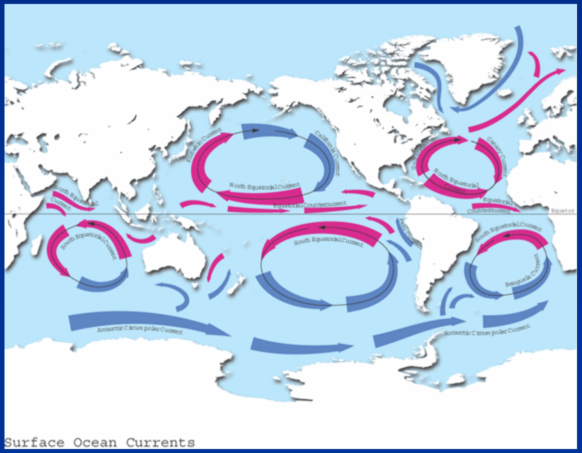
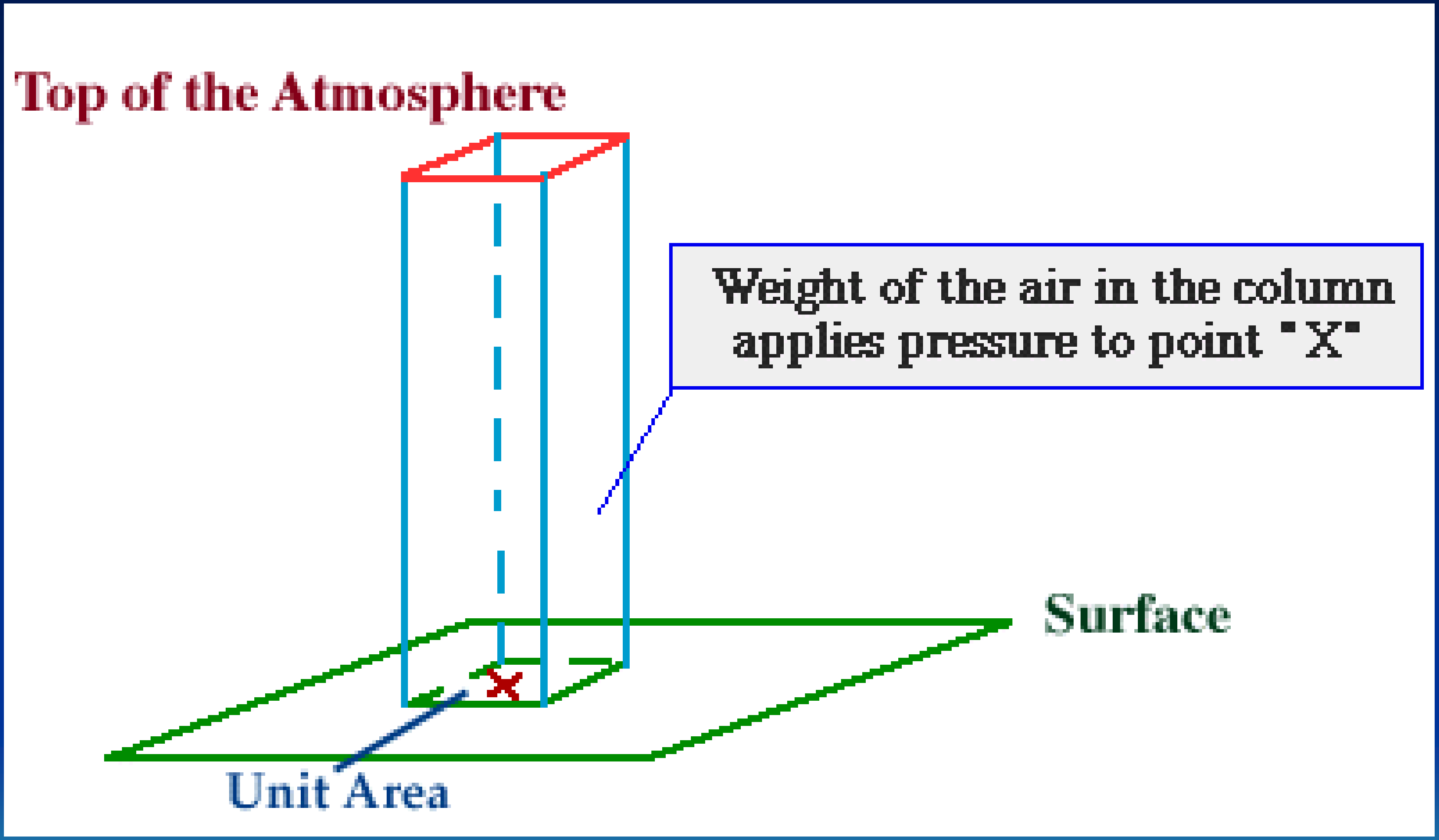
Chapter 7 Atmospheric Pressure and Wind

- Pressure Essentials
- Atmospheric Patterns of Motion
- Horizontal Pressure Gradients
- Cyclones and Anticyclones



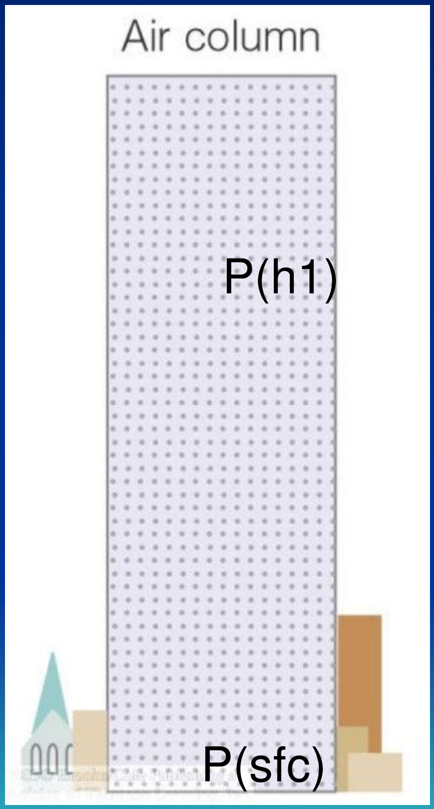

Top of the Atmosphere
Weight of the air in the column applies pressure to point "X"
Surface
Unit Area

General Concept

- Atmospheric (air) pressure: P

Definition: The pressure exerted by the mass of air above a given point.

