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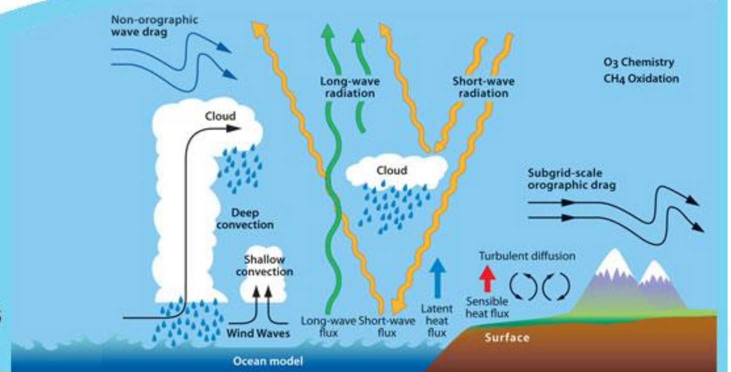

Paper No: 8 Atmospheric Processes

Module: 7 Lapse Rate and Atmospheric Stability

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Description of Module	
Subject Name	**Environmental Sciences**
Paper Name	Atmospheric Processes
Module Name/Title	**Lapse Rate and Atmospheric Stability**
Module Id	EVS/AP-VIII/7
Pre-requisites	
Objectives	• Differentiate lapse rate and atmospheric stability • Understand the origins of different types of lapse rate • Identify the mechanism for vertical displacement of air • Learn about the atmospheric stability process • Evaluate the importance of stabilizing and destabilizing influence • Learn about turbulent dispersion
Keywords	Adiabatic and diabatic processes, DALR, SALR, ELR, inversion, stable, unstable, neutral atmosphere

Module: 7 Lapse Rate and Atmospheric Stability

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1. *Learning outcomes*

After studying this module, you will be able to

- Differentiate lapse rate and atmospheric stability
- Understand the origins of different types of lapse rate
- Identify the mechanism for vertical displacement of air
- Learn about the atmospheric stability process
- Evaluate the importance of stabilizing and destabilizing influence
- Learn about turbulent dispersion

2. *Introduction*

The gaseous mantle covering the earth's surface known as air is constantly moving from one place to another depending upon changes in temperature, pressure and moisture. Atmospheric motion redistributes mass and constituents in a variety of complex configurations. Like any fluid system the atmosphere is governed by the laws of continuum mechanics and is capable of supporting a wide spectrum motions. Thus the movement of air in horizontal or vertical direction is in response to the earth rotation or pressure gradient. Transport of air in both upward and downward directions is generally governed by temperature and turbulence. The degree of stability or instability in the atmospheric system is influenced by these conditions. It is however known that air temperature decreases at higher altitude from the earth surface due to lower molecular activity of the constituent air. Relations between temperature, pressure and height could be established by the adiabatic processes prevailing at the atmospheric system having hydrostatic equilibrium.

2.1. *What is lapse rate ?*

Earth's atmosphere categorized by its thermal properties is reflected in the vertical profile of global mean temperature. As the unit parcel of air moves vertically upward from the surface either by the action of wind or turbulence there would be a constant fall in temperature with increasing height. **The fall in temperature will be 6.5 degrees Celsius for every 1000 m rise in altitude and is known as lapse rate**. The temperature lapse rate is always positive meaning as the altitude increases there is decrease in air temperature. The temperature driven lapse rate is extended up to 10 km that is troposphere beyond that there is a sharp change in the lapse rate. Depending upon the temperature and moisture content of the air there is also variation in the lapse rate.

2.2. Adiabatic process

Adiabatic process signifies warming of a parcel of air by compression or cooling by expansion without transfer of heat or mass into the system. The atmospheric system is continuously governed by both adiabatic and non-adiabatic processes. In the non-adiabatic process air near the ground surface is receiving and releasing heat in the form of short wave and long wave radiation. However above the ground surface in the free atmosphere the short period process is adiabatic. The upward lifting and downward descend of a parcel of air in the atmospheric system is influenced by this process. The adiabatic process is influenced by temperature differences and moisture content in the air parcel and is related to atmospheric lapse rate. Adiabatic behavior of individual air parcel is a good approximation for many atmospheric applications. This process of temperature change is operative only in those air masses which have vertical movement. It is the only process which is responsible for the formation of all kinds of clouds.

