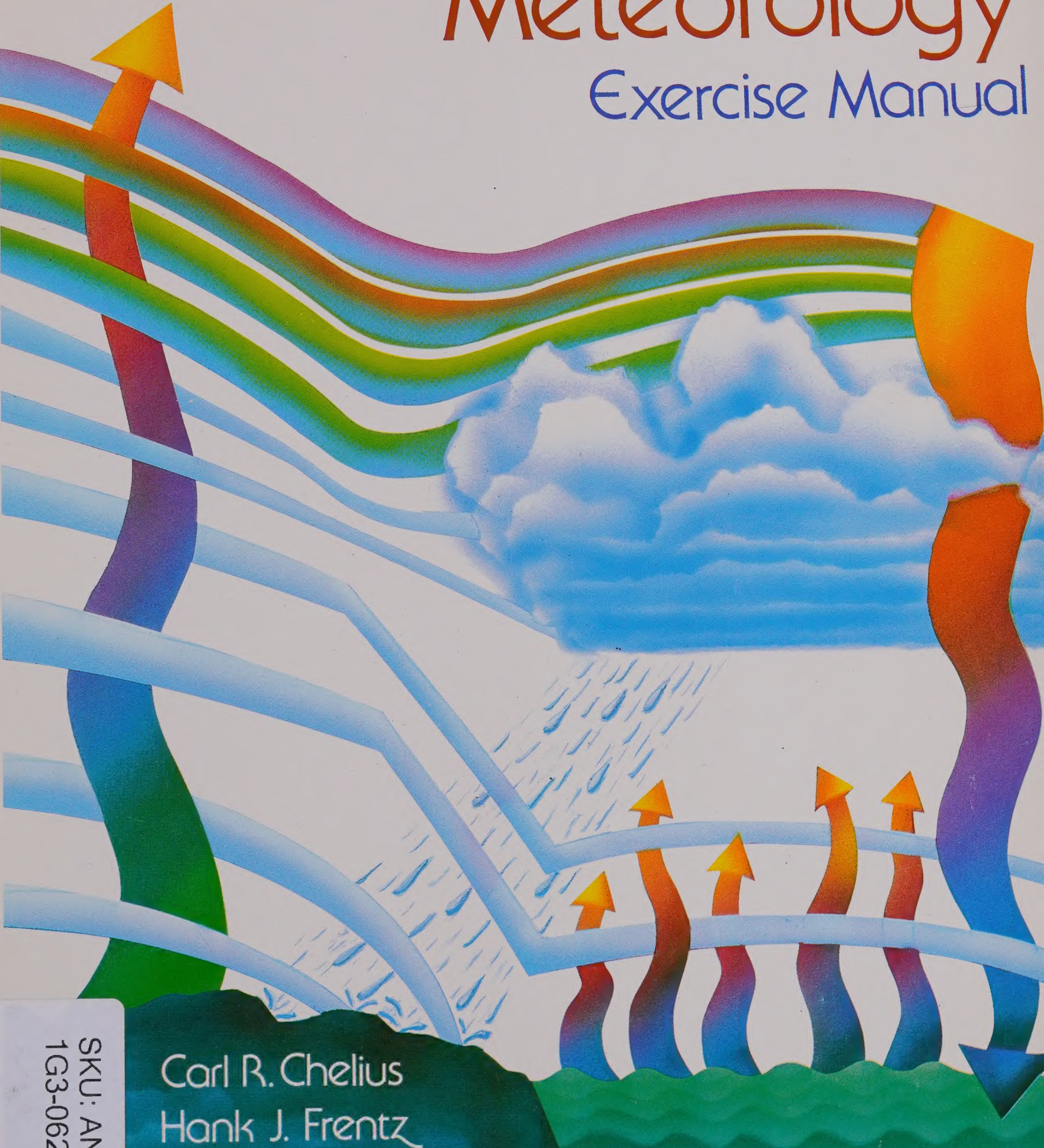
Second Edition

A Basic Meteorology Exercise Manual



Carl R. Chelius
Hank J. Frentz

A BASIC METEOROLOGY EXERCISE MANUAL

Second Edition

Carl R. Chelius
The Pennsylvania State University

Hank J. Frentz
Environmental Resources Management, Inc.
West Chester, Pennsylvania

KENDALL/HUNT PUBLISHING COMPANY
2460 Kerper Boulevard P.O. Box 539 Dubuque, Iowa 52004-0539

ISBN 0–8403–3340–4

C 403340 01

Printed in the United States of America
10 9 8 7 6 5

CONTENTS

PREFACE

This exercise manual for students of basic meteorology may be used as a supplement to a lecture course or used in an independent laboratory course. Although, it has been our intention to provide as complete an explanation as space permitted in each exercise, students may wish to consult basic meteorology texts as additional references. It is hoped that the students using this manual will achieve a basic understanding of the processes in the atmosphere that cause the varied phenomena we call weather.

ACKNOWLEDGMENTS

Many people need to be heartily thanked for making this work possible. Much of the faculty of the Pennsylvania State University Meteorology Department read the manuscript and helped clarify many points. Special thanks must go to Dr. Richard A. Anthes, Dr. John J. Cahir, Dr. John A. Dutton, Dr. John J. Olivero and Dr. Dennis Thomson. Thanks also to Edwin Danaher of the National Environmental Satellite Service for helping us to keep our perspective on several of the exercises. We also wish to thank the National Oceanic and Atmospheric Administration for the use of the satellite photos and maps contained within the exercises. Lastly, special thanks must also be extended to Theresa Frentz and Michelle Shawver for their help in the production of this manual.

TEMPERATURE

In this laboratory exercise you will learn about some of the many factors that influence temperature at the surface of the earth and in the atmosphere.

Simply stated, temperature is that particular state of an object which allows it to pass heat from itself to other objects. This heat exchange occurs provided that the temperature of the original object is higher than any of the other objects. Thus, if two spheres are placed side by side heat will flow from the sphere with the higher temperature to the sphere with the lower temperature. Or, if a cloud passes over a field on a summer afternoon, heat will flow from the unshaded area, which is hotter, to the shaded area, where it is cooler. This "differential heating" leads to several very interesting meteorological phenomena.

Temperature measuring is based on the principle that when an object is heated the molecules that make up the object move faster. This is the principle behind the use of the thermometer, which, in most cases, is simply a closed glass tube partially filled with some suitable liquid. As the temperature increases the molecules move faster, push outward and try to take up more space within the glass tube. When you look at a thermometer, what you see is the fluid rising in the tube (when the thermometer is being subject to heating) which is a result of the accelerated molecular movement of the fluid. As the temperature cools, the molecules move more slowly in the glass tube, you see the fluid shrinking, indicating that the temperature is decreasing.

Liquid-in-glass thermometers were invented early in the seventeenth century. The most common fluid used in thermometers, for meteorological work, is mercury; however, colored alcohol is also used. Another type of thermometer which is used widely around the home is the bimetallic thermometer. These are inexpensive instruments which are commonly used in ovens or outdoors and are easily recognizable by the metal coil contained inside. However, what appears to be a single strip of metal is actually two dissimilar strips of metal (hence, *bi*-metal) welded or riveted together. Based on the principle that different metals expand and contract at different rates at different temperatures, as the temperature changes, the coil "unwinds" or "winds" (because of the fact that one of the metals is changing its shape more than the other). This motion is then communicated to a pointer which moves over a calibrated scale on which you read the temperature. This simple, inexpensive instrument is not greatly accurate since, because of friction between the moving parts, some motion is lost and erroneous temperature readings may result.

Temperature Scales

There are several temperature scales in use. The most common scale in the United States is the Fahrenheit (°F) scale. For scientific work and in use in most European countries is the Centigrade or Celsius (°C) scale. A temperature of 32° on the Fahrenheit scale corresponds to 0° on the Celsius scale. 212°F corresponds to 100°C.

Conversion from one scale to the other can be made by use of the following:

$$°F = (9/5 \times °C) + 32° \qquad °C = 5/9\,(°F - 32°)$$

Another scale used widely in scientific work is the Absolute or Kelvin (°K) scale. The conversion from degrees Celsius to degrees Kelvin can be made by using $°K = °C + 273°$.

Problem 1–1

Complete the following table:

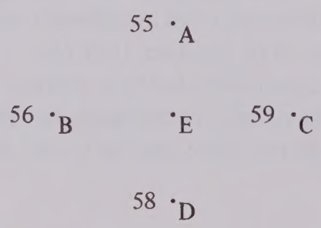
°F	°C	°K
72		
	12	
		296
	–40	
25		
		308
	30	

Do Fahrenheit and Celsius scales ever agree? At what temperature?

Isoplething—the Analysis of Numerical Fields

When looking at a weather map on which temperatures are plotted, it becomes useful to be able to pick out certain temperature patterns easily. That is, which are the warm areas, which are the cold areas, etc. Also, temperatures cannot be known at every point on the map; that is, every 50 or even 100 or 200 miles, simply because the cost would be enormous. In this case, the concept of Isoplething or the Analysis of Temperature Fields becomes useful.

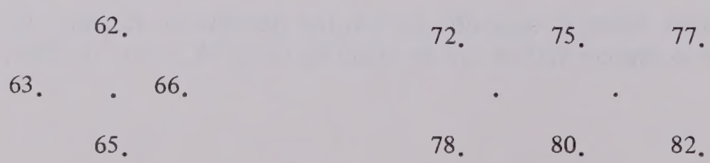
For example, say you know the temperatures (°F) at A, B, C and D below. What would be a reasonable guess of the temperature at E?



If you were driving your car from A to D, you would experience temperatures of 55°, 56°, 57°, and then 58°. Could you say that the temperature at E is 57°? Is this consistent if you drove from B to C? Here your thermometer would register temperatures of 56°, 57°, 58°, then 59°. Therefore, it is reasonable to assume that the temperature at E is 57°.

Problem 1–2

Make a reasonable guess at the temperature (°F) for the points not given.



Meteorologists speak of temperatures presented in this manner as a Temperature Field.

Note in the second part of problem 2, that the determination of the temperatures at the unknown points is more difficult. The reason for this is simply that there are more points to look at and more combinations to consider. If this seems difficult with only seven points, think how it would be if you looked at a weather map with several hundred points on it.

To alleviate this forest versus trees type of problem, meteorologists employ the useful operation known as "isoplething." Isopleth is a Greek word meaning equal (iso)—value (pleth). Simply stated it means to connect equal values of the particular meteorological variable with which you are working with a line. In the case of temperature, the isopleths (which is a general term) are called isotherms and the operation can best be explained by an example.

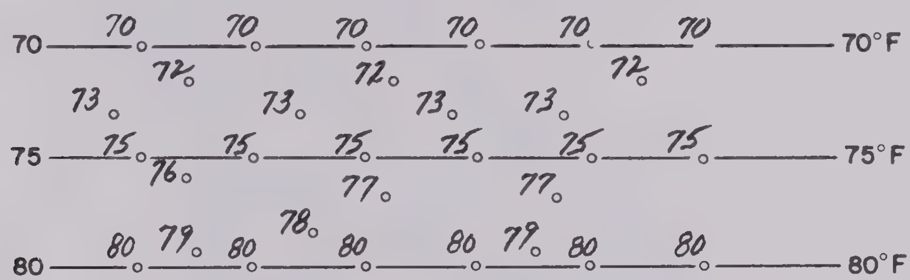


Figure 1–1. Notice that in this figure the isoplething has been done at 5° intervals. That is, there is a 70° isotherm, a 75° isotherm, and an 80° isotherm. This is not a set rule, since isoplething can be done at any interval desired.

In most cases, the isoplething is not as simple as in the above example. Figure 1–2a shows a temperature field (°F) that looks very complicated.

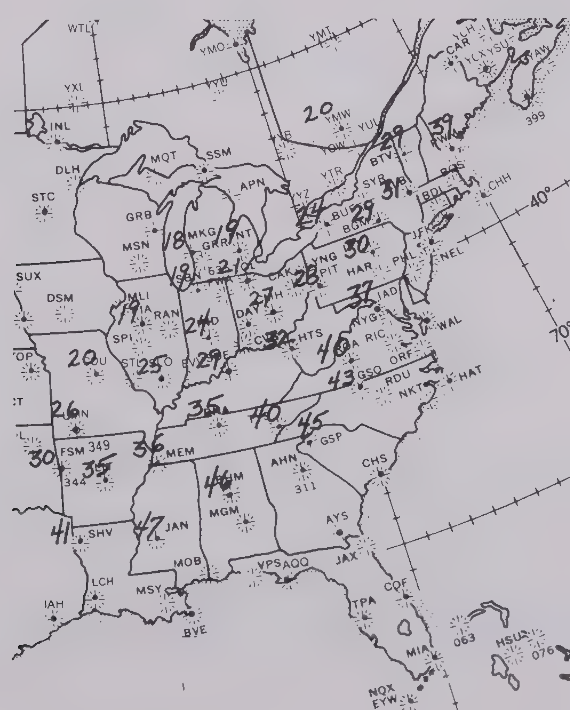


Figure 1–2a

However, after drawing isotherms, in figure 1–2b the field is much easier to study. It doesn't look so cluttered or so confusing. In other words, *isoplething is a means of organizing the data.* Once the field has been isoplethed, it is said that the field has been "analyzed."

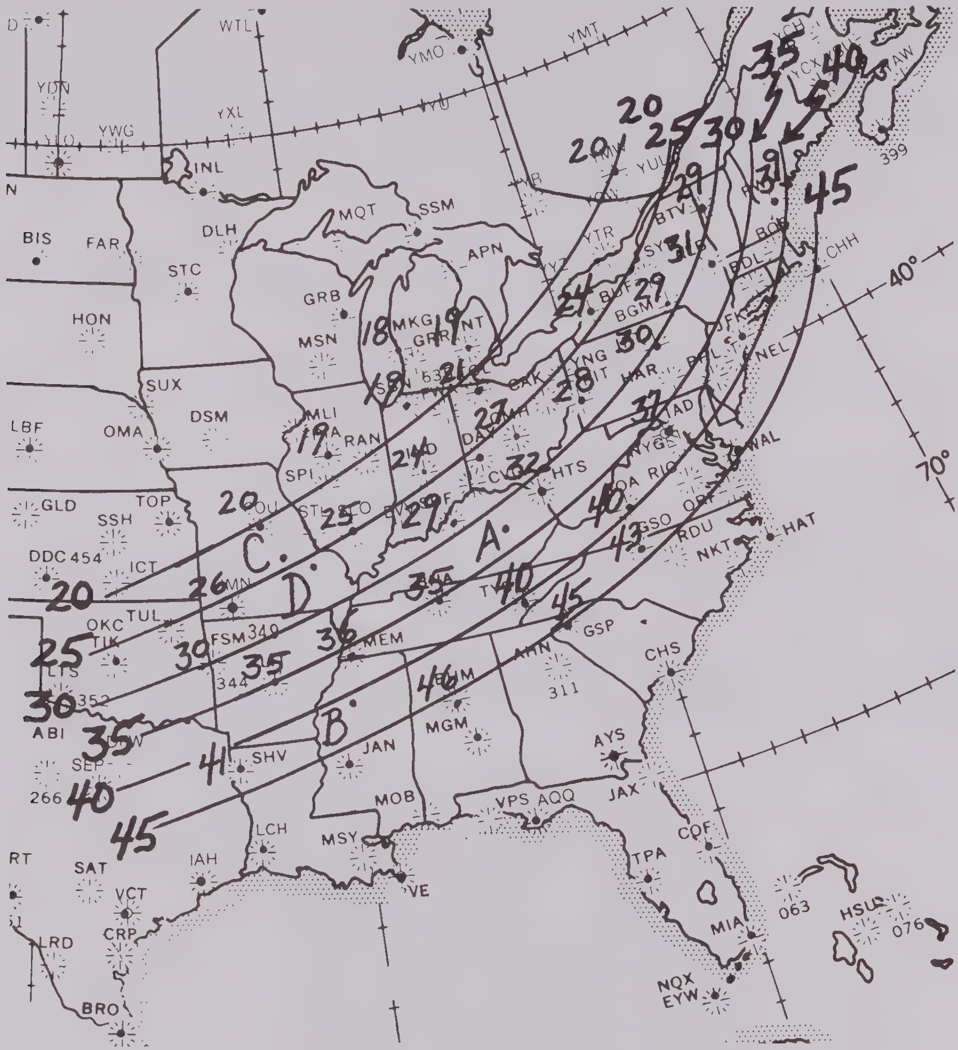


Figure 1–2b

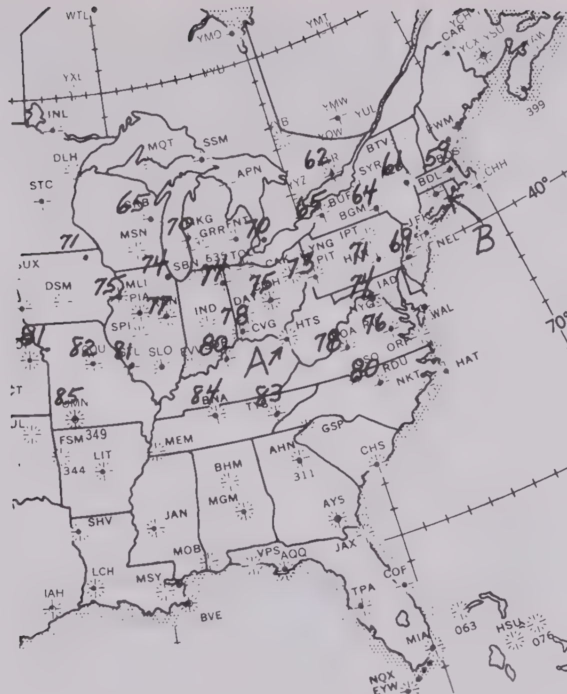
Problem 1–3

In figure 1–2b make a reasonable guess at what the temperatures are at points A, B, C, D.

A ____________°F B ____________°F C ____________°F D ____________°F

Problem 1–4

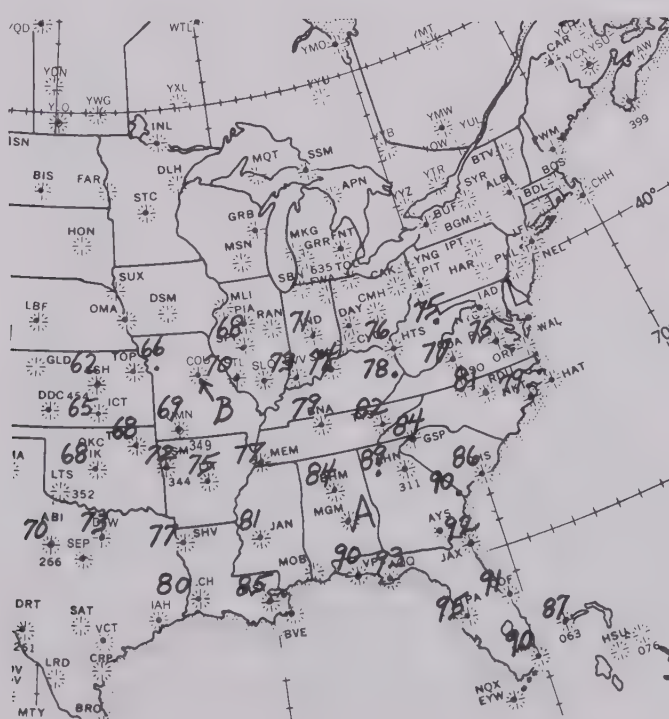
Isopleth the following temperature field at 5°F intervals. What is the temperature at A? ________ at B? __________ Hint: use a soft (#2) pencil; sketch in your lines lightly until you are satisfied.Then darken them.



NATIONAL WEATHER SERVICE

Problem 1–5

Analyze the following temperature field by drawing isotherms at 5°F intervals. Then determine the temperatures at A and B.



Problem 1–6

What is the value of isoplething? Why do meteorologists spend time isoplething temperature fields?

Radiosonde Observations of Temperature

One of the most valuable pieces of equipment available to the meteorologist is the radiosonde. Carried aloft by balloons, the radiosonde consists of a moisture sensing instrument, a pressure sensing instrument and a device for measuring temperature. The balloon transporting the instrument package ascends at a rate of about 1,000 feet per minute and information gained by the sensors is transmitted back to earth. These data are known as a "sounding" and the sounding is usually plotted on meteorological diagrams to give a picture of the vertical structure of the atmosphere.

The atmosphere has a nearly characteristic temperature structure in the vertical. This structure has been determined not only by radiosonde observations, but also by rockets and satellites which carry meteorological instruments. Figure 1–3 depicts a typical or average temperature sounding from the surface to a height of 110 miles. This graph shows that from the surface to about 8 miles atmospheric temperature decreases quite sharply. This region is known as the *troposphere* and is "capped" by the *tropopause* which is just the height where the first minimum temperature is reached. From the tropopause to an altitude of about 20 miles the temperature remains nearly constant (does not change) with height. From 20 miles to about 30 miles, the temperature begins to increase with height reaching a maximum at the *stratopause* which is the "top" of the *stratosphere.* For the next several miles the temperature remains about constant again, but at about 40 miles it begins to decrease, reaching another minimum at 50 miles. This third atmospheric layer is known as the *mesosphere* and, as you may have guessed, the top of the mesosphere is the *mesopause.* From the mesopause upwards the temperature increases, quite sharply at first, then less and less until it reaches a maximum of about 1,500°C at 300 miles. This last layer is known as the *thermosphere.*

For most work, however, the meteorologist is not concerned with the atmosphere up to 300 miles. In fact, meteorologists do not even use altitude as one of the coordinates on their diagrams preferring, instead, to scale the atmosphere according to pressure.

Atmospheric pressure can be illustrated by considering a pile of 5 bricks. Assume each brick weighs 2 pounds. If you were to put a scale at the bottom of the pile, it would register 10 pounds. If you put it under the third brick, the scale would register 6 pounds, and so on.

Air, like the bricks, has weight and the atmosphere "weighs" the most at the bottom and less as you go up, since there is less atmosphere, i.e. less weight, over you. Unlike the bricks where "a change of one brick is a change of 2 pounds," atmospheric pressure changes in the vertical most rapidly near the ground and less and less rapidly as you ascend to greater altitude. Figure 1–4 illustrates this concept with the vertical coordinate scaled by pressure units.

