Lesson 4

Vertical Motion and Atmospheric Stability

This lesson describes the vertical structure of the atmosphere, atmospheric stability and the corresponding vertical motion. Adiabatic diagrams are introduced to help explain atmospheric conditions affecting pollutant dispersion.

Goal

To familiarize you with the vertical temperature structure of the atmosphere and to introduce its relationship to plume dispersion.

Objectives

Upon completing this lesson, you will be able to do the following:

1. Explain the concept of buoyancy
2. Define *lapse rate* and distinguish between dry adiabatic, wet adiabatic, and environmental lapse rates
3. Describe stable, unstable and neutral conditions
4. Given an adiabatic diagram, identify the atmospheric stability category represented
5. Describe how atmospheric stability and inversions affect air pollutant dispersion
6. Describe how four different types of inversions form
7. List five types of plume behavior and relate each to atmospheric conditions

Introduction

The previous lesson discusses horizontal motion of the atmosphere. Vertical motion is equally important in air pollution meteorology, for the degree of vertical motion helps to determine how much air is available for pollutant dispersal. Vertical motions can be attributed to high and low pressure systems, air lifting over terrain or fronts and convection. There are a number of basic principles related to vertical motion that you must be familiar with before you can understand the mechanics and conditions of vertical motion. These principles are presented first and are followed by discussions of instability, stability, and plume behavior. Inversion, where the temperature of the air increases with height, is also discussed.

Principles Related to Vertical Motion

Parcel

Throughout this lesson we will be discussing a *parcel* of air. This theoretically infinitesimal parcel is a relatively well-defined body of air (a constant number of molecules) that acts as a whole. Self-contained, it does not readily mix with the surrounding air. The exchange of heat between the parcel and its surroundings is minimal, and the temperature within the parcel is generally uniform. The air inside a balloon is an analogy for an air parcel.

Buoyancy Factors

Atmospheric temperature and pressure influence the buoyancy of air parcels. Holding other conditions constant, the temperature of air (a fluid) increases as atmospheric pressure increases, and conversely decreases as pressure decreases. With respect to the atmosphere, where air pressure decreases with rising altitude, the normal temperature profile of the troposphere is one where temperature decreases with height.

An air parcel that becomes warmer than the surrounding air (for example, by heat radiating from the earth's surface), begins to expand and cool. As long as the parcel's temperature is greater that the surrounding air, the parcel is less dense than the cooler surrounding air. Therefore, it rises, or is buoyant. As the parcel rises, it expands thereby decreasing its pressure and, therefore, its temperature decreases as well. The initial cooling of an air parcel has the opposite effect. In short, warm air rises and cools, while cool air descends and warms.

The extent to which an air parcel rises or falls depends on the relationship of its temperature to that of the surrounding air. As long as the parcel's temperature is greater, it will rise; as long as the parcel's temperature is cooler, it will descend. When the temperatures of the parcel and the surrounding air are the same, the parcel will neither rise nor descend unless influenced by wind flow.

Lapse Rates

The **lapse rate** is defined as the rate at which air temperature changes with height. The actual lapse rate in the atmosphere is approximately –6 to –7°C per km (in the troposphere) but it varies widely depending on location and time of day. We define a temperature *decrease* with height as a negative lapse rate and a temperature *increase* with height as a positive lapse rate.

How the atmosphere behaves when air is displaced vertically is a function of atmospheric stability. A stable atmosphere resists vertical motion; air that is displaced vertically in a stable atmosphere tends to return to its original position. This atmospheric characteristic determines the ability of the atmosphere to disperse pollutants emitted into it. To understand atmospheric stability and the role it plays in pollution dispersion, it is important to understand the mechanics of the atmosphere as they relate to vertical atmospheric motion.

Dry Adiabatic

For the most part, a parcel of air does not exchange heat across its boundaries. Therefore, an air parcel that is warmer than the surrounding air does not transfer heat to the atmosphere. Any temperature changes that occur within the parcel are caused by increases or decreases of molecular activity within the parcel. Such changes, occur adiabatically, and are due only to the change in atmospheric pressure as a parcel moves vertically. An adiabatic process is one in which there is no transfer of heat or mass across the boundaries of the air parcel. In an adiabatic process, compression results in heating and expansion results in cooling. A dry air parcel rising in the atmosphere cools at the dry adiabatic rate of 9.8°C/1000m and has a lapse rate of –9.8°C/1000m. Likewise, a dry air parcel sinking in the atmosphere heats up at the dry adiabatic rate of 9.8°C/1000m and has a lapse rate of 9.8°C/1000m. Air is considered dry, in this context, as long as any water in it remains in a gaseous state.

The dry adiabatic lapse rate is a fixed rate, entirely independent of ambient air temperature. A parcel of dry air moving upward in the atmosphere, then, will always cool at the rate of 9.8°C/1000 m, regardless of its initial temperature or the temperature of the surrounding air. You will see later that the dry adiabatic lapse rate is central to the definition of atmospheric stability.