2.3. Diabatic process

In diabatic process there is a uniform exchange of heat of the air with the surrounding environment. This exchange of heat is responsible for lowering of temperature. Diabatic process occurs only in these air masses which is either stationary or have a horizontal movement. Diabatic process of temperature change leads to the formation of fog, dew or frost. Under diabatic conditions, air parcel interacts with its environment both thermally and mechanically. Its potential temperature is then no longer conserved. Instead potential temperature changes in proportion to the heat transferred into the parcel. Most of the energy exchanged between earth's surface and the atmosphere and between one atmospheric layer and another is accomplished through radiative transfer. In fact outside the boundary layer and cloud radiative transfer is the primary diabatic influence.

2.4. *Types of lapse rate*

Three types of lapse rate are

- Dry adiabatic lapse rate
- Saturated adiabatic lapse rate
- Environmental lapse rate

2.4.1. *Dry adiabatic lapse rate*

Upward movement of an unsaturated air parcel from its surroundings takes place when affected by temperature differences. As the air parcel rises upward it expands and there is a temperature decrease of 1 degree Celsius for every 100 m increase in altitude. This is known as dry adiabatic lapse rate. The variation in adiabatic lapse rate is dependent upon the variation in atmospheric temperature distribution. Dry adiabatic lapse rate also varies at different levels of the atmosphere. The lifting dry air parcel after attaining condensation changes to saturated lapse rate.

2.4.2. *Saturated adiabatic lapse rate*

The adiabatic description of saturated air parcel is related to the release of latent heat from condensation which is accompanied with transformation of water from one phase to another. Usually saturated lapse rate is smaller compare to dry adiabatic lapse rate. The saturated adiabatic lapse rate has a value of $\cong$ 5.5 degrees Celsius per 1000 m rise in altitude which is slightly smaller than the global- mean lapse rate of the troposphere. Dry adiabatic lapse rate or saturated adiabatic lapse rate is useful for determination of temperature of an air parcel as it rises or sinks in the atmosphere. The lifting condensation level is the altitude at which condensation begins. When it happens two opposite reaction takes place in the air simultaneously resulting cooling at a smaller rate than the dry adiabatic lapse rate.

2.4.3. *Environmental lapse rate*

Environmental lapse rate is related to normal change of air temperature as the air parcel moves upward at a given time and place. It is generally 6.5 degrees Celsius for every 1000 m rise in altitude.

Environmental lapse rate thus represents the ambient air temperature with increase in altitude. One can measure the normal change in air temperature with increasing or decreasing altitude through environmental lapse rate. Environmental lapse rate changes with seasons and regions.

3. Vertical displacement of air

The motions of the atmosphere are governed by the fundamental physical laws of conservation of mass, momentum and energy. Two forces are most important for influencing the atmospheric motion. They are body force and surface force. Body forces act on the centre of mass of a fluid parcel and they have magnitudes proportional to the mass of the parcel. While surface forces act across boundary surface separating a fluid parcel from its surroundings. Their magnitudes are independent of the mass of the fluid parcel. The motionless air which remains under hydrostatic equilibrium is subjected to vertical displacement by forced lifting. In elevated terrain such vertical displacement of air is introduced through buoyancy and is closely related to the stability of the atmospheric mass distribution. In the event of changes in thermodynamic state atmospheric mass distribution is determined by gravity. The vertical pressure gradient force of the atmosphere is then balanced by the gravity. A form of mechanical equilibrium is evolved in the atmospheric system which works accurately in spite of the presence of motion. The hydrostatic equilibrium is ineffective only inside the deep convective towers where vertical acceleration overcomes the gravitational acceleration. Thus vertical displacement of air which is controlled by thermodynamic state of the atmosphere refers to the stability of the atmospheric system. Vertical displacement is shown in Fig. 3.1.

