دانشگاه رازی

Synoptic Meteorology 1

Lecture 11

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INTRODUCTION TO ATMOSPHERIC PRESSURE

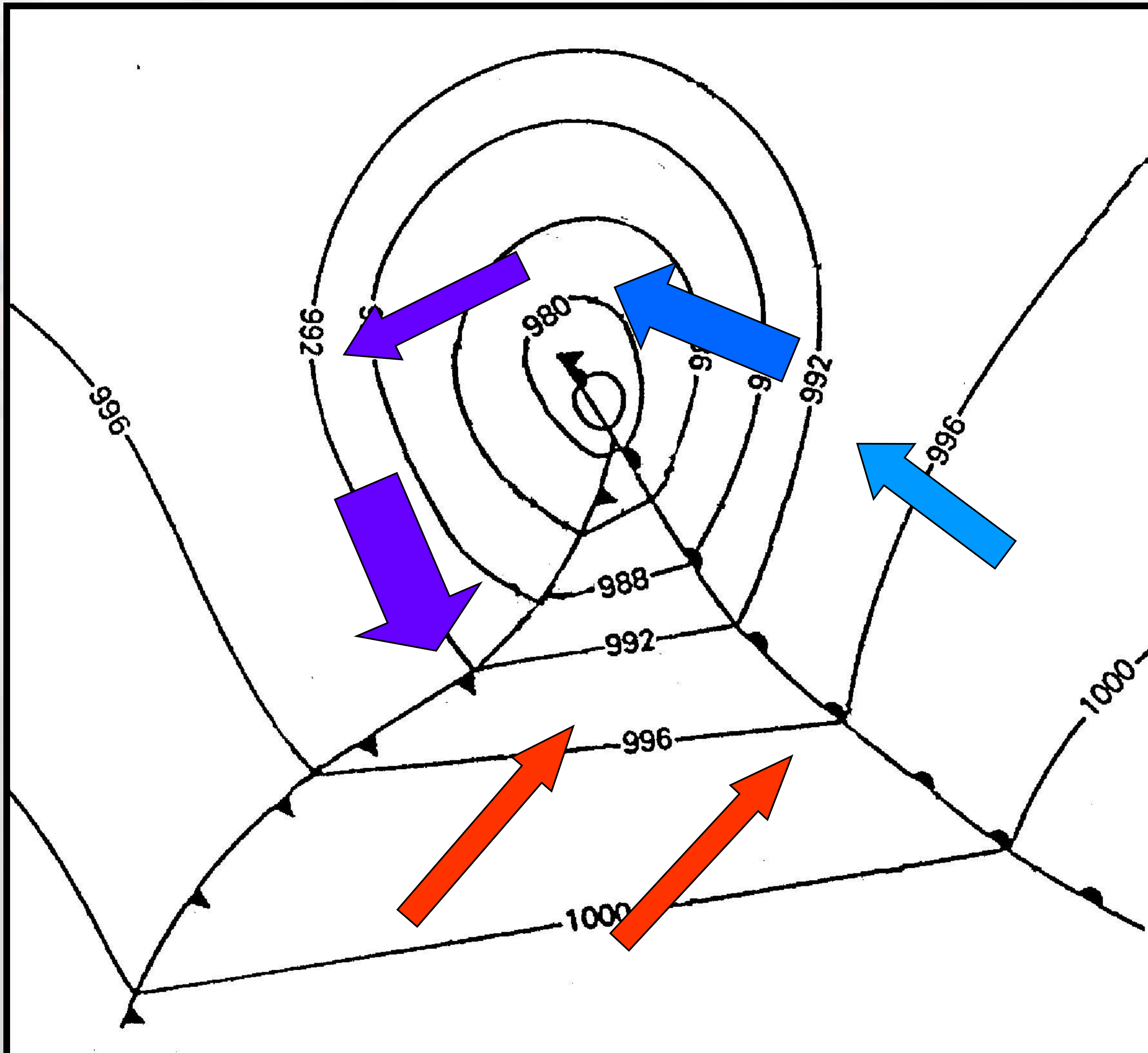
There are two types of weather systems:

- Low pressure systems
- High pressure systems

These systems affect the weather we receive from day to day.

They are caused by differences in atmospheric pressure

THE DEPRESSION WITH WINDS ADDED

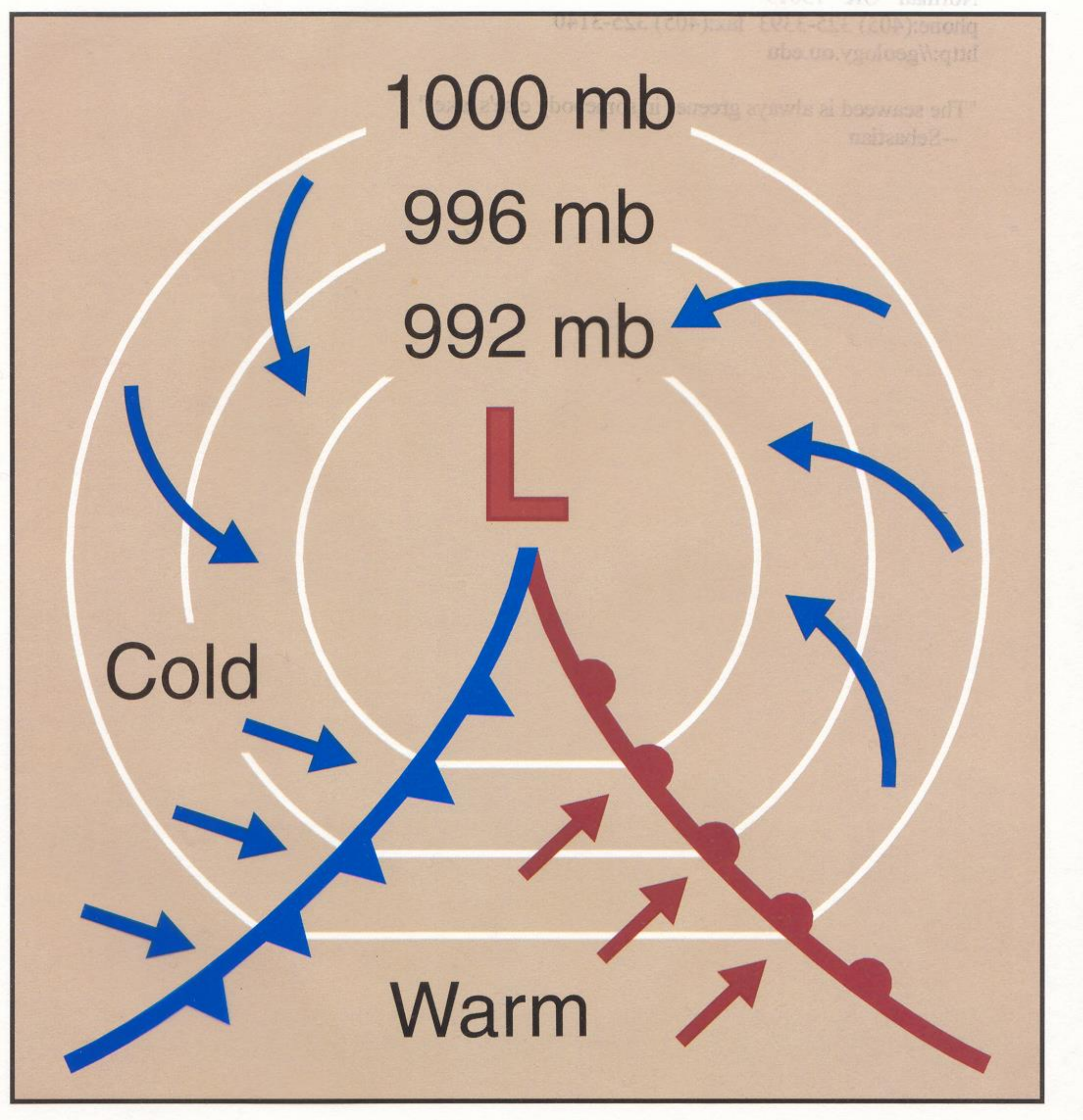


Idealized, simplified surface cyclone:

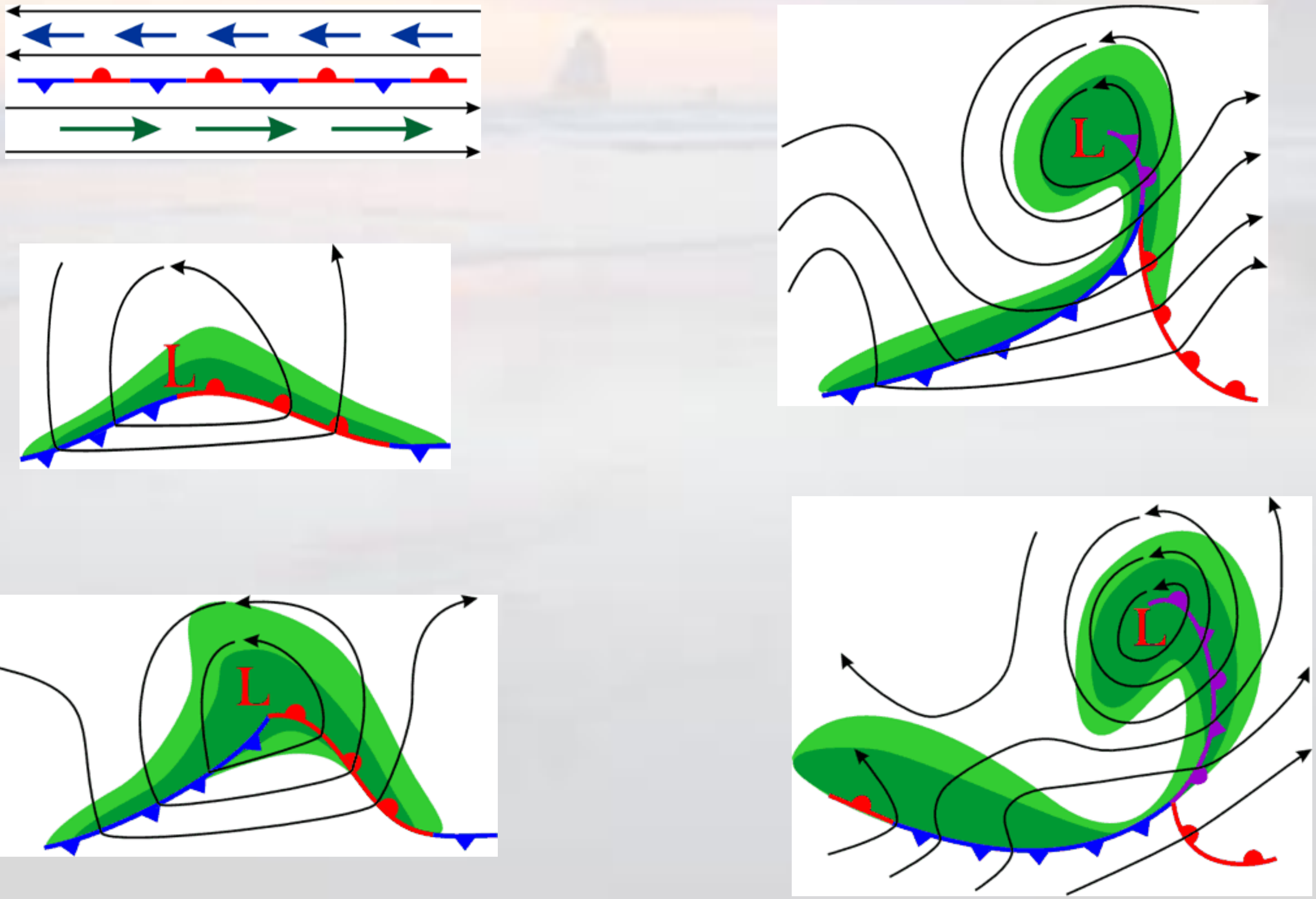
✓ cool air ahead of warm front

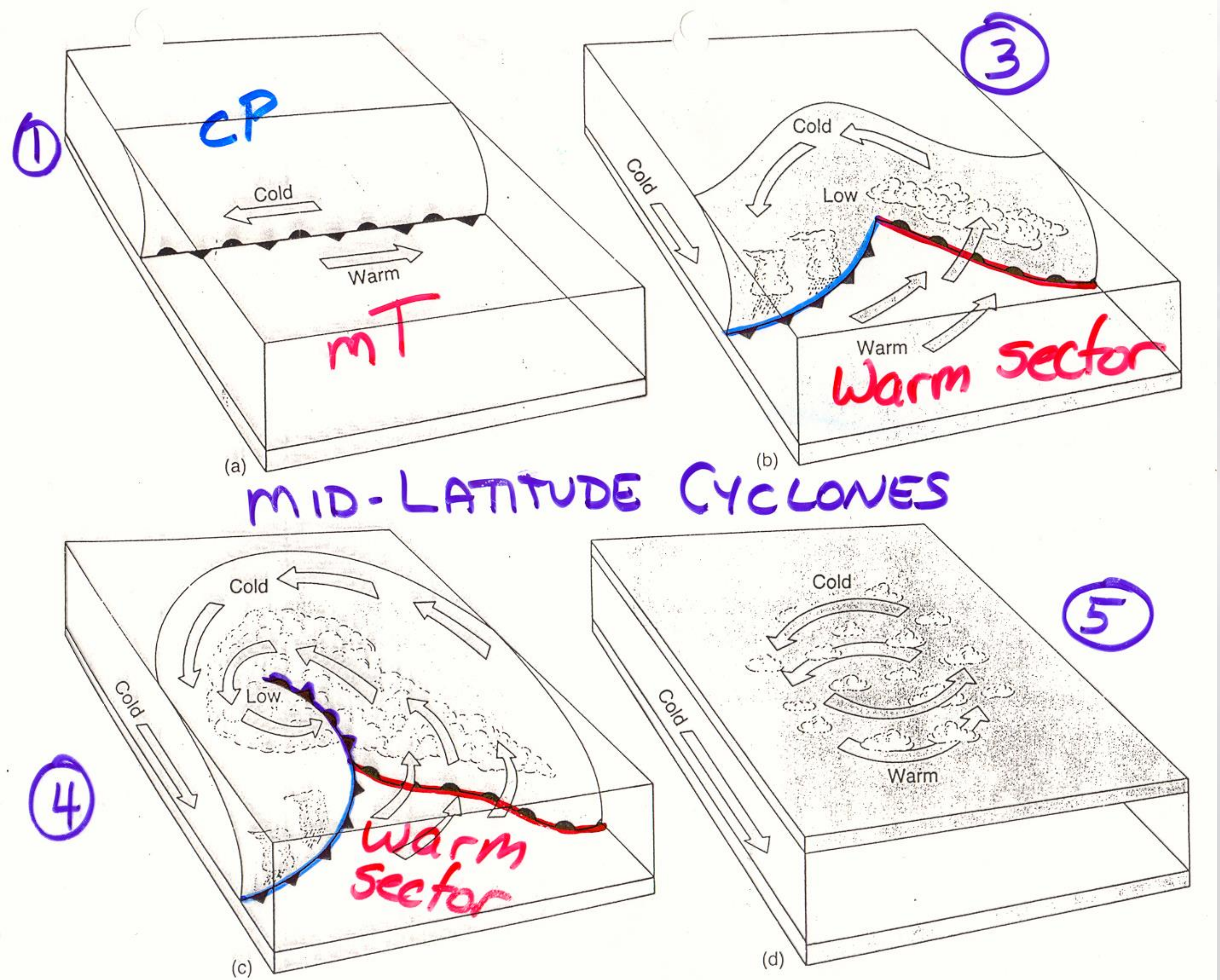
✓ warm sector between cool and cold air

✓ cold air behind the cold front



Classic Mid-latitude Cyclones





Stages in the life cycle of a middle-latitude cyclone as proposed by J. Bjerknes.

