United States
Environmental Protection
Agency

Air Pollution Training Institute
MD 20
Environmental Research Center
Research Triangle Park, NC 27711

EPA 450 2-82-00
December, 1982

Air

450282009

APTI
Course SI:409
Basic Air Pollution Meteorology

Student Guidebook

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Under Contract No.
68-02-3573
EPA Project Officer
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United States Environmental Protection Agency
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711

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General Services Administration
Order Section HH
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Table of Contents

Lesson 1

Course Introduction

Course Description

This training course is a 25-hour self-instructional course using slide/tape presentations and reading assignments dealing with basic meteorology, meteorological effects on air pollution, meteorological instrumentation, air quality modeling, and regulatory programs requiring meteorology. Course topics include the following:

- Solar and terrestrial radiation
- Cyclones and anticyclones
- Wind speed and direction
- Atmospheric circulation
- Cold, warm, and occluded fronts
- Atmospheric stability
- Turbulence
- Meteorological instrumentation
- Plume rise/effective stack height
- Topography
- Air quality models
- Regulatory air quality programs

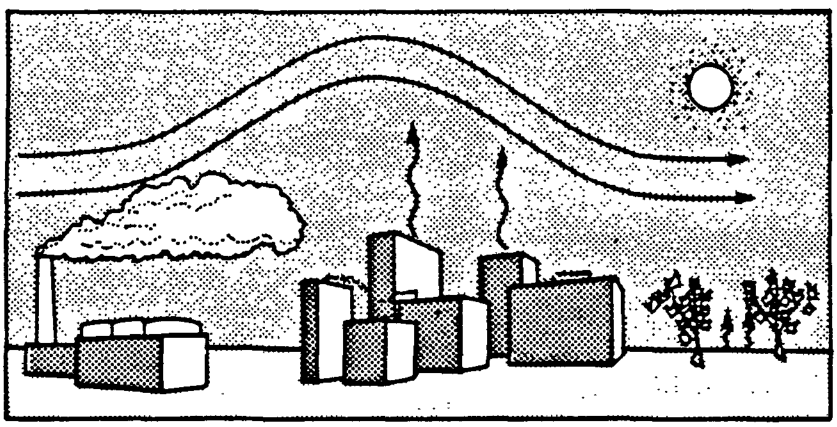

Figure 1-1. Meteorology and pollution dispersion.

Course Goal and Objectives

Goal

The goal of this course is to familiarize you with the fundamentals of meteorology, the atmospheric factors that transport and disperse pollutants, the instruments used to gather meteorological data necessary for air quality modeling, plume rise and effective stack height, categories of air quality models, and the regulatory air quality programs requiring meteorological data.

Objectives

Upon completing this course, you should be able to:

1. describe the effect of solar radiation on the earth-atmosphere system.
2. describe the pressure, wind flow, and vertical motion in cyclones and anticyclones.
3. list the four factors that govern the motion of the wind.
4. describe the importance of atmospheric circulation.
5. describe warm, cold, and occluded fronts.
6. name the four types of atmospheric stability.
7. describe the importance of turbulence in the atmosphere.
8. recognize meteorological instruments used for air pollution and match an instrument to the atmospheric factor it senses.
9. briefly define plume rise and effective stack height.
10. describe four types of topographical features that influence pollutant dispersion.
11. list the four categories of air quality models.
12. identify and describe the three regulatory air quality programs requiring meteorological data.

Requirements for Successful Completion of this Course

In order to receive 2.5 Continuing Education Units (CEUs) and a certificate of course completion, you must:

1. take a mail-in final examination.
2. achieve a final examination grade of at least 70%.

Materials

Reading

SI:409 Student Guidebook, *Basic Air Pollution Meteorology*.

Audio-Visual

Slide/tape presentations: SI:409-2, SI:409-3, and SI:409-6. These are numbered to correspond to the lesson numbers they are used with in this text.

Use of the Guidebook

This guidebook directs your progress through the slide/tape presentations and reading assignments that are listed in the "Materials" section. Each assignment to be completed will be presented in a sequence that you should follow carefully. Use this guidebook as a "roadmap" of the course.

Guidebook Contents

This guidebook contains nine lessons consisting of reading, audio-visual, and suggested supplementary materials. The first lesson gives you an overview of the course. The second lesson has one slide/tape presentation and a reading assignment that discusses radiation and its effects. The third lesson has one slide/tape presentation and a reading assignment that discusses general circulation and winds. The next two lessons are reading assignments covering frontal systems, stability, and turbulence. The sixth lesson has one slide/tape presentation and a reading assignment that discusses meteorological instrumentation. The next three lessons are reading assignments on plume dispersion and air quality modeling. The reading material will be self-paced, presented as text with review questions.

Completing the Review Exercise

To complete a review exercise, place a piece of paper across the page covering the questions below the one you are answering. After answering the question, slide the paper down to uncover the next question. The answer for the first question will be given on the right side of the page separated by a line from the second question (Figure 1-2). All answers to review questions will appear below and to the right of their respective questions. The answer will be numbered to match the question.

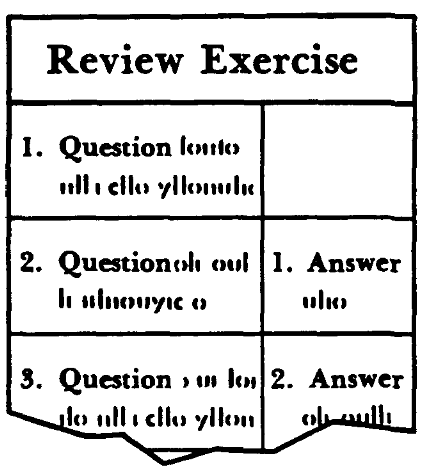

Figure 1-2. Review exercise format.

Using the Slide/Tape Presentations

You do not need to follow the script provided in the appropriate lessons as you view the slide/tape presentation. The script is provided for you to use to review the content. The audiocassette is designed to automatically advance the slides at the correct place in the script if your cassette player has a mechanism for synchronizing audiotape and 35-mm slides.

- To use the slides and audiotape together, advance to the first slide and focus the image.
- Leave the tray positioned at slide #1.
- Place the cassette in the tape player so that the side marked "Automatic Advance" will play. The tape recorder will advance the slides for you.

If you do not have equipment that automatically advances the slides, you can use a 35-mm slide projector and any cassette player.

- Use the side of the tape marked "Manual Advance."
- Set the slide tray to the focus slide, #1, and advance the slides as you hear a "beep" (tone) on the tape.

Lesson Content

- Assignments
  - Slide/tape presentation: slide number and cassette numbers
  - Reading assignment
    - Assignment topics
    - Lesson guidance
- Lesson goal and objectives
- Script from slide/tape presentation
- Text of lesson
- Review exercise

Some supplementary readings will be recommended, but are not required for course completion.

Instructions for Completing the Final Examination

Contact the Air Pollution Training Institute if you have any questions about the course or when you are ready to receive a copy of the final examination.

After completing the final exam return it and the answer sheet to the Air Pollution Training Institute. The final exam grade and course grade will be mailed to you.

Air Pollution Training Institute
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Lesson 2

Heat Balance of the Atmosphere

Assignment

1. View the slide/tape presentation, *Radiation,* which consists of tape SI:409-2 and slides 409-2-1 through 409-2-44.
2. Read pages 2-9 through 2-14 of this guidebook.

Assignment Topics

- Radiation
- Insolation
- Heat distribution

Lesson Guidance

This lesson and the three following it introduce the fundamental concepts of meteorology—the science of the atmosphere and its phenomena. The atmosphere acts as a giant cleanser, removing the wastes produced by the cycles of nature. Since the industrial revolution, the "cleanser" has not been able to keep up with the production of new industrial waste materials. Because some of these wastes are hazardous to human health and may produce future climatic changes, the conditions that cause them to spread throughout the atmosphere must be fully understood. Therefore, basic operations of and components that produce atmospheric circulation around the earth will be discussed before, in Lesson 5, their relationship is tied to the atmosphere's vertical temperature structure and to a discussion of air pollution dispersion.

Lesson Goal and Objectives

Goal

To familiarize you with the source of energy responsible for atmospheric motion, and with the way the earth and atmosphere combine to balance the energy received by the earth.

Objectives

Upon completing this lesson, you should be able to:

1. identify the source of energy that "drives" atmospheric motion.
2. name the most important heat storage constituent of the atmosphere.
3. describe a chain of events that could possibly lead to thunderstorms.
4. explain the reason for a long-term heat balance in the atmosphere.
5. name an atmospheric phenomenon that transports pollution.
6. list the four factors that govern the amount of insolation received by the atmosphere.

Supplementary Reading

Any meteorology textbook such as the ones listed under **References** at the end of this guidebook.

Air Pollution Meteorology—Radiation

Slide	Script	Selected Visuals*
1.		
2.		
3.		
4.		
5.		Air Pollution Meteorology
6.	We are all familiar with raging thunderstorms, howling winds, blinding snowstorms, and hot muggy days.	
7.	We usually think of these weather patterns in terms of the rain, wind, cold, or heat they bring.	Radiation
8.	But these weather patterns do more than create the need for umbrellas, snowsuits,	
9.	windbreakers, and air conditioners.	
10.	The winds, rain, and other meteorological conditions they create can transport, disperse, or trap air pollutants.	
11.	For example, pollutants can be carried from urban areas with many factories. . .	
12.	to rural areas where no factories are in sight for miles.	
13.	Meteorological conditions help dilute—or disperse—pollutants in heavily industrialized areas.	

*illustrations included here, no live shots

Slide **Script** **Selected Visuals**

14. But these conditions can cause air pollution episodes—which are unhealthy concentrations of pollutants.

15. The weather patterns that can transport, dilute, or trap air pollution are caused by movement of the atmosphere and, indirectly, by ocean movement.

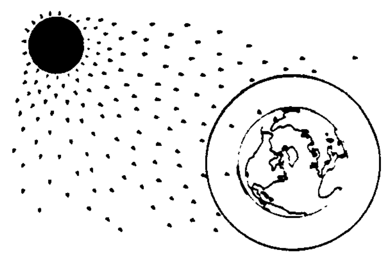
16. But what ***causes*** atmospheric and oceanic movement??

17. It all starts with the sun. The sun gives off energy—or radiation—from a surface that is 6000 kelvin. That is equivalent to more than ***10,000*** degrees Fahrenheit.

6,000 K

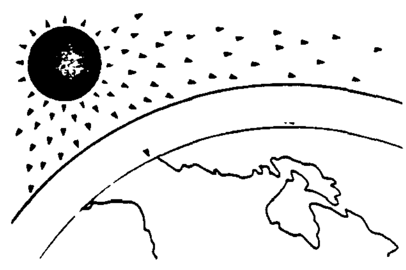
18. If we received all of the sun's radiation, the earth would be so hot that life as we know it could not exist. The surface of the earth—and everything on it—would be parched, much like the surface of Mercury.

19. Luckily, only one one-billionth of the sun's radiation reaches the tip of the earth's atmosphere.

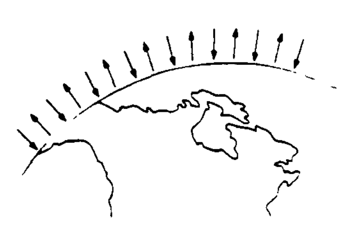


20. And because the atmosphere acts as a filter,

21. only one quarter of *that* radiation ever reaches us at the surface of the earth.

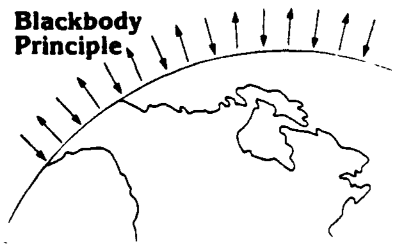


22. The earth and its atmosphere then absorb and reradiate this energy.

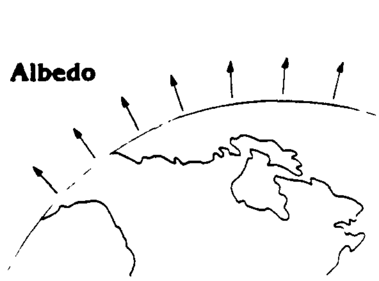


Slide | **Script** | **Selected Visuals**

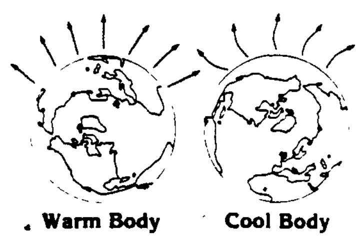
23. The ability to absorb and reradiate energy is referred to by scientists as the ***blackbody principle.***



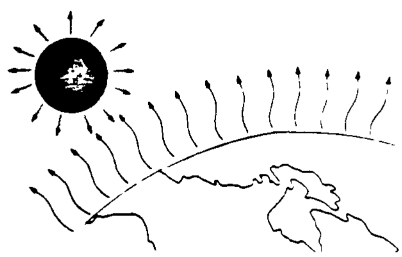
24. The amount of energy radiated by a body is its ***albedo.**** Radiated energy is measured in wavelengths.



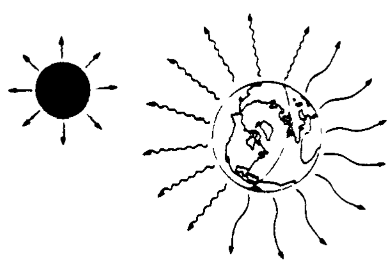
25. How long the wavelengths are depends on the temperature of the body that is radiating them. Warmer bodies radiate shorter wavelengths, and cooler bodies radiate longer wavelengths. The longer wavelengths are more likely to be absorbed by our atmosphere. Thus, they are potentially more useful to us because the earth ***needs*** some of that ***absorbed heat.***



26. Obviously, the sun and the earth have very different temperatures; so, although they both radiate energy, their wavelengths are different. The sun radiates very short wavelengths, and the earth radiates the longer ones.



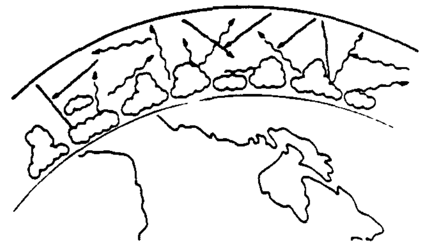
27. As a matter of fact, even the range of wavelengths radiating from the earth is always changing as the earth's surface and atmosphere heat and cool.



*Albedo is actually expressed as a ratio. The fraction of energy radiated by a body compared to the total insolation received is its albedo.

Slide	Script	Selected Visuals

28. Heat is also stored and radiated by the earth's ***atmosphere***. ***All*** of the components of the atmosphere absorb and radiate heat. The most important of these is water vapor.



29. Water vapor stores about six times more heat energy than all the other atmospheric components combined.

30. Water vapor holds or stores this heat and then releases it. Sometimes this heat is released very quickly, in the form of thunderstorms.

31. But sometimes this heat or energy is stored and transported long distances before being released as snow, rain, or other precipitation.

32. For example, water can evaporate over the warm Gulf of Mexico and be transported all the way to North Dakota before it condenses and releases heat.

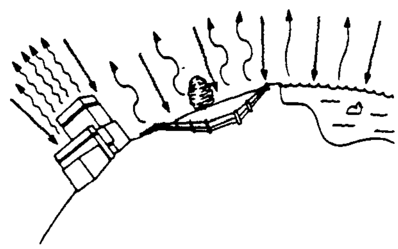
33. Atmospheric water in the form of vapor and precipitation is not the only water that transports heat, however. Water in the oceans also helps maintain the heat balance.

34. Ocean currents take heat from the warm equatorial regions and transport it to the much colder polar regions in the north and south.

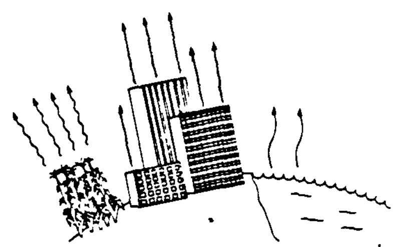
Slide	Script	Selected Visuals

35. For example, during the summer, the ocean near the equator is heated to a very warm temperature. A small tropical storm forms. As the storm drifts westward, it may develop into a hurricane or typhoon. Ocean currents help guide its path. And large quantities of heat are transported away from the equator by the storm.

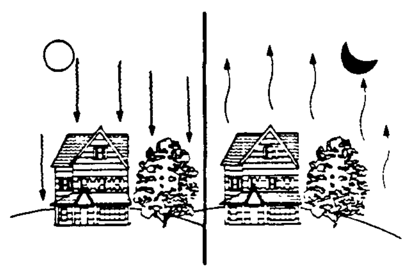
36. Since new energy from the sun is also entering the atmosphere, the earth would overheat if ***all*** of this energy were stored. So, energy must eventually be released back into space. On the whole, this ***is*** what happens. What comes in eventually goes back out, and a heat balance, called the radiational balance, is created.



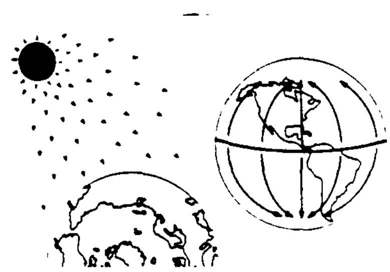
37. Our atmosphere also uses some of this energy—or heat—so some of it is stored for a while before it is released. Some heat is stored for short periods of time, and some is stored for longer periods. This difference in heat storage both creates atmospheric movement and helps maintain the relatively consistent temperatures that support life.



38. Heat is stored by the ***earth*** and everything on it. During the day, when the sun is shining, the earth and objects on it are absorbing and storing heat. At night, when the sun isn't shining, the warmed earth radiates heat back out into space. Some objects hold heat better than others. This is called ~~***differential heating***~~. The rate at which the energy is reradiated back into space varies. But it is all radiated back out as useful long-wave radiation. Both the amount of heat and the rate at which it is radiated play a major role in the creation of atmospheric movement.

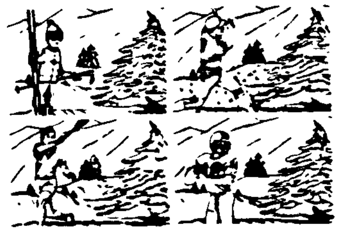


39. We've seen that the sun is the source of energy for atmospheric and oceanic motions. The earth heats unevenly and transfers heat from the equator to the poles. The earth also loses as much radiation as it gains.



Slide	Script	Selected Visuals

40. What all of this heat storage and transfer adds up to is a balance of energy and a finely tuned system. While things within the atmosphere are always heating up or cooling down, the net result is a system that continues to maintain an overall balance of heat:



41. a balance that allows variation sufficient enough to create atmospheric and oceanic movement, yet predictable enough to allow an orderly system of life.

42. Credit: Crew

Radiation

Script and Design: Donald Ballard
Monica Leslie
Marilyn Peterson
Graphics: Betsy Huber
Photography/Audio: David Churchill
Narration: Rick Palmer

43. Credit: Northrop

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Radiation and Insolation

The energy expended in the atmospheric processes was originally derived from the sun. This energy is transferred by radiation of heat by electromagnetic waves. The radiation from the sun has its peak energy transmission in the visible range (0.4 to 0.7 micrometers) of the electromagnetic spectrum. However, the sun also releases considerable energy in the ultraviolet and infrared regions. The greatest part of the sun's energy is emitted in wavelengths between 0.1 and 30 micrometers.

The amount of radiation received on any date at a location on the earth's surface is called *insolation.* Insolation is governed by four factors:

- the solar constant—which depends on:
  - energy output of the sun
  - distance from the earth to the sun
- transparency of the atmosphere
- duration of the daily sunlight period
- angle at which the sun's noon rays strike the earth.

Solar Constant

The solar constant is the amount of radiation received at a point in the earth's outer atmosphere. The "constant" depends on the distance and position of the earth relative to the sun; however, the average amount of radiation received at a given point will not vary significantly. Since the sun essentially emits a constant radiation, it alone would imply constant weather within the atmosphere. However, transparency, duration, and angle are much more important in influencing the amount of insolation received, which in turn changes the weather.

Transparency

Transparency of the atmosphere does have an important bearing upon the amount of insolation that reaches the earth's surface. As shown in Figure 2-1, some of the radiation received by the atmosphere is reflected from the tops of clouds and from the land and water surfaces of the earth.

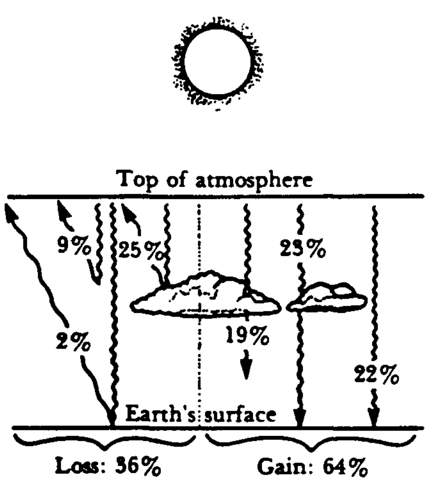


Figure 2-1. Heat balance of the atmosphere.

The general reflectivity is the *albedo* and, for the earth and atmosphere as a whole, is 36% for average conditions of cloudiness over the earth. This reflectivity is greatest in the visible range of wavelengths.

Some of the gases in the atmosphere (notably water vapor) also absorb solar radiation. This reduces the insolation. Water vapor, although comprising only 3% of the atmosphere, on the average absorbs about six times as much solar radiation as all other gases combined. The amount of radiation received at the earth's surface is therefore considerably less than that received outside the atmosphere. The earth reradiates energy in proportion to its temperature. Because of the earth's temperature, the maximum reradiation occurs in the 10μ range, which is in the infrared region of the spectrum. The gases of the atmosphere absorb some of this radiation. Because the atmosphere absorbs much more of the terrestrial radiation (earth and atmospheric reradiation) than solar radiation, some of this heat energy is conserved. This is the *greenhouse effect*.

Transparency is a function of not only cloudiness, but also of latitude. The sun's rays must pass through a thicker layer of reflecting-scattering atmosphere at middle and high latitudes than at tropical latitudes (Figure 2-2). This effect varies with the seasons, being greatest in winter when the sun's rays are lowest on the horizon.

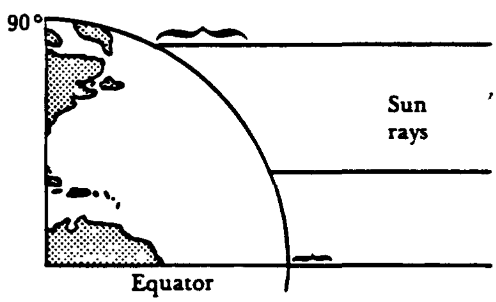


Figure 2-2. Relationship of transparency to latitude.

Daylight Duration

The duration of daylight also affects the amount of insolation received. Daylight duration varies with latitude and the seasons. The longer the period of sunlight, the greater the total possible insolation. At the equator, day and night are always equal. In the polar regions, the daylight period reaches a maximum of twenty-four hours in summer and a minimum of zero hours in winter.

Angle of Rays

The angle at which the sun's rays strike the earth varies considerably as the sun "shifts" back and forth across the equator. A relatively flat surface perpendicular to an incoming vertical sun ray receives the largest amount of insolation. Therefore, areas at which the sun's rays are oblique receive less insolation because the oblique rays are spread over a greater surface area and must pass through a thicker layer of reflecting and absorbing atmosphere (Figure 2-3). This same principle also applies to the daily shift of the sun's rays. At solar noon the intensity of insolation is greatest. In the morning and evening hours, when the sun is at a low angle, the amount of insolation is small.

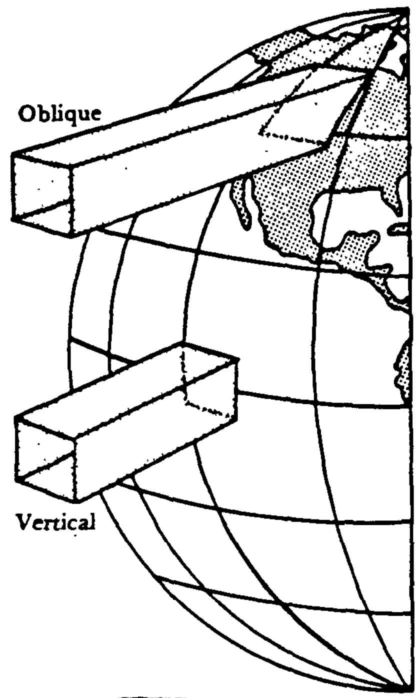


Figure 2-3. Oblique and vertical rays.

Heat Distribution

As seen in this discussion, the world distribution of insolation is closely related to latitude. Total annual insolation is greatest at the equator and decreases regularly toward the poles. Figure 2-4 shows the amount of solar radiation absorbed by the earth and atmosphere compared to the long wave radiation leaving the atmosphere. The amount of insolation received annually at the equator is about four times that received at either of the poles. As the rays of the sun shift seasonally from one hemisphere to the other, the zone of maximum possible daily insolation moves with them. For the earth as a whole, the gains in solar energy equal the losses of earth energy back into space. However, since the equatorial region does gain more heat than it loses, and the poles lose more heat than they gain (as shown in Figure 2-4), something must happen within the atmosphere to distribute heat evenly around the earth. Otherwise, the equatorial regions would continue to heat and the poles would continue to cool. Therefore, in order to reach equilibrium, a continuous large-scale transfer of heat (from low to high latitudes) is carried out by atmospheric and oceanic circulations.

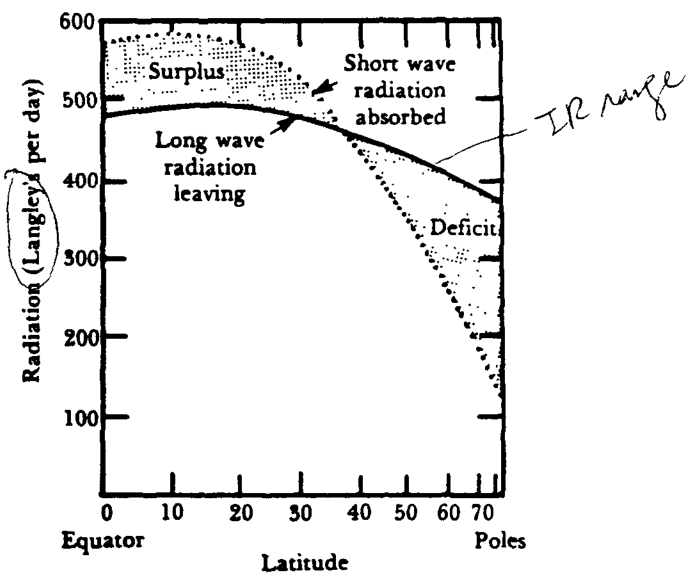


Figure 2-4. Distribution of heat latitudinally.

Heat transfer from the tropics poleward takes place throughout the year, but at a much slower rate in summer than in winter. The reason is that the temperature difference between low and high latitudes is considerably smaller in summer than in winter—only about half as large in the Northern Hemisphere. As would be expected, the winter hemisphere has a net energy loss and the summer hemisphere a net gain. Most of the summertime gain is stored in the surface layers of land and ocean, mainly in the ocean.

The atmosphere is often referred to as a giant "heat engine," driving warm air poleward and bringing cold air toward the equator. Figure 2-5 depicts the simple heat engine. This diagram has coordinates of horizontal distance and height (or pressure). The simple heat engine is based on the principle that warm fluid moves from a heat source to a cold source at low pressure, while cold fluid moves from a cold source to a heat source at high pressure. At the cold source, the warm mass loses heat, increases in density, and sinks; the reverse takes place at the heat source. During winter in the United States or any other middle-latitude area, winds from the south make the air warmer while winds from the north cause the temperature to fall. The movement of warm air masses into the polar regions and cold air masses into the tropics alters the warming and cooling trends that would result from radiation alone.

