Forces of Motion And Sir Isaac Newton

Sir Isaac Newton, the father of mechanics, is one of the most important scientists who ever lived, changing the standards by which scientists think. His genius in mathematics and mechanics is exemplified by his creation of calculus to explain observations of the world around him. In addition, his laws of motion opened the door to progressive new thinking, enlightening the minds of thousands to the nature of things. His laws of motion make up the foundation for which dynamic meteorology exists.

Law of Inertia - A body at rest or in motion will tend to stay that way until acted upon by a net external force.

Law of Acceleration - A change in motion relates directly to a force trying to move it. **F=ma**

Action-Reaction Law - For every action there is an equal and opposite reaction.

It is important to note here the definitions of velocity and acceleration. A quantity that has magnitude only is called a **scalar**. If a quantity has magnitude and a sense of direction, it is called a **vector** and it is represented graphically by an arrow.

Speed is an example of a scalar because it indicates "how fast" something is traveling. Its unit of measurement is the change in position (or distance)/the change in time, e.g. m/s.

Velocity is the vector representation of the scalar speed, therefore it must be given direction, e.g. eastward at 10 m/s.

Acceleration is the vector representation of the change in velocity/change in time, e.g. m/s². Because acceleration is a change in velocity, an object may be accelerating even if its *speed* is not changing if its *direction* is.

Important Forces In The Atmosphere

Perhaps the most readily known force in the atmosphere is gravity, and yet surprisingly, very little is known about this omnipresent force. It was Newton who first tried to understand this force, even if an apple did not fall on his head.

Gravity is an attractive force that exists in every object that has mass. However, it only becomes significant in objects whose mass is very great such as celestial objects, i.e., planets stars and moons. Gravity is therefore dependent upon the object's mass.

The strength of the gravitational force is also dependent upon the distance between two objects. Since gravity is an attractive force, the greater distance between two objects, the smaller the force. The force of gravity is then formulated as follows:

$$F_g = G*m_1*m_2/r^2$$

where r is the separation between two objects of mass m_1 and m_2 and G is the universal gravitational constant. Since F_g-ma, we see that the acceleration of a falling object (g) is

$$g = G*M_{Earth}/r^2$$

We will refer to g as an acceleration with a value of 9.8 m/s² (10 m/s² for simplicity). Notice the acceleration of a falling object is independent of the object's mass. As Galileo proved, two falling objects will fall at the same rate. However, the force of the object hitting your head is not independent of mass!

Centrifugal force is another force that one may be familiar with because of the great appeal of amusement parks. Centrifugal force actually does not exist but because as an object changes direction it experiences an inertial change, that inertial resistance is termed centrifugal force. Actually the change is brought about by a physical force (a twisting track or a string attached to a rock.) It is this force that causes a **centripetal** acceleration (toward the center).

Centripetal acceleration is defined as:

$$a_c = v^2/r$$

where v is the velocity and r is the radius of curvature.

Therefore, the faster an object travels or the tighter the turn, the stronger the "centrifugal" force. Although there is no "actual" force, the force "appears" very real indeed. We call the centrifugal force an **apparent** force and it makes physical understanding a lot easier.

The Coriolis force is another example of another apparent force. In WWI, the Germans developed a cannon which could fire at Paris, but even taking into account winds and air resistance, the cannons consistently shot to the north of the city.

Railroad tracks that allow travel in only one direction tend to wear out on the right side.

These two events illustrate a very real result of a force that does not really exist! The Coriolis force results from objects moving on a rotating sphere. The force is apparent because when viewed from outer space, objects on the earth travel in a straight line. But when in the earth's **frame of reference**, moving objects will deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

The Coriolis force is defined mathematically as:

CF = 2Ω·v·sinϕ

where Ω=7.29x10-5 s-1 which is the rotational frequency of the earth, and ϕ is latitude. Basically, this formula states that the faster an object moves and the closer to the poles it is, the stronger the Coriolis force.

Before we continue with the rest of the atmosphere's forces, let us first compare two examples of the relative strengths of the centrifugal and Coriolis forces.

