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Adiabatic Lapse Rates and Atmospheric Stability

Learning Goals

After studying this chapter, students should be able to:

1. describe adiabatic processes as they apply to the atmosphere (p. 174);
2. apply thermodynamic diagrams to follow the change of state in rising or sinking air parcels, and to assess atmospheric stability (pp. 179–189); and
3. distinguish between the various atmospheric stability types, and describe their causes and consequences (pp. 189–203).

Summary

1. An **adiabatic process** is a thermodynamic process in which temperature changes occur without the addition or removal of heat. Adiabatic processes are very common in the atmosphere; rising

air cools because it expands, and sinking air warms because it is compressed. The rate of change of temperature in unsaturated rising or sinking air parcels is known as the **dry adiabatic lapse rate** (**DALR**). This rate is equal to 10°C/km. When rising air parcels are saturated, they cool at a slower rate because of the release of latent heat. Unlike the DALR, the **saturated adiabatic lapse rate** (**SALR**) is not constant, but we often use 6°C/km as an average value.

2. **Potential temperature** is the temperature an air parcel would have if it were brought to a pressure of 100 kPa. Potential temperature remains constant for vertical motions.
3. The **lifting condensation level** (LCL) is the height at which an air parcel wising from the surface will begin to condense. The LCL depends on the surface temperature and dew-point temperature.
4. The **environmental lapse rate** (**ELR**) is the rate of change of temperature with height. It is measured by a radiosonde as part of an atmospheric sounding.
5. We can use **thermodynamic diagrams** to trace the paths of air parcels moving through the atmosphere. These diagrams allow us to follow changes in the temperature and dew-point temperature of air parcels, determine the height of the LCL and the LFC, predict the amount of liquid water in clouds, and assess atmospheric stability.
6. The environmental lapse rate (ELR) of an air layer determines the stability of that air layer. In an **absolutely unstable** layer, the ELR is greater than the DALR, and vertical motions are favoured. In an **absolutely stable** layer, the ELR is less than the SALR, and vertical motions are suppressed. We can use potential temperature to describe the stability of unsaturated air: if potential temperature increases with height, the air is stable; if potential temperature decreases with height, the air is unstable; and if potential temperature is constant with height, the air is neutral.
7. If the ELF falls between the DALR and the SALR, the atmosphere is **conditionally unstable**. In this sort of atmosphere, unsaturated air is stable, but saturated air is unstable. This is because if air is forced to the LCL, it will begin to cool more slowly and, if it is forced further, will eventually be warmer than the surroundings. At this point, known as the level of free convection (LFC), the air can rise on its own.
8. Any processes that cause the temperature to decrease more rapidly with height will make an air layer more unstable. These processes include any mechanisms that will warm the air near the surface or cool the air aloft. In addition, an air layer can be destabilized by lifting because the top will cool more than the bottom will cool. This is particularly true for air layers that contain more moisture at the bottom than they do at the top. The potential instability of such an air layer is called **convective instability**.
9. Any processes that cause the temperature to decrease less rapidly with height, or produce an **inversion**, will make an air layer more stable. These processes include any mechanisms that will cool the air near the surface or warm the air aloft. In addition, an air layer can become more stable by sinking because the top will warm more than the bottom will warm. The formation of inversions will make the air strongly stable. Surface radiative cooling can produce radiation inversions overnight. Upper-air inversions can form at fronts as warm air rides up and over cold air, or they can form as air sinks in regions of high pressure.
10. Under warm and clear conditions, the lowest 1 or 2 km of the atmosphere acts as an unstable layer by day. The lowest 100 m or so of this layer is characterized by an ELR that is greater than the DALR. Above that is the **mixed layer**, where the ELR is equal to the DALR. This layer is capped by an inversion. On clear, calm nights, a surface inversion forms that prevents air from rising from the surface. As a result, mixing stops, and the mixed layer becomes a residual layer.

