Background physics concepts (again)

position coordinate for location, say x (1-D)

velocity changing position over time (magnitude and direction)

$$v = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}$$

acceleration changing velocity

$$a = \frac{\Delta v}{\Delta t}$$

net force applied to make an object accelerate

$$F_{net} = \sum F = ma \quad (\textit{Newton's 2nd law})$$

pressure force applied per unit area

$$P = \frac{F}{A}$$

Pressure

$$Pressure = \frac{force}{area} \quad , \quad P = \frac{F}{A}$$

- Force in pressure is caused by collisions of gas molecules
- units: pascals (Pa), millibars (mb), or kilopascals (kPa)
- 1 mb = 100 Pa; 1 kPa = 1000 Pa
- pressure at sea level 1013 mb

Clicker question

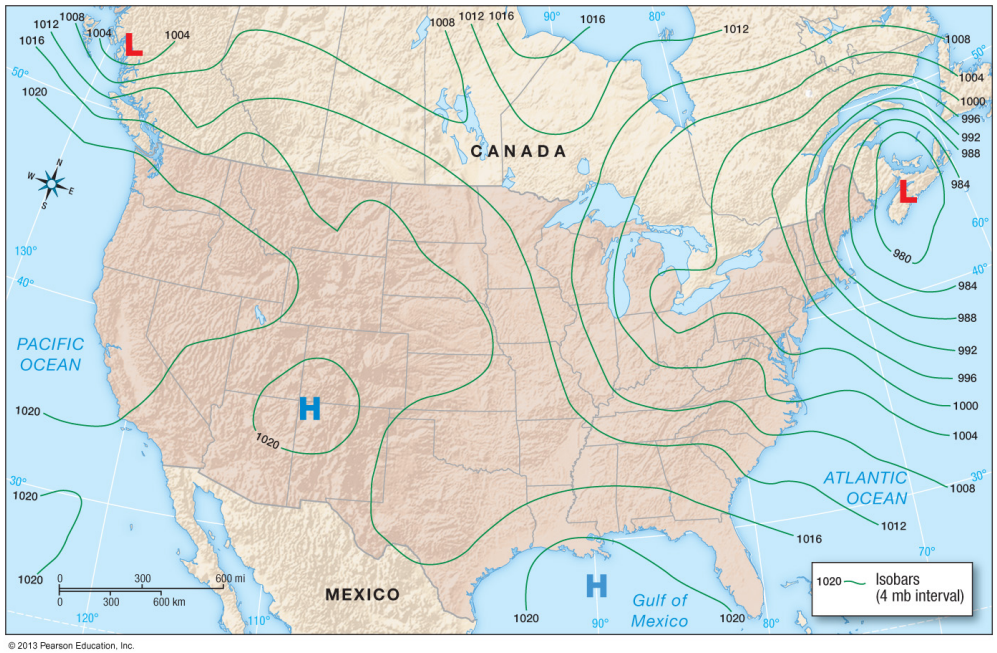
What is the term for the lines on this map?

A. height contours

B. winds

C. isotherms

D. isobars



Clicker question

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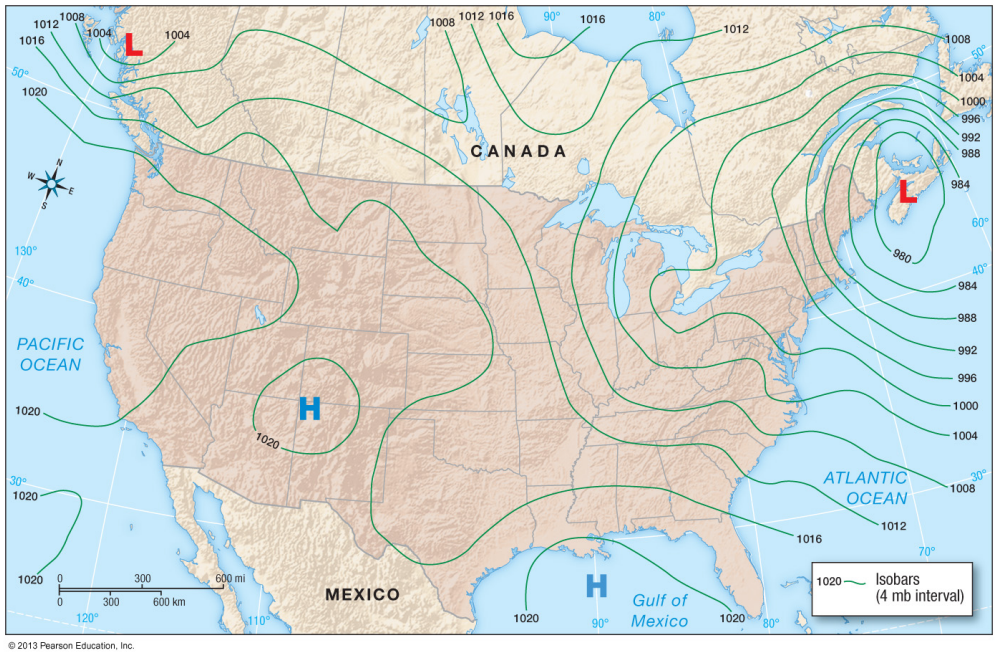
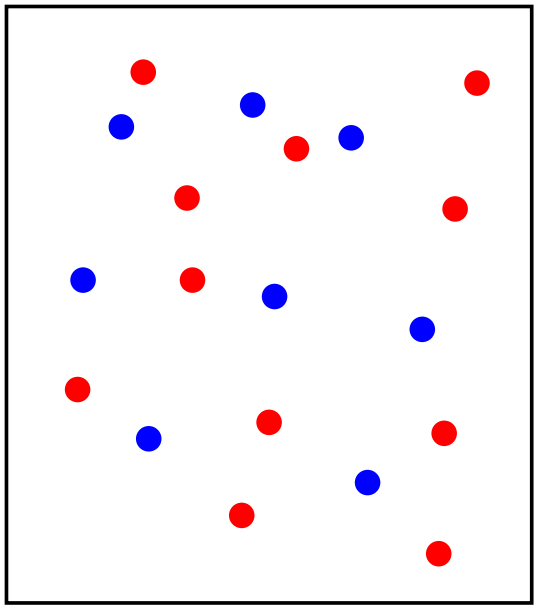
D. isobars