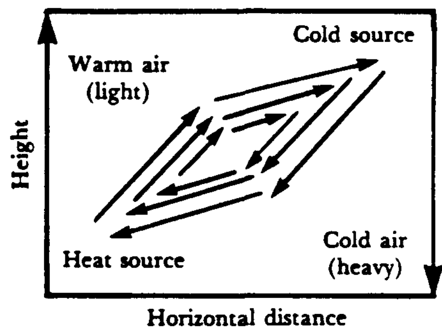


Figure 2-5. Simple heat engine.

Convection current

The oceans also play a role in heat exchange. Warm water flows poleward along the western side of an ocean basin and cold water flows toward the equator on the eastern side. At higher latitudes the east-west position of warm and cold currents in the ocean reverses, but still the warm water moves to higher latitudes and the cold water to lower latitudes. Thus, the oceans contribute to poleward heat transport, accounting for about 25% of the total transport in the subtropical and middle latitudes. Almost all other phenomena of weather and climate, including atmospheric disturbances (storms), work together to equalize the heat balance. As Table 2-1 shows, the greatest transfer of heat is required in the middle latitudes. The greatest turbulence and storminess is found in regions where both horizontal air movement and air-mass movement are greatest.

Since the analogy of the earth as a heat engine was realistic in low latitudes, the whole general circulation was once thought to act as a simple heat engine. Then computations, which were begun in Austria about 1920 and pursued widely from the 1940s onward, demonstrated that the cyclones and anticyclones outside the tropics and the waves in the upper westerlies provided an important means for exchanging heat between the tropics and the polar zone. The importance of the disturbances in the westerlies has been studied compared to the simple heat engine through laboratory experiments conducted by Dave Fultz at the University of Chicago since the late 1940s (Riehl, 1965). This work has lead to theories about the general circulation of the atmosphere, a much more complicated process than described by the simple heat engine principle. This general circulation will be discussed in the next lesson.

Table 2-1. Required heat flux toward the poles across latitudes (10^{19} calories per day).

Latitude	Flux
0	0
10	4.05
20	7.68
30	10.46
40	11.12
50	9.61
60	6.68
70	3.41
80	0.94
90	0

Review Exercise

1. The source of energy responsible for atmospheric and oceanic motion is the ________.	
2. Which of the following stores more heat energy than all other atmospheric constituents combined? a. carbon dioxide b. acid rain c. water vapor d. nitrogen	1. sun
3. How much of the sun's radiation reaches the tip of the earth's atmosphere? a. one quarter of it b. half of it c. one-millionth of it d. one-billionth of it	2. c. water vapor
	3. d. one-billionth of it

4. Since the earth's atmosphere acts as a filter, how much radiation at the tip of the atmosphere reaches the surface of the earth? a. one-quarter of it b. half of it c. all of it d. none of it	
5. The fraction of energy radiated by a body compared to the amount of incoming energy is its a. atmosphere. b. albedo. c. heat balance. d. solar constant.	4. a. one-quarter of it
6. What is differential heating?	5. b. albedo.
7. A heat balance on the earth implies that a. the cold earth holds all of the heat it receives. b. the cold poles hold as much heat as the warm equator radiates. c. everything on the earth and in the atmosphere stores, releases, and transfers heat. d. the earth warms in the winter and cools in the summer.	6. the ability of some objects to hold heat better than others.
8. List the four factors that govern the amount of insolation received by the earth.	7. c. everything on the earth and in the atmosphere stores, releases, and transfers heat.
9. When the air is heavily polluted or clouded, more/less direct insolation will be received. This is because of __________.	8. • solar constant • atmosphere's transparency • daily sunlight duration • sun's angle at noon
10. True or False? Oblique rays produce more heating per unit area than vertical rays do.	9. less, absorption of solar radiation by atmospheric gases
	10. False

Lesson 3

Circulation of the Atmosphere

Assignment

1. View the slide/tape presentation, *Pressure Systems, Winds, and Circulation,* which consists of tape SI:409-3 and slides 409-3-1 through 409-3-74. This presentation is an overview of the reading material in this lesson and in Lesson 4.
2. Read pages 3-15 through 3-20 of this guidebook.

Assignment Topics

- Atmospheric pressure
- Isobars and the pressure gradient
- Factors affecting wind motion
- Pressure systems

Lesson Goal and Objectives

Goal

To familiarize you with the atmosphere's scales of motion, atmospheric pressure, wind motion, and air masses in the Northern Hemisphere.

Objectives

Upon completing this lesson, you should be able to:

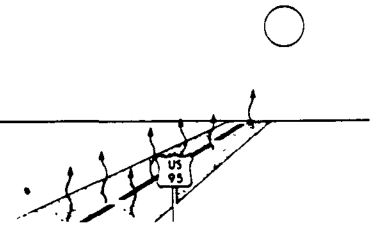
1. define high pressure and low pressure.
2. name three forces that determine wind direction and speed within the earth's friction layer.
3. describe the way cyclones and anticyclones are created by air movement.
4. name the four scales of motion of the atmosphere and recognize their size relationship to each other.

Pressure Systems, Winds, and Circulation

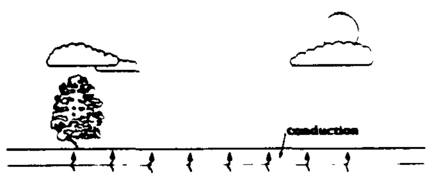
Slide	Script	Selected Visuals*
1.		**Pressure Systems, Winds, and Circulation**

2. Everything on the earth absorbs, stores, and then reradiates the sun's energy. Some parts of the earth heat more readily than other parts. This is known as differential heating. For example, in the summertime a plowed field heats quickly and stores vast amounts of heat. On the other hand, a large lake does not heat well.

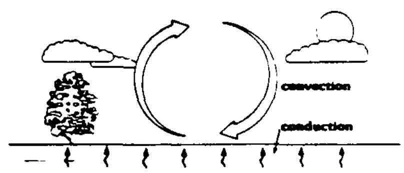
3. Differential heating of the earth affects the air above it. When the earth is warm, the air immediately above it becomes warm. This happens because heat always moves to an area of less heat.



4. This warming happens because of two principles. Conduction is the transfer of heat that takes place when something touches a heated surface. In this case, the air touches the heated earth and gains some of that heat.



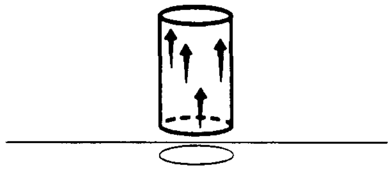
5. However, a few inches above the earth's surface, convection takes over the heat transfer process. Convection is vertical mixing of air. The warm air near the bottom rises, and as it rises displaces cooler air. This cooler air descends to within a few inches of the earth's surface where it is heated. This cycle continues as long as the earth is warmer than the surrounding air.



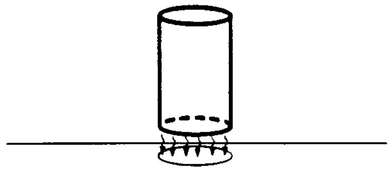
*illustrations included here, no live shots

Slide **Script** **Selected Visuals**

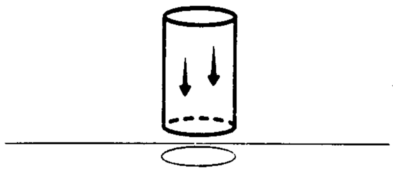
6. Picture an imaginary column of air above a warm spot on the earth. Since warm air holds moisture well, this warm air above the warm earth is moist, light, and buoyant. In fact, it is so buoyant that the air in the column rises—much as a balloon is light and buoyant and rises.



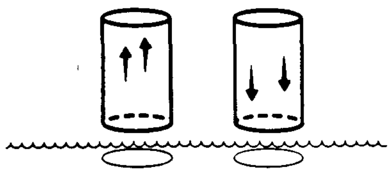
7. Now picture a similar column of air above a cold spot on the earth. Because the heat is moving toward an area of less heat, what little heat is in the air is transferred to the cool earth, leaving the air even cooler than it was.



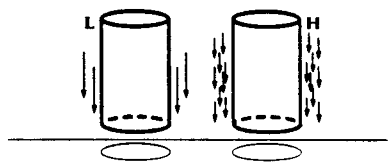
8. Since cool air does ***not*** hold moisture well, this cool air above the cool earth is dry and fairly heavy. It is ***not*** buoyant and does ***not*** rise. In fact, it may even descend.



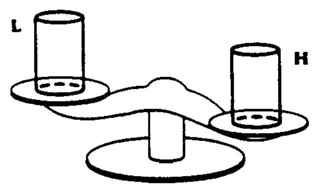
9. These same two situations can also occur over warm and cold bodies of ***water***. But ***wherever*** they occur, when the air is warm, light, and buoyant there is low pressure. When the air is cool, heavy, and ***not*** buoyant there is high pressure.



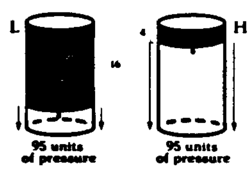
10. The term "pressure" refers to the weight of the air. In other words, it refers to the amount of force that the air exerts on the area directly ***below*** it.



11. The air in a ***low*** pressure area is light and buoyant, so it exerts relatively ***little*** pressure on the land below it. On the other hand, the air in a ***high*** pressure area is dense and heavy; therefore, it exerts a lot ***more*** pressure on the land below it. To help you remember which is which, associate the first letter of the word "low," an "L," with the word "light"; associate the first letter of the word "high," an "H," with the word "heavy."



12. Suppose two columns of air are each twenty centimeters tall and of the same diameter. Centimeter-for-centimeter, the high pressure column is heavier. For example, it might take only four centimeters of the heavier air to exert as much pressure as sixteen centimeters of the lighter air.



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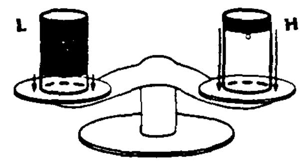
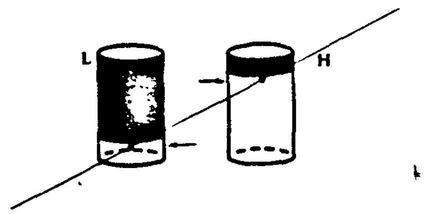
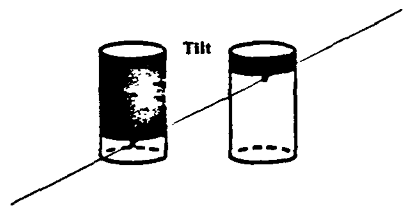
13. If we choose points of equal pressure, one will be near the bottom of the low pressure column, but the other will be near the top of the high pressure column.



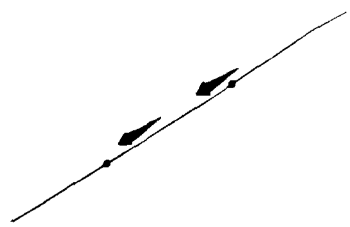
14. The relative positions of the points of equal pressure are important. In our imaginary columns, one point is high up in the column and the other is low in the column. If we connect these two points of equal pressure with a line, the line is slanted.



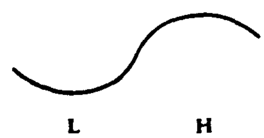
15. The line shows the steepness—or *tilt*—between points of equal pressure in the high and low pressure areas. This tilt is instrumental in the formation of wind.



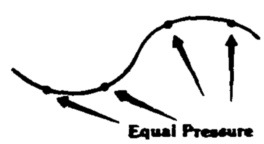
16. Wind is created by differences in pressure. Picture, again, the tilt of the pressure areas. Air flows down this tilted surface—much like a marble rolls down a hill. The steeper the tilt, the faster the air flows down it.



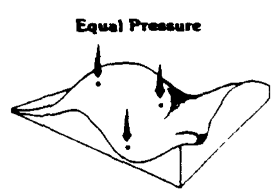
17. Of course, air isn't really found in columns. The cool and warm air found above the earth actually forms "hills" and "valleys" of high and low pressure. ~~Wherever there are "hills" of high pressure,~~ there will be associated "valleys" of low pressure.



18. Just as we could draw a line to connect points of equal pressure within our imaginary columns of air, we can represent points of equal pressure in our atmosphere by drawing the silhouette of these hills and valleys. This, of course, gives us only a two-dimensional picture.



19. Our atmosphere is actually three-dimensional. If we form a three-dimensional picture of the hills and valleys of high and low pressure, every part of the surface represents points of equal pressure. We can refer to this as a pressure surface.



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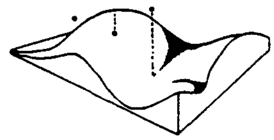
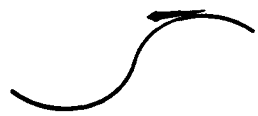
20. For example, every point on the surface has equal pressure exerted on it. Any point below the surface has more pressure exerted on it, and any point above the surface has less pressure exerted on it.



21. As we have seen, the pressure surface tilts and air flows downward along the surface.

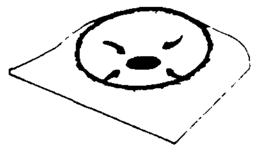
22. Generally, a large high pressure area—or hill—is only slightly tilted near its center, so the air flows relatively slowly there. We say that the wind is blowing lightly.



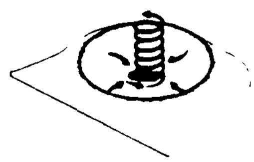
23. However, near its associated low pressure area—or valley—the tilt is steeper, somewhat like a cliff. Here the air flows faster, and we say that the wind is blowing strongly.

24. We can picture the air flowing down the pressure surface as if it were air flowing down the side of a hill. It is being pulled downhill by gravity.

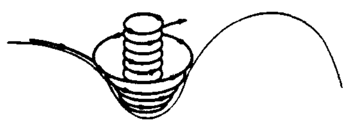
25. As it flows faster, it is affected by other forces in the atmosphere, and it begins to flow around and down in a counter-clockwise direction.*



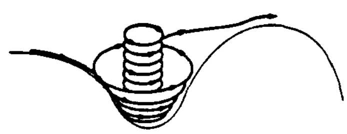
26. When the rotating wind hits the valley floor, it can spiral downward no further, so it starts spiraling up the center of the valley. We now have the ***start*** of a low pressure ***system.***



27. Unlike the low pressure ***area*** described earlier, the low pressure ***system*** has turning winds and is dynamic. The spiraling wind helps create more spiraling wind, which in turn helps keep it going. Until other factors in the atmosphere affect it, the air just keeps on spiraling.



28. The air coming out of the center of a low pressure system cools as it rises and more or less spills over onto the adjacent high pressure area. As the spilled air rotates down and around the high pressure ***area,*** it is referred to as a high pressure ***system.*** Thus the two systems help to perpetuate each other.



*in the Northern Hemisphere. Flow is clockwise in the Southern Hemisphere.

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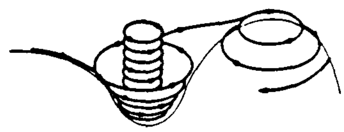
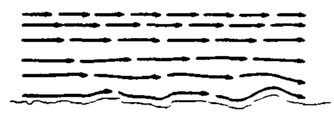
29. Where there is a low pressure system, there will ***always*** be an associated high pressure system.

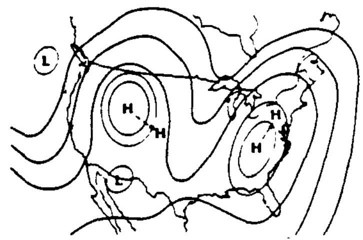


30. This is, of course, a simplified picture of how wind is created and how it flows. If the earth were smooth and slick, this simple picture would be quite accurate. However, the surface of the earth is neither smooth nor slick; therefore, there is friction. This friction causes the air flow near the surface to slow down and change direction.

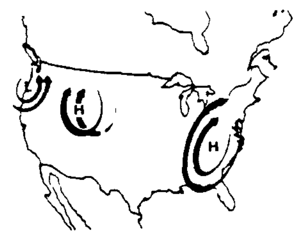
31. As we get further and further from the surface, friction becomes less and less of a factor in wind speed and direction. And finally, if we get high enough up into the atmosphere, friction doesn't affect wind at all. This point is called the planetary boundary layer. The effect of friction is to cause variations in the speed and direction of the wind created by the high and low pressure ***areas***.



32. The pressure areas that create wind and their associated pressure systems are short-lived. They form, stay around for a while, move to another location, and then dissipate.



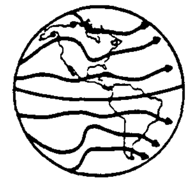
33. Pressure systems do not always form in the same place, and they are of various sizes.



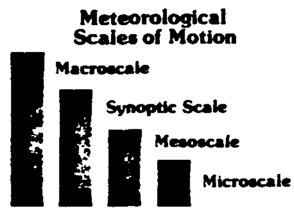
34. Consequently, the winds associated with them do not always cover the same area and do not always last for the same amount of time. The pressure areas and their associated winds are relatively localized.

Slide	Script	Selected Visuals

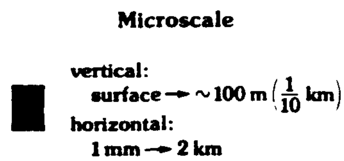
35. But this localized wind is ***not*** the only air flow in our atmosphere. There are very large areas of air circulating in our atmosphere. Unlike wind, these air flows are ***not*** caused by high- and low-pressure areas.



36. To describe larger air flows, and to compare them to the winds we have just described, we need some unit of measure or a scale. Meteorologists use four "scales of motion" to help describe the relative sizes of these and other meteorological phenomena.

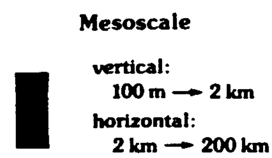


37. The smallest of these is the ***micro***scale. It covers a vertical distance of up to 100 meters and a horizontal distance of up to 2 kilometers.



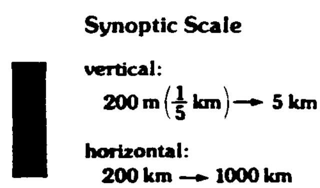
38. When a meteorologist reports that the winds at the airport are 11 kilometers per hour, he is describing microscale wind flow.

39. The ***meso***scale covers a vertical distance of up to 2 kilometers and a horizontal distance of up to 200 kilometers.



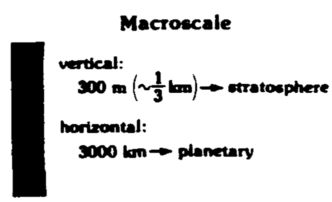
40. For example, thunderstorms are mesoscale phenomena.*

41. The third, the ***synoptic*** scale, covers a vertical distance of up to 5 kilometers and a horizontal distance of up to 1000 kilometers.



42. Low- and high-pressure systems are synoptic scale phenomena.

43. The fourth, and largest, scale is the ***macro***scale. It covers large portions of the earth or the whole earth.

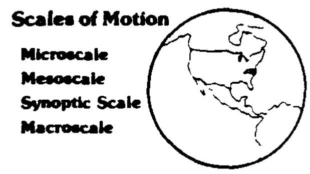


*This applies to the horizontal component; however, these reach much greater heights, depending on the severity of the storm.

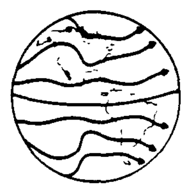
Slide | **Script** | **Selected Visuals**

44. The large areas of wind flow we are about to discuss are macroscale phenomena.

45. These four scales of motion—the microscale, the mesoscale, the synoptic scale, and the macroscale—can be used to help describe any meteorological phenomena.



46. We mentioned earlier the very large areas of air circulating in our atmosphere. We also said that these are macroscale phenomena. To help you understand the large areas of air flowing around our planet, pretend that the earth does ***not*** rotate. This will allow us to see what happens to these large areas of air in the atmosphere without the complications caused by rotation.



47. If the earth were not rotating, we would see a very predictable circulation pattern. Cells—or self-contained areas of rotating air—would extend from the equator to the poles.

48. Since the equator would receive more of the sun's radiation, the air there would be hotter than the air at the poles. The air at the equator would be warm, moist, and buoyant, and the air at the poles would be cold, dry, and heavy.

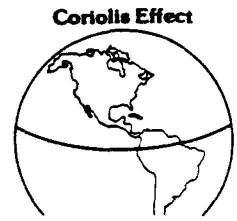
49. The warm, moist air at the equator would result in thunderstorms. The release of heat during the storms would cause the air to continue to rise and as it reached the upper limit of our atmosphere and could rise no further, it would begin to move toward the polar regions and continue to cool.

50. In the Northern Hemisphere, the air flow near the surface would always be out of the north because the cooler air from the North Pole would return to the equator to be reheated.

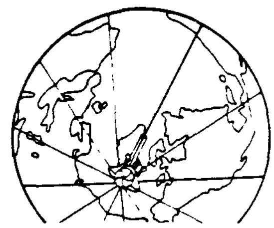
Slide **Script** **Selected Visuals**

51. But the earth ***does*** rotate. And this rotation takes the relatively simple air flow just described and changes it into a very complex situation. And it creates an air flow that is, in general, from west to east.

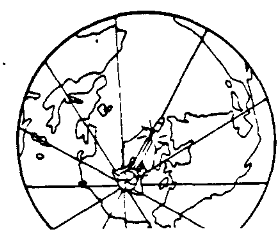
52. The air flow situation becomes complex because of a factor called the Coriolis effect. This effect makes all moving objects appear to turn to the right.



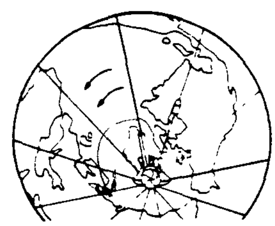
53. Suppose that you're standing on the North Pole. You have a rifle and you line it up with a specific longitude line.



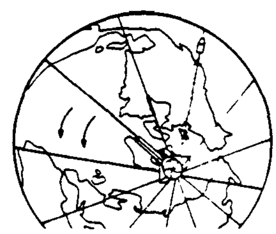
54. You fire the rifle, and the bullet begins to move ***straight ahead.***



55. However, since you are standing on the earth and it is rotating, you and the earth are rotating toward the left. The bullet, of course, continues on its straight path.



56. As you and the earth rotate further and further to the left, the bullet ends up more and more to the right of the original longitude line. Thus, in terms of your position—since you don't ***feel*** yourself rotating—the bullet seems to be moving to the right.



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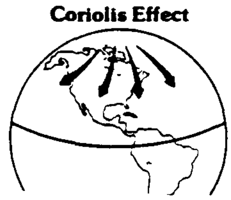
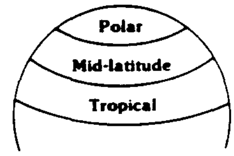
57. In a like manner, from ***our*** perspective in the Northern Hemisphere the atmosphere and air flow we described earlier turn to the right because we are rotating to the left with the earth. This is the Coriolis effect.

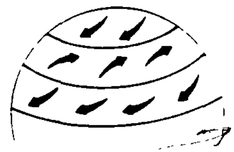


58. As the air flow turns to the right, it divides each of the hemispheres into three cells.

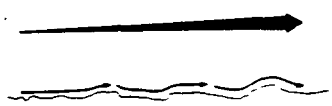
59. Consider the Northern Hemisphere. It has a polar cell, a mid-latitude cell, and a tropical cell.



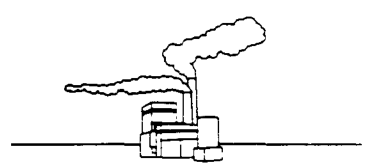
60. The air flow in these cells is not simple the way it was for our ***non***rotating earth. The air flow follows a spiral or corkscrew pattern. Thus, the air movement in the atmosphere is much more complex and much less predictable than would be the case if the earth did not rotate.



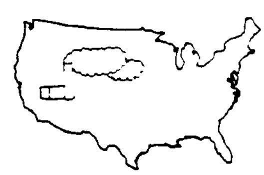
61. In addition to the large-scale circulation are the many winds that flow in various directions from hundreds of low- and high-pressure areas.



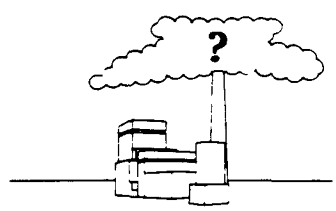
62. It's these variations of the west-to-east flow that make airflow over a given area difficult, and often impossible, to predict accurately.



63. If the wind flow were strictly from west to east—without variation—then it would be easy to predict the transport of air pollution. Pollution would always travel east from its source and would encircle the earth in a very predictable manner.



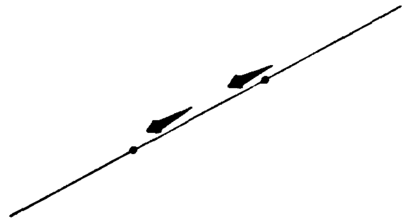
64. But since the basic west-to-east air flow is full of variations, it is often difficult to predict with any certainty where our pollution is going next.



Slide	Script	Selected Visuals

65. In the last lesson, we looked at the sun's radiation and how it affects the atmosphere and oceans of the earth.

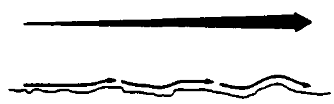
66. Then in this lesson we've talked about how differential heating causes pressure surfaces to tilt, and this tilt causes the wind to start flowing.



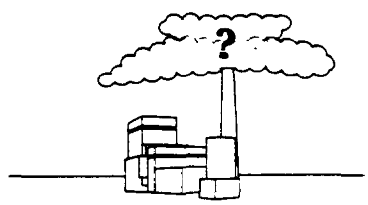
67. In addition to this localized air flow, there are large masses of air circulating in our atmosphere.

68. These air masses are affected by the earth's rotation and the Coriolis effect and become three large air cells in each of the hemispheres.

69. In general, the flow of air in our atmosphere is from west to east. This is because of the earth's rotation. But superimposed on this general west-to-east air flow are the localized winds that blow in various directions.



70. Therefore, predicting the direction and concentration of air pollutants must be based on long-term studies* using instruments and methods developed primarily for air pollution monitoring. These topics will be discussed in following lessons.



71. Credit: Crew

Pressure Systems

Script and Design: Donald Bullard
Monica Leslie
Marilyn Peterson
Graphics: Betsy Huber
Photography/Audio: David Churchill
Narration: Rick Palmer

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*To make accurate predictions, studies are needed to back up short-term judgements. These studies are based on actual experiences which are used as data for air quality models.

Slide	Script	Selected Visuals
72. Credit: Northrop		Lecture development and production by: Northrop Services Inc. under EPA Contract No. 68-02-2374
73. Credit: NET		Northrop Environmental Training

The General Circulation

Introduction

The previous lesson discussed the necessity of having a heat balance in the atmosphere. Heat was shown to transfer from the warm equatorial regions to the cold polar regions to maintain this heat balance. This transfer of heat is the main cause of atmospheric motion on the earth. The rotation of the earth modifies this motion but does not cause it, since the atmosphere essentially rotates with the earth.

If the earth did not rotate, rising air above the equator would move poleward, give up some of its heat, sink, and return toward the equator as a surface current. However, as Figure 3-1 illustrates, atmospheric circulation, as developed by Palmēn, is based on rotation that causes three major cells of wind flow in each hemisphere. The rotation causes a spiral pattern of wind flow from poles to equator. Winds in the Northern Hemisphere are deflected to the right; therefore, flow from the tropics toward the poles becomes more westerly and flow from the poles toward the equator tends to become easterly. The result is that most of the motion is around the earth in zonal patterns, with less than one-tenth of the motion between the poles and equator (meridional). In the latitudes of the westerlies, high speed winds blow from west to east near the tropopause. The winds, called polar front jet streams, are extremely forceful. The jet streams do not remain long in one position, but meander and are constantly changing position. This causes changes in the location of the polar front and perturbations along the front. Migrating cyclones and anticyclones result. These play an important part in heat exchange, transferring heat northward.

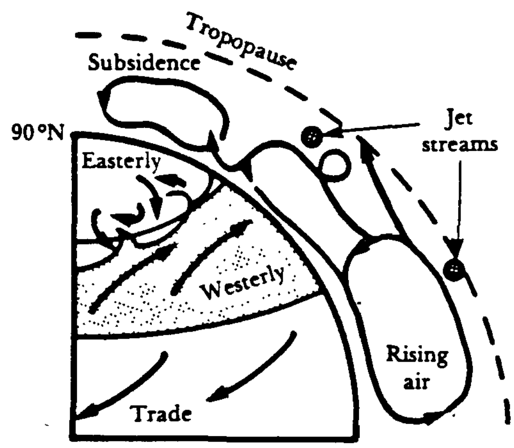


Figure 3-1. General circulation model.

