Introduction to Meteorology

16 Wind

Introduction

Wind makes the freezing air cooler on winter nights, and cools down the heat on hot days. Wind is closely related to weather phenomena. Wind is the movement of air driven by the differential heating of air. In order for an object to move, a force must act on the object. Force is a vector quantity having both magnitude and direction. Object moves in the direction in which the force acts.

Contents

1. Dynamics of the wind
2. Fundamental force
3. Apparent force

Learning objectives

1. Describe the types of forces that generate wind.
2. Explain the fundamental force and apparent force.

Learning Activities

1. Dynamics of the wind

Vorticity, a measure of the microscopic rotation of a fluid, is the vector field expressed as a curl of velocity. Divergence refers to the fractional rate of change in the area of a fluid parcel.

Learning Activities

1. Dynamics of the wind

1) Divergence of the vorticity

The vorticity (ω) is a curl of velocity which can be expressed in Cartesian height coordinate as follows.

$$\omega = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}, \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}, \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$$

In large-scale meteorology, we are usually concerned only with the vertical components of the vorticity, which is expressed as

$$\zeta \equiv \vec{k} \cdot (\nabla \times \vec{U})$$

Divergence is expressed as follows,

$$\nabla \cdot \vec{V}$$

In Cartesian coordinates, it is expressed as follows. Negative divergence is called convergence.

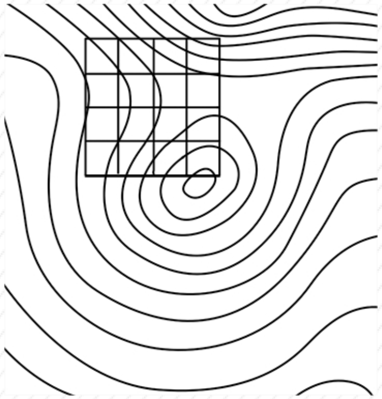
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

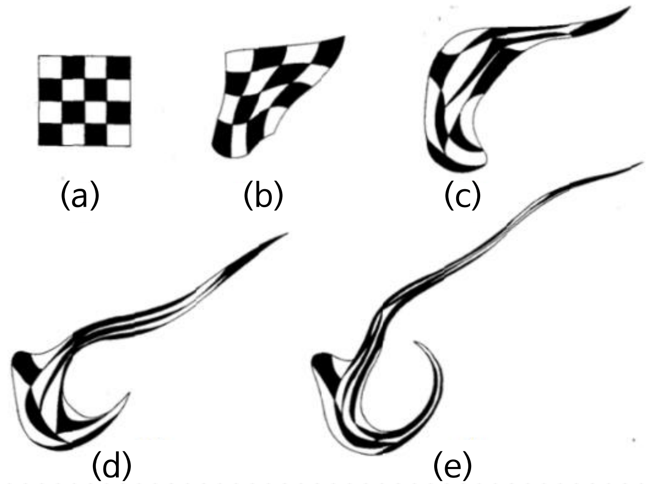
Learning Activities

1. Dynamics of the wind

2) Deformation fields

The deformation field is the sum of shearing and stretching. As shown in the figure, the deformation can form a weather front by changing the horizontal gradient of scalar quantities such as the temperature and humidity field.





※ Source: Studies on the General Development of Motion in a Two-Dimensional Ideal Fluid (Pierre Welander, Tellus, 7 (1955)) p146

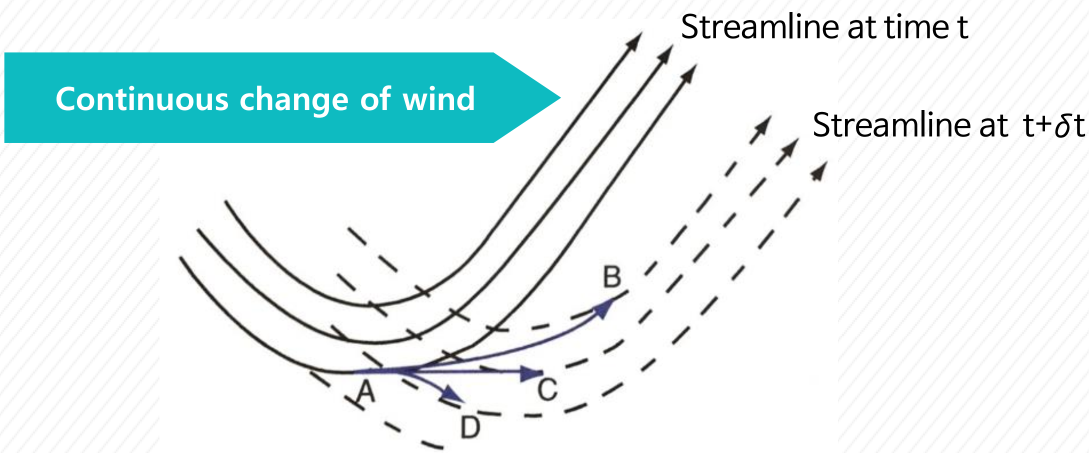
Air masses embedded in a steady-state wind field look like Figure (a). The intensity of the wind is stronger as the interval of the isobar gets narrower, and the flow changes in the order of (a) to (e).