Key Terms

Absolutely stable The state in which an air layer is stable for saturated and unsaturated air parcels; this occurs when the ELR is less than the SALR. (p. 192)

Absolutely unstable The state in which an air layer is unstable for saturated and unsaturated air parcels; this occurs when the ELR is greater than the DALR. (p. 192)

Atmospheric stability A measure of the tendency for a parcel of air, once disturbed, to move vertically in the atmosphere due to temperature differences. (p. 174)

Chinook The Canadian name for a warm, dry wind that blows down the leeward side of a mountain range. (p. 183)

Conditionally unstable The state in which an air layer is unstable on the condition that it becomes saturated; this occurs when the ELR is greater than the SALR but less than the DALR. (p. 192)

Convectively unstable The condition of an air layer in which the lower air is moist and the upper air is dry, so that the layer has the potential to become unstable if it is lifted. (p. 197)

Cumuliform cloud Cloud that is heaped in form and often exhibits strong vertical development. (p. 195)

Dry adiabatic lapse rate (DALR) The rate of change of temperature of a rising or sinking unsaturated air parcel. (p. 174)

Environmental lapse rate (ELR) The change in temperature with height in the atmosphere. (p. 179)

Frontal inversion An upper-air inversion that forms at a front because warm air rides over colder air. (p. 199)

Isentropes Lines of constant potential temperature or entropy. (p. 181)

Isohumes Lines of constant atmospheric moisture. (p. 179)

Isotherms Lines of constant temperature. (p. 179)

Level of free convection (LFC) The height at which air can rise due to its own buoyancy. (p. 194)

Lifting condensation level The height at which a rising parcel of air will reach its dew-point temperature and the water vapour it contains will begin to condense. (p. 178)

Mixed layer A turbulent air layer that extends from near the surface to an upper-air inversion; the temperature lapse rate through most of this layer is close to the DALR. (p. 202)

Neutral stability The condition of an air layer in which the ELR is equal to the DALR when the air is dry or to the SALR when the air is saturated, so that an air parcel that is displaced will be the same temperature as the surrounding air. (p. 201)

Potential temperature The temperature an unsaturated air parcel would have if brought adiabatically to a pressure of 100 kPa. (p. 175)

Radiation inversion A surface-based inversion that forms as air near the surface cools by emitting more radiation than it is absorbing. (p. 198)

Saturated adiabatic lapse rate (SALR) The rate of change of temperature of a rising or sinking saturated air parcel. (p. 177)

Stratiform cloud Cloud that is layered in form. (p. 197)

Subsidence inversion An upper-air inversion that commonly forms in the subsiding air of a high-pressure area, as air sinks from above and warms. (p. 199)

Tephigram The thermodynamic diagram used in Canada. (p. 179)

Thermodynamic diagrams Graphs that can be used to show the change in the state of the atmosphere with height and to determine the changing state of rising or sinking air parcels. (p. 174)

Wet-bulb potential temperature The wet-bulb temperature that an air parcel would have if brought adiabatically back to 100 kPa. (p. 181)

Key Equations

Potential temperature

$$\theta = T\left(\frac{100}{P}\right)^{\frac{R_d}{c_p}}$$

Answers to Selected Review Questions (p. 204)

1. **Why does an air parcel cool as it rises and warm as it sinks? Why does saturated air cool more slowly than unsaturated air?**

   As a rising air parcel expands, it performs work on its surroundings, causing it to cool. As a sinking air parcel is compressed, the surroundings are performing work on it, causing it to warm. Saturated air cools more slowly than unsaturated air because as the water vapour in the saturated parcel condenses, it will release latent heat.