Wind

Wind is the basic element in the general circulation of the atmosphere. Wind movements from small gusts to large air masses all contribute to transport of heat and other conditions of the atmosphere around the earth. Winds are always named by the direction from which they blow. Thus a "north wind" is a wind blowing from the north toward the south. If a wind vane is allowed to turn freely, it will always point into the wind. When wind blows more frequently from one direction than from any other, the direction is termed the *prevailing* wind.

Wind speed increases rapidly with height above the ground level, as frictional drag decreases. Wind is commonly not a steady current but is made up of a succession of gusts, slightly variable in direction, separated by lulls. Close to the earth, wind gustiness is caused by irregularities of the surface, which create eddies. Eddies are variations from the main current of wind flow. Larger irregularities are caused by convection—or vertical transport of heat. These and other forms of turbulence contribute to the movement of heat, moisture, and dust into the air aloft.

Creating Wind

Wind is nothing more than air in motion. Although the motion is in three dimensions, the horizontal component is the most useful for determining wind direction and speed. Three forces affect the wind: deflection (Coriolis), pressure gradient, and friction.

Coriolis Force

The first force, the Coriolis, is an apparent force. It occurs because wind flow above the earth has a tendency to move in a straight path while the earth rotates underneath. When viewed from the earth, especially from the poles, the wind will appear to be deflected to the right of the observer in the Northern Hemisphere and to the left of the observer in the Southern Hemisphere (Figure 3-2). This apparent force on the wind seems to

- increase as wind speed increases,
- remain at right angles to wind direction, and
- increase with an increase in latitude (i.e., exert more "force" as viewed from the poles than as viewed from the equator).

The effect of this deflecting force is to make the wind seem to change direction on earth. Actually, the earth is moving with respect to the wind.

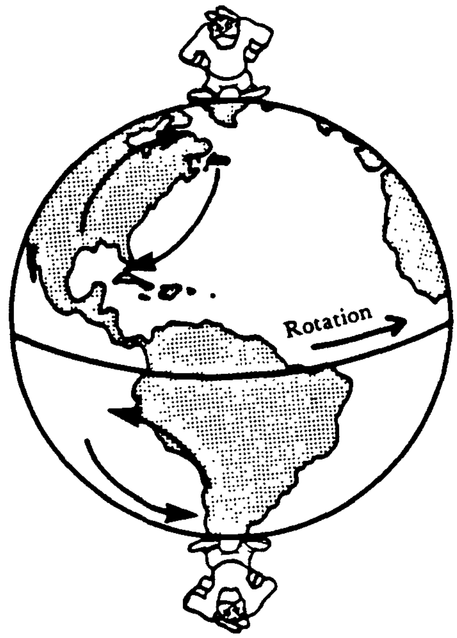


Figure 3-2. Coriolis (deflecting) force as seen from each pole.

Pressure Gradient Force

Wind is also caused by nature's attempt to correct differences in air pressure. Wind will flow from areas of high pressure to low pressure. Isobars, connecting points of equal pressure, may follow *straight lines or form rings around the highest or* lowest pressure in a geographic location.

The pressure gradient is the rate and direction of pressure change. It is represented by a line drawn at right angles to the isobars as shown in Figure 3-3. Gradients are steep where isobars are closely spaced. The wind will move faster across steep gradients. Winds are weaker where the isobars are farther apart because the slope between them is not as steep; therefore, wind does not build up as much force.

As we said, wind moves from areas of high to low pressure, but because of the Coriolis force (effect of the earth's rotation), wind does not flow parallel to the pressure gradient.

isobar lines

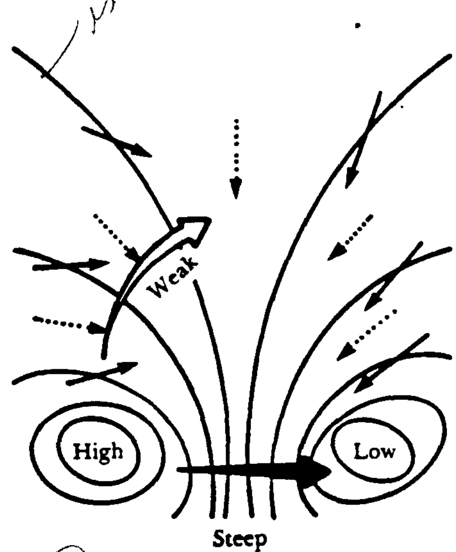


Figure 3-3. Pressure gradients.

high pressure → low pressure

Isobar line — constant pressure line

parallel to the constant pressure line

Friction

Friction, the third major force affecting the wind, comes into play at up to 1000 meters above the earth's surface. Above the friction layer and at latitudes greater than 20°, the Coriolis force and the pressure gradient force are in balance and the isobars are straight lines. As shown in Figure 3-4, the balanced forces create a wind that will blow parallel to the isobars. This is called the geostrophic wind. In the Northern Hemisphere low pressures will be to the left of the wind. The reverse is true in the Southern Hemisphere.

Within the friction layer, the Coriolis force, pressure gradient force, and friction all exert an influence on the wind. Isobars are curved or closed within the friction layer. The Coriolis force and the pressure gradient force are thrown out of balance due to frictional drag acting on one of the forces.

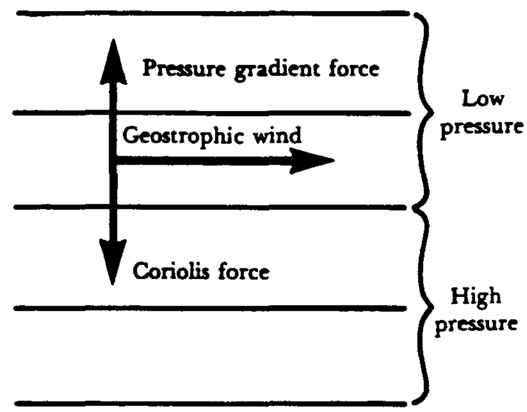


Figure 3-4. Balanced wind flow above friction layer (N. Hem.).

Pressure Systems

When friction reduces the influence of the Coriolis force on the wind's direction, the resultant wind is then influenced more by the pressure gradient force and begins to move from areas of high to low pressure, as shown in Figure 3-5. The difference between these two forces is the centripetal acceleration, or net acceleration, toward the center. In the Northern Hemisphere the air will curve counterclockwise. This motion causes the formation of a cyclone, a pressure system with its lowest pressure in the center. This system is represented by closed isobars around the low.

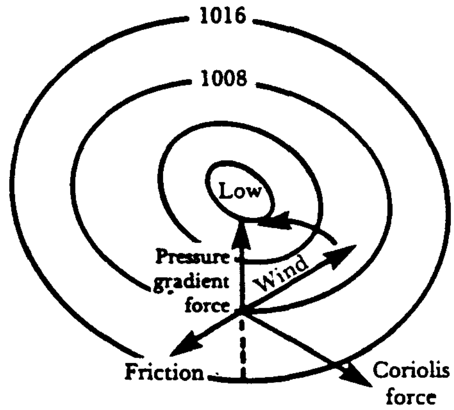


Figure 3-5. Unbalanced wind flow within friction layer toward low pressure (cyclone).

In the case of an anticyclone, the pressure force accelerating outward must be exceeded by the Coriolis force, as shown in Figure 3-6. This will cause the air to accelerate centripetally toward the center and move in a circular clockwise path in the Northern Hemisphere. The highest pressure will be in the center and the winds will blow out from the center.

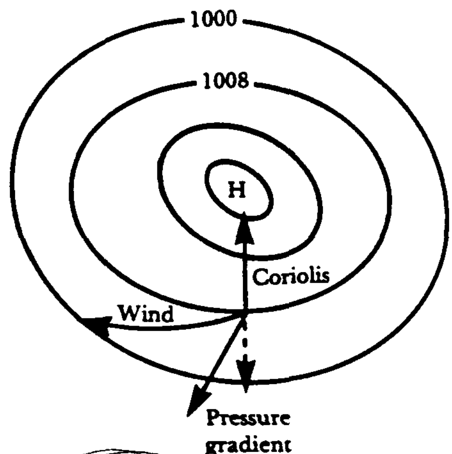


Figure 3-6. Wind flow around a high pressure system.

after 1000 miles, loses friction w/ earth

Therefore, as shown in Figure 3-7, the combined effects of pressure gradient force, Coriolis force, and friction cause airflow in a cyclone to be *convergent*, with surface winds flowing obliquely across the isobars toward the center of the low. In an anticyclone the circulation is *divergent*, with surface winds moving obliquely across the isobars outward from the center. This is a two-dimensional representation of pressure. As shown in the slide program for this lesson, systems are actually three-dimensional, appearing as adjoining hills and valleys of air. Pressure systems are represented on weather maps as illustrated in Figure 3-8. (Note that a pressure system is depicted by the isobars forming a circle around the high or low.) The relationship of cyclones and anticyclones to weather patterns will be discussed in the next lesson.

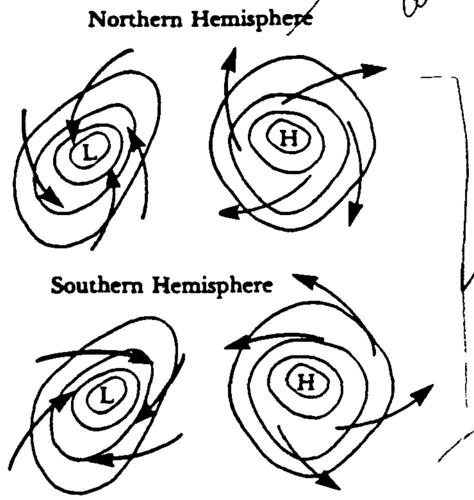


Figure 3-7. Cyclone and anticyclone circulation.

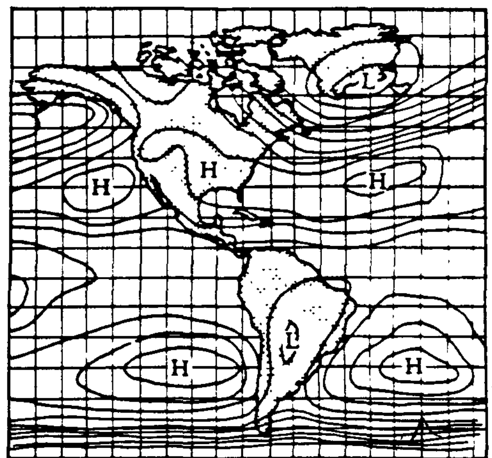


Figure 3-8. Pressure systems.

Wind turns toward lower pressure.

$$\frac{\bar{U}_z}{\bar{U}_0} = \left(\frac{z}{z_0}\right)^n$$

Review Exercise

1. Most of the air motion in the atmosphere is zonal, or __________ the earth, while only one-tenth is meridional, or __________.	
2. Palmén's model divides the earth into __________ cells in each hemisphere. a. two b. three c. four	1. around, between equator and poles
3. Since the earth rotates, the Coriolis force makes the wind appear to ____________________ in the Northern Hemisphere.	2. b. three
4. In reality, with respect to the Coriolis force, the wind follows a straight/curved path while the earth rotates underneath.	3. turn to the right
5. When air touches the heated earth and in turn becomes warm, __________ has just occurred.	4. straight
6. The heating process that causes the vertical mixing of the air above the earth's surface is a. conduction. b. convection.	5. conduction
7. Lines that represent points of equal pressure are called __________.	6. b. convection.
8. The air in a low-pressure area is a. light and buoyant. b. light and dense. c. heavy and buoyant. d. heavy and not buoyant.	7. isobars
9. The tilt or steepness between isobars is called the __________.	8. a. light and buoyant.
10. Strong winds are associated with __________-spaced isobars.	9. pressure gradient
	10. closely

Lesson 4

Frontal Systems

Assignment

Read pages 4-3 through 4-8 of this guidebook.

Assignment Topics

- Fronts
- Air masses

Lesson Guidance

The graphic representations of frontal zones are greatly simplified. For a more accurate cross-sectional picture and more information refer to the text by Saucier given in Supplementary Reading.

Lesson Goal and Objectives

Goal

To familiarize you with the basic characteristics of warm fronts, cold fronts, occluded fronts, and introduce some of the effects that fronts have on pollution in the atmosphere.

Objectives

Upon completing this lesson, you should be able to:

1. identify three frontal systems from descriptions or pictures representing each.
2. describe the physical situation of slope, clouds, and precipitation found with each front.
3. describe the effects of warm and cold fronts on pollution trapping.
4. identify the two properties that define an air mass.
5. recognize, by region of origin and symbol, the six classifications of air masses.

Supplementary Reading

If more information is needed about frontal systems, the following references are suggested:

Saucier, W. J. 1955. *Principles of Meteorological Analysis*. University of Chicago Press. Pages 134 through 142, 345 through 348.

Slade, D. H. editor. *Meteorology and Atomic Energy*. 1968. Section 2.34, pages 21 through 24.

Anticyclones, Cyclones, and Fronts

Migrating areas of high pressure (anticyclones) and low pressure (cyclones) and the fronts associated with the latter are responsible for the day-to-day changes in weather that occur over most of the mid-latitude regions of the earth. The low pressure systems in the atmospheric circulation form along frontal surfaces separating masses of air having different temperature and moisture characteristics. The formation of a low pressure system is accompanied by the formation of a wave on the front consisting of a warm front and a cold front, both moving around the low pressure system in a counterclockwise motion. This low pressure system is referred to as a cyclone. The life cycle of a typical cyclone is shown in Figure 4-1. The triangles (▲) indicate cold fronts and the semicircles (◓) indicate warm fronts. The five stages depicted here are:

1. beginning of cyclonic circulation,
2. warm sector well defined between fronts,
3. cold front overtaking warm front,
4. occlusion (merging of two fronts), and
5. dissipation.

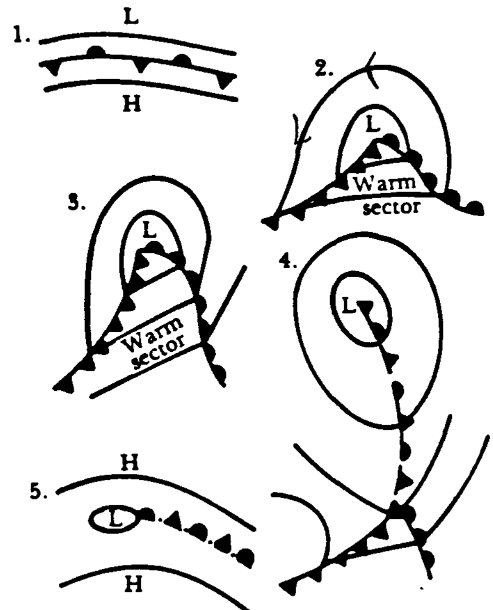


Figure 4-1. Life cycle of a cyclone.

Four frontal patterns—warm, cold, occluded, and stationary—can be formed by air of different temperatures. The *cold front* (Figure 4-2) is a transition zone between warm and cold air where the cold air is moving in over the area previously occupied by warm air. Cold fronts generally have slopes from 1:50 to 1:150, meaning that for every 1 kilometer of vertical distance covered by the front, there will be 50 to 150 kilometers of horizontal distance covered. The rise of warm air over an advancing cold front and the subsequent expansive cooling of this air lead to cloud cover and precipitation following the position of the surface front. (The surface front is the location where the advancing front touches the ground.)

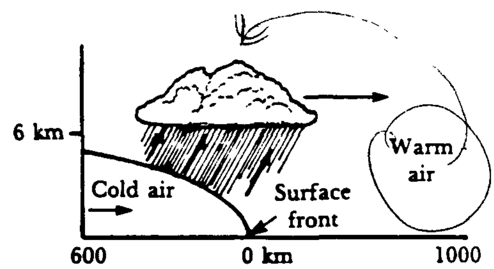


Figure 4-2. Advancing cold front.

Warm fronts, on the other hand, separate advancing warm air from retreating cold air and have slopes on the order of 1:100 to 1:300 due to the effects of friction on the trailing edge of the front. Precipitation is commonly found in advance of a warm front, as can be seen in Figure 4-3.

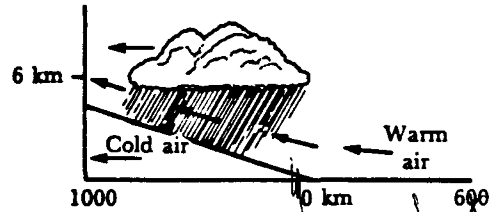


Figure 4-3. Advancing warm front.

When cold and warm fronts merge—the cold front overtaking the warm front—*occluded fronts* form (Figure 4-4). Occluded fronts can be called cold front or warm front occlusions, as shown in Figure 4-5, but, in either case, a colder air mass takes over an air mass that is not as cold.

As either type of occluded front approaches, the clouds and precipitation resulting from the occluded front will be similar to those of a warm front (Figure 4-3). As the front passes, the clouds and precipitation will resemble those of a cold front (Figure 4-2). Therefore, it is often impossible to distinguish between the approach of a warm front and the approach of an occluded front. Regions with a predominance of occluded fronts have a great deal of low cloud cover, small amounts of precipitation, and small daily temperature changes.

The last type of front is the *stationary front*. As the name implies, the air masses around this front are not in motion. It will resemble the warm front in Figure 4-3 and will manifest similar weather conditions. Figure 4-6 shows how a stationary front is represented on a map. The abbreviations cP and mT stand for continental Polar and maritime Tropical air masses. A stationary front can cause bad weather conditions that persist for several days.

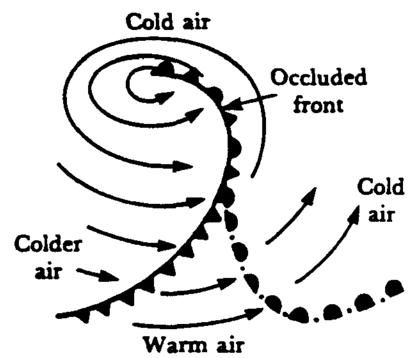


Figure 4-4. Occluded front.

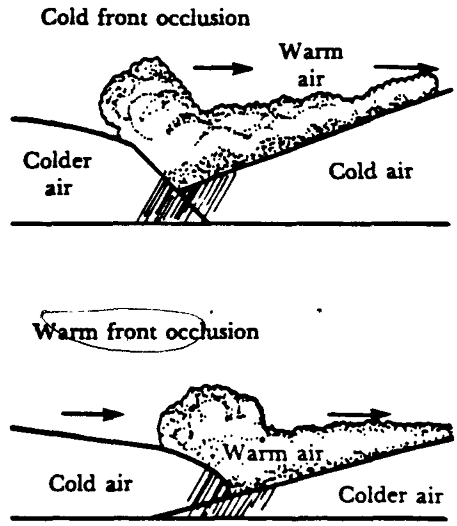


Figure 4-5. Cold and warm front occlusions.

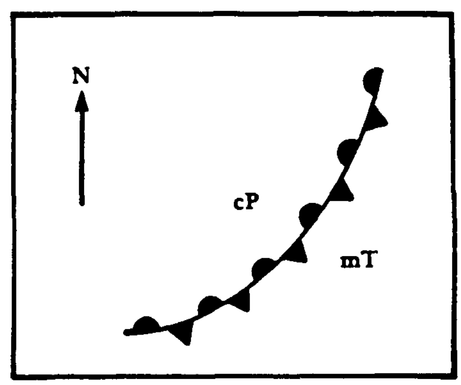


Figure 4-6. Stationary front represented on a map.

Frontal Trapping

Frontal systems are accompanied by inversions. Inversions occur whenever warm air rises over cold air and "traps" the cold air beneath. Within these inversions there is relatively little air motion, or the air becomes relatively stagnant. (In Lesson 5, we will discuss the effect of inversions on air pollution concentrations.) This frontal trapping may occur with either warm fronts or cold fronts. Since a warm front is usually slower moving than a cold front, and since its frontal surface slopes more gradually, trapping will generally be more important with a warm front. In addition, the low level and surface wind speeds ahead of a warm front—within the trapped sector—will usually be lower than the wind speeds behind a cold front.

Most warm frontal trapping will occur to the west through north from a given pollutant source, and cold frontal trapping will occur to the east through south of the source.

Air Masses

Air masses are macroscale phenomena, covering hundreds of thousands of square miles and extending upward for thousands and ten thousands of feet. They are relatively homogeneous volumes of air that have acquired the characteristics of a certain world region. The processes of radiation, convection, condensation, and evaporation condition the air over a period of several days into an air mass. Air masses develop more commonly in some regions than in others. These areas of formation are known as *source regions* and they determine the classification of the air mass. Air masses are classified as *maritime* or *continental* according to origin over ocean or land, and *arctic, polar,* or *tropical* depending principally on the latitude of origin. Table 4-1 summarizes air masses and their properties. Fronts generally separate air masses. Figure 4-7 shows an advancing warm front between Tropical maritime (mT) and Polar continental (cP) air masses.

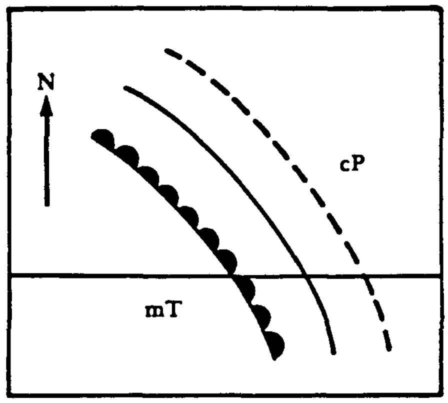


Figure 4-7. Warm front between two air masses.

Weather characteristics of an air mass depend on two basic properties: the vertical distribution of temperature and the vertical distribution and amount of moisture. The first property, in addition to indicating a warm or cold air mass, indicates the *stability* of the air mass. Stability influences the extent of vertical movement of the air mass in the atmosphere. Stability, an important influence on the spread (dispersion) of air pollution, will be covered in the next lesson.

Moisture is the second basic property in an air mass. Moisture plays such a significant role in weather and climate that it is commonly treated separately from the other constituents of air. In one or more of its forms, atmospheric moisture is a factor in humidity, cloudiness, precipitation, and visibility. Water vapor and clouds affect the transmission of radiation both to and from the

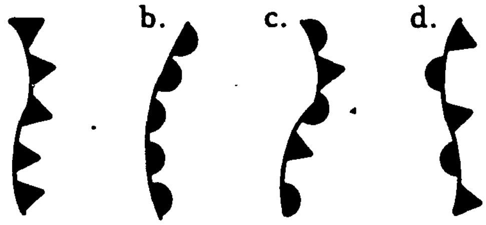
Table 4-1. Classification of air masses.

Name	Origin	Properties	Symbol
Arctic	Polar regions	Low temperatures, low specific but high summer relative humidity, the coldest of the winter air masses	A
Polar continental*	Subpolar continental areas	Low temperatures (increasing with southward movement), low humidity, remaining constant	cP
Polar maritime	Subpolar area and arctic region	Low temperatures, increasing with movement, higher humidity	mP
Tropical continental	Subtropical high-pressure land areas	High temperatures, low moisture content	cT
Tropical maritime	Southern borders of oceanic subtropical, high-pressure areas	Moderate high temperatures, high relative and specific humidity	mT
Equatorial	Equatorial and tropical seas	High temperature and humidity	E

*The name of an air mass, such as Polar continental, can be reversed to continental Polar, but the symbol, cP, is the same for either name.

earth's surface. Through the process of evaporation water vapor also conveys latent heat into the air, giving it a function in the heat exchange (as well as in the moisture exchange) between the earth and the atmosphere. Atmospheric water is gained by evaporation but lost by precipitation. Only a minute fraction of the earth's water is stored as clouds and vapor in the atmosphere at any one time. The net amount at the end of any given period for a particular region is an algebraic summation of the amount stored from a previous period, the gain by evaporation, the gain or loss by horizontal transport, and the loss by precipitation. This relationship expresses the water balance of the atmosphere. Moisture, as it relates to the stability of the atmosphere, will also be discussed in the next lesson.

Review Exercise

1. ________ fronts separate advancing warm air from retreating cold air. a. Warm b. Cold c. Occluded	
2. ________ fronts have slopes of from 1:50 to 1:150. a. Warm b. Cold c. Occluded	1. a. Warm
3. Generally, ________ fronts have a cloud cover and precipitation following the position of the surface front. a. warm b. cold	2. b. Cold
4. Match the following symbols with the fronts they denote. a. b. c. d.  • occluded • warm • stationary • cold	3. b. cold
5. Precipitation is generally found in advance of a ________ front. a. warm b. occluded c. stationary d. warm, occluded, or stationary	4. a. cold b. warm c. occluded d. stationary
6. Fronts generally separate ________.	5. d. warm, occluded, or stationary
7. Air masses are named by their source regions based on their origin over ________ or ________ and their ________.	6. air masses
	7. land, sea, latitude

8. List two land based air masses.	
9. The uniformity of an air mass is based on two physical properties. What are they?	8. • continental Polar • continental Tropical
	9. temperature moisture content

Lesson 5

Vertical Motion and Atmospheric Stability

Assignment

Read pages 5-3 through 5-21 in this guidebook.

Assignment Topics

- Principles related to vertical motion
- Stability and instability
- Stability and plume behavior

Lesson Guidance

This lesson includes simplified adiabatic diagrams. Adiabatic diagrams represent the average conditions in the area surrounding the site of the temperature profile. When temperature changes with spatial distribution, adiabatic diagrams are needed for each area.

Lesson Goal and Objectives

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 should be able to:

1. briefly explain the concept of buoyancy.
2. recognize the four major categories of lapse rates.
3. describe unstable conditions.
4. describe stable conditions.
5. define four types of inversions.
6. name five types of plume behavior and relate each to atmospheric conditions.

Supplementary Reading

If more information is needed about atmospheric stability, the following references are suggested:

Byers, Horace S. 1957. *Meteorology*. McGraw-Hill, pages 511 through 519.

Slade, D. H. editor. *Meteorology and Atomic Energy*. 1968. U.S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, TN, pages 42 through 45, 66 through 77.

Introduction

The two previous lessons discussed horizontal motion of the atmosphere. Vertical motion is equally important in air pollution meteorology, for the degree of vertical motion largely determines how much air is available for pollutant dispersal. 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.

Principles Related to Vertical Motion

Parcel

Throughout the lesson we will be discussing a *parcel* of air (also referred to as an air mass). This parcel is a relatively well-defined body of air (a constant number of molecules) that acts as a whole. Self-contained, except on its boundaries, 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

Holding other conditions constant, the temperature of air (a fluid) increases as atmospheric pressure increases, and conversely decreases as pressure decreases. The rate of change in atmospheric temperature with elevation is the *lapse rate*.

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. If the cooling does not reduce the parcel's temperature to that of the surrounding air, then the parcel has less mass than the cooler surrounding air. Therefore, it rises, or is buoyant. As it rises, its pressure decreases and, therefore, its temperature decreases as well. The initial cooling of a parcel has the opposite effect. In short, warm air rises and cools, while cool air descends and warms.

The extent to which a 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 it 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

Dry Adiabatic

A parcel of air does not exchange heat across its boundaries except by eddy diffusion at its surface. Therefore, any changes in temperature within the parcel are caused by increases or decreases of molecular activity within the parcel. Such changes, called *adiabatic*, are due only to the change in atmospheric pressure. The rate of adiabatic heating or cooling of a dry air parcel is 10°C/1000 m. This is known as the *dry adiabatic rate*. Air is considered dry, in this context, as long as any water in it remains in a gaseous state.

The dry adiabatic rate is a fixed rate, entirely independent of ambient air temperature. A buoyant parcel of dry air, then, will always cool at the rate of 10°C/1000 m, regardless of its initial temperature or the temperature of the surrounding air. You will see later that the dry adiabatic rate is central to the definition of atmospheric stability.