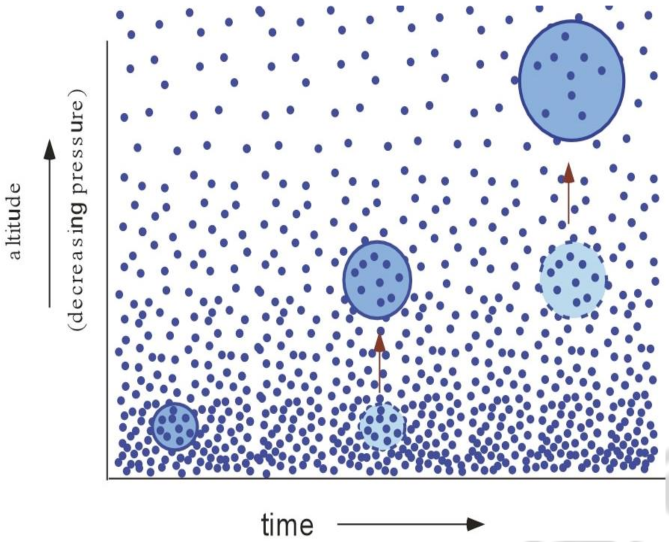


Fig. 3.1. Vertical displacement of parcel of air

4. Stability process

Stability refers the gravitational resistance of the air parcel to vertical displacement. It results from the fundamental buoyant adjustment and is determined by the vertical stratification of density or potential temperature. It also influences the dynamics of many kinds of atmospheric motions which in turn are responsible for determining variations. Static stability is commonly represented by the square of the buoyancy frequency which plays a role in theories for flow instabilities, wave propagation and forced motions. These theories apply to a wide range of spatial scales. The stability of a layer determined its ability to support vertical motion and transfer of heat, momentum and constituents. To conserve mass vertical motion must be compensated by horizontal motion. Hydrostatic stability therefore also influences horizontal transport. The three dimensional turbulence which disperses atmospheric constituents also involves both horizontal and vertical motions. Consequently suppressing vertical motion simultaneously suppresses the horizontal component of three dimensional eddy motion and hence turbulent dispersion. A layer that is stably stratified inhibits vertical motion while a layer that is unstably stratified promotes vertical motion through the negative restoring force of buoyancy. The buoyancy factors under stable and unstable conditions reflect a conversion between potential and kinetic energy.

4.1. *Stable atmosphere*

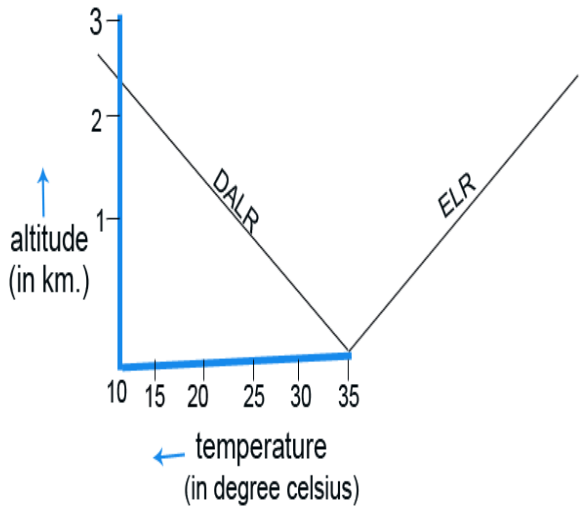
The atmosphere has a tendency to resist vertical motion and this is known as stability. Normal flow of air in the atmosphere is to be horizontal. When this flow is disturbed, a stable atmosphere tries to resist any upward or downward displacement and tends to return quickly to its horizontal flow. The degree of stability of an atmospheric layer is determined by comparing its temperature lapse rate with the appropriate adiabatic rate. A temperature lapse rate less than the dry-adiabatic lapse rate for an unsaturated air parcel is considered stable because vertical motion is damped. The stability of the atmosphere is dependent upon the temperature of an air parcel and the temperature of the environment which is expressed as **DALR > ELR** or **TAP < TSA.**

Where, DALR = Dry adiabatic lapse rate, ELR = Environmental lapse rate, TAP = Temperature of the air parcel (DALR), TSA = Temperature of the surrounding air (ELR). Fig. 4.1. shows the condition for absolute stability in atmosphere.

