** - the most prominent jet stream, located above the polar front in the upper troposphere between the midlatitude tropopause and the polar tropopause in the middle latitudes

Atmospheric Characteristics of Cyclones



- Ideally, a mature wave cyclone can be divided into warm and cold sectors about a low center
 - Lowest air temperatures occur to the northwest of the storm center
 - Continental polar or arctic air flow southward and eastward
- Steep air pressure gradient found on the west side of the surface low
 - Strong winds
- The cold front is south of the low center
 - A relatively narrow band of ascending air
 - Accompanied by cumuliform clouds, convective showers and thunderstorms

Climatically Favored Regions of Cyclogenesis

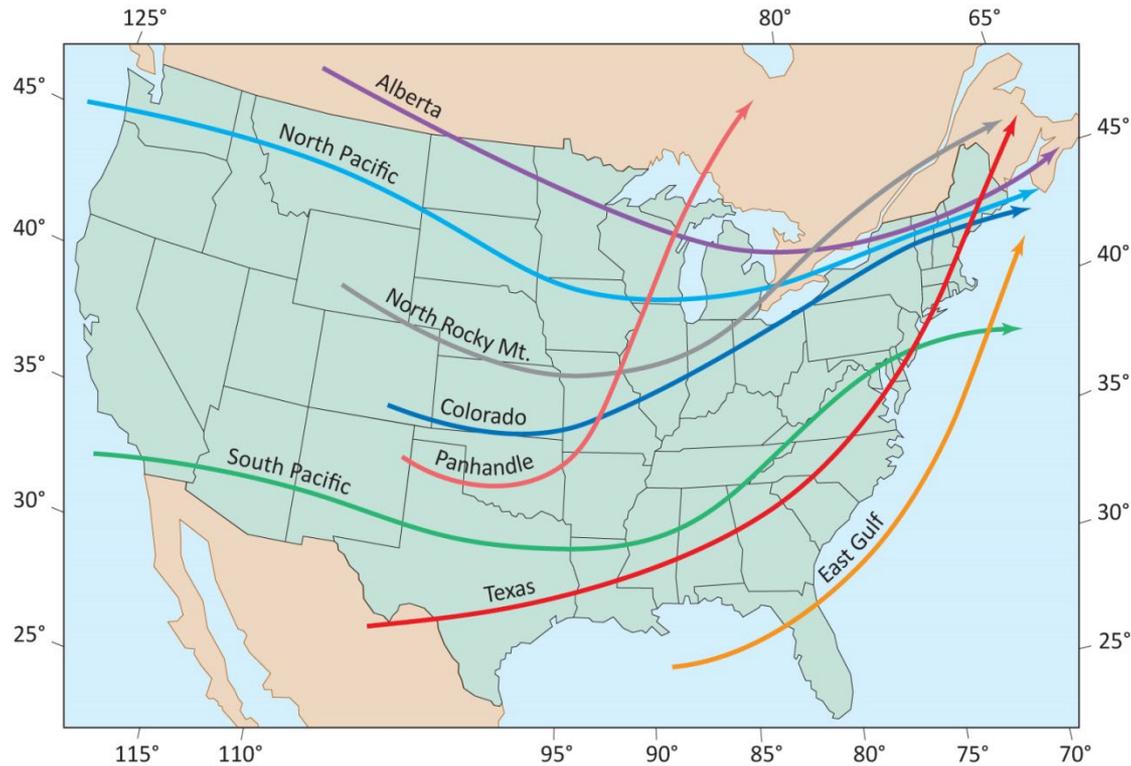


- Extratropical cyclones originate and require
 - Weak atmospheric stability, favoring ascending motion of air
 - A nearby source of warm, humid air, which favors condensation of water vapor at low levels that releases latent heat and increases buoyancy
 - Strong horizontal temperature gradients in the lower troposphere that give rise to fronts
 - The jet stream oriented above so diverging air aloft evacuates the rising air that has converged near the central low pressure

Climatology of Cyclone Paths

- The specific track taken by an extratropical cyclone depends on the pattern of upper-level westerlies
- Storm centers move in the direction of the wind that blows directly above the surface low pressure system in the mid-troposphere near the 500-mb level
 - At about half the speed of the 500-mb winds
- Cyclones that form in the south yield more precipitation than those that develop in the north
- In winter, the mean position of the polar front and jet stream shifts southward
 - Cyclogenesis is more frequent in the coterminous United States
- Cyclone tracks displaced equatorward during extended cold intervals, and poleward during warm episodes

Climatology of Cyclone Paths



- **Alberta Clipper** - the principal tracks of cyclones that develop to the lee of the Canadian Rockies in Alberta and travel rapidly east across southern Canada or the northern tier states
- **Nor'easter** - the principal tracks of cyclones that track toward the northeast along the East Coast

Big Ideas

- Pressure gradient force, Coriolis force, friction and gravity interact in initiating and affecting atmospheric circulation
- Horizontal and vertical air motions in anticyclones and cyclones determine weather
- The principal features of atmospheric circulation are the ITCZ, trade winds, subtropical highs, the westerlies, polar front, subpolar lows, polar easterlies and polar highs
- Aloft, in the middle and upper troposphere, winds blow
 - Counter to the surface trade winds in tropical latitudes
 - In a west-to-east wave pattern at middle and high latitudes

Big Ideas

- Through the course of a year, components of the planetary-scale circulation shift north and south with the Sun, influencing regional climates
- Synoptic scale wind and cyclone climatology emphasizes the link between the westerly winds aloft and the weather and climate of middle latitudes
 - Westerlies produce horizontal divergence aloft for the development of cyclones, steer storms and influence air mass trajectories

Key Terms

- Force
- Pressure
- Pressure gradient
- Pressure gradient force
- Coriolis Effect
- Coriolis force
- Geostrophic wind
- Gradient wind
- Wind vane
- Cup anemometer
- Scatterometer
- Synoptic scale
- Mesoscale
- Microscale
- Subtropical high
- Horse latitudes
- Westerlies
- Trade winds
- Intertropical convergence zone (ITCZ)
- Circumpolar vortex
- Front
- Friction
- Molecular viscosity
- Eddy viscosity
- Eddies
- Boundary layer
- Gravity
- Polar front
- Hadley cell
- Trade wind inversion
- Rossby waves
- Meridional flow
- Zonal flow
- Blocking pattern
- Arctic Amplification
- Norwegian Cyclone Model
- Cyclogenesis
- Jet stream
- Polar front jet stream
- Alberta Clipper
- Nor'easter