A function of density and temperature



- P(sfc) is related to number of air molecules above
- P(sfc) > P(h1)

Recall: in the atmosphere, air pressure decreases with height !!

Pressure Essentials

- Pressure – force exerted/unit area (weight above you)
- units - Pascals (Pa) or millibars (mb)
- Sea level pressure (SLP) = 1013.2 mb
- Pressure important factor in controlling weather conditions → wind, clouds, ppt.

Pressure Essentials (cont.)

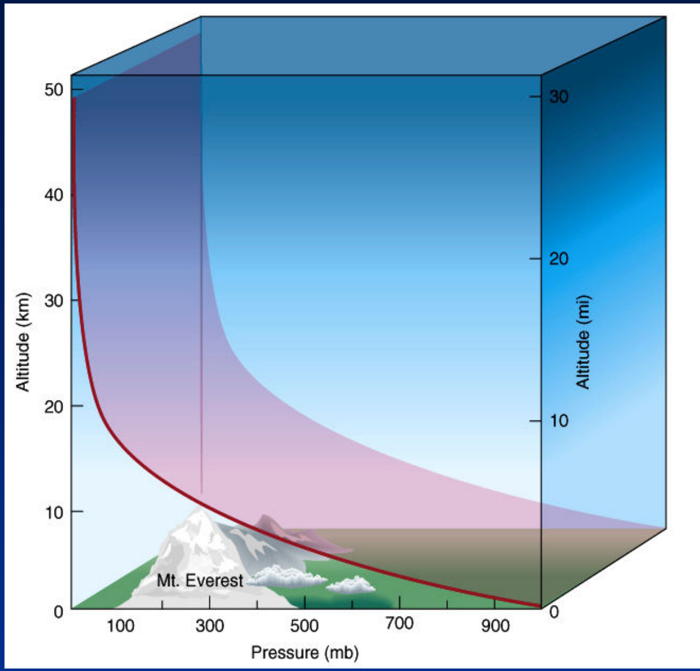
- pressure can be increased by:
  - increasing density
  - Increasing temperature
- atmosphere is mixture of gases → partial pressure
- Dalton's Law: sum of partial pressures equals total pressure
- pressure decreases non-linearly with height

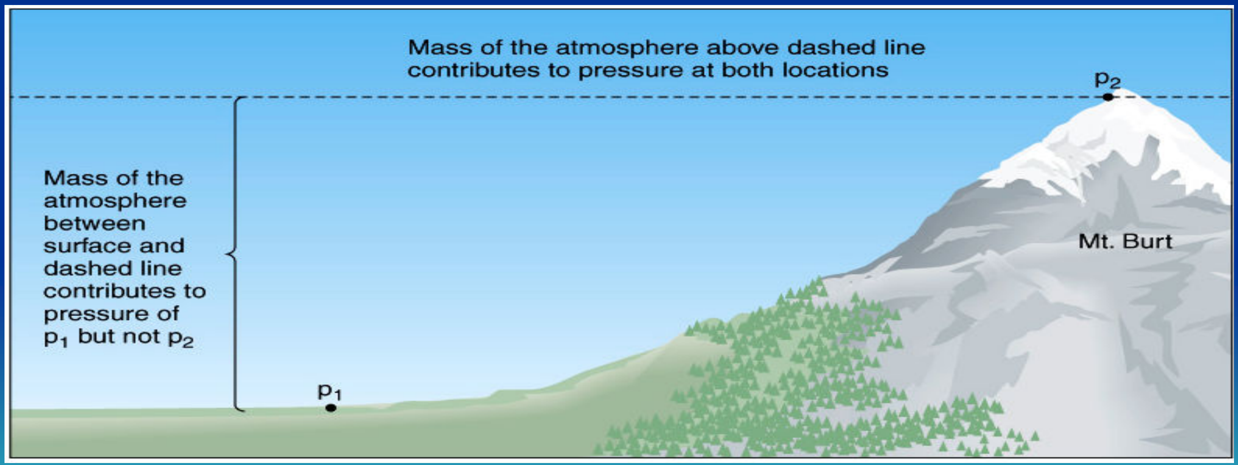
- Vertical and Horizontal Changes in Pressure
  - Pressure decreases with height
  - Compressibility causes a non-linear decrease with height

- pressure will be less at P2 than at P1 due to pressure decreasing with height

- recording stations are reduced to <u>sea level pressure</u> equivalents

- pressure differences responsible for movement of air → equilibrium





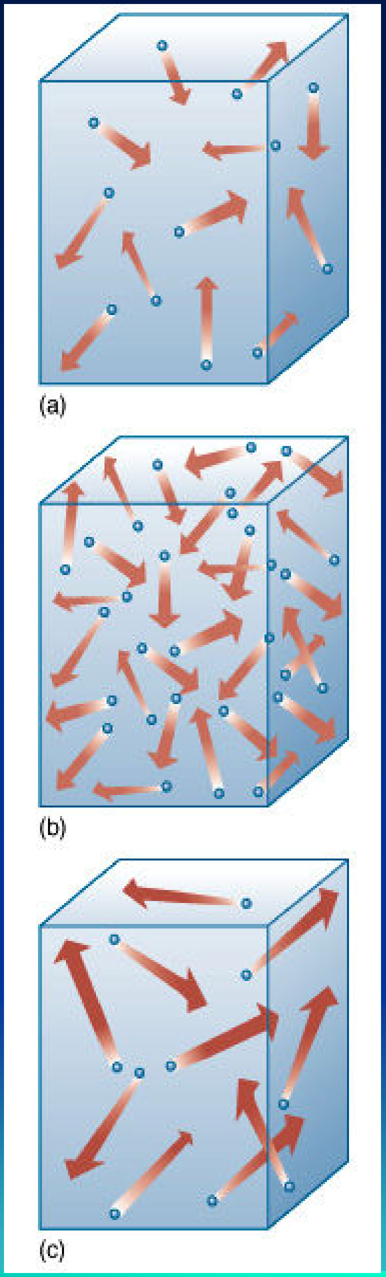
The Equation of State (Ideal Gas Law)

Pressure = density x temperature x 287 J kg^{-1} K^{-1}

[$p = \rho TR$]

- describes relationships between pressure, temperature, and density
- at constant temperatures, an increase in air density will cause a pressure increase
- Under constant density, an increase in temperature will lead to an increase in pressure