Atmospheric stability can be observed around industrial areas when the emissions from the stack are cooler than the surrounding air. The tendency will be for the emission to resist an upward movement and to move horizontally along the stack opening. Fig. 4.2 shows the stable, unstable and neutral condition of the atmosphere.

4.2. *Unstable atmosphere: DALR < ELR*

The atmosphere is unstable when a parcel of air starting at equilibrium is displaced slightly upward relative to its surrounding environment. The air parcel finds itself warmer than its environment at its new altitude and therefore continues to see spontaneously away from its starting point. Thus the degree of stability or instability of an atmospheric layer is determined by comparing its temperature lapse rate with the appropriate adiabatic rate. Lapse rate greater than dry-adiabatic favours vertical motion of the air parcel and is known as unstable atmosphere. The unstable air parcel tends to adjust itself through mixing and overturning to a more stable condition. Super-adiabatic lapse are not ordinarily found in the atmosphere except near the surface of the earth on clear sunny days. When an unsaturated layer of air is mixed thoroughly its lapse rate tends towards neutral stability. Fig. 4.3 shows the comparison with the measured lapse rate (solid black lines) and dry-adiabatic lapse rate (dashed black lines). The reaction of lifting or lowering of air parcel is shown by red arrows with respect to the temperature of its environment.



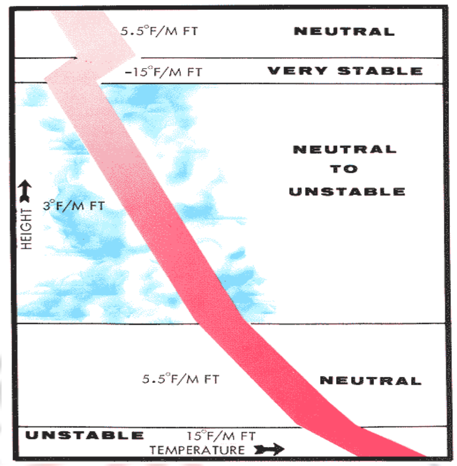


Fig. 4.1. Condition for absolute stability: (ELR = DALR)