Now, graphing the atmosphere's vertical temperature structure using pressure as the vertical coordinate we get the result shown in figure 1–5. A height scale is also included for reference.

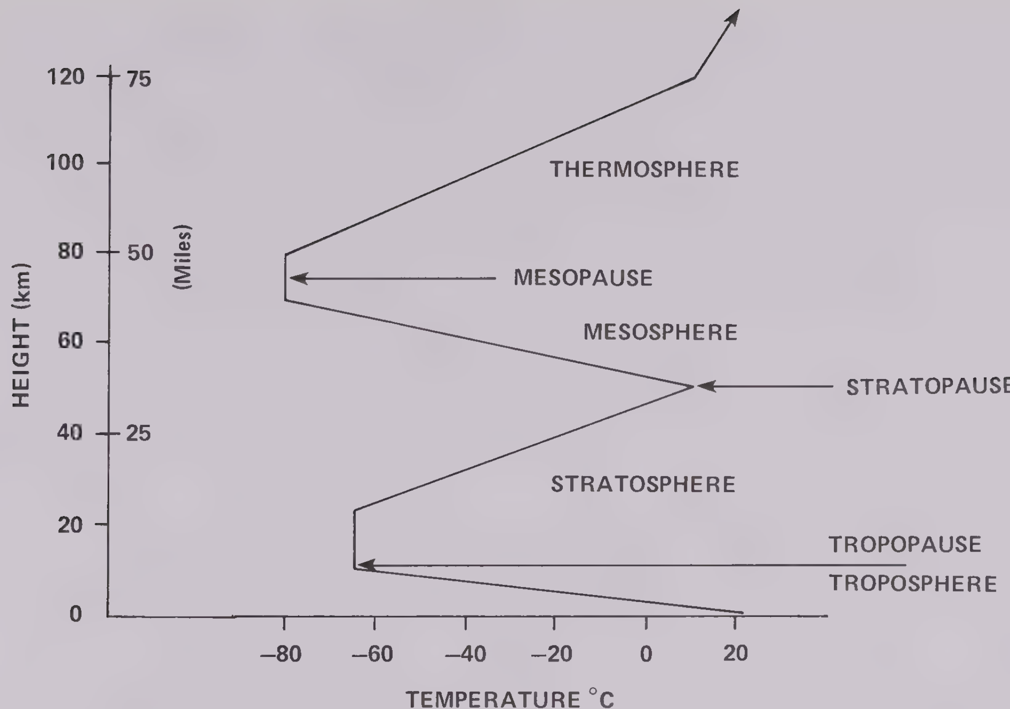


Figure 1-3

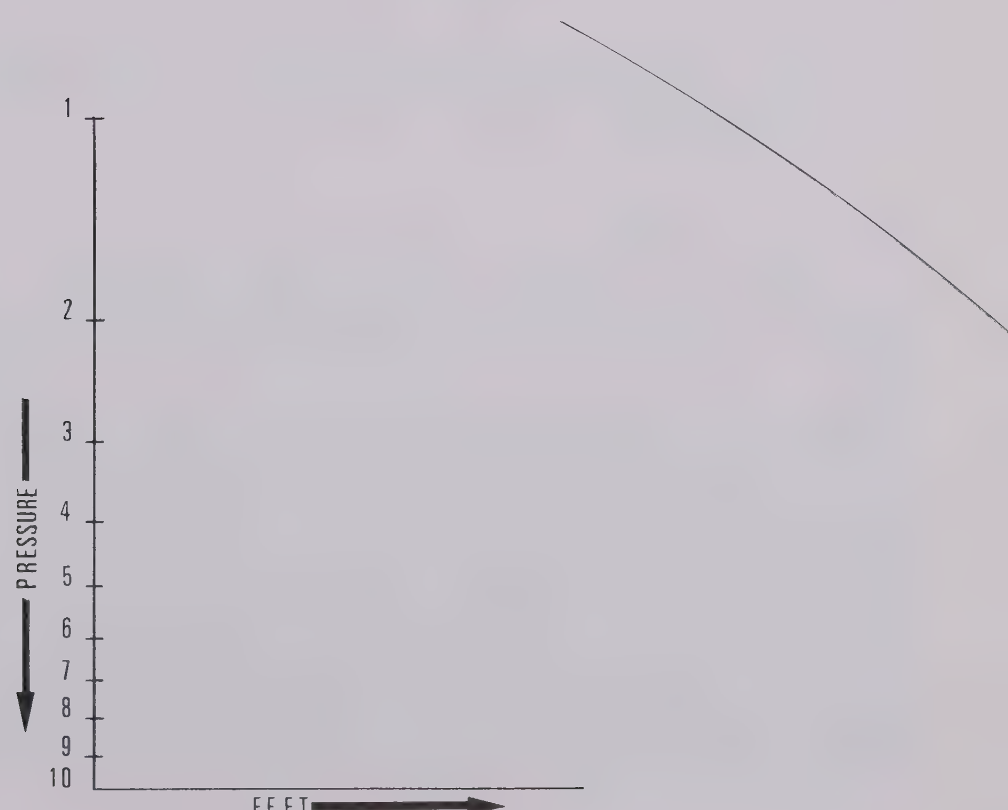


Figure 1–4

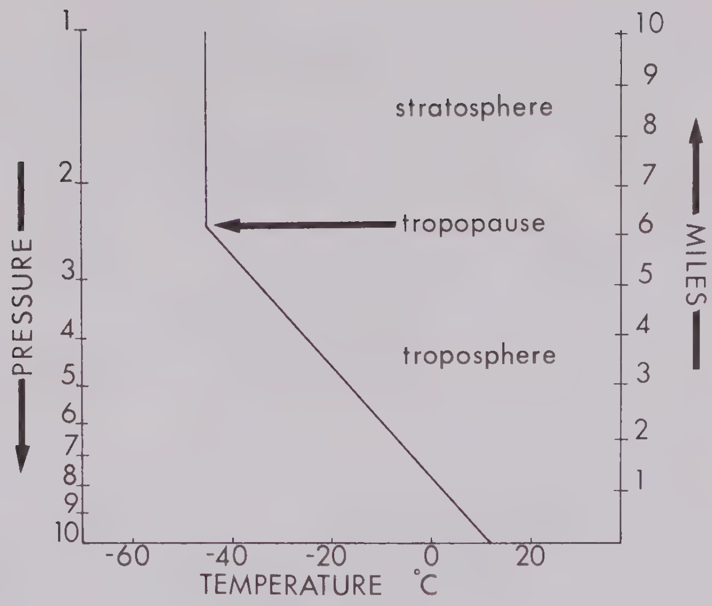


Figure 1–5

By comparing figure 1–5 with figure 1–3 it can be seen that except for the troposphere and a portion of the stratosphere the other atmospheric layers are not included when scaling the vertical according to pressure. In meteorology, this is by far the most practical manner to illustrate the vertical structure of the atmosphere since most of the world's weather occurs in the troposphere. In fact, for most work, meteorologists consider 100 millibars (a pressure unit—illustrated by 1 in figures 1–4 and 1–5) to be the "top" of the atmosphere. The levels above 100 mb are not normally included on such charts for conventional meteorological analysis.

Temperature and Elevation

It is common knowledge that snow covers the highest mountain peaks in the summer and, in the winter, forecasts of "rain with chance of snow in the higher elevations" are often heard in hilly regions. Indeed, most people have experienced cooling temperatures during leisurely rides up gently sloping mountains. The cause of this temperature change with altitude is linked to changes in pressure and volume.

As already stated atmospheric pressure changes most rapidly in the vertical. Since pressure is a force (per unit area), consider a cube of air being acted on by this pressure force. As the cube of air rises, the pressure decreases and so the force acting on the cube becomes less. Now the cube can expand since the "force" acting on the walls is less. As the cube continues to rise, the pressure force becomes less and less and it can continue to expand.

But does this affect the temperature? And if so, how? For an answer try spraying the contents of an aerosol can onto your hand. No matter where the can was stored, the spray will be cool. For the liquid, as it is released from the can, experiences a rapid decrease in pressure and a rapid expansion. What if you tried to put the liquid back into the can? You would need to exert a force on the liquid to compress it to a small size to fit into the can. This would cause the temperature of the liquid in the can to rise. The same thing can be done with a tire. Pump it up and the air will warm. (Feel the tire valve.) Let the air out and it will be cool.

To summarize, then, air that rises goes through a reduction in pressure, it expands and, therefore, cools. Conversely, air that sinks, experiences an increase in pressure, hence, it is squeezed together, and the temperature rises. Or to put it another way, when our "box" of air (meteorologists refer to this as a "parcel") is displaced in the vertical and the temperature of the air in the parcel is not affected by radiation (the sun heating the parcel) or by mixing with the surroundings, (that is, the imaginary walls let nothing in or out) and the air that makes up the parcel is dry, then the parcel will change temperature by 5½°F for every 1,000 feet of vertical movement (up or down).

The rate of decrease of temperature with height is known as a *lapse rate* and this 5½°F/1,000 ft is specifically known as the *dry-adiabatic lapse rate* (meaning there is no moisture in the parcel and there is no heat being added to or lost by the parcel).

Problem 1–7

A parcel at the ground is lifted 8,000 feet. Its original temperature is 52°F. What is the final temperature?

Problem 1–8

The lapse rate in °C and meters is 1°C for every 100 meters (1 meter = 3.3 ft). A parcel sinks from 1,500 m to 900 m. If the original parcel temperature is −2°C, what is the final temperature of the parcel?

From the past two sections, one fact should be quite apparent: in the portion of the atmosphere where most of the world's weather takes place (which is the troposphere) the temperature normally tends to decrease with increasing height and increase with decreasing height. But, unfortunately, this is not always the case.

On any clear night, close to the ground, the temperature may increase rather than decrease with height. This can occur in almost any locale due to the great amount of heat leaving the earth and flowing back into space. This great loss of surface warmth can cause the air near the ground to be as much as 10°C colder than the air two or three thousand feet above it. Conditions such as this where the temperature increases with height are known as *temperature inversions*. Figure 1–6 shows graphically the differences between normal dry-adiabatic atmospheric lapse rates and lapse rates during inversions.

It is well to point out here that the atmospheric lapse rate is not always dry adiabatic. Remember the somewhat stringent conditions placed on the parcel to warm or cool adiabatically; dry, no radiation

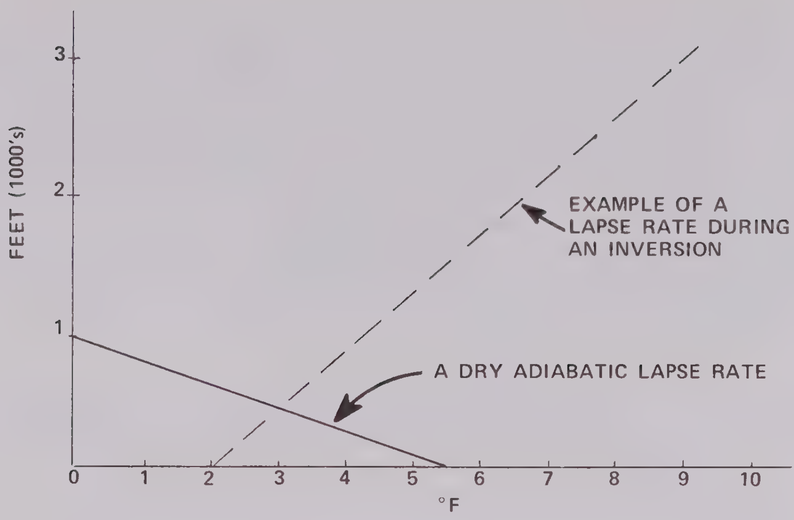


Figure 1–6

loss or gain, and no mixing with the environment. If these conditions are violated, the lapse rate will be different than the dry-adiabatic lapse rate.

Problem 1–9

Why must the sky be clear for a temperature inversion to occur at the surface?

The Greenhouse Effect

On a cloudy night heat rising from the surface of the earth is reflected back to earth upon hitting the clouds. This results in a warmer surface temperature than if the sky were clear which would allow the heat to escape to space and allow the surface to cool. In a manner somewhat analogous to this phenomena, the entire atmosphere acts as a blanket to keep the earth from becoming a vast, frozen wasteland during the night.

The surface temperature of the sun is about 6,000°K (10,340°F). At this temperature, energy leaving the sun is mainly in a form known as *short-wave radiation.* The atmosphere is transparent for much short-wave radiation and, as a result, this energy can penetrate the atmosphere and warm the earth. The earth will also radiate energy, but because its temperature is relatively low (say, 290° to 300°K) it radiates energy in a form known as *long-wave* radiation. The atmosphere is not transparent to most of this long-wave radiation which is absorbed by the atmosphere thereby trapping the energy. This entire process is similar to what was once thought to occur in a greenhouse (hence, "The Greenhouse Effect") with the panes of glass acting as the atmosphere which allow the short-wave radiation to penetrate to the plants and soil inside the greenhouse. This "mini-Earth" upon warming radiates long-wave radiation which cannot penetrate the glass (atmosphere) thus allowing the inside of the greenhouse to stay warm.

Problem 1–10

The greenhouse was once thought to produce an effect almost identical to the earth's atmosphere as explained above. Over the years, however, it has been determined that the air in the greenhouse does *not* stay warm for the same reasons that the earth does. There is, in fact a much simpler reason. Take a look at this diagram. Can you think of this reason?

Temperature and Surface Covering

As well as being affected by elevation and terrain, temperature is also affected by surface covering. The surface covering of a region is predominantly affected by the amount of moisture in the atmosphere and it is the moisture at the surface which plays a large part in determining how high the surface temperature will rise.

The main direction of flow of air in the United States is from west to east (the "westerlies"). In other words, air coming off the Pacific will gradually move to the Atlantic. It is this westerly flow of air which gives rise to the vast expanses of desert east of the Rockies. Air, flowing off the Pacific Coast is very moist, gaining this moisture from the ocean. As it moves inland to the Rocky Mountains it is forced to rise to great heights. This upward motion causes the moisture in the air to condense and fall out as rain or snow. Upon descending the mountains the air is now dry and this dry air promotes vast regions of clear skies east of the mountains (since the moisture that must be present for clouds to form is not available). With few clouds in the sky to block out the rays of the sun, the temperature in this region can become very hot. However this is only part of the story, for the lack of clouds also means there is a lack of rain, which means that the *surface* is very dry. Because of this, there is no water in the ground, on the ground, or above the ground contained in plants to be *evaporated*. Lack of evaporation means that all of the energy reaching the earth is used to heat the surface. Deserts, then, form because there is a high degree of incoming solar radiation (**insolation**) and because there is no water present to be evaporated which would cool the air. (By the same token, the lack of clouds means that at night the heat stored in the ground can readily escape to space allowing the desert to become very cold.)

Perhaps you can now see why farm fields and other areas with vegetation do not become so hot. Moving eastward towards the Atlantic Ocean, we again pick up sources of moisture (the Atlantic Ocean and the Gulf of Mexico). Therefore, there should be more clouds, hence less insolation, and also more rain. The increase of rain allows plants to grow and water to be stored in the ground. Evaporation of the water in these "reservoirs" causes the air to cool because, again, evaporation is a cooling process.

In this discussion don't be misled into thinking that all of this must happen on such a large scale. Let us say that a shower wets one side of a street but not the other side. Which side will have the cooler temperature? The wet side, of course, since there is moisture to be evaporated. In fact, the wet side of the street will continue to be cooler until all the moisture is evaporated (therefore all of the cooling is finished).

Diurnal Temperature Variations

In the northern hemisphere, the sun is highest in the sky at about noon each day. Therefore, it would be at this time that the sun's rays would be striking the earth most directly (that is, the angle between the sun's rays and the earth is the smallest). This, then, should be the time of day when the maximum temperature should occur since the concentration of solar energy on the surface is greatest. But is it? Think for a minute of those warm, summer afternoons by the pool or the beach. Are you hotter at noon or at three or four o'clock? If you spend any time outdoors, especially in the summer, you probably remember being warmer at mid-afternoon, about three o'clock, than at noon. So does this mean that the concept discussed above about the sun angle is in error or are there other events taking place? The latter of course is true, and to explain it, return once again to what has been said about the earth being both a receiver and emitter of radiation.

At all times of the day, the earth receives and emits energy. During the morning hours, however, when the sun is rising and moving across the sky, the earth receives more energy than it emits and this causes the temperature to rise. It is not until the reception and emission of radiation are equal that the time of *maximum* temperature occurs. After this point, the earth begins to emit more than it receives and the temperature begins to decrease. The time of minimum temperature, then, occurs when the emission once again balances the reception of energy. This usually occurs shortly after dawn.

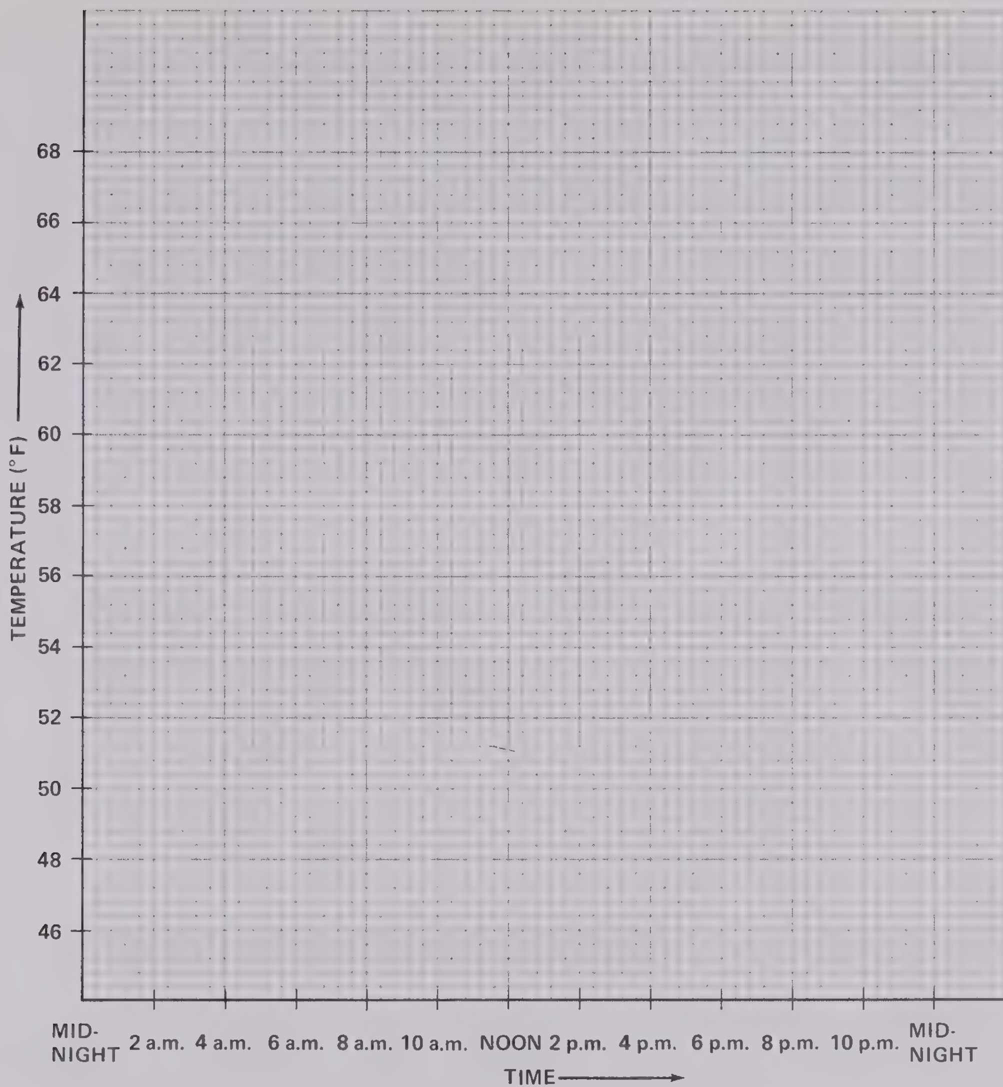
Problem 1–11

You might be hotter at three or four o'clock in the summer but at what time do you *tan* best? Explain.

Problem 1–12

The following are data of the average temperature (°F) for each hour of day at Pittsburgh, Pa., during May 1963. Plot the data on a graph and use it to explain the ideas of the preceding section.

Hour	Temp.	Hour	Temp.	Hour	Temp.	Hour	Temp.
Midnight	51°	6 a.m.	47°	noon	64°	6 p.m.	64°
1 a.m.	50°	7 a.m.	50°	1 p.m.	66°	7 p.m.	62°
2 a.m.	49°	8 a.m.	54°	2 p.m.	66°	8 p.m.	59°
3 a.m.	48°	9 a.m.	58°	3 p.m.	67°	9 p.m.	57°
4 a.m.	47°	10 a.m.	60°	4 p.m.	67°	10 p.m.	55°
5 a.m.	46°	11 a.m.	62°	5 p.m.	66°	11 p.m.	54°



TEMPERATURE (°F)
68
66
64
62
60
58
56
54
52
50
48
46
MID-NIGHT
2 a.m.
4 a.m.
6 a.m.
8 a.m.
10 a.m.
NOON
2 p.m.
4 p.m.
6 p.m.
8 p.m.
10 p.m.
MID-NIGHT
TIME

Summary

This exercise on temperature has attempted to give some useful information to explain many everyday occurrences which you experience, but may not be able to readily explain. It also contains much introductory material for discussions to come. In other words temperature is not just something interesting to broadcast over the radio each day, but a knowledge of temperature and temperature patterns can be used to predict the occurrence of many other meteorological phenomena. For example, knowing what the lapse rate is on a particular summer day is useful in determining whether or not thunderstorms may form. The latitudinal temperature variations throughout the year (to be discussed later) are directly related to the intensity of major storms between winter and summer. The differences in temperature between water and land are directly related to upper air patterns throughout the year as well as playing a role in snowfall intensity near the Great Lakes in winter. And, finally, many of the things discussed so far can be tied together in order to predict the maximum temperature for a particular day, among them the atmosphere's ability to absorb and reflect solar radiation and the amount of evaporation that may occur. Many of the ideas represented here will be drawn upon in future discussions.

MOISTURE

The mixture of water vapor with the permanent gases of the atmosphere has occasioned a number of "Humidity Problems" over which the student is in danger of becoming more or less confused.