A simple adiabatic diagram demonstrates the relationship between elevation and temperature. (Elevation is also used to imply pressure in more complicated adiabatic diagrams.) The dry adiabatic rate is indicated by a broken line, as shown in Figure 5-1, 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.

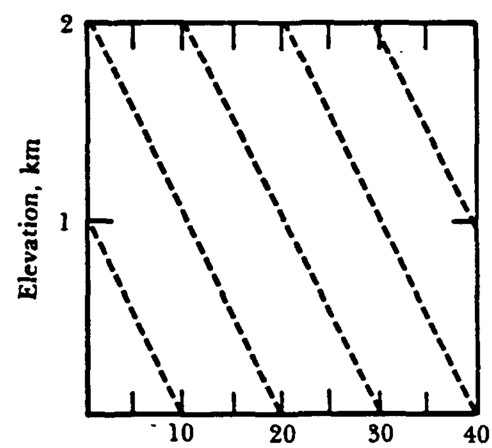


Figure 5-1. Dry adiabatic rate.

Wet Adiabatic

A rising parcel of dry air containing water vapor will continue to cool at the dry adiabatic 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 condenses. (Recall that cooler air holds less water vapor than does warmer air.) Condensation releases latent heat in the parcel, and thus the cooling rate of the parcel slows. This new rate, called the ***wet adiabatic rate,*** is shown in Figure 5-2. Because of differences in prevailing humidity, the wet adiabatic rate, unlike the dry rate, is not the same world-wide. In the middle latitudes, however, it is assumed to be approximately 6 °C/1000 m.

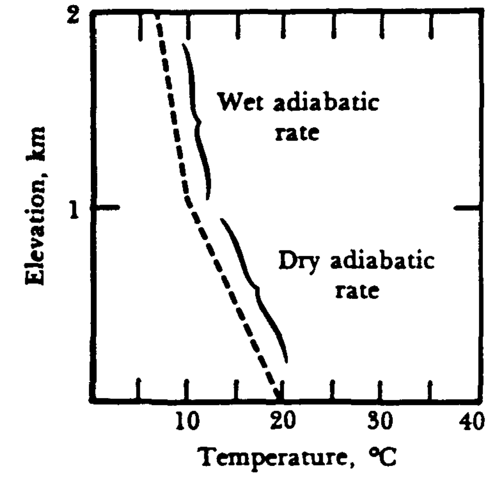


Figure 5-2. Wet adiabatic rate.

Atmospheric

The actual temperature profile of the ambient air is called the *atmospheric lapse rate*. Sometimes called the prevailing or environmental 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 5-3 shows, the temperature profile can vary considerably with altitude, sometimes changing at a rate greater than the dry adiabatic rate and sometimes changing less. When temperature actually increases with altitude, the atmospheric rate is negative. In Figure 5-4, this negative lapse rate occurs at elevations of from 200 to 350 meters. A negative rate is particularly important in air pollution, because it limits vertical air motion.

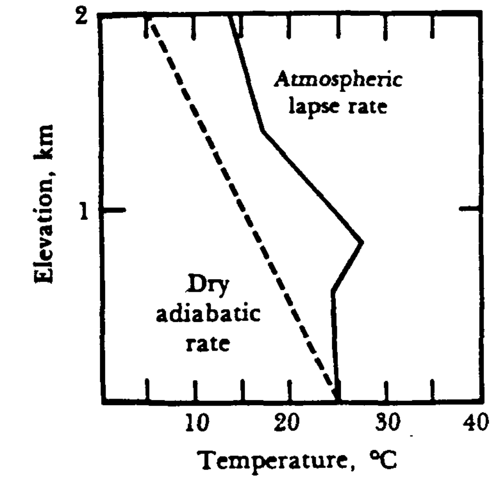


Figure 5-3. Atmospheric lapse rate.

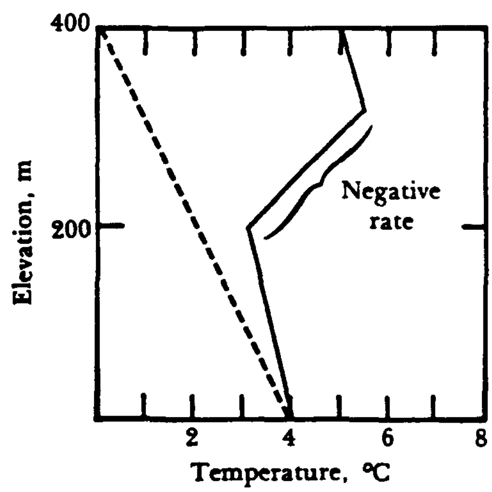


Figure 5-4. Negative lapse rate.

Mixing Height

Remember the analogy of the air parcel as a balloon. Figure 5-5 shows three ways in which the adiabatic rate affects buoyancy. In each situation assume that the balloon is filled at ground level with air at 20 °C, then transported manually to a height of 1 km. The air in the balloon will expand and cool to 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.

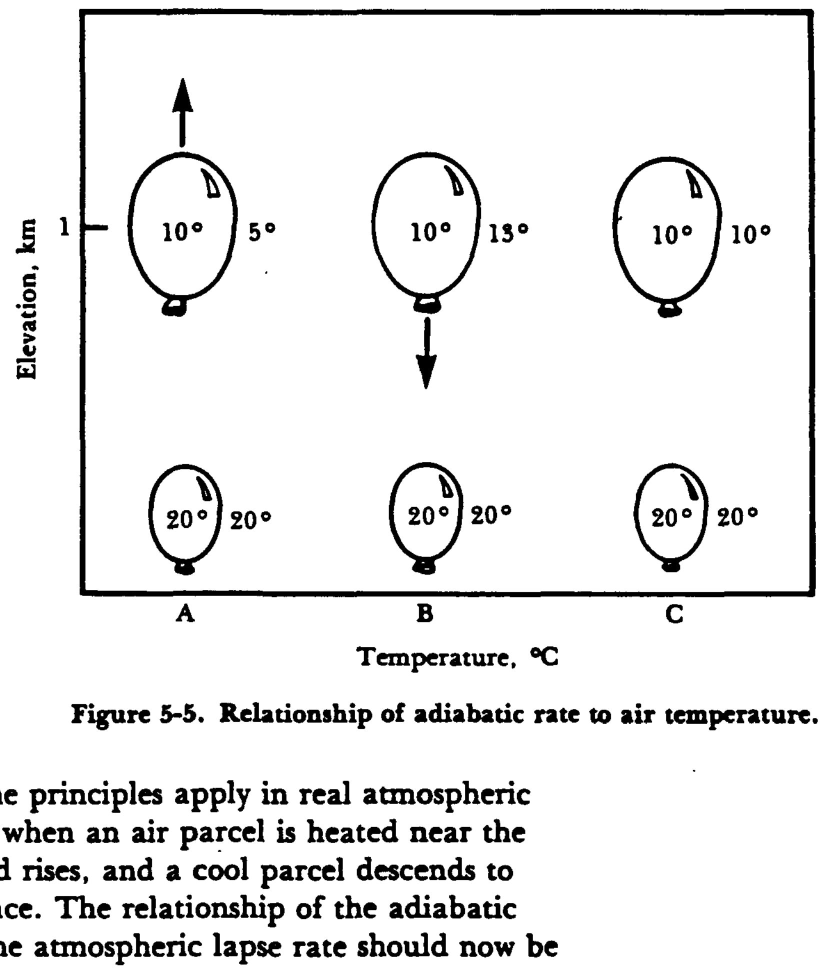


Figure 5-5. Relationship of adiabatic rate to air temperature.

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 rate and the atmospheric 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 5-6, the point at which the air parcel's adiabatic rate intersects the atmospheric lapse rate (temperature profile) is known as the *mixing height*. This is the air parcel's maximum level of ascendence. In cases where no intersection occurs (when the atmospheric lapse rate is consistently greater than the adiabatic rate), the mixing height may extend to the tropopause, the upper boundary of the lower atmosphere. The air below the mixing height is the *mixing layer*. The larger the mixing layer, the greater the volume of air in which pollutants can be diluted.

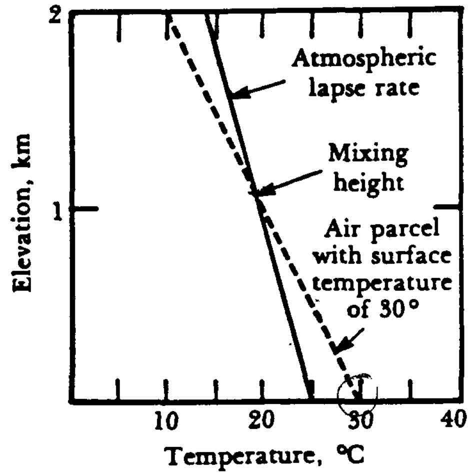


Figure 5-6. Mixing height.

Review Exercise

1. A relatively well-defined body of air that does not readily mix with the surrounding air is a(n) a. air column. b. air mass. c. air parcel. d. hot air balloon. e. b and c above	
2. The temperature of air increases/decreases as atmospheric pressure increases.	1. e. b and c above • air mass • air parcel
3. What two atmospheric factors influence the buoyancy of an air parcel?	2. increases
4. If the temperature of a parcel of air is cooler than the surrounding air, it will usually a. ascend. b. descend. c. stay in the same place.	3. temperature and pressure
	4. b. descend.

5. The atmospheric, or prevailing, lapse rate is the a. rate of pressure change in the atmosphere. b. rate of wet air vs. pressure change. c. temperature profile of the atmosphere. d. rate of frontal system passage.	
6. The change in the temperature of an air parcel due to a change in atmospheric pressure is called a. advective. b. adiabatic. c. slope. d. prevailing.	5. c. temperature profile of the atmosphere
7. The dry adiabatic rate is indicated by a ________ line of constant ________.	6. b. adiabatic.
8. The dry adiabatic rate is a. 6°C/1000 meters. b. <1°C/1000 meters. c. 10°C/1000 meters. d. 7.5°C/1000 meters.	7. broken, slope
9. True or False? The dry adiabatic rate is fixed, entirely independent of ambient air temperature.	8. c. 10°C/1000 meters.
10. The dry adiabatic rate becomes the wet adiabatic rate once it reaches the ________.	9. True
11. At the wet adiabatic rate, the cooling rate of the air parcel is usually a. the same as at the dry rate. b. slower than at the dry rate. c. faster than at the dry rate.	10. dew point (or condensation temperature)
12. True or False? The wet adiabatic rate is the same world-wide. At all latitudes it is 6°C/1000 meters.	11. b. slower than at the dry rate.
13. The actual temperature profile of the ambient air is the ________ lapse rate.	12. False
14. True or False? The atmospheric lapse rate influences the extent to which a parcel of air can rise or descend.	13. atmospheric
	14. True

15. The maximum level to which a parcel of air will ascend under a given set of conditions is known as the a. ascend/descend level. b. mixing trough. c. mixing height. d. mixing layer.	
16. The adiabatic lapse rate for a given air parcel will intersect the atmospheric lapse rate at the a. mixing trough. b. moisture rate. c. mixing height. d. none of the above	15. c. mixing height.
17. A large mixing layer implies that air pollutants have a greater/lesser volume of air for dilution.	16. c. mixing height.
	17. greater

Atmospheric Stability

The degree of stability of the atmosphere is determined by the temperature difference between an air parcel and the air surrounding it. This difference can cause the parcel to move vertically; i.e., it may rise or fall. This movement is characterized by four basic conditions that describe the general stability of the atmosphere. In *stable* conditions, this vertical movement is discouraged, whereas in *unstable* conditions the air parcel tends to move upward or downward and to continue that movement. When conditions neither encourage nor discourage air movement beyond the rate of adiabatic heating or cooling, they are considered *neutral*. When conditions are extremely stable, cooler air near the surface is trapped by a layer of warmer air above it. This condition, called an *inversion*, allows virtually no vertical air motion. These conditions are directly related to pollutant concentrations in the ambient air.

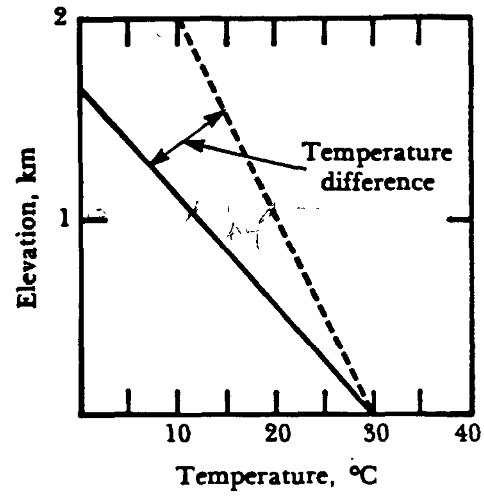


Figure 5-7. Enhanced buoyancy associated with instability (superadiabatic rate).

Unstable Conditions

Remember that an air parcel that begins to rise will cool at the dry adiabatic rate until it reaches the dew point. If the surrounding atmosphere has a lapse rate greater than the adiabatic rate (cooling at more than 10°C/1000 m), the rising parcel will continue to be warmer than the surrounding air. This is a *superadiabatic* rate. As Figure 5-7 shows, the temperature difference actually increases with height, and buoyancy is enhanced.

As the air mass rises, cooler air moves underneath. It, in turn, may be heated and begin to rise. Under such conditions, vertical motion in both directions is enhanced, and considerable vertical mixing occurs. The degree of instability depends on the degree of difference between dry adiabatic and environmental lapse rates. Figure 5-8 shows both slightly unstable and very unstable conditions.

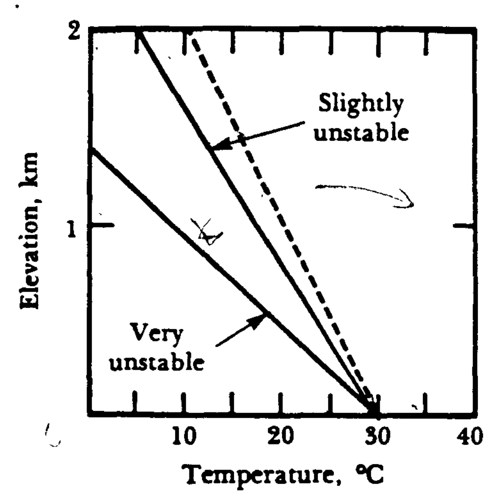
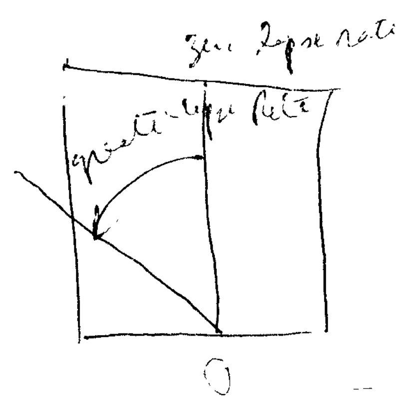


Figure 5-8. Unstable conditions.



Unstable conditions most commonly develop on sunny days with low humidity and low wind speed. The earth rapidly absorbs heat and transfers some of it to the surface air layer. There may be one buoyant air mass if the thermal properties of the surface are uniform, or there may be numerous parcels if the thermal properties vary.

Another condition that encourages instability is the cyclone (low pressure system), which is characterized by rising air, clouds, and precipitation.

Neutral Conditions

When the environmental lapse rate is the same as the dry adiabatic rate, the atmosphere is in a neutral condition (Figure 5-9). Vertical air movement is neither encouraged nor hindered. The neutral condition is important as the dividing line between stable and unstable conditions.

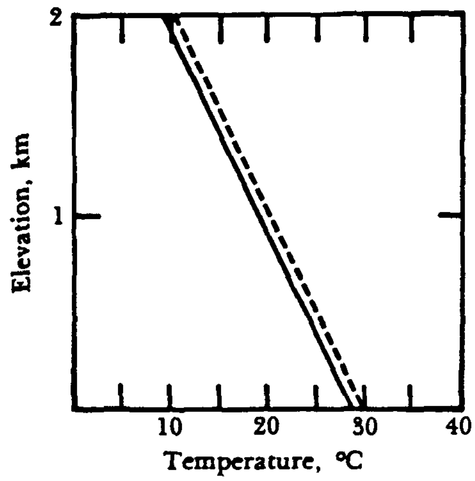


Figure 5-9. Neutral condition.

Stable Conditions

When the atmospheric lapse rate is less than the adiabatic rate (cools at less than 10 °C/1000 m), the air is stable and resists vertical motion. This is *a subadiabatic* rate. A rising parcel of warm air in stable conditions cools faster than its surroundings. At some point it reaches the same temperature as the surroundings and will not rise further. As with instability, the degree of stability depends on the difference between the atmospheric and adiabatic rates (Figure 5-10).

Stable conditions are most likely to occur when there is little or no wind on cloudy days with no strong surface heating, and at night.

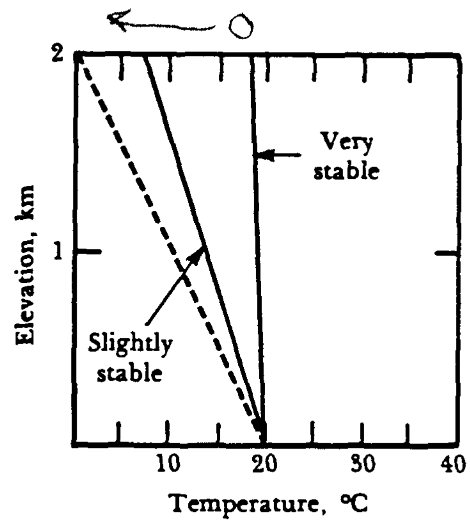


Figure 5-10. Stable conditions.

Conditional Stability and Instability

In the previous discussion of stability and instability, we have assumed the dry adiabatic rate for a rising air mass. Very often, however, the air mass reaches the dew point and begins to cool more slowly, at the wet adiabatic rate. This change in the rate of cooling may change the conditions of stability. Conditional instability will occur when the atmospheric lapse rate is greater than the wet adiabatic rate but less than the dry rate. This is illustrated in Figure 5-11. Stable conditions occur up to the condensation level and unstable conditions occur above it.

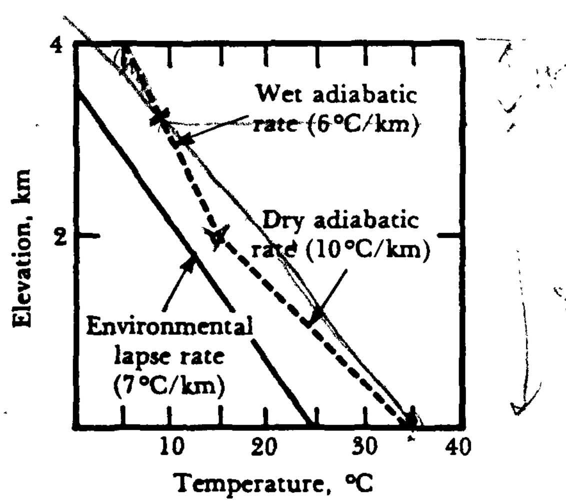
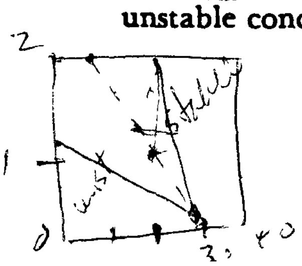


Figure 5-11. Conditional instability.



Inversions

An inversion occurs when the temperature of the atmosphere increases with altitude. An example of the lapse rate for an inversion is depicted in Figure 5-12. In effect, an inversion acts as a "lid" on vertical air movement and reduces the mixing layer; the air in the mixing layer is usually extremely stable. High concentrations of air pollutants are often associated with inversions. The four major types of inversions are caused by different atmospheric interactions and can persist for different amounts of time.

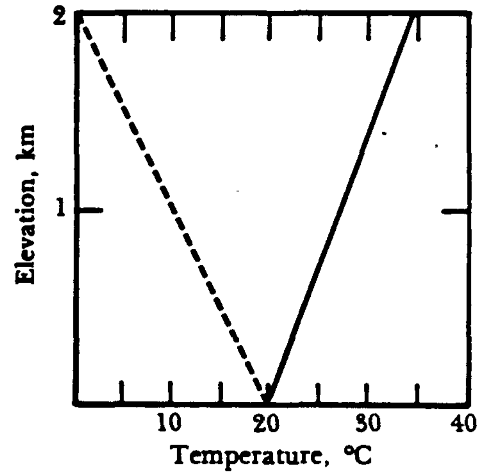


Figure 5-12. Temperature inversion.

Radiation

The radiation inversion is the most common form of surface inversion and occurs when the earth's surface cools rapidly. As the earth cools, so does the layer of air close to the surface. If this air cools to a temperature below that of the air above, it becomes very stable, and the layer of warmer air impedes any vertical motion (Figure 5-13).

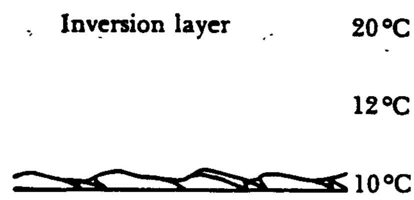


Figure 5-13. Radiation inversion.

Radiation inversions usually occur in the late night and early morning under clear skies, when the cooling effect is greatest. The same conditions that are conducive to nocturnal radiation inversions are also conducive to instability during the day. Diurnal cycles of daytime instability and nighttime inversions are relatively common. Therefore, the effects of radiation inversions are often short-lived. Pollutants trapped by the inversions are dispersed by vigorous vertical mixing after the inversion breaks down. Figure 5-14 illustrates this diurnal cycle.

In some cases, however, the daily warming that follows a nocturnal radiation inversion may not be strong enough to erode the inversion layer. For example, thick fog may accompany the inversion and reduce the effect of sunlight the next day. Under the right conditions, several days of radiation inversion, with increasing pollutant concentrations, may result. This situation is most likely to occur in an enclosed valley, where nocturnal, cool, downslope air movement can reinforce a radiation inversion and encourage fog formation.

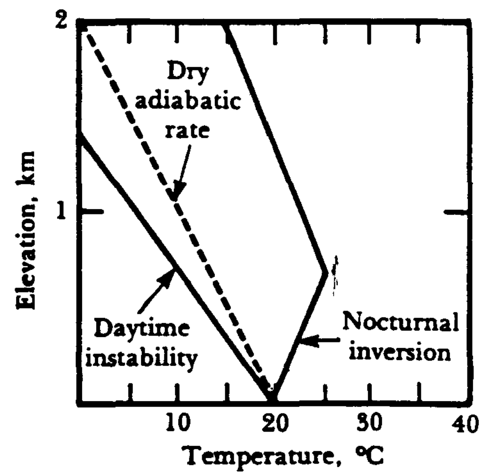


Figure 5-14. Diurnal cycle.

In locations where radiation inversions are common and tend to be relatively close to the surface, tall stacks that emit pollutants beyond the inversion layer can help reduce surface-level pollutant concentrations.

Subsidence

The subsidence inversion (Figure 5-15) is almost always associated with anticyclones (high pressure systems). Recall that air in an anticyclone descends and flows outward in a clockwise rotation. As the air descends, the higher pressure at lower altitudes compresses and warms it at the dry adiabatic rate. Often this warming occurs at a rate faster than the atmospheric lapse rate. The inversion layer thus formed is often elevated several hundred meters above the surface—during the day. At night, because of lower air cooling, the base of a subsidence inversion often descends, perhaps to the ground. In fact, the clear, sunny days characteristic of anticyclones encourage radiation inversions, so that there may be a surface inversion at night and an elevated inversion during the day. Although the mixing layer below the inversion may vary diurnally, it will never become very deep.

Subsidence inversions, unlike radiation inversions, last a relatively long time. This is because they are associated with both the semipermanent anticyclones centered on each ocean and the slow-moving migratory anticyclones moving generally west to east in the United States. When an anticylone stagnates, pollutants emitted into a mixing layer cannot be diluted. As a result, over a period of days, pollutant concentrations may rise. The most severe air pollution episodes in the United States have occurred either under a stagnant migratory anticyclone (New York, Pennsylvania) or under the eastern edge of the Pacific semipermanent anticyclone (Los Angeles).

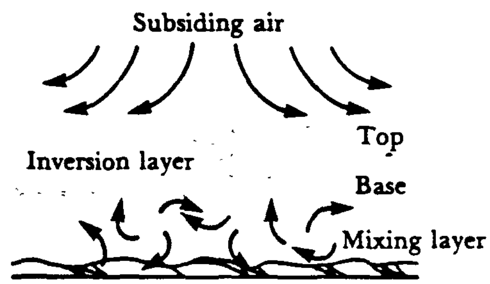


Figure 5-15. Subsidence inversion.

Frontal

Lesson 4 mentioned frontal trapping, the inversion that is usually associated with both cold and warm fronts. At the leading edge of either front, the warm air overrides the cold, so that little vertical motion occurs in the cold air layer closest to the surface (Figure 5-16). The strength of the inversion depends on the temperature difference between the two air masses. Because fronts are moving horizontally, the effects of the inversion are usually short-lived, and the lack of vertical motion is often compensated by the winds associated with the frontal passage. However, when fronts become stationary, inversion conditions may be prolonged.

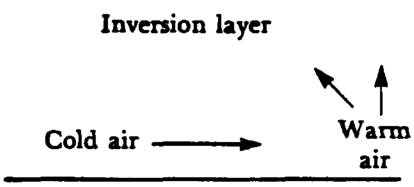


Figure 5-16. Frontal inversion (cold front).

Advective

Advective inversions are associated with the horizontal flow of warm air. When warm air moves over a cold surface, convection cools the air closest to the surface, causing a surface-based inversion (Figure 5-17). This inversion is most likely to occur in winter when warm air passes over snow cover or extremely cold land.

Another type of advective inversion develops when warm air is forced over the top of a cooler air layer. This kind of inversion is common on the eastern slopes of mountain ranges (Figure 5-18), where warm air from the west overrides cooler air on the eastern side of the mountains. Denver often experiences such inversions. Both kinds of advective inversions are vertically stable but may have strong winds under the inversion layer.

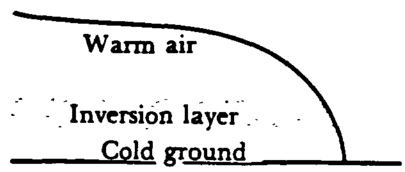


Figure 5-17. Surface-based advective inversion.

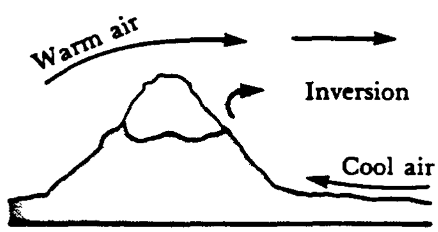
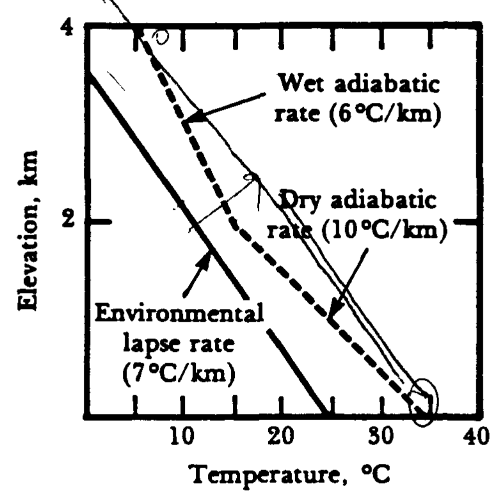


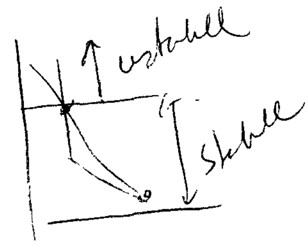
Figure 5-18. Terrain-based advective inversion.