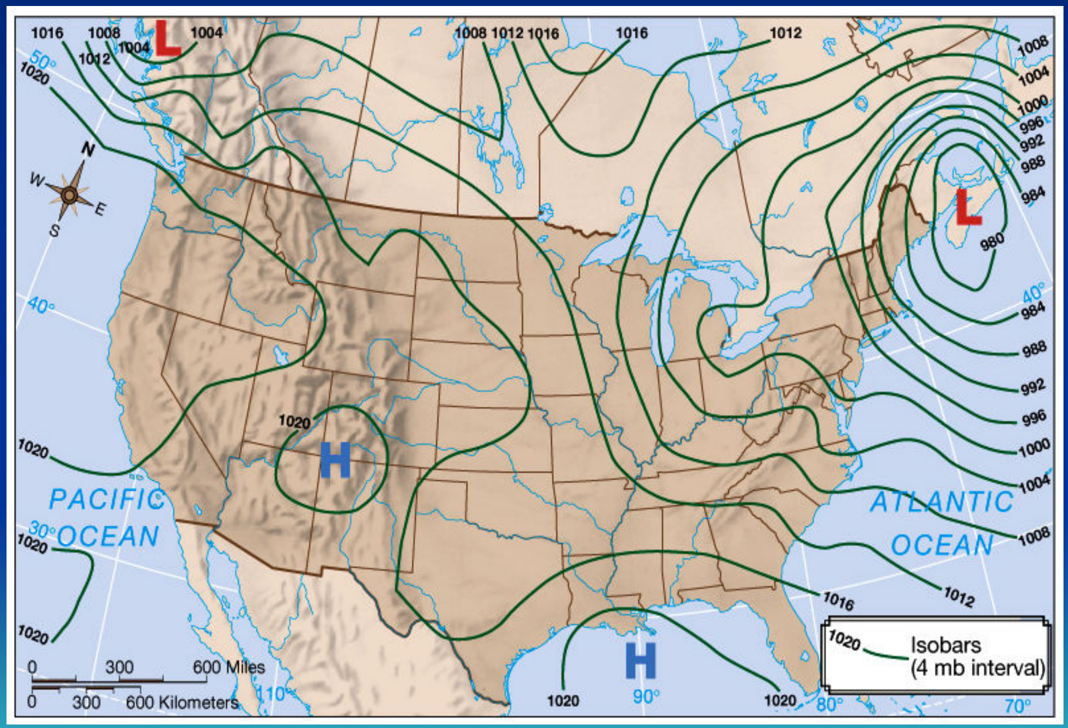
- Molecular movement in a sealed container: pressure increased by increasing density (b) or temperature (c)



The Distribution of Pressure

- Pressure maps depict isobars, lines of equal pressure
- Through analysis of isobaric charts, pressure gradients are apparent
  - Steep (weak) pressure gradients are indicated by closely (widely) spaced isobars

A weather map depicting the sea level pressure distribution for March 4, 1994

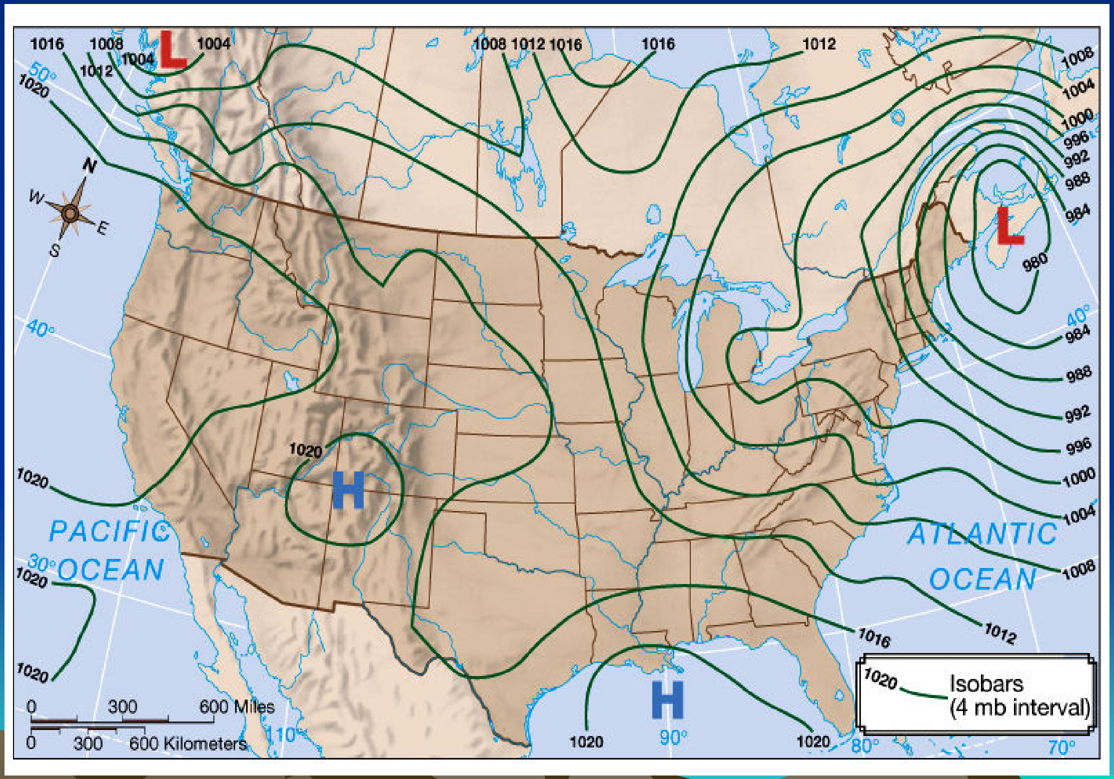


Pressure Gradients

- The <u>pressure gradient force</u> initiates movement of atmospheric mass, wind, from areas of higher to areas of lower pressure
- Horizontal wind speeds are a f(x) of the strength of the pressure gradient

Horizontal Pressure Gradients

- Typically only small gradients exist across large spatial scales (4% - continental scale)
- Smaller scale weather features, such as hurricanes and tornadoes, display larger pressure gradients across small areas



Pressure Force

Consider a cubic box of air, of dimension $\Delta x \times \Delta y \times \Delta z = \mathcal{V}$.

The pressure acts *normally* on each face of the cube.

