Introduction to Meteorology

17 Balanced wind

Introduction

The forces that affect the motion of the atmosphere include gravity, pressure gradient force, frictional force, centrifugal force, and Coriolis force. In some cases, certain forces are so small compared to other forces that they can be ignored. How does the balance between these forces impact on the flow type?

Contents

1. Hydrostatic balance
2. Geostrophic wind and gradient wind
3. Inertial wind and cyclostrophic wind
4. Surface wind and thermal wind

Learning objectives

1. Explain the balance of the forces that cause the wind.
2. Describe the types of wind depending on the balance of forces.

Learning Activities

1. Hydrostatic balance

The air pressure decreases by about 1 hPa by 10m altitude. Such vertical pressure gradient is much greater than the horizontal pressure gradient at the center of the typhoon. However, strong vertical wind is not observed in the atmosphere due to the atmospheric force-balance in the vertical direction.

Upward pressure gradient force ≒ **Downward gravitational force**

Learning Activities

1. Hydrostatic balance

If pressure gradient force and the gravity balance in the vertical direction, this is called a hydrostatic balance or hydrostatic equilibrium. The vertical acceleration is zero in hydrostatic equilibrium. The equation of hydrostatic balance is expressed as follows:

$$-\frac{1}{p}\frac{\Delta p}{\Delta z} = g$$

where Δp is the pressure gradient for the vertical distance Δz, and g represents the gravitational acceleration. This expression can be expressed again as follows, which is the hydrostatic equation:

$$\Delta p = -pq\Delta z$$

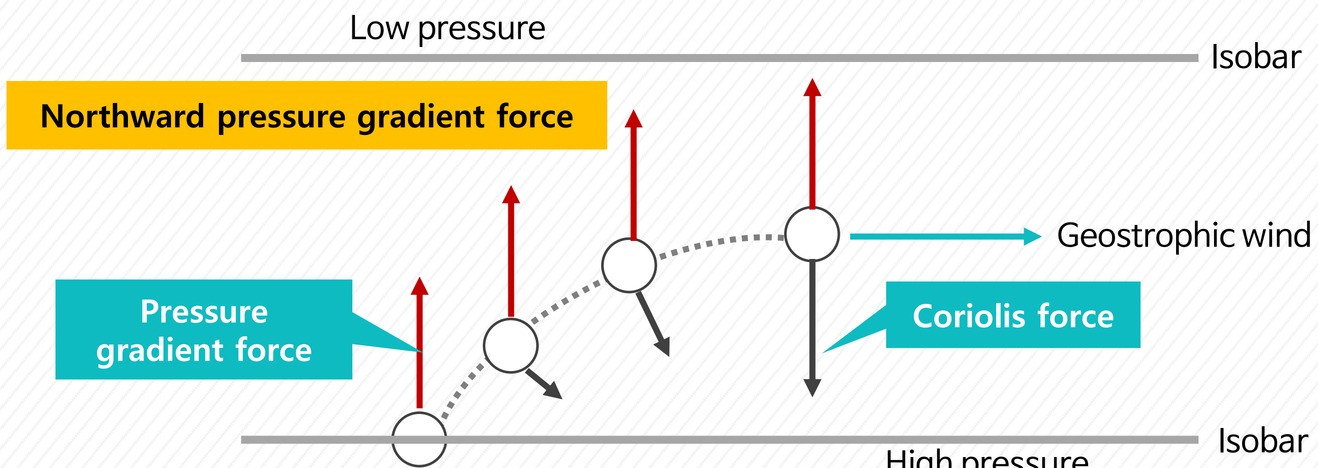
This equation relates the pressure gradient with height difference. Using this equation, it can be calculated that the pressure decreases about 1hPa when the air is 10m above the surface.

Learning Activities

2. Geostrophic wind and gradient wind

1) Geostrophic wind

The most dominant balance occurs between the horizontal pressure gradient force and the Coriolis force. It is referred to as geostrophic balance and the wind is called geostrophic wind. Since the centrifugal force is not included, only straight motion is considered.