current
weather
isobars



Partial pressures, Dalton's law

partial pressure: pressure exerted by one species of gas in a mixture of gases



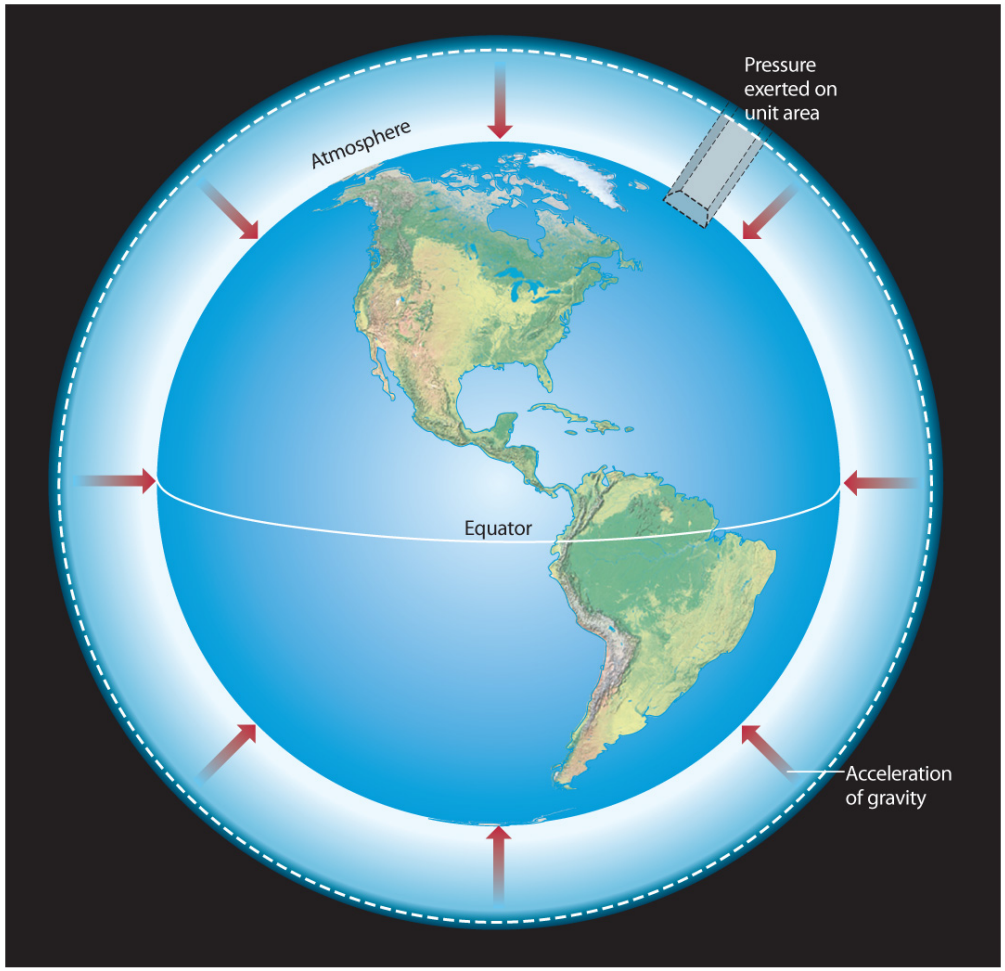
Dalton's Law:

$$P_{total} = P_{red} + P_{blue}$$

The total pressure is equal to the sum of the partial pressures of each gas

Surface pressure

The weight of the air in a column above the surface determines the surface pressure



Surface vs sea-level pressure

sea level pressure: pressure at sea level

surface pressure: pressure at the surface

Surface vs sea-level pressure

sea level pressure: pressure at sea level

surface pressure: pressure at the surface, can be at different elevations

Clicker question

Which box has the lowest pressure?

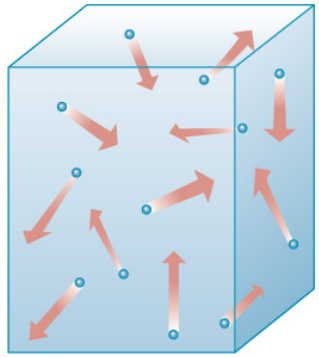
A. A

B. B

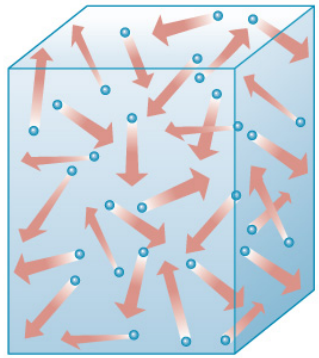
C. C

D. Two of the above are the lowest pressure

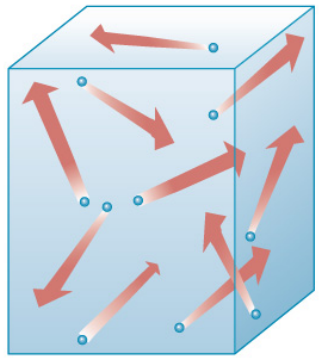
E. All have same pressure



(a)



(b)



(c)

Clicker question

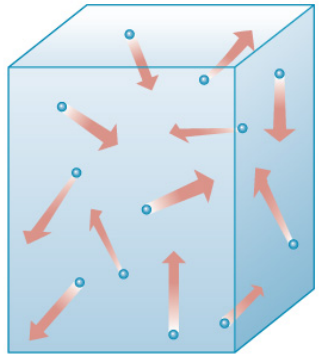
How can pressure be increased in this example of a sealed container of air?

A. decreasing density

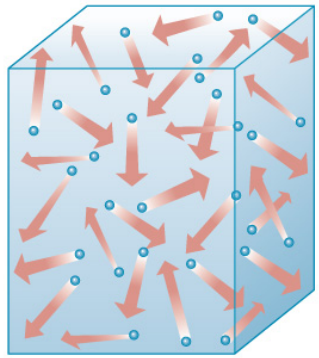
B. increasing density

C. increasing temperature

D. both B and C are correct



(a)



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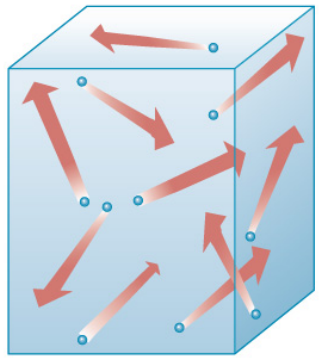


(c)

Clicker question

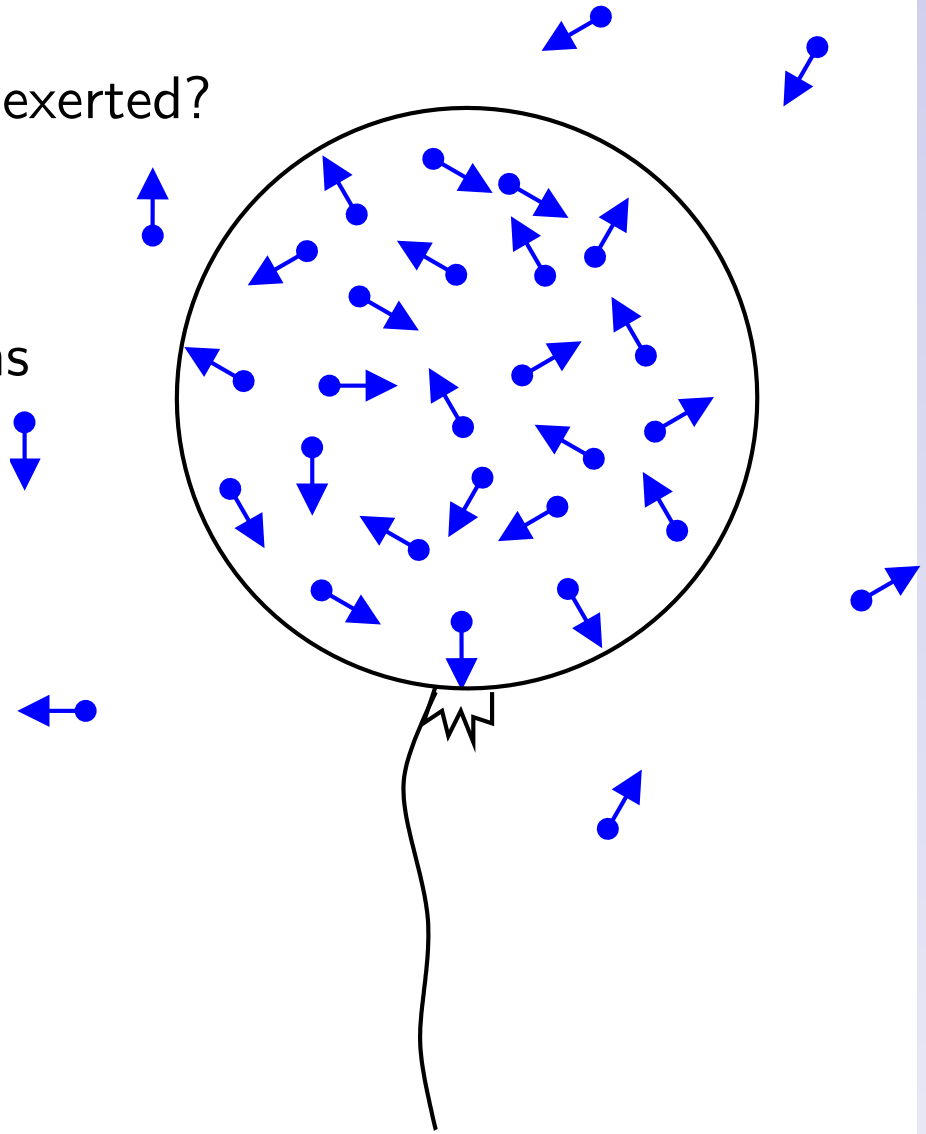
Which direction is pressure exerted?