Net force on left-hand face:

$$p(x) \cdot \Delta y \Delta z$$

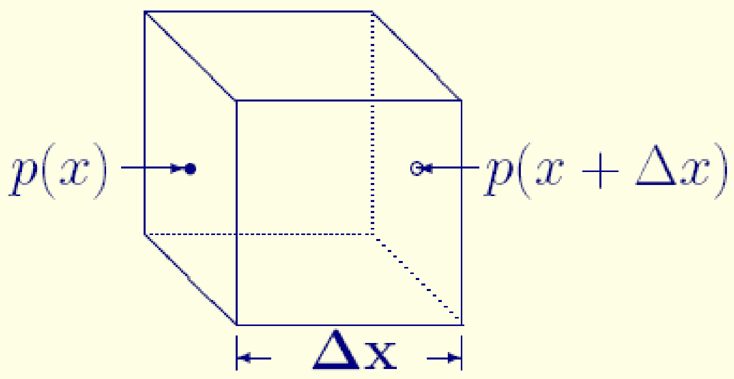
Net force on right-hand face:

$$-p(x + \Delta x) \cdot \Delta y \Delta z$$

Total pressure force in the x-direction:

$$-\Big[p(x + \Delta x) - p(x)\Big] \cdot \Delta y \Delta z$$

Pressure on Box



Total pressure force in x-direction:

$$-\Big[p(x+\Delta x)-p(x)\Big]\cdot\Delta y\Delta z = -\left(\frac{p(x+\Delta x)-p(x)}{\Delta x}\right)\cdot\Delta x\Delta y\Delta z$$

But $\Delta x\Delta y\Delta z=\mathcal{V}$, so the force <u>per unit volume</u> is:

$$-\left(\frac{p(x+\Delta x)-p(x)}{\Delta x}\right)\approx-\frac{\partial p}{\partial x}$$

A parcel of mass m has volume $\mathcal{V}=m/\rho$, so a unit mass has volume $1/\rho$. The pressure force <u>per unit mass</u> in the x-direction is thus

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}$$

Similar arguments apply in the y and z directions. So, the vector force <u>per unit mass</u> due to pressure is

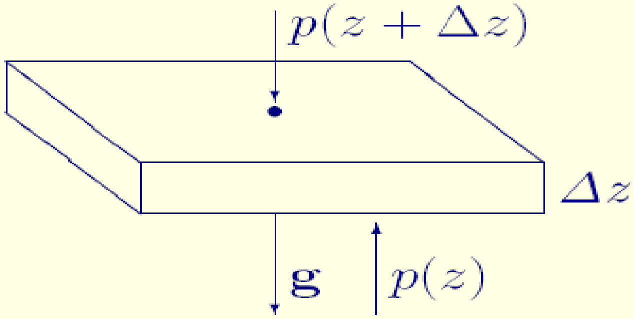
$$\mathbf{F}_p=\left(-\frac{1}{\rho}\frac{\partial p}{\partial x},-\frac{1}{\rho}\frac{\partial p}{\partial y},-\frac{1}{\rho}\frac{\partial p}{\partial z}\right)=-\frac{1}{\rho}\nabla p\,.$$

This force acts in the direction of lower pressure.

Hydrostatic Balance

For a fluid at rest, the pressure at a point depends on the weight of fluid vertically above that point.

The pressure difference between two points on the same vertical line depends only on the weight of fluid between them.



$$\begin{aligned} \textbf{Force Upward on Box}: \quad & +[p(z)\cdot \Delta x \Delta y] \\ \textbf{Force Downward on Box}: \quad & -[p(z+\Delta z)\cdot \Delta x \Delta y + mg] \end{aligned}$$

For equilibrium, the net force must be zero:

$$\frac{p(z+\Delta z) - p(z)}{\Delta z}\cdot \Delta x \Delta y \Delta z + mg = 0\,.$$

This may be written

$$\frac{\partial p}{\partial z} \cdot \mathcal{V} + mg = 0\,,$$

or, dividing through by the volume,

$$\frac{\partial p}{\partial z} + \rho g = 0\,.$$

This is the Hydrostatic balance equation. It implies an exact balance between the vertical pressure gradient and gravity.

For an atmosphere at rest, hydrostatic balance holds exactly.

Hydrostatic Equilibrium

- explains why air doesn't continuously blow upward or get pulled downward
- The downward force of gravity is balanced by a strong vertical pressure gradient (VPG) → creates hydrostatic equilibrium
- Local imbalances initiate various up- and downdrafts
- The Role of Density in Hydrostatic Equilibrium
  - dense atmosphere experiences greater gravitational force
    - force = mass x acceleration (gravity)
  - to maintain hydrostatic equilibrium balanced by greater vertical pressure gradient force

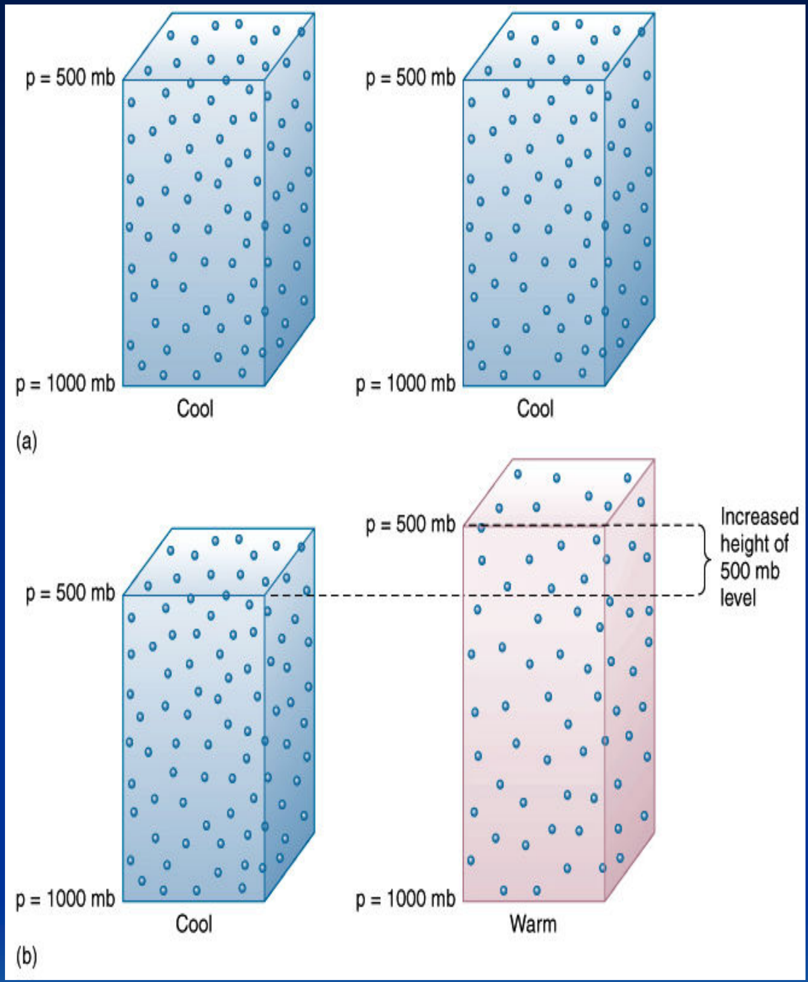
• denser the atm, the greater the VPG and the gravitational force (balance)