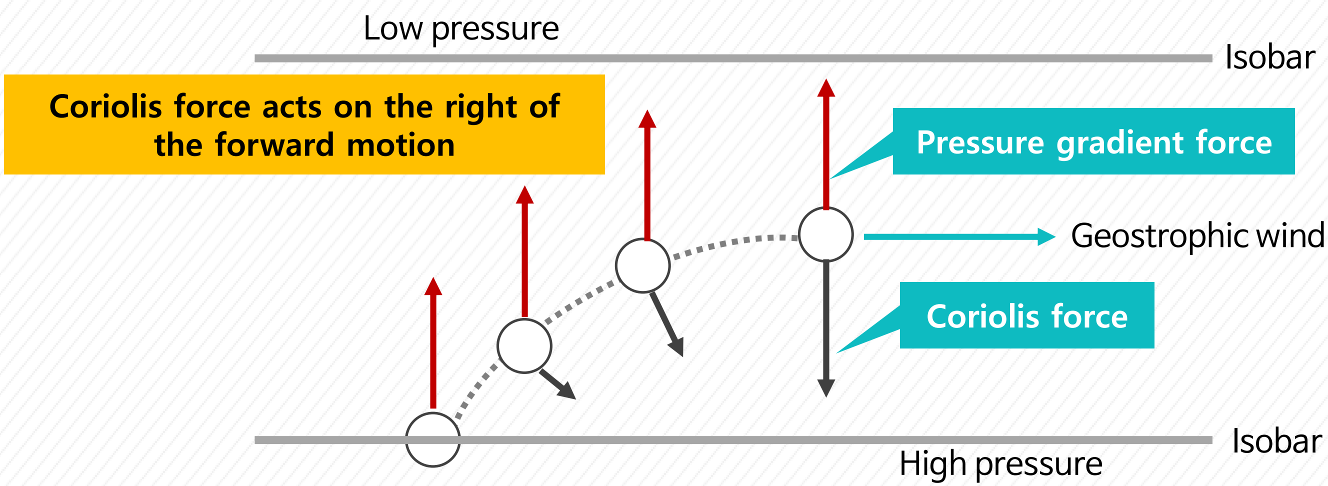


※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p133

Let's see how an air parcel in the Northern Hemisphere reaches the geostrophic balance. If a parcel is at rest at the leftmost position, the pressure gradient force is the only horizontal force acting on the parcel. When the air parcel accelerates northward, the Coriolis force begins to act proportionally to the windspeed resulting in air parcel to accelerate to the right.

Learning Activities

2. Geostrophic wind and gradient wind



※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p133

In the Northern Hemisphere, the Coriolis force acts to the right of the forward motion. Eventually, the pressure gradient force and Coriolis force become the same in magnitude and opposite in direction. At this point, the two forces are balanced and the velocity remains constant. The geostrophic wind is parallel to the isobars. In the Northern (Southern) Hemisphere, the low pressure is always on the left (right) of the geostrophic wind.

Learning Activities

2. Geostrophic wind and gradient wind

The geostrophic balance can be expressed as

$$-\frac{1}{\rho}\frac{\Delta p}{\Delta s}$$

Where Δp is the pressure difference between the two neighboring isobars and Δs is equivalent to the distance between the two isobars. The geostrophic wind speed (Vg) is:

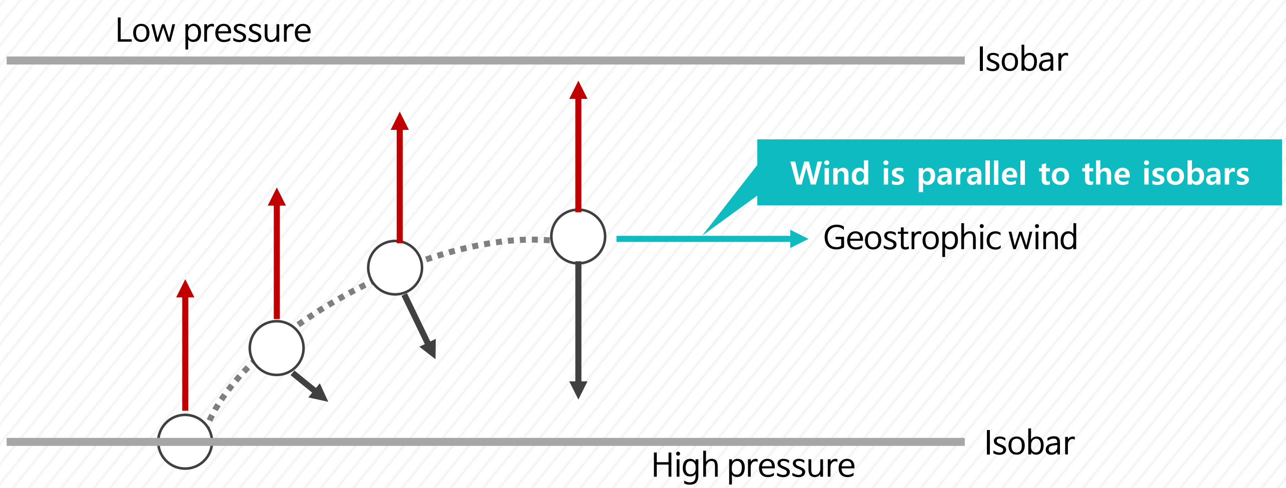
$$V_g = \frac{1}{2\Omega\rho sin\phi}\frac{\Delta p}{\Delta s}$$