Fig. 4.2. Condition of stability and instability in the atmosphere

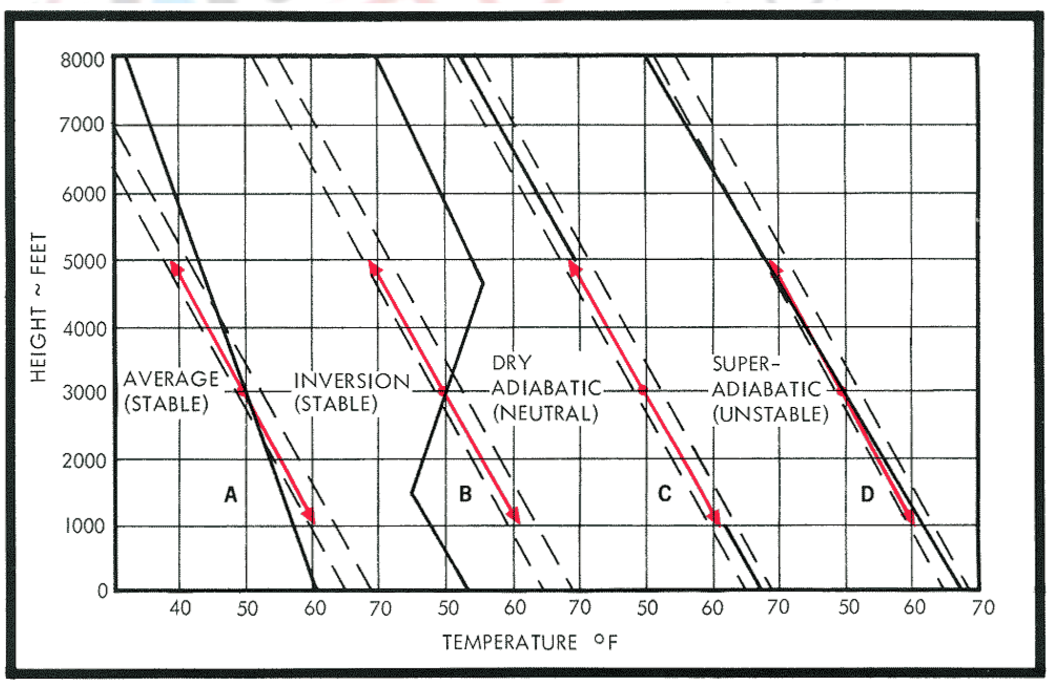


Fig. 4.3. Relationship between stability and instability in the atmospheric system

4.2.1. *Conditionally unstable atmosphere*

The atmosphere which has a lapse rate lying between dry and moist adiabats is said to be conditionally unstable. It is stable with respect to a lifted air parcel as long as the parcel remains unsaturated but it is unstable with respect to a lifted parcel that has become saturated. Fig. 4.4 shows the condition of conditionally unstable atmosphere.

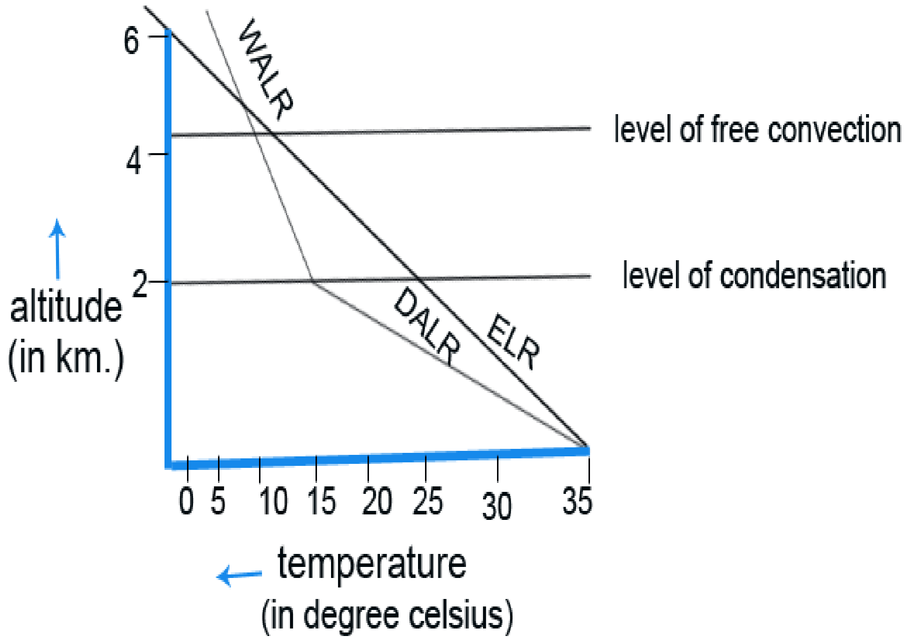


Fig. 4.4. Conditionally unstable atmosphere

4.3. *Neutral atmosphere*

In the absence of saturation, an atmospheric layer is neutrally stable if its lapse rate is the same as the dry adiabatic lapse rate. Under this particular condition, any existing vertical motion is neither damped nor accelerated. In neutrally stable atmospheric condition temperature structure is not static. It is continually changing. Any warming of the lower portion or cooling of the upper portion of a naturally stable layer to become unstable and it will then not only permit but also assist vertical motion.