A. upward

B. downward

C. outward in all directions

D. inward in all directions



Differences in pressure

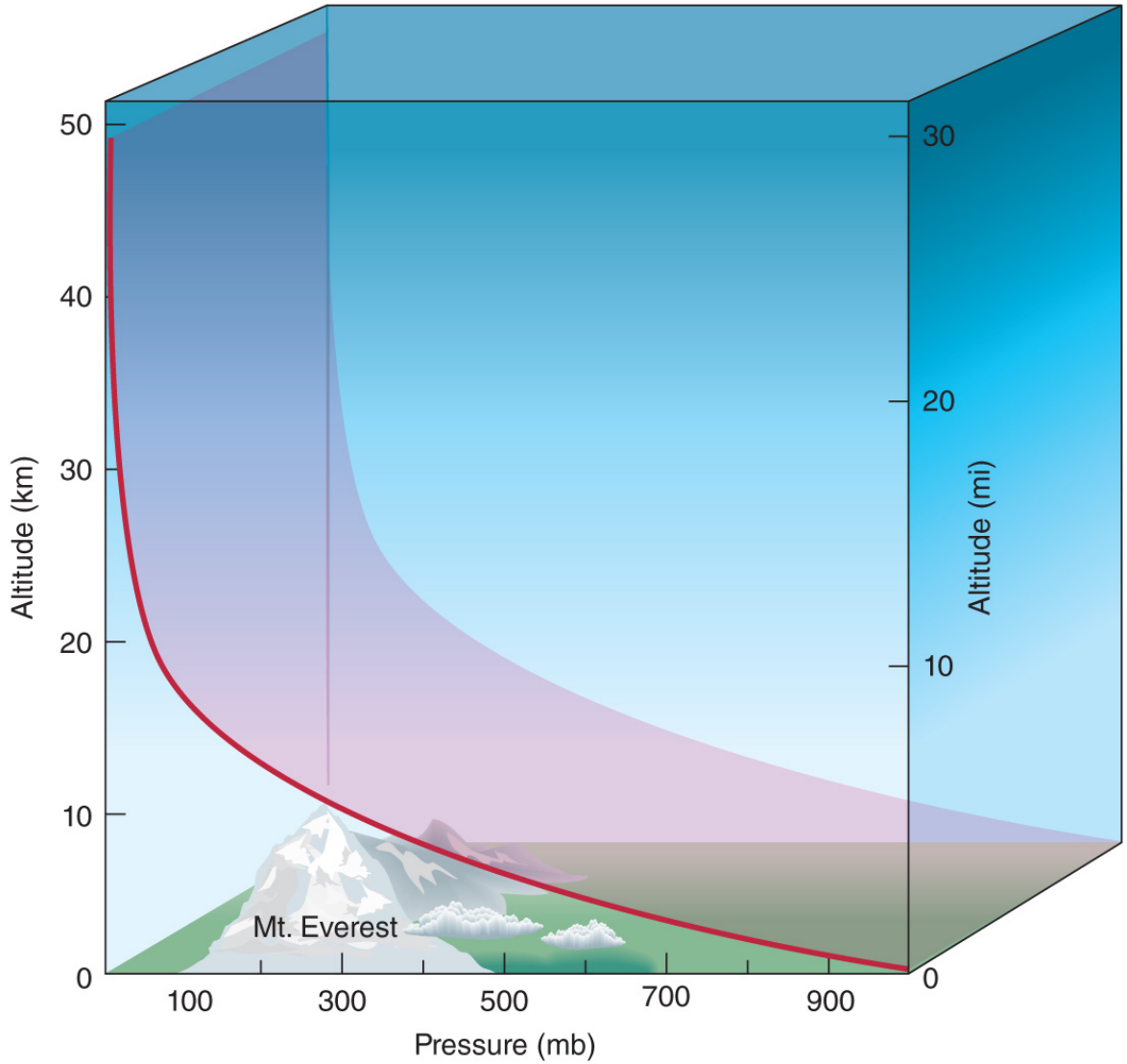
Areas of high pressure adjacent to areas of low pressure will

Differences in pressure

Areas of high pressure adjacent to areas of low pressure will cause air to move from high pressure to low pressure (wind).

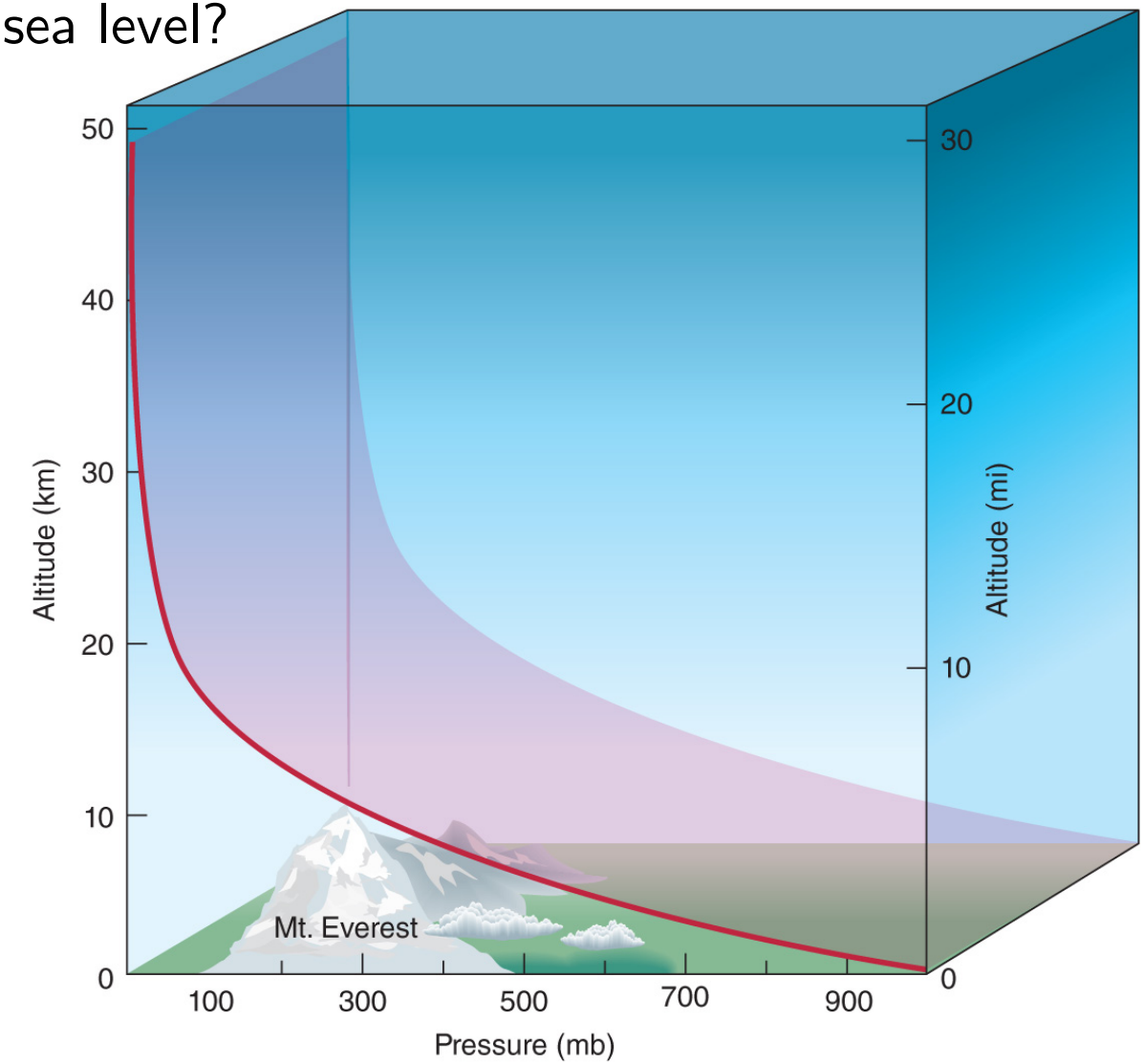
Air moves toward equilibration.