The geostrophic wind speed becomes stronger as the spacing of isobars is closer. In fact, on weather chart, strong wind exists where isobars are very close together. At lower latitudes and higher altitudes (where the air density is lower), the geostrophic wind becomes stronger for a fixed pressure gradient. At the equator, geostrophic wind cannot be defined.

Learning Activities

2. Geostrophic wind and gradient wind

2) Gradient wind



※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p133

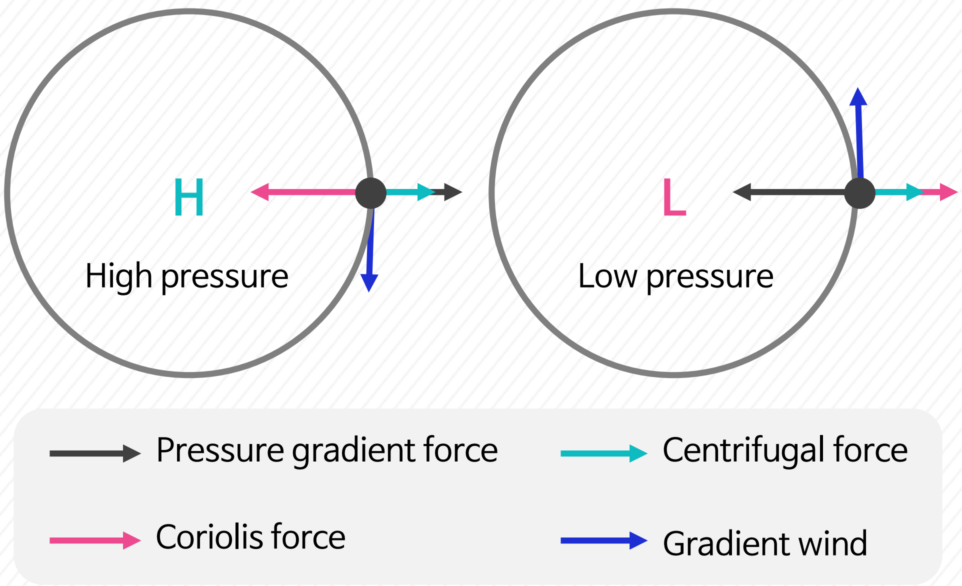
The above mentioned geostrophic wind means that the wind must be straight and parallel to the isobars. However, in the real atmosphere this rarely happens. In the upper atmosphere, wind generally blows along a curved path. It means that the centrifugal force must act on the air parcel. The wind which results from the balance between pressure gradient force, centrifugal force and Coriolis force is called a gradient wind.

Learning Activities

2. Geostrophic wind and gradient wind

The following describes gradient winds and their associated forces in the Northern Hemisphere.

In a high pressure system, the pressure gradient force is directed outward from the center, the Coriolis force is directed to the right of the forward motion, and the centrifugal force is always directed outward. On the other hand, in a low pressure, the pressure gradient force is directed toward the center, the Coriolis force and centrifugal force both are outward. Therefore, at the high pressure, the sum of the pressure gradient force and centrifugal force is equal to the Coriolis force. As three forces are balanced, the gradient wind blows.
In the case of low pressure, the sum of the Coriolis force and Centrifugal force equals the pressure gradient force.