4.4. *Diurnal and Seasonal Variations in Stability*

Stability frequently varies through a wide range in different layers of the atmosphere for various reasons. Layering aloft may be due to an air mass of certain source region characteristics moving above or below another air mass with a different temperature structure. The inflow of warmer air at the bottom or colder air at the top of an air mass promotes instability, while the inflow of warmer air at the top or colder air at the surface has a stabilizing effect. **Diurnal changes** in surface heating and cooling produce daily changes in stability. The amount of solar radiation received at the surface during the summer is considerably greater than in winter. Temperature profiles and stability reflect **seasonal variation** in atmospheric stability.

5. *Stabilizing and Destablizing Influences*

The stability of the atmospheric system is modified by internal motion that rearranges air. However the overall stability of the atmosphere is external heat transfer which shapes the thermal structure. The vertical distribution of temperature provides insight into how stability is established and it reflects the effective stratification of mass. The stability of the atmospheric system imply that a layer is destabilized by heating from below and cooling from aloft. These are the influences exerted on the troposphere by exchanges of energy with the earth surface and deep space. Fig. 5.1 shows the processes of stabilizing and destabilizing influences.

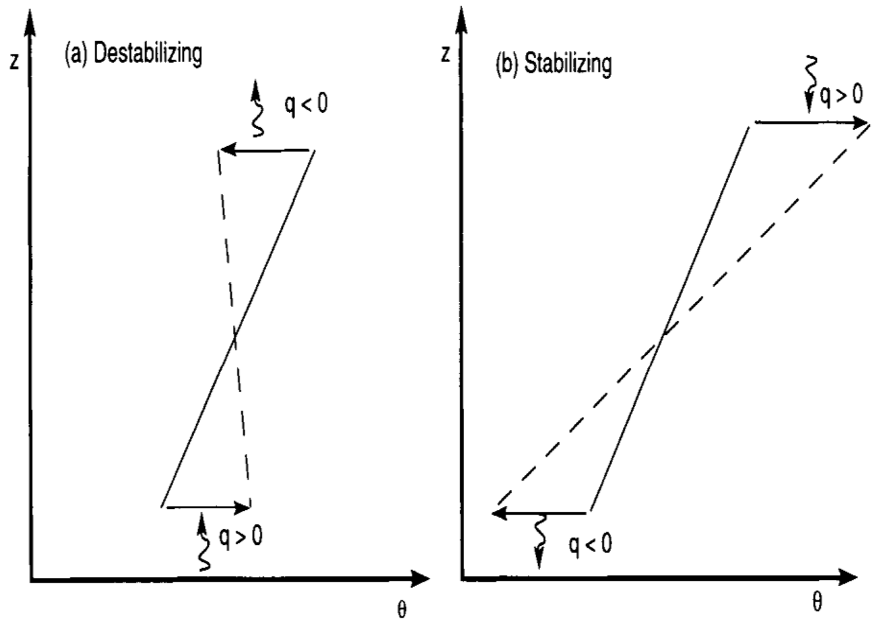


Fig. 5.1. (a) Destabilizing influences heating from below and cooling from above (b) Stabilizing influences heating from above and cooling from below (q = potential temperature, z = height, θ = temperature)

The stability of a layer determines its ability to support vertical motion. It also supports transfer of heat, momentum and constituents. To conserve mass, vertical motion must be compensated by horizontal motion. Hydrostatic stability therefore influences horizontal transport. Three-dimensional turbulence, which disperses atmospheric constituents, involves both vertical and horizontal motion. Consequently supressing vertical motion simultaneously supresses the horizontal component of three-dimensional eddy motion and hence turbulent dispersion.

6.1. Convection

Vertical stability controls the development of vertical motion and hence mixing by three-dimensional turbulence. Regions of weak or negative stability favours convective overturning, which results in efficient mixing of air. This situation is common near the ground surface because absorption of SW radiation destabilizes the surface layer. Introducing moisture from below has a similar effect. By increasing the equivalent potential temperature of surface air, it makes the overlying layer potentially unstable. When conditions are favourable small disturbances evolve into a fully developed convection. Fig. 6.1 shows the condition for convection. Cumulas convection is favoured in tropical troposphere by high sea surface temperature and strong insolation. These are responsible for large transfer of radiative, latent and sensible heat from the earth's surface which destabilizes the troposphere. Opposing these destabilizing influence is the cumulus convection.Reinforced by the release of latent heat, it maintains much of the tropical troposphere to neutral stability.