Review Exercise

1. Vertical mixing due to buoyancy is increased when atmospheric conditions are a. unstable. b. neutral. c. stable. d. extremely stable.	
2. On cloudy days with no strong surface heating, atmospheric conditions are likely to be a. unstable. b. neutral. c. stable. d. extremely stable.	1. a. unstable.
3. Unstable atmospheric conditions most commonly develop a. on cloudy days. b. on sunny days. c. on cloudy nights. d. on clear nights.	2. c. stable.
4. The cyclone, or low pressure system, will generally encourage a. unstable conditions. b. neutral conditions. c. stable conditions. d. inversions.	3. b. on sunny days.
	4. a. unstable conditions.

5. This illustration depicts which stability category?
   a. stable below 1000 meters
   b. conditional stability above 1000 meters
   c. neutral from 0 to 2000 meters
   d. conditional instability above 2000 meters





6. A(n) __________ acts as a lid on vertical air movement.

5. d. conditional instability above 2000 meters

7. When the earth's surface cools rapidly, such as between late night and early morning under clear skies, a(n) __________ inversion is likely to occur.

6. inversion

8. When vigorous vertical mixing follows a radiation inversion, pollutant plumes will
   a. be trapped near the surface.
   b. be dispersed away from their source.

7. radiation

9. The subsidence inversion is associated with __________ because it usually forms high above/at the surface during the day.

8. b. be dispersed away from their source.

10. A subsidence inversion generally tends to last for a relatively short/long period of time compared to a radiation inversion.

9. anticyclones, high above

11. Surface-based inversions associated with horizontal air flow, such as when warm air moves over a cold surface, are called __________ inversions.
    a. subsidence
    b. frontal
    c. advective
    d. adiabatic

10. long

11. c. advective

Stability and Plume Behavior

The degree of atmospheric stability and the resulting mixing height have a large effect on pollutant concentrations in the ambient air. Although the discussion of vertical mixing did not include a discussion of horizontal air movement—or wind—you should be aware that horizontal motion does occur under inversion conditions. Pollutants that cannot be dispersed upward may be dispersed horizontally by surface winds.

The combination of vertical air movement and horizontal air flow influences the behavior of plumes from point sources (most commonly industrial stacks). Lesson 7 will discuss plume dispersion in greater detail. However, this lesson will describe several kinds of plumes that are characteristic of different stability conditions.

The *looping* plume of Figure 5-19 occurs in highly unstable conditions and results from turbulence caused by the rapid overturning of air. While unstable conditions are generally favorable for pollutant dispersion, momentarily high ground-level concentrations can occur if the plume loops downward to the surface.

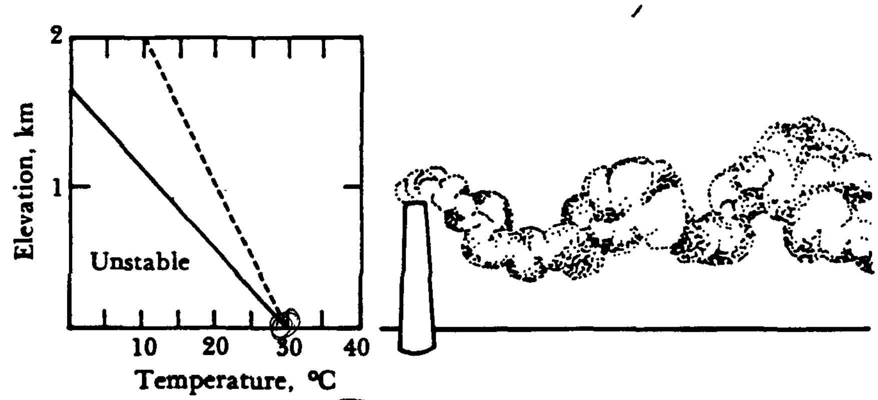


Figure 5-19. Looping plume.

The *fanning* plume (Figure 5-20) occurs in stable conditions. The subadiabatic lapse rate discourages vertical motion without prohibiting horizontal motion, and the plume may extend downwind from the source for a long distance. Fanning plumes often occur in the early morning during a radiation inversion.

– Stable and moves horizontally.

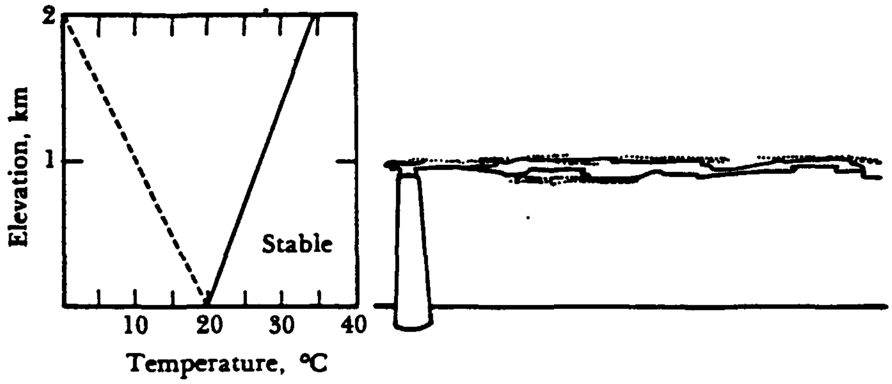


Figure 5-20. Fanning plume.

The *coning* plume (Figure 5-21) is characteristic of neutral conditions or slightly stable conditions. It is likely to occur on cloudy days or on sunny days between the breakup of a radiation inversion and the development of unstable daytime conditions.

Obviously a major problem for pollutant dispersion is an inversion layer, which acts as a barrier to vertical mixing. The height of a stack in relation to the height of the inversion layer may often influence ground-level pollutant concentrations during an inversion.

slowly spread around

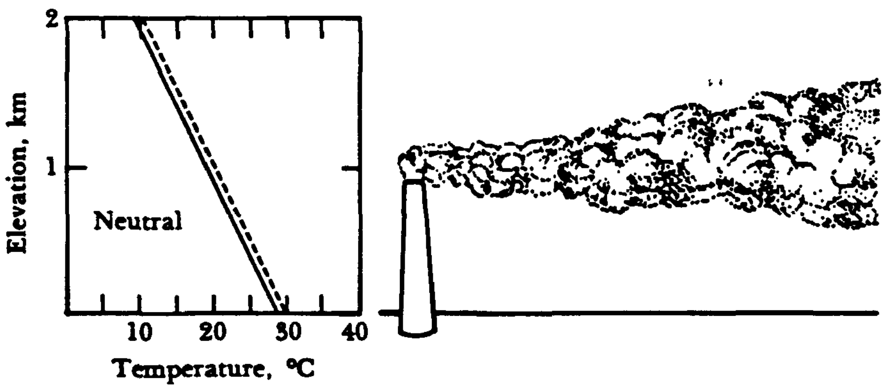


Figure 5-21. Coning plume.

When conditions are unstable above an inversion (Figure 5-22), the release of a plume above the inversion results in effective dispersion without noticeable effects on ground-level concentrations around the source. This condition is known as *lofting*.

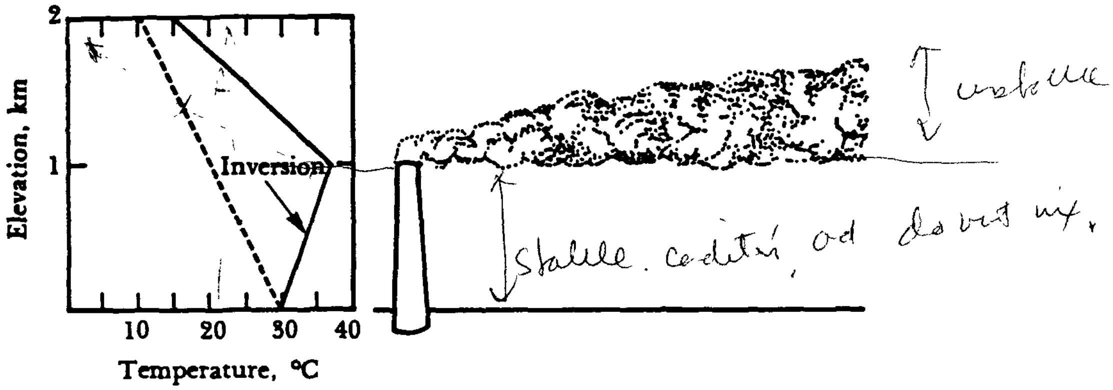


Figure 5-22. Lofting plume.

If the plume is released just under an inversion layer, a serious air pollution situation could develop. As the ground warms in the morning, air below the inversion layer becomes unstable. When the instability reaches the level of the plume that is still trapped below the inversion layer, the pollutants can be rapidly transported down toward the ground (Figure 5-23). This is known as *fumigation*. Ground-level pollutant concentrations can be very high when fumigation occurs. Sufficiently tall stacks can prevent fumigation in most cases.

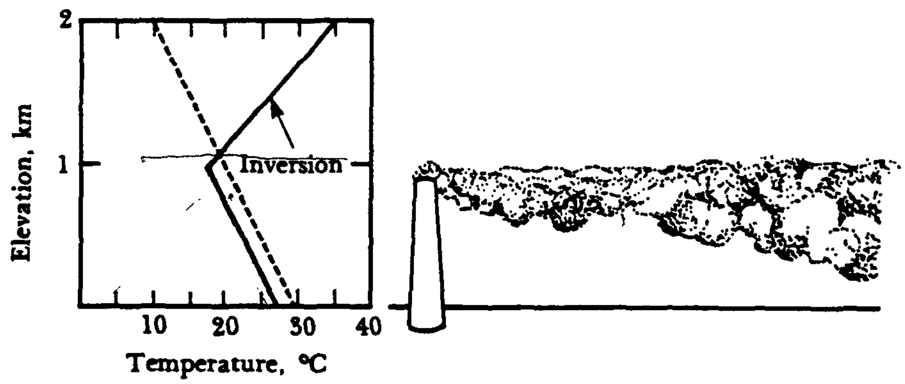


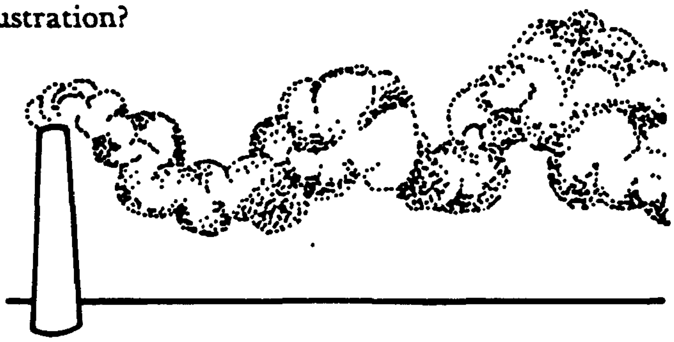
Figure 5-23. Fumigation.

Thus far you have learned the basic meteorological conditions and events that influence the movement and dispersal of air pollutants in the atmosphere. Lesson 7 explores more fully the behavior of pollutants around point sources, while the next lesson discusses the instrumentation used for meteorological measurement.

Review Exercise

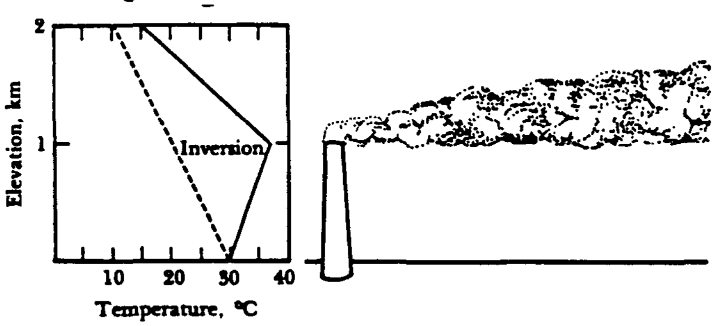
1. The ________ plume is characteristic of neutral or slightly stable atmospheric conditions.
   a. fanning
   b. looping
   c. coning
   d. lofting

2. What is the name of the plume depicted in this illustration?



1. c. coning

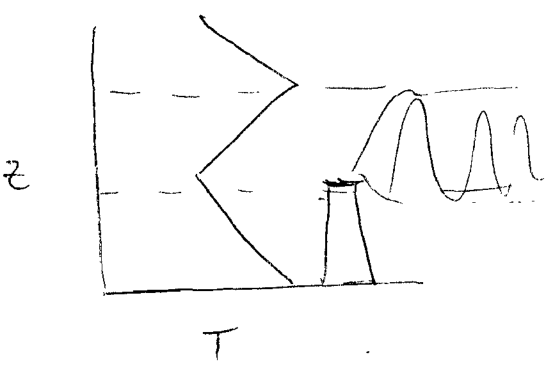
3. Which plume is represented by this lapse rate and stack height?



2. looping

3. lofting

4. A fanning plume will occur when atmospheric conditions are generally a. highly unstable. b. stable. c. neutral.	3. lofting
5. The looping plume can cause ________ ground-level concentrations of air pollutants.	4. b. stable
6. If a plume is released just <u>under/over</u> an inversion layer, a serious air pollution situation could develop.	5. high
7. The plume in this drawing is an example of a. coning. b. looping. c. fumigation. d. lofting. 	6. under
	7. c. fumigation.



Plume Trapping

Lesson 6

Meteorological Instruments

Assignment

View the slide/tape presentation, *Air Pollution Meteorology Instruments,* which is tape 409-6 and slides 409-6-1 through 409-6-77.

Assignment Topics

- Wind speed instruments
- Wind direction instruments
- Temperature instruments
- Instrument siting procedures

Lesson Goal and Objectives

Goal

To familiarize you with the meteorological instruments that measure and record the atmospheric variables of wind speed, wind direction, and temperature—especially those useful for air pollution studies.

Objectives

Upon completing this lesson, you should be able to:

1. associate three meteorological instruments with the atmospheric variables they measure.
2. recognize a wind speed instrument used for air pollution studies.
3. recognize a wind direction instrument used for air pollution studies.
4. describe the temperature sensor and recording system most useful for air pollution studies.
5. identify the role of the transducer in an instrument system.
6. describe the location of a temperature gauge on an active stack.

Supplementary Reading

1. Pages 6-3 through 6-38 in APTI Course 411 *Air Pollution Meteorology—Student Manual,* "Meteorological Instruments" and "Exposure of Instruments" by Ronald C. Hilfiker describe the instruments used by air pollution meteorologists as well as provide some background on the development of instruments.
2. Wilson, David J. and Dennett D. J. Netterville, "Influence of Downwind High-Rise Buildings on Stack Design," *Air Pollution Meteorology,* APCA Reprint Series, March 1977.

Air Pollution Meteorology Instruments

Slide	Script	Selected Visuals*
1.	No narration	FOCUS
2.		
3.		Air Pollution Meteorology Instruments
4.	In an industrialized society, the chemical makeup of the atmosphere is constantly changing.	
5.	Winds, heat, and other natural processes carry air pollutants from industrialized centers	
6.	to rural farm lands or into urban areas where they become trapped;	
7.	or up into the global circulation pattern.	
8.	Meteorological instruments have been developed that measure these natural processes.	
9.	Analyzing meteorological data helps forecast the routes and destinations of air pollutants,	
10.	and helps predict the amount of pollutant matter that will arrive at a new location. People working to solve air pollution problems can use this data to evaluate applications for locating new industrial sources and for changing existing sources.	

*illustrations included here, no live shots

Slide | **Script** | **Selected Visuals**

11. For air pollution meteorology studies, wind speed, wind direction, and temperature are the most important atmospheric variables to measure. They are responsible for the transport and dispersion of pollutants. To accurately forecast the fate of pollutants, we need to collect detailed information about these variables.

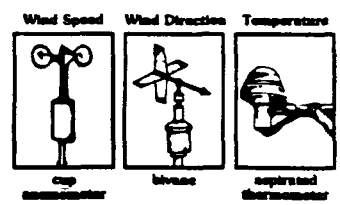
Wind Speed Wind Direction Temperature

12. In the past, many of the instruments used by meteorologists were not capable of providing this detail.

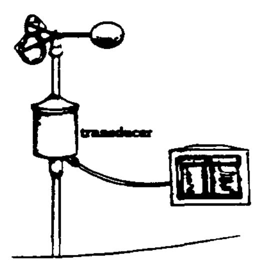
13. With increased concern about the impact of air pollutants on our environment and health, these instruments have been refined. Let's discuss the different instruments that measure and record these atmospheric variables. All of these instruments should, in general, be easy to operate, durable, accurate, precise, and sensitive.

14. Instruments that measure wind speed are anemometers. Instruments that measure wind direction are wind vanes. And, instruments that measure air temperature are thermometers.

Air Pollution Instruments

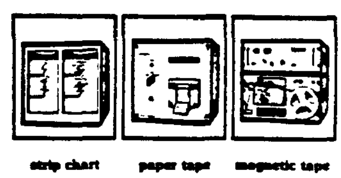


15. Once atmospheric energy is measured, it must be converted to energy that can be recorded so it can be analyzed. A transducer performs this function.



16. Other instruments display information in a readable form. These are recorders, and they record data continuously, digitally, or magnetically.

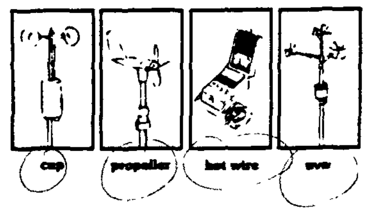
Recorders



Slide	Script	Selected Visuals

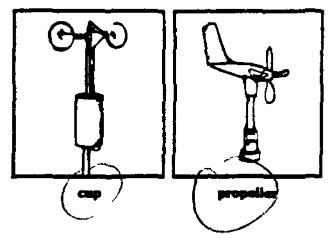
17. Wind speed can be measured by several different instruments or aerodynamic sensors that fall loosely under the general term "anemometer."

Wind Speed Instruments



18. The most commonly used and preferred wind speed sensors are "rotating anemometers." They revolve about a shaft that is positioned either vertically or horizontally, and they come in two designs: cup and propeller.

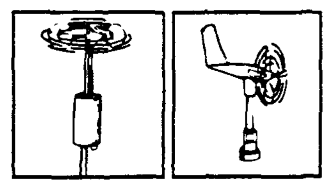
Rotating Anemometers



19. These rotating anemometers have several advantages that make them desirable. First, there is a direct relationship between cup or propeller rotation, and wind speed. In other words, as the wind speed increases, the cups or propellers rotate the movable spindle faster.

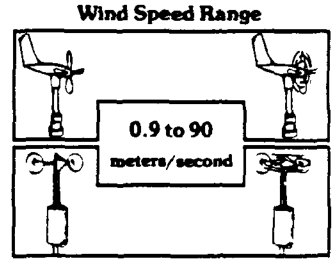
threshold speed not be needed.

Rotation ∝ Wind Speed

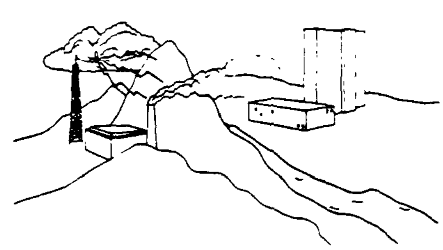


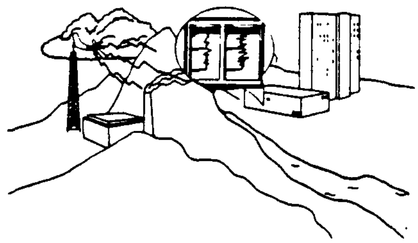
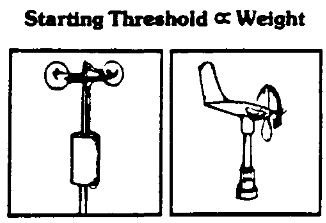
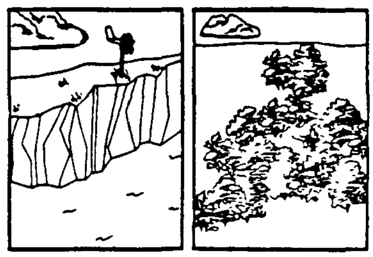
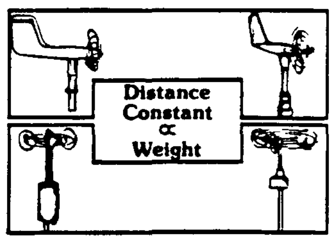
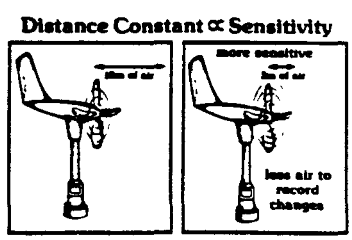
20. Second, rotating anemometers can measure a wide range of wind speeds—from approximately 0.9 meters to 90 meters per second.

Wind Speed Range



21. Third, once anemometers are calibrated, they measure consistently over several years of operation and are unaffected by changes in temperature, pressure, or humidity. Therefore, they require little maintenance.



Slide	Script	Selected Visuals
22.	And finally, data can be transmitted accurately to a remote location and recorded.	
23.	Previously, propeller and cup anemometers were constructed to withstand extreme weather conditions and to provide ***average*** information. Currently, their sensitivity is more important.	
24.	Sensitivity is determined by the "starting threshold," which is the wind speed required to start the anemometer turning. Low starting speeds are possible because newer cups or blades are made of lightweight aluminum or plastic. The most efficient ***cup*** anemometers have 3 cups rotating around a vertical shaft, while two or four ***blades*** are commonly found on lightweight ***propeller*** anemometers.	
25.	Blade size can vary from 15 to 45 centimeters. Smaller blades are used where high winds are likely to occur. Larger blades are used when lower starting speeds are desired as in areas where light winds might occur.	
26.	A design consideration common to both propeller and cup anemometers is the ***distance constant.*** It is the amount of wind that must pass by before the instrument responds to a certain change in wind speed. A lightweight instrument will be more responsive than will a heavy one. less dC is better instrument,	
27.	A more sensitive instrument will have a smaller distance constant. This instrument will respond quickly to rapid changes in wind speed. Therefore, the instrument with a smaller distance constant is more desirable for air pollution studies.	

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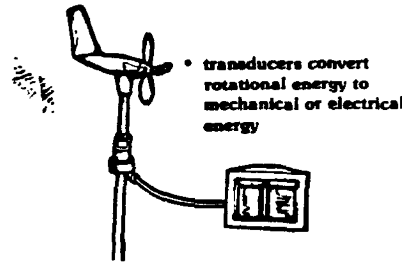
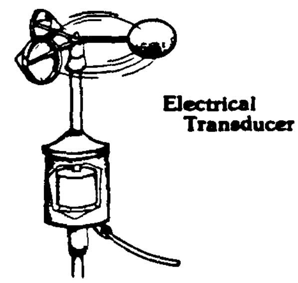
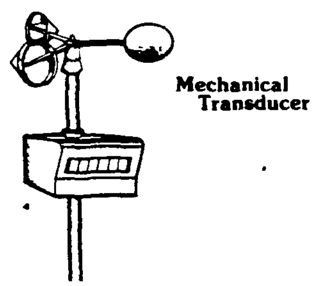
28. Once the wind speed is measured by a rotating anemometer, it must be transmitted to a recording device. This is achieved with a transducer. The transducer converts rotational energy to easily transmittable electrical or mechanical energy.



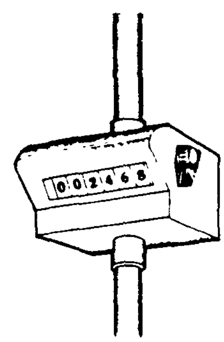
29. Electrical transducers have a rotating shaft that drives a small electrical generator. As the cups or propellers turn faster, the generator's voltage output increases. This output remains linear throughout the wind speed. Electrical transducers usually provide a ***time plot*** of the wind speed. In other words, the wind speeds for a certain time period can be recorded.



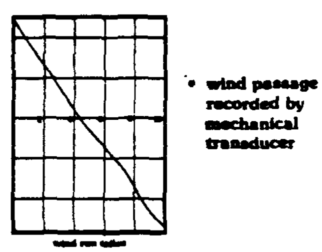
30. Anemometers with mechanical transducers are especially useful when the desired output is ***total miles*** of wind passage rather than a time plot of wind speed.



31. Mechanical transducers simply count or accumulate the number of turns of the cupwheel or propeller. The total number of turns per unit time depends on the linear displacement of wind or the "wind run" that occurs.



32. Data is then transmitted and the output is recorded continuously by event marker pens on strip charts. Strip chart recorders respond rapidly to changing electrical or mechanical outputs to produce a ***continuous*** record of instantaneous wind speed with time. This example shows wind passage recorded by a mechanical transducer.



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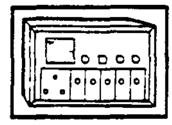
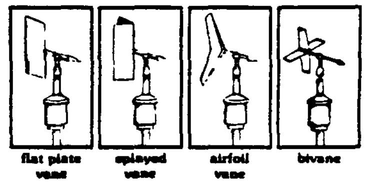
33. Electrical output can also be recorded by data loggers. Data loggers store instantaneous wind speed information in computer memory for later use.

Memory Analog Data Storage

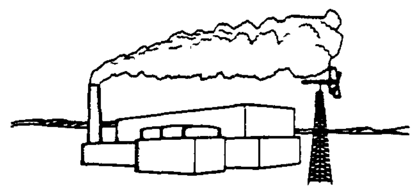


34. In addition to wind speed, another important wind factor is needed for air pollution studies. This is "wind direction." Wind direction is measured using a variety of instruments, including one of the oldest, the "wind vane." Many variations of the basic design have been marketed. The flat plate, splayed vane, air foil, and bivane are names of wind vanes referring to the tail design.

Wind Direction Instruments



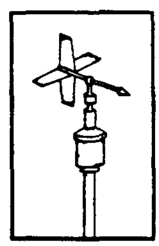
35. Wind determines the general direction that a pollutant travels. Typically, a wind vane is mounted asymmetrically and is free-turning on a vertical axis. It always points ***into*** the wind.



One point data

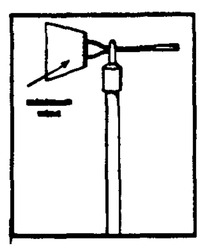
36. As with wind speed instruments, construction material determines the vane's primary use. Heavy vanes can measure only average wind direction. Lightweight vanes are much more sensitive to fine analyses of wind direction and turbulence. Their tails are made of thin gauge aluminum or plastic, or molded expanded polystyrene.

37. Of the wind vanes mentioned, the "bivane" is the most efficient for air pollution studies. Bivanes swing up and down as well as from side to side with changing wind direction, measuring horizontal and vertical wind movements. Bivanes are made of very light material and use low friction bearings resulting in an extra-responsive instrument.



Bivane

38. As with anemometers, there are important measurements of wind vane sensitivity. The first is the ***starting threshold.*** It is the minimum wind perpendicular to the tail surface that will cause the vane to turn.



Starting Threshold $\propto$ Weight

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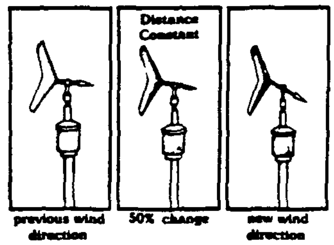
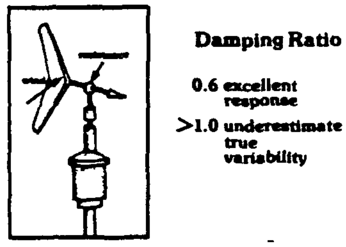
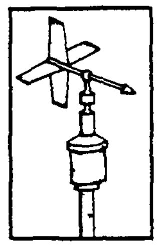
39. The ***distance constant*** is the length of wind that must pass the vane for it to respond to a 50% change in direction. (Pause).



40. And, the ***damping ratio*** is a measure of the vane's mechanical resistance to movement. Wind vanes with low ratios of about 0.6 give the best response to changes in wind direction. Instruments with ratios higher than 1.0 underestimate the true variability of the wind.



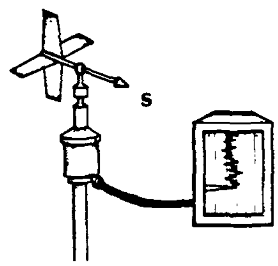
41. As with anemometers, the output signal for vanes is produced by a transducer and may be either mechanical or electrical.