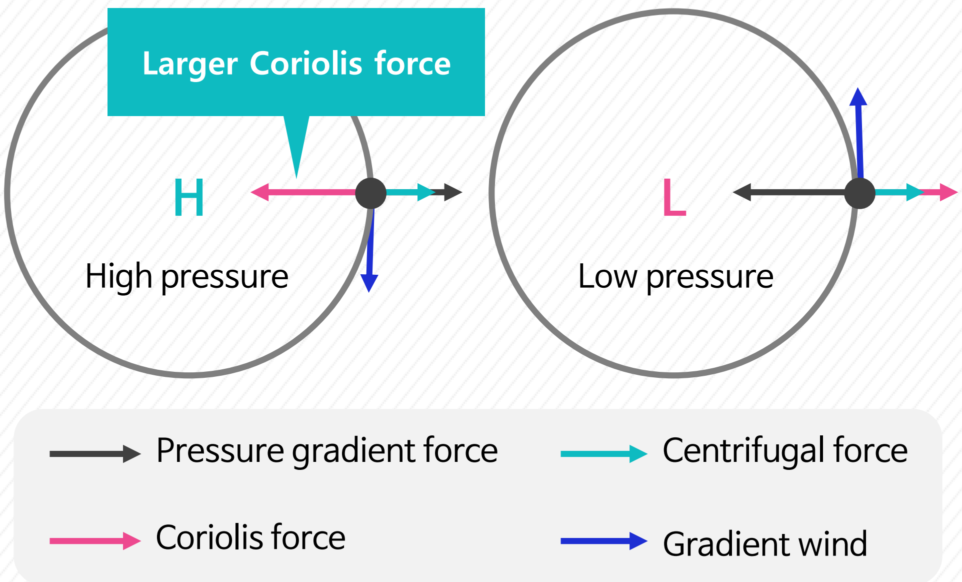
※ Source: Environmental atmospheric science
(Kim, Kyung-Eak et al., Donghwa Technology) p134

Learning Activities

2. Geostrophic wind and gradient wind

The geostrophic winds are the same in high and low pressure systems if the interval of isobars is equal and lines are straight. However, the gradient winds are different in low and high pressure systems. It is stronger in the high pressure system.

As shown in the figure, when the interval of isobar is the same, the gradient wind speed is larger at high pressure than at low pressure because of the larger Coriolis force. In the real atmosphere, the wind is stronger in the low pressure area than in the high pressure area, because the interval of isobar is narrower, so the pressure gradient force is larger. Since the geostrophic wind speed is determined by the magnitude of pressure gradient force, if comparing the Coriolis force, the gradient wind speed is larger than the geostrophic wind, thus super-geostrophic. On the other hand, in low pressure system, the gradient wind is weaker than the geostrophic wind, thus sub-geostrophic.



※ Source: Environmental atmospheric science
(Kim, Kyung-Eak et al., Donghwa Technology) p134

Learning Activities

2. Geostrophic wind and gradient wind

The speed of the gradient wind can be represented as:

$$V = -\frac{fR}{2} \pm \left(\frac{f^2R^2}{4} - \mathrm{R}\frac{\partial\phi}{\partial n}\right)^{1/2} = -\frac{fR}{2} \pm \left(\frac{f^2R^2}{4} + \mathrm{fR}V_g\right)^{1/2}$$

Since V must be real and nonnegative, the possible solutions are thereby restricted to:

$$\left|fV_g\right| = \left|\frac{\partial\phi}{\partial n}\right| < \frac{|R|f^2}{4}$$

As a result, the pressure field is always uniform and the wind is calm in high pressure system.

Learning Activities

3. Inertial wind and cyclostrophic wind

1) Inertial wind

An inertial wind is a wind in which the Coriolis force and the centrifugal force are balanced:

$$2V\Omega sin\phi = \frac{V^2}{R}$$

Solving this equation for the radius of curvature R yields the following equation:

$$R = \frac{V}{2\Omega sin\phi}$$

Because there is no pressure gradient force, the velocity V is constant. Therefore, if the latitude is almost constant, the radius of curvature R is constant. The air parcel will follow circular paths with radius of curvature R. In the Northern (Southern) Hemisphere, it shows clockwise (counter clockwise) flow.