• heating causes density to decrease in a column of air

• the column contains the same amount of air, but has a lower density to compensate for its greater height

• the heated column has a lower VPG (the distance between 1000 mb and 500 mb has increased)

• the rate at which pressure decreases is f(x) of density



Exercise: Vertical Pressure Gradient

Suppose the atmosphere is in a state of hydrostatic balance.
Calculate approximately the pressure drop over a vertical distance of 100 m, assuming the density is constant at $\rho = 1.2\,\mathrm{kg\,m^{-3}}$ and $g = 9.8\,\mathrm{m\,s^{-2}}$.

⋆ ⋆ ⋆

The hydrostatic equation gives

$$\frac{\Delta p}{\Delta z} + \rho g = 0\,.$$

Substituting the numerical values gives

$$\Delta p = -\Delta z \rho g = -100\,\mathrm{m} \times 1.2\,\mathrm{kg\,m^{-3}} \times 9.8\,\mathrm{m\,s^{-2}}$$

(negative, since pressure decreases upwards). Evaluating this gives

$$|\Delta p| = 1176\,\mathrm{kg\,m^{-1}s^{-2}} = 1176\,\mathrm{Pa} = 11.76\,\mathrm{hPa}\,.$$

The hectoPascal, numerically equal to the millibar, is the pressure unit most commonly used in practice.

Note that the assumption of constant density is unrealistic over large vertical distances. We will relax this assumption presently.

Vertical Variation of Pressure

Let's consider an *isothermal* atmosphere at rest. Let the constant temperature be T_0. The hydrostatic equation and the equation of state are

$$\frac{\partial p}{\partial z} + g\rho = 0\,, \qquad p = R\rho T_0\,.$$

Combining these we have

$$\frac{\partial p}{\partial z} = -g\frac{p}{RT_0}\,, \qquad \text{so} \qquad \frac{dp}{p} = -\frac{g\,dz}{RT_0} = -\frac{dz}{H}\,,$$

where we define the <u>scale-height</u> by $H = RT_0/g$.

We integrate over the range $p_0 = p(0)$ to $p = p(z)$ to get

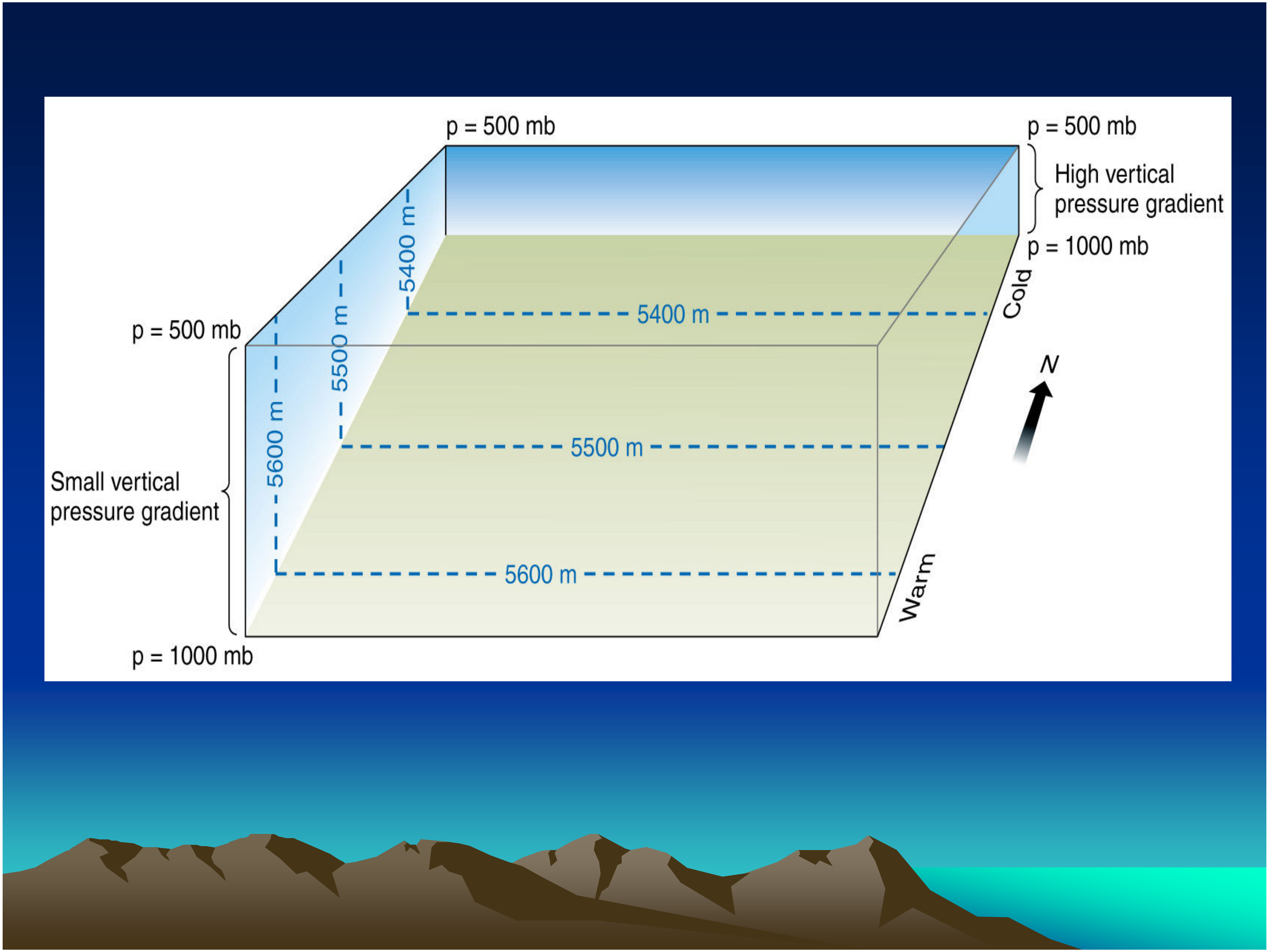
$$\log\left(\frac{p}{p_0}\right) = -\frac{z}{H}$$