W. J. Humphreys
in "Physics of the Air"

Introduction

The amount of gaseous water vapor in the atmosphere varies from nearly zero to as much as four percent. This extreme variability is due to the fact that water can exist as a solid, a liquid or a gas at the temperatures normally found on our planet.

Meteorologists are interested in the amount of water vapor present in the atmosphere for several reasons: (1) the condensation of water vapor produces precipitation and (2) the release of *latent heat* during condensation and freezing of water is an important source of energy while the absorption and release of *radiation* by water vapor affects the earth's energy budget.

Moisture

The words "moist" and "moisture" most likely conjure up in your mind various degrees of wetness. Clearly, when speaking of atmospheric moisture something more precise and meaningful is needed other than phrases such as "slightly moist" or "moist" or even "dripping wet." Obviously, the problem is one of definition since all the possibilities of "moist" have different meanings to different people. But how can something as nebulous as "moisture" be quantified and described? Should it be measured with a ruler as, say, 2.7 inches or 0.89 cm? Or could it be weighed somehow to reveal data such as 14 gms, 22 gms, etc? Perhaps it could be thought of as an invisible force, in the same manner as air, and speak of how much of it is pressing down on your head at any given time?

The answer to these above questions is, oddly enough, "Yes, all of these can be used to measure and describe atmospheric moisture." But before we go into the details, let's review some material on molecular processes.

Water can exist in three states: solid, liquid, and gas. The gaseous state is invisible, as is air, and usually mixes readily with air. This invisible moisture will be referred to as water vapor. At any given temperature only a certain amount of water vapor can be present, the amount being dependent on the temperature. (The higher the temperature, the more water vapor can be present.) The liquid state of water in the atmosphere is commonly thought of as rain (when the water drops are large) and fog (when the water drops are small) and the solid state as snow and ice.

The processes that occur when water changes state are summarized in figure 2–1.

Molecular Motion

The temperature of a substance is proportional to the mean (average) kinetic energy (energy of motion) of the molecules that comprise the substance. For example, in a thermometer, an increase in

To: \ From:	Liquid	Solid	Gas
Liquid	* *	Melting	Condensation
Solid	Freezing	* *	Sublimation
Gas	Evaporation or Vaporization	Sublimation or Vaporization	* *

Figure 2–1

temperature causes the molecules that comprise the fluid to move faster. As a result, the fluid expands which can be seen by watching the rise of the fluid in the tube. Likewise, when there is a decrease in temperature, the fluid shrinks as the molecules within the fluid move more slowly.

Now, consider a container of water. The water has a certain temperature based on the motion of the water molecules. That is, there are fast moving molecules and slow moving molecules with the temperature based on the average motion of all the molecules. Since the molecules are constantly moving, there is no reason to believe that they must all stay in the container. It would seem reasonable to believe that the faster moving molecules could leave since they have the greatest energy and can therefore break away from the rest. But, if a fast moving molecule leaves, what happens to the mean molecular motion? It must decrease and therefore the temperature must decrease.

As an analogy to the above, consider ten cars moving on a freeway. Five cars move at 60 mph and five move at 40 mph. The mean speed is then $((5 \times 60) + (5 \times 40)) \div 10 = 50$ mph. Approaching an exit ramp, one of the cars moving at 60 mph darts off the freeway. Now the mean speed is $((4 \times 60) + (5 \times 40)) \div 9 = 48.8$ mph.

But what if the car that left immediately returned to the freeway on the next entrance ramp so that once again there are ten cars, 5 at 60 mph and 5 at 40 mph? Obviously in this situation the mean speed of the cars will remain 50 mph (except for the brief period when the car was off the road). If in the container of water, for each molecule that leaves one molecule returns, the mean molecular motion will not change, and therefore, neither will the temperature of the water. Obviously, in this instance, the water level will not change since there is no net departure of water molecules. This condition where the same number of molecules are reentering as are leaving is known as the equilibrium state.

However, what would happen if we heated the water? Molecules of water would escape rapidly because they gain energy. Therefore, if molecules are leaving, the water must be cooling. But how can cooling occur if we are heating the water?

Suppose we take the container of water, put a thermometer in it, seal it in an airtight box and apply heat so that the water begins to boil. The molecules of water will begin to escape very rapidly from the water into the open air inside the box. However, because the box is sealed, these molecules will also begin to warm. The temperature inside the box, then, can increase greatly as we apply more heat to the box. (This continued heating occurs *so long as the box is sealed.*)

Let's digress for a moment and see why it is so important to keep the box sealed. As an analogy, suppose you hiked up a high mountain. You come to your campsite, put a pot of water on to boil, and plan to wait five or six minutes before it's ready. Surprisingly, however, after only two or three minutes your pot of water is boiling, and ready to be poured. Why? Atmospheric pressure decreases with increasing altitude. The pressure, then, on top of the mountain is less than sea level pressure. This pressure decrease is the reason why the water boiled so rapidly (that is, at a lower temperature than if you were at sea level). Actually, if you were up as high as 473 mb (about 20,000 ft), the water would boil at 176°F rather than at 212°F which is the boiling point at 1,013 mb (average sea level pressure), at 23 mb it would boil at room temperature (about 68°F) and at 6 mb, 32°F would be the boiling point.

Conversely, if you *increased* the atmospheric pressure water would boil at a much *higher* temperature: at 1,986 mb the boiling point is 248°F; at 6,171 mb water will boil at 320°F.

This brings us to the reason why the box must be sealed. By sealing off the box from the outside atmosphere and then applying heat, the pressure inside the box can increase far above the normal sea level pressure. This increase in pressure will allow the water to boil at higher and higher temperatures rather than 212°F.

Now let's take away the box. Water molecules are now rocketing out of the water into the free air. We look at the thermometer in the water and amazingly we see that the temperature has dropped to 212°F (100°C) and it will not budge above that point even though we have a fire roaring under the container. Clearly, cooling must be occurring in the water to prevent its temperature from rising further. In fact, with each additional amount of heat that is added to the water (in excess of the heat needed to bring the water to the boiling point) a certain amount of molecules escape the water causing it to cool. (This is something like pouring water into a glass with no bottom.) This excess heat, the heat that goes into transforming the liquid to a vapor (the molecules from being *in* the water to *outside* the water) is known as the *Latent Heat of Evaporation.*

Air does not hold water vapor in the same way that a sponge holds liquid water. In fact, the same number of water molecules would be present above a liquid water surface if there were no other gas molecules there at all. The amount of water present in the gaseous state depends on the energy of the molecules in the liquid. In other words, the higher the temperature, the more energetic the molecules and the faster the rate at which they leave the liquid.

The number of molecules falling back into the liquid is proportional to the number of molecules present in the gaseous state. When the number of molecules entering the liquid is equal to the number leaving, we say the system is saturated, and the pressure of the water molecules in the space above the liquid water is called the saturation vapor pressure.

Problem 2–1

Discuss, in terms of molecular movement, why you feel chilled when coming out of a pool on a sunny, dry day (or even stepping out of your shower).

Can the latent heat of evaporation be recovered? Suppose we return to our sealed container of water and attach a pipe to it which allows the steam to flow to another chamber (see figure 2–2). We allow cold water to flow past the chamber, thus cooling the inside. Looking inside the chamber, we see that the steam flowing into it does not remain steam for very long. Rather, water is collecting in the bottom of the chamber. We are, therefore, reversing the original process. If two thermometers are immersed in the water, one on each side of the box, we see that the water that has flowed past the chamber (T_2 in the picture) is warmer than the water that has not yet flowed past the chamber (T_1).

How can the water become warm if the box is being cooled? Because when the vapor returns to the liquid state (condensation) the same quantity of heat that went into evaporating the drops (in the first process) is returned to the system. This heat is known as the *Latent Heat of Condensation.*

Let's use the results from the above experiment and apply them to the atmosphere. You have no doubt experienced the refreshing coolness of the air after a summer rain shower. As the rain falls through the air, which, let us assume, is "unsaturated" (which means the actual vapor pressure is less than the

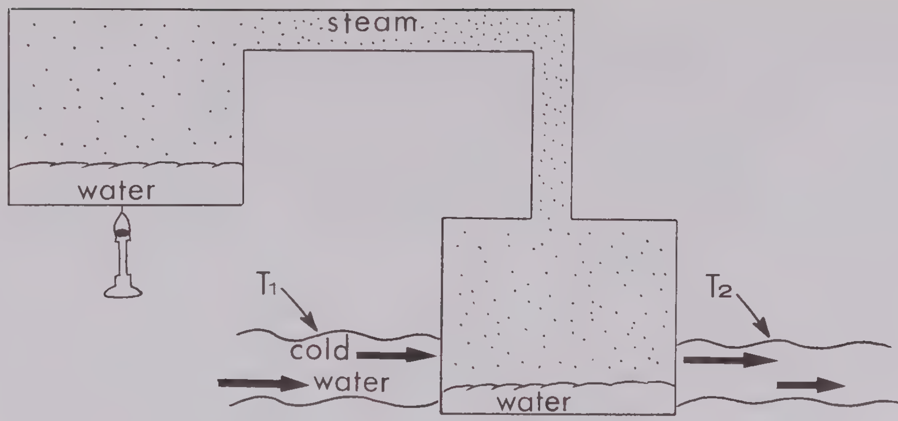


Figure 2–2

saturation vapor pressure) each individual rain drop acts as a container of water. Rather than receiving heat from a fire, the rain drop receives heat from the surrounding atmosphere. Cooling, then, occurs because the droplet evaporates and cools (due to the fact that it is losing faster moving molecules). It then passes this cooling on to the surrounding environment through a process known as conduction.

When condensation takes place, the moisture in the air is cooled not by a flowing stream of cold water, but by the cold air itself; and at the moment the vapor is transformed into a droplet, a quantity of heat is returned to the environment.

An example of the importance of this latent heat of condensation can be seen in the hurricane. As these storms, which are born over oceans, draw large quantities of moist air into them, the air cools and condenses. The latent heat of condensation that is released is a form of energy and it is this energy that drives the hurricane to destructive force.

Warm Air Vapor Pressure versus Cold Air Vapor Pressure

Suppose we again return to our box with the container of water in it. Attached to the box is a device for measuring the pressure exerted by the water vapor in the box. (All gases exert a pressure. That pressure exerted by water vapor is known as the vapor pressure.) The higher the reading on the vapor pressure meter, the more vapor there is in the box.

Initially, we take a vapor pressure reading and then apply heat to the water. Now we see that the vapor pressure reading has increased. While we continue to heat the water, the air in the box is also warming and the vapor pressure is continually rising. That is, the air inside the box contains more and more water vapor. What can you conclude from this experiment? Simply, that more water vapor can be present in warm air than cold air.

Problem 2–2

You have just moved into a new house and find that the previous owners left behind a humidifier and a dehumidifier. Which would you use in summer? Why? Which would you use in winter? Why? Would you ever use them both at the same time? Why or why not?

Moisture Variables

All of the variables used to quantify the amount of moisture in the atmosphere can be divided into two classes: (1) Those variables which depend *only* on the amount of water vapor in the air, and (2) those variables which depend not only on the amount of water vapor in the air, but also on the temperature of the air. The members of the first group are known as absolute measures and those of the second group are known as relative measures ("relative" measuring meaning "related" to temperature). No special order of presentation will be made as to absolute or relative measures.

Vapor Pressure (e) and Saturation Vapor Pressure (e_s)

The total atmospheric pressure at any time is actually the sum of many small pressures for each of the constituents of the earth's atmosphere contributes a pressure to that of the total atmospheric pressure. For example, there is a pressure exerted by oxygen, a pressure exerted by hydrogen, nitrogen, and all of the other gases which make up the air we breathe. The contribution to the total atmospheric pressure which is made by water vapor is known as the vapor pressure. Since the vapor pressure only changes when the amount of water vapor in the air changes, e is an absolute measure of the air's vapor content.

There is, however, a limit as to how much of the total pressure can be made up by water vapor. This limit is known as the saturation vapor pressure and it is defined to be the maximum pressure that water vapor can exert at any given temperature.

E_s is a relative measure of atmospheric moisture since temperature plays a direct role. As in the case of the dew point, when the temperature increases, the atmosphere allows more water vapor to be present, but the water vapor may or may not take advantage of the situation.

Dew Point (T_d)

Perhaps the most widely used measure of atmospheric moisture in meteorology is the dew point. The dew point is defined as the temperature, expressed in degrees centigrade or Fahrenheit, at which the moisture in the atmosphere will condense when cooled at constant pressure. As an example, think of what happens when you pour a cold drink into a glass. Before pouring, the outside of the glass is dry; but, moments after you pour, the glass becomes wet. What happened? The air around the glass had a certain amount of water vapor. When the cold drink was poured into the glass the air around the glass immediately began to cool and, when the air was cooled to the dew point, moisture began to condense onto the nearest object: the glass. (This is another important point: for condensation to occur, the water vapor in the air must have something to condense "onto.") Now, using these ideas and those presented in the temperature exercise, can you think of the events that take place in order for clouds to form?

Since warm air has a higher saturation vapor pressure than cold air, one would expect to see dew points, on the average, higher in summer than in winter. Though the temperature of the air is a limiting value as to how high the dew point can go, (that is, once the temperature equals the dew point condensation occurs), the temperature of the air does not directly affect the dew point. In other words, if the temperature of the air changes, the dew point does not have to change (the air's saturation vapor pressure changes, but the dew point can stay the same). However, if the amount of moisture present changes, then the dew point has to change. The dew point, then, is a measure of the absolute water vapor present in the volume of air.

Mixing Ratio (w) and Saturation Mixing Ratio (w_s)

Let us say that it is possible to extract a small quantity of the atmosphere and weigh it on a scale. This portion of the atmosphere is just a representative sample of the entire atmosphere and, therefore, we should expect it to be made up of the usual atmospheric gases, including water vapor. The mixing ratio is defined to be the weight (actually mass) of water vapor (M_v) in the sample divided by the weight (mass) of dry air (M_d)in the sample: $w = \frac{M_v}{M_d}$. Note that the temperature does not appear in the equation. Therefore, since the mixing ratio does not depend on temperature, it is an absolute measure of the moisture in the atmosphere.

Again, there is a limit as to how much water vapor can be present in the volume of air. When discussing vapor pressure, this limit is known as the saturation vapor pressure. With mixing ratio, this limit is known as the saturation mixing ratio and it is directly related to temperature. It is defined to be the maximum amount of water vapor (in grams) that can be present in one kilogram of dry air at any given temperature. It is also defined to be the mixing ratio the air sample would have if it were saturated. Therefore, when the air is saturated, $w = w_s$. These mixing ratios are usually expressed inparts per thousand. $\frac{4 \text{ gms}}{1 \text{ kg}}$ (4 grams of water vapor to 1,000 grams of dry air) is a typical value for dry air while $\frac{30 \text{ gms}}{\text{kg}}$ to $\frac{40 \text{ gms}}{\text{kg}}$ are about the maximum value for very moist air.

Relative Humidity (RH)

The most common measure of atmospheric moisture used by the general public is relative humidity. No new concepts need be introduced since relative humidity is just the ratio of several of the variables already discussed.

Relative humidity can be defined as:

$$RH = \frac{\text{Amount of water vapor present}}{\text{Maximum amount of water vapor at the current temperature}}$$

$$\text{That is, } RH = \frac{w}{w_s} \times 100$$

Relative humidity can also be measured in terms of pressure:

$$RH = \frac{\text{The contribution made by water vapor to the total atmospheric pressure}}{\text{The maximum pressure that water vapor can exert at the current temperature}}$$

$$\text{That is, } RH = \frac{e}{e_s} \times 100$$

Both ratios are multiplied by 100 in order to allow RH to be expressed in "percent."

Relative humidity is the most common variable used to express atmospheric moisture (at least to the general public) and though it is not an inaccurate measure of moisture, it is not the most accurate. This is because relative humidity is a relative measure of moisture which means, again, that it is dependent on the air temperature. (Note the denominators of the above two equations.)

As an example of the less desirable characteristics of RH, consider the second equation (though the first will do). Let us say that a particular air mass remains over an area for twenty-four hours. Therefore, the vapor pressure does not change for this period of time since the amount of moisture associated with this air mass does not change. Let us say that it is also an ordinary day, being warmer during the daylight hours than at night. Since warm air has a higher saturation vapor pressure than cold air, e_s will be higher during the day than at night. Since the denominator of the equation is greater during the day, RH is lower during the day than at night when the air cools and the denominator is smaller. If you did not know this fact, you might compare the relative humidity for day and night and conclude that the air is more moist at night. Actually, the absolute moisture content of the air has not changed, rather it is the decrease in temperature that caused the increase in the relative humidity.

Precipitable Water (W)

Precipitable water is the amount of liquid water that would result if all the water vapor in the atmosphere over a given area were to suddenly condense and fall out. This is analogous to squeezing a wet sponge and having the liquid water fall out. Here, the liquid water is the water vapor in the atmosphere and the squeezing action is the condensing process.

Dew Point Depression ($T - T_d$) and Wet Bulb Depression ($T - T_w$)

Two other relative measures of the atmosphere's moisture content are the dew point depression $T - T_d$ and wet bulb depression $T - T_w$. This last will be explained later, but for now both are simply measures of the air's closeness to saturation. That is, large depressions indicate that the air is relatively (related to T) dry, small depressions indicate that the air is relatively moist and if $T - T_d$ or $T - T_w$ equal zero, the air is saturated.

Problem 2–3

Would you expect the relative humidity to be greater in the morning or afternoon? Explain. (Assume the air's absolute moisture content does not change.)

Problem 2–4

"Warm air always has a higher vapor pressure than cold air." Discuss the validity of this statement.

Problem 2–5

You take a hot shower and your bathroom fills up with steam. Does w increase or decrease? w_s? What about dew point depression?

Instrumentation

There are several instruments in common use for measuring atmospheric moisture.

Hair Hygrometer

This is the type of humidity instrument most often sold in gift shops grouped with barometers and thermometers. It is based on the fact that hair changes length according to the amount of moisture in the air and it is constructed simply by attaching a hair to a pointer and calibrating the pointer to a dial graduated in percentage of relative humidity. Then, as the air's moisture content changes, the hair changes length and the change in RH shows up on the dial. Hair hygrometers are not the most accurate instruments to measure relative humidity.

Dew Point Hygrometer

The dew point hygrometer makes use of physical principles in a more realistic manner than the hair hygrometer. The basis for its use is the latent heat of evaporation and the result that can be gained from it is the dew point. An example of a dew point hygrometer is shown in figure 2–3.

A liquid that evaporates easily (such as ether) is placed into the chamber and air is slowly pumped into the chamber to promote evaporation. As the liquid evaporates, the temperature decreases as can be seen on the thermometer. The mirrored surface is attached to the outside of the chamber. In front of the mirror is air being fed in from the fresh air intake. Now as the chamber cools, the mirror will cool by conduction which will then cool the air in front of the mirror. The cooling is continued until a fog forms on the mirror (condensation). At this point, the temperature is read and this temperature (by definition) is the dew point temperature.

If done carefully, this yields good results, but obviously, the instrument is quite cumbersome.

A variation of the dew point hygrometer can be easily constructed at home.

Take a tin plated can and fill it about half full with water. Hold a small thermometer in the water and gradually stir in small amounts of cracked ice. (Stand back so as not to breathe on the can.) When a fog forms on the can, read the thermometer. The value should be close to the dew point.

One drawback of the dew point hygrometer is that tables are needed to calculate RH from the dew point and air temperature.

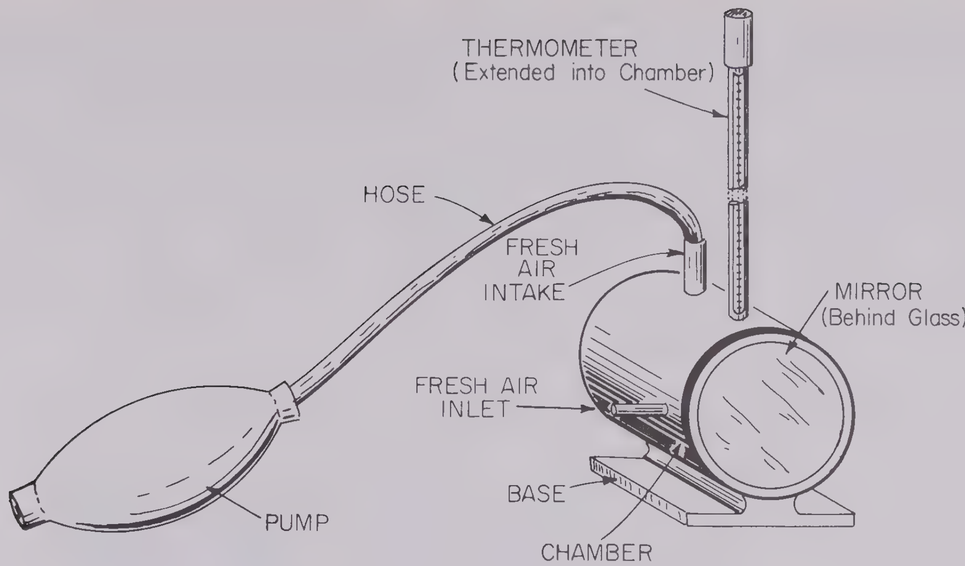


Figure 2–3. A dew point hygrometer.

Sling Psychrometer

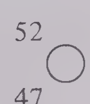
The sling psychrometer is the most accurate of all the atmospheric moisture measuring instruments. It consists of two thermometers mounted side by side on a metal plaque. A handle is attached to enable the user to swing the instrument. One thermometer has a piece of clean cloth wrapped around the bulb. This bulb is known as the wet bulb. The other thermometer is the dry bulb. To use, dip the cloth in clean (preferably distilled) water. Swing the instrument in a circle for a minute or two. (This will cause evaporation and cooling, with the rate of cooling dependent on how much water vapor is present. The resulting temperature is known as T_w — the wet bulb temperature). Read T_w. Continue the process three or four times until two T_w readings are nearly equal. Note the dry bulb temperature (which is just the air temperature — T). From these two values, T and T_w, and tables, the RH and dew point can be ascertained. By using the equation $e = e_s^* - .35(T - T_w)$ the vapor pressure can also be calculated (e_s^* is the saturation vapor pressure at the *wet bulb* temperature). In this equation, both T and T_w must be read in °F.