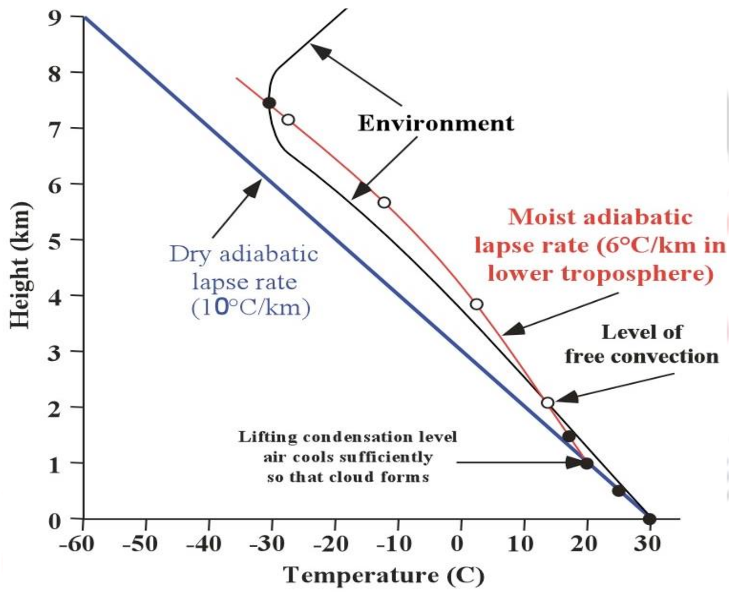


Fig. 6.1. Condition for convection

6.2. Inversion

Inversion describe the atmospheric conditions when the temperature increase with altitude rather than decreases. Inversions result from the selective absorption of earth's radiation by the water vapour in the air, and also from the sinking of air which results in its compression and heating. When air is subsiding the compressed air heats adiabatically, causing the air parcel to become warmer than surface air below it. Rising currents of cool air lose their buoyancy and are thereby inhibited from rising further when they reach the warmer, less dense air in the upper layers of the temperature inversion.

6.3. *Nocturnal Inversion*

Heat transfer from the earth's surface and convection compete for control of stratification. Their competetion is illustrated by the formation and breakup of the nocturnal inversion, strong stability near the surface that often develops at night. Arid and cloud free condition permit efficient LW cooling to space. Surface temperature then decreases sharply after sunset. To preserve thermal equilibrium, heat is absorbed radiatively and conductively from the overlying air. This process cools the surface layer from

below, stabilizing it. Strongly stable, the nocturnal inversion supresses vertical motion. It also supresses three-dimensional turbulence, which requires vertical eddy motion.

7. *Summary*

- Lapse rate is the change of temperature with increase in altitude.
- Adiabatic process is any process occurring without the gain or loss of heat within the system.
- Diabatic process occurs in those air masses which are stationary or have horizontal motion.
- A constant rate of cooling of the air parcel is referred to as the dry adiabatic lapse rate, while the rate of cooling beyond the condensation level is known as adiabatic lapse rate.
- Environmental lapse is the ambient air temperature with increase in height and varies with seasons and regions.
- Dry adiabatic lapse rate is neither dependent on the initial moisture present in the air parcel nor on the initial temperature of the air.
- Wet adiabatic lapse rate is less than the dry adiabatic lapse rate.
- Static stability measures the gravitational force of an air parcel to vertical displacement. Stationary air parcel is characterized by stability while rising air parcel is characterized by instability.
- Regions of weak or negative stability favours convective overturning. Thermal inversion occurs when layer of warm air settles over a layer of cooler air that lies near the ground.
- Thermal inversion is quite significant during winter season.