Vertical changes in pressure



Vertical changes in pressure

Is the pressure at the top of Mt. Everest greater than the pressure at sea level?



Equation of state

Ideal gas law

A state variable is a variable that describes the state of a system

An equation of state is an equation that relates state variables

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Ideal gas law

A state variable is a variable that describes the state of a system

An equation of state is an equation that relates state variables

The ideal gas law is an equation of state for a gas made up of non-interacting particles

The ideal gas law is a good approximation for atmospheric gases.

Equation of state

Ideal gas law

$$p = \rho R T$$

p = pressure
ρ = density
$R = 287$ J/kg·K = gas constant for dry air
T = temperature in Kelvin

Clicker question

For air at constant pressure, what happens to the density if the temperature increases?

A. increases

B. decreases

C. stays constant

Horizontal pressure gradients at surface

- Lines of constant pressure are called

Horizontal pressure gradients at surface

- Lines of constant pressure are called isobars
- On a weather map, isobars are sea level pressures
- Distance between isobars gives information about how much pressure changes from one point to another

$$\textit{horizontal pressure gradient} = \frac{\Delta p}{\Delta x}$$

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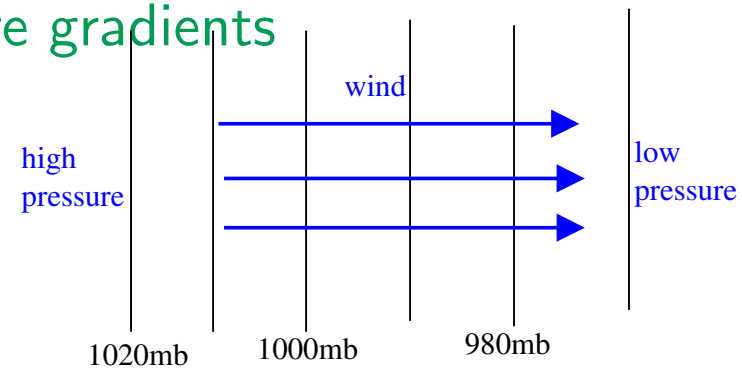
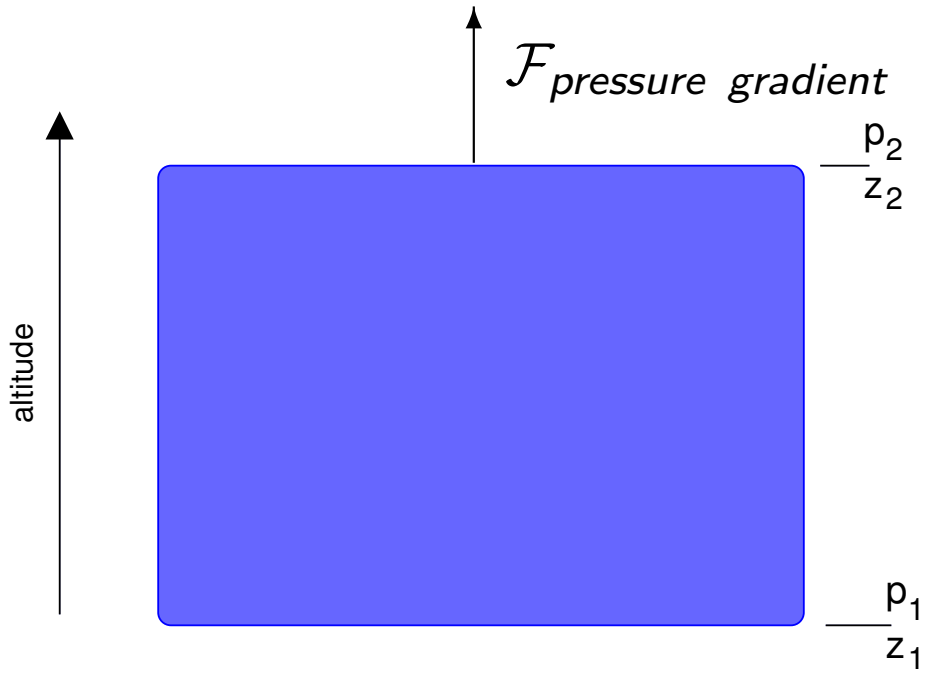
$$horizontal\ pressure\ gradient = \frac{\Delta p}{\Delta x}$$

- The pressure gradient force is the force that drives wind from high pressure to low pressure
- pressure gradients

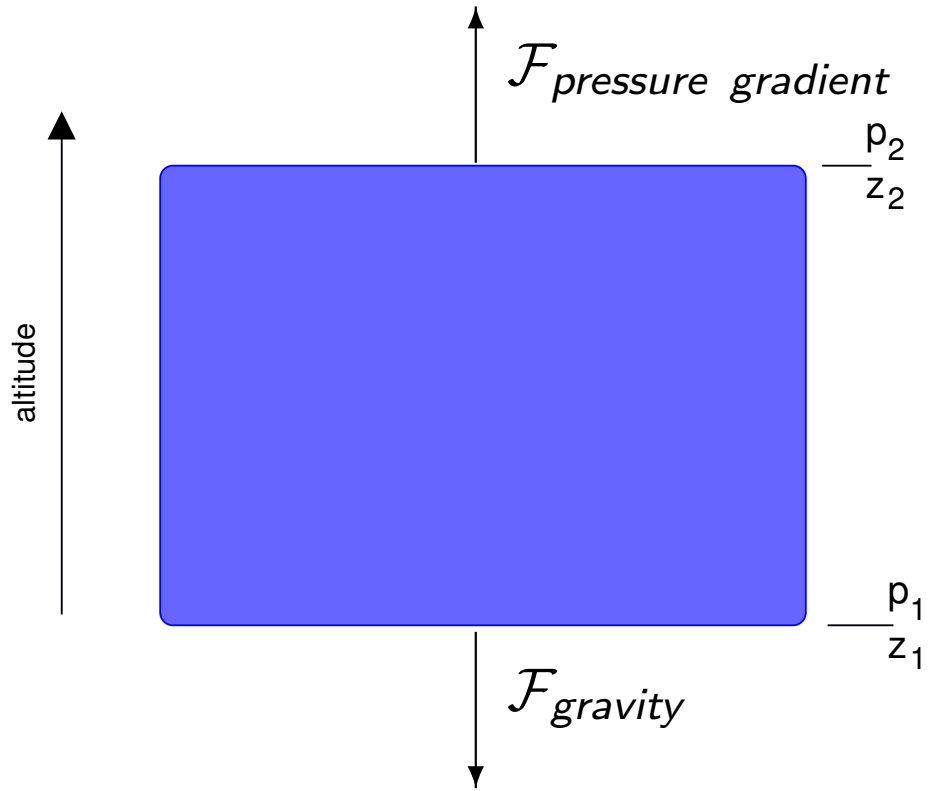


Vertical pressure gradients

Vertical pressure gradients



Vertical pressure gradients



Let $\mathcal{F}$ denote force per unit mass, then

$$\sum \mathcal{F}_z = \mathcal{F}_{pressure\ gradient} + \mathcal{F}_{gravity} = a$$

Hydrostatic Balance

When the vertical pressure gradient force balances the gravitational force,

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Hydrostatic Balance

When the vertical pressure gradient force balances the gravitational force,

- Newton's 2nd law $\rightarrow a = 0$
- $\mathcal{F}_{pressure\ gradient} + \mathcal{F}_{gravity} = 0$
- and we have hydrostatic equilibrium (balance):

$$\frac{\Delta p}{\Delta z} = -\rho g$$

Clicker question

When a column of air is heated, what happens to the vertical pressure gradient?