or

$$p(z) = p_0 \exp(-z/H)\,.$$

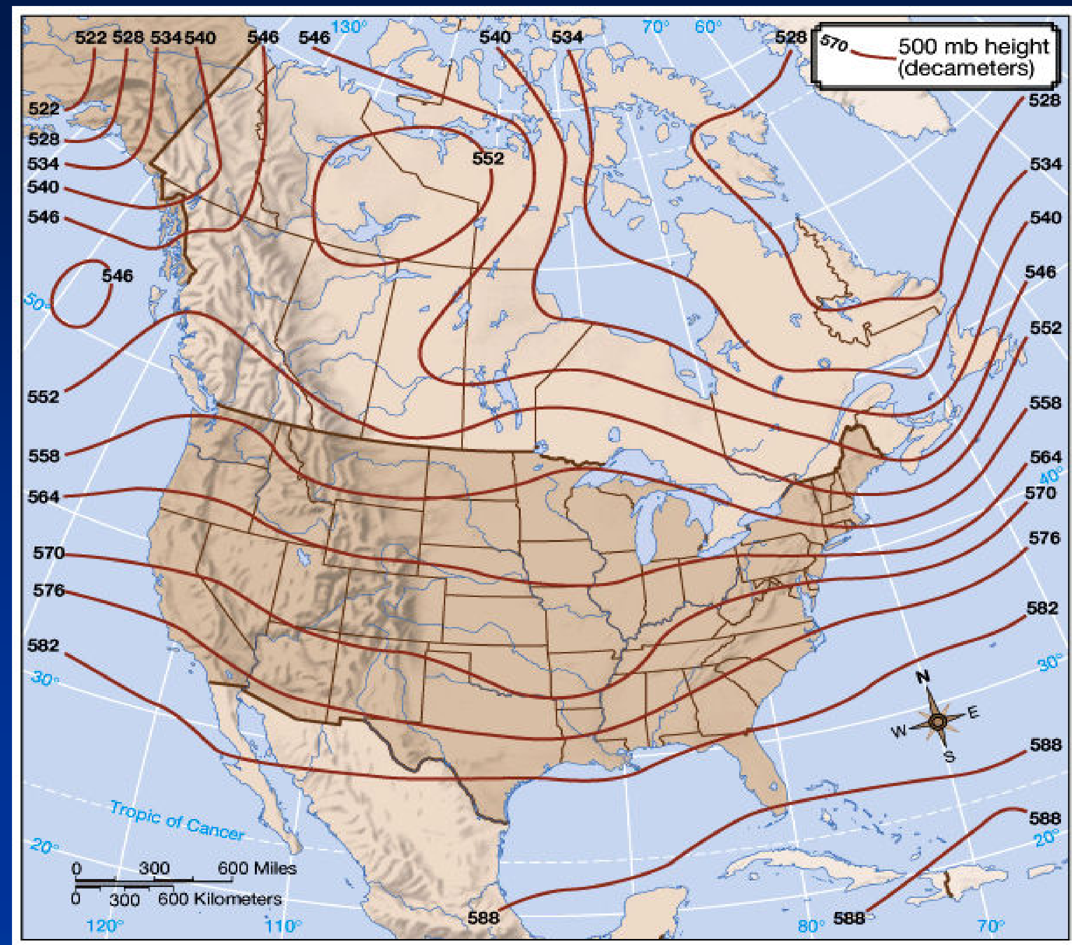
Thus, *<u>pressure decreases exponentially with height</u>*.

Since $\rho = p/RT_0$, *density also decreases exponentially* with height.

