Date: 18.11.2020

Geography (Hons)-Paper-CT5-3rd Semester

Weather: stability and instability; Barotropic and baroclinic conditions.

Questions

1. What do you mean by atmospheric stability and instability?
2. What do you mean by Barotropic and Baroclinic conditions?
3. What do you mean by conditional instability?

The Concept of Atmospheric Equilibrium:

In meteorology the term '*stability'* is used to indicate a condition of *equilibrium*.

There are three types of *equilibrium*-

i. *Stable equilibrium*
ii. *Unstable equilibrium*
iii. *Neutral Equilibrium*

The following characteristics render the discussion of atmospheric *equilibrium* complicated:

i. The atmosphere being compressible, the density of air undergoes progressive change as it descends or ascends.
ii. When a *saturated* air mass rises, the *latent heat of evaporation* is released which warms up the air. The warming of rising air in this way affects its density. The changes brought about in the density of an air mass materially affect the atmospheric *equilibrium*.

To test the *stability* or *instability* of the atmosphere, it is to be seen as to what happens to any parcel of air which is displaced through a small vertical distance from its initial height. If in its new position it is subjected to forces which tend to restore it to its original position, the atmosphere is considered to be in *stable equilibrium*. Contrary to it, if in its new position it is subjected to no forces tending either to restore it to its original level, or to displace it still further from its original position, the atmosphere is said to be in *neutral equilibrium*. However, the *equilibrium* is said to *unstable* when in its new position, it is subjected to forces tending it to displace still further from its original position.

It is true that a moving parcel of air will at all stages of its ascent take up automatically the pressure of its immediate environment. Therefore the relative densities of the moving parcel of air and of its surroundings will be largely determined by the absolute temperatures.

When the distribution of temperature and density is such as to resist vertical movements, the atmosphere is said to be in *stable equilibrium*. Under these conditions, an element of air, even if displaced, tends to returns to its original position after some time. Thus, when the atmosphere is in the state of *stable equilibrium* there is complete absence of convective activities and the weather remains clear. Such a condition is not conducive to precipitation. On the contrary, when there is a tendency in the air to move further after being displaced, it is said to be in *unstable* *equilibrium*. Under these circumstances, the atmospheric conditions are favourable for convective activities which result in cloud formation and abundant precipitation.

Atmospheric Stability and Lapse Rate:

Atmospheric stability is defined—

as that condition in the atmosphere in which vertical motions are absent or definitely restricted

and conversely atmospheric instability is defined—

as that condition in the atmosphere in which vertical motions are prevalent.

According to Trewartha —"Air is said to be stable, and consequently antagonistic to precipitation, if it is non-buoyant and resists vertical displacement. Voluntary vertical motions are largely absent in stable air. On the other hand, if displacement results in buoyancy and a tendency for further movement away from the original position, the air is unstable".

The stability of air is determined by the distribution of temperature in the atmosphere at various heights. This measure of the change of temperature is called the **lapse rate** which is altogether different from the *adiabatic lapse rates*. As we know, the *lapse rates* always vary with time and place (lapse rate lies between 4.6 °C/1000 metres to 35°C/1000 metres),. The *dry-adiabatic lapse* rate is always the same (10° C/1000 metres). By noting at any level the difference in temperature between an air parcel moving upward and the surrounding atmosphere, *stability* or *instability* can be ascertained. In other words, the *environmental lapse rate* prevailing in the atmosphere makes the atmosphere *stable* or *unstable*. If the *lapse rate* exceeds the *dry-adiabatic lapse rate*, the air is bound to be in the state of *unstable equilibrium*, and it will tend to rise further. On the other hand, if the *lapse rate* is lower than the *dry-adiabatic lapse rate*, there will be *stability* in the air. Such an air parcel, even if pushed up strongly, tends to return to its original position. Such a state of *equilibrium* resists vertical motions in the atmosphere.