A. it becomes steeper

B. it becomes more gradual

C. nothing

D. it becomes horizontal

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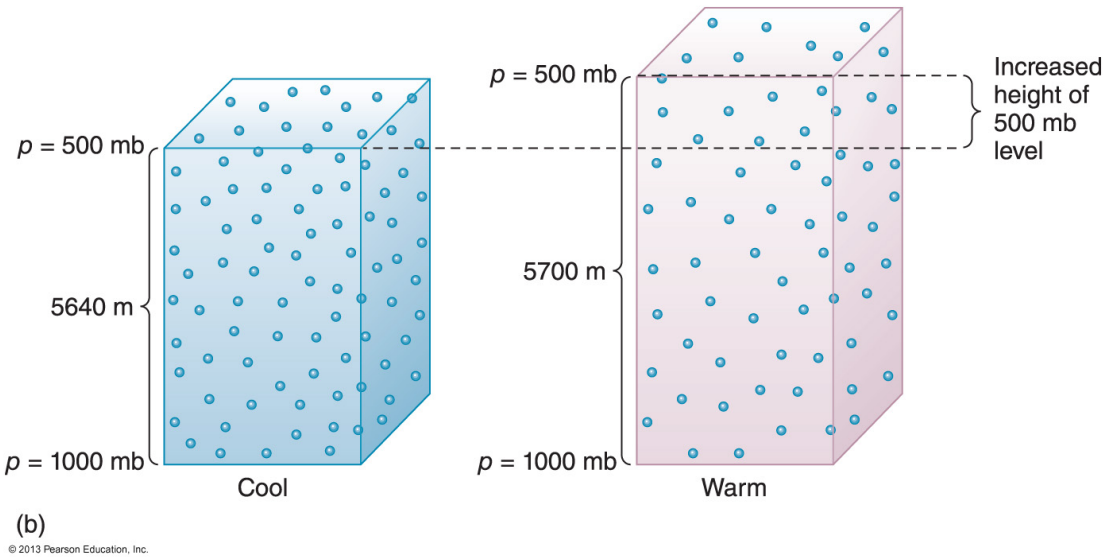
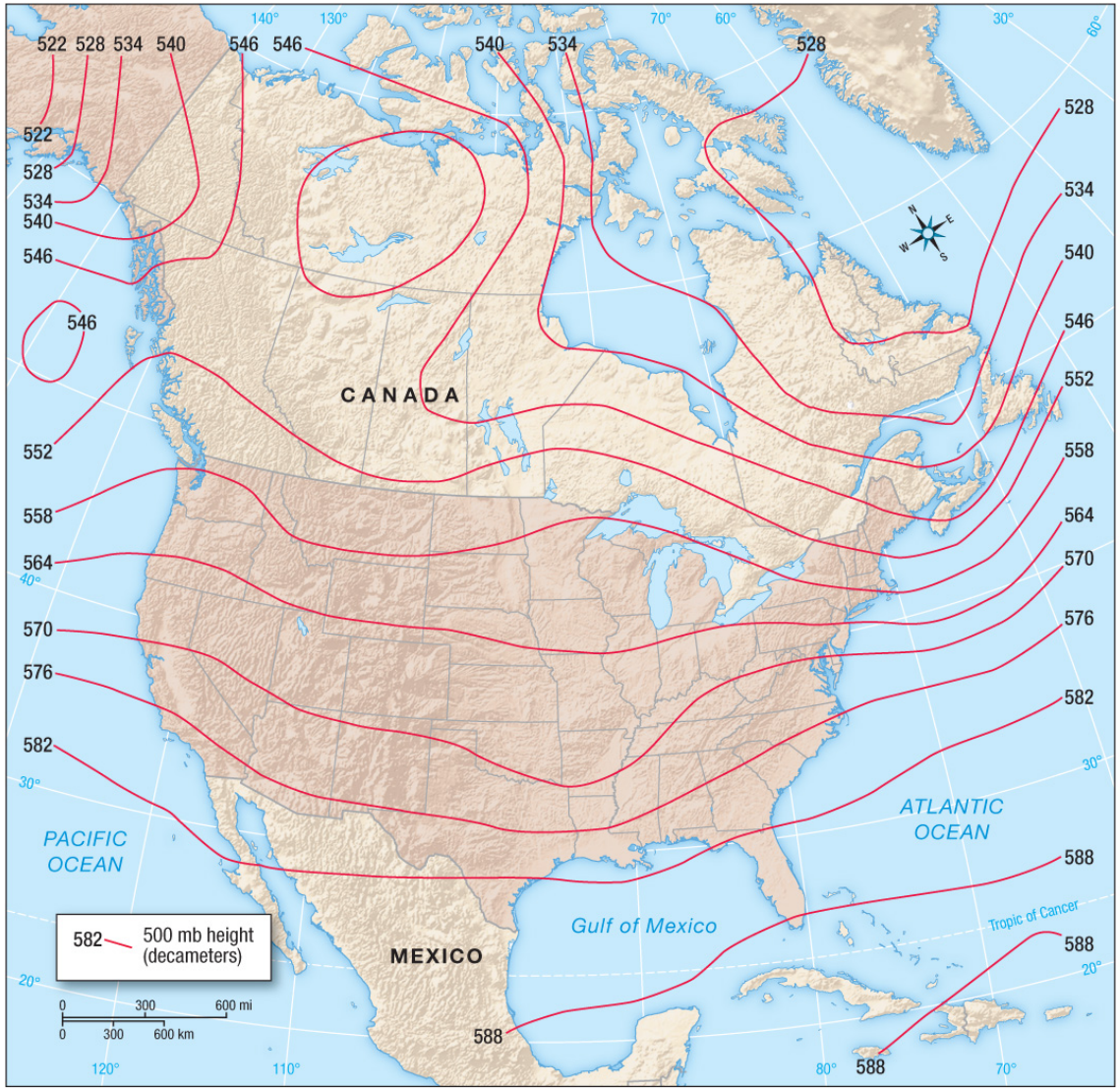


Upper level horizontal pressure gradients

horizontal pressure gradients



Forces affecting wind speed and direction

- pressure gradient force
- Coriolis force
- friction

Relevant physics concepts

momentum: $p = mv$

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angular momentum: rotational momentum with magnitude $L = mvr$ (mass×velocity×distance from axis of rotation)

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angular momentum: rotational momentum with magnitude $L = mvr$ (mass×velocity×distance from axis of rotation)

- angular momentum is a vector
- For Earth's rotation, direction of angular momentum is along axis of rotation
- Angular momentum is conserved unless a torque (rotational force) acts to change it

Coriolis force

- Coriolis force: apparent force that deflects an object as a result of a rotating reference frame
- Rotating Earth
- Rotation and apparent deflection
- Coriolis movie

Coriolis force

- Coriolis force: apparent force that deflects an object as a result of a rotating reference frame
- Rotating Earth
- Rotation and apparent deflection
- Coriolis movie
- is a result of conservation of angular momentum
- is sometimes called a "fictitious force", it is a real force in non-inertial reference frame (an *inertial* reference frame is one that does not accelerate)

Clicker question

You fire a cannonball due north from Socorro, NM. The cannonball

A. appears to curve to the left because the Earth rotates under the ball while it is in the air.

B. appears to curve to the right because the distance of the ball from the axis of rotation decreases, so by conservation of momentum its horizontal velocity must increase.