The sling psychrometer is bulky and requires tables; but, it is relatively easy to use and relies solely on basic physical principles and simple instruments thereby making it extremely accurate. Note that in the equation $T - T_w$ is the wet bulb depression.

The Station Model

Introduced now is an extremely useful device used in one form or another on all weather maps. This is the station model which allows a great amount of meteorological information to be plotted on maps in a concise manner and a limited amount of space. Temperature, moisture, wind, pressure, sky cover, weather and precipitation data are contained on the model. All are presented in a specific form and a specific location which *must never be violated.*

The bare form of the station model is a circle. The data listed above are then plotted around, in or on the circle. Temperature and moisture, the two meteorological variables thus far discussed, are plotted on the model as shown below.



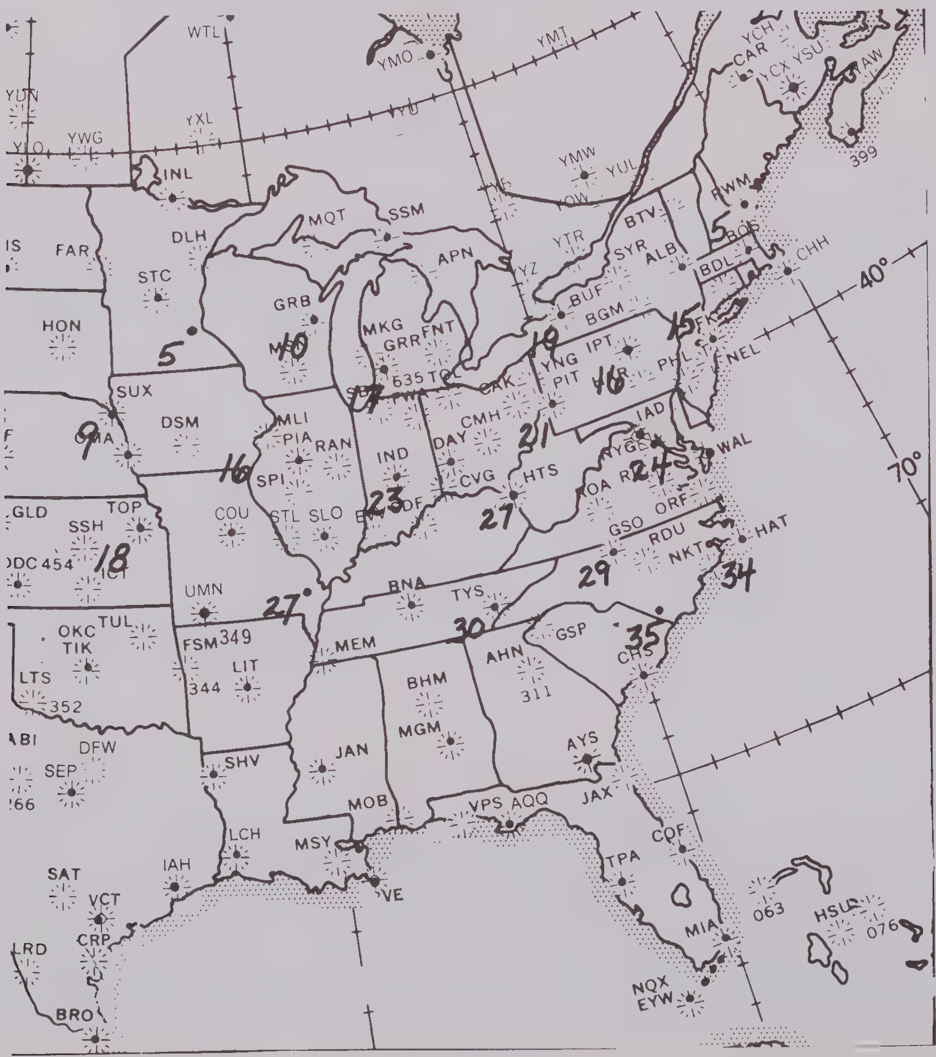
Here, 52 is the air temperature in degrees Fahrenheit and 47 is the dew point temperature, also in degrees Fahrenheit. Note that the degree symbols (°) are *not* included. (If you look back to the numerical field presented in the first lab, you will see that this is the manner in which the air temperature has been presented.)

On surface maps the air temperature and dew point temperature are in degrees Fahrenheit (though in the future temperatures may be plotted in degrees Celsius). On upper air maps, the air temperature is in degrees Celsius and, rather than the dew point temperature being plotted, the dew point depression is presented.

In future exercises you will see how the remaining pressure, wind, precipitation, etc., data are included on the model.

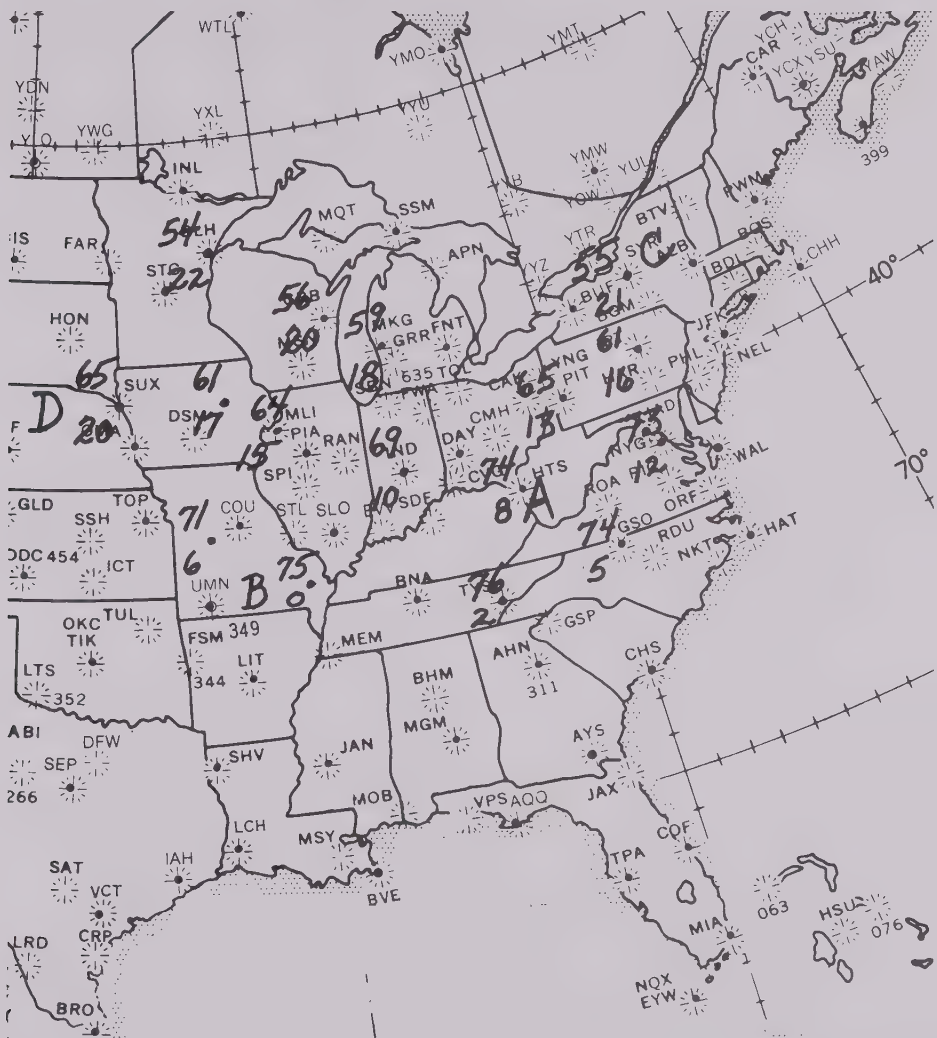
Problem 2–6

Analyze the dew point field below at 5° intervals.



Problem 2–7

Analyze the dew point depression field below at 5° intervals. The lower number in the plotted station model is the dew point depression. What are the dew points at stations A,B,C,D?



Computations

This section is devoted to example calculations to show you how to calculate unknown values of the moisture variables presented in the last section. For some of the calculations, you will need to refer to Table 2–1: "Vapor Pressures Corresponding to Various Temperatures." You may find it useful to think of this table as "The Contributions Made by Water Vapor to the Total Atmospheric Pressure for Various Temperatures." Care must be used here because: (1) If the temperature you have is a dew point temperature, then the corresponding pressure is the vapor pressure; that is, the actual pressure being exerted by water vapor at that moment; (2) If the temperature is the air temperature, then the corresponding pressure is the saturation vapor pressure which is the maximum amount of water vapor that the air can hold at that air temperature. Remember that e_s is dependent on air temperature, nothing more. (3) If the temperature is the wet bulb temperature, then the corresponding pressure is e_s^* the vapor pressure at the wet bulb temperature.

TABLE 2–1
Saturation Vapor Pressures Corresponding to Various Temperatures

°F	mb	°F	mb	°F	mb	°F	mb
−20	.43	15	2.74	45	10.09	80	34.6
−15	.57	20	3.47	50	12.19	85	40.7
−10	.75	25	4.40	55	14.63	90	47.7
− 5	.98	30	5.55	60	17.51	95	55.7
0	1.30	32	6.10	65	20.86	100	64.9
5	1.66	35	6.87	70	24.79	105	75.3
10	2.14	40	8.36	75	29.33	110	87.2

Example 1

Given: $w = 7 \frac{gms}{kg}$ $w_s = 14 \frac{gms}{kg}$

Find: RH

Solution: $RH = \frac{w}{w_s} \times 100$

$= \frac{7}{14} \times 100$

$= 0.5 \times 100 = 50\%$

Example 2

Given: $e = 8.36$ mb $e_s = 17.51$ mb

Find: RH, T, T_d

Solutions: $RH = \frac{e}{e_s} \times 100$

$= \frac{8.36}{17.51} \times 100$

$= 48\%$

To find T and T_d, simply refer to table 2–1. If $e = 8.36$ mb, the dew point must be 40°F. If $e_s = 17.51$, the air temperature must be 60°F.

Example 3

Given: $T = 80°F$ $T_w = 70°F$

Find: RH, T_d

Solution: Use table 2–1

$T = 80°$ therefore, $e_s = 34.6$ mb

$T_w = 70°$ therefore, $e_s^* = 24.79$ mb

Now, since $RH = \frac{e}{e_s} \times 100$, all you need is e, and

$$\begin{aligned} e &= e_s^* - .35(T - T_w) \\ &= 24.79 - .35(80 - 70) \\ &= 24.79 - .35(10) \\ &= 24.79 - 3.5 \\ &= 21.29 \end{aligned}$$

$$\begin{aligned} RH &= \frac{e}{e_s} \times 100 \\ &= \frac{21.29}{34.6} \times 100 \\ &= 61.5\% \end{aligned}$$

To find T_d, use table 2–1. Since $e = 21.29$ mb, $T_d = 66°F$

Example 4

Given: $RH = 70\%$ $e_s = 12.19$ mb

Find: T_d

Solution: $RH = \frac{e}{e_s} \times 100$

$$\begin{aligned} .7 &= \frac{e}{e_s} \\ (.7)(e_s) &= e \\ (.7)(12.19) &= e \end{aligned}$$

therefore, if $e = 8.53$ mb, T_d must be 41°F

Example 5

Given: $RH = 70\%$ $w_s = 10 \frac{gm}{kg}$

Find: w

Solution: $RH = \frac{w}{w_s} \times 100$

$$\begin{aligned} .7 &= \frac{w}{10} \\ (.7)(10) &= w \\ 7\,\frac{gm}{kg} &= w \end{aligned}$$

Example 6

Given: $RH = 50\%$ $e = 10.09$ mb

Find: T

Solution: $RH = \frac{e}{e_s} \times 100$

$$\begin{aligned} .5 &= \frac{10.09}{e_s} \\ e_s &= \frac{10.09}{.5} \\ &= 20.18 \text{ mb} \end{aligned}$$

therefore, if $e_s = 20.18$ mb, T must be 64°F

Problem 2–8

Show all work.

a. Given: $e = 2.74$ mb, $e_s = 4.40$ mb

Find: RH, T_d, T

b. Given: $e_s = 20.86$, $T_d = 50°F$

Find: RH

c. Given: $w = 8 \frac{gms}{kg}$, RH = 62%

Find: w_s

d. Given: $T = 70°F$, $T_w = 50°F$

Find: T_d, RH

e. Given: RH = 50%, e_s = 8.36 mb

Find: e

Plot: T, T_d on the station model

f. Given: RH = 80%, e = 29.33 mb

Find: T

g. Given: e = 10.09 mb, e_s = 10.09 mb

Find: RH

Problem 2–9

Can T_d ever equal T_w?

Can T_d ever exceed T_w?

Summary

In this exercise you have been introduced to many of the processes that govern the amount of moisture in the atmosphere. The moisture variables discussed are used everyday for weather forecasting.

All of the material discussed here is basic to a good understanding of meteorology. You will see many of these ideas in future exercises, especially in the exercise on "Clouds and Precipitation."

WINDS AND PRESSURE

Introduction

In this exercise we will examine another meteorological phenomenon—the wind. As we observe the atmosphere around us, we can see that it is almost always in motion. This motion must be caused by some external or internal factor. It is the purpose of this laboratory exercise to acquaint you with the winds and the atmospheric forces that cause them.

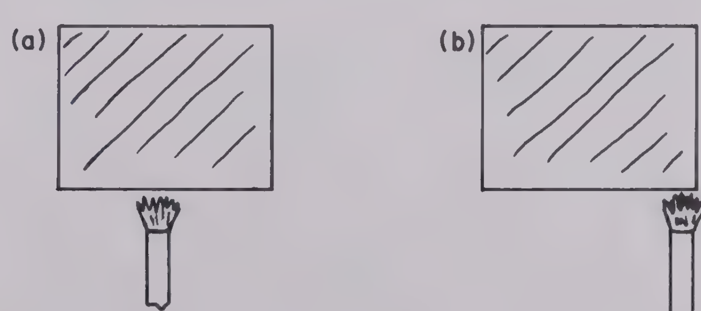
The Source of the Wind

The vast majority of the earth's atmospheric energy comes from the sun. The earth receives solar radiation from the sun at a constant rate. This energy is reradiated by the earth back to space at the same rate that it is received. This is an important point, because unless the earth's outgoing radiation balances the incoming solar radiation, the temperature of the earth would not remain the same. In other words, if the earth received more radiation from the sun than it lost because of its own radiation, the earth would gradually become warmer. On the other hand, if the earth lost more energy than it received, it would cool. All of these radiations, incoming and outgoing, do balance on a *large-scale, long-time average.* This means that over the whole year, averaged over the whole surface of the earth, the radiation balances; i.e., the outgoing and incoming energies are equal. However, at any particular time, some of the earth is receiving more radiation than other parts, while the earth as a whole loses energy at a relatively even rate. Thus, during the summer in the Northern Hemisphere, the sun is high in the sky, the day in temperate latitudes is about 15 hours long, and temperatures are uniformly high across the United States. During this period, the North American continent (as well as Europe, Asia and North Africa) receives more radiation than it loses, while the Southern Hemisphere loses more than it receives. As the seasons change, the Southern Hemisphere receives more radiation, while the Northern Hemisphere receives less. Thus, during a whole year, the radiation "budget" is balanced.

In almost any fluid, the colder liquid or gas is heavier than the warmer fluid. Because of this, when a fluid is heated unevenly, the warmer portion is lighter and rises while the cooler fluid sinks and replaces the heated part. This process is called convection, and is a means of transferring heat from one area to another.

Problem 3–1

Draw arrows in the diagrams below indicating the direction of fluid flow: (each box is filled with fluid)



The atmosphere reacts in much the same way as the fluid in the boxes. Where the sun is highest in the sky and the sun's rays are most nearly perpendicular to the surface of the earth, the air is heated. Where the sun's rays reach the earth at an angle, the energy is attenuated by the large amounts of the atmosphere through which it travels. Also, the angle at which the rays strike causes the energy to be spread over a larger surface. Figure 3–1 below illustrates this; note that each "beam" of the sun's energy is the same size and intensity.

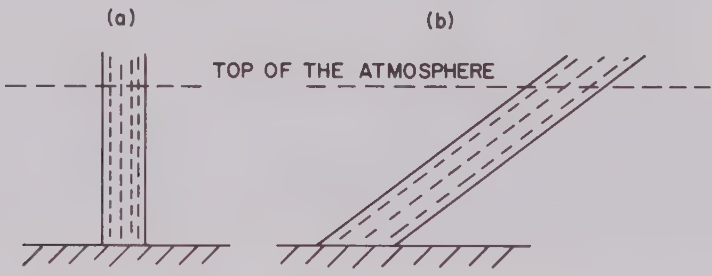
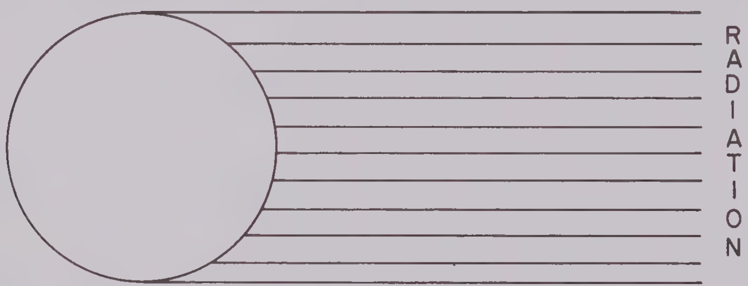


Figure 3–1

Notice that the same amount of radiation enters the top of the atmosphere in each case, but the energy at (b) arrives after passing through a larger amount of the atmosphere and its reduced energy is spread over a larger area of the ground and is thus less intense.

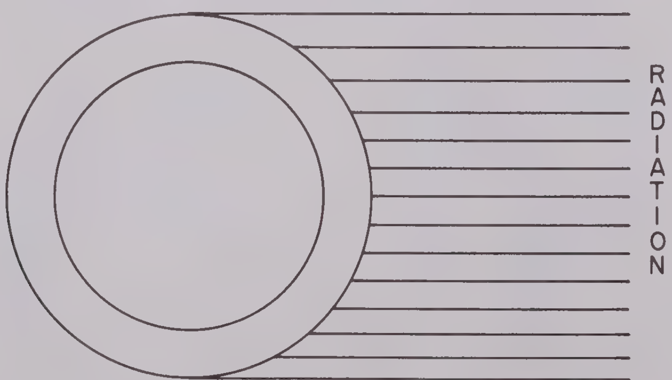
Problem 3–2

On the hypothetical planet below, color the warmer regions red, and the cooler areas blue.



Problem 3–3

If we put an atmosphere on our planet, the uneven heating should cause some sort of atmospheric motion. What types of motion should result from this heating? Draw arrows in the diagram below to illustrate the atmosphere's motion.



Notice that in our simplified model of a planet, we now have air rising at the equator and sinking at the poles. This would make the surface wind pattern quite simple. In the Northern Hemisphere, all the winds would blow from the North Pole directly southward, warm up as the air reached the equator, rise, flow northward in the upper atmosphere, and then cool and sink as the polar regions are reached. The Southern Hemisphere would experience the same pattern with equatorward flowing winds at the surface and poleward flowing winds aloft.

The pattern is not so simple as that, however. If we look at the actual wind pattern on the surface of the globe, we find convection such as we described above only in the equatorial regions. Air does indeed rise in low latitudes and travel poleward. By latitude 30° the air has cooled enough to sink. The mean circulation areas north and south of 30° latitude are not dominated by vertical convection cells as are the tropics. Instead, the cold air to the north mixes with the warm southerly air in a horizontal convection pattern. The cold air pushes toward the equator while the warm air is displaced toward the poles. This exchange is made possible by the large storms called *wave cyclones* that are found in the temperate zones.

From the above discussion, you might think that the surface winds all blow north and south. By observation of the earth's winds, we see that this is not true. There is a force called the Coriolis force that is caused by the earth's rotation. This force causes winds to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. When the Coriolis force is applied to the north-south wind pattern caused by differential heating, we get the results shown in figure 3–2.