For a tornado, let us assume v = 50m/s and r = 200m.

If ϕ = 40˚, sin 40˚ = .643

a_c = v²/r therefore, a_c = 50²/200 = **12.5 m/s²**

CF = 2Ω·v·sinϕ = **.005 m/s²**

We can compare answers and say that compared to the centrifugal force, the Coriolis force is insignificant.

For a low pressure system, let us assume v = 10m/s, r = 5000km which is 500,000m and ϕ= 40˚.

a_c = .0002 m/s² CF = .001 m/s²

We can compare force and say that the Coriolis force is five times greater than the centrifugal force. This is too small a difference to ignore.

Friction simply stated is a force that acts to slow an object. Friction is important when air is moving near the earth's surface but not as important higher in the atmosphere. More will be stated later as we talk about combining these forces.

The Cause of the Winds - Pressure Gradient Force

Whenever the word "gradient" is mentioned, one should immediately associate with "difference". The **pressure gradient force** (**PGF**) therefore is a force resulting from a difference in pressure:

PGF = -(1/ρ) dp/dx

Consequently, if in the same distance the difference in pressure is increased, the PGF is greater, or similarly, if the difference is the same, the smaller the distance between two set values of pressure, the greater the PGF.

An **isobar** is a line of constant pressure. Every value on an isobar is the same. Likewise, an isotherm is a line of constant temperature and an isoheight is a line of constant height. When determining the strength of the PGF, it is useful to look at the distance between two

isobars of a set difference, dp or ∆p. The closer the isobars, or the tighter they are **packed**, the stronger the PGF.

Because of a difference in pressure, air will travel from high to low pressure to try to balance the imbalance. If one imagines a marble rolling down an incline from high to low, one can visualize air traveling "down the gradient". Therefore, the stronger the gradient, the faster the winds.

Combining the Forces

Newton said that any change in motion must be the result of applied external forces. In the atmosphere, these forces are gravity and PGF (pressure gradient force) in the vertical, which gives us the hydrostatic balance; and PGF, Coriolis, centrifugal and frictional forces in the horizontal (or compass directions). We will now try to understand how these forces combine to produce the winds.

Case I - Linear Upper-Level Flow (Geostrophic)

At "steady-state", the two forces are counterbalanced, i.e. the resultant force is zero. The wind blows parallel to the isobars with no acceleration.

RULE 1: The PGF always acts from high to low.

RULE 2: The Coriolis force always acts perpendicular to the right of the motion (in the northern hemisphere.)

Buys-Ballot Law: With the wind at your back, low pressure is to your left.

Case II - Curved Upper-Level Flow (Gradient)

We now add curved flow to the above equation, which means we will have to consider the effects of centrifugal force.

This time, the Coriolis force needs to balance both the PGF and the centrifugal force,

If V < Vg then the wind is considered **subgeostrophic**. The Coriolis force needs to be greater than in the geostrophic case to balance the PGF.

If V > Vg then the wind is considered **supergeostrophic**. The Coriolis force does not need to be as great as in the geostrophic case to balance the PGF.

RULE 3: Centrifugal force always acts outward from the radius of curvature.

Cyclonic: the direction the earth rotates. In the NH, counterclockwise, in the SH, clockwise. Indicates the flow around a low. The opposite is **anticyclonic**.

Case III   Curved Flow with Friction   (Surface Winds)

Adding friction to the winds tends to slow the wind speed and hence deflect it across the isobars toward low pressure. As a result, wind will converge toward the center of the low and diverge from the center of a high.

RULE 4: Friction always acts opposite the direction of motion, causing the wind to deflect across the isobars toward lower pressure.

<u>Vertical Balance - The Hydrostatic Equation</u>

Air does not fall or fly away from the earth because there exists a balance of forces in the vertical direction as well. Gravity, which is accelerating the air toward the earth, is balanced by the PGF in the vertical, or PGF = g. If we manipulate this equation by substituting terms from the ideal gas law, and apply calculus, we obtain a relationship between ∆T and ∆z, which states that the thicker the atmosphere, the warmer the temperatures. This is known as the **thickness relation**. Here ∆z refers to the vertical distance between two isobaric surfaces (pressure levels.) In meteorology, it is often the distance between 1000 mb and 500 mb. Simply stated, the thicker the layer, the warmer the temperatures.