C. follows the Earth's rotation and does not appear to curve at all.

Fundamental characteristics of the Coriolis force

The Coriolis force

1. produces an apparent deflection of all moving objects, regardless of direction of motion
2. is zero at the equator and increases with latitue (max at the poles)
3. acting on a moving object increases with the object's speed
4. only changes the direction of a moving object, not it's speed

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$$\mathcal{F}_{Coriolis} = 2\Omega v \sin\phi$$

- Ω is the Earth's rate of rotation
- v is the speed of the object
- ϕ is latitude

Friction

Air near the surface experiences frictional drag which decreases the speed.

Friction

Air near the surface experiences frictional drag which decreases the speed. Air just above the near-surface air also experiences drag as a result of the slower moving underlying air.

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Air near the surface experiences frictional drag which decreases the speed. Air just above the near-surface air also experiences drag as a result of the slower moving underlying air.

planetary boundary layer: the layer near the surface that is affected by frictional drag (about the lowest 1.5 km)

free troposphere: the rest of the troposphere that is not affected by frictional drag

- effect of friction

Factors affecting horizontal wind speed and direction

Factors affecting horizontal wind speed and direction

- pressure gradient force: $\vec{\mathcal{F}}_{PG}$
- Coriolis force: $\vec{\mathcal{F}}_{C}$
- friction: $\vec{\mathcal{F}}_{f}$

with $\mathcal{F}$ the force per unit mass (i.e., acceleration)

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$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \vec{\mathcal{F}}_{PG} + \vec{\mathcal{F}}_{C} + \vec{\mathcal{F}}_{f}$$

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$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \vec{\mathcal{F}}_{PG} + \vec{\mathcal{F}}_C + \vec{\mathcal{F}}_f$$

Very often, the net horizontal acceleration is zero, so the other forces balance

Winds in the free troposphere

Clicker question

In the free troposphere, which force is negligible?

A. pressure gradient force

B. Coriolis force

C. friction

$$\vec{a} = \vec{\mathcal{F}}_{PG} + \vec{\mathcal{F}}_C + \vec{\mathcal{F}}_f \approx 0$$

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$$\vec{\mathcal{F}}_{PG} + \vec{\mathcal{F}}_C \approx 0$$

Geostrophic flow

geostrophic flow: when the pressure gradient force approximately balances the Coriolis force in the upper atmosphere

$$\vec{\mathcal{F}}_{PG} + \vec{\mathcal{F}}_{C} \approx 0$$

Clicker question

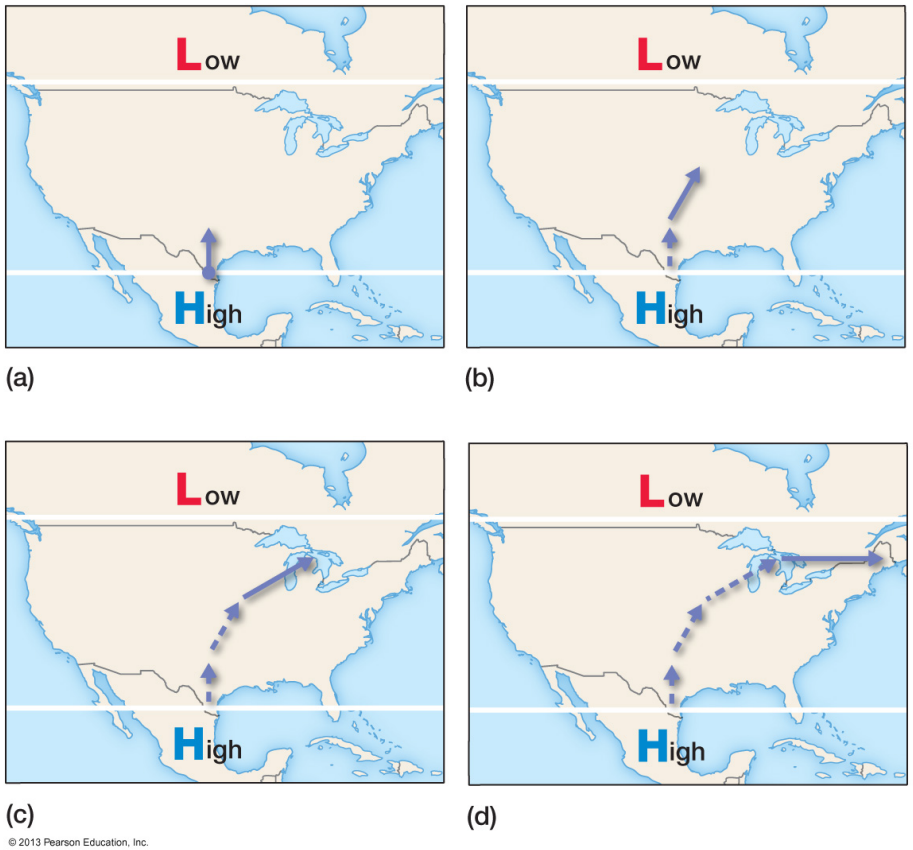
An air parcel starts from rest in a high pressure area and the trajectory is shown. The initial magnitude of the Coriolis force (figure a) is

A. zero

B. equal to the pressure gradient force

C. greater than the pressure gradient force

D. not enough information to answer this



Clicker question

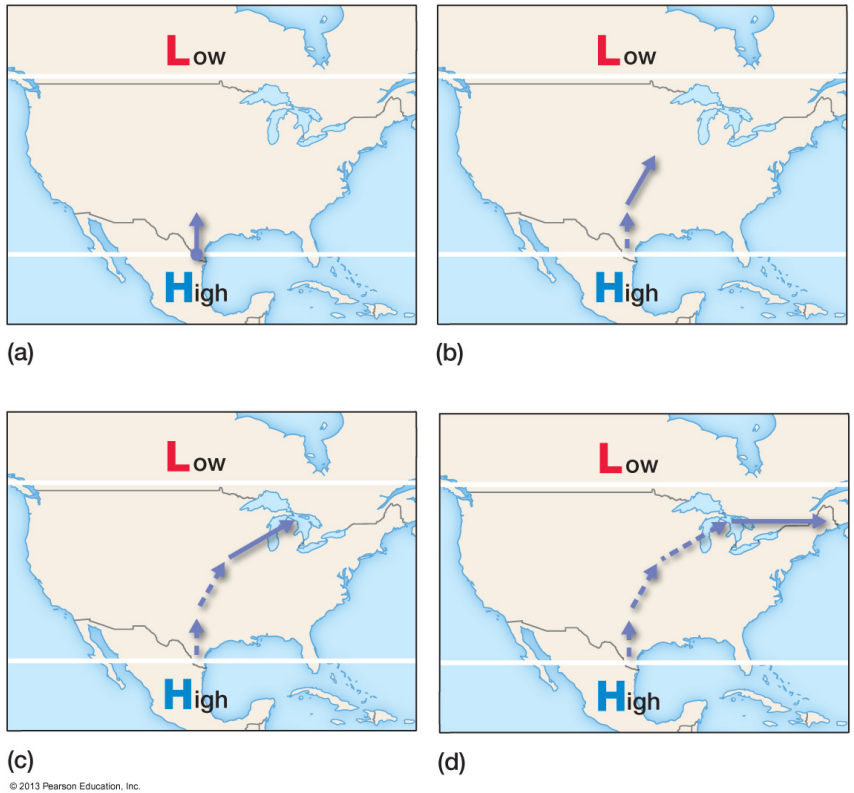
The direction of the air parcel after frame (d) will

A. follow the isobars

B. will turn toward the low pressure by the PGF

C. will keep turning toward the right by the Coriolis force

D. not enough information to answer this



Geostrophic wind

Which of the following statements is false?