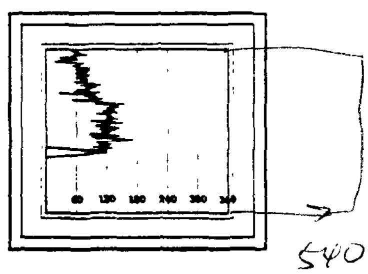
42. The signal relays the wind vane's position to a recording device. In this case the wind is blowing from the south.

Wind direction is circular,

0 - 540°



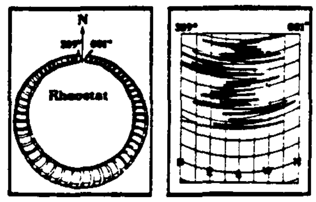
43. The recording device for a ***continuous*** record of wind direction is the strip chart similar to the chart used for wind speed. Strip chart recorders display all of the variations in the positions of the wind vane. These positions are recorded in degrees from true north.



Slide	Script	Selected Visuals

44. There is one drawback to using a 360° strip chart. A gap must be left in the electrical circuit. This gap is always pointed north. When the wind blows ***from*** the north the recorder pen wanders because the direction just east of north is on one side of the chart, and the direction just west of north is on the other side of the chart. The pen will swing from side to side as the wind fluctuates around north.

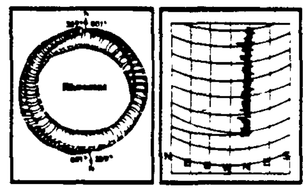
360° Strip Chart



45. To avoid the problem caused by the gap in the 360° circuit, a 540° chart was designed. Notice the new positions of north, east, south, and west on the chart. This chart keeps the pen trace in the central portion of the chart when wind is blowing from the north and eliminates the pen's side-to-side swing.

Reostat

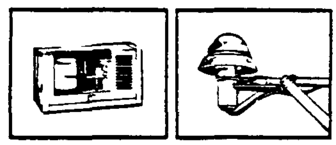
540° Strip Chart



46. The last instrument discussed in this presentation is the thermometer or temperature gauge. Thermometers sample ambient air temperature. Ambient air temperature is one of the important variables used to determine the large-scale stability of the atmosphere at a given location.

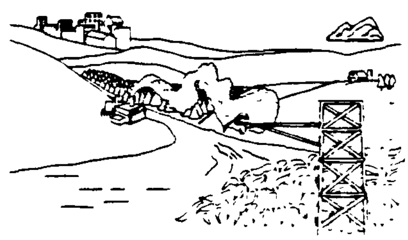
Less important compared to wind speed and direction,

Temperature Instruments



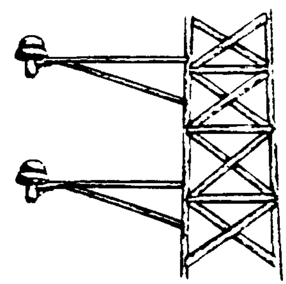
thermograph — aspirated thermometer

47. This information in turn helps predict the concentration and duration of air pollution for this location.



48. Since a measure of the vertical structure of the atmosphere is important, thermometers must be mounted at different heights from the surface throughout the lower atmosphere. These instruments must have an accurate system to measure and transmit data.

to calculate lapse rate,

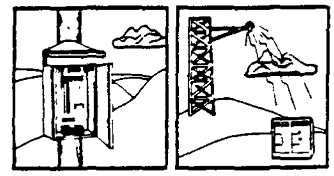


49. The electrical thermometer is accurate and is widely used in air pollution studies to measure temperature differences between heights in the atmosphere.

Slide	Script	Selected Visuals

50. Data from an electrical thermometer can be stored on a recording device at the instrument or transmitted to any location to be recorded. One recorder can store the temperature differences for several thermometers covering an entire area under study.

Temperature Recorders

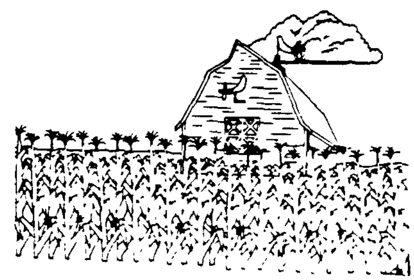


51. Unlike wind instruments, a rapid response rate from temperature sensors is not desirable. Temperature tends to be an air mass phenomenon, whereas wind tends to be localized and can change rapidly.

52. All instruments, including those discussed here, must be sited or placed correctly to get usable data. An instrument is sited correctly when it receives accurate data about the area of interest.

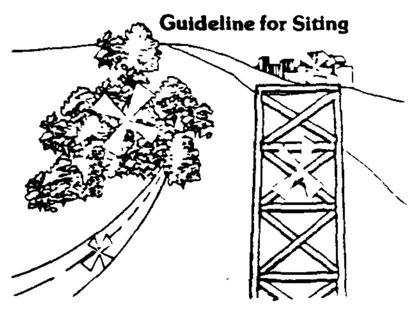
Instrument Siting

53. In other words, if you want to know the average wind direction across a particular field, where would you locate a wind vane—on the barn's roof or under its eaves? The correct location—on the roof—is probably obvious. However, many factors influence instrument siting.



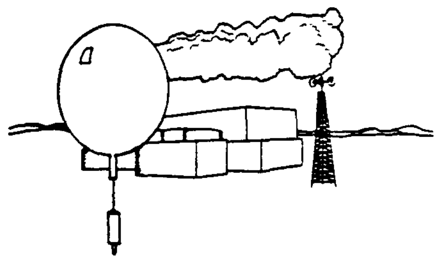
54. Wind measurements that represent a fairly large geographic area are often needed. The United States Environmental Protection Agency has approved guidelines to be followed when siting instruments.

55. The general rule is that the instrument's accuracy should not be influenced by outside factors such as buildings, trees, towers, or pavement.

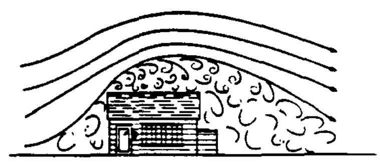


Slide	Script	Selected Visuals

56. Wind speed and direction instruments are usually sited together. Instruments are sited in three general areas: on or near a surface, on towers, and aloft.

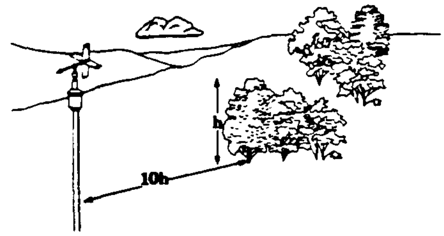


57. Since air flow around obstructions on the surface is turbulent, a random location of the instrument would not give accurate readings. Instruments must be placed above or outside the turbulent "cavity" area produced by the obstruction.

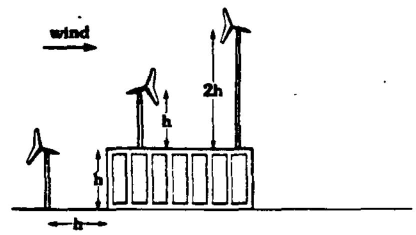


10 times

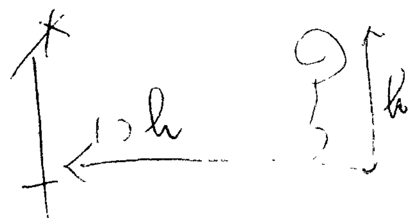
58. In a field, an instrument should be placed at a distance 10 times the height of the tallest object at the edge of the field. For example, if a tree is 10 feet tall, the instrument would be placed 100 feet away from it.



59. For a building standing alone in open terrain, the site should be one building height above the roof on the upwind side or at least twice the building height above the roof on the downwind side. For instruments sited away from a building, the distance should be one building height away on the upwind side.



60. When several buildings are clustered together, as in an urban situation, the guidelines are no longer so simple. The siting location depends on the information needed for the study. The needed information could be about street level winds or about general urban-wide winds. If uncertainty about siting arises, then professional advice should be sought.

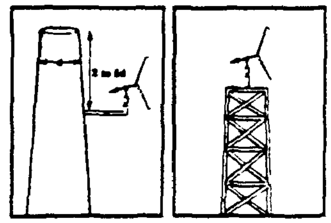


61. In a valley or on rough terrain, the influence of local effects such as channeling and trapping on general wind flow patterns must be determined. Then a decision must be made whether to sample the local effects, the larger pattern,—or both—for purposes of the study. Siting procedures for hills and ridges are as difficult as those for a city since they produce similar flow patterns.

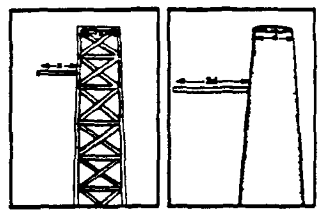
Slide **Script** **Selected Visuals**

62. Temperature instruments located near the earth's surface must be shielded from sources of heat, such as concrete parking lots and buildings, and out of ***direct*** light from the sun. Otherwise, temperature readings may be too high. Therefore, thermometers are usually encased in white louvered containers.

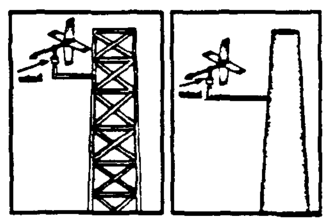
63. If instruments must be sited on closed stacks or open towers, the instruments should not be influenced by them. Instruments should never be located within 2 to 5 stack diameters of the top of an active stack. A location on top of a tower above the turbulent cavity will generally give accurate readings.



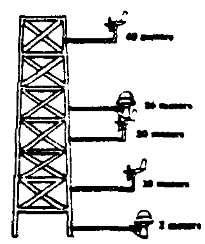
64. When locating any instruments on the side of a tower or stack, they should be placed out on a boom. On a tower they should be out by one side length. On a stack they should be out twice the stack diameter.



65. Wind vanes should be put on a boom that faces into the most frequent wind direction.



66. Wind and temperature instruments are placed in a different manner. The spacing between instruments is important for proper readings. Wind sensors are spaced logarithmically apart because wind speed is approximately logarithmic with height. Temperature sensors are placed vertically 13 meters or more apart.



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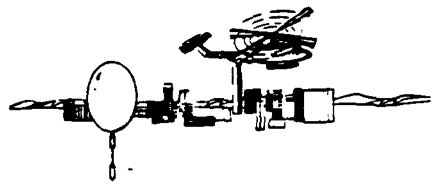
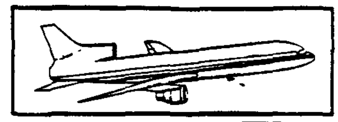
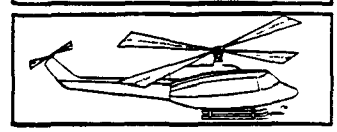
67. To obtain pollution information about the general circulation pattern, instruments are sited aloft in balloons, aircraft, and rockets. Balloon launchings should be in areas free from obstructions.



68. Instruments on aircraft should be located at least two feet forward of the wingtips. On helicopters, the forward tip of the skids is the most accurate location, provided the helicopter is moving forward fast enough to project downwash behind the sensor. If recorders are located inside the aircraft, mounting them in plastic or sponge rubber will reduce vibrations.





69. Most recorders for airborne instruments, however, are remotely located. If recorders are part of a radar or radio tracking equipment system, this equipment should be located on top of a hill with few or no obstructions on the horizon.

70. In summary, correct instrument siting is crucial to obtain usable data for air pollution studies. Whether to site near the surface, on stacks or towers, or aloft depends on which atmospheric phenomena are most useful to the study.

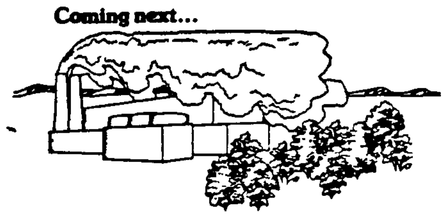
71. Anemometers, vanes, and thermometers as well as other instruments used to sample atmospheric variables have been modified for air pollution study purposes. These instruments are an optimum combination of sensitivity, durability, accuracy, preciseness, simplicity, and convenience.

72. Air pollution forecasters monitor and record atmospheric conditions to anticipate pollution buildup and to predict areas where that buildup is most likely to occur.

73. This information helps air pollution control agencies decide where to locate new industrial sources and which geographical areas may be in danger from overpollution.

Slide | **Script** | **Selected Visuals**

74. The next lesson discusses the dispersion of pollutant plumes through the atmosphere and their effect on the environment.



75. Credit: Crew

Air Pollution Meterology Instruments

Technical Content: Donald Bullard
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Photography/Audio: David Churchill
Narration: Rick Palmer

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Review Exercise

For questions 1 through 3, match the appropriate meteorological instrument with the atmospheric variable that it measures.

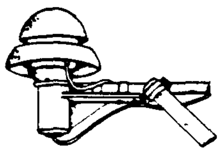
1. anemometer
2. wind vane
3. thermometer

a. wind direction
b. wind speed
c. temperature

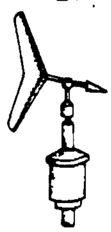
---

4. From the following meteorological instruments, choose an anemometer.

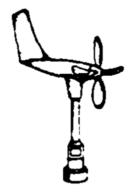
a.



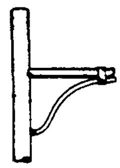
b.



c.



d.

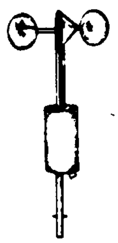


1. b. wind speed
2. a. wind direction
3. c. temperature

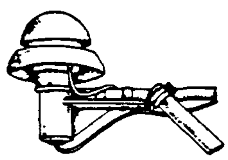
---

5. From the following meteorological instruments, choose a wind vane.

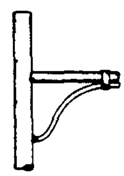
a.



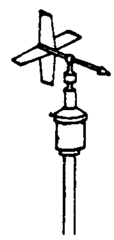
b.



c.



d.



4. c.

---

6. A transducer is required in an anemometer system to
   a. change rotational motion into an electrical signal.
   b. record wind information.
   c. record the time the instrument is operating.
   d. none of the above

5. d.

---

7. True or False? An aspirated temperature gauge that uses electrical resistance to measure temperature is the most useful in air pollution studies.

6. a. change rotational motion into an electrical signal.

8. A temperature sensor a. must always be located next to the wind sensors. b. should never be mounted directly on stacks. c. is not necessary for air pollution studies. d. measures total solar radiation through temperature readings.	7. True
	8. b. should never be mounted directly on stacks.

Lesson 7

Plume Dispersion

Assignment

Read pages 7-1 through 7-16 of this guidebook.

Assignment Topics

- Stack height and plume rise
- Atmospheric dispersion estimates
- Topographical effects on plumes

Lesson Goal and Objectives

Goal

To introduce you to the effects of stack height and plume rise on plume dispersion, some factors involved in making dispersion estimates, and the influences of topography on wind flow and plume dispersion.

Objectives

Upon completing this lesson, you should be able to:

1. define plume rise.
2. define effective stack height.
3. state three assumptions necessary for a plume to be Gaussian.
4. recognize two stack and effluent characteristics responsible for plume rise.
5. recognize Briggs' plume rise formula and be able to identify the terms included in it.
6. recognize the units that stack effluent is expressed in.
7. state the relationship of momentum and buoyancy to plume rise.
8. recognize the statistical distribution and assumptions about it used by Turner to define plume spread.
9. describe four topographical categories and their effects on the atmosphere.

Introduction

Smoke and other pollutants, called effluent, enter the atmosphere in a number of ways as shown in Figure 7-1. For example, the wind blows dust off of the ground. When swamps rot, methane is released. When garbage is burned, foul-smelling smoke drifts downwind. An operating factory will emit smoke from its stacks. There are many other examples of pollutant release.

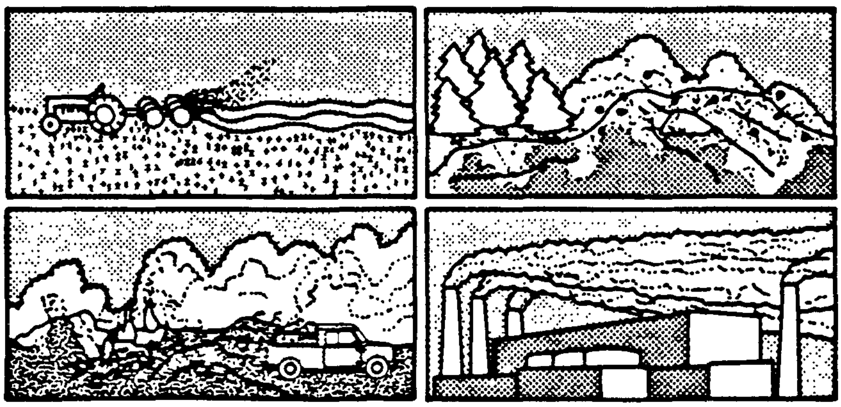


Figure 7-1. Dispersion mechanisms.

One method of pollution release has received more attention than any other; that of pollution released from smoke stacks. Smoke stacks come in all sizes—from a small pipe on a building's roof to a giant stack 1500 feet high (Figure 7-2). Their function is to release pollutants at an elevation higher than the surface. The object of the release height is to aid in dispersing the pollutant into the atmosphere. An accepted fact is that taller stacks disperse pollutants better than shorter stacks.

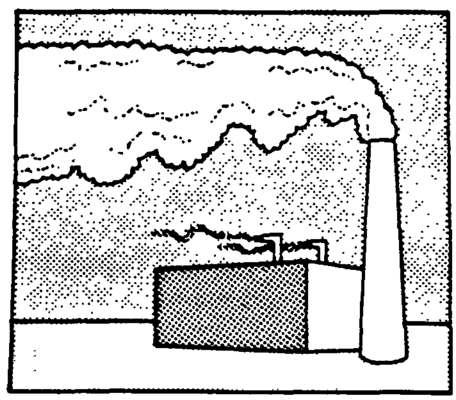


Figure 7-2. Effluent release.

Plume Rise

As you observe smoke from a stack, you will notice that the smoke usually rises above the top of the stack (Figure 7-3). The distance that the plume rises above the stack is called *plume rise.* It is actually calculated as the distance to the imaginary centerline of the plume rather than to the upper or lower edge of the plume. Plume rise, Δh, depends on the stack's physical characteristics and on the effluent's (stack gas) characteristics. For example, the effluent characteristic of stack gas temperature in relation to the surrounding air temperature is more important than the stack characteristic of height. The difference in temperature between the stack gas and ambient air determines plume density, and density affects plume rise. Therefore, smoke from a short stack could climb just as high as smoke from a taller stack.

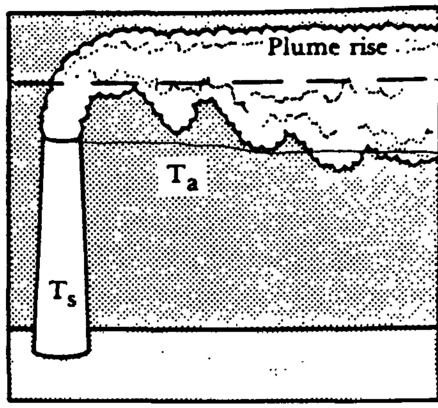


Figure 7-3. Plume rise.

Momentum and Buoyancy

Stack characteristics are used to determine momentum, and effluent characteristics are used to determine buoyancy (Figure 7-4). *Momentum* of the effluent is initially provided by the stack. It is determined by the speed of the effluent as it exits the stack. As momentum carries the effluent out of the stack, atmospheric conditions begin to affect the plume.

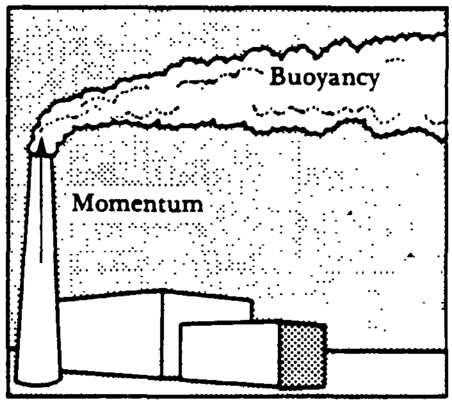


Figure 7-4. Momentum and buoyancy.

The condition of the atmosphere, including the winds and temperature profile along the path of the plume, will largely determine the plume's rise (Figure 7-5). As the plume rises from the stack, the wind speed across the stack top begins to tilt the plume. Wind speed usually increases with distance above the earth's surface. As the plume continues upward the stronger winds tilt the plume even farther. This process continues until the plume may appear to be horizontal to the ground. The point where the plume looks level may be a considerable distance downwind from the stack. Wind speed is important in blowing the plume over. The stronger the wind, the faster the plume will tilt over.

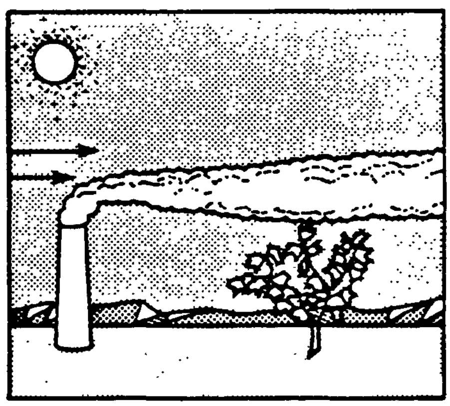


Figure 7-5. Wind flow affects plume rise.

Plume buoyancy is a function of temperature. In Figure 7-6, when the effluent's temperature, T_s, is warmer than the atmosphere's, T_a, the plume will be less dense than the surrounding air. In this case, the density difference between the plume and air will cause the plume to rise. The greater the temperature difference, ΔT, the more buoyant the plume. As long as the temperature of the pollutant remains warmer than the atmosphere, the plume will continue to rise. The distance downwind where the pollutant cools to atmospheric temperature may be quite far from its original release point.

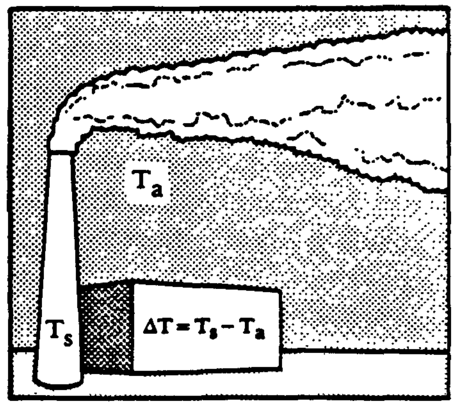


Figure 7-6. Temperature affects plume buoyancy.

Buoyancy is taken out of the plume by the same mechanism that tilts the plume over—the wind. As shown in Figure 7-7, mixing within the plume pulls atmospheric air into the plume interior. The faster the wind speed, the faster this mixing with outside air takes place. This mixing is called *entrainment*. Strong wind "robs" the plume of its buoyancy very quickly so that on windy days the plume does not climb very high above the stack.

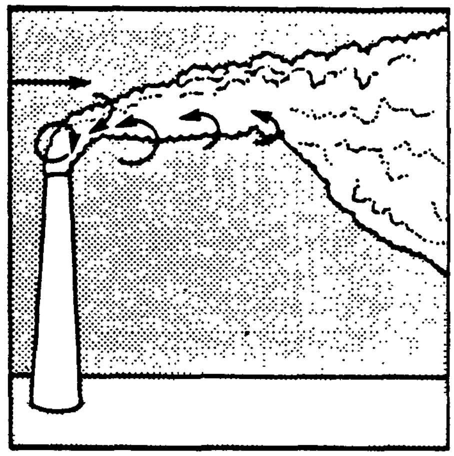


Figure 7-7. Wind speed affects entrainment.

Formulas

Many individuals have studied plume rise over the years. The most common plume rise formulas are those of Gary A. Briggs. One of these is included in Figure 7-8. Plume rise formulas are to be used on plumes with temperatures greater than the ambient air temperature.

$$\Delta h = 1.6\, F^{1/3}\, u^{-1}\, x^{2/3}$$

Where:

- h = plume rise above the stack
- F = flux
- u = average wind speed
- x = distance from the source

Figure 7-8. Briggs' plume rise formula.

As we said, plume rise formulas determine the imaginary *centerline* of the plume. Plume rise is a linear measurement expressed usually in feet or meters (Figure 7-9). The centerline is where the *greatest concentration* of pollutant occurs. Several techniques are used to calculate pollutant concentrations away from the centerline. The next section covers one technique.

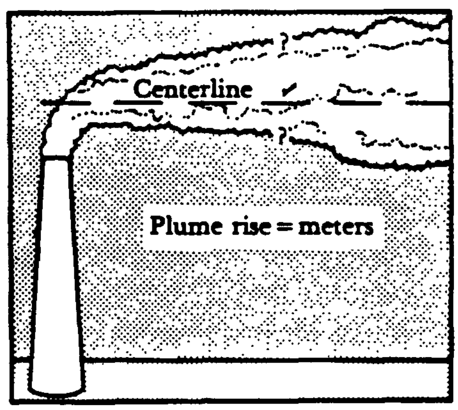


Figure 7-9. Plume rise formulas determine plume centerline, but not edges.

Review Exercise

1. True or False? Plume rise is the height that pollutants rise above a stack. This distance, Δh, is to the edges of the plume.	
2. Plume rise from a stack is due to a. heat and type of pollutant. b. momentum and buoyancy. c. the composition of the stack. d. none of the above	1. False
3. Plume rise formulas like those developed by Briggs are to be used on a. plumes that are colder than the ambient air. b. plumes that are hotter than the ambient air. c. plumes that are the same temperature as the ambient air. d. none of the above	2. b. momentum and buoyancy.
4. How are plume rise calculations expressed? a. grams/second b. meters/second c. grams/meter^3 d. meters	3. b. plumes that are hotter than the ambient air.
5. The momentum term in plume rise equations generally involves a. ambient air temperature, wind speed, stack gas temperature. b. wind speed, stack gas temperature, stack opening diameter. c. stack gas velocity. d. stack outside radius.	4. d. meters
6. True or False? Buoyancy terms in plume rise equations always depend on the difference between stack gas temperature and the ambient air temperature.	5. c. stack gas velocity.

$$\Delta h_m = \frac{3d(V_s)}{U(h)}$$

stack diameter; V_s → stack gas exit velocity (actual flowrate); $U(h)$ → wind speed at h. (momentum)

7. Atmospheric air pulled into the plume interior by mixing within the plume is called ________. The speed with which the process occurs is directly proportional to ________.	6. True
	7. entrainment wind speed.

Dispersion Estimates

The methods suggested by Briggs or any other plume rise investigator calculate only the imaginary centerline of a plume. These methods do not provide any information as to the ground level concentration estimates of pollutant downwind (Figure 7-10). Plume rise determination aids only in fixing the distance from the ground of the area of the plume having the largest pollutant concentration. D. B. Turner, in his *Workbook of Atmospheric Dispersion Estimates* (as well as other modelers), has used the Gaussian or normal distribution (Figure 7-11) to identify the variation of the pollutant concentration away from the center of the plume. This distribution of atmospheric variables such as wind speed and temperature is time averaged and may not be used for instantaneous "pictures" of the plume. Time averages of 10 minutes to one hour are commonly used. Then, and only then, can the pollutant concentration be assumed to be normally distributed in the plume.

The plume centerline distance from the ground, called *effective stack height,* H, is determined by adding plume rise, Δh, to the physical height of the stack, h_s. Knowing this centerline distance from the ground allows the calculation of the amount of pollutant that will reach the ground (Figure 7-12). This amount of pollutant is determined from the Gaussian distribution. Concentrations are at maximum at the centerline and decrease toward the edges of the plume. Graphs are available that give the appropriate plume size factors for distances downwind from the

Normal distribution is assumed.