3. **If an unsaturated air parcel rises adiabatically, how will temperature, vapour pressure, relative humidity, dew-point temperature, absolute humidity, mixing ratio, and potential temperature be affected? Will these properties increase, decrease, or stay constant? How will the same properties be affected if a saturated air parcel rises adiabatically? (You may want to draw a chart to compare your answers for the unsaturated parcel to those for the saturated parcel.)**

	Temp.	**Vapour Pressure**	**Relative Humidity**	**Dew-point Temp.**	**Absolute Humidity**	**Mixing Ratio**	**Potential Temp.**
Unsaturated	decrease	decrease	increase	decrease	constant	constant	constant
Saturated	decrease	decrease	constant	decrease	decrease	decrease	constant

5. **How can we use potential temperature to distinguish between stability types?**

   If the potential temperature decreases with height, the air layer is unstable. If the potential temperature increases with height, the air layer is stable. If the potential temperature is constant with height, the air layer is neutral.

7. **How are stable atmospheric conditions different from unstable atmospheric conditions?**

   Unstable conditions occur when temperature decreases rapidly with height in the atmosphere. This leads to a well-mixed, turbulent atmosphere. Rising air forms cumuliform clouds, winds are gusty, and pollutants are easily dispersed. Stable conditions occur when temperature decreases very gradually with height or increases with height in the atmosphere. This inhibits thermal turbulence. Stratiform clouds form in stable conditions, winds are usually light, and pollutants are not easily dispersed.

9. **How can winds and cloud cover influence stability?**

   Winds and cloud cover can lead to neutral stability. Winds cause mixing which can produce an ELR that is the same as the DALR. With overcast skies, the surface will not be strongly cooled or heated. Strong stability or instability will not develop when it is windy or overcast.

Answers to Selected Problems (p. 205)

1. **Calculate the potential temperature in each case. Check your answer using the blank emagram in Figure 8.5. (You may want to scan or photocopy the emagram so that you can mark the points on the graph.)**
   a) T = 21°C, P = 94 kPa
   b) T = 0°C, P = 76 kPa

a) $$\theta = T\left(\frac{100}{P}\right)^{\frac{Rd}{Cp}}$$

$$= 294\left(\frac{100\,\text{kPa}}{94\,\text{kPa}}\right)^{0.286}$$

$$= 299.2\ \text{K}$$

$$= 26.2°\text{C}$$

b) $\theta = T\left(\frac{100}{P}\right)^{\frac{Rd}{Cp}}$

$= 273\left(\frac{100\,\text{kPa}}{76\,\text{kPa}}\right)^{0.286}$

$= 295.3$ K

$= 22.3$°C

3. **Use Equation 8.5 to calculate the LCL for the air parcel in examples 8.6 and 8.7. Use the height scale on the thermodynamic diagram used in these examples to compare your answer to that determined in Example 8.7.**

$(z_{LCL}) = 125\ (T - T_d)$

$= 125\ (25 - 15)$

$= 1250$ m

5. **At 88 kPa, the temperature is 9°C and the dew-point temperature is −1°C. Use the thermodynamic diagram in Figure 8.5 to answer the following questions.**
   - **a) If this air rises to 80 kPa, what will be its temperature, dew-point temperature, and relative humidity?**
   - **b) What is the LCL for this air? What are the temperature and dew-point temperature at the LCL? Check these values by calculating them.**
   - **c) What is the wet-bulb temperature at 88 kPa?**
   - **d) If this air continues to rise to 55 kPa, what will be its temperature, dew-point temperature, and liquid water content?**
   - **e) If 1 g/kg of water falls as precipitation and the air then descends, what will be the temperature and dew-point temperature at 90 kPa? What will be the relative humidity?**
   - **f) If all the water had precipitated out, what would be the temperature and dew-point temperature in e)?**

a) $T = 0.5$°C

$T_d = -2.5$°C

$RH = \left(\frac{r}{r_s}\right) \times 100\%$

$RH = \left(\frac{4\,g/kg}{5\,g/kg}\right) \times 100\%$

$RH = 80\%$

b) LCL = 76 kPa

$T = T_d = -3°C$

c) $T_w = 4.5°C$

d) $T = T_d = -19°C$

$r_{L =}\ r_T - r_s$

$r_L = 4\ g/kg - 1.5\ g/kg$

$r_L = 2.5\ g/kg$

e) The air now contains 1.5 g/kg of vapour and 1.5 g/kg of liquid water.