A simple adiabatic diagram demonstrates the relationship between elevation and temperature. The dry adiabatic lapse rate is indicated by a broken line, as shown in Figure 4-1, beginning at various temperatures along the horizontal axis. Remember that the slope of the line remains constant, regardless of its initial temperature on the diagram.

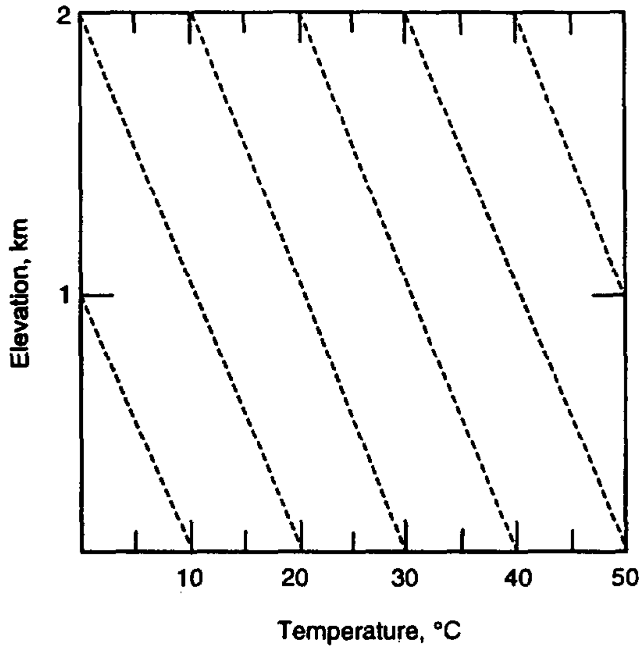

Figure 4-1. Dry adiabatic lapse rate

Wet Adiabatic

A rising parcel of dry air containing water vapor will continue to cool at the dry adiabatic lapse rate until it reaches its condensation temperature, or dew point. At this point the pressure of the water vapor equals the saturation vapor pressure of the air, and some of the water vapor begins to condense. Condensation releases latent heat in the parcel, and thus the cooling rate of the parcel slows. This new rate, called the **wet adiabatic lapse rate**, is shown in Figure 4-2. Unlike the dry adiabatic lapse rate, the wet adiabatic lapse rate is not constant but depends on temperature and pressure. In the middle troposphere, however, it is assumed to be approximately –6 to –7°C/1000 m.

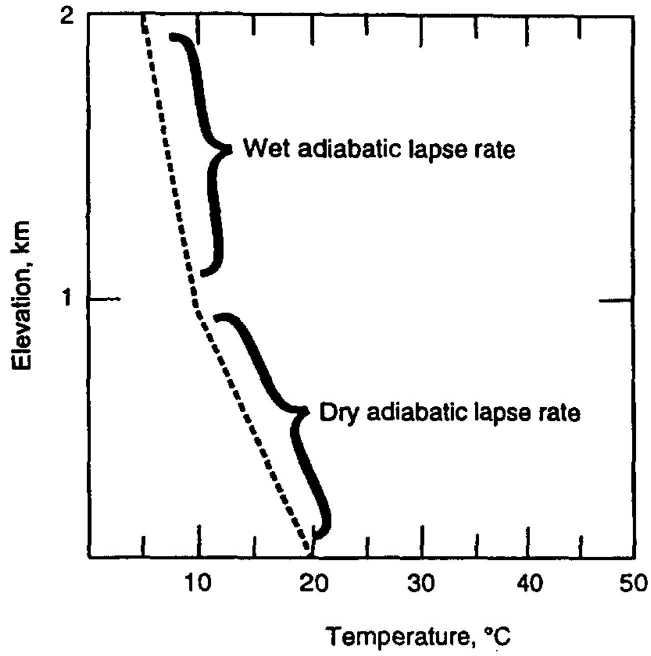

Figure 4-2. Wet adiabatic lapse rate

Environmental

As mentioned previously, the actual temperature profile of the ambient air shows the **environmental lapse rate.** Sometimes called the **prevailing** or **atmospheric lapse rate**, it is the result of complex interactions of meteorological factors, and is usually considered to be a decrease in temperature with height. It is particularly important to vertical motion since surrounding air temperature determines the extent to which a parcel of air rises or falls. As Figure 4-3 shows, the temperature profile can vary considerably with altitude, sometimes changing at a rate greater than the dry adiabatic lapse rate and some times changing less. The condition when temperature actually increases with altitude is referred to as a **temperature inversion.** In Figure 4-4, the temperature inversion occurs at elevations of from 200 to 350 m. This situation is particularly important in air pollution, because it limits vertical air motion.