A. Geostrophic flow occurs when the pressure gradient force exactly balances the Coriolis force.

B. The geostrophic wind is non-accelerating.

C. The geostrophic wind is parallel to isobars.

D. Geostrophic wind occurs both in the free troposphere and in the planetary boundary layer.

E. Geostrophic wind is a special case of gradient flow.

Clicker question

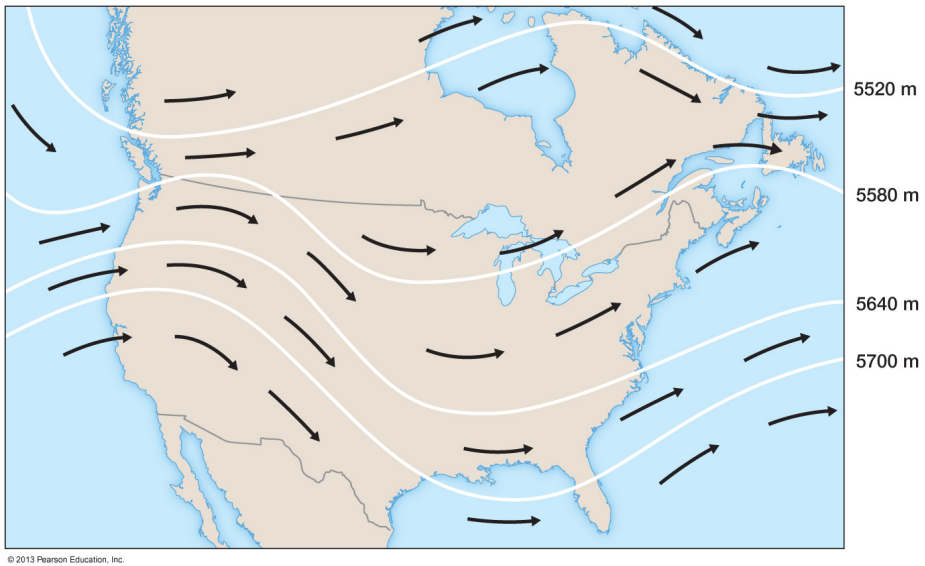
The wind shown below is an example of

A. geostrophic wind

B. ageostrophic flow (super- or sub-geostrophic)

C. gradient flow

D. trough

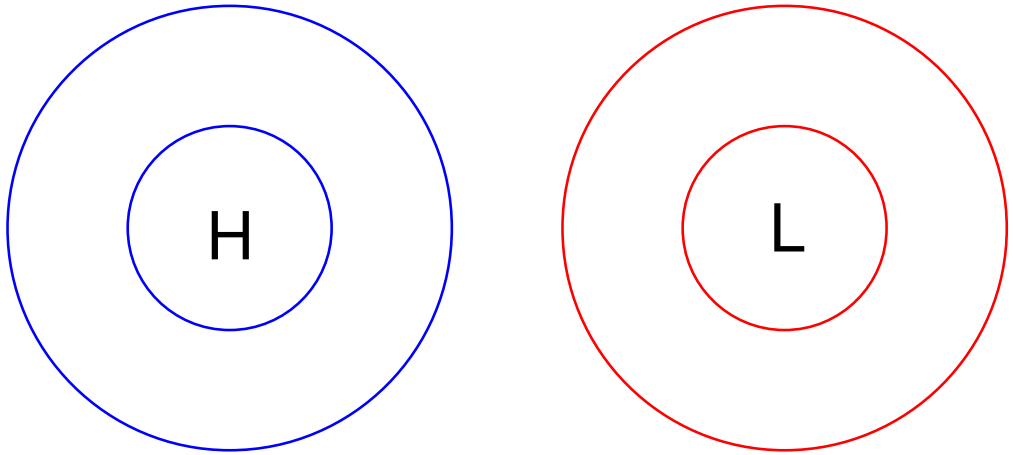


Gradient flow

Gradient flow

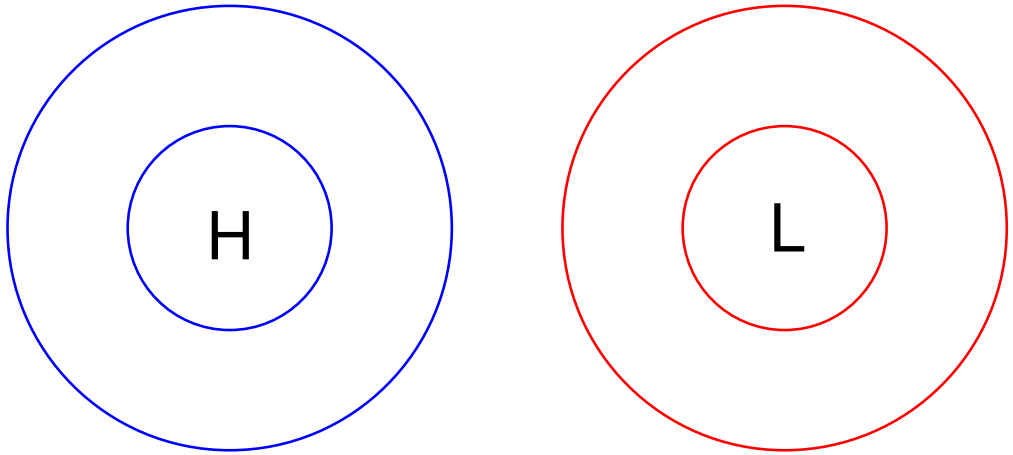
- wind follows isobars
- occurs in the upper atmosphere where flow is unaffected by surface friction
- Geostrophic flow is a special case of gradient flow
- Geostrophic (1st frame) and gradient (4th frame) flows

Ageostrophic flow



- pressure gradient force vs. Coriolis:
  - high pressure: Coriolis wins (clockwise in NH)
  - low pressure: pressure gradient wins (counterclockwise in SH)

Ageostrophic flow



- pressure gradient force vs. Coriolis:
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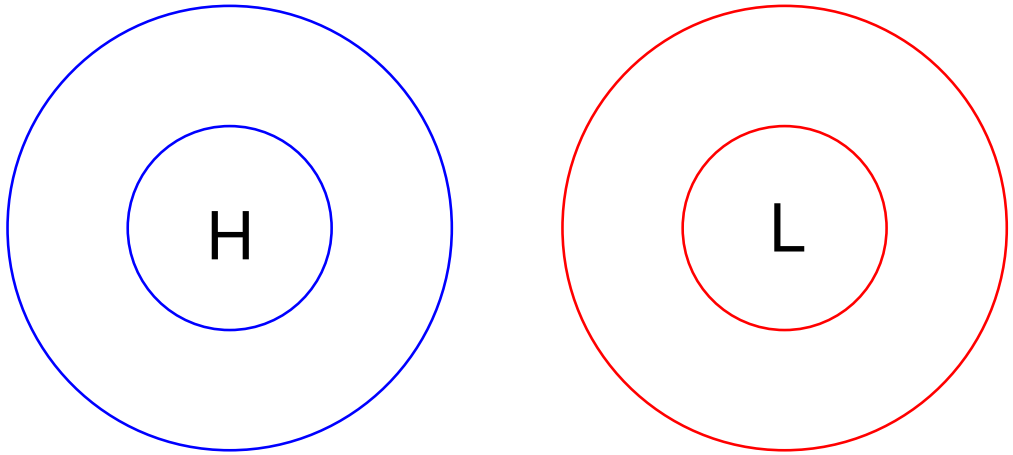
- Ageostrophic flow: pressure gradient and Coriolis force do not balance.