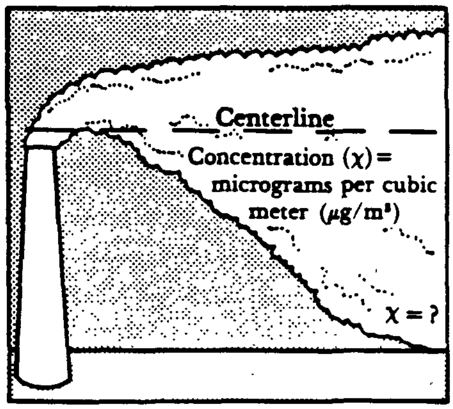
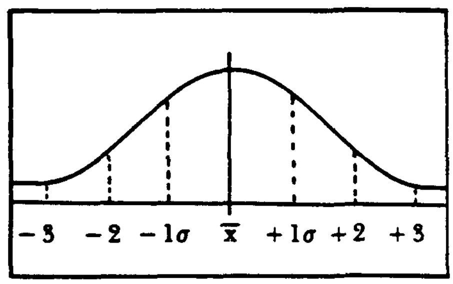
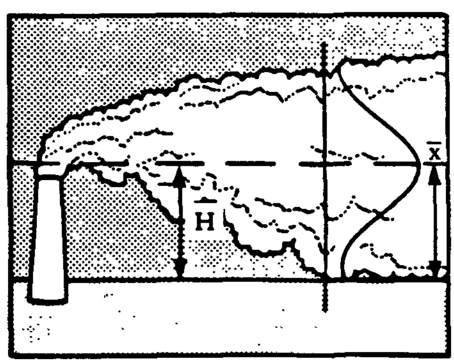


Figure 7-10. Ground-level concentration (χ) not determined by plume rise formulas.



x̄ = mean (maximum concentration)
σ = standard deviation symbol

Figure 7-11. Gaussian distribution.



H = effective stack height
x̄ = maximum concentration mean

Figure 7-12. Effective stack height.

$\chi = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot \exp\left[-0.5\left(\frac{H_{eff}}{\sigma_z}\right)^2\right]$; H_{eff}: effective plume height, (stack height + plume rise)

stack. These graphs (Figure 7-13) are logarithmic in scale and consider horizontal and vertical spreading only. The plume is not allowed to stretch or thin out in the downwind direction. The **A** through **F** factors are atmospheric stability indicators. The basic calculation formulas allow the plume edge to "bounce" off or reflect from the ground without losing any pollution. In fact, the material in the plume must be maintained for the Gaussian distribution to be used.

If only ground-level concentrations underneath the centerline of the plume are desired, the basic formula will reduce appropriately and fewer factors will be required (Figure 7-14). If there is no smoke stack and the smoke is generated at the ground, as in a burning garbage dump, then a simple formula may be used for calculations.

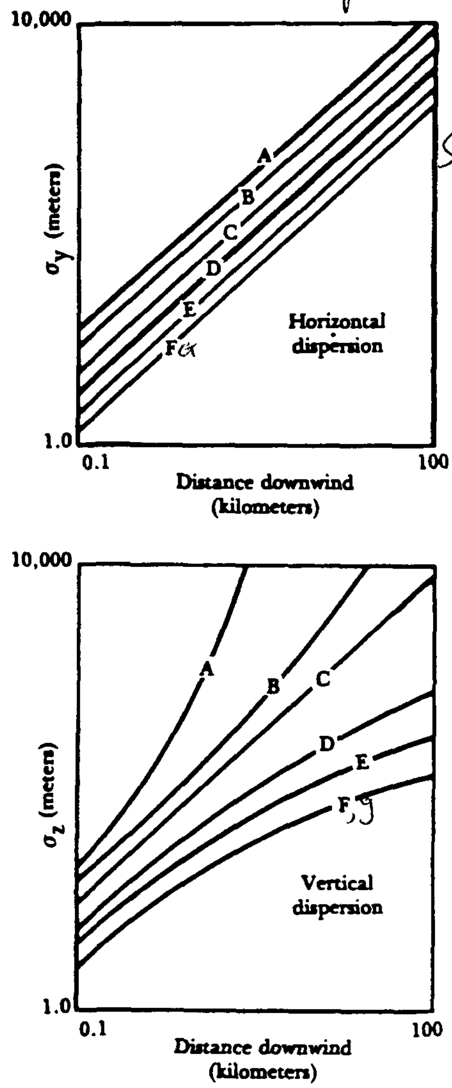


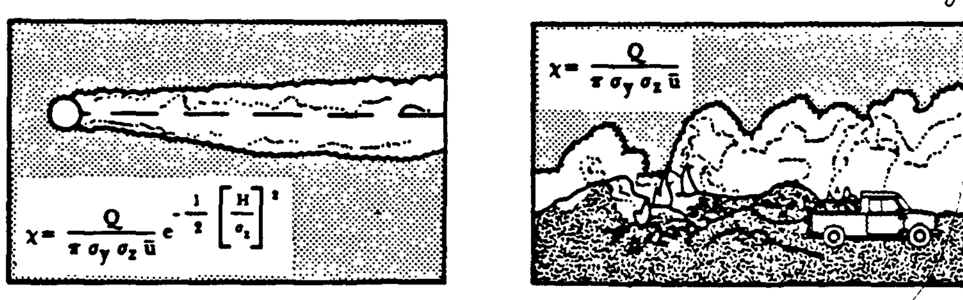
Figure 7-13. Plume size graphs (log scales).

Plume Size Factors

The horizontal and vertical plume size factors, σ_y and σ_z, are functions of wind speed, cloud cover, and surface heating by the sun. Table 7-1 relates these factors to lines on the *plume size graphs* used to determine the size of the plume with distance downwind. Note that A, B, and C refer to daytime with unstable conditions; D refers to overcast or neutral conditions at night or during the day. E and F refer to nighttime, stable conditions and are based on amount of cloud cover.

For computation purposes, the Gaussian distribution simplifies concentration variations within a plume. Deposition and transformation of pollutants are ignored by the Gaussian distribution presented here.

(σ a fn (depends on stability class and downwind distance))



Plume centerline concentration — **Figure 7-14. Appropriate Gaussian formulas.**

χ (concentration) $= \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp[-0.5 \ldots]$; χ: conc; Q: emission rate gm/sec; u = wind speed at stack top (m/sec); $\sigma_y \sigma_z$ = horz + vert std dev. (m)

$= gm/m^3 \times 10^6 = \mu g/m^3$

Table 7-1. Key to stability categories.

Surface wind	Insolation			Night	
Speed (at 10 m) (m/sec)	Strong	Moderate	Slight	≥4/8 low cloud*	≤3/8 cloud
<2	A	A-B	B	—	—
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

*Thinly overcast

Note: Neutral Class, D, should be assumed for overcast conditions during day or night.

The Gaussian distribution, as well as plume rise, depends on the ground being approximately flat along the path of the plume (Figure 7-15). Uneven terrain caused by valleys, hills, and mountains will affect the dispersion of the plume so that the Gaussian distribution must be modified. These modifications are exponential and depend on the earth's topography. Terrain features affect atmospheric wind flow and stability. The various categories of topography are discussed in the following section. For information on the use of exponents in the Gaussian distribution equation, you can refer to the EPA *User's Guides* for specific air quality models.

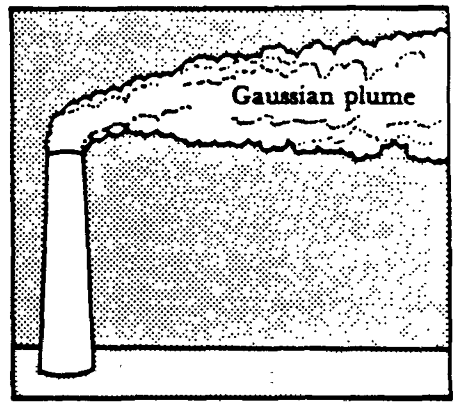


Figure 7-15. Flat terrain for Gaussian distribution.

Topography

The physical characteristics of the earth's surface are referred to as terrain features. As shown in Figure 7-16, these features can be grouped into four categories: flat, mountain/valley, land/water, and urban.

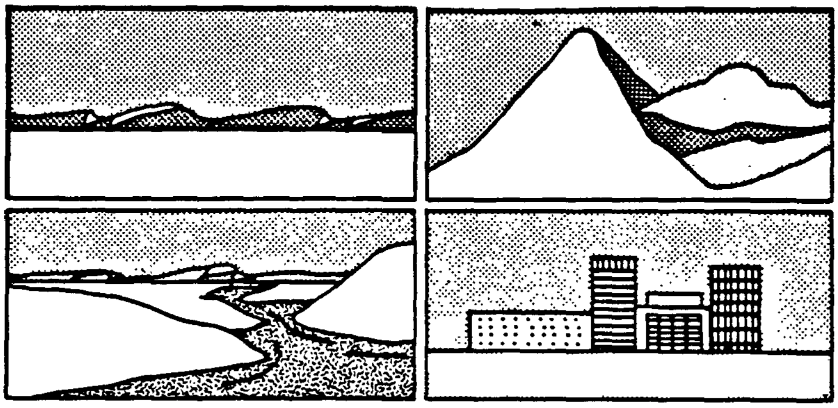


Figure 7-16. Topography.

Topographical features affect the atmosphere in two ways as shown in Figure 7-17: thermally (through heating) and geometrically (also known as mechanically). The thermal effect is caused by differential heating. Objects give off heat at different rates. For example, a grassy area will not give off as much heat as a cement parking lot. The geometric effect is caused by different sizes and shapes of objects. For example, a building affects wind differently than trees affect it.

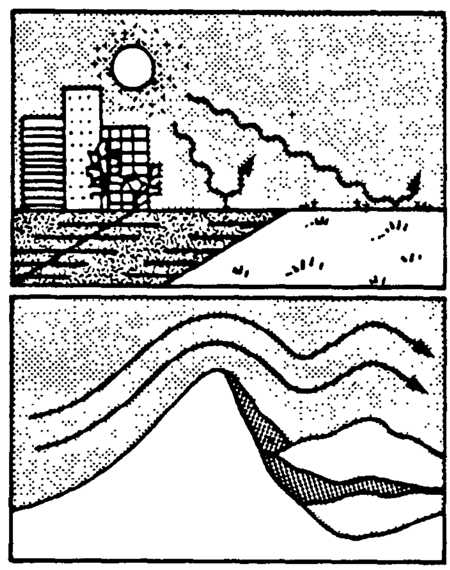


Figure 7-17. Topographical effects on heat and wind flow.

Flat

Although very little of the earth's surface is completely flat, some terrain is called flat for topographical purposes. Included in this category are oceans, even though they have a surface texture; and gently rolling features on land (Figure 7-18).

The *geometric* effect of flat terrain is limited to the amount of roughness of either natural or manmade features that are on the ground. Table 7-2 contains some representative roughness lengths. Note the variation of wind with height over different size elements. These features induce a frictional effect on the wind speed and result in the well-known wind profile with height (Figure 7-19).

The *thermal* effect of flat terrain is due to natural or manmade features. For example, water does not heat very much but concrete heats exceptionally well. The concrete then releases large amounts of heat back into the air; water does not. Air rises over heated objects in varying amounts (Figure 7-20). Rising air is called convection.

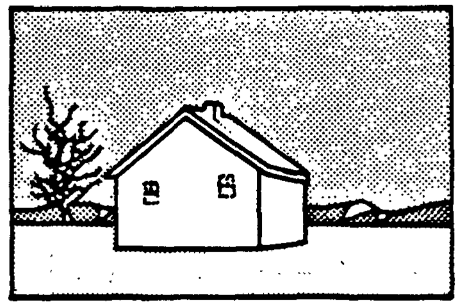


Figure 7-18. Flat terrain.

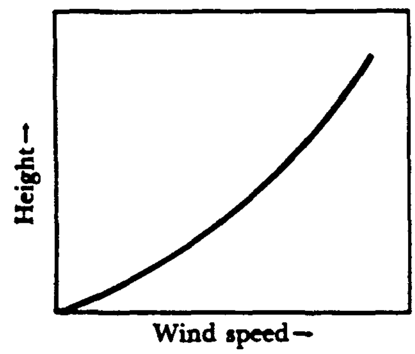


Figure 7-19. Wind profile.

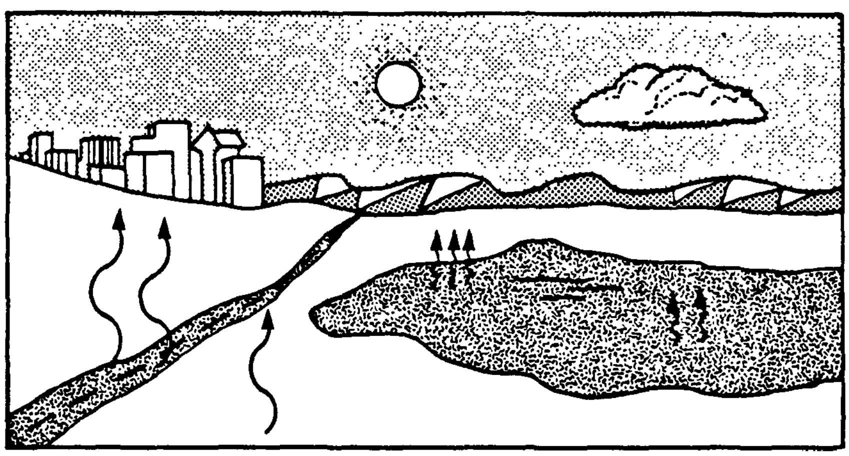


Figure 7-20. Differential heating.

Table 7-2. Roughness factors for various surfaces.

Type of surface	h(cm)	z_0(cm)	Author
Fir forest	555	283.0	Baumgartner (1956)
Citrus orchard	335	198.0	Kepner et al. (1942)
Large city (Tokyo)		165.0	Yamamoto and Shimanuki (1964)
Corn *$u_{6.2} = 35$ cm sec^{-1} $u_{6.2} = 198$ cm sec^{-1}	300	 127.0 71.5	Wright and Lemon (1962)
Corn $u_{4.0} = 29$ cm sec^{-1} $u_{4.0} = 212$ cm sec^{-1}	220	 84.5 74.2	Wright and Lemon (1962)
Wheat $u_{1.7} = 190$ cm sec^{-1} $u_{1.7} = 384$ cm sec^{-1}	60	 23.3 22.0	Penman and Long (1960)
Grass $u_{2.0} = 148$ cm sec^{-1} $u_{2.0} = 343$ cm sec^{-1} $u_{2.0} = 622$ cm sec^{-1}	60-70	 15.4 11.4 8.0	Deacon (1953)
Alfalfa brome $u_{2.2} = 260$ cm sec^{-1} $u_{2.2} = 625$ cm sec^{-1}	15.2	 2.72 2.45	Tanner and Pelton (1960b)
Grass	5-6 4 2-3	0.75 0.14 0.32	 Rider et al. (1963) Rider (1954)
Smooth desert		0.03	Deacon (1953)
Dry lake bed		0.003	Vehrencamp (1951)
Tarmac		0.002	Rider et al. (1963)
Smooth mud flats		0.001	Deacon (1953)

*The subscript gives the height (in meters) above the ground at which the wind speed, u, is measured.

Mountain/Valley

The second type is mountain/valley terrain. This combination shown in Figure 7-21 is also called complex terrain.

All air pollution investigators agree that atmospheric dispersion in complex terrain areas can be very different from, and much more complicated than, that over flat ground. The problems with terrain have been investigated in fluid modeling labs and by field experiments.

The *geometric effect* of mountain/valley terrain is invariably connected to the size, shape, and orientation of the features. The numerous combinations of mountain/valley arrangements include a single mountain on flat terrain, a deep valley between mountains, a valley in flat terrain, or a mountain range. However, as in Figure 7-22, air tends to flow up and over an obstacle in its path with some air trying to find its way around the sides. If an elevated temperature inversion caps the higher elevation, then the air must try to find its way around the sides of the mountain. If the air flow is blocked, then trapping or recirculation of the air occurs. At night, hills and mountains induce downslope wind flow because the air is cooler at higher elevations. Usually downslope winds are light. However, under the right conditions, the wind speeds may be in excess of 45 meters per second (100 miles per hour).

The *thermal effect* of mountain/valley terrain is also connected to the size, shape, and orientation of the features. Again, while every combination of mountain/valley effects cannot be explained, some generalizations can be illustrated. Mountain/valleys heat unevenly because of the sun's motion across the sky (Figure 7-23). In the morn-

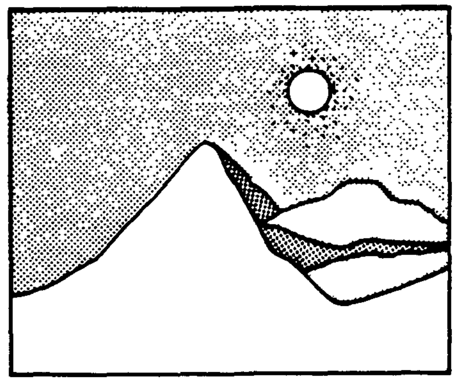


Figure 7-21. Mountain/valley (complex) terrain.

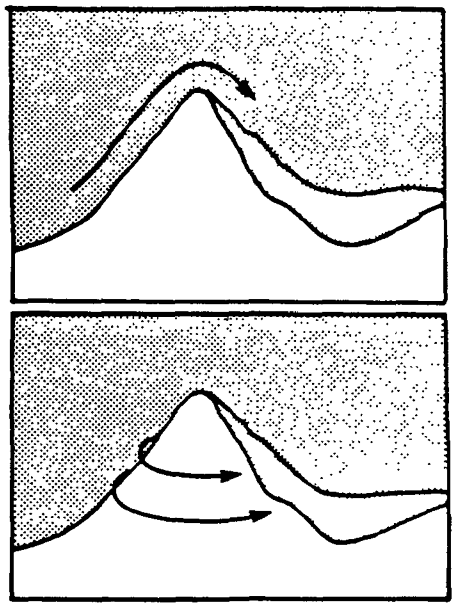


Figure 7-22. Wind flow over and around mountains (geometric effect).

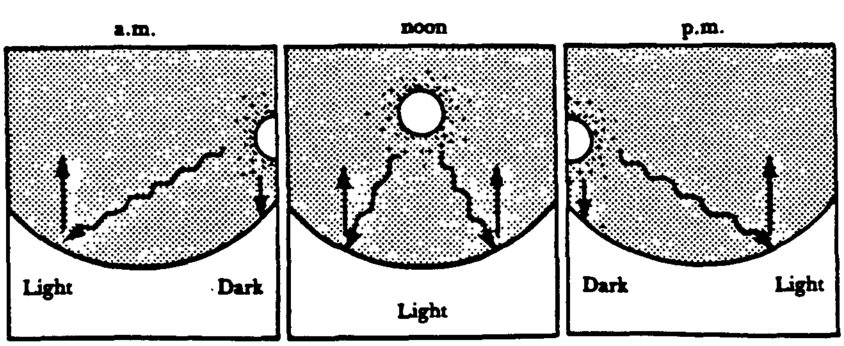


Figure 7-23. Thermal effect in valley (air rises when land is lighted).

ing, one side of a mountain or valley is lit and heated by the sun. The other side is still dark and cool. Air rises on the lighted side and descends on the dark side. At midday both sides are "seen" by the sun and are heated. The late afternoon situation is similar to the morning. After dark, the air drains down into the valley from all higher slopes.

The other heating effect is due to land features. Tree covered areas will heat less than rocky slopes or bare ground. A detailed knowledge of specific terrain areas is important to interpret the complex terrain's effect.

Land/Water

The third type of terrain is a land/water interface (Figure 7-24). Partly because of convenience, a number of large cities are located next to bodies of water. The land and water not only exhibit different roughness characteristics but different heating properties. The air flow and thus plume dispersion and transport can be very difficult to predict.

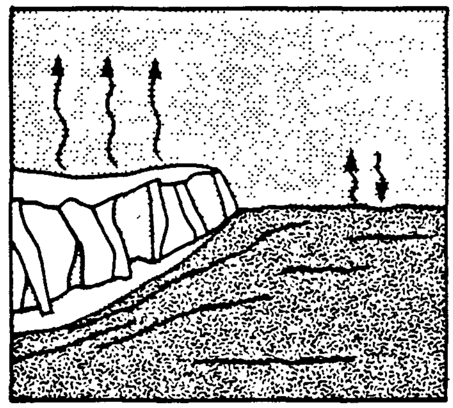


Figure 7-24. Thermal effect at land/water interface.

The thermal properties of land and water are radically different. Land and objects on it will heat and cool at various rates. We have seen the effects of land's thermal properties above. However, water heats and cools relatively slowly. Water temperatures do not vary much from day-to-day or from week-to-week. Water temperatures follow the seasonal changes, being delayed by as much as 60 days. For example, the warmest ocean temperatures are in early fall, and the coolest ocean temperatures are in late spring.

As the sun shines on the water surface, evaporation and some warming take place. The thin layer next to the air cools due to evaporation and mixes downward, overturning with the small surface layer that has warmed. This mixing of the layer close to the surface keeps the water temperature relatively constant.

The warmer daytime temperatures over the land cause the air to become less dense and rise. The cooler air over the water is drawn inland and becomes the well-known seabreeze. At night, the air over the land cools rapidly, and the air over the water is warmer. A return flow called the land breeze is created. The wind speeds in a land breeze are light; whereas the wind speeds in a seabreeze can be quite fast.

As shown in Figure 7-25, the roughness features of land and water are also different. The water appears to be quite smooth to the flow of air. As the wind speed increases, the water surface is disturbed, and waves form. With waves induced by strong wind the water surface is no longer as smooth as it was with a light wind. However, water is still smoother than most land features. Because of the change from relatively smooth water to rougher land, the air flow changes direction. The amount of direction change depends on the amount of roughness change.

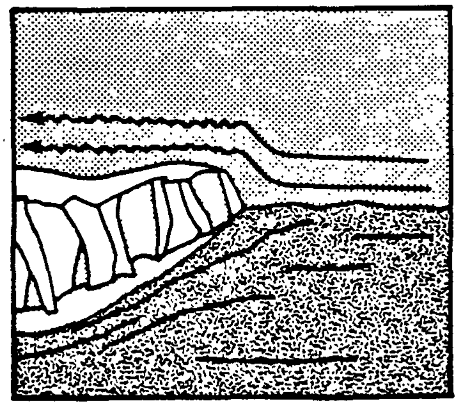


Figure 7-25. Mechanical effect at land/water interface.

Urban

Urban areas exhibit all of the characteristics of flat, mountain/valley, and land/water terrains. Also urban areas add tremendous amounts of manmade pollution to the atmosphere.

The thermal effect of the urban area is quite pronounced (Figure 7-26). Building materials such as brick, concrete, and macadam absorb and hold heat efficiently. After the sun goes down, the urban area continues to exchange heat between buildings, etc. Heat is transmitted upward to create a dome over the city. It is called the *heat island* effect. The city emits heat all night. Just

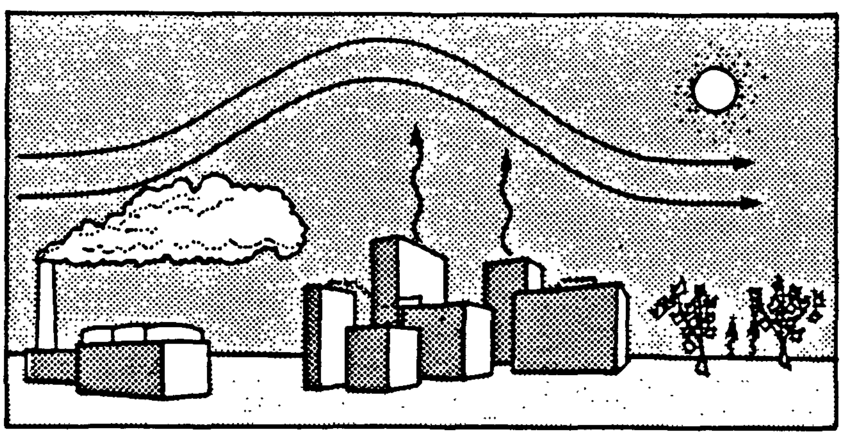


Figure 7-26. Thermal and mechanical effects of cities.

when the urban area begins to cool, the sun comes up again. Generally, the city areas never revert to stable conditions because of the continual heating.

The geometric effect of the urban area is much like complex terrain. The buildings, separately and collectively, offer a mountain shape to the air flow. The higher the buildings in midtown, the more the air must go up and over. Also, the street areas channel and direct the flow in intricate ways. Just as the mountain/valley terrain could not be accurately predicted, the urban areas defy accurate description.

Review Exercise

1. True or False? Effective stack height is determined by adding plume rise to the physical height of the stack.	
2. Turner, in the *Workbook of Atmospheric Dispersion Estimates* (WADE), uses a distribution called the a. geometric b. weibull c. Gaussian d. Poisson	1. True
3. One of the assumptions of the distribution that Turner uses in his *Workbook* is that the a. source continuously emits pollutants. b. terrain must be log-normally distributed. c. distribution in the horizontal direction is bimodal. d. pollutant falls out of the plume immediately after release from the source.	2. c. Gaussian
For 4 through 6, match the type of atmospheric stability to the appropriate Pasquill-Gifford stability categories. 4. unstable — a. E-F 5. neutral — b. A-B-C 6. stable — c. D	3. a. source continuously emits pollutants.

7. The sigma y and sigma z used in the Gaussian dispersion formulas are defined as a. atmospheric pressure at points y and z. b. standard deviations of pollutant concentration in the horizontal and vertical directions. c. temperature variations in the y and z directions. d. none of the above.	4. b 5. c 6. a
8. Which of the following is typical of a pollution concentration calculation? a. $\varrho = 75\ \mu g/m^2$ b. $\beta = 150\ \mu l/m^3$ c. $\gamma = 100\ \mu g/m^3$ d. $\chi = 100\ \mu g/m^3$	7. b. standard deviations of pollutant concentration in the horizontal and vertical directions
9. The four general categories of terrain are: a. marsh, flat, complex, rolling. b. flat, mountain/valley, urban, complex. c. flat, mountain/valley, land/water, rural. d. flat, mountain/valley, land/water, urban.	8. d. $\chi = 100\ \mu g/m^3$
10. What effects do topographical features have on the atmosphere?	9. d. flat, mountain/valley, land/water, urban.
	10. thermal, geometric

Lesson 8

Introduction to the *Guideline on Air Quality Models*

Assignment

Read pages 8-1 through 8-5 of this guidebook.

Assignment Topics

- Regulatory programs
- Air quality model recommendations
- Data requirements
- Model calibration and validation
- Model categories

Lesson Goal and Objectives

Goal

To familiarize you with the *Guideline on Air Quality Models*, and general categories of air quality models available.

Objectives

At the end of this lesson, you should be able to:

1. name the three air quality programs that evolved from the 1977 amendments to the Clean Air Act.
2. name the document that summarizes the essentials of three air quality programs.
3. choose the reason why the *Guideline on Air Quality Models* was written.
4. identify the section of the *Guideline on Air Quality Models* that recommends specific air quality models.
5. identify the four general categories of air quality models.

Introduction

Air quality modeling is required by law. Congress mandated the use of modeling in the 1977 Clean Air Act Amendments. Three air quality programs evolved that require modeling to estimate the impact of air pollution on the environment. They are Control Strategy Evaluation, New Source Review, and Prevention of Significant Deterioration. Each of these programs have supporting documents containing specific air quality modeling requirements. One document summarizes the essential points of all three programs. It is the *Guideline on Air Quality Modeling*, EPA 450/2-78-027. The *Guideline* was written to promote consistency among modelers so that all air quality modeling activities would be based on the same recommendations.

Guideline Topics

The *Guideline* has six sections. It covers air quality models including their purpose, development, use for different regulatory programs, data requirements, and validation/calibration. Recommended air quality models are summarized in an appendix. Our discussion will begin with Section 3, "Requirements for Concentration Estimates."

Section 3: Requirements for Concentration Estimates

Section 3 covers Control Strategy Evaluation, New Source Review, and Prevention of Significant Deterioration. In Control Strategy Evaluation, emission limits should be based on concentration estimates for the averaging time that results in the most stringent control requirements. An air quality model (AQM) is used to determine which averaging time—annual, 24-hour, 8-hour, 3-hour—causes the standards to be exceeded. For example, if the annual averaging time results in the largest concentrations, then it would be chosen for emission control limits.