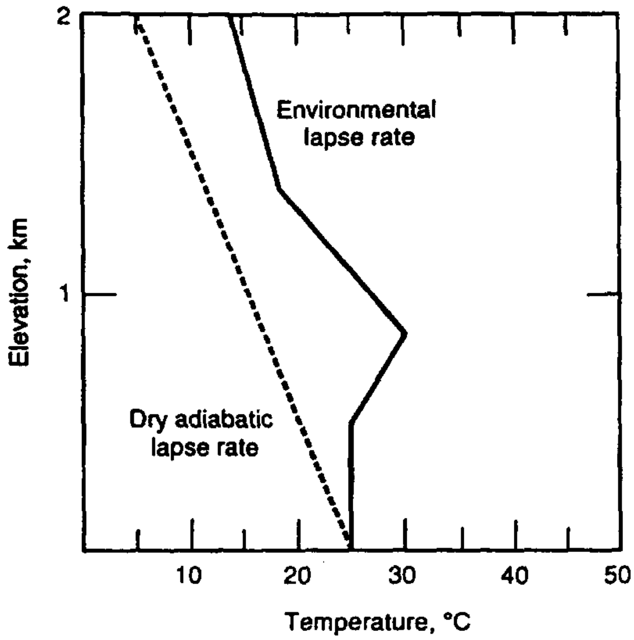

Figure 4-3. Environmental lapse rate

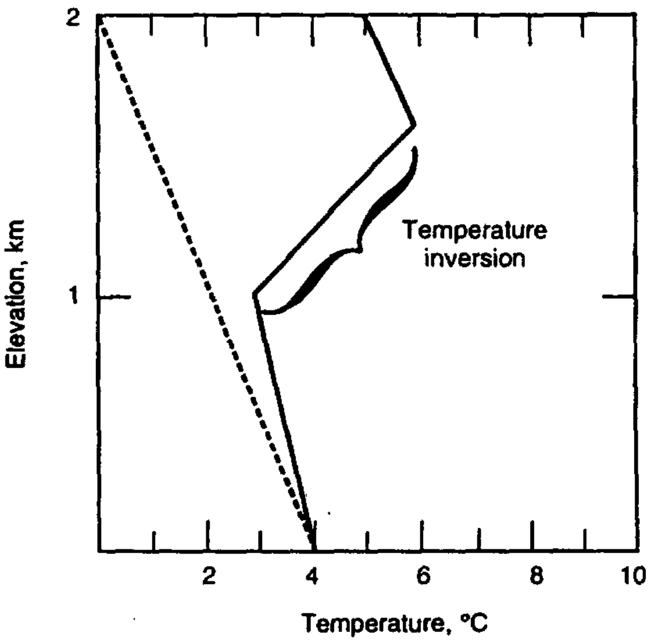

Figure 4-4. Temperature inversion

Mixing Height

Remember the analogy of the air parcel as a balloon. Figure 4-5 shows three ways in which the adiabatic lapse rate affects buoyancy. In each situation assume that the balloon is filled at ground level with air at 20°C, then lifted manually to a height of 1 km (for example, lifted by the wind over a mountain ridge). The air in the balloon will expand and cool to about 10°C. Whether the balloon rises or falls upon release depends on the surrounding air temperature and density. In situation "A," the balloon will rise because it remains warmer and less dense than the surrounding air. In situation "B," it will sink because it is cooler and more dense. In situation "C," however, it will not move at all, because the surrounding air is the same temperature and density.

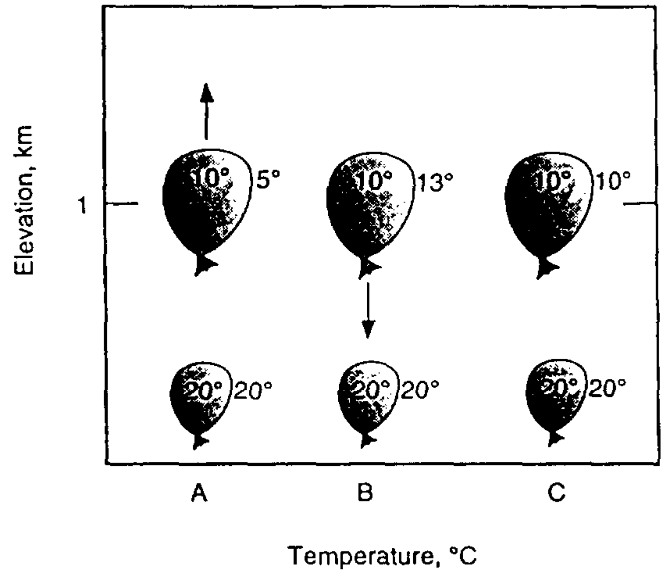

Figure 4-5. Relationship of adiabatic lapse rate to air temperature

The same principles apply in real atmospheric conditions when an air parcel is heated near the surface and rises, and a cool parcel descends to take its place. The relationship of the adiabatic lapse rate and the environmental lapse rate should now be apparent. The latter controls the extent to which a parcel of air can rise or descend.

In an adiabatic diagram, as shown in Figure 4-6, the point at which the air parcel cooling at the dry adiabatic lapse rate intersects the ambient temperature profile "line" is known as the **mixing height**. This is the air parcel's maximum level of ascendance. In cases where no intersection occurs (when the environmental lapse rate is consistently greater than the adiabatic lapse rate), the mixing height may extend to great heights in the atmosphere. The air below the mixing height is the **mixing layer**. The deeper the mixing layer, the greater the volume of air into which pollutants can be dispersed.