WINDS AROUND A HIGH PRESSURE SYSTEM

Winds always blow **from** high pressure **to** low pressure

Winds blow outwards **clockwise** from high pressure

Winds blow gently, because the isobars are far apart.

Forces Driving Synoptic-Scale Air Motions

There are five primary forces that govern large-scale atmospheric motions:

Pressure Gradient Force

Gravity

Coriolis Force

Friction

Centrifugal Force

Newton's 2nd Law of Motion

Pressure Gradient Force

Pressure gradient = $\Delta p/d$

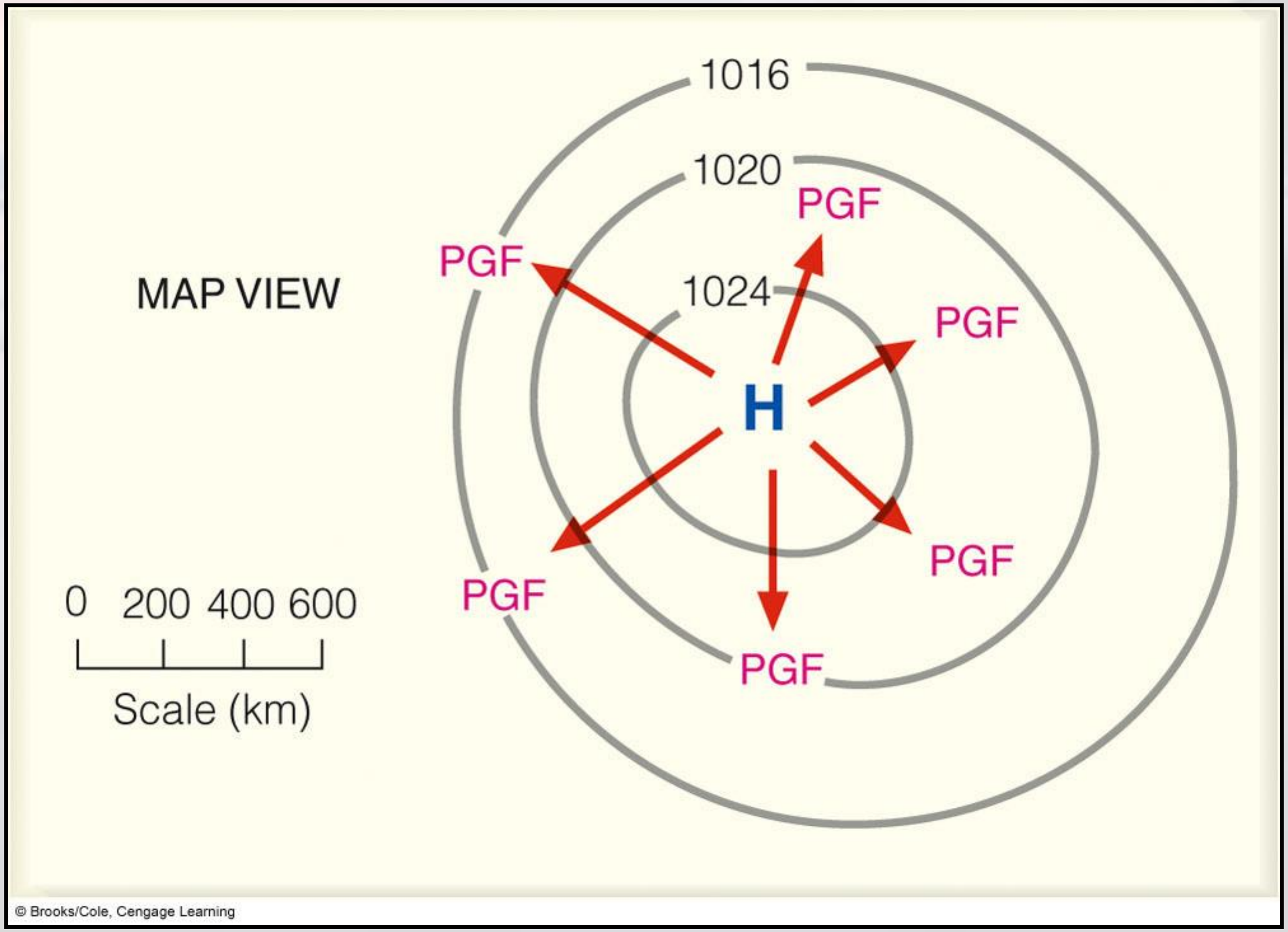
Δp: difference in pressure
d: distance

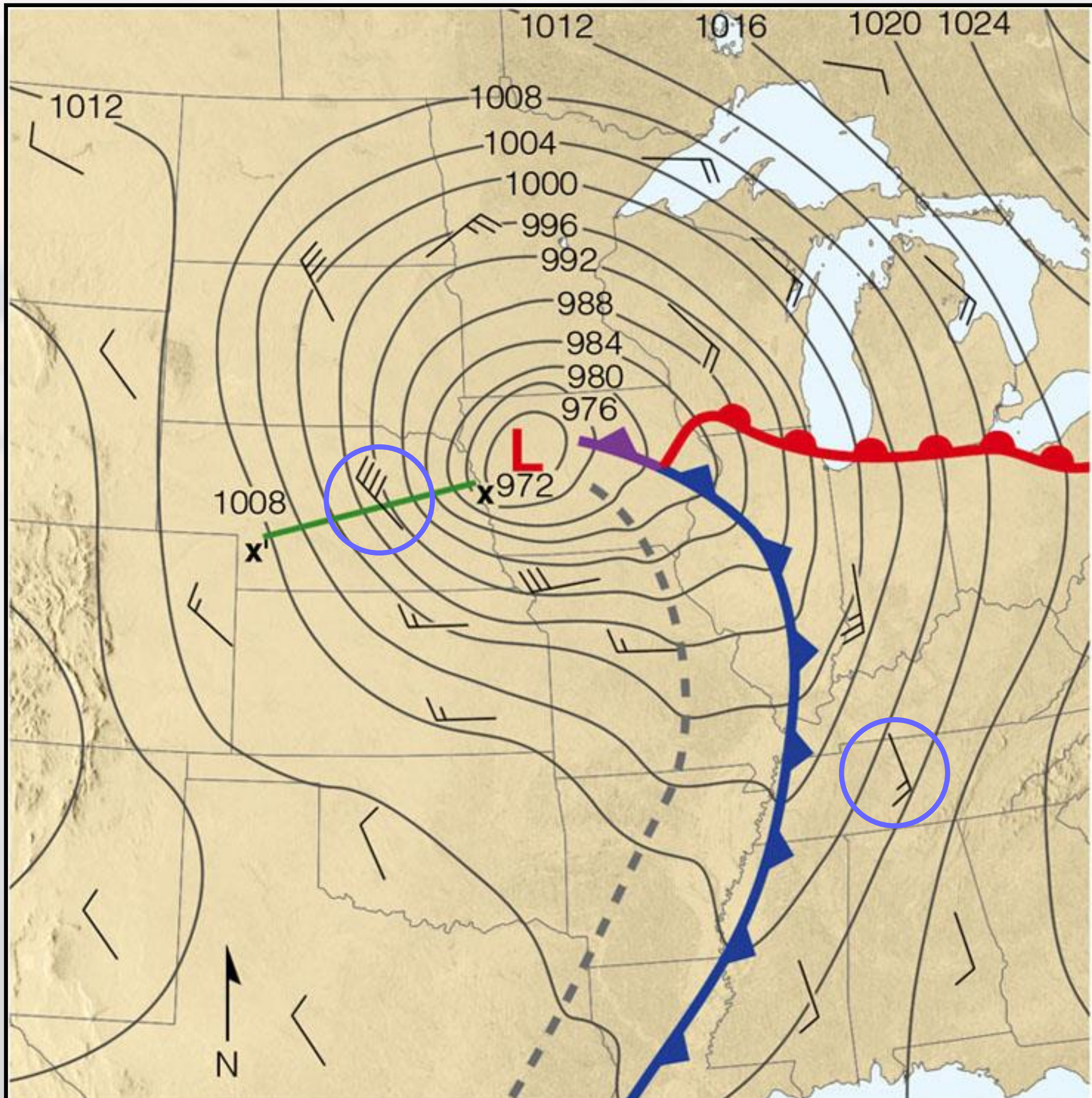
PGF has direction & magnitude

Direction: directed from high to low pressure at right angles to isobars
Magnitude: directly related to pressure gradient

Tight lines (strong PGF) = stronger wind

<u>PGF is the force that causes the wind to blow</u>


1016
1020
1024
PGF
PGF
PGF
PGF
PGF
PGF
H
MAP VIEW
0 200 400 600
Scale (km)
© Brooks/Cole, Cengage Learning


1012
1016
1020
1024
1012
1008
1004
1000
996
992
988
984
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976
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972
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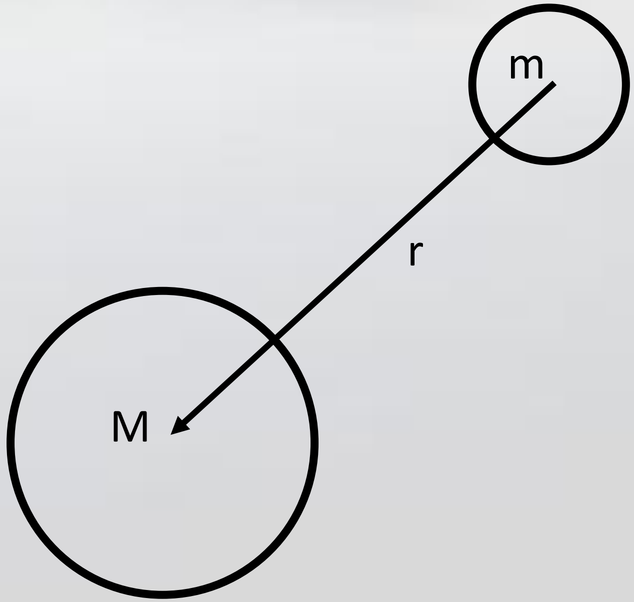
N

Gravitational Force

Newton's law of universal gravitation states that gravitational force exerted by mass M on mass m is:

$$\vec{F}_g = -\frac{G\,Mm}{r^2}\left(\frac{\vec{r}}{r}\right)$$



The Gravity Force

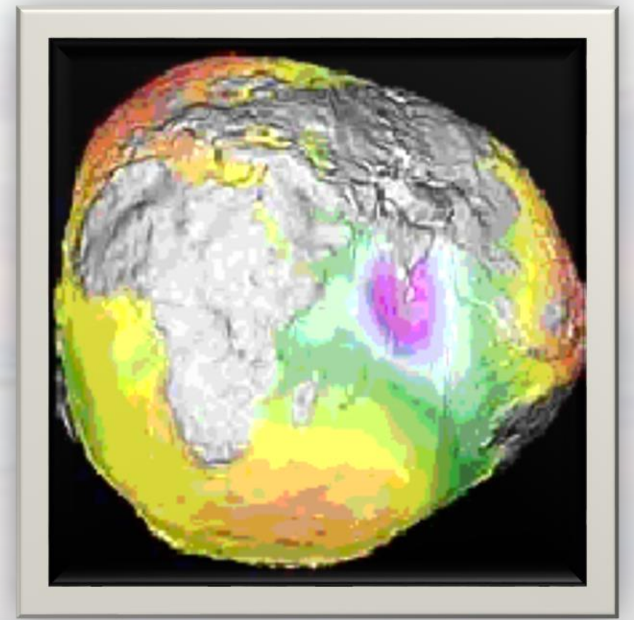
$$\vec{g}^* = \vec{g}$$

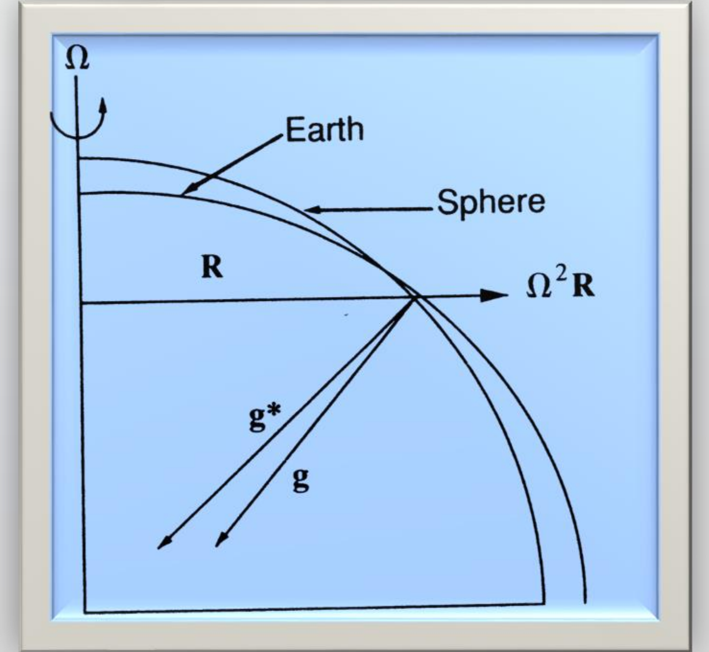
$$\vec{g}^* = \vec{g} \rightarrow pole$$

$$g = g^* - \Omega^2 R \rightarrow Equator$$

$$\Delta g = g_{pol} - g_{Eq} = 5.2 cm/s^2$$

$$g_x = 0, g_y = 0, g_z = -g$$





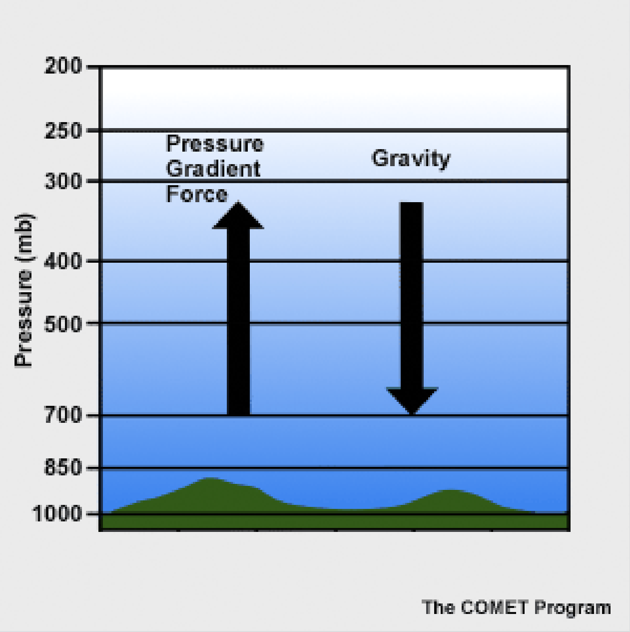
Vertical PGF – Gravity – Hydrostatic Balance