The interrelationship between atmospheric *stability* and *lapse rates* has been illustrated in the following figure. In the left hand side of the diagram the surface air is at a temperature of 35 ° C with a lapse rate of 6 °C per kilometer. Imagine that a parcel of air with 35 ° C temperature at the ground is forced upward as shown in the figure. After the air has reached a height of 1 kilometre, its temperature has come down to 25° C, while the temperature of the surrounding air is about (35-6) 29°C. Obviously the ascending air is colder than the environment at the same level and must sink downward. This parcel of air would tend to come back to its original position unless some outside force is applied to it, because further ascent would cause it to become colder and heavier than the surrounding air. The relationship between the *actual lapse rate* and the *dry adiabatic lapse rate* is such as to resist vertical movement. Such air is said to be in *stable*

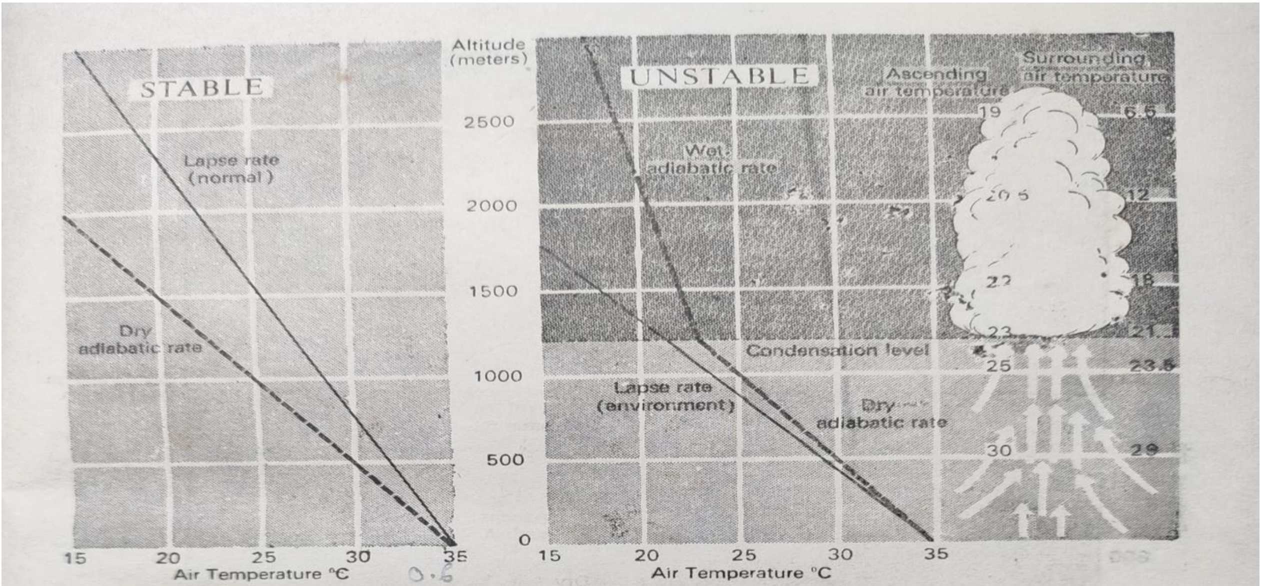


Fig. 13.2 Stability and instability of the atmosphere. The lapse rate less than the dry adiabatic rate means stable air. When the lapse rate exceeds the dry adiabatic rate the air is unstable.

equilibrium. It is to be noted that in this case the existing *lapse rate* is lower than the *dry-adiabatic rate of cooling*.

The right hand side drawing in figure is a diagrammatic representation of the state of *unstable equilibrium*. In this case the ascending air parcel at the height of 1 kilometre has cooled down to 25° C, while the temperature of the surrounding air at the same level is only about 24° C. The rising air is warmer and lighter than the surrounding air. In such a situation, the rising air will continue to rise and expand. Here the rate of cooling of the ascending air is lower than that of the surrounding air, because the *lapse rate* is higher than the *dry-adiabatic lapse rate*. Such an air is considered to be *unstable*. This case illustrates the behaviour of the atmosphere when *unstable equilibrium* conditions prevail.

