Chapter 6: Atmospheric Stability

Key Terms

adiabatic process
air parcel
capping inversion
Convective Available Potential Energy (CAPE)
Convective Inhibition (CINH) Index
cold front
condensation level
conditionally unstable
convection
convergence
dry adiabatic lapse rate
environment
environmental lapse rate
inversion
K Index
lapse rate
level of free convection
Lifted Index (LI)
lifting condensation level
lifting mechanism
moist adiabatic lapse rate
neutral stability
sea breeze
Showalter Index
Severe Weather Threat (SWEAT) Index
stable
Total Totals Index
unstable
upslope

Answers to questions in the textbook, except for *Use the Severe and Hazardous Weather Website,* are provided.

CHECK YOUR UNDERSTANDING 6.1

1. What is the significance of stability with respect to severe thunderstorms?
   A. Stability determines the location and intensity of convective storms in the atmosphere.
2. What is an adiabatic process?
   A. An adiabatic process is one in which a parcel of air does not mix with its environment or exchange heat energy with its environment.
3. What is the approximate value of the dry and moist adiabatic lapse rates in the lower atmosphere?
   A. The dry adiabatic lapse rate is 10°C/km and the moist adiabatic lapse rate, in the lower atmosphere, is approximately 6°C/km.
4. What is the name of the lapse rate obtained from rawinsonde measurements?
   A. The environmental lapse rate.

CHECK YOUR UNDERSTANDING 6.2

1. How is the density of an air parcel related to its temperature and to atmospheric stability?
   A. Warm air is less dense than cold air. Stability is determined by comparing the density of air parcel to the environmental air surrounding the parcel. Air parcels displaced upward (downward) that become more (less) dense than their environment will return to their original position indicating a stable environment. Air parcels displaced upward (downward) that become less

(more) dense than their environment will accelerate away from their original position indicating an unstable environment.

2. As the environmental lapse rate becomes larger, does the atmosphere become more stable or less stable? Why?
   A. Less stable because the environmental temperature will decrease with height at a faster rate with a large lapse rate. This means that a rising parcel is more likely to be warmer than the environment and more likely to rise.
3. What is meant by "conditional instability"?
   A. The condition required for instability is that the displaced parcel of air be saturated. (Unsaturated air parcels will be stable, saturated air parcels will be unstable.)
4. What is the difference between the lifting condensation level and the level of free convection?
   A. The lifting condensation level is the altitude where condensation first occurs when an air parcel is lifted from the surface (cloud base). The level of free convection is the altitude where a rising air parcel becomes buoyant. The level of free convection typically is at a higher altitude than the lifting condensation level.

CHECK YOUR UNDERSTANDING 6.3

1. What are four ways that air parcels can be lifted?
   A. (1) fronts, (2) sea breeze (or lake breeze), (3) topography, (4) convergence at low levels.
2. How does heating of the ground by sunlight affect the stability of the lower atmosphere?
   A. Heating the ground warms the air and makes the lower atmosphere less stable.
3. Why do meteorologists assess atmospheric stability by using stability indices rather than explicit calculations using lapse rates from soundings?
   A. Stability indices generated from rawinsonde data or computer model output can be contoured and viewed as a map, allowing meteorologists to estimate stability quickly over a broad region like the United States.

TEST YOUR UNDERSTANDING

1. What does it mean if air is "stable" or "unstable"?
   A. If air is displaced vertically it will return to its position if the environment is "stable" and it will continue to move vertically in the direction of the displacement if the environment is "unstable".
2. What is convection?
   A. "Convection" describes buoyant vertical air currents within the atmosphere, often resulting in the formation of cumulus clouds.
3. What is meant by the term "air parcel"?
   A. An air parcel is a small volume of air that is assumed to retain its identity as it moves through the atmosphere.
4. What do the inflation of a tire and the descent of an air parcel have in common?
   A. Both involve compression, which warms air.