The vertical PGF acts to accelerate air upward

Gravity acts to accelerate air parcels downward (or toward the Earth's center of mass)

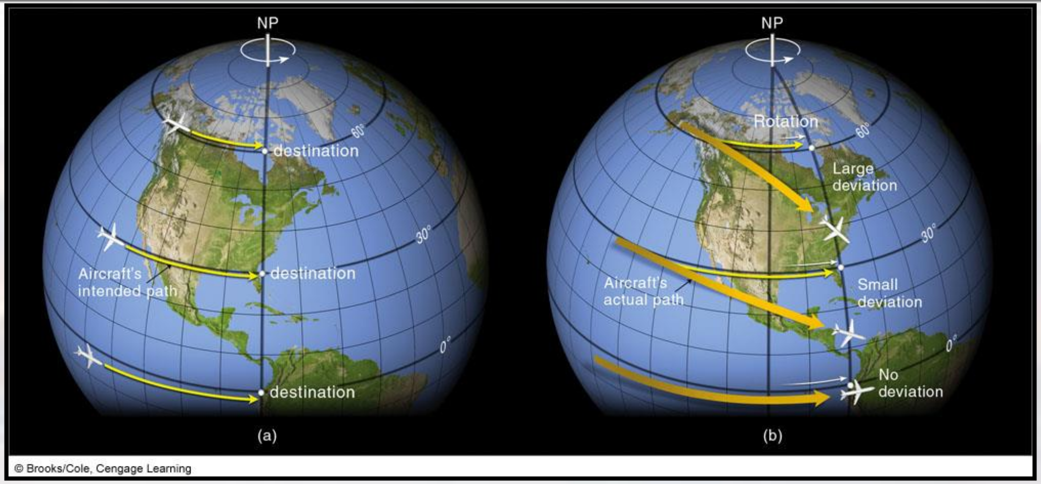
These two forces largely balance each other
This balance is called Hydrostatic Balance

For large-scale (or synoptic-scale) atmospheric motions vertical accelerations are negligible, observed vertical motions are weak (1-5 cm/s), and thus, hydrostatic balance is a valid assumption



$$-\frac{1}{\rho}\frac{\partial p}{\partial z} = g$$

Coriolis Force



Apparent deflection due to rotation of the Earth

Right in northern hemisphere and left in southern hemisphere

Stronger wind = greater deflection

No Coriolis effect at the equator greatest at poles.

Only influence direction, not speed

Only has significant impact over long distances

Coriolis = $2\ v\ \Omega\ \sin\varphi = f\ v$

Horizontal PGF – Coriolis Force – Geostrophic Balance

Horizontal PGF:

Acts to accelerate air from regions of high pressure toward regions of low pressure

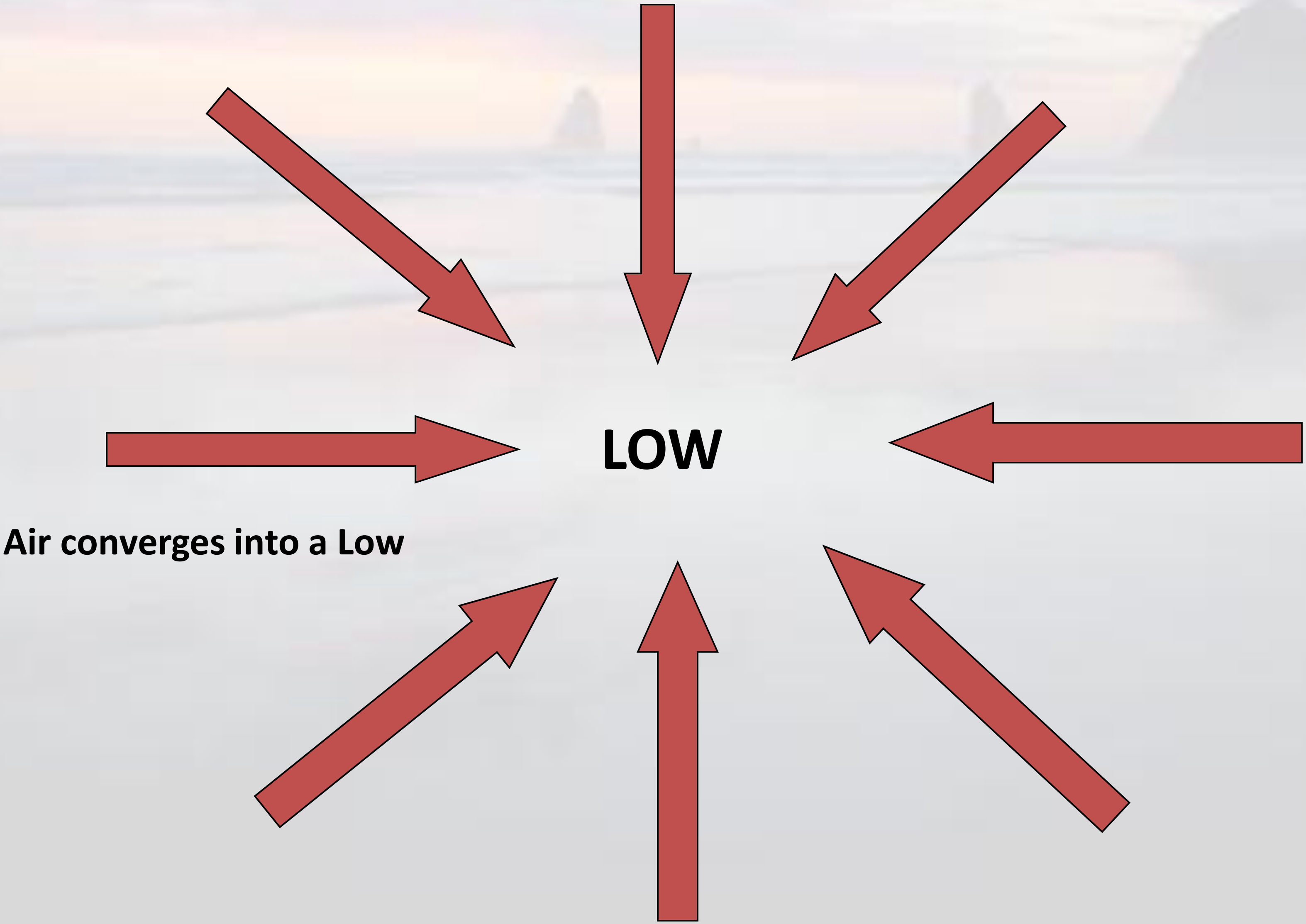
Coriolis Force:

Apparent force (Earth is rotating reference frame)

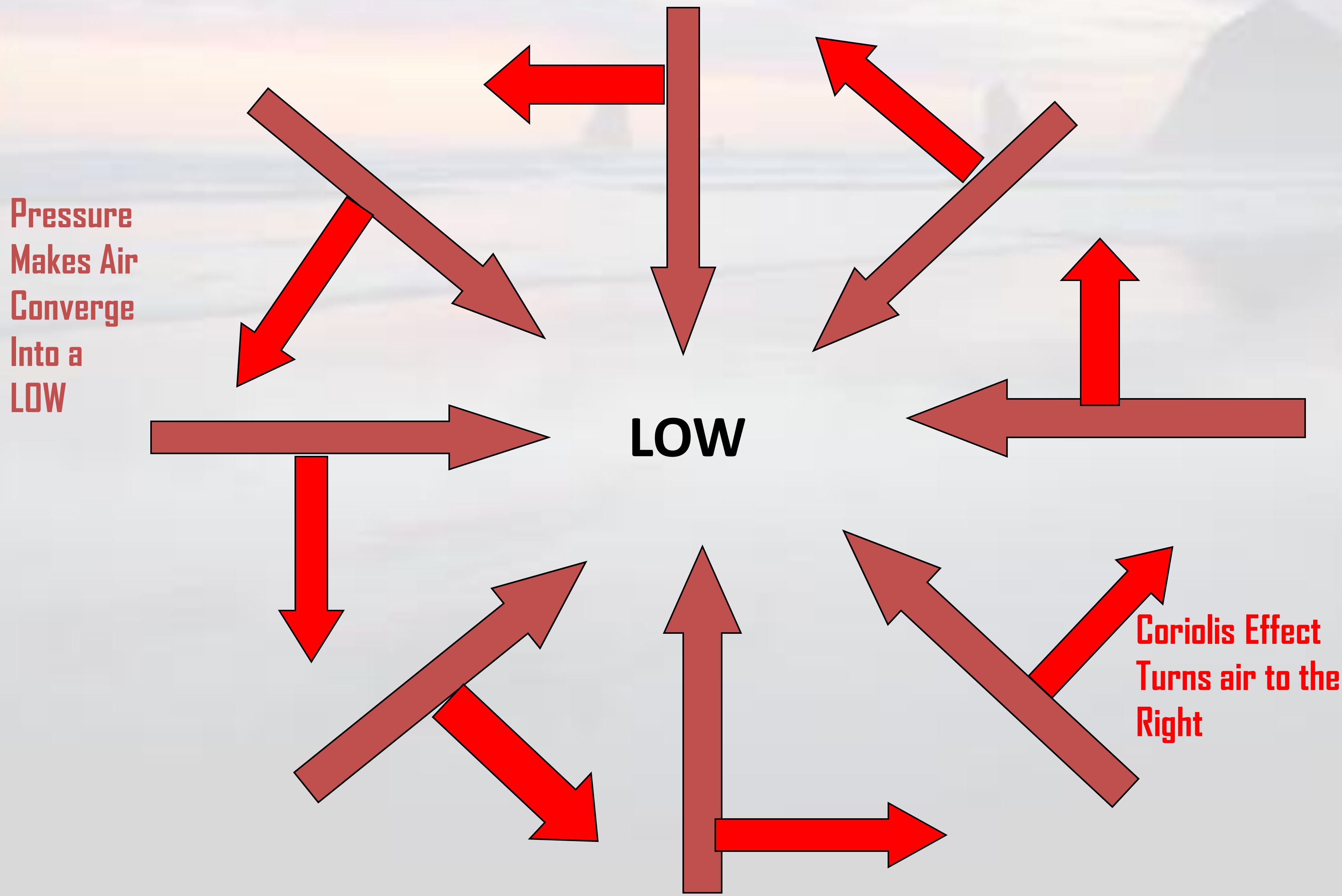
Always acts to accelerate air 90° to the right of the wind vector in the northern hemisphere