Thus, to examine whether an air mass is *stable* or *unstable* a comparison should be made between its *lapse rate* and the *dry-adiabatic rate* of cooling.

There are occasions when the lapse rate in certain layer of the atmosphere is found to be about 4.6° C per 1000 metres. Under this situation, when the *lapse rate* is less than the *wet adiabatic rate*, even at the point of condensation no vertical motions develop in the atmosphere. In this case the air is said to be ***absolute stable.*** Temperature inversion is a typical example of absolute stability. The inversion layer present in the atmosphere acts as a lid to the ascending currents of air. Just beneath the base of the inversion layer the upward rising smoke is forced to spread out in horizontal plane. In winter, it is common sight at about sunset near human settlements where

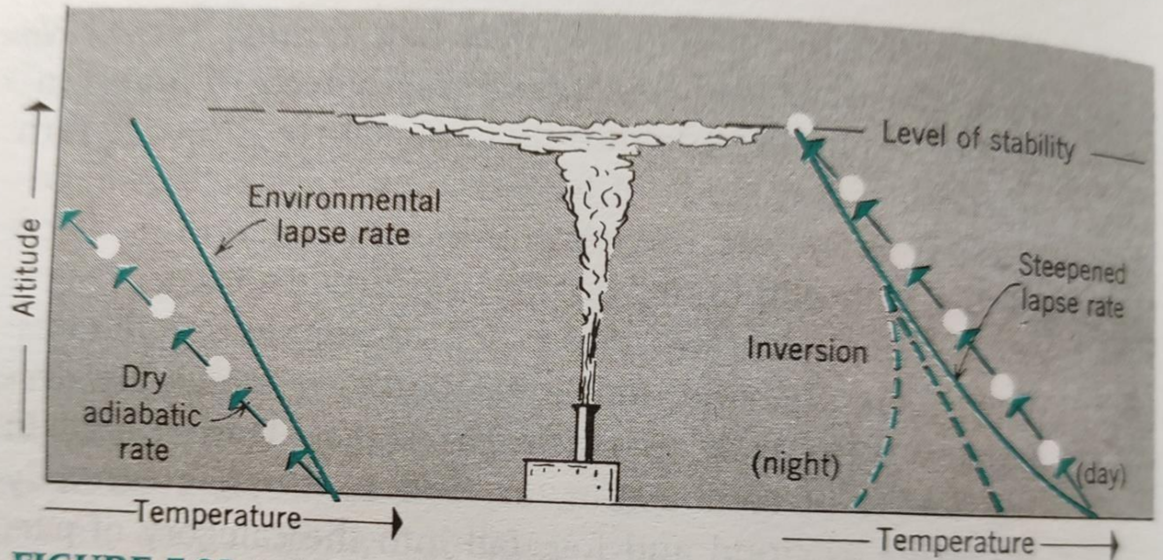


FIGURE 7.25 Relation of dry adiabatic lapse rate (circles) to various environmental lapse rates.

rising columns of smoke from domestic chimneys are not allowed to move upward beyond a certain level. This level is provided by the base of the inversion layer.

Absolute instability:

When the distribution of temperature is such that at every level the *environmental lapse rate* is greater than the *dry adiabatic lapse rate*, the displaced parcel of air has a tendency to continuously move upward till its temperature is equal to that of the surrounding air. Such a state of continued vertical movement of the ascending air is called **absolute instability**. When there is general *instability* in the atmosphere, an impulse, whatsoever, is needed to displace a given volume of air. Intense surface heating by the sun's rays or a physical barrier in the path of the air streams is such mechanism which initially produces the trigger-effect and forces the air to move upward. Under the conditions of *absolute instability*, the displaced air masses continue its ascent till a level is reached where the temperature difference between it and the surrounding air is reduced to zero.