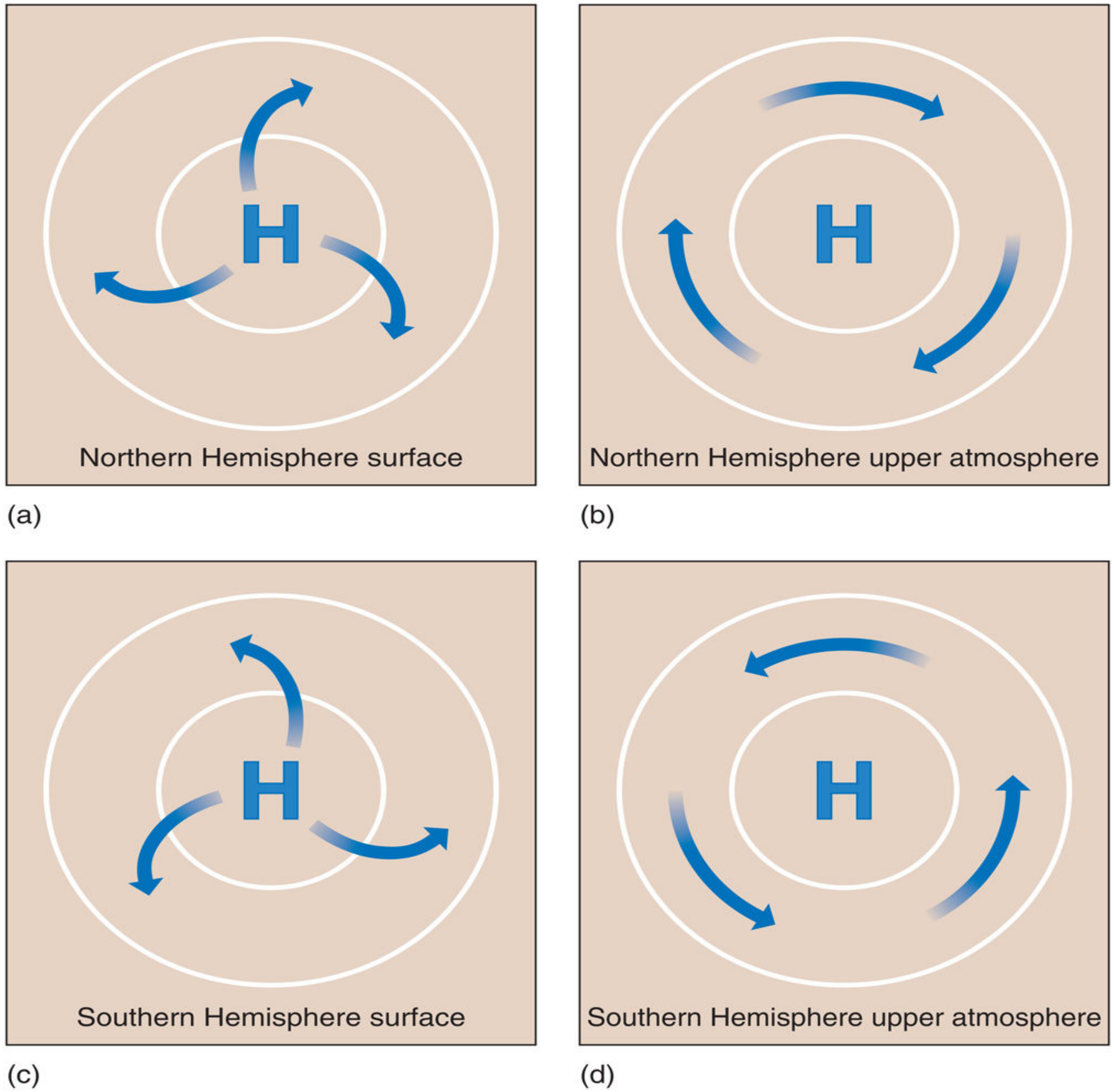


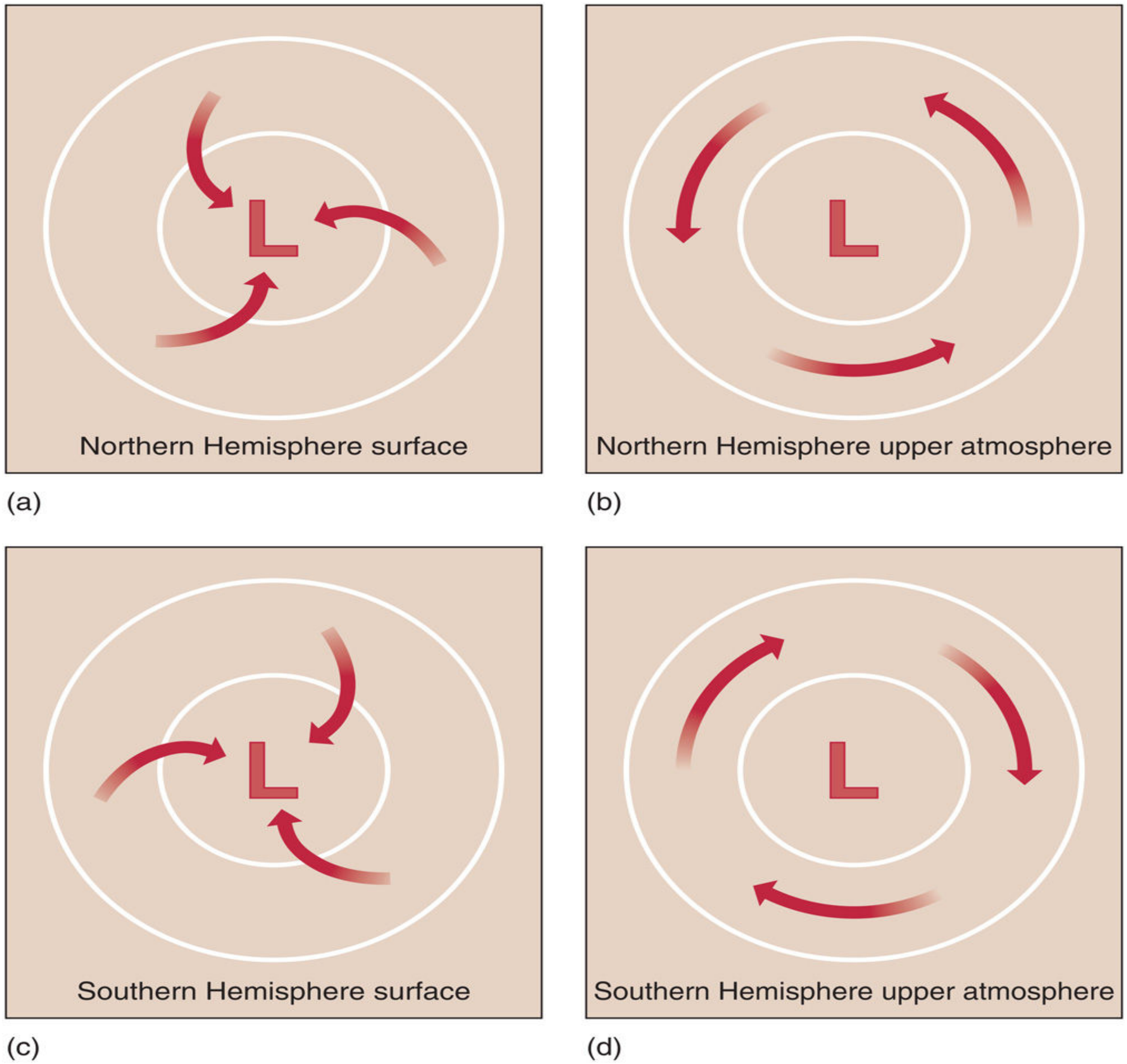
p = 500 mb
p = 500 mb
High vertical
pressure gradient
p = 1000 mb
Cold
5400 m
5500 m
5600 m
5400 m
5500 m
5600 m
p = 500 mb
N
Small vertical
pressure gradient
Warm
p = 1000 mb

- Height contours indicate the pressure gradient
- 10% difference across North America
- can produce high winds in upper atmosphere