Learning Activities

3. Inertial wind and cyclostrophic wind

The period (P) of the inertial wind that makes circular motion is

$$P = \frac{2\pi R}{V} = \frac{2\pi}{2\Omega sin\phi} = \frac{0.5days}{sin\phi}$$

As it is equivalent to the time needed for the Foucault pendulum to rotate 180 degrees, this period is often called the 0.5 pendulum day.

Because Coriolis force and centrifugal force are generated by the inertia of the fluid in the rotating Earth, such motion is called inertial oscillation. A circle with radius of curvature R formed by this motion is called inertia circle.

Learning Activities

3. Inertial wind and cyclostrophic wind

2) Cyclostrophic wind

If the horizontal scale is small enough, the Coriolis force can be ignored. When the pressure gradient force and centrifugal force are balanced, such wind is called cyclostrophic wind and can be expressed as:

$$-\frac{1}{\rho}\frac{\Delta p}{\Delta s} = \frac{V_c^2}{R}$$

Solving this equation with respect to the velocity is the following:

$$V_c = \left(\frac{R}{\rho}\frac{\Delta p}{\Delta s}\right)^{1/2}$$

The negative sign indicating direction is omitted here.

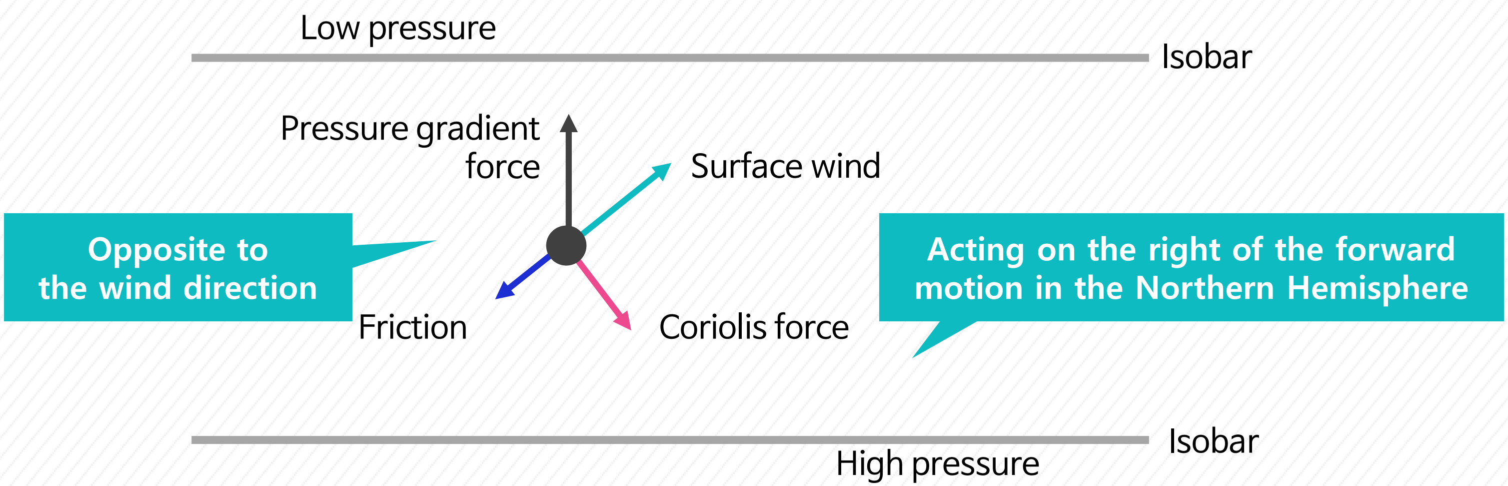
In order for the wind to keep the balance between the pressure gradient force and centrifugal force, the motion is always centered on the low pressure. Therefore, the cyclostrophic wind can be either clockwise or counterclockwise around the low pressure. Small scale cyclostrophic wind, such as dust devils, can rotate in any direction.

Learning Activities

4. Surface wind and thermal wind

1) Surface wind

The surface wind blows when the pressure gradient force, the Coriolis force and frictional force are in balance.