Mechanical instability:

At times, there are abnormal situations when the *lapse rate* is too steep (35° C per 1000 metres [lapse rate lies between 4.6 °C/1000 metres to 35°C/1000 metres), and the upper layers of the atmosphere become far denser than the underlying layers. Under these special circumstances there is an automatic overturning of air without any initial impulse being applied to it. Such a situation is known as **mechanical instability**. This state of atmospheric equilibrium helps in the formation of **tornadoes**, the most violent revolving storms of very small size.

Conditional Instability:

The term 'conditional instability' refers to the state of a column of air when its vertical distribution of temperature is such that the layer is *stable* for dry air but *unstable* for saturated air. This occurs when moist air has a lapse rate between the *dry* and *wet adiabatic rates* (between 0.5° C and 1° C per 100 metres). For the first vertical ascend the ascending air parcel is cooler than the surrounding air and it is, therefore, considered stable. Since above the *condensation level* the *latent heat of condensation* is returned to the rising air, further cooling takes place at the *wet-adiabatic rate* which is less than the *environmental lapse rate*. However, the *lapse rate* being greater than the *wet adiabatic rate*, from the level of free convection upward the rising air parcel of air is warmer than the surrounding air. From this level along its ascent the parcel would continue to rise without any impulse and is considered *unstable*. Thus, the air that was initially *stable* is made *unstable* by forced ascent during *which latent heat of condensation* is added to it. A column of rising air may be *stable* and *unstable* at different elevations as a result of *condensation* after sufficient uplift and cooling. The word *conditional* is prefixed because only if the air is forced upward initially can it become unstable. *Conditional instability* is said to be most common type of *instability*.

In *conditional instability* the *lapse rate* is less than the *dry-adiabatic* and greater than the *moist-adiabatic lapse rates*. Besides, there are two most important prerequisites for this state of equilibrium:

i. the ascending air parcel should be moist or saturated and
ii. the air parcel should get a very strong initial uplift so that it would reach the condensation level under the impulse.

Conditional Instability:

Sometimes under special circumstances an air layer of several hundred metres thick with several thousand square kilometres areal extent is forced to rise. Such an extensive and thick layer of air may be moist in its lower part and dry in the upper part. Thus, an anomaly is produced in the vertical distribution of humidity. Such a type of uplift causes the air, which may be initially *stable*, to become *unstable* from the *adiabatic effect* on internal temperature-humidity conditions. Hence, it may be concluded that, in general, *saturation lifting* decreases the *stability* even more than does *unsaturated lifting*. The mechanism of *convective instability* is significant in the dynamics of weather conditions. When *convectively or conditionally unstable air masses*, in which the surface layers are humid and the moisture content decreases with height, are lifted,

there is heavy precipitation from *cumulonimbus type of clouds*. Besides, *convective instability* in the layers of the atmosphere is a contributory factor in the formation of violent storms like—

- tornadoes,
- thunderstorms and

- squalls etc.

Rossby made an extensive study of the various aspects of *convective instability*. According to him, this type of *instability* is produced in such layers of the atmosphere in which the equivalent potential temperature decreases with increasing altitude.

Stability, Lapse Rates and Altitude:

The following figure shows the relationship between atmospheric stability, various kinds of lapse