5. Why does an air parcel cool as it rises?
   A. Air parcels rising through the atmosphere expand because they encounter lower pressure. Expansion requires work, and the energy required to expand the air comes from the thermal energy of the air. With less thermal energy, the air's temperature is lowered.
6. Which of the following is (are) a constant: dry adiabatic lapse rate, moist adiabatic lapse rate, environmental lapse rate?
   A. Only the dry adiabatic lapse rate is constant (10°C/km). The moist adiabatic lapse rate and environmental lapse rate vary with altitude.
7. Describe the motion of a vertically displaced air parcel in a stable atmosphere, an unstable atmosphere, and a neutral atmosphere.
   A. An air parcel when displaced vertically will return to its original position in a stable atmosphere, accelerate away from its original position in an unstable atmosphere, and remain at its new position in a neutral atmosphere.
8. What is the reason why the moist adiabatic lapse rate is different from the dry adiabatic lapse rate?
   A. Latent heat released during condensation in saturated air offsets some of the cooling due to decompression as air rises.
9. An inversion is indicative of a stable layer in the atmosphere. Briefly explain why this is so.
   A. The environmental temperature increases with an increase in altitude within an inversion. As a parcel of air rises upwards, its temperature always decreases due to decompression. In an inversion, the environmental temperature will increase with altitude while the air parcel temperature decreases. Under these conditions, if an air parcel rises, it will always become more dense than the surrounding environment and will return to its original position (stable).
10. If the environmental lapse rate in the lower troposphere is approximately 5ºC/km, would you expect strong convection to develop? Why or why not?
    A. No. A lapse rate of 5°C/km indicates a stable atmosphere. Rising air, saturated (6ºC/km) or unsaturated (10ºC/km), will always be colder than its surrounding environment and the air will return to its original position.
11. Would strong convection be expected to develop if the environmental lapse rate was 8ºC/km? Explain.
    A. Possibly, if air was lifted beyond its level of free convection. A lapse rate of 8°C/km indicates a conditionally unstable atmosphere. If a saturated parcel is lifted in this environment, condensation will occur during the ascent and the parcel will continue to rise on its own – a convective cloud will develop.
12. Explain why atmospheric stability at a particular location can change.
    A. If the lapse rate of a layer of air changes, the stability of that air will change. Lapse rates can be changes by heating and or cooling the bottom of a layer of air relative to the top of the layer, or by warm or cold air moving into a region at the top or bottom of a layer.
13. Is the atmosphere likely to be more unstable in mid-afternoon or in early morning? Why?

A. Mid-afternoon. Incoming solar radiation heats air during the day near the surface, causing the air to become less dense and more buoyant, resulting in rising parcels and potentially cumulus clouds.

14. What is the lifting condensation level?

A. The lifting condensation level is the altitude at which condensation first occurs in a lifted air parcel.

15. What is the level of free convection?

A. The level of free convection is the altitude at which a lifted air parcel first becomes buoyant and can rise on its own.

16. List five ways that an air parcel can be brought to its level of free convection.

A. (1) lifting along a cold front, (2) lifting along a sea breeze, (3) lifting along topography, (4) low-level convergence, (5) solar heating of air near the surface.

17. Cumulus clouds are present in Denver, Colorado. What lifting mechanism discussed in the text is *least* likely to have caused the clouds to form? Why?

A. Lifting along a sea breeze. Denver is far from large bodies of water where sea breezes develop. All four other mechanisms could have caused the air to rise.

18. Would you expect air parcels to be lifted in areas where surface winds are convergent or divergent? Why?

A. Convergent. Surface air that converges together from all directions "piles up" and must go somewhere. It cannot move into the ground and therefore is forced to rise. Divergent air flow will result in sinking motions as air moves down from above to replace air moving away from the central location.

19. Why are cumulonimbus clouds less common in winter than in summer in the United States?

A. Atmospheric conditions are more stable during winter, in general. Surface air temperatures are relatively cold in winter compared to air aloft (environmental lapse rates are smaller) and it is more difficult for air to become buoyant. During summer, environmental lapse rates are larger, surface air parcels are warmed by solar heating in the daytime and air is more likely to become buoyant.

20. What is the Lifted Index? How is the value of the Lifted Index related to the severity of storms?

A. The Lifted Index is a measure of instability of the atmosphere. The LI is calculated by subtracting the temperature of a parcel lifted to 500 mb (from the surface) from the temperature of the environment at 500 mb. The lower the value of Lifted Index, the more potential for severe thunderstorms.

21. Determine if the data for each sounding indicates that thunderstorms will develop and if so, if the storms will be severe.

(a) The Davenport, Iowa July sounding shows:
K-Index = 38, LI=-1.5, SI= -1.6, CAPE=150, TT=48, SW=225

(b) The Nashville, Tennessee July sounding shows:
K-Index = 34, LI=-4.2, SI= -1.3, CAPE=2027, TT=46, SW=244

(c) The International Falls, Minnesota July sounding shows:
K-Index = -11, LI=+13.6, SI= 15.6, CAPE=9, TT=25, SW=108

A. Using Table 6.2

(a) Davenport: yes, thunderstorms are likely. They would probably not be severe.
(b) Nashville: yes, thunderstorms are likely. They probably would be severe.
(c) International Falls: no, thunderstorms are not likely.

TEST YOUR PROBLEM-SOLVING SKILLS

1. You are taking a hot-air balloon ride on a clear, calm November evening. The environmental lapse rate is 5°C/km. As the balloon rises, you compare the temperature inside the balloon (via digital readout) with the reading on a thermometer you hold in the passenger basket. After a few bursts of flame at an altitude of 1 km (3280 ft), the temperature inside the balloon is 68°F (20°C), and the temperature in the basket is 32°F (0°C). All of the balloon's controls (including the ballast control) then freeze and become inoperative, causing the balloon to enter a state of free drift. Assuming that the balloon's expandable skin does not conduct any heat, what is the maximum altitude you could reach before the balloon stops rising? (Hint: The maximum altitude would be reached if the balloon's skin, basket and passengers had negligible weight.)
   A. Find altitude where T(inside) = T(outside).
   T(inside) = 20°C - 10°C/km × Z, where Z is the altitude the balloon rises
   T(outside) = 0°C - 5°C/km × Z
   So Z = 4 km. Balloon started at 1 km, so peak altitude = 5 km.