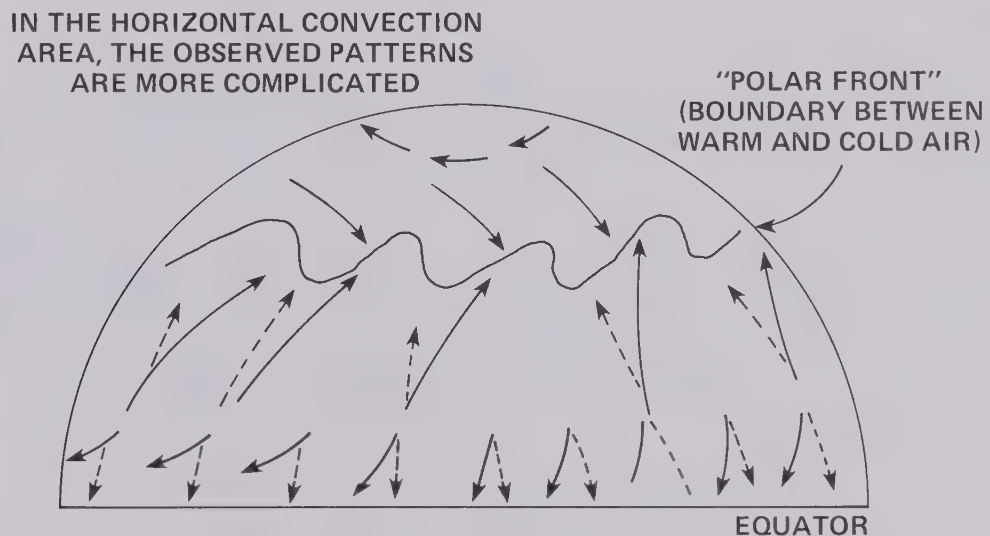
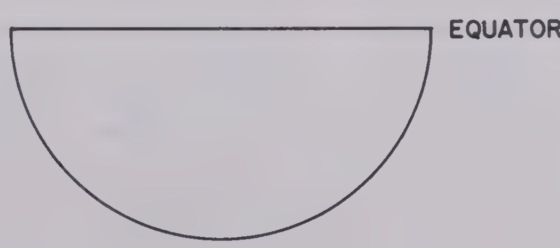


Figure 3–2

Problem 3–4

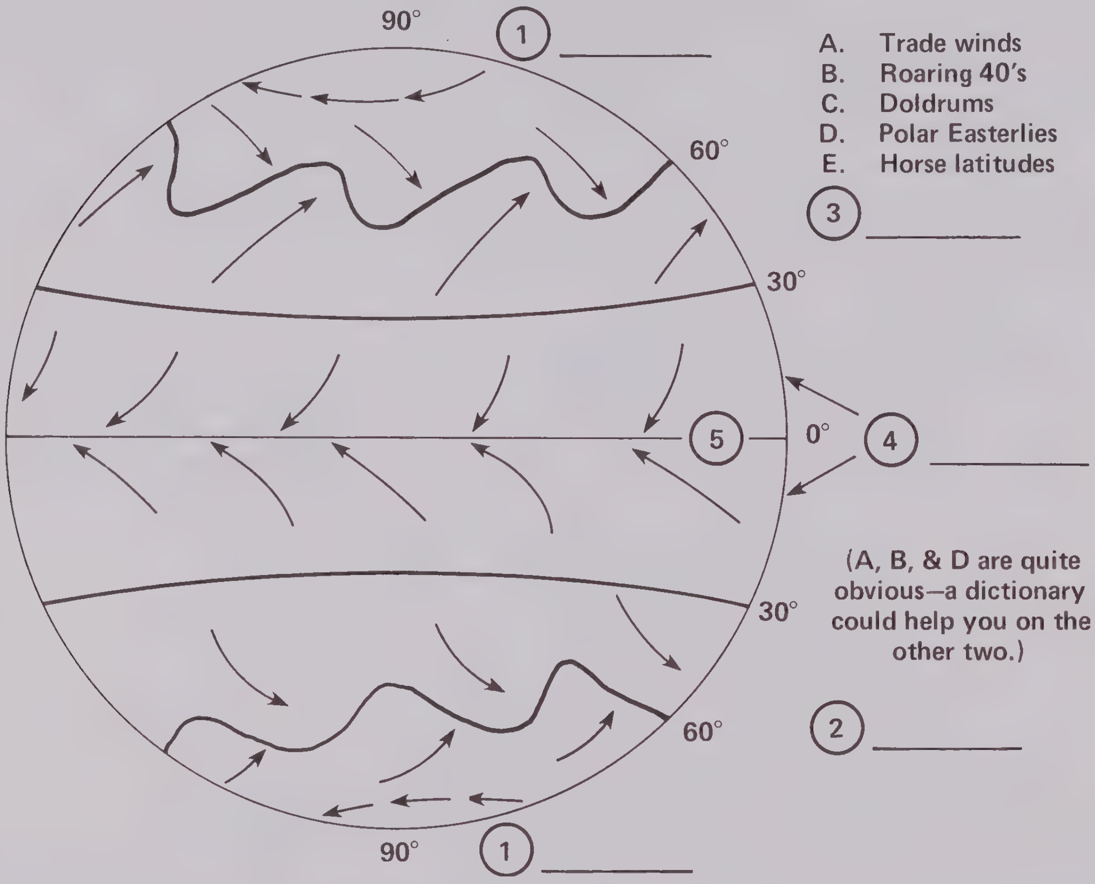
Keeping in mind that the Coriolis force acts to the left in the Southern Hemisphere, draw in the surface winds:



Now you have a pretty complete picture of the general circulation of the planetary atmosphere as it was known to the early seafarers who were the first to observe the general wind circulation. These seamen gave names to the different bands of winds they encountered as well as names to areas of calms and storms.

Problem 3–5

Here is a map of the surface winds in the general circulation. Can you match the descriptive names to the geographical areas and/or wind patterns on the map?



A. Trade winds
B. Roaring 40's
C. Doldrums
D. Polar Easterlies
E. Horse latitudes

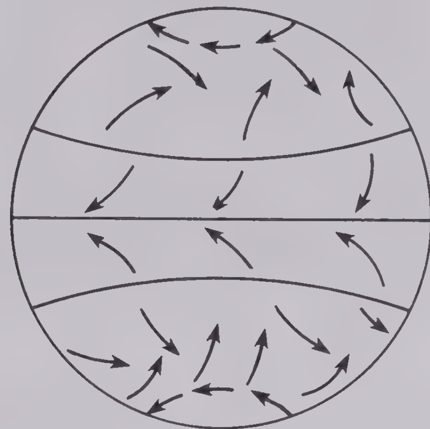
(A, B, & D are quite obvious—a dictionary could help you on the other two.)

It was mentioned earlier in this exercise that the heated air was lighter and that the colder air was heavier. In question (1) you drew in the motions that would be expected in two tanks when an uneven heat source was applied. Warmer air is less dense than cold air at the same pressure. When two air masses exist side by side and have different temperatures, the warmer air will rise because of buoyancy, while the colder air will sink. By this we can see that the cold, dense air has the tendency to "spread," like cold syrup poured on a plate, and that it spreads under the upward moving warm air.

When the total weight of the atmosphere is considered, it is found that the weight above one particular point is different than the weight of the atmosphere above another point on the earth's surface. This weight for a given area is called *pressure*. Where the air is dense and heavy, the pressure is high. Where the air is warm and light, the pressure is relatively low. These are called thermal highs and lows. Sometimes high (and low) pressure systems are caused by the motion of the upper winds. These are called dynamic highs (lows) and will be introduced in exercise 6. Looking once more at the general circulation pattern, we see places where air is moving away from an area. What type of pressure does this represent? Where the air is converging (i.e., in the doldrums), what kind of pressure would one expect?

Problem 3–6

On the globe pictured below, indicate areas of high pressure by a line of H's and areas of low pressure by a line of L's.



Problem 3–7

Now look at plate 3–1 on the next page. Notice the area near the equator. What do you see there (clear/cloudy)? Looking at the map above, we should see that this is an area of (high/low) pressure. Also, if we look at the Horse Latitudes we can see an area of generally (clear/cloudy) skies in the center of the United States. This area is an area of (high/low) pressure. From this we can see that (high/low) pressure areas may be associated with clear skies and (high/low) pressure areas may be associated with cloudy skies.

All of the motion in the atmosphere is caused by this difference in pressure from one place on the earth to the other. The atmosphere is always attempting to equalize its temperature (and therefore its density). However, the exceedingly large mass of the atmosphere, coupled with the fact that it is subject to friction forces make it impossible for it to adjust to changes of temperature instantly. The moving air that we call wind is the result of the unceasing motion of the atmospheric fluid in its search for equilibrium.

Pressure: Measurement and Depiction

When we think of pressure as the weight of the atmosphere above us, it becomes logical to think of the pressure as a continuous variable. By "continuous" we mean that every place on the surface of the earth has a pressure, and if you go from one place to another, the pressures you encounter in travelling between the two places will show a smooth transition of pressure from that of the starting point to the pressure at the destination. For instance, if the pressure were plotted at discrete points along the track, we can connect the values with a relatively smooth curve, as shown in figure 3–3.

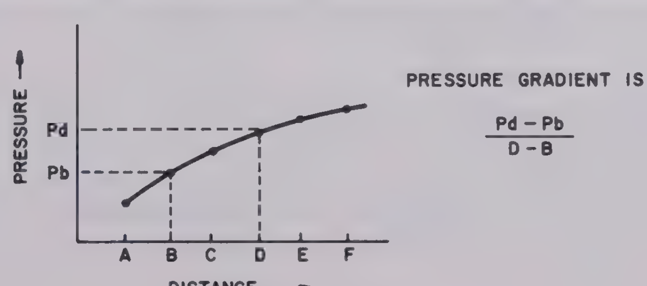


Figure 3–3

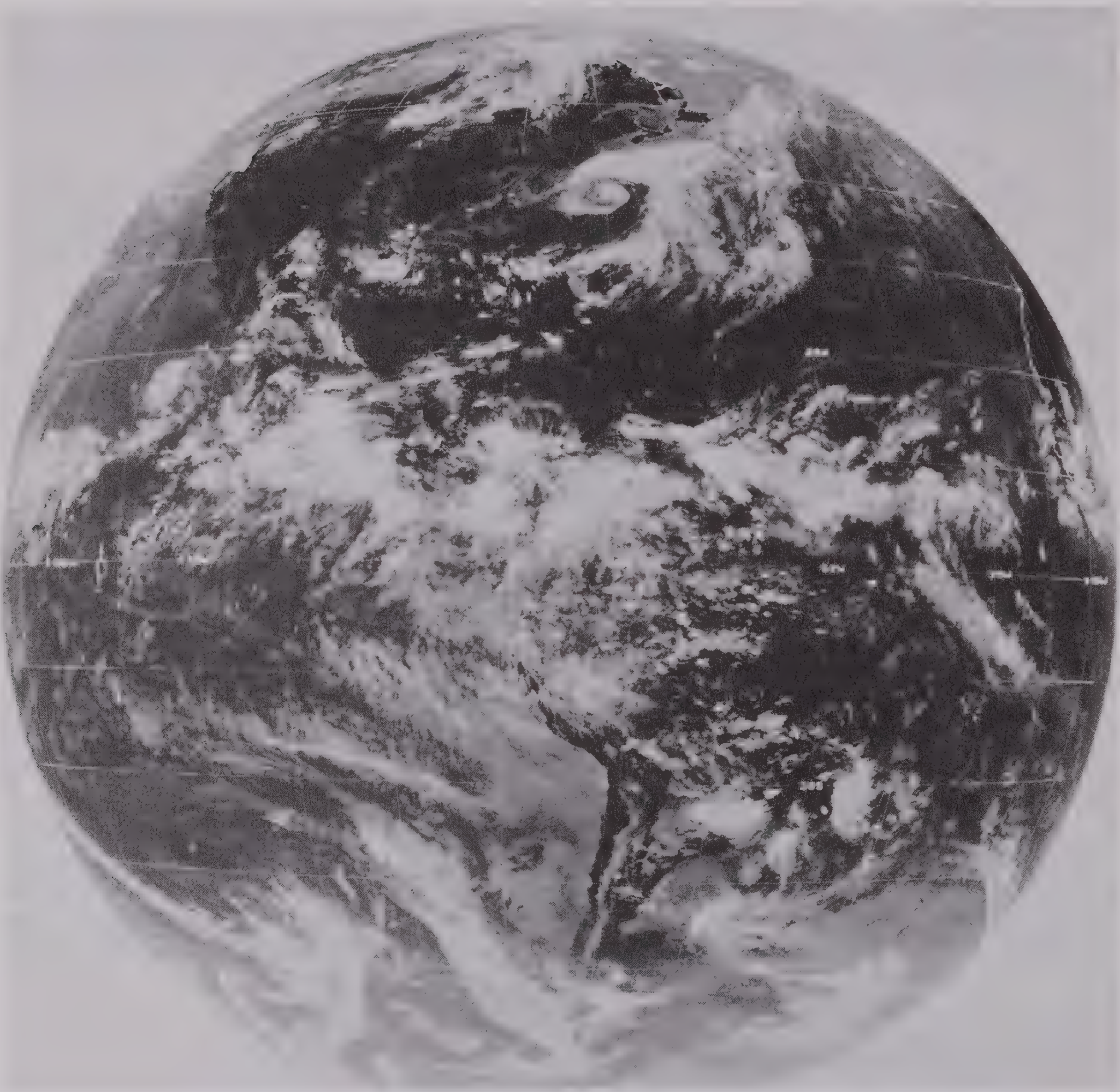


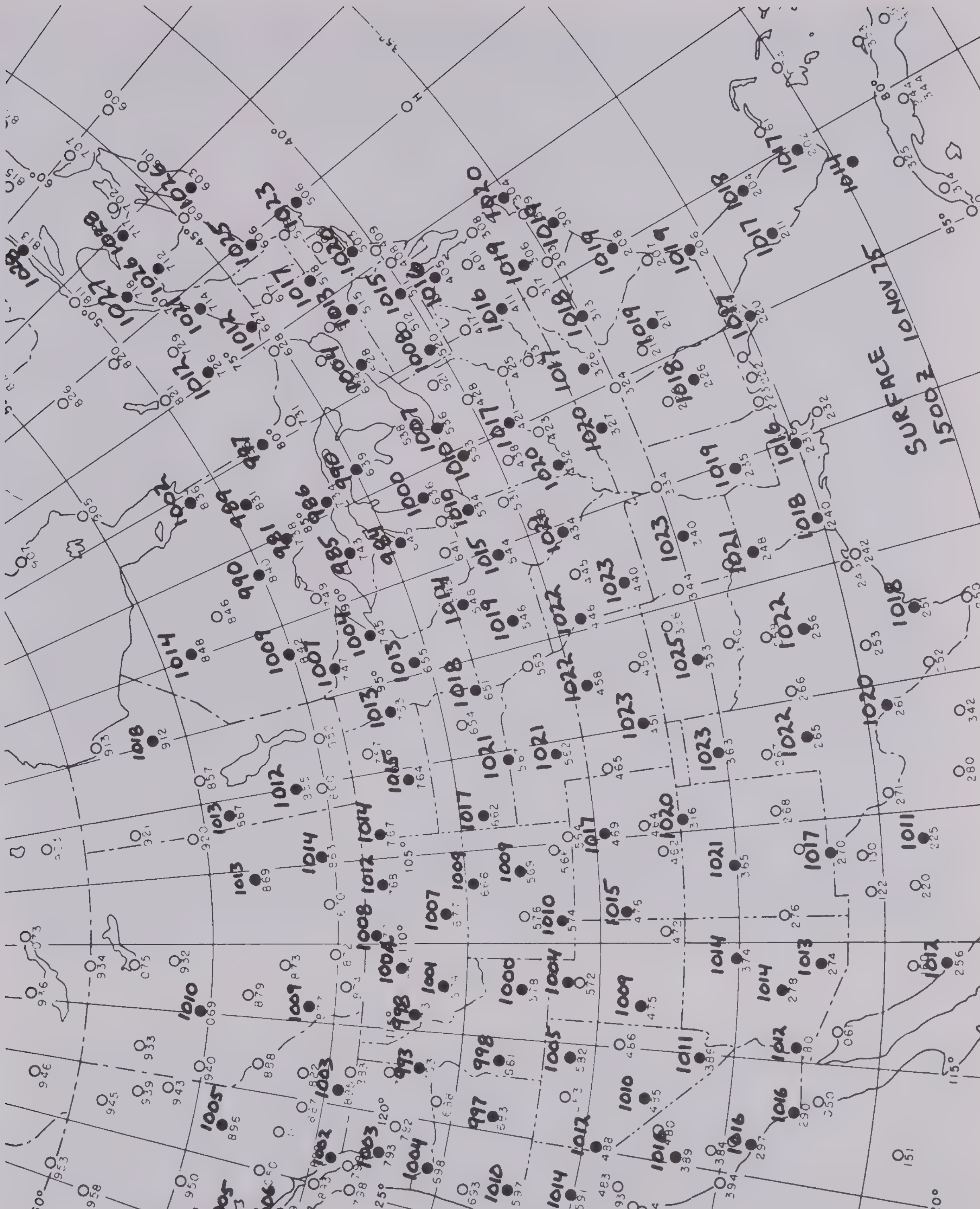
Plate 3–1

Figure 3–3 shows a gradual rise in pressure as we go from A to F. Likewise, if the route of travel were reversed, the trace would show a gradual decrease. The rate at which pressure changes over a given distance is called the pressure gradient. A large change of pressure means that the pressure gradient is large, while a small change of pressure indicates a small pressure gradient.

Problem 3–8

Using the techniques of isoplething you have already learned, analyze the pressure field on page 37 starting with 1,000 mb and using intervals of 4 mb; (i.e., 1,000, 996, 992, etc.)

When you have finished this, compare the isobars (lines of equal pressure) with plate 3–2, which is a satellite photograph for the same time. What type of pressure (high/low) corresponds best with clear air? What type of pressure system (high/low) is found where a large amount of cloudiness is present?


SURFACE 10 NOV 75
1500Z

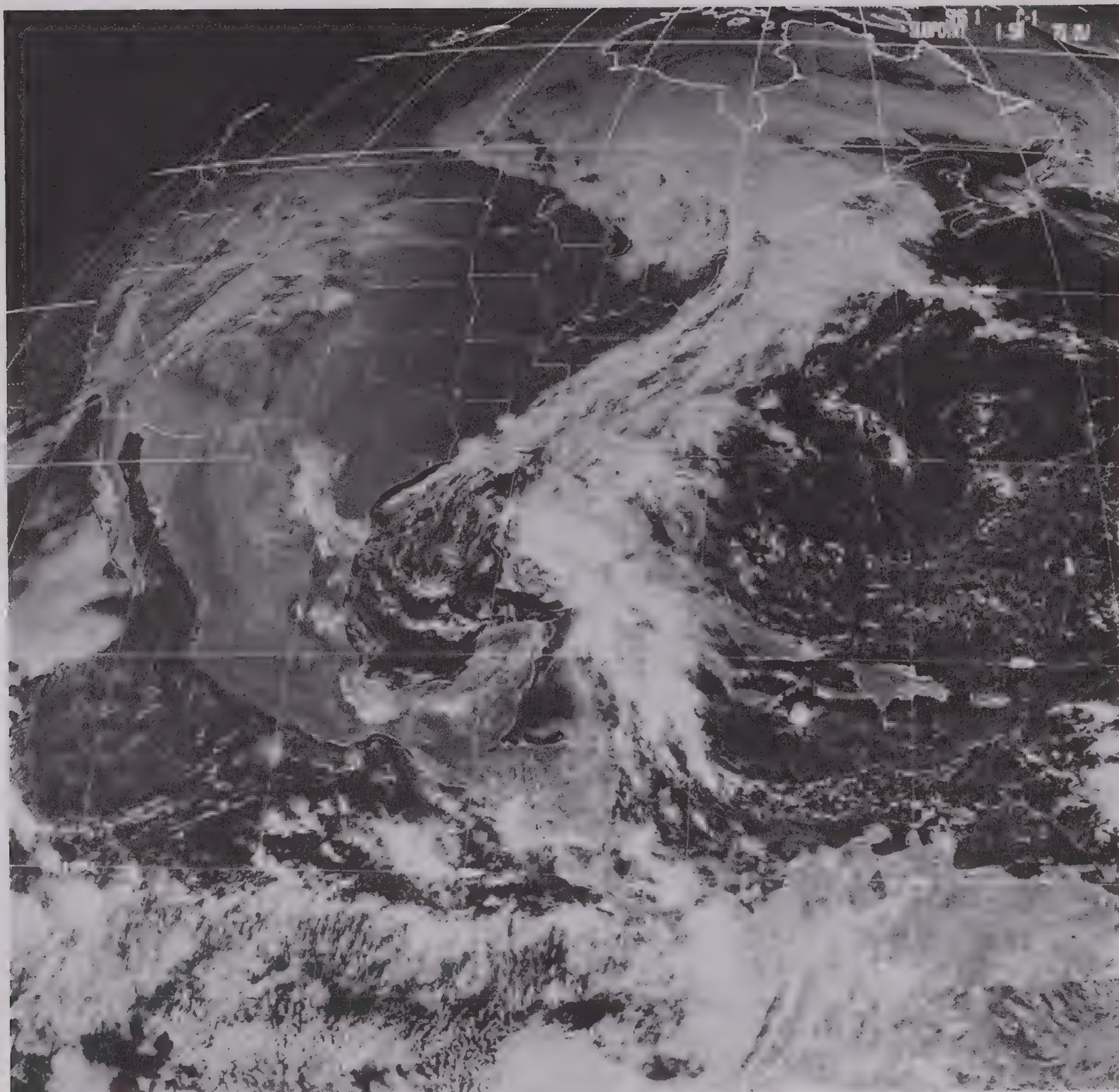


Plate 3–2

Because the pressure varies quite rapidly in the vertical (from a value of about 15 pounds per square inch (psi) at the surface to almost zero at an elevation of 20 miles and only slightly in the horizontal (about 1.45 psi over the whole earth), the decrease in pressure due to height must be eliminated somehow so that the more useful (horizontal) pressure variations are preserved. This is done by correcting the observed (or station) pressure to what that pressure would be if the observer were at sea level. Thus, if an observer were at Denver (elevation 5,280 feet), he might record a pressure of 12.19 psi. This would be the station pressure. Before the pressure is transmitted to other stations, a set of tables must be used to convert the station pressure to sea level pressure.

Early barometers were often made of mercury. It was found that the weight of the atmosphere at sea level could support a column of mercury about 30 inches high.

In figure 3–4, a simple mercury barometer is pictured. It should be obvious from the diagram that increased air pressure would make the column of mercury rise in the glass tube. Likewise, a decrease in pressure would cause the mercury column to shrink.

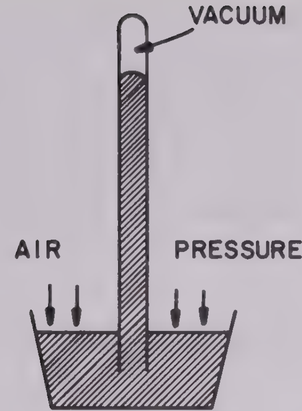
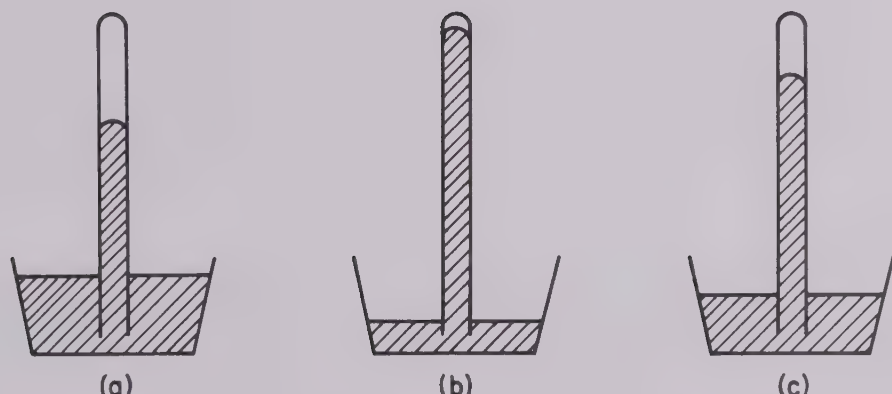


Figure 3–4

Problem 3–9



a. Which of these barometers indicates the highest atmospheric pressure? ________________

b. Which of these barometers indicates the lowest atmospheric pressure? ________________

The atmosphere has been given a unit of measure called the "bar" (weight) and one bar equals 14.5 pounds per square inch (psi) or an atmospheric pressure of one bar would support a column of mercury 29.92″ high at a temperature of 59°F. In modern usage, pressure is usually reported in millibars (1/1,000 of a bar). One millibar (mb) equals .0145 psi, .75 mm of mercury, or .030 inches of mercury.