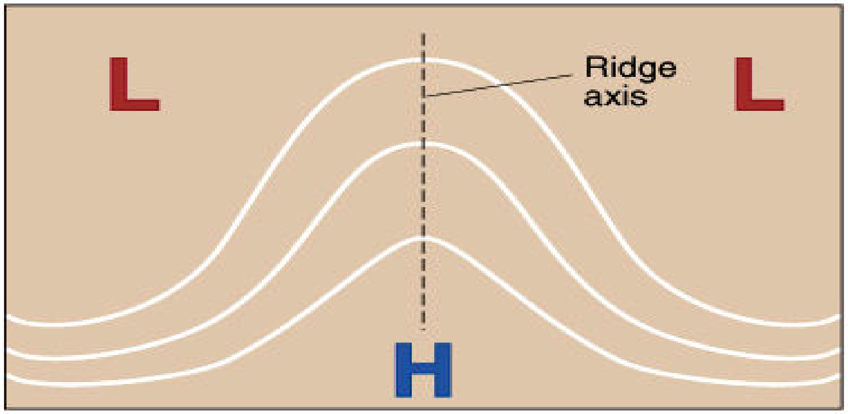


500 mb height contours for May 3, 1995

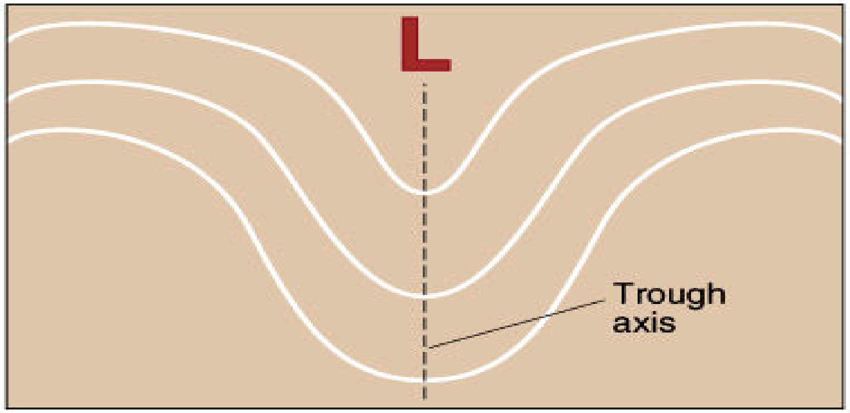

H
Northern Hemisphere surface
(a)
H
Northern Hemisphere upper atmosphere
(b)
H
Southern Hemisphere surface
(c)
H
Southern Hemisphere upper atmosphere
(d)


L
Northern Hemisphere surface
(a)
L
Northern Hemisphere upper atmosphere
(b)
L
Southern Hemisphere surface
(c)
L
Southern Hemisphere upper atmosphere
(d)

Ridges and troughs in the northern hemisphere

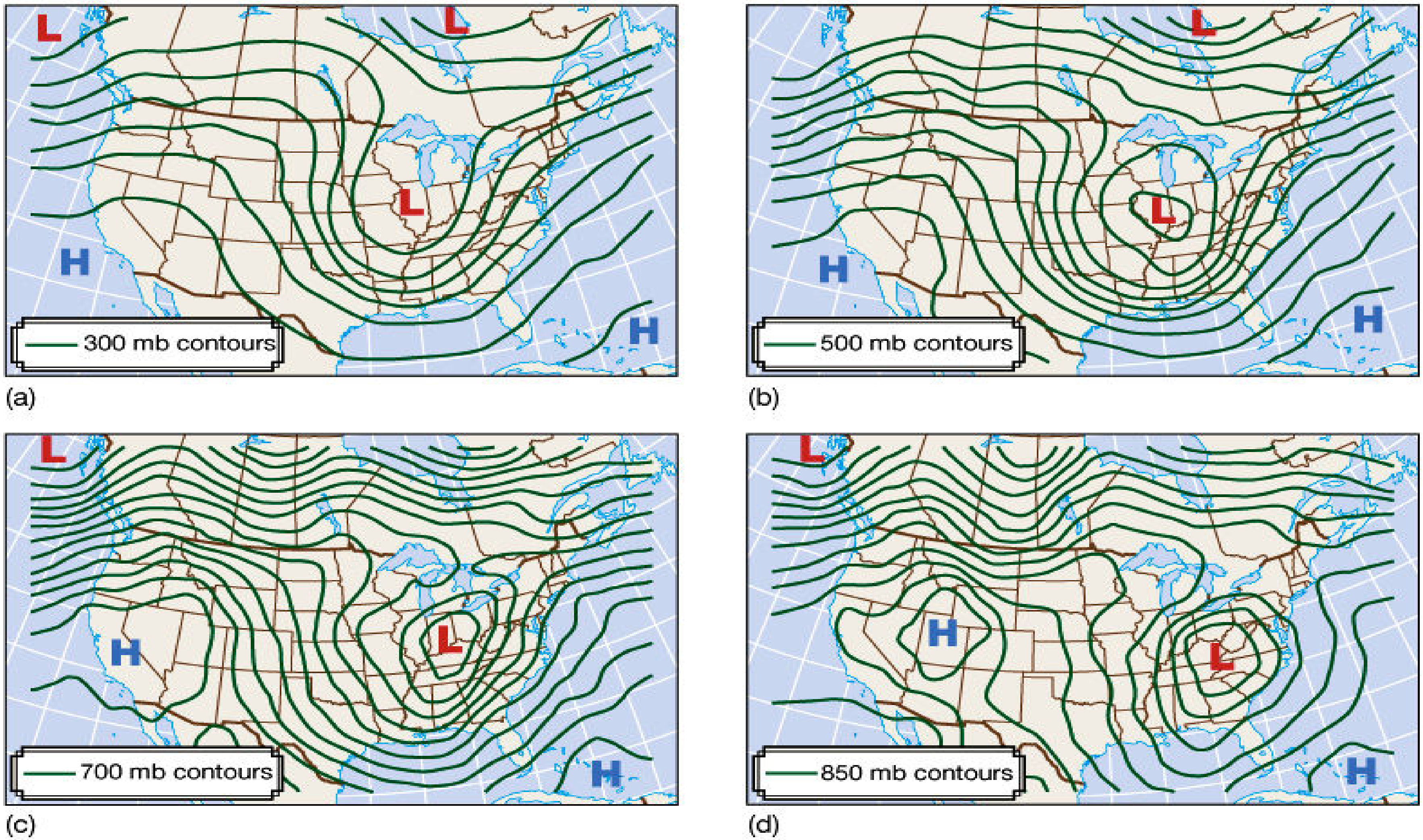


(a)



(b)

Maps depicting troughs, ridges, cyclones, and anticyclones



- *High pressure areas (<u>anticyclones</u>) → clockwise airflow in the Northern Hemisphere (opposite flow direction in S. Hemisphere)*
  - *Characterized by descending air which warms creating clear skies*

- *Low pressure areas (cyclones) → counterclockwise airflow in N. Hemisphere (opposite flow in S. Hemisphere)*
  - *Air converges toward low pressure centers, cyclones are characterized by ascending air which cools to form clouds and possibly precipitation*

- *In the upper atmosphere, <u>ridges</u> correspond to surface anticyclones while <u>troughs</u> correspond to surface cyclones*