Learning Activities

1. Dynamics of the wind

3) Streamline and trajectory

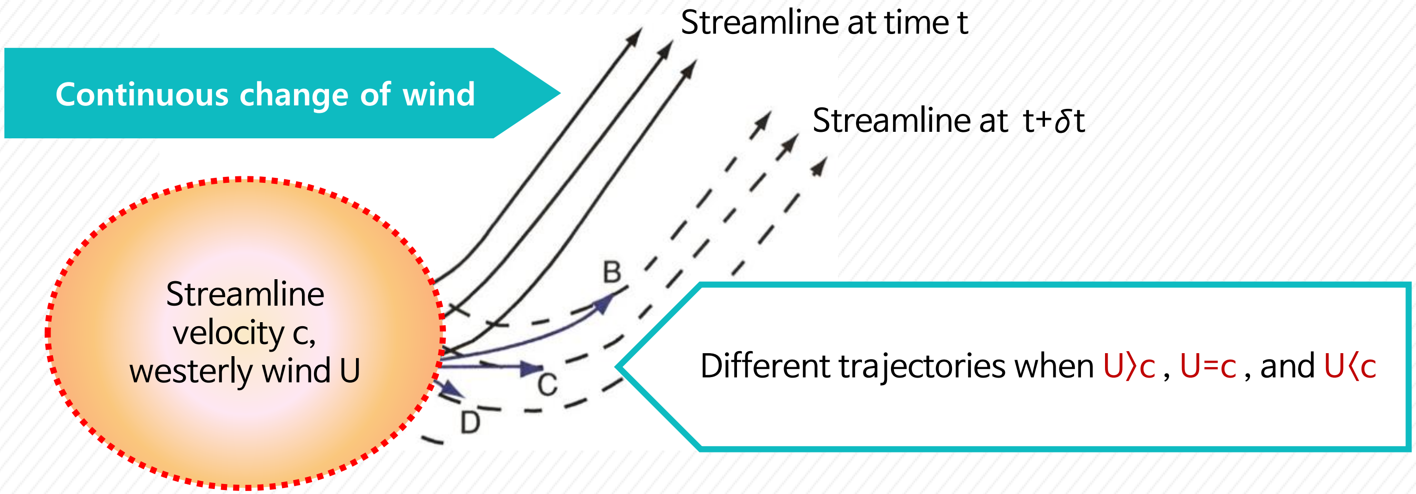
If the wind field changes occasionally, the trajectory of the wind and streamline is not the same. The solid line is the streamline at time t and the dotted line is the streamline at time t + δt



Learning Activities

1. Dynamics of the wind

When the velocity of the streamline is c and the westerly wind is blowing uniformly with a velocity U, the AB, AC, and AD trajectories are different in the cases of U⟩ c, U = c, and U ⟨c.



Learning Activities

2. Fundamental forces

The fundamental forces that affect atmospheric motion include gravitational force, pressure gradient force and friction. According to Newton's law of universal gravitation, there exists a force between two objects that is proportional to their masses and inversely proportional to the square of the distance between the two objects.

Learning Activities

2. Fundamental forces

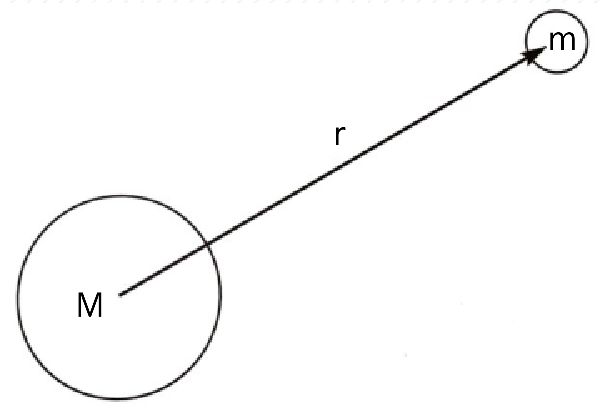
1) Gravity

If the distance between the object M and m is r, the force exerted upon small m by big M is given by:

$$F_g = -\frac{GMm}{r^2}\left(\frac{\vec{r}}{r}\right)$$

$\vec{r}$ is the direction toward m, and G is the gravitational constant.
If the Earth's mass is M and the mass of the atmosphere is m, then the force per unit mass of the atmosphere by the Earth's gravitation is

$$\frac{F_g}{m} \equiv \vec{g}^* = -\frac{GM}{r^2}\frac{\vec{r}}{r}$$



※ Source: Atmospheric environmental science (Min, Kyung-Deok et al., Sigma Press) p103

Learning Activities

2. Fundamental forces

Assume that the average radius of the Earth is a, and the distance from the mean sea level is z, and the Earth is a perfect sphere, then r = a + z. Accordingly, g^* can be expressed as:

$$\vec{g}^* = \frac{\vec{g}_0^*}{(1+\frac{z}{a})^2}$$

$-(GM/a^2)(\vec{r}/r)$
Gravitational acceleration for air parcel above sea level:

g_0^* is the gravitational acceleration for an air parcel above the sea level. Usually z ⟨⟨ a, thus g_0^* almost equals to g^* and can be considered as a constant.

Learning Activities

2. Fundamental forces

Gravity is the force that the Earth pulls on an object. Strictly speaking, gravity is a combination of universal gravity and centrifugal force. However, the centrifugal force is relatively small, so gravity and universal gravity is almost the same.

The direction of gravity is towards the center of earth and is perpendicular to the surface. Gravity can be calculated as mass times the gravitational acceleration which is approximately 9.8 ms $^{-2.}$. Gravity per unit mass equals to gravitational acceleration.

If gravity were the only force acting on the air, then all the air would fall down by gravity. But that does not happen because there is a vertical component of pressure gradient force that is nearly equal in magnitude and opposite in direction.

Learning Activities

2. Fundamental forces

2) Pressure gradient force

As learned in the earlier chapters, atmospheric pressure changes with temperature and density. The relationship between air pressure (p), temperature (T), and density (ρ) is expressed by the following equation.

$$p = \rho RT$$

p : Pa (pascal)
ρ : kgm^{-3}
T : Temperature K

Constant R: 287 $Jkg^{-1}K^{-1}$

As shown before, the expression above is called an ideal gas law or equation of state, in which the p is in Pa (pascal), ρ in kgm^{-3}, and T in the absolute temperature K. In this case, a gas constant R is 287 $Jkg^{-1}K^{-1}$. Wind is caused by the atmospheric pressure difference. The larger the pressure difference between the two points, the stronger the wind. The difference in pressure between the given two points is called the pressure gradient, and the force due to pressure gradient is called the pressure gradient force (PGF).

Learning Activities

2. Fundamental forces

PGF always directs from higher toward lower pressure. PGF is a function of pressure difference, distance between two points, and air density. The PGF per unit mass is expressed as:

$$F_{pg} = -\frac{1}{\rho}\frac{\Delta p}{\Delta s}$$

Difference of pressure and distance

Air density

The negative (−) sign indicates that the PGF works in the direction opposite to pressure gradient. Assuming that the PGF is the only force on the air, the air will move from higher toward lower pressure perpendicular to the isobars. If the pressure changes abruptly in a short distance, the PGF becomes large and the wind blows strongly. In general, the PGF in vertical direction is much larger than the horizontal direction in the atmosphere.

Learning Activities

2. Fundamental forces

3) Frictional force

Friction refers to the resistance force caused by the difference in velocity between two objects when they are in contact with each other. When the wind speed near the surface of the Earth is reduced by the surface, it is called the surface friction (drag force).

The Earth's surface is not flat, and the terrain is complicated by mountains, buildings and trees. Due to this complex terrain, the surface becomes rough and the wind speed decreases when the wind blows over it. The frictional force generated by the terrain acts in the opposite direction to the wind direction. Frictional force per unit mass F_r is expressed as:

$$F_r = -kV$$

Wind velocity

Parameter K represents the surface roughness

Negative sign
→ Frictional force is opposite to the wind direction

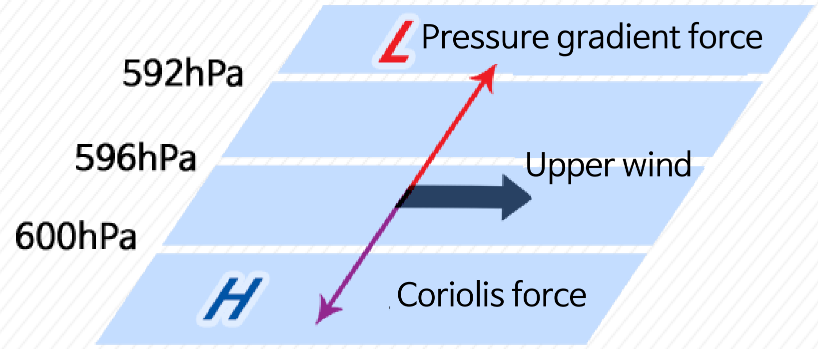
Learning Activities

2. Fundamental forces

Frictional forces increase as the surface roughness and wind speed increase. Therefore, friction is generally weaker over a flat surface or a calm ocean surface, than the friction in areas with trees, buildings or mountains. Frictional forces in the atmosphere act largely in atmospheric layers up to about 1.5 km from the ground, which is called planetary boundary layer (PBL) or simply boundary layer.

Above the PBL, the frictional force is so small that the atmosphere is almost free from friction. This layer is called the free atmosphere. Due to the frictional force, the direction of the wind on the surface is not parallel to the isobars, but across the isobars.

Surface (without friction)



Learning Activities

3. Apparent force

To express the atmospheric motion on Earth, it is natural to deal with atmospheric motion in a fixed reference frame (inertial frame) against the Earth. But observers are measuring atmospheric motion on the rotating frame. Therefore, although air motion is stationary in the fixed inertial reference frame, it is accelerating because of the Earth's rotation when viewed from the absolute reference frame.

The reference system that changes with the rotation of the earth is a non-inertial reference frame (rotating reference frame). On the other hand, the coordinate system fixed to space is called the inertial (fixed) reference frame.

Since Newton's laws of motion apply only to a fixed reference frame, in order to apply Newton's laws of motion in a rotational system, the acceleration of the coordinate system must be considered. In other words, to take into account the acceleration effect of the coordinate system, we have to introduce apparent force into Newton's second law. For a coordinate system that rotates constantly, like Earth, we have to consider the centrifugal force and the Coriolis force, which are apparent forces.

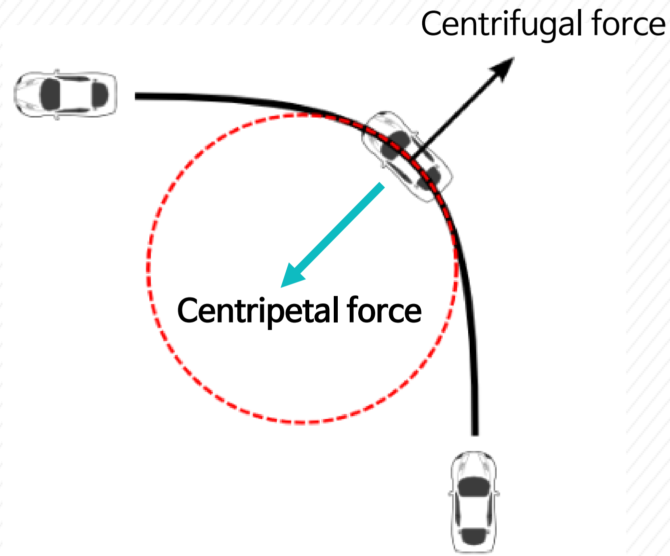
Learning Activities

3. Apparent force

1) Centrifugal force

When an object moves in a curve, the object is accelerated even if the speed of the object does not change. This acceleration is called centripetal acceleration.

When we drive a car, suddenly turning the car will fall in the opposite direction of rotation and in this case we will experience a centripetal acceleration. The centrifugal force works in the opposite direction to the centripetal force with the same magnitude. Since the centripetal force always points to the axis of rotation, the centrifugal force is directed to the outside. Centrifugal force (F_{ce}) acting on the body of a unit mass is expressed by the following equation.



$$F_{ce} = \frac{V^2}{R}$$

where V is the velocity and R is the radius of curvature of the path. Therefore, centrifugal force increases with increasing velocity and decreasing radius.