When an observation of station pressure is taken and converted to sea level pressure, it is plotted on a weather map. As with the temperature and dew point, the pressure occupies a unique position on the station model. This position is in the upper right-hand corner of the model and consists of three numbers. These three numbers are a sort of shorthand to try to keep the model as uncluttered as possible. The station pressure (in mb) is converted to the three figure code in the following manner: If a map plotter were to read a station pressure of 997.2 mb, the first thing he would do would be to discard the leading 9 (if the pressure were 1,013.6, he would discard the 10). This would leave him with a value of 97.2. Next, he would throw away the decimal point, leaving 972. This number he would plot in the upper right-hand corner of the station model. To read this coded number, the process is reversed. First add the decimal to the number. For instance, if our three digit number was 132, we would put a decimal point between the 3 and the 2, giving us the number 13.2. Next we must decide whether to put a nine or a ten in front of the 13.2. We can make this decision based on our knowledge of the possible range of values the earth's sea level pressure can have. From our observations, we know that the lowest pressures that might be expected are in the range of 960.0 to 970.0 mb. The highest pressure we are likely to see is about 1,050.0 mb. So, we use a trial and error method and put either a 9 or a 10 in front of our 132. Suppose we try a nine first. We find that our number is now 913.2. Upon inspection we see that 913.2 does not fit into the possible range of 960.0 to 1,050.0 mb that we know we might encounter. Thus, nine is the wrong number to use and ten is the correct one, yielding 1,013.2 mb. This number is within the possible range of pressures so we know it is correct. With practice, you will be able to recognize which numbers call for a nine and which numbers call for a ten.

Problem 3–10

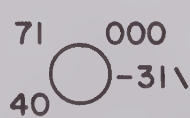
To see if you can properly encode and decode pressure values, perform the required operations on the example below:

a. Encode these pressures:	b. Decode these pressures:
1,031.7 ______	133 ______
997.2 ______	853 ______
1,000.0 ______	007 ______
987.3 ______	971 ______
1,010.9 ______	332 ______
992.7 ______	900 ______

Pressure Tendency

Pressures appear on surface maps which are issued at three hour intervals. Because the change in pressure over a period of time is a useful tool in predicting the movement of pressure systems, these changes are also plotted on the station model. To calculate the change in pressure (called the pressure tendency) over a set time period—three hours in this case—subtract the pressure on the current map from the pressure on the map that was plotted at the same station three hours ago.

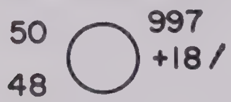
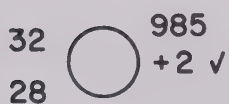
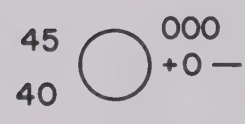
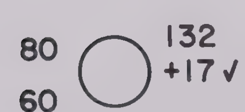
As an example, suppose a station reported a pressure of 1,010.7 mb three hours ago and the current pressure is 1,012.2 mb. The pressure has risen 1.5 mb in the last three hours and we would say that the pressure tendency is *plus* 1.5 mb. If the pressure had been 999.7 mb three hours ago and is now 996.0 mb, the difference would be 3.7 mb in a *negative* sense. In other words, the pressure tendency is −3.7 mb. These tendencies are plotted right under the station pressure, to the right of the station model's circle. As in the pressure code, the decimal point is dropped but the minus or plus sign is retained. An example of a station that has a correct pressure of 1,000.0 mb and had a pressure of 1,003.1 mb three hours ago is given here:



Notice the line (\) to the right of the pressure tendency. This line is a miniature graph showing how the pressure changed. In this case, the straight line that starts downward to the right indicates a steady decrease of pressure over the last three hours. If you were to see a "check" symbol (✓) this would mean that the pressure was falling at the start of the three hour period and then began to rise during the latter part of the period. Where the line is unbroken (—,\,/), the pressure tendency is said to be continuous. Where the line is broken (✓,/‾, _, _/, ‾\ etc.), the pressure tendency is said to be discontinuous.

Problem 3–11

As an exercise to see if you understand the concept of pressure tendency, here are some abbreviated station models. Calculate the pressure three hours ago and indicate by a C or D whether the change was continuous or discontinuous.

Station Model	**Pressure 3 Hours Ago**	**C/D**
		
		
		
		
		

Plotting the Wind

One consequence of pressure gradients is the resulting wind, which is a manifestation of the atmosphere's attempts to equalize its pressure. Wind can have three components, two horizontal and one vertical, but since the horizontal winds are much larger than the vertical winds, we plot only two dimensional winds on our weather maps.

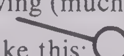
When we consider the wind direction, we think of it as *coming* from somewhere. To us, a north wind makes us think of a snowy blustery wind because it is *coming* from the north, usually a colder climate, while a south wind brings to mind gentle, warm breezes for similar reasons: the climate is generally warmer to the south. When we wish to plot the wind direction of our station model, we indicate the wind direction by drawing a line into the circle in the direction from which the wind is blowing (much like an arrow sticking into an apple). An example of a plotted northwest wind would look like this:  an east wind would be plotted like this:  A calm wind would be plotted like this: . We can depict the velocity of the wind by putting barbs or "feathers" on the wind direction arrow. Each full barb indicates 10 knots (one knot equals one nautical mile/hour or 1.15 mph). A half line indicates a wind velocity of five knots. Because the number of lines becomes hard to count on our map as the wind speeds get higher, a fifty knot wind is depicted by a solid "flag."

Table 3–1 shows what wind arrows would look like for winds of different velocities. In all cases, the wind is from the west.

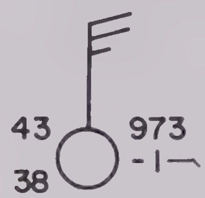
TABLE 3-1

Symbol	Velocity kts
	0
	5
	10
	15
	20
	25
⋮	⋮
	50
	55
	60
⋮	⋮
	100
	105
	110
etc.	etc.

Problem 3–12

In the following station models, find the wind directions and velocities (direction and speed). Note that the wind velocity barbs always point in a clockwise direction.

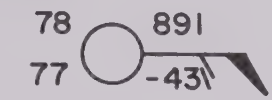
(a)



Direction ______________

Velocity ______________

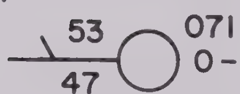
(d)



____

____

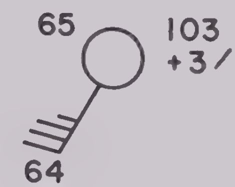
(b)



____

____

(e)



____

____

(c)

____

____

Summary

Upon completion of this exercise, you should be able to recognize the types of cloudiness that are associated with high and low pressure systems. You should be able to plot pressure, pressure tendencies, and winds on the station model as well as the temperature and dew point you learned about earlier. By being able to analyze a continuous field such as pressure or temperature fields, the concepts of gradients and their effects on the wind (in the case of pressure) may be more easily seen.

CLOUDS AND THE PRECIPITATION PROCESS

Introduction

The formation of precipitation is a very important process within our atmosphere. Without it, most, if not all of the earth's land areas would be deserts. In fact, since the oceans are a result of the condensation and precipitation of water from the primeval atmosphere, it is doubtful if oceans would even exist on our planet without the precipitation process.

Causes of Precipitation

Before the atmosphere can generate precipitation either as raindrops or as snow or sleet, clouds must be available. Clouds are necessary because the tiny water droplets of which they are composed are the building blocks from which the larger water drops or ice pellets are manufactured. For a cloud to form, there must be enough water vapor in the air and there must be some means of condensing the water vapor into the tiny visible droplets that make up clouds.

Referring back to exercise 2, Moisture, you will recall that cold air has a lower saturation vapor pressure than warm air. In other words, the saturation vapor pressure, e_s, gets smaller as the temperature of the air gets colder. It would stand to reason then, that if a parcel of air was cooled, it would eventually reach a point where the saturation vapor pressure, e_s, is equal to the pressure of water vapor actually present in the parcel of air represented by e. This would mean that the air is saturated.

Problem 4–1

a. What would the relative humidity be in this situation (where $e = e_s$)? RH = ________ %.

b. If this saturation should occur at a temperature of 10°C, what would the dew point be?

Td = ________ .

Once the point is reached where the temperature and the dew point temperature are equal, any further cooling must be accompanied by a corresponding reduction of the dew point. The reason for this is that the dew point temperature exceeds the temperature of the air only in rare cases. In other words, the value of e_s is the maximum vapor pressure at a given temperature. There is an obvious way to change the dew point temperature—to raise T_d there must be moisture added to the air; to lower T_d, moisture must be subtracted from the air. Therefore, to reduce the temperature below its original dew point, moisture must be extracted. This is done by the condensation of the water vapor as the air cools.

Now, we have our needed mechanism to extract existing water vapor and to condense it into small cloud droplets. All that is needed is to cool the air below its original dew point temperature and we have our cloud. Well, almost—there is one more ingredient needed to cause condensation. Investigation in the laboratory shows that the condensation of water droplets in perfectly clean air is not an easy accomplishment. In fact, without a suitable nucleus (dust, minute salt crystals, smoke particles), large supersaturations—i.e., relative humidities of up to 400% are possible. Our atmosphere is far from pristine. There are great amounts of pollutants and other aerosols which are able to act as nuclei for the condensation of cloud droplets.

Thus, we have the ingredients necessary for cloud formation: moisture in the air; a method to extract the moisture (cooling); and nuclei to act as a site for condensation. For the remainder of this exercise, it will be assumed that moisture is available and there are sufficient nuclei present for condensation. We will now direct our attention to the remaining ingredient—cooling.

When a gas expands, it cools. Likewise, if a gas is compressed, its temperature increases. The easiest method of expanding a gas is to reduce the pressure that confines it. For instance, pushing down the top button on a can of insect repellent allows the contents under pressure to expand into the lesser pressure outside of the can. If you were to put your finger into the spray, you would find it colder to your touch than either the can or the surrounding atmosphere. The reason for this is that some portion of the internal energy of the compressed gas has been used to expand the gas leaving less energy in the form of heat. To reverse this process, try pumping air into a bicycle tire with a hand pump. After you have exerted a certain amount of energy pumping air into the tire, reach down and feel the fitting that connects the pump tube to the tire valve.

Problem 4–2

a. What would you expect its temperature to be—hot or cold?

b. Why?

c. From this we could say that expansion is a (heating, cooling) process and compression is a (heating, cooling) one.

In order to cool a portion of the air by expanding it, we must find a way to reduce the pressure that surrounds it. To do this, it is helpful to assign some special capabilities to that portion of air which we wish to cool. The first special characteristic is that the air in question does not mix with the surrounding environment; the second is that there be no exchange of heat across the boundary between our parcel of air and its environment; and the third is that the process is frictionless.

With these assumptions in mind, let's see what happens to a parcel of air that is lifted mechanically (i.e., pushed or carried upward by some external source). Imagine a bushel basket filled with air. To keep track of this particular basket full of air, we color it green. (Remember, that this air cannot mix with the surrounding atmosphere, nor can it transfer heat across the boundary between the green air and the adjacent environment.) We begin with the green air at the same temperature as its surroundings. Now, we start to climb up a mountain carrying our bushel basket. As we climb up the mountain, the pressure of the atmosphere surrounding our basket decreases allowing the parcel of air to expand. By the time we reach the top of our mountain (if it is high enough), our bushel basket will look like a giant green popover (figure 4–1).

The air in our parcel has expanded because of the decrease of pressure around it. The reverse happens when we descend from the summit of the mountain. The increasing pressure forces the parcel of air to compress and by the time we reach the bottom of our mountain the parcel will have regained its original pressure and volume.

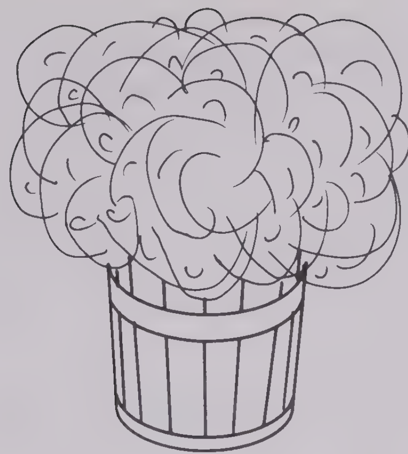


Figure 4–1

Now, let's repeat our experiment, only this time, we will carry a barometer and thermometer with us. Because the parcel of air cannot exchange heat with its surroundings, any change in the temperature of the parcel must come as a result of cooling and heating caused by the expansion and contraction of the gas in the parcel. So this time as we go up the mountain, we record the temperature of the parcel for various heights above sea level. Suppose the following table were a result of the experiment.

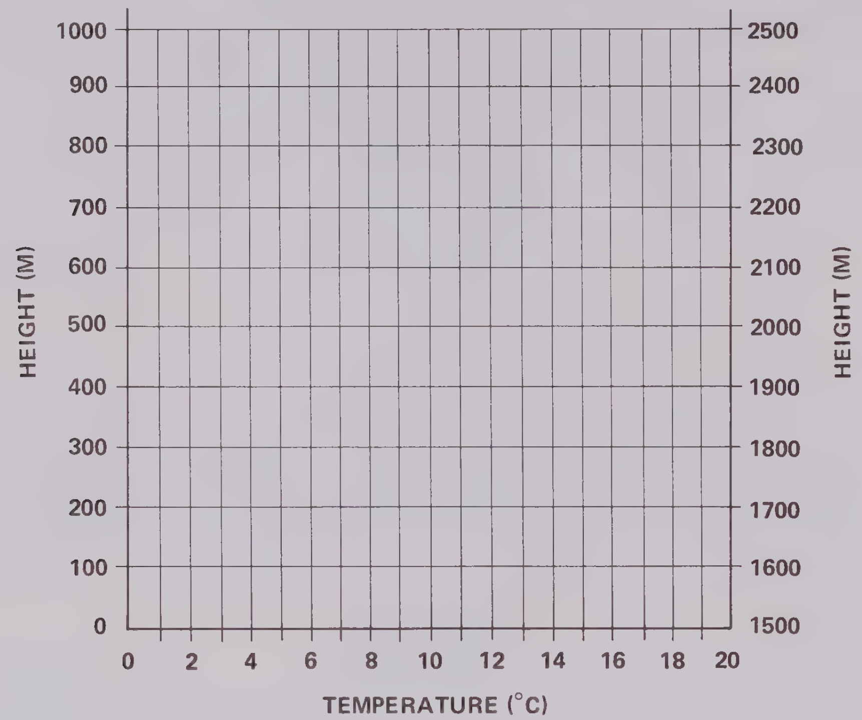
TABLE 4–1

Height(m)	Going Up Temperature (°C)	Coming Down Temperature (°C)
0	15.5	15.5
50	15.0	15.0
100	14.5	14.5
150	14.0	14.0
200	13.5	13.5
250	13.0	13.0
300	12.5	12.5
350	12.0	12.0
400	11.5	11.5
450	11.0	11.0
500	10.5	10.5
550	10.0	10.0
600	9.5	9.5
650	9.0	9.0
700	8.5	8.5
750	8.0	8.0
800	7.5	7.5
850	7.0	7.0
900	6.5	6.5
950	6.0	6.0
1000	5.5	5.5

Is it any surprise that the temperatures are the same on the downward trek?

Problem 4–3

a. Graph the above data from table 4–1 using the height on the y axis at the left and the temperature as the x axis. Let the temperature range be between 0°C and 20°C.



b. Suppose that the experiment was repeated at another time on another mountain and the following data were gathered:

TABLE 4–2

Height(m)	T°C	Height(m)	T°C
1500	10.0°	2050	4.5
1550	9.5	2100	4.0
1600	9.0	2150	3.5
1650	8.5	2200	3.0
1700	8.0	2250	2.5
1750	7.5	2300	2.0
1800	7.0	2350	1.5
1850	6.5	2400	1.0
1900	6.0	2450	0.5
1950	5.5	2500	0.0
2000	5.0		

Using the right-hand y axis so that the range is from 1,500 (corresponds to 0 on the left-hand axis) to 2,500. Plot these data (table 4–2) as you did the first set.

c. Calculate the slope of the line plotted in (A).

What is the slope? ______________________°/100m

Calculate the slope in (B) ______________________°/100 m

d. Suppose you repeated the experiment at other times and other places. What do you think that the slope of the temperature versus altitude line would be?

By now you should realize that the slope of this line, called the "lapse rate", is constant. Because of the original contraints placed on our experiment, we can call the slope the **"dry adiabatic lapse rate."** (Adiabatic = occurring without loss or gain of heat—in this case we mean insulated from the surrounding environment.) This means that whenever air is lifted adiabatically, it will cool at the rate calculated in question 3c. It should be pointed out here that this lapse rate only holds for *dry air*. Once condensation occurs, the latent heat of condensation released into the parcel modifies its lapse rate somewhat. This is called the **"moist adiabatic lapse rate."**

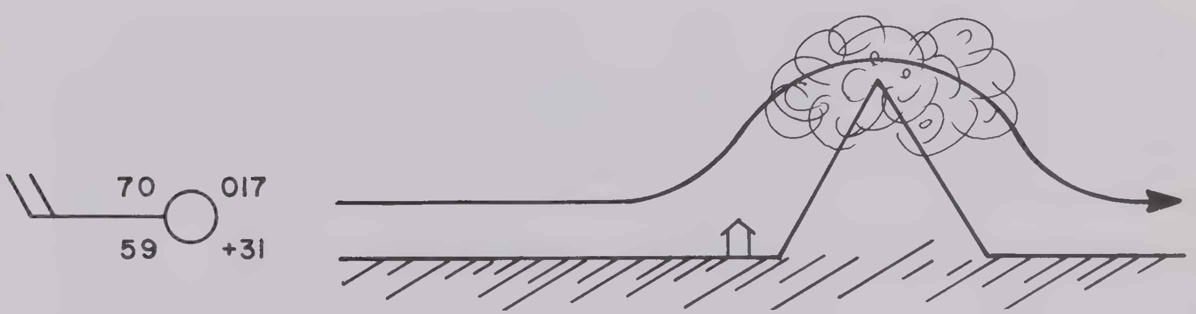
Problem 4–4

You calculated the dry adiabatic lapse rate in °C/100 m. What is the dry adiabatic lapse rate in °F/1,000 ft.? Remember that 9 Fahrenheit degrees = 5 Celsius degrees, and 1,000 m = 3,280 feet.

Until now we have been talking about "lifting" the air, but have not really explained just what is involved in the natural processes that cause the air to be lifted in some way. Suppose that we have a landscape that is essentially a flat plain with a mountain range at the eastern edge of the plain. Let us further stipulate that the mountain range runs north to south. If a wind blows across the plain from west to east (a west wind), it will blow against the base of the mountain range and the air will be pushed up the side of the mountain. This type of lifting is called *orographic* lifting.

Problem 4–5

Here is an hourly weather observation, taken at a station at the base of the western slope of the mountain range mentioned above:



If the air is pushed up the mountain, how far above the base of the mountain would you expect to find the base of the cloud? (Remember, the temperatures given in the station model are in degrees Fahrenheit.)

____________________ feet

Another way in which air is lifted is by a colder, denser air mass displacing an air mass that is less dense. The cold air mass moves much as a mound of cold syrup or molasses would spread out when it is poured on a plate. This advancing air pushes the less dense air upward. This lifting is called *frontal lifting* and is the cause of precipitation along cold and warm fronts. These fronts will be explained more fully in a later exercise.

A major precipitation producer in the temperate latitudes is the *extratropical cyclone*. The extensive precipitation pattern in these great storms is caused by two types of lifting: *frontal lifting* and upward motion caused by *cyclonic convergence*. The causes of this lifting will be more fully explained in a subsequent exercise.

The most intense rains usually are the product of convective showers and thunderstorms. These showers are most numerous in the late spring and summer seasons and are of short duration and of limited scope geographically. The mechanism that causes vertical motions in these storms is similar to that in the frontal lifting case in that the warmer, lighter air is more buoyant than colder, denser air. Unequal surface heating causes colder air to exist side by side with warmer air.

Returning to the dry adiabatic lapse rate, we have seen that it can be plotted as a straight line on a temperature-height graph. Since the dry adiabatic lapse rate is really the description of the slope of the line, there can be any number of lines depicting dry adiabatic lapse rates (called dry adiabats) depending on the original air temperature. In other words, no matter what temperature the air had at the surface, if it is lifted under adiabatic conditions, it will cool at the dry adiabatic lapse rate. So, for example, an air parcel that has a temperature of 18°C will cool to 8°C if it is lifted one kilometer. Likewise, a parcel having a temperature of 30°C will cool to 15°C if lifted to a height of 1,500 meters. The important thing here is that no matter what the temperature of the air is originally, it will cool at the dry adiabatic lapse rate as it is lifted so long as condensation has not yet begun. (In all of the above discussion, it has been assumed that the air remains "dry"—that is, no condensation has yet formed as a result of the lifting even though water vapor is present in the air parcel.)

The vertical temperature profile of the atmosphere normally shows a decrease of temperature with height. However, at any particular time and place, the measured values of temperature versus height in the atmosphere may take on very different characteristics. For instance on a certain day at 8:00 a.m. at Pittsburgh, the temperature height curve might look like the graph in figure 4–2.

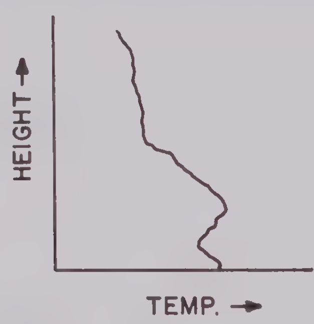


Figure 4–2

On another day the temperature profile might look like figure 4–3.