$T = 13°C$

$T_d = -4.5°C$

$$RH = \left(\frac{r}{r_s}\right) \times 100\%$$

$$RH = \left(\frac{4\,g/kg}{10.5\,g/kg}\right) \times 100\%$$

$RH = 38.1\%$

f) If all the water precipitates out, the air contains 1.5 g/kg of vapour.

$T = 28°C$

$T_d = -12°C$

Study Questions

For suggested answers, see below.

1. Why do saturated adiabats curve on a thermodynamic diagram?

2. What is Normand's rule? What is an important result of the application of Normand's rule?

3. Why is there a greater chance that an air layer will be unstable when it is saturated than when it is unsaturated?

4. How can lifting a layer cause it to become more unstable?

5. Why is a convectively unstable layer sometimes described as potentially unstable?

Additional Problems

For answers, see below.

1. A parcel of air at a height of 3000 m above sea level has a temperature of 6°C. What is its potential temperature?

2. A parcel of air at a height of 4500 m above sea level and a pressure of 62 kPa has a temperature of –4°C. Determine its potential temperature.

3. In a rising air parcel, 1.7 g/kg of water vapour is condensing. What is the saturated adiabatic lapse rate under these conditions?

4. A parcel with a temperature of 33°C and a dew-point temperature of 20°C rises from the surface.
   a) What is the LCL of this parcel? Use Equation 8.5.
   b) If this air rises to 3500 m, what will be its temperature? Assume that the SALR is 5.5°C/1000 m.

5. At a pressure of 90 kPa, an air parcel has a temperature of 16°C and a dew-point temperature of 3°C. If the air parcel rises to an altitude where the pressure is 80 kPa, what will be its temperature and dew-point temperature? Use the thermodynamic diagram in Figure 8.5.

6. At 80 kPa, the temperature is 2°C and the dew-point temperature is –12°C. Use the thermodynamic diagram in Figure 8.5 to answer the following questions.
   a) If this air rises to 70 kPa, what will be its temperature, dew-point temperature, and relative humidity?
   b) What is the LCL for this air? What are the temperature and dew-point temperature at the LCL?
   c) What is the wet-bulb temperature at 80 kPa?
   d) If this air continues to rise to 50 kPa, what will be its temperature, dew-point temperature, and liquid water content?
   e) If 0.5 g/kg of water falls as precipitation and the air then descends, what will be the temperature and dew-point temperature at 85 kPa? What will be the relative humidity?
   f) If all the water had precipitated out, what would be the temperature and dew-point temperature in e)?

7. Air at 100 kPa on the windward side of a mountain has a temperature of 22°C and a dew-point temperature of 8°C. This air rises to the summit, the pressure at which is about 70 kPa. If all the water precipitates out on the windward side of the mountains, what will be the temperature, dew-point temperature, and relative humidity on the leeward side of the mountain, where the pressure is 100 kPa? Use the thermodynamic diagram in Figure 8.5.

8. Suppose that an air layer has a depth of 2 km. The temperature at the bottom of the air layer is 17°C and the temperature at the top of the air layer is 7°C. How will the ELR of this air layer change if the surface air warms 5°C?

Answers to Study Questions

1. The curve reflects the fact that saturated air will cool more slowly near the surface, where air generally contains more water vapour than does the air higher up. (p. 181)

2. Normand's rule states that for a given air parcel, the dry adiabat corresponding to the parcel's temperature, the isohume corresponding to the parcel's dew-point temperature, and the saturated adiabat corresponding to the parcel's wet-bulb temperature, intersect at the parcel's LCL.
An important result of the application of Normand's rule is that if we know the temperature and dew-point temperature of an air parcel, we can determine its wet-bulb temperature. (p. 181)

3. The release of latent heat in a rising saturated air parcel increases the likelihood that a displaced saturated parcel will be warmer than its environment. (pp. 192–193)