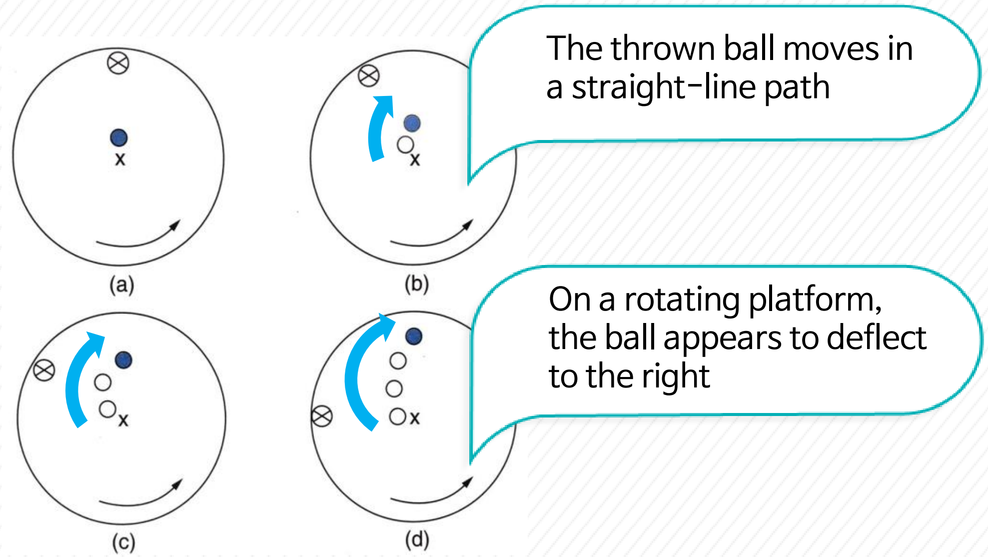
Learning Activities

3. Apparent force

2) Coriolis force

Pressure gradient force makes the air to move from higher to lower pressure. Therefore, the magnitude of PGF is used to determine the strength of the wind. When discussing the direction of the wind, we must consider the earth's rotation.

To illustrate the effect of the earth's rotation on a moving object, let's assume a counter-clockwise rotating plate. The ball placed on the rotating plate moves in a straight line, but a curved trajectory is drawn on the plate. If a person is observing the movement of a ball on a rotating plate, the ball appears to be curving to the right. All objects in the Northern Hemisphere deflect to the right. This force is called the Coriolis Force after a French scientist Gaspard Coriolis who worked it out mathematically.



※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p131

Learning Activities

3. Apparent force

Coriolis force acts perpendicular to a moving object, and can only change the direction of the object but not the speed. The Coriolis force (F_{co}) per unit mass is:

$$F_{co} = 2V\Omega \sin\phi$$

where Ω is the Earth's angular velocity, Φ is the latitude, and V is the speed of the object.

Coriolis force acts to deflect a fluid parcel to the right (left) of its forward motion in the Northern (Southern) Hemisphere. The force magnitude is zero at the equator and increases as latitude increases. The force is proportional to the velocity of a parcel. It does not alter wind speed but only wind direction

Summary

1. Dynamics of the wind

Vorticity	A measure of the microscopic rotation of a fluid
Divergence	A fractional rate of change in the area of a fluid parcel
Deformation	Change in scalar quantity and generate weather front
Streamline and trajectory	Streamline and trajectory may be the same depending on wind speed

Summary

2. Fundamental forces

Gravity	• Gravity is the force that the Earth pulls on an object. • Gravity is directed towards the center of earth and is perpendicular to the surface. Gravity is mass times the gravitational acceleration.
Air pressure	• Air pressure is the force exerted by the air molecules over a given area. • Depends on temperature and density.
Pressure gradient force	• The pressure difference between two points.
Frictional force	• Resistance force caused by the difference in velocity between two objects when they are in contact with each other. • Wind speed near the surface of the earth is reduced by the surface roughness. Friction is $F_r = -kV$ • Frictional forces in the atmosphere act largely in atmospheric layers up to about 1.5km from the ground, which is called planetary boundary layer (PBL).

Summary

3. Apparent force

- The reference frame that changes with the Earth's rotation is a non-inertial (rotating) reference frame. The coordinate system fixed to space is called the inertial (fixed) reference frame.
- Apparent force occurs due to the rotation of the system.

Centrifugal force	• The centrifugal force works in the opposite direction to the centripetal force with the same magnitude • Centrifugal force is $F_{ce} = \frac{V^2}{R}$
Coriolis force	• Coriolis force acts to deflect a fluid parcel to the right (left) of its forward motion in the Northern (Southern) Hemisphere. • The force magnitude is zero at the equator and increases as latitude increases. • The force is proportional to the velocity of a parcel. • It does not alter wind speed but only wind direction.