Magnitude is proportional to the wind speed

Northern Hemisphere Cyclone Map View

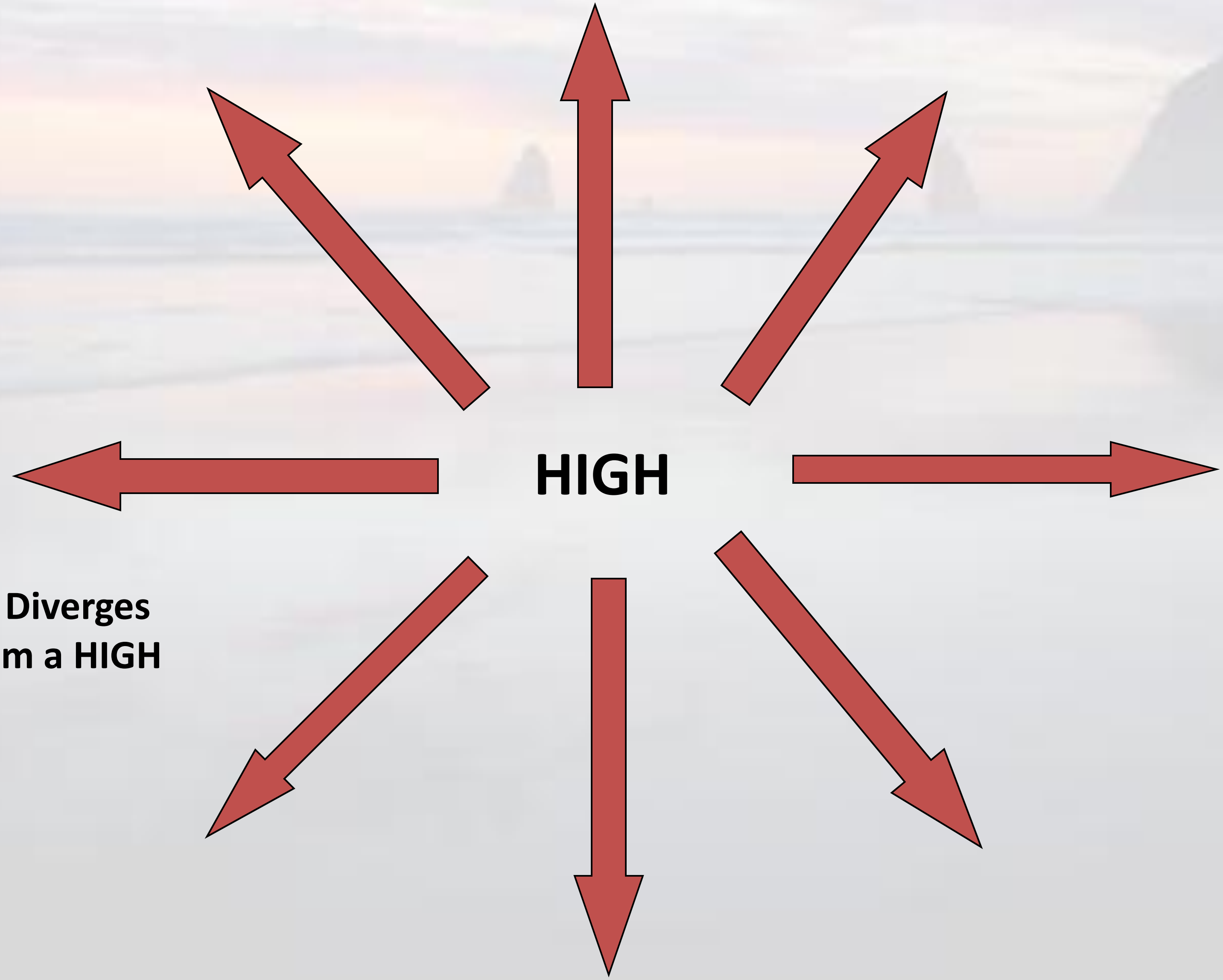


Coriolis Effect turns Wind to Right



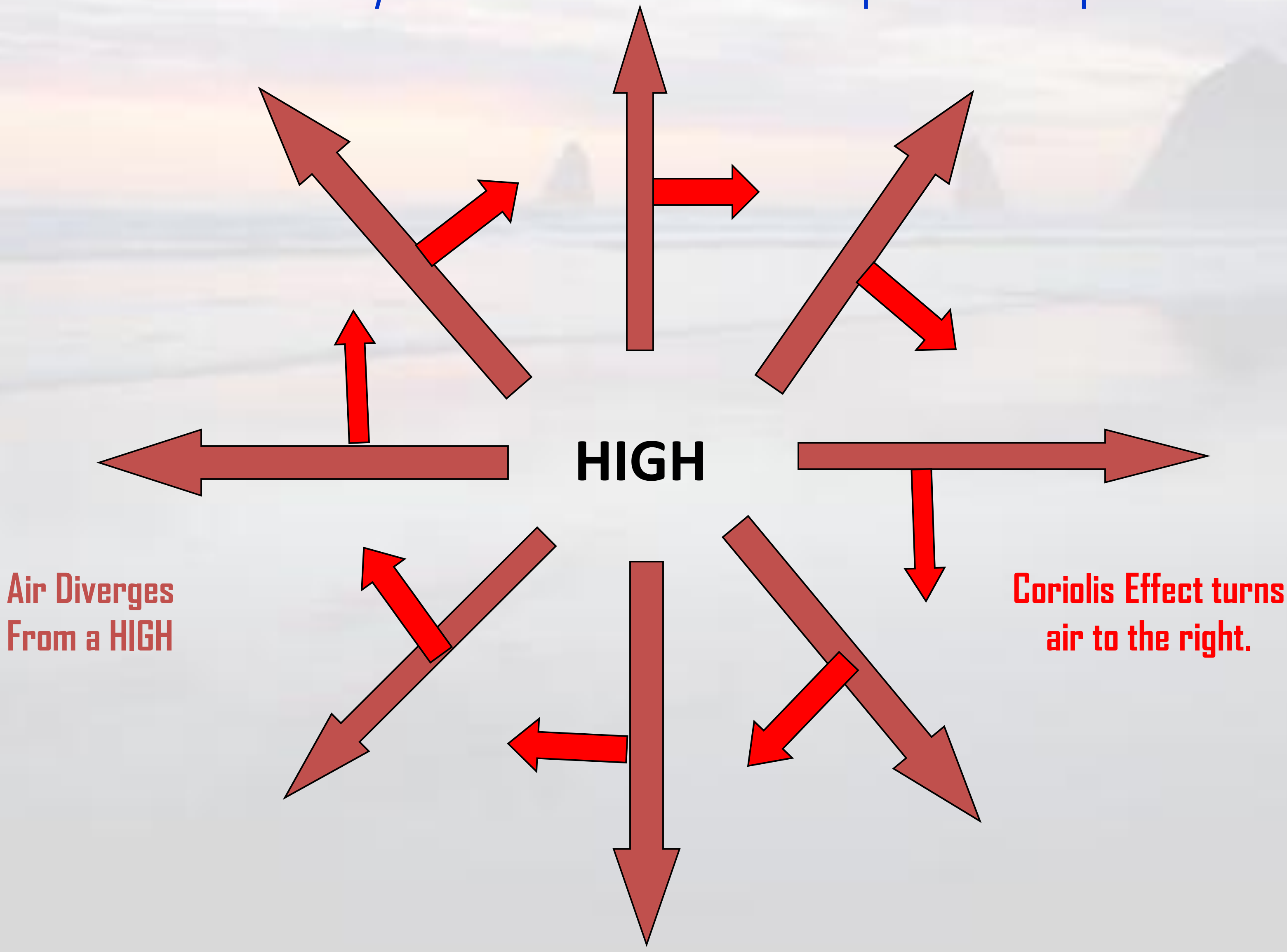
COUNTERCLOCKWISE AROUND A CYCLONE

Anticyclone in Northern Hemisphere – Map View



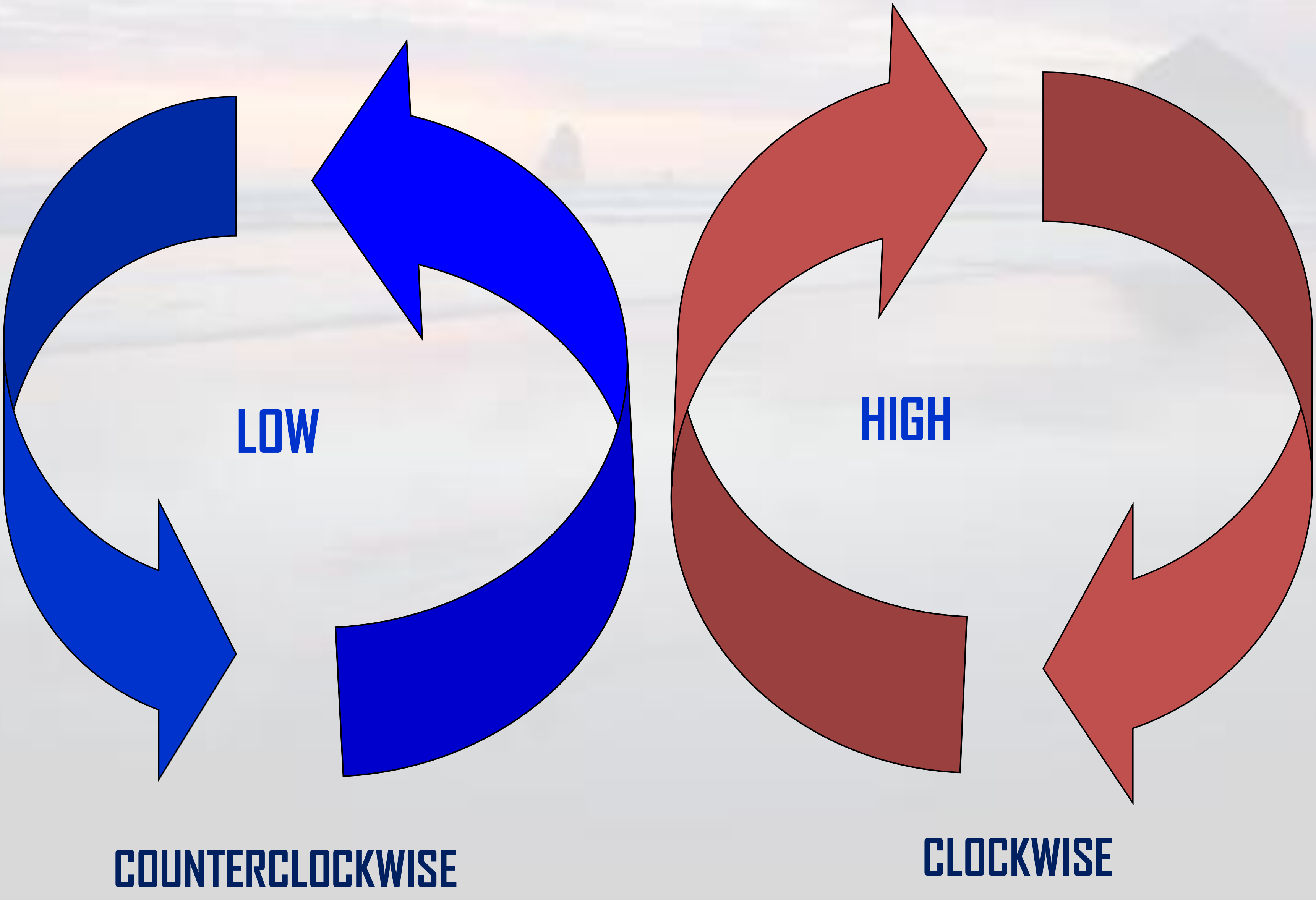
Air Diverges From a HIGH

Anticyclone in Northern Hemisphere – Map View

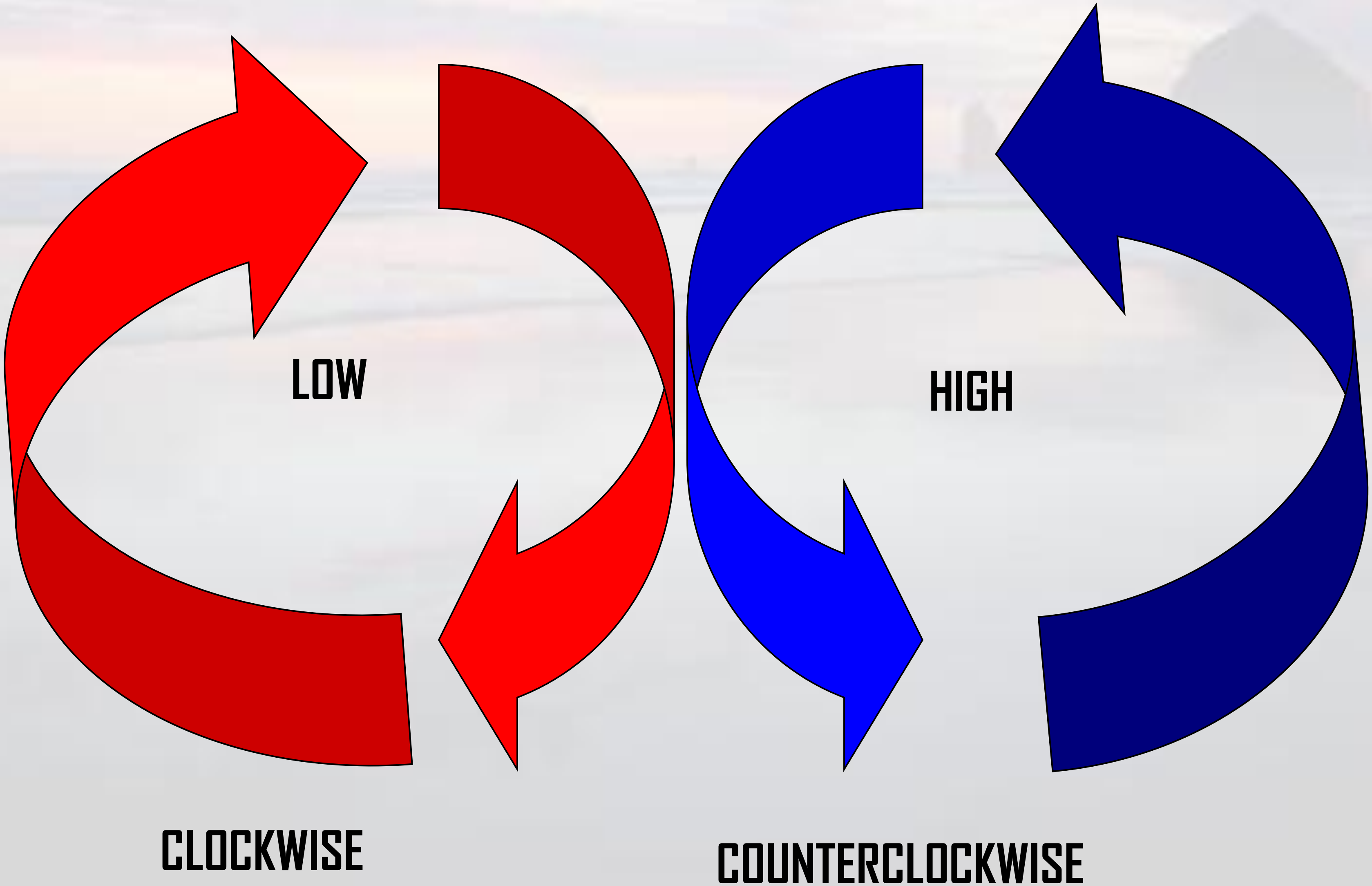


WIND BLOWS CLOCKWISE AROUND A HIGH

Northern Hemisphere



Southern Hemisphere Opposite

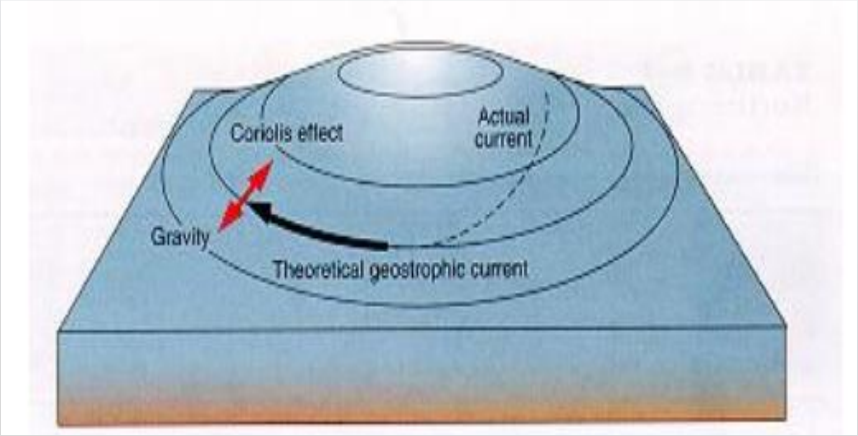


Geostrophic Balance

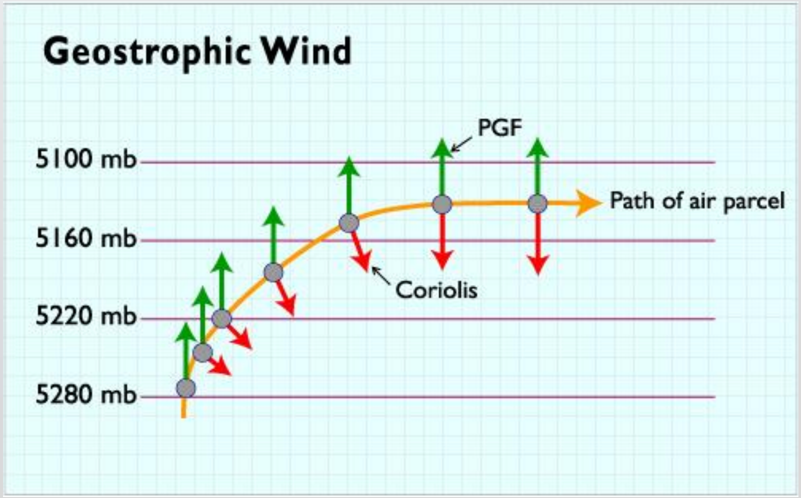
When the Coriolis and horizontal PGF are equal and opposite → Geostrophic Wind

Results in air flow parallel to isobars on height surfaces and height contours on pressure surfaces

Geostrophic balance is valid assumption for large-scale atmospheric motions above the surface (where friction plays a role…)



Flow down the pressure gradient



Horizontal PGF – Coriolis Force – Friction

Horizontal PGF:

Acts to accelerate air from regions of high to low pressure

Coriolis Force:

Always acts to accelerate air 90° to the right (left) of the wind vector in the northern (southern) hemisphere

Friction

Always acts to slow air parcels down as they move over rough terrain (land, trees, buildings, hills, etc.)