Ageostrophic flow



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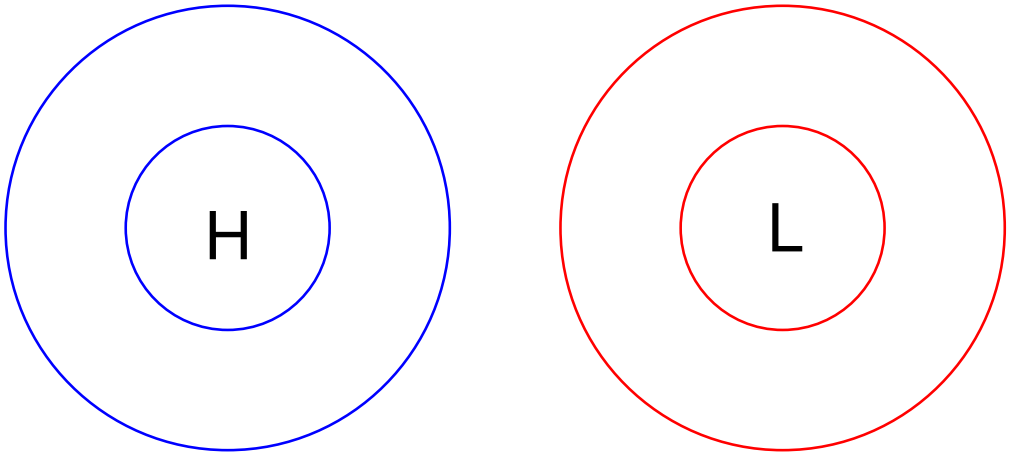
  - low pressure: pressure gradient wins (counterclockwise in SH)
- Ageostrophic flow: pressure gradient and Coriolis force do not balance.
- cyclones and anti-cyclones are an example
- ageostrophic occurs whenever the particle is accelerating
- ageostrophic flow in middle two frames

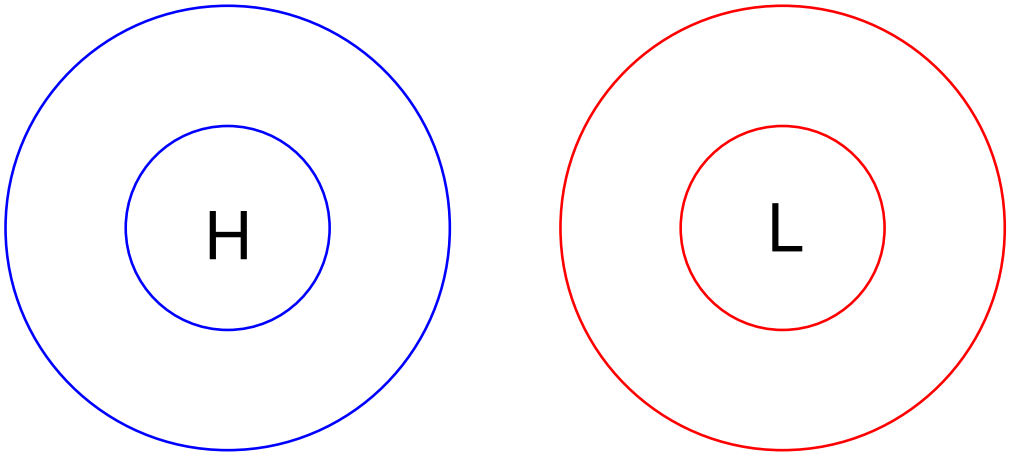
Cyclones and anti-cyclones



cyclone: closed low pressure systems

anti-cyclone: closed high pressure systems

Cyclones and anti-cyclones



cyclone: closed low pressure systems

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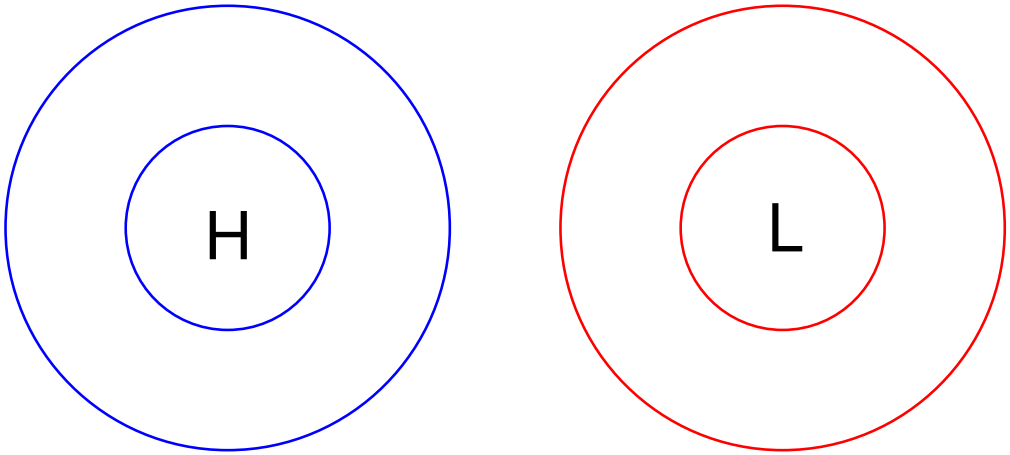
- Which direction does the wind flow in the NH? SH?

Cyclones and anti-cyclones



cyclone: closed low pressure systems

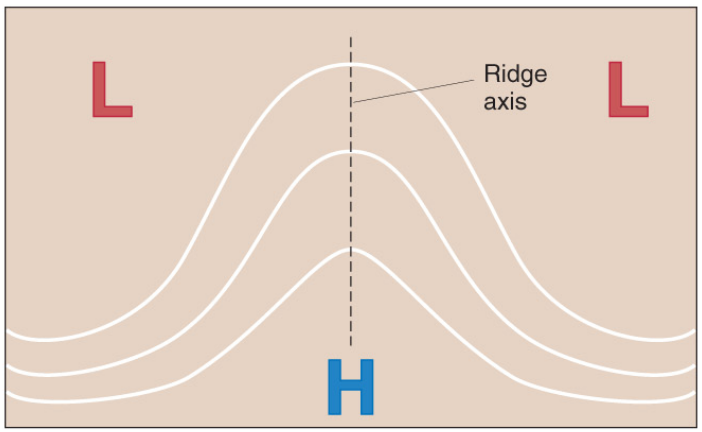
anti-cyclone: closed high pressure systems

- Which direction does the wind flow in the NH? SH?
- How does the flow change between the free tropopause and the boundary layer?
- PGF, Coriolis & friction

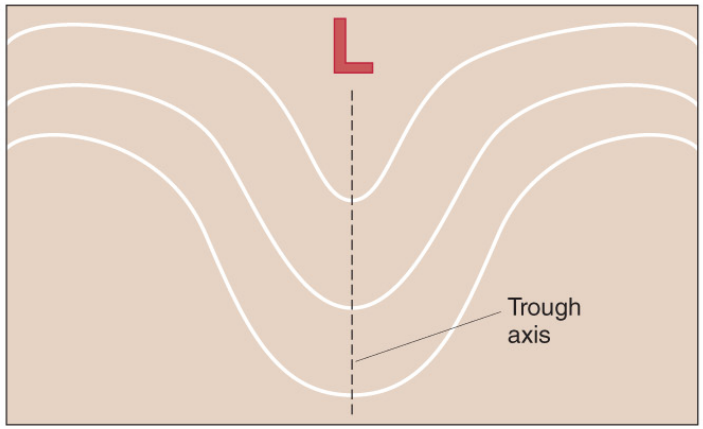
Troughs and Ridges

trough: elongated area of low pressure

ridge: elongated area of high pressure



(a)



(b)

Don't forget!

- Right-hand rules in NH!
- Left-hand rules in SH!