A new source or major modification of a source that would increase allowable emissions by 50 tons per year, 500 pounds per day, or 100 pounds per hour should have an air quality analysis made. An air quality model is used to determine if the source will cause a violation of a National Ambient Air Quality Standard. Also an AQM is used if a proposed new source or an addition to an existing source might make air quality that is already bad, worse.

In the PSD program, air quality models should be used in all significant deterioration evaluations. Allowable increments or these maximum allowable increases in pollutant concentrations for sulfur dioxide and particulate matter are specified in the Clean Air Act Amendments of 1977. A reprint of Section 3 is included in the next lesson.

Section 4: Air Quality Models

Section 4 of the *Guideline* recommends air quality models for a variety of applications: point and multisource models for sulfur dioxide (all averaging times), models for carbon monoxide, models for nitrogen dioxide, and models for special situations. The air quality models recommended are used in the three programs mentioned above.

Section 5: Data Requirements

Section 5 discusses source data, meteorological data, receptor siting and background air quality as they apply to specific air quality models. Each of these data bases cannot be considered in isolation. Together, over time, they can provide valuable information when planning both New Source Reviews and Control Strategy Evaluations.

Section 6: Model Calibration/Validation

Section 6 discusses the methods for validating or calibrating air quality models. Any application of an air quality model may have shortcomings that cause estimated concentrations to be in error. *Validation* is the process of comparing observed air quality data with model estimates. *Calibration* is the process of changing the model so that the model estimates more closely agree with observed air quality data. Specific recommendations about calibrating short-term models are discussed.

Section 7: Appendix

The appendix lists seven models: AQDM, APRAC-1A, CDM, RAM, CRSTER, TCM, and TEM. It also itemizes seventeen characteristics of each model. The characteristics enable the model user to select an appropriate model for a specific application.

Model Categories

Air quality models can be categorized into four general classes: empirical, numerical, physical, and Gaussian (or distributional) models.

An *empirically*-derived air quality model is based on the analysis of source data, meteorological data, and air quality data. Given a set of observations from air monitoring and meteorological stations, statistical techniques are used to calculate relationships among variables. Usually, regression and spectral analysis techniques are used. Empirical models are not applicable beyond the range of conditions included in the data used in their development and improvement.

A *numerical* air quality model uses mathematical equations to simulate the effects of turbulence, chemical transformations, deposition, etc., on air pollution transport and dispersion. Numerical models attempt to duplicate atmospheric processes. They are appropriate for multisource applications involving reactive pollutants. Since these models usually require complex equations in their simulations and large computers to solve the complex formulations, they are not generally recommended for use.

Physical models are used to investigate pollutant dispersion for situations too complicated to be simulated by mathematical techniques. The wind tunnel and water tank are structures where realistic mock-ups of situations are tested. One advantage of physical modeling is that years of field study time can be simulated in a matter of weeks. Another advantage is that they aid in improving mathematical models by filling in knowledge gaps in current models.

Some examples of diffusion studies using physical modeling are: simulation of power plant plumes, effects of complex terrain, and effects of roughness on transport and dispersion of pollutants.

Gaussian models or other models that use the Gaussian distribution for their basis are among the most widely used air quality models. They are generaly considered to be state-of-the-art techniques for estimating the impact of nonreactive pollutants (one that is not changed by some process into a different substance). Although numerical models may be more appropriate than the Gaussian for reactive pollutants, Gaussian are more widely used. Gaussian models also simulate the effect of chemical and physical processes on pollution transport and dispersion using simpler algebraic expressions than required for the numerical models. The air quality models recommended by USEPA for regulatory purposes are all Gaussian models.

Review Exercise

1. Name the three air quality programs that evolved from the Clean Air Act Amendments of 1977.	
2. The document that summarizes the essentials of the three air quality programs is the a. *Guideline on Air Quality Programs,* EPA 450/2-78-027. b. *Guideline on Air Quality Program Summaries,* EPA 450/2-78-027. c. *Guidelines on Air Quality Summaries,* EPA 450/2-78-027. d. *Guideline on Air Quality Models,* EPA 450/2-78-027.	1. • New Source Review • Control Strategy Evaluation • Prevention of Significant Deterioration

3. What was the reason the USEPA wrote the document EPA 450/2-78-027? a. Air quality modeling should be consistently applied. b. Directions on how to repair air quality models weren't available. c. Directions on how to write an air quality model weren't available. d. none of the above	2. d. *Guideline on Air Quality Models*, EPA 450/2-78-027.
4. True or False? The section of EPA 450/2-78-027 that recommends specific air quality models is Section 4 called "Air Quality Models."	3. a. Air quality modeling should be consistently applied.
5. What are the four general categories of air quality models?	4. True
For each of the following, match the category of air quality model with its definition. 6. empirical ___ a. investigate pollutant dispersion for complicated situations through simulation 7. numerical ___ b. derived from an analysis of source data, meteorological data, and air quality data 8. physical ___ c. use complex equations to simulate the effects of turbulence, chemical transformations, deposition, etc., on pollutant transport and dispersion 9. Gaussian ___ d. techniques for estimating the impact of nonreactive pollutants, and use simple algebraic expressions for reactive pollutants	5. • empirical • physical • numerical • Gaussian
	6. b 7. c 8. a 9. d

Lesson 9

Introduction to Meteorological Requirements for State Implementation Plans, New Source Review, and Air Quality Modeling

Assignment

This lesson contains reading from Section 3 and 5 of the *Guideline on Air Quality Models,* EPA 450/2-78-027. These are pages 9-1 through 9-12 in this Guidebook.

Assignment Topics

- Requirements for regulatory programs
- Meteorological data requirements

Lesson Goal and Objectives

Goal

To familiarize you with the meteorological requirements of State Implementation Plans (SIPs), New Source Review (NSR), and Air Quality Modeling (AQM).

Objectives

At the end of this lesson, you should be able to:

1. identify how meteorology is used in SIPs, NSR, and AQMs.
2. name the concentration estimate most frequently used to specify short-term emission limits in SIPs.
3. identify the reason "worst case" meteorological conditions are necessary in regulatory programs.
4. name the analysis used to estimate concentrations in NSR when required.
5. name the four meteorological factors that are required as a minimum to describe atmospheric transport in SIPs and NSR.

Introduction

The Clean Air Act Amendments of 1977 require State Implementation Plans, New Source Review including Prevention of Significant Deterioration (PSD), and air quality modeling. These regulatory programs require knowledge of the present pollutant loading of the atmosphere, air quality modeling in given situations, and progress in cleaning up the atmosphere. Implicit in air pollution programs is a knowledge of the meteorological climatology of the area in question.

When air quality modeling is required, the specific model used (from a simple screening tool to a refined analysis) will need meteorological data. The data can vary from a few factors such as average wind speed and Pasquill-Gifford stability categories to a mathematical representation of turbulence. Whatever model is chosen to estimate air quality, the meteorological data quality must match the quality of the model used. For example, average wind speed used in a simple model will not be sufficient for a complex model.

The reading assignment for this lesson taken from the *Guideline on Air Quality Models* discusses the essentials of SIPs, NSR, PSD, and the data requirements for air quality modeling.

Section 3: Requirements for Concentration Estimates*

Specific air quality standards and increments of pollutant concentrations must be considered for control strategy evaluations and for new source reviews, including prevention of significant deterioration. This section specifies general requirements for concentration estimates and identifies the relationship between emission limits and air quality standards/increments for these applications.

Control Strategy Evaluations

SIP-related emission limits should be based on concentration estimates for the averaging time which results in the most stringent control requirements. In all cases these concentration estimates are assumed to be a sum of the concentration contributed by the source and an appropriate background concentration.

If the annual average air quality standard is exceeded by a greater degree (percentage) than standards for other averaging times, the annual average is considered the restrictive standard. In this case the sum of the highest estimated annual average concentration and the annual average background provides the concentration which should be used to specify emission limits. However, if a short-term standard is exceeded by a greater degree and is thus identified as the restrictive standard, other considerations are required because the frequency of occurrence must also be taken into account.

*Source: EPA 450/2-78-027 *Guideline on Air Quality Models.*

Historically, when dispersion model estimates are used to assist in judging whether short-term NAAQS will be met, and ultimately in specifying appropriate emission limits, one of three types of concentration estimates is used: (1) the highest of all estimated concentrations, (2) the second-highest of all estimated concentrations, or (3) the highest of second-highest concentrations estimated for a field of receptor sites. The highest of second-highest concentrations for a field of receptors is obtained as follows: (1) frequency distributions of short-term concentrations are estimated for each site in a field of receptors; (2) the highest estimated concentration at each receptor is discarded; (3) the highest of the remaining concentration estimates from the field of receptor sites is identified. Throughout this guideline that concentration estimate is referred to as the *highest, second-highest* concentration.

The first two types of estimates have been applied most often in specifying emission limits. However, they may be unnecessarily restrictive in many situations. The third type of estimate is more consistent with the criteria for determining violations of the NAAQS, which are identified in *Guidelines for Interpretation of Air Quality Standards*. That guideline specifies that a violation of a short-term standard occurs at a site when the standard is exceeded a second time. Thus, emission limits which are to be based on an averaging time of 24 hours or less should be based on the highest, second-highest estimated concentration plus a background concentration which can reasonably be assumed to occur with that concentration. (See the section, "Background Air Quality," page 9-9, for a discussion of the factors and variety of situations that should be considered.)

An estimate of the highest, second-highest concentration which is based on many well-chosen receptor sites may well reveal previously unidentified "hot spots." Such an estimate may provide a more conservative and realistic indication of the potential for NAAQS violations and of the appropriate emission limits than do actual measurements at a few monitoring sites. However, if the data available for modeling are limited to a short period, or source data are generalized, the estimated highest, second-highest concentration is unlikely to provide a true indication of the threat to air quality standards. Thus it is essential that an adequate data base be available (see Section 5: "Data Requirements" on page 9-5). Data for a time period of sufficient length should be considered so that there is reasonable certainty that meteorological conditions associated with the greatest impacts on air quality are identified. Similarly, detailed source data are required so that the air quality impact can be assessed for the source conditions likely to result in the greatest impact.

There are two exceptions to the above requirement to use the highest, second-highest estimated concentrations. The first situation occurs where monitored air quality data from specific sites indicate that concentrations greater than those estimated can occur with little or no impact from the source(s) in question. For the purpose of specifying emission limits, these measured concentrations should be ranked ahead of the estimated concentrations in the frequency distribution of concentrations at that specific monitoring (receptor) site.

The second situation occurs where the Regional Administrator identifies inadequacies in the data base or the models for a particular application. As a result of these inadequacies he may determine that there is a lack of confidence in an emission limit based on the highest, second-highest concentration or that this concentration simply cannot be estimated. In this case, until such time as the necessary data bases are acquired or analytical techniques are improved, the use of the highest estimated concentration to determine source impact and to evaluate control strategies may be justified.

New Source Reviews

Reviews for new sources that require an air quality impact analysis should determine if the source will (1) cause or exacerbate violations of a NAAQS or (2) cause air quality deterioration which is greater than allowable increments. For reviews relative to both the NAAQS and prevention of significant deterioration (PSD), the air quality impact analysis should generally be limited to the area where the impact exceeds "significant concentration increments." Such significant increments are defined in EPA's PSD regulations (40 CFR 52.21) and in EPA's Emission Offset Ruling (40 CFR Part 51, Appendix S). In addition, due to the uncertainties of estimates for large downwind distances, the air quality impact analysis should generally be limited to a downwind distance of 50 kilometers from the source, regardless of the above mentioned significant increments. The following subsections further identify requirements for concentration estimates associated with air quality standards and with prevention of significant deterioration.

Meeting Air Quality Standards

For each new source or major modification of a source which would increase allowable emissions by 50 tons per year, 500 pounds per day, or 100 pounds per hour, an air quality analysis should be performed to determine if the source will cause or exacerbate a violation of a NAAQS. For such new sources located in an attainment area, the concentration estimates should meet the same requirements that are applicable to control strategy evaluations. The determination of whether or not the source will cause an air quality violation should be based on (1) the highest estimated concentration for annual averages and (2) the highest, second-highest estimated concentration for averaging times of 24-hours or less. The most restrictive standard should be used in all cases to establish the potential for an air quality violation. Background concentrations should be added in assessing the source's impact. The two exceptions to the shorter-term averaging times which were noted in the preceding section also apply here; i.e., monitored data with higher concentrations and inadequacies in data bases or model.

Prevention of Significant Deterioration

Air quality models should be used in all significant deterioration evaluations. Allowable increments for sulfur dioxide and particulate matter are set forth in the Clean Air Act Amendments of 1977. These maximum allowable increases in pollutant concentrations may be exceeded once per year, except for the annual increment. Thus, in significant deterioration evaluations for short-term periods the highest, second-highest increase in estimated concentrations should be less than or equal to the permitted increment.

Since the Clean Air Act Amendments express special concern for Class I PSD areas, any expected impacts for these areas must be considered. Thus, the distance limitation of 50 kilometers and the significant concentration increments discussed in the introduction to the Section on "New Source Reviews" do not apply. In addition, where an exemption to the Class I increments is requested and approved pursuant to section 165(d)(2)(D) of the Clean Air Act, the source may cause the Class I increments to be exceeded on a total of 18 days during any annual period. In this case, it is necessary to select the hightest estimated concentration in the field of receptors for each of the 365 days. These 365 values are then ranked and the 19th highest is used to determine emission limits. However, the highest, second-highest concentration may not exceed a somewhat higher increment specified in section 165(d)(2)(D)(iii).

Section 5: Data Requirements

It is essential that appropriate source and meteorological data be used with any recommended model. Such data, and related procedures for estimating these data, constitute an integral part of the model. It is often overlooked that few of the variables input to a model are directly measured or routinely available. Submodels must appropriately convert the available source and meteorological data to a form that the air quality model can accept. It is also important that a variety of load/emissions conditions, and that a wide range of meteorological conditions based on several years of data, be considered in evaluating control strategies and in determining source impact for new source reviews, including prevention of significant deterioration. In addition, there is a need to judiciously choose receptor sites and to specify background air quality. This section identifies requirements for these data bases.

Source Data

Sources of pollutants generally can be classified as point, line and area sources. Point sources are generally considered to be those that emit a substantial amount of an air pollutant, e.g., 50 tons per year, from a stack or group of stacks. Line sources are generally confined to roadways and streets along which there are well-defined movements of motor vehicles. Area sources include the multitude of minor sources with individually small emissions that are impractical to consider as separate point or line sources. Area sources are typically treated as a grid network of square areas, with pollutant emissions distributed uniformly within each grid square. Descriptions of individual models should be referenced for specific emissions inventory requirements.

For situations involving one or a few point sources the following are minimum requirements for new source review and control strategy evaluations. Design process rate or design load conditions must be considered in determining pollutant emissions. Other operating conditions that may result in high pollutant concentrations should also be identified.* A range of operating conditions, emission rates, and physical plant characteristics based on the most recently available data, should be used in the model with the multiple years of meteorological data (see the following section, "Meteorological Data") to estimate the source impact. The following example (power plant) typifies the kind of data on source characteristics and operating conditions that are required:

1. Plant layout. The connection scheme between boilers and stacks, and the distance and direction between stacks, building parameters (length, width, height, location and orientation relative to stacks) for plant structures which house boilers, control equipment, etc.
2. Stack parameters. For all stacks, the stack height and diameter (meters), and the temperature (K) and volume flow rate (actual cubic meters per second) or exit gas velocity (meters per second) for operation at 100 percent, 75 percent and 50 percent load.
3. Boiler size. For all boilers, the associated megawatts and pounds of steam per hour, and the design and/or actual fuel consumption rate for 100 percent load for coal (tons/hour), oil (barrels/hour), and natural gas (thousand cubic feet/hour).
4. Boiler parameters. For all boilers, the percent excess air used, the boiler type (e.g., wet bottom, cyclone, etc.), and the type of firing (e.g., pulverized coal, front firing, etc.).
5. Operating conditions. For all boilers, the type, amount and pollutant contents of fuel, the total hours of boiler operation and the boiler capacity factor during the year, and the percent load for winter and summer peaks.
6. Pollution control equipment parameters. For each boiler served and each pollutant affected, the type of emission control equipment, the year of its installation, its design efficiency and mass emission rate, the date of the last test and the tested efficiency, the number of hours of operation during the latest year, and the best engineering estimate of its projected efficiency if used in conjunction with coal combustion; data for any anticipated modifications or additions.

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*Malfunctions which may result in excess emissions are not considered to be a normal operating condition. They generally should not be considered in determining allowable emissions. However, if the excess emissions are the result of poor maintenance, careless operation, or other preventable condition, it may be necessary to consider them in determining source impact.

7. Data for new boilers or stacks. For all new boilers and stacks under construction and for all planned modifications to existing boilers or stacks, the scheduled date of completion, and the data or best estimates available for items 1 through 6 above following completion of construction or modification.

Typically for line sources, such as streets and highways, data are required on the width of the roadway and its center strip, the types and amounts (grams per second per meter) of pollutant emissions, the number of lanes, the emissions from each lane and the height of emissions. The location of the ends of the straight roadway segments must be specified in appropriate grid coordinates. More detailed information and data requirements for modeling mobile sources of pollution are provided in the guideline on indirect sources.

For multi-source urban situations, detailed source data are often impractical to obtain. In these cases, source data should be based on annual average conditions. Area source information required are types and amounts of pollutant emissions, the physical size of the area over which emissions are prorated, representative stack height for the area, the location of the centroid or the southwest corner of the source in appropriate grid coordinates. If the model accepts data on area-wide diurnal variations in emissions, such as those estimated by emissions models which are based on urban activity levels and other factors, those data should be used.

In cases where the required source data are not available and cannot be obtained, the data limitation should be identified. Due to the uncertainties associated with such a limitation the use of the highest estimated concentration to determine source impact and to evaluate control strategies may be justified until such time that a better data base becomes available.

For control strategy evaluations the impact of growth on emissions should be considered for the next 10-20 year period. Increases in emissions due to planned expansion of the sources considered or planned fuel switches should be identified. Increases in emissions at each source which may be due to planned expansion of the sources considered or planned fuel switches should be identified. Increases in emissions at each source which may be associated with general industrial/commercial/residential expansion in multi-source urban areas should also be considered. However, for new source reviews, the impact of growth on emissions should generally be considered for the period prior to the start-up date for the source.* Such changes in emissions should consider increased area source emissions, changes in existing point source emissions which were not subject to preconstruction review, and emissions due to sources with permits to construct, but have not yet started operation.

*A new source may result in specific and well defined secondary emissions which can be accurately quantified. Secondary emissions are those resulting from operation of the source, but not directly emitted by the source, e.g., emissions from shipping at a port terminal. The reviewing authority should consider such secondary emissions in determining whether the source would cause or contribute to a violation of the NAAQS. However, since EPA's authority to perform indirect source review relating to parking-type facilities has been restricted by statute, consideration of parking-type secondary impacts is not required.

Meteorological Data

For a dispersion model to provide useful and valid results, the meteorological data used in the model must be representative of the transport and dispersion conditions in the vicinity of the source that the model is attempting to simulate. The representativeness of the data is dependent on (1) the proximity of the meteorological monitoring site to the area under consideration, (2) the complexity of the terrain in the area, (3) the exposure of the meteorological monitoring site and (4) the period of time during which the data are collected. The representativeness of the data can be adversely affected by large distances between the source and receptors of interest and valley-mountain, land-water, and urban-rural characteristics of the area.

For new source review and control strategy evaluation, the meteorological data required as a minimum to describe transport and dispersion in the atmosphere are wind direction, wind speed, atmospheric stability, mixing height or related indicators of atmospheric turbulence and mixing. Site-specific data are preferable to data collected off-site. The availability of such meso- and micro-meteorological data collections permits more detailed meteorological analyses and subsequent improvement of model estimates. Local universities, industry, pollution control agencies and consultants may be sources of such data. The parameters typically required can also be derived from routine measurements by National Weather Service stations. The data are available as individual observations and in summarized form from the National Climatic Center, Asheville, N.C. Descriptions of individual models should be referred to for specific meteorological data requirements. Many models require either hourly meteorological data or annual stability wind roses.

It is preferable for the meteorological data base used with the air quality models to include several years of data. Such a multi-year data base allows the consideration of variations in meteorological conditions that occur from year to year. The exact number of years needed to account for such variations in meteorological conditions is uncertain and depends on the climatic extremes in a given area. Generally five years yields an adequate meteorological data base. However, if long-term records are not available, it may be necessary to limit the modeling and subsequent analyses to a single year of meteorological data. The use of one year of data might also be justified if the climatological representativeness of that data can be demonstrated. A longer record from a nearby National Weather Service site could be used to check for representativeness.

The number of National Weather Service stations for which multiple years of hourly weather data are available is increasing significantly. Several EPA offices have ordered such data for a large number of stations. It is clear that more detailed analyses than previously considered for SIP evaluations and new source review are necessary. Thus, for areas where meteorological conditions are adequately represented by weather stations, the use of multiple years of meteorological data appears to be viable and justified.

Where representative meteorological observations are not available, the concentration estimates may be limited to consideration of worst case conditions. An analysis of worst case conditions should be based on reasonable interpretations of climatological data and should consider such critical plume characteristics as looping, coning, limited mixing, fumigation, aerodynamic downwash and plume impaction on terrain. Due to the uncertainties of this approach, the use of the highest estimated concentration to determine source impact and to evaluate control strategies may be justified until such time that a better base becomes available.

Receptor Sites

A receptor site is a location for which an air pollution concentration is estimated. The choice of locations for receptor sites significantly affects the evaluation of source impact and control strategy effectiveness. It is most important to identify the location where the maximum concentrations occur, both short- and long-term. The receptors selected must allow sufficient spatial detail and resolution so that the location of the maximum or highest, second-highest concentration is identified.

The receptor sites in the vicinity of large point sources at which maximum concentrations are likely to occur can be identified by (1) estimating concentrations for a sufficiently dense array of receptors to identify concentration gradients and (2) subsequently refining the location of the maximum by estimating concentrations for a finer array of receptors in the general areas of maximum concentrations. Another technique is to use a simple model such as PTMAX in combination with joint frequency distributions of wind speed, wind direction and stability to identify the downwind distance and direction at which the highest concentrations are most likely to occur.

Background Air Quality

To adequately assess the significance of the air quality impact of a source, background concentrations must be considered. Background air quality relevant to a given source includes those pollutant concentrations due to natural sources and distant, unidentified man-made sources. For example, it is commonly assumed that the annual mean background concentration of particulate matter is 30-40 $\mu g/m^3$ over much of the Eastern United States. Typically, air quality data are used to establish background concentrations in the vicinity of the source under consideration. However, where the source is not isolated, it may be necessary to use a multi-source model to establish the impact of all other nearby sources during dispersion conditions conducive to high concentrations.

If the point source is truly isolated and not affected by other readily identified man-made sources, two options for determining background concentrations from air quality data are available. The preferable option is to use air quality data collected in the vicinity of the source to determine mean background concentrations for the averaging times of interest when the point source itself is not impacting on the monitor. The second option applies when no monitors are located in the vicinity of the source. In that case, average measured concentrations from a "regional" site can be used to establish a background concentration.

For the first option it is a relatively straightforward effort to identify an annual average background from available air quality data. For shorter averaging times, background concentrations are determined by the following procedure. First, meteorological conditions are identified for the day and similar days when the highest, second-highest estimated concentration due to the source occurs. Then the average background concentration on days with similar meteorological conditions is determined from air quality measurements. The background for each hour is assumed to be an average of hourly concentrations measured at sites outside of a 90° sector downwind of the source. The 1-hour concentrations are then averaged to obtain the background concentrations for the averaging time of concern.

If air quality data from a local monitoring network are not available, then monitored data from a "regional" site may be used for the second option. Such a site should characterize air quality across a broad area, including that in which the source is located. The technique of characterizing meteorological conditions and determining associated background concentrations can then be employed.

If a small number of other identifiable sources are located nearby, the impact of these sources should be specifically determined. The background concentration due to natural or distant sources can be determined using procedures already described. The impact of the nearby sources must be summed for locations where interactions between the effluents of the point source under consideration and those of nearby sources can occur. Significant locations include (1) the area of maximum impact of the point source, (2) the area of maximum impact of nearby sources, and (3) the area where all sources combine to cause maximum impact. It may be necessary to identify these locations through a trial and error analysis.

If the point source is located in or near an urban multi-source area, there are several possibilities for estimating the impact of all other sources. If a comprehensive air monitoring network is available, it may be possible to rely entirely on the measured data. It is necessary that the network include monitors judiciously located so as to measure air quality at the locations of the point source's maximum impact and locations of the highest concentrations in the area. If the point source is not yet operating, its calculated impact can be added to these measured concentrations. If the source already exists and is contributing to the measured concentrations, its calculated contribution should be subtracted from the measured values to estimate the concentration caused by other manmade sources and by background.

If the monitored data are inadequate for such an analysis, then multi-source models can be used to establish the impact of all other sources. These models should be used for appropriate pollutants and averaging times to identify concentrations at the times and locations of maximum point source impact. The times and locations of maximum impact due to all other sources must also be identified. If a model is not available for the appropriate averaging times, statistical techniques can be used with an appropriate model to extrapolate from one averaging time to another. All statements in this guide regarding the data requirements and validity of air quality models are applicable to analyses of this type.

For control strategy evaluations, the impact growth on area-wide emissions and on concentrations caused by nearby sources should also be considered for the next 10-20 year period. To determine concentrations in future years, existing air quality should be proportionately adjusted by the anticipated percent change in emissions in the vicinity of individual monitoring sites. However, for new source reviews, changes in existing air quality should generally be considered for the period prior to the start-up date of the source.

Review Exercise

1. Meteorological data are necessary when a new source review is required. It is necessary because a. new source reviews are conducted by the meteorologist only. b. the State governor personally reviews every NSR. c. air quality modeling under NSR uses meteorological data. d. none of the above	
2. Short-term emission limits use which concentration estimate more frequently? a. third highest b. second highest c. highest, second-highest d. highest	1. c. air quality modeling under NSR uses meteorological data.
3. The meteorological condition that will help in computing the highest possible pollution concentration is called a. worst case b. best case c. most frequent case d. last case	2. c. highest, second-highest
4. The analysis used to determine whether a source will cause violations of NAAQS or cause deterioration larger than allowable increments is a. major modification review. b. air quality impact. c. significant increment analysis. d. violation analysis.	3. a. worst case

5. The four meteorological factors necessary in NSR and control strategy evaluation are a. humidity, wind speed, wind direction, stability. b. precipitation, stability, wind speed, wind direction. c. solar radiation, stability, mixing, mixing height. d. wind speed, wind direction, stability, mixing height.	4. b. air quality impact.
	5. d. wind speed, wind direction, stability, mixing height.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 450/2-82-009	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE APTI Course SI:409 Basic Air Pollution Meteorology		5. REPORT DATE December, 1982 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Donald Bullard and Marilyn Peterson		8. PERFORMING ORGANIZATION REPORT NO
9. PERFORMING ORGANIZATION NAME AND ADDRESS Northrop Services, Inc. P.O. Box 12313 Research Triangle Park, NC 27709		10. PROGRAM ELEMENT NO. B 18A2C 11. CONTRACT/GRANT NO. 68-02-2374
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Manpower and Technical Information Branch Air Pollution Training Institute Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

This training course is a 25-hour self-instructional course using slide/tape presentations and reading assignments dealing with basic meteorology, meteorological effects on air pollution, meteorological instrumentation, air quality modeling, and regulatory programs requiring meteorological data. Course topics include the following:

- Solar and terrestrial radiation
- Wind speed and direction
- Cyclones and anticyclones
- Atmospheric circulation
- Cold, warm, and occluded fronts
- Atmospheric stability
- Turbulence
- Meteorological instrumentation
- Plume rise and effective stack height
- Topography
- Air quality models
- Regulatory air quality programs

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Training Meteorology Air Quality Modeling Plume Dispersion	Training Course Self-instructional course with a/v materials	13 B 5 I 68 A

18. DISTRIBUTION STATEMENT Unlimited Available from National Audio Visual Center, National Archives and Records Service, GSA, Order Service HH, Washington, D.C. 20409	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 125
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)