Only affects air in the lowest 1-2 km near the surface

Results in large-scale convergence (divergence) in association with low (high) pressure systems near the surface

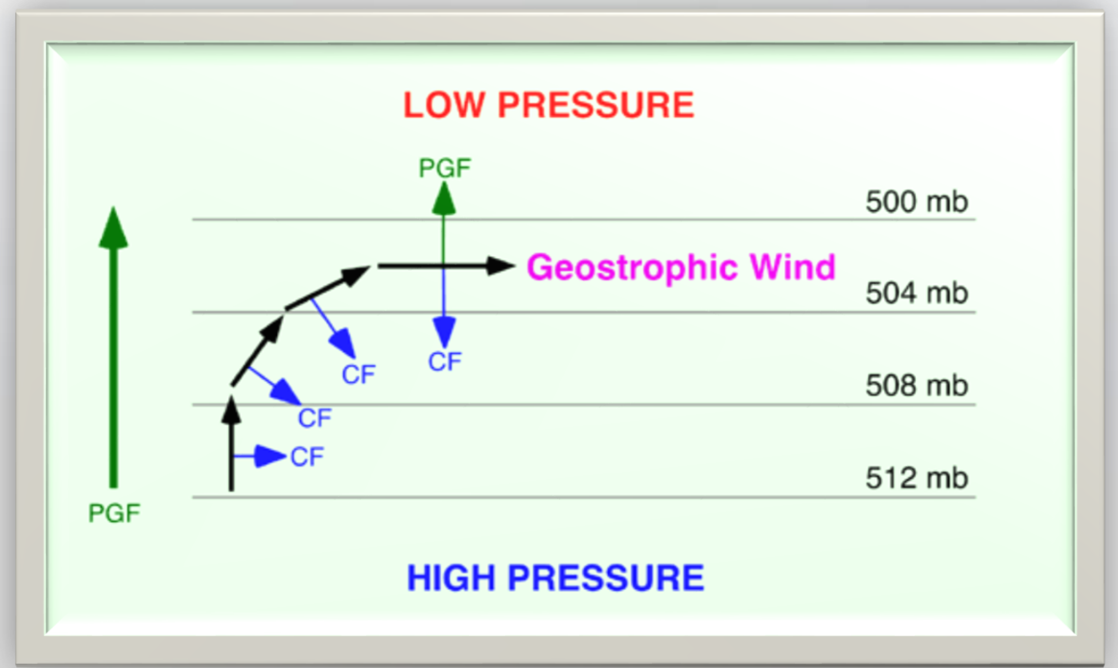
Geostrophic Wind

Winds aloft (above ~1000 m) flowing in a straight line, a balance between 2 forces:

Pressure gradient force (PGF)

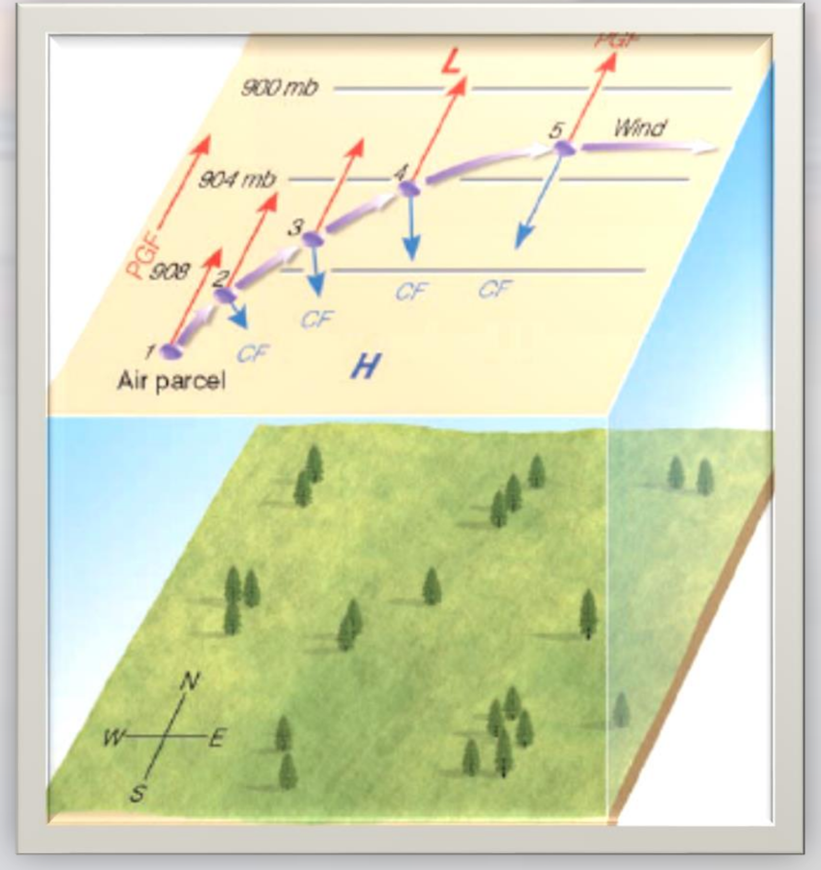
Coriolis 'force' (CF)

A wind that begins to blow across the isobars is turned by the Coriolis 'force' until Coriolis 'force' and PGF balance



geostrophic wind

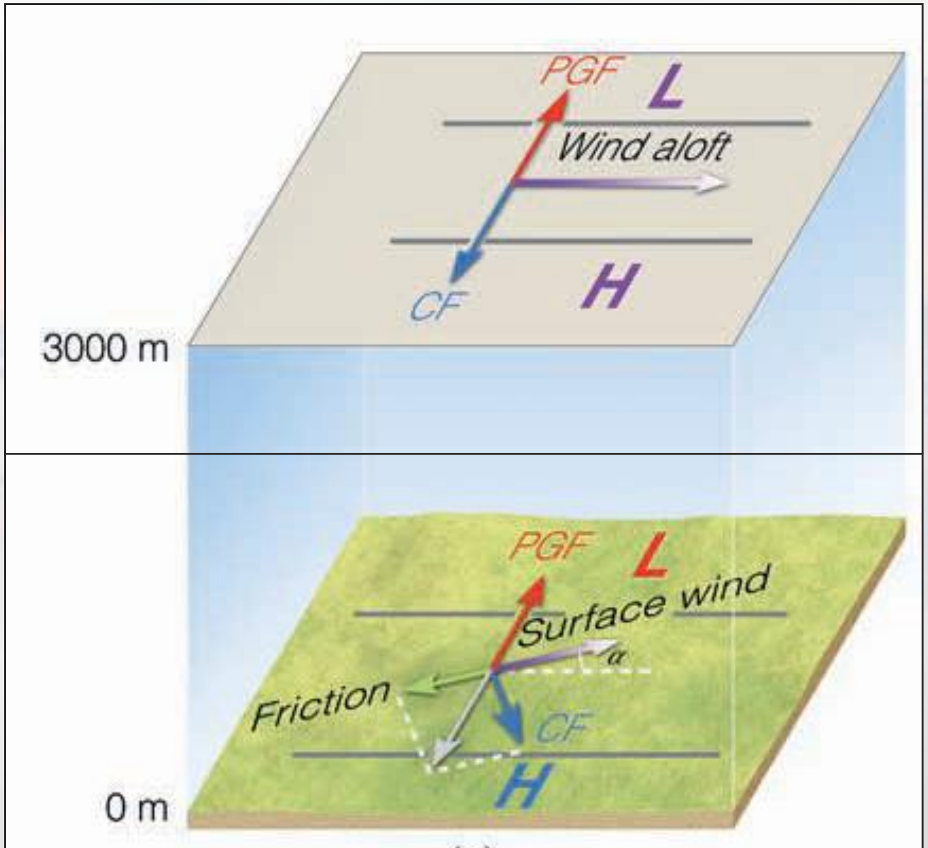
Above the level of friction, air initially at rest will accelerate until it flows parallel to the isobars at a steady speed with the pressure gradient force (PGF) balanced by the Coriolis force (CF).



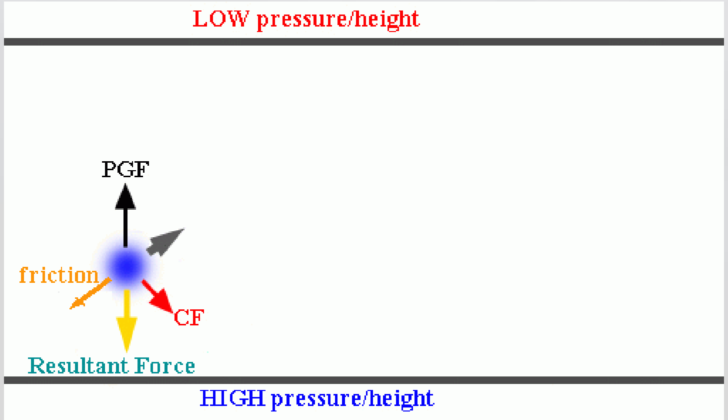
Wind blowing under these conditions is called geostrophic as a result, which force becomes smaller, the PGF or the CF?

therefore, the winds cross the isobars, directed towards the lower pressure

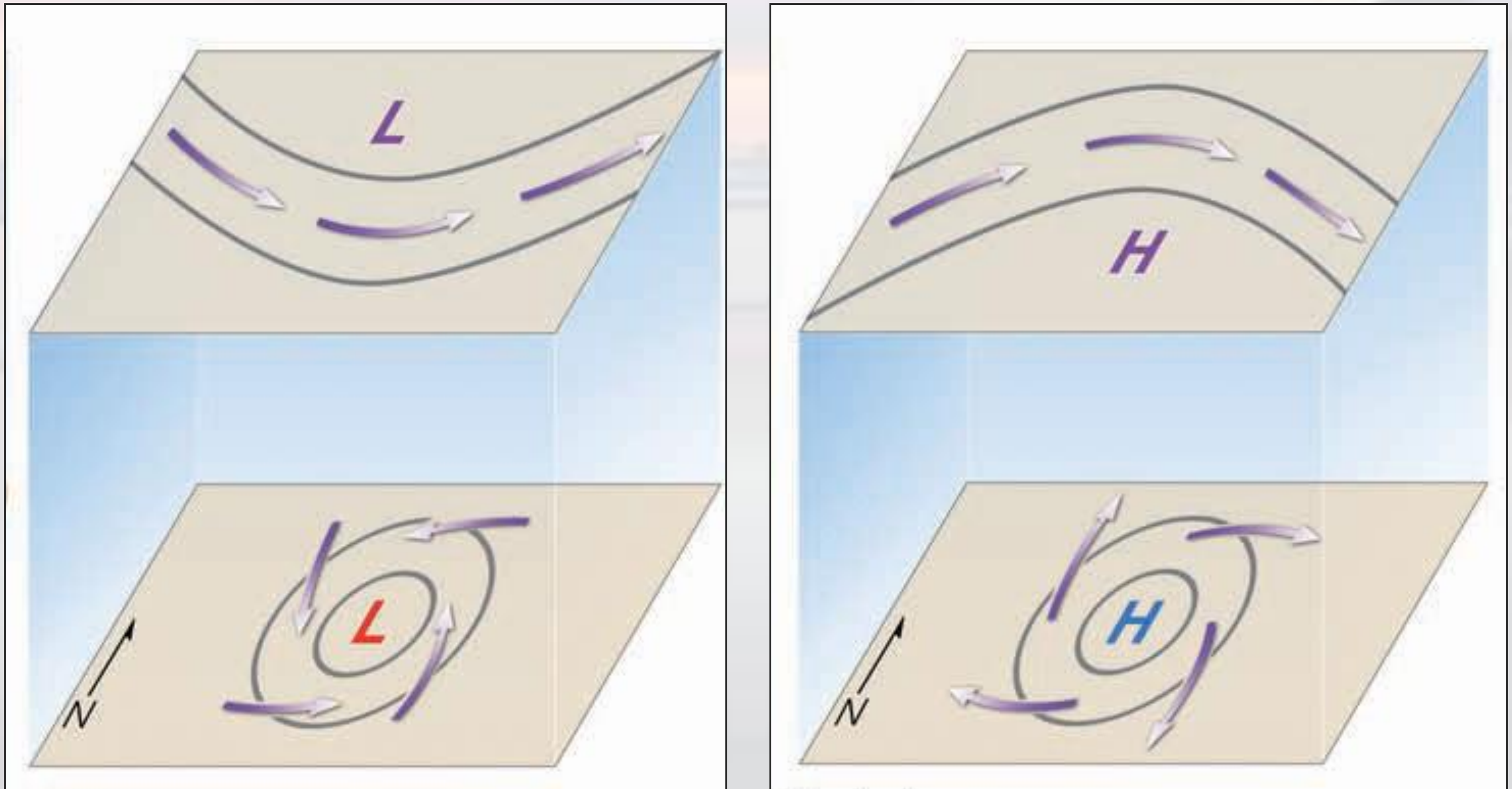
$$\text{friction} + CF + PGF = 0$$



(a)

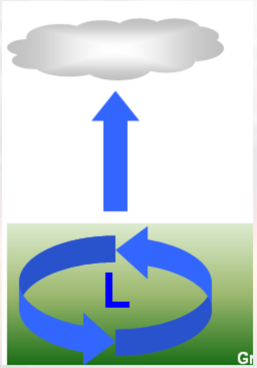


Effect of friction on flow around lows and highs

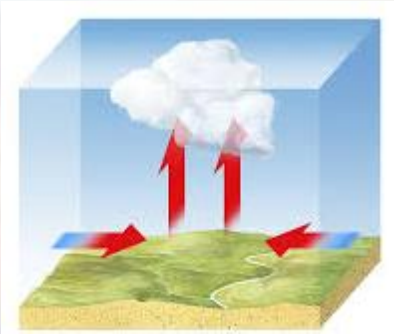


(b) Northern Hemisphere

Due to the frictional turning of the wind such that it crosses the isobars, what can you infer about the vertical motions in the vicinity of a surface low, surface high