2. Consider air flowing onshore at the surface from the Pacific Ocean with a temperature of 50°F (10°C) and a dewpoint of 41°F (5°C). The onshore airflow is forced to ascend the mountains of the western United States, where its trajectory reaches a maximum elevation of 3 km (9540 ft). The air then descends to the plains of Colorado, where the elevation is 1.5 km (4920 ft). Assume that the air's dewpoint decreases at 2°C/km of ascent prior to saturation, increases at the same rate during descent, and decreases at the moist adiabatic lapse rate of 6°C/km during saturated ascent.
   (a) Calculate the relative humidity of the air as it comes onshore. (Hint: use Fig. 1.9)
   A. T=10°C so sat. vapor pressure ≈ 12.3 mb (from Chapter 1)
   T_d = 5°C so vapor pressure ≈ 8.7 mb
   RH ≈ 8.7 / 12.3 * 100 ≈ 70%
   (b) Determine the temperature, dewpoint and relative humidity of the air at the top of the mountains (3 km).
   A. First find the altitude where T = T_d
   T = 10°C - 10°C/km × Z
   T_d = 5°C - 2°C/km × Z
   Z = 0.625 km, at which altitude T = 3.75°C
   Next find the temperature at mountaintop.
   T = 3.75°C - 6°C/km × (3 – 0.625) km = -10.5°C.
   Air is saturated at 3 km, so T_d = T and RH = 100%
   (c) Determine the temperature, dewpoint and relative humidity of the air when it reaches the Plains of Colorado (1.5 km).
   A. T = -10.5°C + 10°C/km × 1.5 km = 4.5°C.
   T_d = -10.5°C + 2°C/km × 1.5 km = -7.5°C.

RH = 41%

(d) Suppose the air descended farther to sea level. What would be its temperature and relative humidity? Explain why the values are different from when the air first came onshore.

A. T = -10.5°C + 10°C/km × 3 km = 19.5°C
T_d = -10.5°C + 2°C/km × 3 km = -4.5°C
RH = 20%.
The value is different because moisture was removed as precipitation during ascent over mountains.

3. The following data are from a hypothetical sounding.

Pressure (mb)	Height (m)	Temp. (°C)	Dewpoint (°C)	Lapse Rate (°C/km)	Parcel. T (°C)	Stability
1000	0	14	10	*N/A*	*14*	
980	200	16	12	*-10*		*stable*
950	500	14	12	*6.7*	*9*	*stable*
900	1000	11	11	*6*	*6*	*neutral*
850	1500	5	5	*12*	*3*	*abs. unstable*
800	2000	2	-3	*6*	*0*	*neutral*
700	3000	-9	-16	*11*	*-6*	*abs. unstable*
600	4000	-16	-18	*7*	*-12*	*cond. unstable*
500	5500	-23	-25	*4.7*	*-21*	*stable*
400	7000	-28	-30	*3.3*	*-30*	*stable*
300	8500	-30	-34	*1.3*	*-39*	*stable*
200	10,000	-30	-35	*0*	*-48*	*stable*
100	12,000	-27	-36	*-1.5*	*-60*	*stable*

(a) Plot the sounding (temperature and dewpoint) on a copy of the Stuve diagram given in Appendix B.

(b) Are any inversions present in this sounding? If so, in which layers? (Identify "layers" according to the pressures at their top and bottom, e.g., the "400 to 500 mb" layer.)

A. Yes. The 1000 to 980 mb layer and the 200 to 100 mb layer.

(c) Are any layers absolutely unstable? If so, which one(s)?

A. Yes. The 900 to 850 mb layer and the 800 to 700 mb layer

(d) Are any layers neutral? If so, which one(s)?

A. No. To be neutral, the entire layer would have to be saturated and have a lapse rate of 6C/km or unsaturated and have a lapse rate of 10C/km. No layer meets this exact criteria.

(e) Where is the level of free convection for a parcel that is lifted from the surface? (You may assume that the dewpoint of an *unsaturated* air parcel decreases during lifting at a rate of 2°C/km; a *saturated* parcel must have temperature = dewpoint.)

A. Students could solve graphically or mathematically.
LCL is 950 mb (14C-10C/km*Z = 10C-2C/km*Z) so LFC = 500 m
LFC is ~760 mb (2400 m)

Cloud base is at 950 mb where T and T_d are 9°C. Above the cloud base, the rising parcel cools at moist adiabatic lapse rate (6°C/km). Once it rises to 760 mb (~2400 m) the parcel T and the environmental T will be equal.

(f) If the parcel in (e) reaches the level of free convection, to what altitude will it rise? (Assume the moist adiabatic lapse rate stays constant at 6°C/km.)

A. 445 mb (~6400m). The parcel will rise until it reaches the equilibrium level.

(g) What is the Lifted Index for this sounding? (Assume the parcel is lifted from the surface.)

A. LI = -2