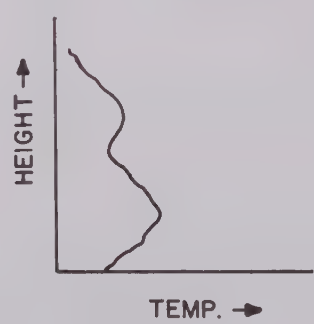


Figure 4–3

You can see that the vertical temperature profile is ever-changing and depends on various climatic, synoptic, and local factors. Let us now superimpose the line representing the dry adiabatic lapse rate on such a profile (figure 4–4). In this case, if we were to lift the air from the ground level to height h_1, it would cool to a temperature of T_1, while the environment around it would have a temperature of T_2. Notice that $T_1 < T_2$ and thus the air that has been lifted is colder (and therefore more dense) than the air in the environment. This colder air tends to sink back down to its original level. When this occurs, we say that the air is *stable.*

Suppose that the air cools more rapidly with height than the dry adiabatic lapse rate. On a temperature versus height graph, the graph will look like that in figure 4–5.

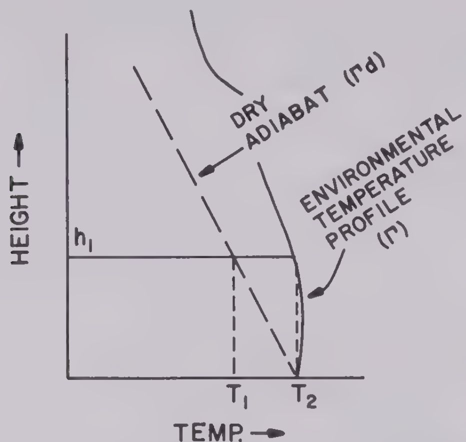


Figure 4–4

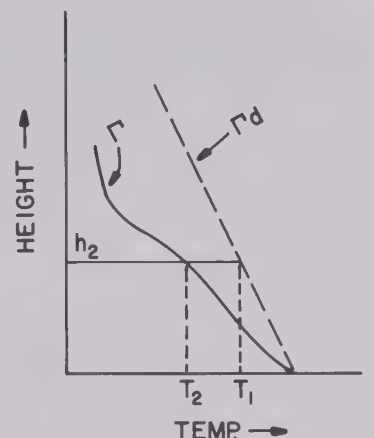
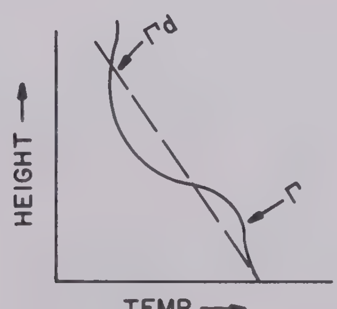


Figure 4–5

Here we see that a parcel lifted to the height h_2 cools to a temperature of T_1 while the environment has a temperature of T_2. In this case, $T_1 > T_2$ which means that the parcel is warmer than its environment, and is therefore less dense. Thus, the parcel would tend to rise due to an upward buoyancy force because its displaced volume of environmental air is heavier than the parcel of air itself. When this occurs, we say that the air is *unstable*. The atmosphere is said to be *stable* when its lapse rate is less than the dry adiabatic lapse rate, just as it is *unstable* when its lapse rate is greater than the dry adiabatic lapse rate (lapse rate $= -\dfrac{\triangle T}{\triangle h}$).

Problem 4–6

Indicate the stable and unstable layers in the atmosphere with a lapse rate pictured on the graph below.



Thus far, we have discussed only *dry* air—that is, air in which condensation has not yet occurred. Once the air has cooled to its dew point and condensation commences, it no longer cools at the dry adiabatic lapse rate. Because heat is released to the air when condensation occurs, the air cools less rapidly. When air is lifted to the point at which a cloud begins to form, it then cools at a different rate which we call the *moist adiabatic lapse rate.* This moist adiabatic lapse rate is not a constant, but is dependent on temperature and pressure. For a temperature of 15°C and at a sea level pressure of 1,000 mb, the moist adiabatic lapse rate has a value of about 5°C/1,000m or 0.5°C/100 m. The graph (figure 4–6) shows a case in which the atmosphere is *unstable* with respect to the moist adiabatic lapse rate, but is *stable* with respect to the dry adiabatic lapse rate. In this case, a lifted parcel would cool along the dry adiabat and unless lifted mechanically (orographically or frontally, for example) would tend to sink back to its original level. But if it is forced upward until condensation occurs, it then cools along the moist adiabat and is *unstable* from that point on. When the atmosphere is stable for dry motions, but unstable after condensation occurs, it is said to be *conditionally unstable.*

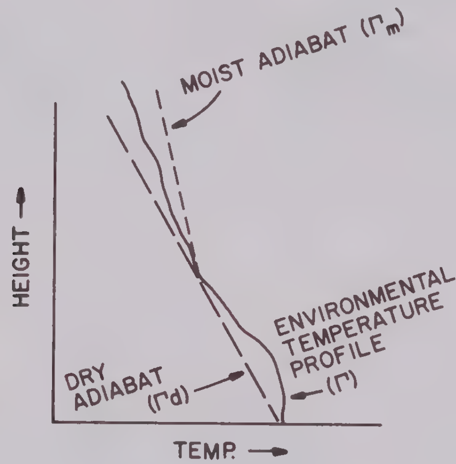
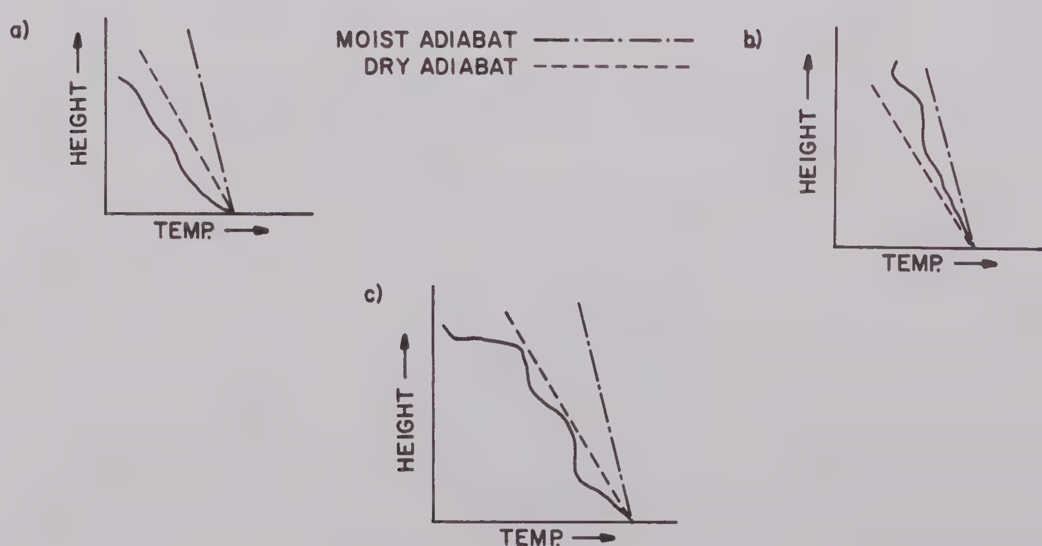


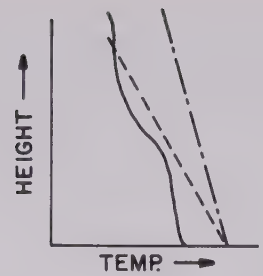
Figure 4–6

Problem 4–7

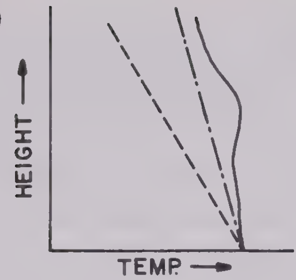
Ascertain whether the following atmospheres are, on the average, stable, unstable or conditionally unstable.



d)



e)



Formation of Raindrops in Tropical Maritime Clouds

So far, we have been concentrating on the processes that lead to the formation of clouds. In this section, we will look at some of the ways that cloud droplets grow into raindrop size. It has been shown in laboratory experiments that for a cloud droplet to grow 100 times in size by further condensation alone, a time span of about 2 to 3 days is needed. But many clouds form, mature and produce rain within an hour or two, so we must conclude that there are other processes at work within the microstructure of the cloud itself.

Problem 4–8

If a cloud droplet has a diameter of 20 microns ($\left(\frac{20}{1,000,000}\right)$ meter) and grows to a diameter of 2,000 microns ($\left(\frac{2,000}{1,000,000}\right)$ meter), the volume has increased by ________________ times. (Volume of a sphere = $(4/3)\ \pi r^3$.)

In any cloud, the water droplets are falling with a small velocity relative to the air around them. However, since most clouds are formed in regions of rising air, the droplets are often rising (or at least stationary) when viewed in relation to the ground. Very small objects have terminal velocities[1] that are proportional to their size. This means that small cloud droplets that are of uniform size will tend to fall at the same speed and thus fairly few collisions will occur between them.

Because collision between equal size cloud droplets are rare, it follows that unequal size droplets must be responsible for the majority of those that do occur. How do droplets grow at different rates when their environment is essentially the same for all droplets? An answer to this may be found in the fact that cloud droplets are formed on very small particles called condensation nuclei. Each microscopic nucleus forms a site for the condensation of water vapor. These nuclei are of varied composition such as combustion products (smoke), dust, Kaolin (fine clay) and salt crystals. Laboratory experiments indicate that large condensation nuclei grow larger cloud droplets than do small nuclei. These few giant nuclei, as they are called, are generally composed of large salt crystals caused by evaporation of ocean spray. As might be expected, these giant nuclei are most numerous in air masses over (or near) oceans.

When cloud droplets of unequal size coexist in the same volume, or parcel, of air, they will fall at different speeds. The larger (and heavier) droplet will have a terminal velocity that is faster than the smaller cloud droplets in close proximity to it. When this happens, the result is often a coalescence (or merging) of the smaller, slower droplet and the larger, overtaking one. The result is a still larger droplet which falls even faster relative to the smaller cloud droplets. Then there is an even greater possibility of collision. It is by this process of collision and coalescence that some cloud droplets grow to raindrop size in time scales that are compatible with the lives of observed clouds.

1. Any object that is allowed to fall freely in the earth's gravitation field will eventually reach a maximum fall velocity. This velocity occurs when the acceleration due to gravity is balanced by air resistance and friction. This maximum velocity is called the terminal velocity of an object.

Problem 4–9

Assume that a cloud measures a kilometer on a side. This cube-shaped cloud is made up of cloud droplets that have a diameter of 20 microns (20×10^{-4} cm) and there are 20 droplets per cubic centimeter of cloud.

a. What is the total volume of the cloud in cm^3?

b. What is the volume of water (in cm^3) in each 20 micron droplet?

c. What is the total volume of water (in cm^3) in the cloud?

d. What is the total mass of water in the cloud (in gm)?

e. If all of the water in the cloud could be "squeezed" out into a pan that measures 1 km × 1 km, how deep would the water be in the pan?

f. How much does this water weigh in pounds? (1 lb = 454 gm)

g. How deep is the water in inches? (1 in. = 2.54 cm)

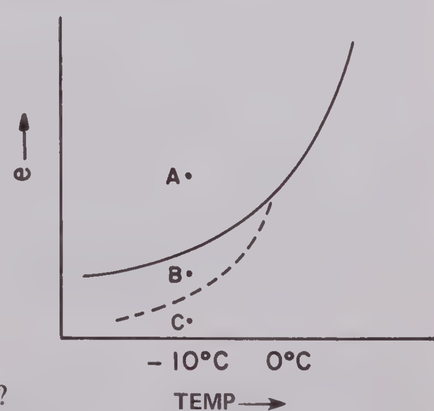
The Bergeron-Findeisen Process

There is another process that produces large cloud droplets in supercooled clouds. It was described by T. Bergeron in 1935 and later expanded by Findeisen in 1938. It has been experimentally verified that the saturation vapor pressure over ice is less than the saturation vapor pressure over water at the same temperature. This saturation vapor pressure deficit (about 0.25 mb at −12.5°C) means that when ice crystals and cloud droplets exist in the same air parcel, the ice tends to grow at the expense of the cloud droplets.

The way that this happens is this: Suppose a parcel of air has a number of supercooled (below 0°C) droplets that are in equilibrium with the air in the parcel. That is to say that there are as many water molecules leaving each droplet as are condensing onto the surface of the droplet. When this situation occurs, the air between the droplets is said to be saturated and a state of equilibrium exists. Now, if an ice crystal should fall into the cloud, from a cirrus cloud perhaps, the situation changes. Because the ice has a lower value of e_s than the cloud droplets at the same temperature, the air is supersaturated with respect to ice. This means that the ice has more water molecules falling onto its surface than it has leaving it. Therefore, the ice has a net gain of mass. Because the ice is collecting more water than it is supplying to the atmosphere, there is a net loss of water molecules from the atmosphere in the parcel. In other words, the vapor pressure, e, is reduced. In the original situation, e was equal to e_s and the relative humidity was 100%. Now, e is less than e_s and the relative humidity is less than 100%.

Problem 4–10

Here is a vapor pressure versus temperature plot; the solid line is the saturation vapor pressure curve for water, and the dashed line is e_s for ice.



a. If a cloud droplet were introduced into the atmosphere with a temperature and vapor pressure as indicated by point A, would the droplet collect water (i.e., grow in size) or would it evaporate?

b. Suppose a droplet were introduced at point C on the graph—would it grow or evaporate?

c. If our droplet were put in at point B, what would happen?

If the above seems unclear to you, let's look at this process in a laboratory setting. Suppose we have a small tank (figure 4–7) that is divided into two compartments. We place ice in one section and supercooled water (at the same temperature as the ice) in the other. We allow the system time to reach equilibrium; i.e., the air in each compartment becomes saturated. The fact that the saturation vapor pressure over water is higher than that over ice is depicted by having more dots (representing water molecules) on the water side of the tank than on the ice side. When saturation is achieved, there are just as many molecules leaving the ice as are falling onto the ice from the air in the tank. The same is also true on the water side. Now, let us open up the partition so as to allow the air from one side to mix into that of the other (figure 4–8). This will distribute the water vapor equally throughout the system. Because there are

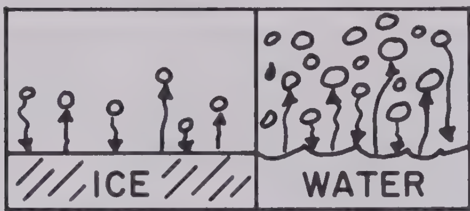


Figure 4–7

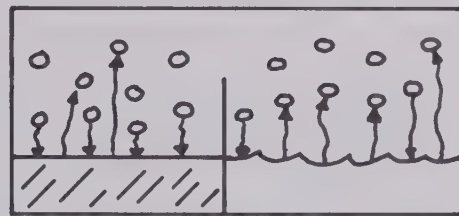


Figure 4–8

now more molecules on the ice side than previously, more molecules will fall on the ice than will be leaving the ice surface. Likewise, there are fewer molecules on the water side than there were before, so more molecules will leave the water than will be returning from the air above it. If we keep the air well mixed, it will be supersaturated in the ice compartment (allowing a net deposition of water molecules on the ice) and unsaturated over the water (causing a net evaporation of water). Thus, if the process is allowed to continue, the water will completely evaporate and the vapor will then be deposited on the ice (figure 4–9).

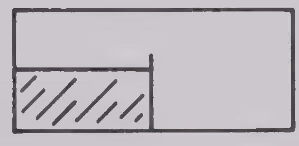


Figure 4–9

d. Now take an ice crystal and put it in the atmosphere at point A. Would it grow or evaporate?

e. Inserted at point C would the ice crystal grow or evaporate?

f. Consider point B. Would you expect an ice crystal to grow there?

g. If we placed a droplet *and* an ice crystal side by side in an atmosphere with vapor pressure and temperature as represented by point B, what would happen? (see c and f above)

Problem 4–11

a. When the vapor pressure (e) of the atmosphere was greater than the saturation vapor pressure over ice, there was a net __________ (gain, loss) of mass of the ice.

b. When the vapor pressure, e, falls below the saturation vapor, e_s, of the water droplet you would-expect a net __________ (gain, loss) of mass of the water droplet.

You can see from question 11 that there is a net transfer of water from the cloud droplets to the ice. As the ice grows, it begins to fall faster than the cloud droplets near it and thus collides with smaller droplets. These freeze onto the ice particle causing it to grow even more. From this point the ice grows much as a water drop does until it reaches the warmer regions of the cloud where it melts and appears as a raindrop.

The Bergeron-Findeisen Process is important to continental clouds which often lack the giant nuclei found in tropical maritime cumuli. The question is often asked: Where do the ice crystals come from to initiate the process? Because small relatively pure droplets of water can supercool to an amazing degree ($-40°C$ in some cases) before freezing takes place, it is uncommon for cloud droplets to freeze in the $-5°C$ to $-15°C$ environments of many continental cumulus clouds. Most ice crystals are introduced into the tops of the clouds by natural "seeding" processes. For instance, ice could be blown from the top of a thunderstorm to settle into the tops of a cumulus cloud deck far down wind. Another possibility is that ice could fall from cirrus clouds into lower cloud layers.

There is a way that ice can form within a cloud environment. Certain natural substances that can act as ice nuclei can exist in clouds. Kaolin and quartz particles that are found in the atmosphere are examples of these natural ice nuclei. Chemicals such as AgI (silver iodide), PbI (lead iodide) and copper sulfide (CuS) have been found to be efficient ice nuclei during laboratory experiments. As a result of these experiments, some attempts were made to increase the rainfall from supercooled clouds by adding dry ice to them. The dry ice further cooled the droplets and froze them. These frozen droplets acted as nuclei for further condensation. Some degree of success was achieved and scientists then introduced the smoke of various burning chemicals (AgI, PbI, etc.) into suitable clouds. In this case the smoke particles acted as nuclei for condensation just as a small ice crystal might. It was found that silver iodide smoke was a very efficient ice nucleating agent. This chemical has been introduced into clouds via rockets, flares, aircraft mounted generators, and generators at ground level. While the cost per pound of silver iodide is quite high, its efficiency (millions of particles are produced when a pound of AgI is burned) and ease of handling makes it very economical to use.

Problem 4–12

a. One of the most effective uses of silver iodide has been to clear airports when visibility has been obscured by a supercooled fog. Describe the process by which the airport visibility would be improved.

b. Would this technique work for any fog? If not, why not?

Problem 4–13

a. Silver iodide is a good seeding agent because

   (1) it is economical to use
   (2) it is easy to handle and distribute
   (3) it provides freezing nuclei
   (4) all of the above

b. If water droplets and ice crystals exist in the same air parcel, and the temperature is slightly below freezing

   (1) the water drops grow at the expense of the ice crystals
   (2) the ice crystals grow at the expense of the water drops
   (3) neither crystals or drops grow at the expense of the other
   (4) water droplets freeze into ice pellets, the ice crystals remain unchanged

c. The Bergeron-Findeison process can operate because air which is unsaturated with respect to water may at the same time be

(1) unsaturated with respect to ice
(2) supersaturated with respect to ice
(3) free of water vapor
(4) doesn't work in the atmosphere

Summary

In this exercise, you have been introduced to the various causes of clouds and precipitation in our atmosphere. You have been shown that the mere availability of water vapor is not enough; there must also be some method of lifting (and thereby cooling) the air. Once clouds have formed, other processes must be present to initiate precipitation. In warm clouds, collision and coalescence appear to be dominant and in supercooled clouds, the Bergeron-Findeisen ice crystal process is the main mechanism.

Meteorologists have, in the past two decades, been able to utilize the icelike qualities of some chemicals to change the microstructure of supercooled clouds in order to cause rain and/or snow. Much of this work is not conclusive and ongoing research is attempting to refine weather modification techniques.

FRONTS AND EXTRA-TROPICAL CYCLONES

Introduction

When you did the exercise on Winds and Pressure, you were told that the convection pattern of the atmosphere in the more northerly latitudes (above 35° latitude) was essentially horizontal in nature. This horizontal convection is more complex than the vertical convection cells that are found in the equatorial regions of the globe. This exercise will attempt to acquaint you with the boundary between the colder air close to the poles and the warmer air near the equator. Circulations along this zone are found to be both cyclonic (counterclockwise) and anticyclonic (clockwise). As far as precipitation is concerned, the cyclonic flows (storms) are the most significant. In all cases, except where specifically mentioned otherwise, we are dealing with the Northern Hemisphere.

Wind Patterns Around Pressure Systems

We have learned that there are regions of high and low pressures scattered about the surface of the earth. We also have noted that there are different weather patterns around each of these systems. In this section we will examine these pressure systems and the reason for their unique wind patterns. To simplify the presentation somewhat, we shall deal with a very special wind. This wind is horizontal, frictionless, nonaccelerated, and hypothetical. Because we have put these constraints on the system, we have only two forces acting on our wind. These forces are the *pressure gradient force* (pgf) and the *coriolis force* (f). This theoretical wind is called the *geostrophic wind.*

To begin our discussion of the geostrophic wind, let's examine each of these forces. The pressure gradient force is that force that causes fluids to move from areas of high pressure to areas of lower pressure. If this were the only force that affected the atmosphere, all winds would blow directly away from high pressure regions toward low pressure regions. See figure 5–1.

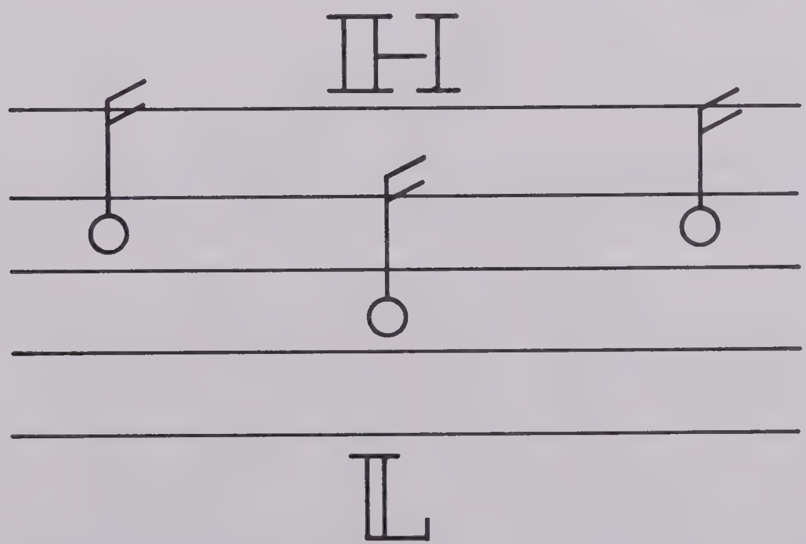
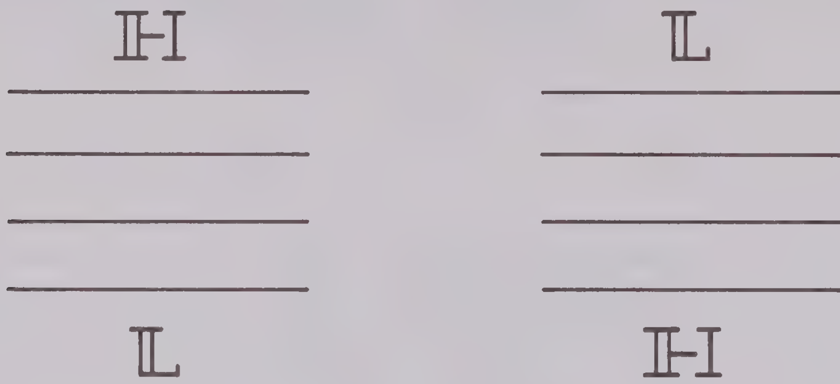


Figure 5-1

Problem 5–1

In the pressure pattern below, draw arrows showing the direction of the pressure gradient force (pgf). (The pgf is normally shown as an arrow from higher pressure to lower pressure.)