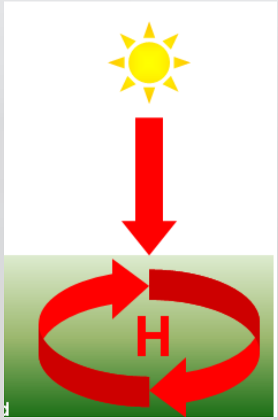
Rising Air near Lows



Rising air cools; water vapor in the air condenses to form clouds/precipitation

Lows tend to bring cloudy, wet weather

Sinking air near Highs



Sinking air warms and dries out

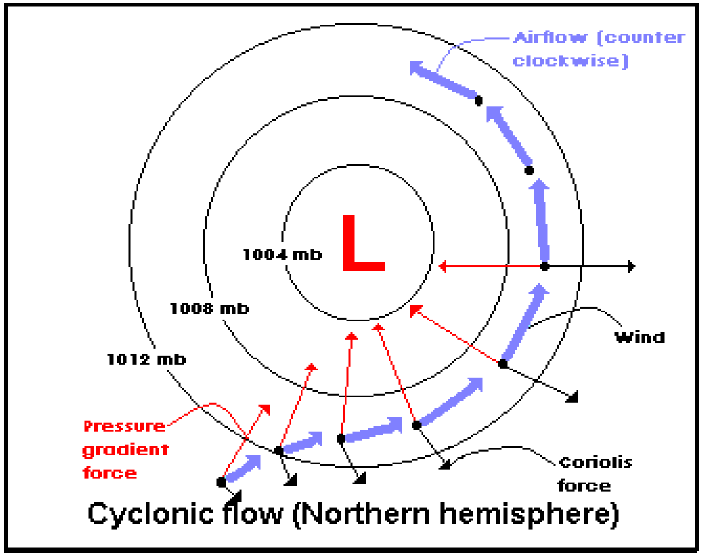
Highs tend to bring fair, dry weather

Cyclonic Flow

Counter-clockwise flow (N Hemisphere)

rising air

Occurs in association with low pressure systems (called "cyclones" or L.P.)

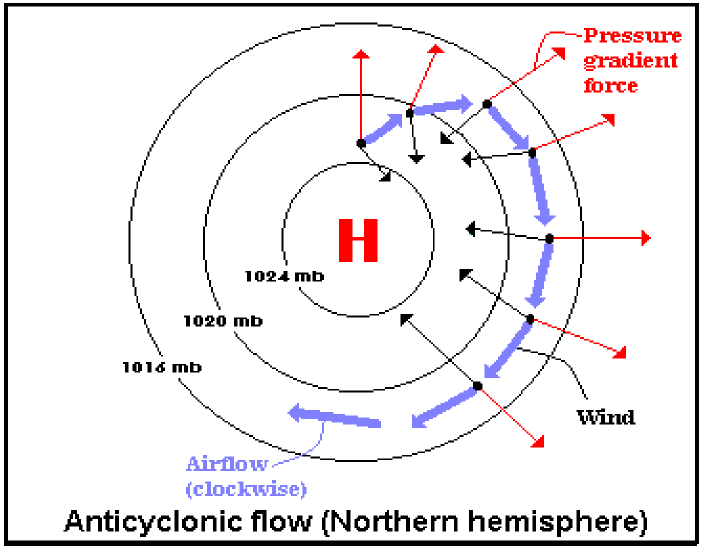


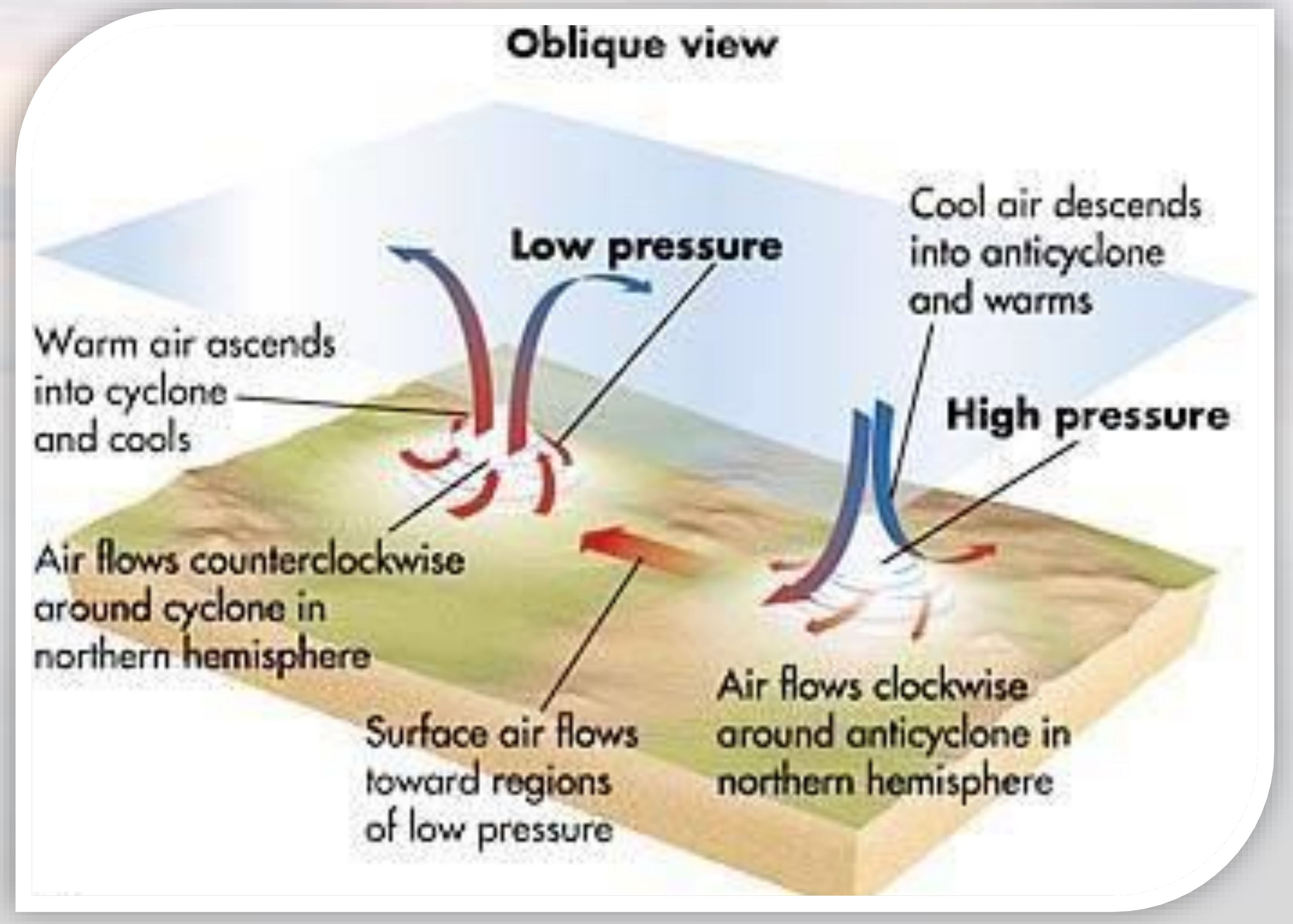
Anticyclonic Flow

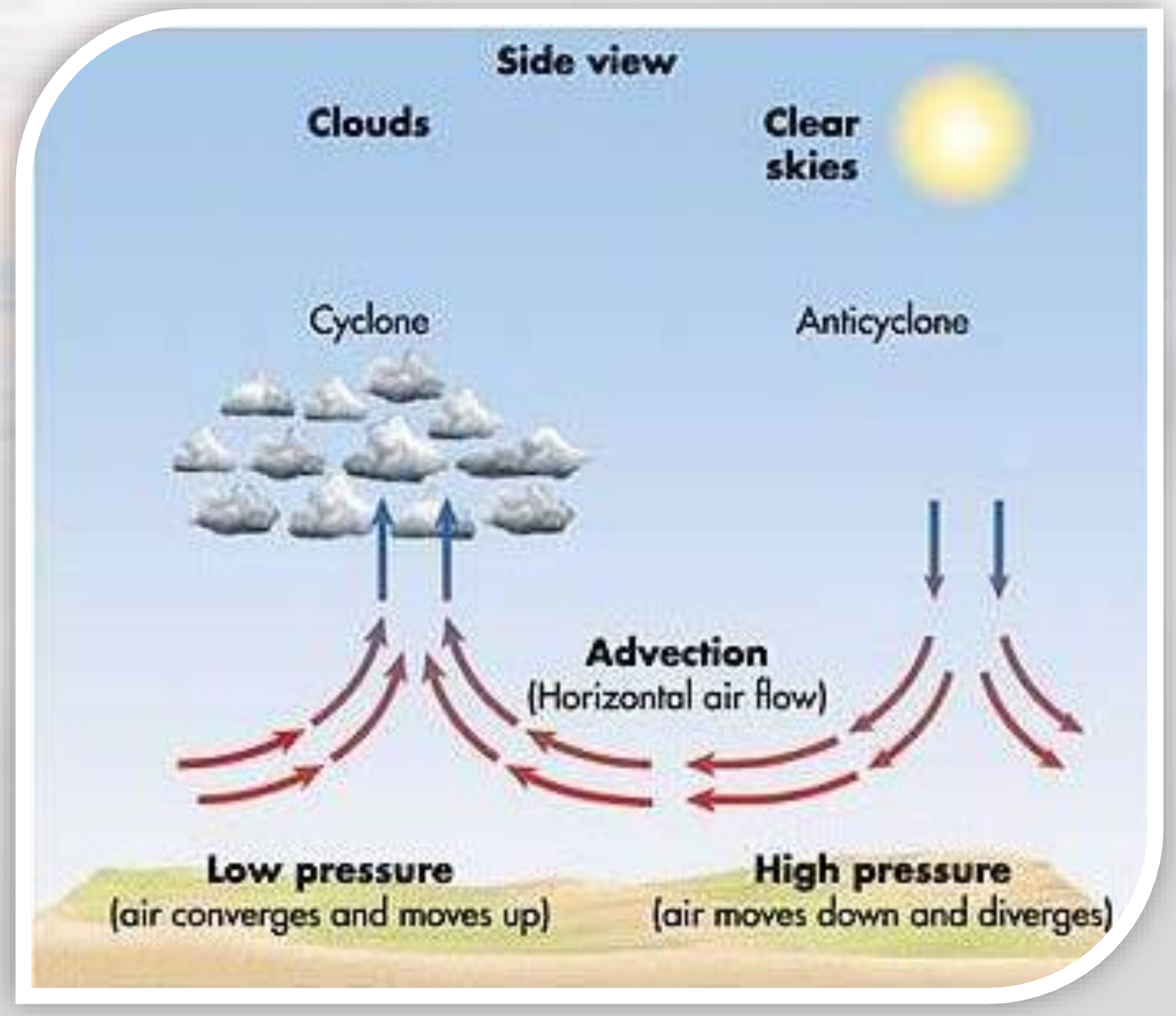
Clockwise flow (N Hemisphere)

descending air

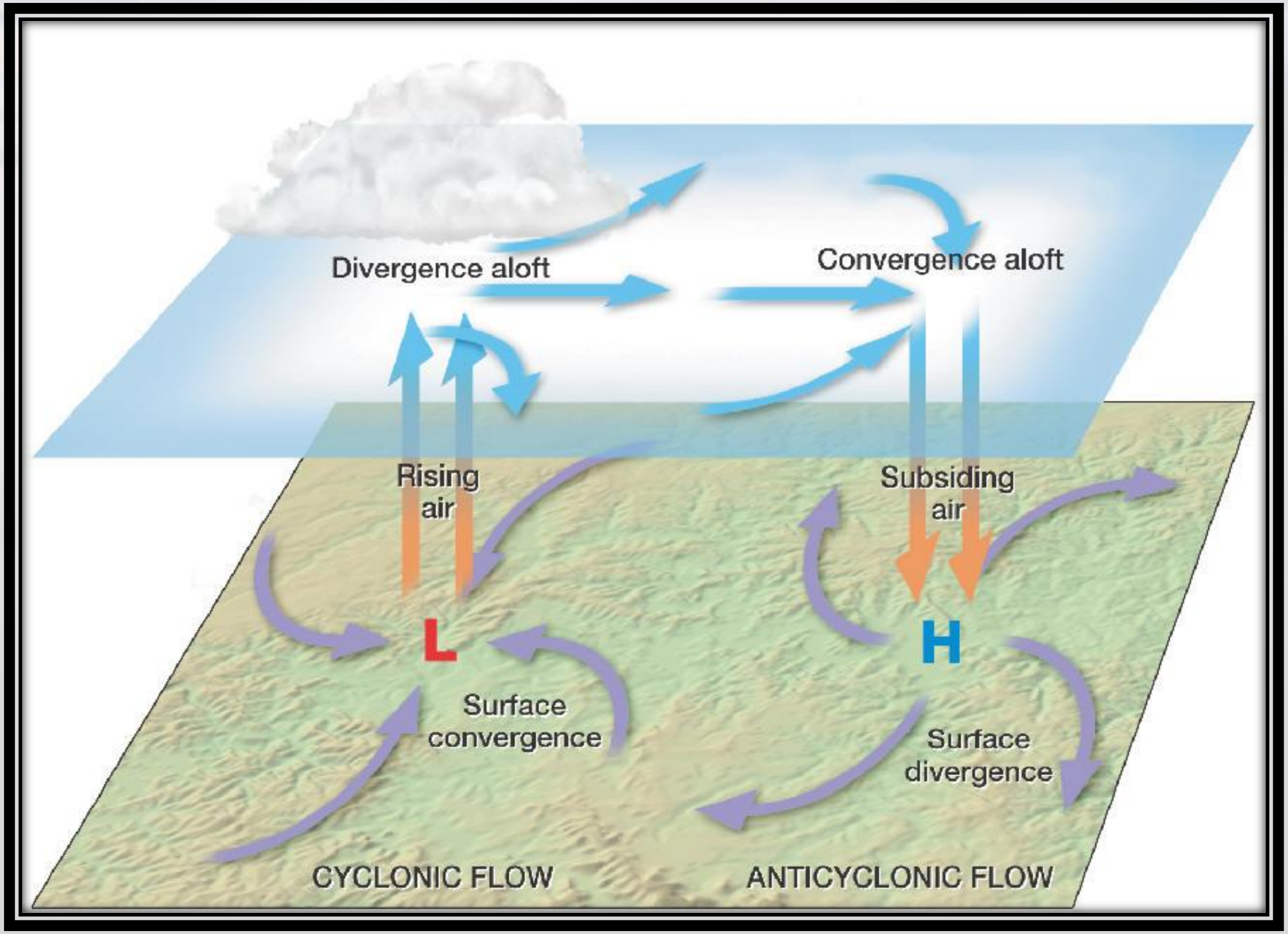
Occurs in association with high pressure systems (called "anticyclones" or H.P.)