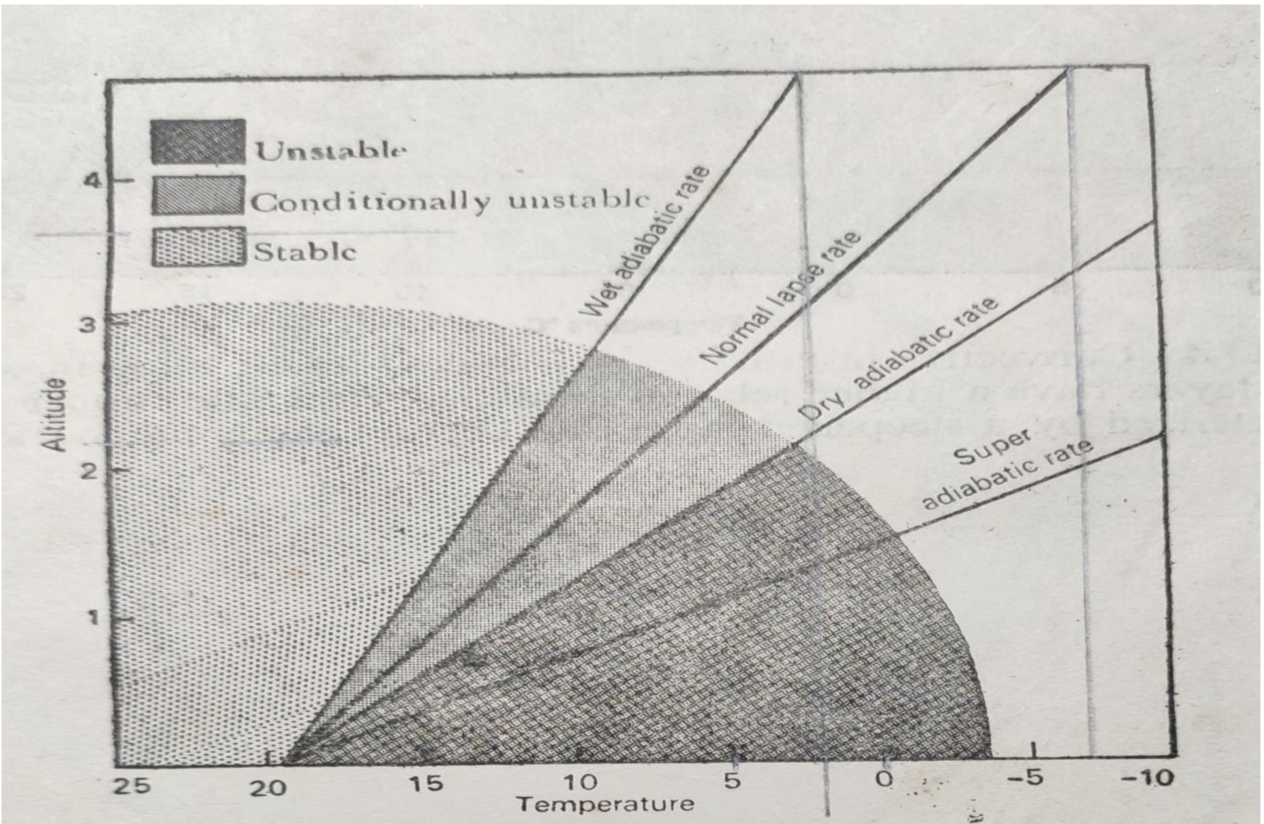


Fig. 13.5 Variation in the lapse rates and the degree of atmospheric stability.

rates and altitude. If the air parcel being displaced is not saturated, the criteria for stability, instability and neutrality may be as follows:

i. The column of air is said to be *stable* when its prevailing *lapse rate* is less than the *dry –adiabatic lapse rate*, i.e. when y<yd.
ii. The column of air is said to be *unstable* when its prevailing *lapse rate* is greater than the *dry –adiabatic lapse rate*, i.e. when y>yd.
iii. The column of air is said to be in *neutral equilibrium* when its prevailing *lapse rate* has the same value as the *dry –adiabatic lapse rate*, i.e. when y=yd.

iv. The column of air has *conditional instability* when its prevailing lapse rate lies between the values for the *dry-adiabatic* and *saturation adiabatic* (*wet-adiabatic*) *lapse rates,* i.e. when yd>y>ym.