<u>Sea Breezes</u>

- Pressure starts out equal but due to unequal surface heating, the thickness over the land (sea at night) is greater.
- An upper-level high develops over the land creating divergence and a subsequent drop in surface pressure.
- Air begins rising and is coupled with low-level convergence.
- The circulation completes its loop and water-laden air rises, cools and produces condensation and clouds.
- Thunderstorms may develop if atmospheric instability is enhanced by surface heating.
- Sea breezes occur mid to late afternoon when land-sea temperatures differences are greatest.
- In early pre-dawn hours, a reverse circulation may be induced, known as a **land breeze**.

Air Masses

An air mass is a large area of air with similar characteristics, the most important being temperature and dew point temperature. The air mass is defined by the source region of the air mass. If the source region is over water, the dew point will be higher and the air mass is considered **maritime**. If the opposite is true, it is named **continental**. There are four temperature characteristics defining the air mass' source region from coldest to warmest: **arctic**, **polar**, **tropical**, and **equatorial**. We will use primarily polar and tropical. By combining these, there are four basic air masses: continental tropical (**cT**), continental polar (**cP**), maritime tropical (**mT**), and maritime polar (**mP**). An important quality of air masses is that they are modified by time and thus can be difficult to classify by only by temperature and dew point on a first inspection. There is a way of comparing two air masses. A **front** is simply defined as a narrow transition zone between disparate air masses.

Fronts and Extra-Tropical Cyclones

A front is a narrow transition zone, or boundary, between disparate synoptic scale air masses whose primary discontinuity is density. Fronts are commonly associated with a moisture gradient, a pressure trough, a wind shift and/or various sensible weather phenomena. A front is a convergent boundary. It is synoptic scale along the length of the front, but mesoscale across the front itself.

Rules for Finding Fronts

1. Look for a strong temperature gradient (difference). The front will be at the warm side of the sharpest gradient.
2. Likewise, look for a strong dew point gradient. The front will be on the warm side of the gradient.
3. The front will be found in a pressure trough.
4. Look at the three-hour pressure changes, known as tendencies. With the passage of the front the pressure will decrease then increase, giving a trace, which looks like a check mark, or **check tendency**.
5. Look for a sharp change in the wind direction. A cyclonic shear in the wind usually indicates frontal passage.
6. Check weather and cloud patterns that are usually associated with different kinds of fronts.

There are four types of fronts: cold, warm, occluded and stationary. Each front marks the transition zone between air masses.

Cold fronts are marked by blue lines with triangles pointing toward the warm air, indicating the direction of motion. Slope (m) = 1/50 to 1/150

Cold fronts usually generate strong lifting and hence ahead of the front there are usually areas of moderate to strong convection. Precipitation is usually in the form of showers and thunderstorms.

Warm fronts are marked by red lines with half circles penetrating the cold air and indicating the direction of motion. m = 1/100 to 1/300

Warm fronts generally force air to rise over the frontal boundary and continuous precipitation is likely. However if the air on the warm side of the front is unstable, thunderstorms and showers are possible.

A front's speed is determined by the component of wind perpendicular to the front on the cold side. In other words, a cold front is where cold air advances and a warm front is where cold air retreats.

Stationary fronts are marked by alternating blue lines with a triangle and red lines with a half-circle, using the same convention as before. There is little or no movement.

Occluded fronts occur when the cold front "overtakes" the warm front, pushing the warm air above the surface.

There are two types of occluded fronts: **warm-type** and **cold-type**.

Frontogenesis is the beginning of a front.

Frontolysis is the death of a front.

Cyclogenesis is the beginning of a wave cyclone.

A wave cyclone begins with a perturbation along a stationary front, causing the winds to adjust to pressure falls.