※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p137

The friction acts in the opposite direction to the wind direction. Coriolis forces are directed to the right and perpendicular to the wind direction in the Northern Hemisphere.

Learning Activities

4. Surface wind and thermal wind

Coriolis force+ Friction = Pressure gradient force
(Direction: Opposite)

The summation of the Coriolis and frictional force are comparable to the pressure gradient force with opposite direction.

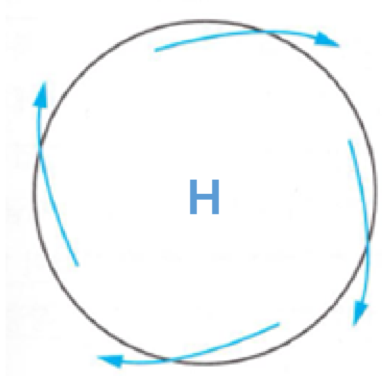
Comparing the surface wind with the geostrophic wind, the effect of friction can be recognized. Friction reduces the wind speed and wind direction. In particular, it deflects the wind toward the low pressure side. Such deflection causes vertical motion.

Learning Activities

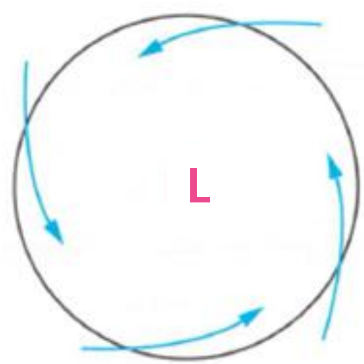
4. Surface wind and thermal wind

In the Northern Hemisphere, surface friction produces an inflow of air around a low and an outflow of air around a high. To replace the laterally spreading (converging) air of a high (low) pressure surface area, the air aloft converges (diverges) and slowly descends (ascends).

Surface wind around a high



Surface wind around a low



※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p137

Learning Activities

4. Surface wind and thermal wind

The types of wind we have examined so far are summarized as follows.

	Pressure gradient force	Coriolis force	Centrifugal force	Frictional force
Geostrophic wind	O	O		
Gradient wind	O	O	O	
Inertial wind		O	O	
Cyclostrophic wind	O		O	
Surface wind	O	O	(O) *	O

* Curved motion also includes centrifugal force

※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p137

Learning Activities

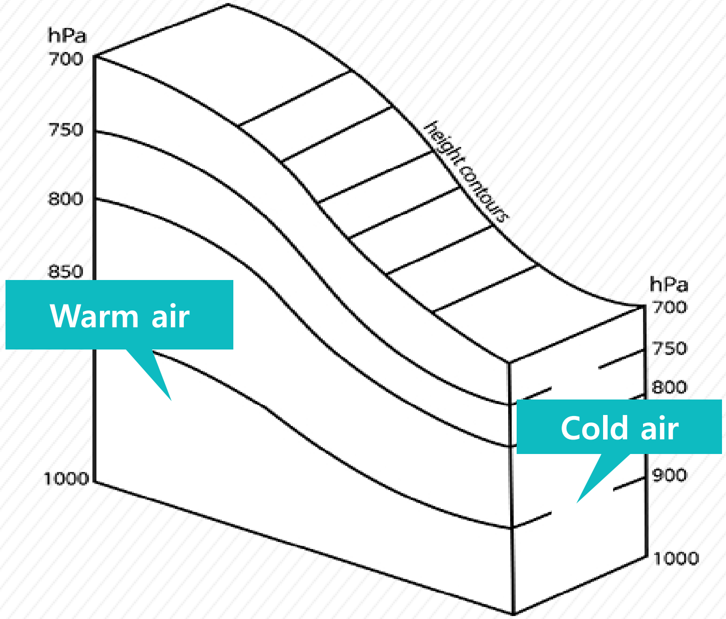
4. Surface wind and thermal wind

2) Thermal wind

The following shows the pressure gradient owing to temperature difference.