when,

y=*prevailing lapse rate*

yd=*dry-adiabatic lapse rate,* and

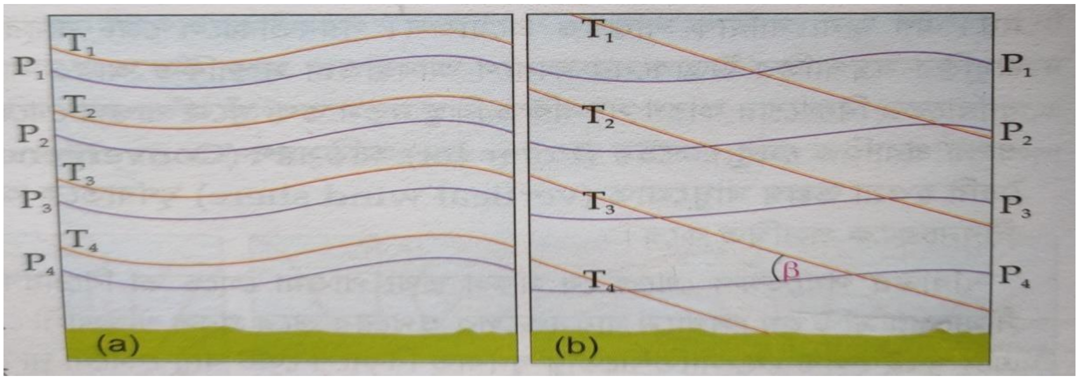
ym=*saturation adiabatic lapse rate*.

Barotropic and Baroclinic conditions:

The frontal theory of cyclones has proved useful in the prediction of the formation and movement of cyclonic storms. But this theory is not in conformity with a mathematical model for the origin and development of a wave cyclone on a sloping frontal surface. In other words, it has no mathematical foundation in explaining the initial stages of cyclone development.

Baroclinic Wave Theory is based on the fact that cyclones of the extratropical regions may form even without any pre-existing front between the polar and the tropical air masses. Further, it considers the cyclones and anticyclones as an integral part of the general atmospheric circulation. The most important feature of this theory is that it was evolved through the use of mathematical and numerical analysis of weather forecasting.

The **concept of baroclinicity denotes** the state of stratification in the atmosphere in which surfaces of constant pressure intersect surfaces of constant density (which depends mostly on temperature). **Barotrophy** on the other hand, is the state of stratification in the atmosphere in which surfaces of constant pressure and constant density are parallel.



T stands for equal temperature level P stands for equal pressure level

Barotropic condition **Baroclinic condition**

These conditions depict the atmospheric conditions which relate to the stability or instability. ‘Hydrodynamic stability’ is another term used to refer to this type of overall stability of the atmosphere in so far as the formation of cyclones is concerned.

According to the baroclinic theory, cyclones and anticyclones in the temperate region form as a result of the baroclinic instability. The potential energy in the zonal flow is converted into kinetic energy of the eddies. Baroclinicity in the atmosphere is represented by a frontal region.

In the troposphere, there is a continuous decrease in temperature from the equator towards the poles. The meridional temperature gradient goes on increasing and it makes the zonal flow unstable. At a certain stage the flow is broken down into a number of cyclonic and anticyclonic circulations.

It may be pointed out that the wind and temperature gradients aloft are different from those at the surface. We also know that the meandering jet stream produces ridges and troughs in the upper air flow. A ridge of high pressure draws warm air towards the pole. A trough of low pressure, on the other hand, allows cold air to move towards the equator. Thus, the wave flow of the upper westerlies provides an important mechanism for the growth of cyclonic storms which, in turn, redistribute energy. Transfer of heat that takes place across the temperate zone is affected by the cyclones and anticyclones. The existence of wave and eddies in the general flow pattern of the globe is essential for the maintenance of latitudinal heat balance. The wavy pattern aloft largely determines the pressure patterns at the surface.