4. The layer of air will expand as it rises. Air at the top of the layer will rise further than air at the bottom of the layer will. Therefore, the top of the layer will cool more than the bottom will and the temperature decreases more quickly with height than it did before the air layer rose. Destabilization will be even greater if the lower part of the layer is moist and the upper part is dry. This is because once the moist lower part of the layer becomes saturated it will cool even more slowly than the top due to the release of latent heat. (pp. 196–197)

5. A convectively unstable layer refers to a layer of air that has the potential to become unstable if it is lifted because of its moisture distribution (the lower air is moist and the upper air is dry). (p. 197)

Answers to Additional Problems

1. $\theta = T + \Gamma_d z$

$$\theta = 6°C + \left(\frac{1°C}{100\,m}\right)3000\,m$$

$$= 36°C$$

2. $\theta = T\left(\frac{100}{P}\right)^{\frac{R_d}{c_p}}$

$$\theta = 269\,K\left(\frac{100\,kPa}{62\,kPa}\right)^{0.286}$$

$$= 308.4\ K$$

$= 35.4°\text{C}$

3. $\Gamma_s = \Gamma_d - \left(\frac{L_v\, r}{c_p\, \Delta z}\right)$

$$\Gamma_s = 10\,\text{K/km} - \left[\frac{(2.26 \times 10^6\ \text{J/kg})(1.7 \times 10^{-3}\ \text{kg/kg})}{(1004\,\text{J kg}^{-1}\,\text{K}^{-1})(1\,\text{km})}\right]$$

$= 10\text{K/km} - 3.8\ \text{K/km}$

$= 6.2\ \text{K/km}$

$= 6.2°\text{C/km}$

4. a) $z_{LCL} = 125(T - T_d)$

$= 125(33°\text{C} - 20°\text{C})$

$= 1625\ \text{m}$

b) The air parcel will cool at the DALR until it reaches the LCL:

$$33°\text{C} - (1625\,\text{m})\left(\frac{1°\text{C}}{100\,\text{m}}\right) = 16.8°\text{C}$$

The parcel will then cool at the SALR:

$$16.8°\text{C} - (1875\,\text{m})\left(\frac{0.55°\text{C}}{100\,\text{m}}\right) = 6.5°\text{C}$$

At 3500 m, the temperature of the air parcel will be 6.4°C.

5. $T = 6.5°\text{C}$

$T_d = 1°\text{C}$

6. a) $T = -8.5°\text{C}$

$T_d = -13.5°\text{C}$

$\text{RH} = \left(\frac{r}{r_s}\right) \times 100$

$$= \left(\frac{1.9\,\text{kPa}}{2.8\,\text{kPa}}\right) \times 100$$

$= 67.9\%$

b) LCL = 64 kPa

$T = T_d = -14.5°C$

c) $T_w = -2.5°C$

d) $T = T_d = -30°C$

$r_s = 0.65$ g/kg

$r_L = r_T - r_s$

$= 1.9 - 0.65$ g/kg

$= 1.25$ g/kg

e) If 0.5 g/kg of water is lost as precipitation, there is 1.4 g/kg of water total (where 0.75 g/kg is liquid water).

$T = 8°C$

$T_d = -16.5°C$

$$RH = \left(\frac{r}{r_s}\right) \times 100$$

$$= \left(\frac{1.3\,\text{kPa}}{8\,\text{kPa}}\right) \times 100$$

$= 16.3\%$

f) If all of the water precipitates out then there is 0.65 g/kg of water (all vapour).

$T = 11°C$

$T_d = -24°C$

7. At the summit there is 7 g/kg of water (5 g/kg of water vapour and 2 g/kg of liquid water).

On the leeward side at 100 kPa:

$T = 27°C$

$T_d = 3°C$

$$RH = \left(\frac{r}{r_s}\right) \times 100$$

$$= \left(\frac{5\,\text{kPa}}{24\,\text{kPa}}\right) \times 100$$

$$= 20.8\%$$

8. Initially, the ELR is 5°C/km (absolutely stable). After warming, the ELR will be 7.5°C/km and the air will be conditionally unstable.