According to the hypsometric equation, the thickness between two isobaric surfaces is smaller in a cold column of air than in a warm column. This will result in a slope of isobaric surfaces and the slope increases with height. Therefore, the horizontal temperature gradient induces vertical pressure gradient, which can also lead to a change on geostrophic wind with height. The difference in geostrophic wind between two levels is called the thermal wind and can be expressed as:

$$\overrightarrow{V_{th}} = \overrightarrow{V_{g^2}}$$



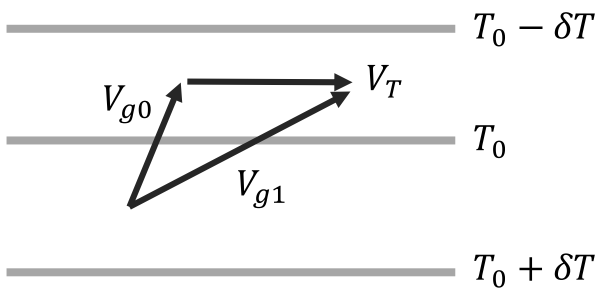
※ Source: University of Wyoming (http://www-das.uwyo.edu/~geerts/cwx/notes/chap12/thermal_wind.html)

Under the constraint of thermal wind relation, the advection of temperature can be estimated. If thermal wind turns counter-clockwise with height, it is called *Backing*. If clockwise, it is called *Veering*. *Backing* is related to cold advection, and *Veering* is related to warm advection.

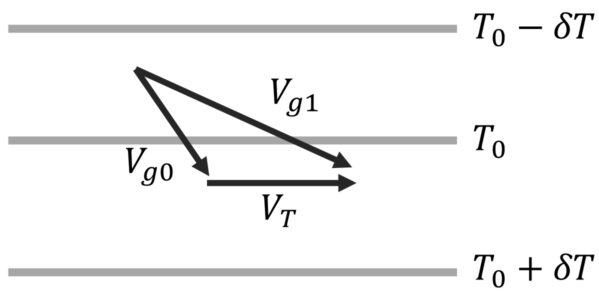
Learning Activities

4. Surface wind and thermal wind

Veering in the Northern Hemisphere



Backing in the Northern Hemisphere



Summary

1. Hydrostatic balance

- If vertical pressure gradient force and Earth's gravitational force are in balance, this is called a hydrostatic balance or hydrostatic equilibrium.
- he hydrostatic balance is expressed as $-\frac{1}{p}\frac{\Delta p}{\Delta z} = g$ or $\Delta p = -pq\Delta z$ which indicates that air pressure decreases by increasing altitude.

Summary

2. Geostrophic wind

- Winds balanced by the Coriolis and pressure gradient forces.
- Geostrophic wind speed is given by $V_g = \frac{1}{2\Omega\rho sin\phi}\frac{\Delta p}{\Delta s}$
- Geostrophic wind is stronger where the spacing of isobars is closer, in lower latitudes and in higher altitudes (where the air density is lower).

Summary

3. Gradient wind

- Winds balanced by the Coriolis, pressure gradient and centrifugal forces.
- In a high, the sum of the pressure gradient force and centrifugal force is equal to the Coriolis force.
- In a low, the sum of the Coriolis force and Centrifugal force is equal to the pressure gradient force
- Under the same pressure gradient force, the gradient wind speed is larger in high pressure system.

Summary

4. Inertial wind

- Wind balanced by Coriolis force and the centrifugal force.
- Inertial oscillation: oscillation by the inertia of the fluid
- Inertia circle: a circle formed by inertial wind.
- The radius of curvature $\mathrm{R} = \frac{V}{2\Omega sin\phi}$ and period $\mathrm{P} = \frac{2\pi R}{V} = \frac{2\pi}{2\Omega sin\phi} = \frac{0.5days}{sin\phi}$ (period is often called the 0.5 pendulum day)

Summary

5. Cyclostrophic wind

- Wind balanced by the pressure gradient force and centrifugal force.
- Wind speed is given by $V_c = (\frac{R}{\rho}\frac{\Delta p}{\Delta s})^{1/2}$
- Cyclostrophic wind is always centered on the low pressure.

Summary

6. Surface wind

- The surface wind is balanced with the pressure gradient force, the Coriolis force and frictional force.

Summary

7. Thermal wind

- Vector difference of geostrophic wind between two levels.
- With the thermal wind relation, the advection of temperature can be estimated.
- Backing is related to cold advection and Veering is related to warm advection.