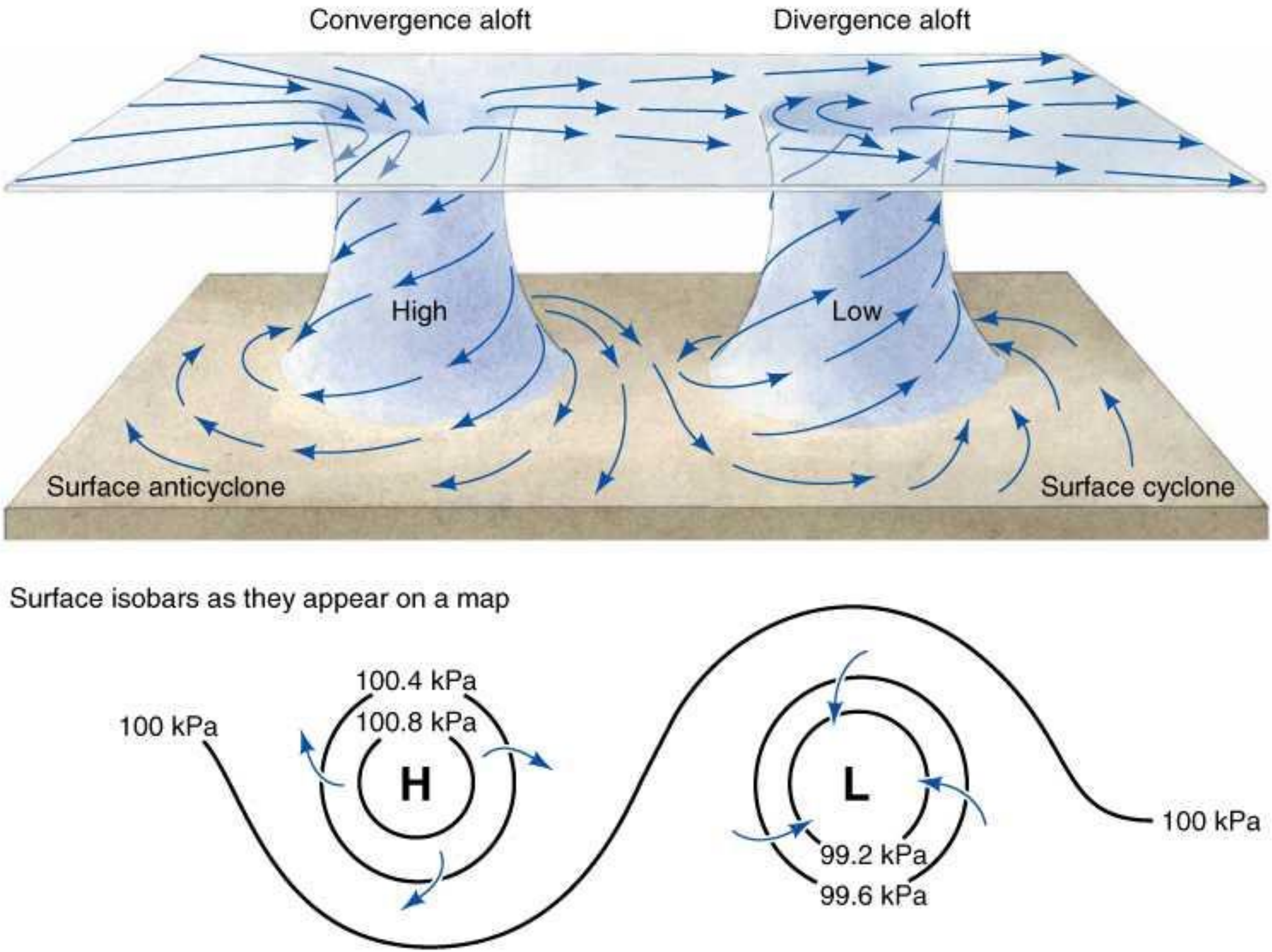



Oblique view
Low pressure
Cool air descends into anticyclone and warms
Warm air ascends into cyclone and cools
High pressure
Air flows counterclockwise around cyclone in northern hemisphere
Air flows clockwise around anticyclone in northern hemisphere
Surface air flows toward regions of low pressure

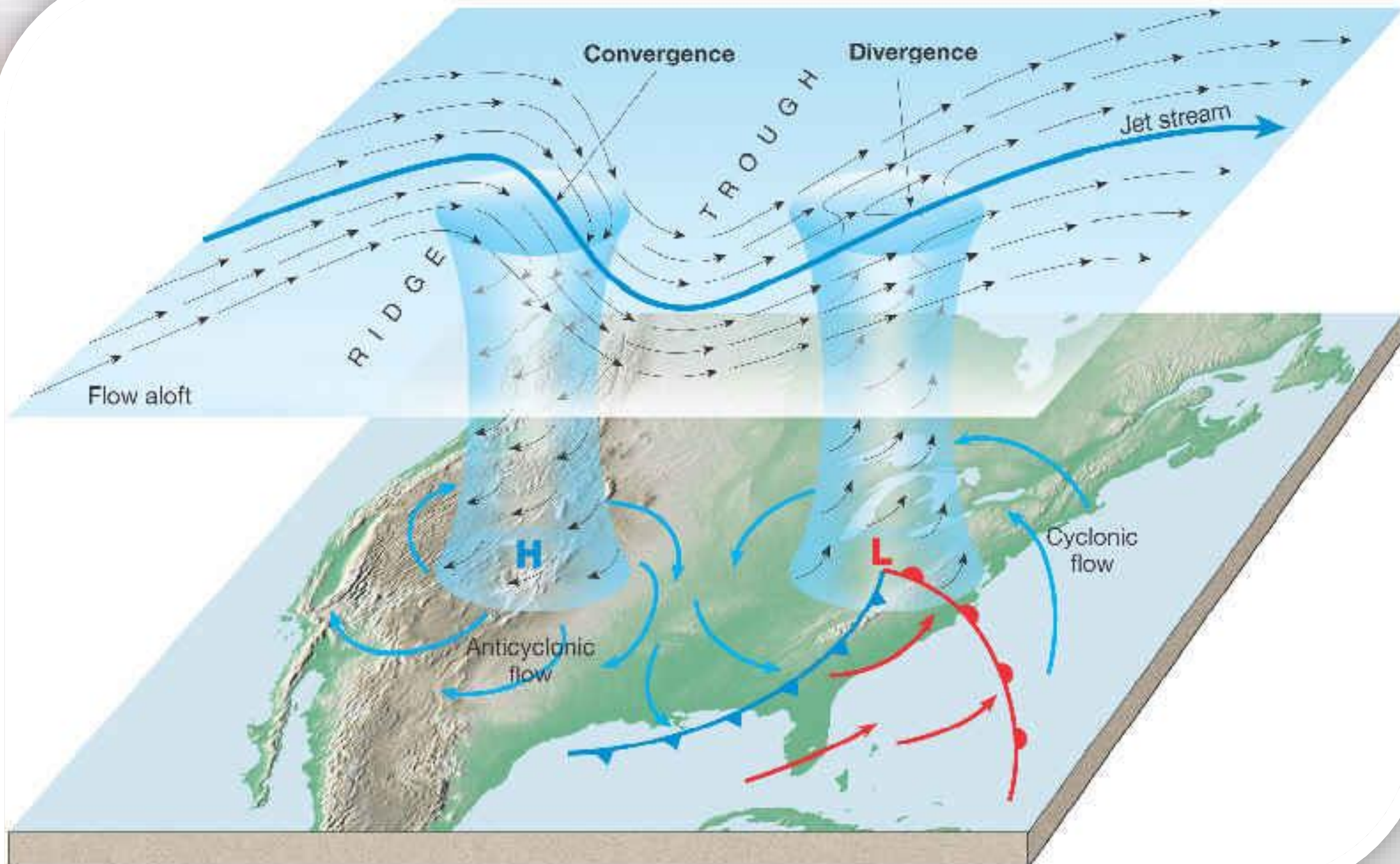

Side view
Clouds
Clear skies
Cyclone
Anticyclone
Advection
(Horizontal air flow)
Low pressure
(air converges and moves up)
High pressure
(air moves down and diverges)

A low, or cyclone, has converging surface winds and rising air causing cloudy conditions.
A high, or anticyclone, has diverging surface winds and descending air, which lead to clear skies and fair weather.





Convergence aloft
Divergence aloft
High
Low
Surface anticyclone
Surface cyclone
Surface isobars as they appear on a map
100.4 kPa
100.8 kPa
100 kPa
H
L
99.2 kPa
99.6 kPa
100 kPa


Convergence
Divergence
TROUGH
Jet stream
RIDGE
Flow aloft
H
L
Cyclonic
flow
Anticyclonic
flow

Gradient Balance

Horizontal PGF – Coriolis Force – Centrifugal –

<u>Horizontal PGF:</u> Accelerates air from regions of high to low pressure

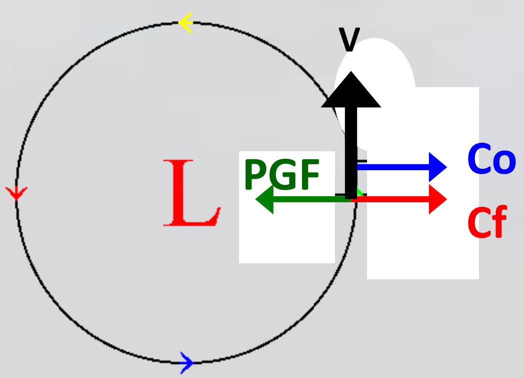
<u>Coriolis Force (Co):</u> Accelerates air 90° to the right of the wind vector

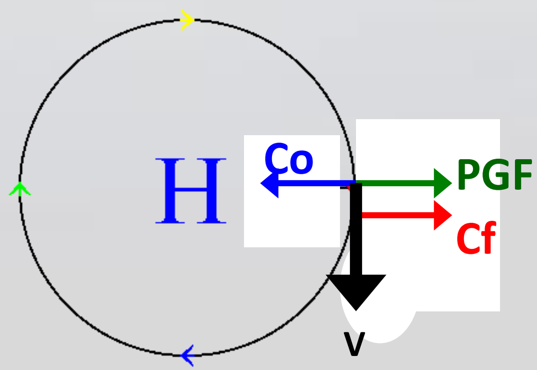
<u>Centrifugal Force (Cf):</u> Results from and applies to curvature in the flow

Accelerates air outward away from the center of rotation

Magnitude is proportional to wind speed

When (Cf + Co) are equal and opposite PGF for flow around a cyclone → Gradient Wind





WHAT IS A FRONT?

sloping zones of pronounced transition in the thermal and wind fields

They are characterized by relatively large:

Horizontal temperature gradients

Static stability

Absolute vorticity

Vertical wind shear

FRONTAL SLOPE

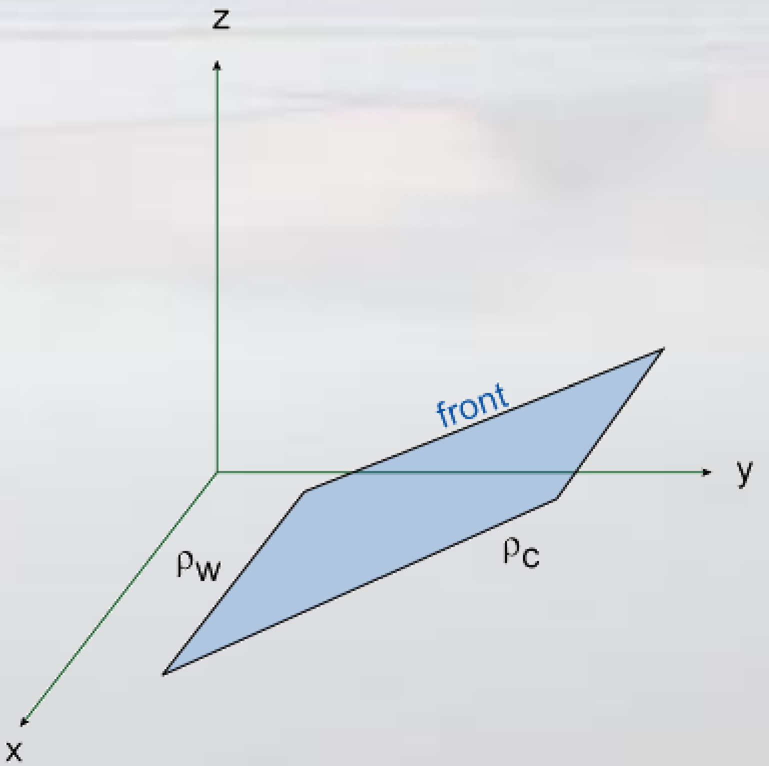
Let's now ignore any along-frontal variation (in the x direction) and derive an equation for the frontal slope (dz/dy)

Then, the change in pressure can be written as:

$$dP = \frac{\partial P}{\partial y} dy + \frac{\partial P}{\partial z} dz \qquad (1)$$

Dividing by dy gives:

$$\frac{dP}{dy} = \frac{\partial P}{\partial y} + \frac{\partial P}{\partial z}\frac{dz}{dy} \qquad (2)$$



From the hydrostatic equation, we know:

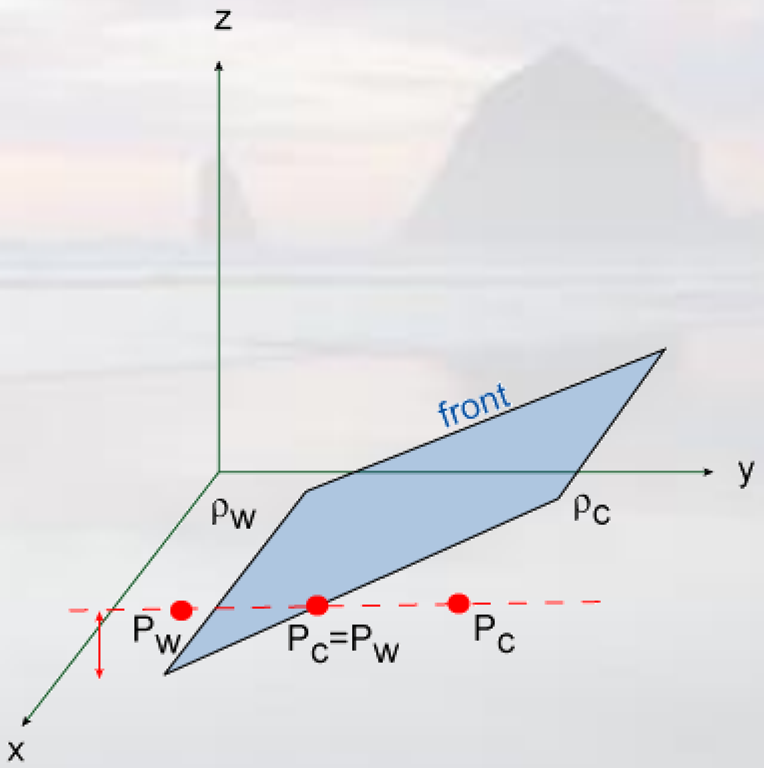
$$\frac{\partial p}{\partial z} = -\rho g$$

So, substituting the hydrostatic equation into the equation for dP/dy gives:

$$\frac{dP}{dy} = \frac{\partial P}{\partial y} - \rho g \frac{dz}{dy} \qquad (3)$$

On the front, since Pressure is continuous, then $P_c = P_w$

Therefore: $$\left(\frac{dp}{dy}\right)_w = \left(\frac{dp}{dy}\right)_c \qquad (4)$$



Substituting (4) into (3) gives:

$$\left(\frac{dP}{dy}\right)_w = \left(\frac{\partial P}{\partial y}\right)_w - \rho_w g \frac{dz}{dy} \qquad (5)$$

$$\left(\frac{dP}{dy}\right)_c = \left(\frac{\partial P}{\partial y}\right)_c - \rho_c g \frac{dz}{dy} \qquad (6)$$

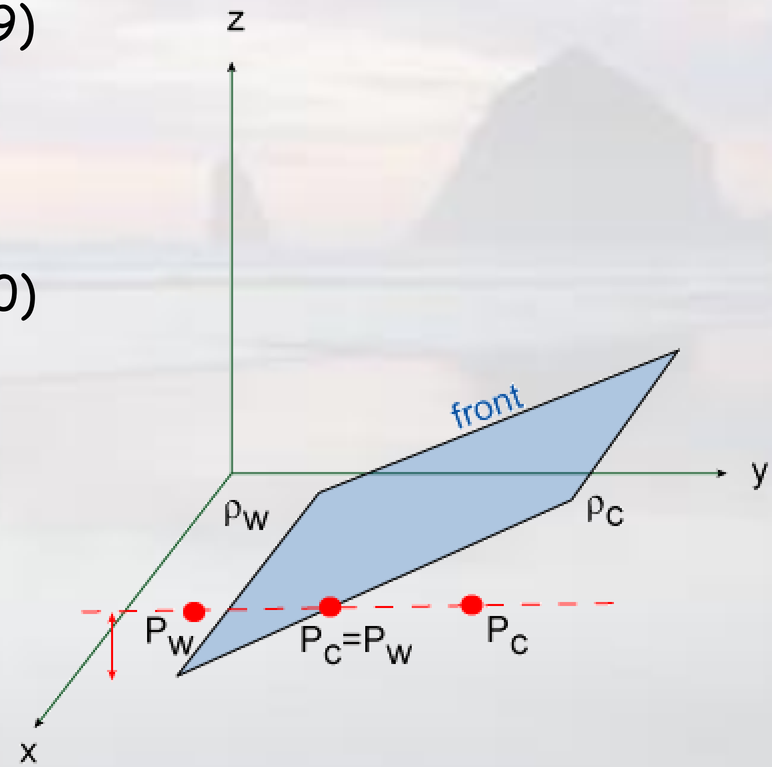
(5)=(6)

$$\left(\frac{\partial P}{\partial y}\right)_w - \rho_w g \frac{dz}{dy} = \left(\frac{\partial P}{\partial y}\right)_c - \rho_c g \frac{dz}{dy} \qquad (7)$$

$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c = \rho_w g \frac{dz}{dy} - \rho_c g \frac{dz}{dy} \qquad (8)$$

$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c = \left(\rho_w g - \rho_c g\right)\frac{dz}{dy} \qquad (9)$$

$$\frac{dz}{dy} = \frac{\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c}{g\left(\rho_w - \rho_c\right)} \qquad (10)$$



Now, since dz/dy is not equal to zero, and is usually > 0 (front slopes upward and to the north), then from (10):

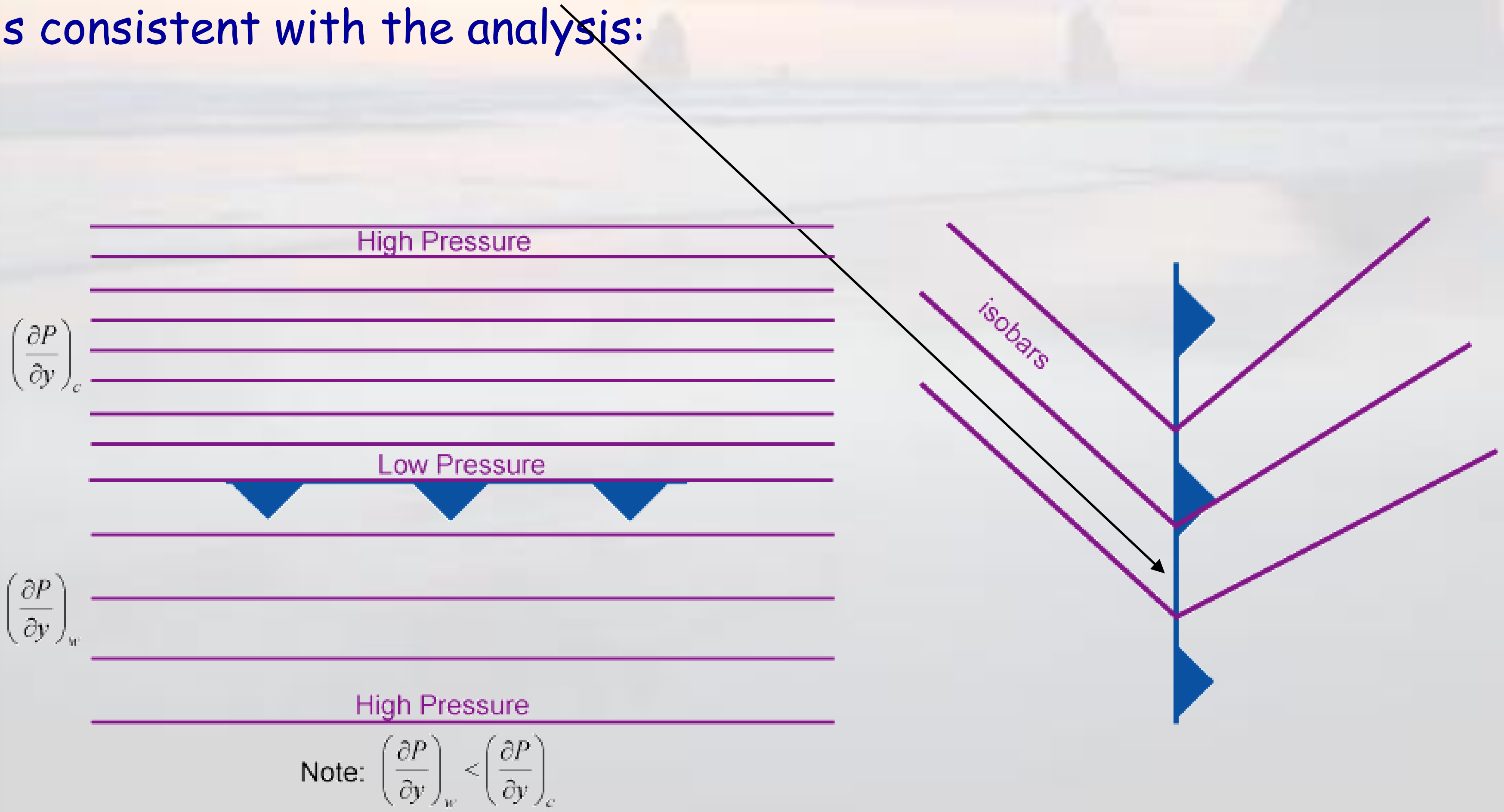
$$\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c < 0 \qquad (11)$$

or

$$\left(\frac{\partial P}{\partial y}\right)_w < \left(\frac{\partial P}{\partial y}\right)_c \qquad (12)$$

So, while pressure *is* continuous across the front, the pressure gradient *is not* continuous across the front.

Therefore, the isobars ***must*** **kink** at the front so that the above statement is consistent with the analysis:



Horizontal winds across the front

How do the horizontal winds vary across the front?

Assuming that the flow is geostrophic and there is no variation in the y direction, the geostrophic wind can be written as:

$$u_g = -\frac{1}{\rho f}\frac{\partial p}{\partial y} \qquad (13)$$

On the warm and cold sides of the front:

$$u_{gw} = -\frac{1}{\rho_w f}\left(\frac{\partial p}{\partial y}\right)_w \qquad (14)$$

$$u_{gc} = -\frac{1}{\rho_c f}\left(\frac{\partial p}{\partial y}\right)_c \qquad (15)$$

$$\frac{dz}{dy} = \frac{\left(\frac{\partial P}{\partial y}\right)_w - \left(\frac{\partial P}{\partial y}\right)_c}{g(\rho_w - \rho_c)} \qquad (16)$$

(14) and (15) into (16)

$$\frac{dz}{dy} = \frac{-\rho_c f u_{gc} + \rho_w f u_{gw}}{g(\rho_c - \rho_w)} \qquad (17)$$

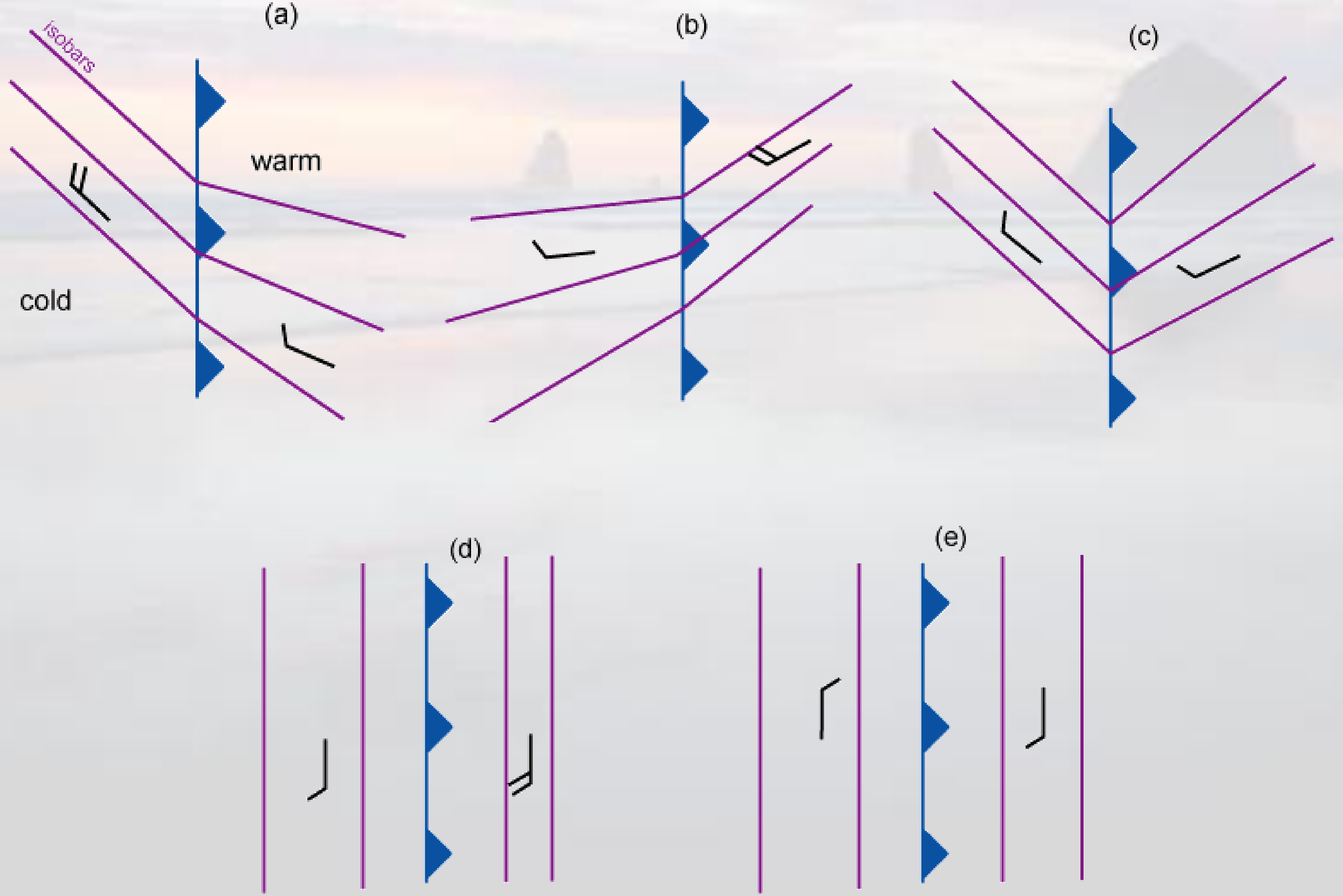
$$\bar{\rho} = \frac{(\rho_c + \rho_w)}{2}$$

$$\frac{dz}{dy} \approx \frac{\bar{\rho} f\left(u_{gw} - u_{gc}\right)}{g\left(\rho_c - \rho_w\right)} \qquad (18)$$

Again, if dz/dy > 0, then $u_{gw} - u_{gc} > 0$ or $u_{gw} > u_{gc}$

Therefore, cyclonic shear vorticity must exist across the front.

Here are some possibilities:


(a)
isobars
warm
cold
(b)
(c)
(d)
(e)

Margules Equation for frontal slope

Recall the equation for frontal slope: $$\frac{dz}{dy} \approx \frac{\bar{\rho} f\left(u_{gw} - u_{gc}\right)}{g\left(\rho_c - \rho_w\right)}$$

Using the equation of state, it can be shown that this equation can be written as:

$$\frac{dz}{dy} \approx \frac{\bar{T} f\left(u_{gw} - u_{gc}\right)}{g\left(T_w - T_c\right)}$$

Substituting in typical values:

$$\frac{dz}{dy} \approx \frac{10^{-4} s^{-1} \cdot 300k \cdot 10ms^{-1}}{10ms^{-2} \cdot 10K} \approx 1/300$$

This value is similar to what is observed