According to the **baroclinic theory**, the north-south perturbations of wind velocity are accompanied by vertical velocities in ascending air currents of the warm and moist air, and descending air currents of the cold and dense air.

Rising air currents give rise to following currents of air from the adjoining regions. The converging air currents develop a cyclonic spin because of the effect of Coriolis force. As the air gets closer to the axis of rotation its rotational velocity increases. This is in conformity with the principle of the conservation of angular momentum. In the northern hemisphere, there is counter-clockwise circulation around the centre. As the cyclone develops in intensity, the ascent of air is more vigorous. This results in more and more in condensation and the release of latent heat. The continued intensification of the cyclone results in proportionate fall of pressure in the cyclone.

To summarise, this **baroclinic wave theory** was developed through the use of mathematical techniques. According to this theory, the north-south temperature gradient makes the upper air flow unstable. The air flow assumes a wavy flow which under special circumstances breaks into cyclones and anticyclones. Through these atmospheric disturbances, the greatest heat exchange in the mid-latitude region is made possible. Cyclones and anticyclones, according to this theory, are non-frontal in origin, and may be taken to be a part and parcel of the general circulation pattern.

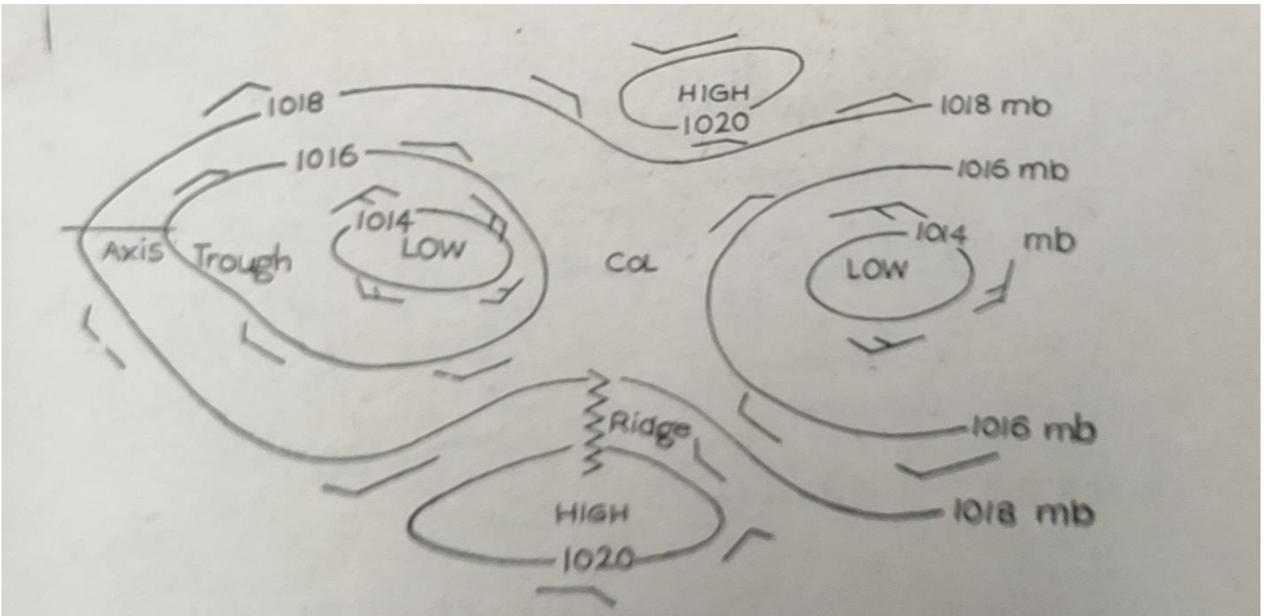


Fig. 4. Pressure and Wind systems.

An outward extension from a low is a ‘trough’ and that from a high is a ‘ridge or wedge’. The area between two highs and lows is a ‘col’.