At the **occluded** stage, the lowest pressure exists about one day after the formation of the occluded front. With time, the occlusion lengthens.

Thunderstorms

There are four types of thunderstorms:

- single-cell (or air mass)
- multicell cluster
- multicell (or squall line)
- supercell

The differences arise because of different atmospheric profiles, especially those concerned with vertical shear. As stated earlier, air mass thunderstorms are usually produced in areas of very little vertical shear. Supercell storms are typically the most severe. Multicell storms are a result of the splitting of parent thunderstorm cells and often form in a line known as a **squall**. A squall line refers to a line of thunderstorms that usually develop ahead of forcing along a line, like along a cold front. Almost all organized convection requires that the following conditions are met:

- warm, moist air at low levels
- cool, dry air at upper levels
- upper-level divergence (around 500mb)
- generally low pressure near the surface

In these conditions, thunderstorm formation is probable, although the vertical profile of winds may lead to a greater possibility of supercell development rather than multicell thunderstorms.

Multicellular storms consist of a series of evolving cells. At low levels, cooler air diverging from the downdraft intersects the inflowing air along a gust front, creating a region of strong low-level convergence favorable for new updrafts. These tend to form on the right or right rear flank of the storm system. It is the presence of vertical wind shear that results in the "tilting" of the updraft and downdraft. Because of the tilting, the less buoyant downdraft air will not destroy the updraft and hence deprive itself up supersaturated updraft air.

The most important distinction of thunderstorm types is found by asking a single question: "Does the thunderstorm have a rotating updraft?" If it does, the thunderstorm is considered to be a supercell, no matter what configuration other cells are in. Thunderstorms with a rotating updraft (mesocyclone) are responsible for the preponderance of severe weather associated with thunderstorms.

Hurricanes - North America; India/Australia – Cyclone; Eastern Asia – Typhoon; China Sea - Baguio

Conditions Necessary for the Development of Tropical Storms

- SST at least 26°C late summer, early fall
- Coriolis force; outside of 3° lat. (usually between 5° and 25°)
- Very little vertical shear (surface and upper tropospheric easterlies)
- Temperature relatively constant over large surface areas
- A disturbance (a wave in the ITCZ or thunderstorms off the west coast of Africa)

Only 10% of these disturbances intensify, and once they intensify, only 70% will reach tropical storm status; sustained winds ≥ 35 kts. A hurricane is a tropical storm with sustained winds greater than 65 kts (74 mph)

Thunderstorms release large amounts of latent heat, warming the mid- and upper-troposphere. As a result of this heating, air begins to diverge consequently lowering the surface pressure. Surface convergence is enhanced by friction. However, because of the warm waters, the adiabatic cooling as the air crosses the isobars is balanced by conductive heating. A warm core is thus maintained, perpetuating the storm. If there were vertical shear, the heat in the core of the hurricane would be transported away from the area of maximum surface convergence. Friction therefore balances the storms strength by limiting its intensity but maintaining its fuel supply (latent heat).

The **eye** of the hurricane is the "calm in the middle of the storm" where the skies are clear and winds subside to near calm. The eye is formed as the intensity of the storm increases. The winds rotating around the center of the storm can no longer make the turn due to the law of the conservation of angular momentum. Air spins rapidly as the air crosses the isobars toward lower pressure. However, it rises before it gets to the exact center. The eye wall, which surrounds the eye, contains the most turbulent conditions and the most intense thunderstorms. The eye remains clear because of small amounts of subsidence to fill the void of air at the surface.

- Typical diameter ~ 650 km
- Typical eye diameter < 50 km
- Typical pressures – 900-950 mb (below 900 mb have been recorded)

Spiral bands of thunderstorms spiral out from the hurricanes center giving warning of its approach and the storm the familiar octopus-like form.

The **storm surge** is the most deadly and destructive part of a hurricane. For every 1 mb drop of atmospheric pressure, the sea level raise 1 cm. Coupled with strong on-shore winds, and a "sloshing" effect, the level of the sea can raise several meters, inundating the shore with a wall of water and several meters higher with enormous waves.