The second force that acts on a fluid in motion is the Coriolis force (f). This force is a consequence of the earth's rotation and always acts at 90° to the right of the wind direction in the Northern Hemisphere, and is proportional to the wind speed (i.e., the faster the wind blows, the stronger the Coriolis force). The Coriolis force is also dependent on latitude, being stronger at the North Pole for a given wind speed than at low latitudes. In fact, the horizontal effect of the Coriolis force is zero at the equator. How does this force affect the wind flow? If we take a low pressure system and start the wind flowing everywhere from higher pressure to lower pressure, the moving air would be immediately acted upon by the Coriolis force: The sum of these two forces causes the wind to change its direction. See figure 5–2.

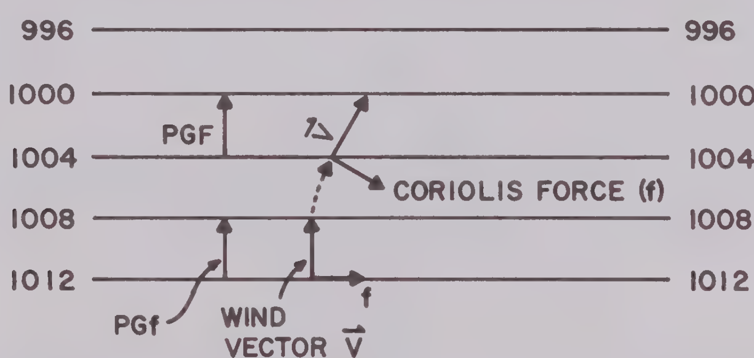


Figure 5–2

The Coriolis force continues to act to the right of the wind (W) causing further deflection until the Coriolis force is exactly opposite the pressure gradient force and the wind is in balance. See figure 5–3.

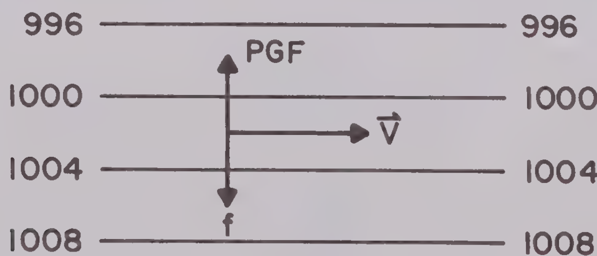
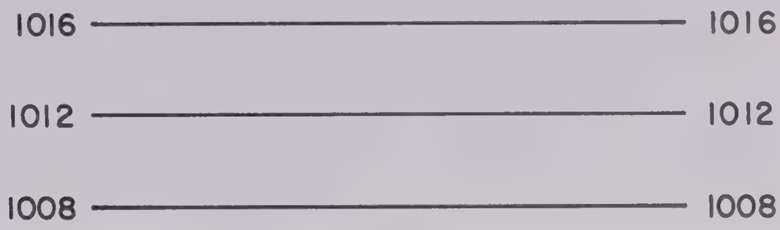


Figure 5–3

In effect, the wind is blowing in a counterclockwise manner about a low pressure area. Because this is a hypothetical system (no friction or acceleration allowed—i.e., a steady state), the wind blows parallel to the isobars.

Problem 5–2

Draw a similar set of force vectors for this pressure system. Label the pressure gradient force (pgf), the wind vector (V) and the Coriolis force (f).



Now we all know that friction does exist. Let's take a look at how friction would affect our balance of forces. In figure 5–4, the pgf does not change with the addition of friction. The wind velocity does slow down because of friction and then the Coriolis force is not as great.

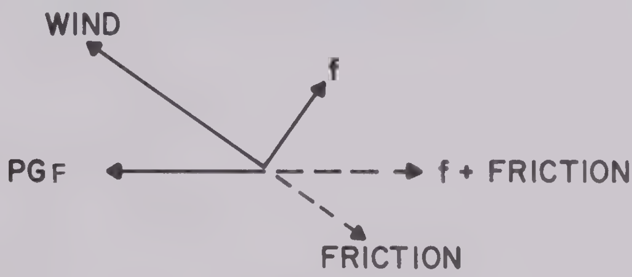


Figure 5–4

Note in figure 5–4 that the resultant (sum) of the Coriolis and friction forces still balances the pressure gradient force and the wind is still at right angles to the Coriolis force. Figure 5–5 shows how a low pressure system would look with friction added:

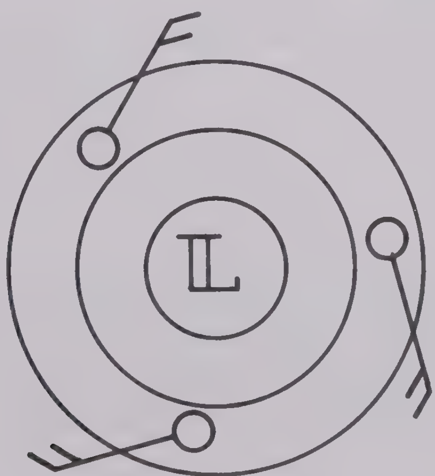
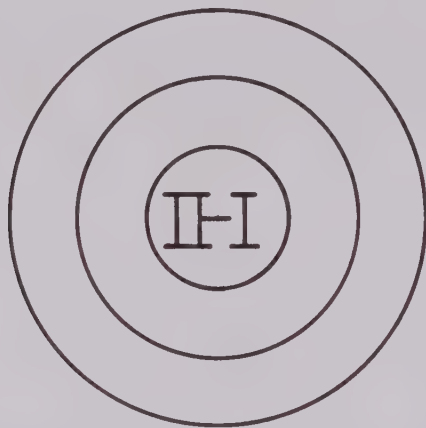


Figure 5–5

The wind is no longer parallel to the isobar but is flowing across them toward lower pressure.

Problem 5–3

Draw the wind pattern around the high pressure system below. Include friction.



Problem 5–4

Draw the geostrophic wind flow by putting arrows indicating direction of the wind.

(a) High

Low

(b) Low

High

Problem 5–5

Do the same as in (4) above with friction included.

(a) High

Low

(b) Low

High

The Polar Front

A *front* is the transition zone between two distinct masses of air of different properties. This means that fronts can separate masses of air of different temperatures or of different moisture contents. One example of such a front is the boundary between cold, relatively dry polar air and the warmer, more humid air of the temperate zone. This front is called the *Polar Front*.

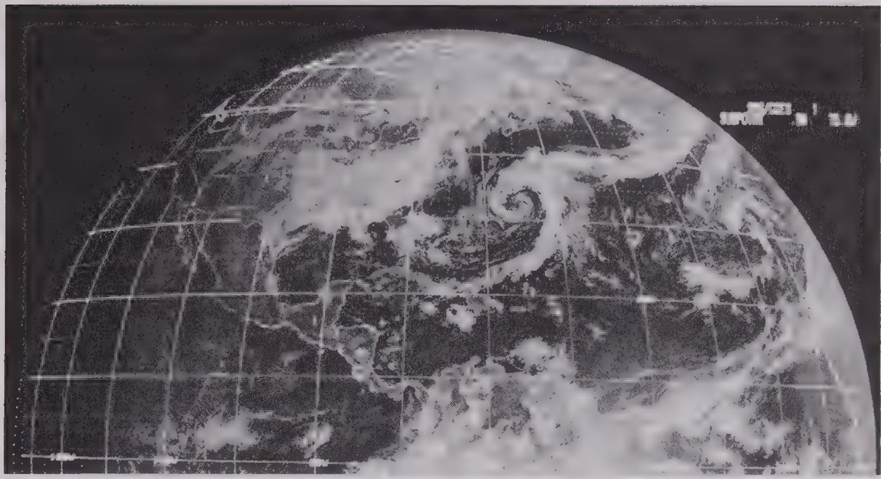


Plate 5–1

Problem 5–6

Look at plate 5–1. Can you see a region of cloudiness that looks like a long thin curving line? That line of cloudiness is caused by "Frontal Lifting." (Look back to exercise 4 for a review of causes of precipitation.) Can you explain the mechanism that caused the large areas of cloudiness that appear on the front?

Because cold air is more dense that warm air at the same pressure, cold air displaces the warmer air. This means that the wind direction in the cold air indicates the direction that the transition zone (front) is moving. Normally, the component of wind perpendicular to the front is used to indicate direction. For example, as in figure 5–6, if the front is oriented N-S with the cold air to the west, and the wind is from the northwest in the cold air, we would resolve the wind into components as in the diagram and say the front is moving east.

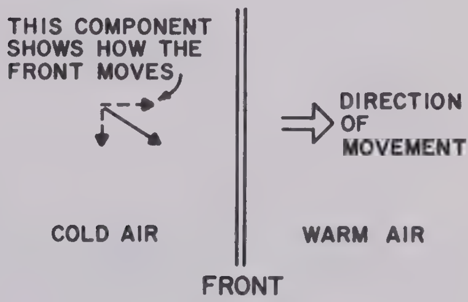
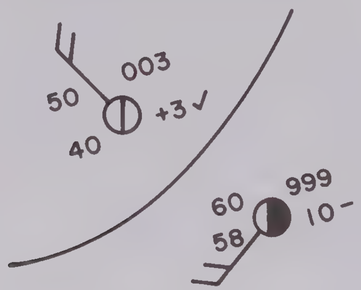


Figure 5–6

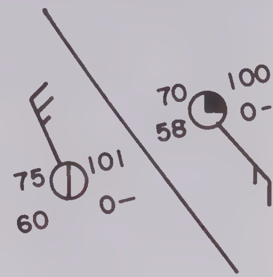
Problem 5–7

Draw arrows to indicate the direction of motion of the fronts in the diagrams below.

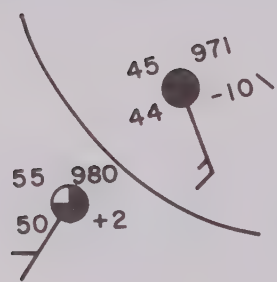
a.



c.



b.



We give fronts names which depend on the direction of motions of the cold air. If the cold air is advancing, the front is called a *cold front*. If the cold air is retreating, it is called a *warm front*. If there is no apparent motion at the front, we call it a stationary front.

Problem 5–8

Look back at question 7 and identify the fronts as warm, cold or stationary.

a.

c.

b.

Location of Fronts

When a meteorologist is plotting and analyzing a map, he must be able to deduce from the data available the position of any fronts that may appear in the geographical area covered by the map. The exact positioning of fronts is not always easy. In many cases, the front can be located by the use of simple rules, but sometimes experience and even intuition must be used.

The most obvious means of locating a front would be temperature. Because a front normally separates a cold air mass from a warm one, shouldn't the temperature in the two air masses be a key to the frontal location? The answer is yes—but only in a very general way. A front is a transition zone between the two masses. This means that instead of a sharp temperature drop as one enters the colder air, the temperature may change gradually over several tens of miles. By convention, the exact geographical location of a front is considered to be the leading edge of the cold air. Because stations that record and transmit meteorological data are located at certain geographical locations, the front zone pictured in figure 5–7 might fall entirely between stations and not appear on the map. So it is entirely possible that temperature alone will not sufficiently locate a front.

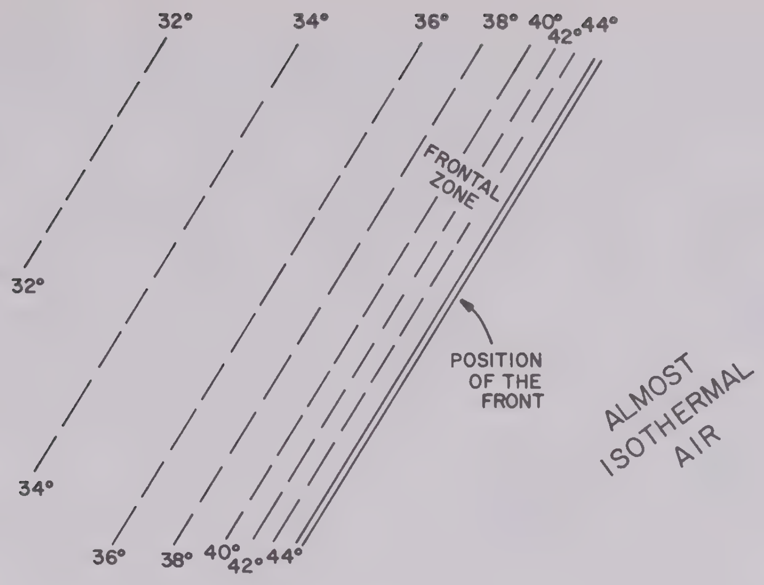


Figure 5–7

The dew point, like the temperature, helps to locate the front in a general sense, but is not sufficient by itself to nail down the exact position. As you already know from exercise 2, dew points are generally lower in cold air than they are in warm air. So there should be a general drop in dew point temperatures across a front. But like temperature, the dew point is not an infallible guide.

By examining figure 15–1, you can see that the isobars "kink" at the front with the kink pointing toward higher pressure. As the example in figure 5–8 shows, the kink in the isobar illustrates the surface wind direction.

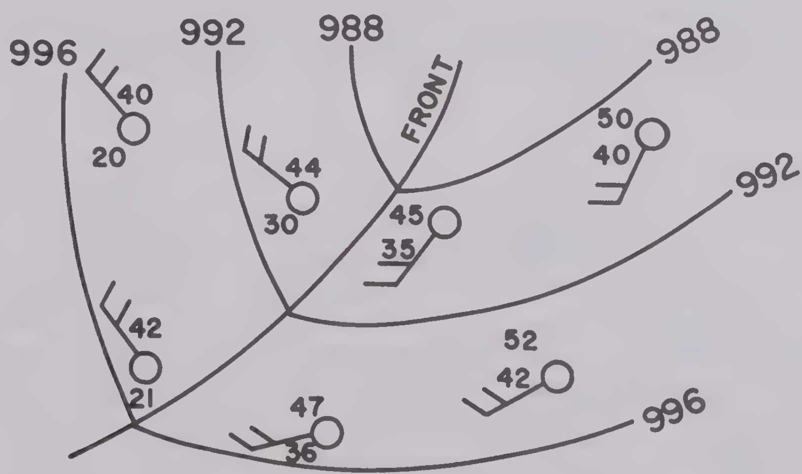
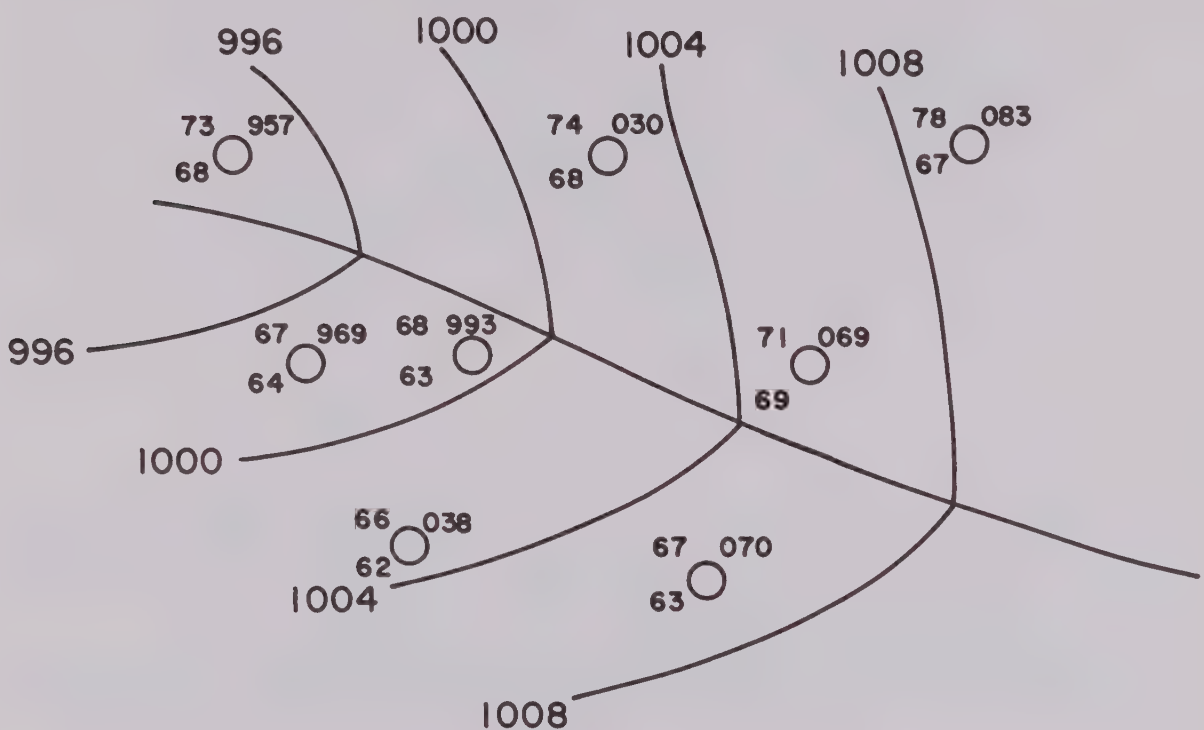


Figure 5–8

Notice the wind shift across the front. There are basically southwest winds in the warmer air and northwest winds behind the front. As you can see, the temperature alone is not enough to locate the front. The wind shift is most useful in this case.

Problem 5–9

Plot the wind direction in the pressure field below. How does the wind change across the front? ____________________ What type of front is it? ______________________________



When a meteorologist plots and analyzes a map, he first plots the data for each station. Then he locates the fronts, using temperature changes, dew point changes, changes in wind direction, and weather patterns as aid as in figure 5–9a.

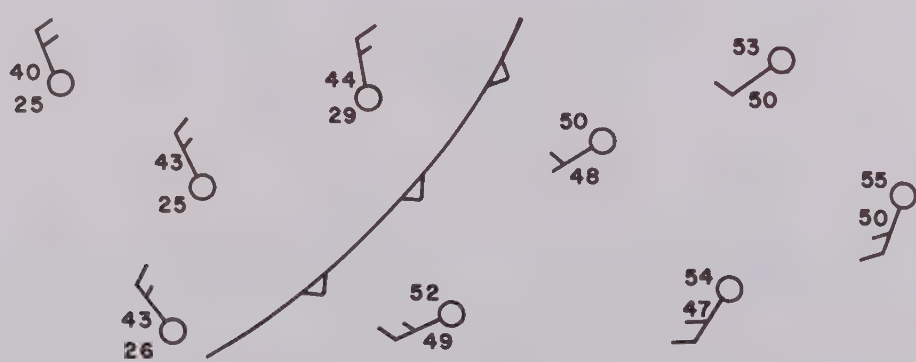


Figure 5–9a

He then would draw in the isobars as in figure 5–9b.

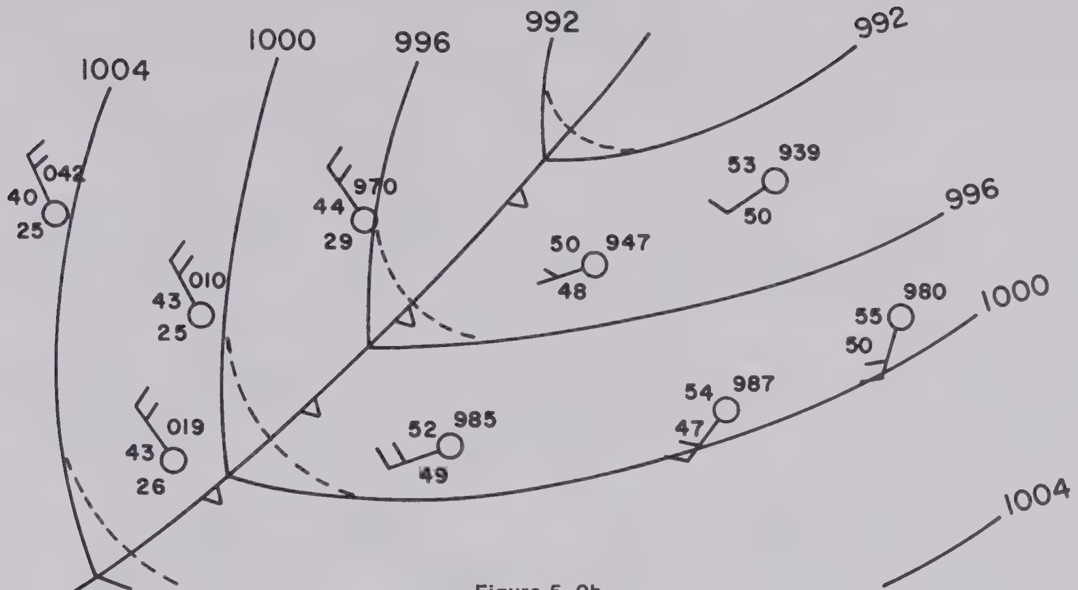


Figure 5–9b

Once he has decided his fronts are correct, he adjusts the isobars to give the proper "kink" at the front.

Problem 5–10

The map on page 68 has been plotted for you. Analyze the pressures by starting at 1,000.0 mb and drawing isobars every 4.0 mb as needed. Locate the front(s), draw them in using the proper symbols (warm front; cold front) and readjust the isobars as needed. Use a soft (#2) pencil so as to make erasures easily.

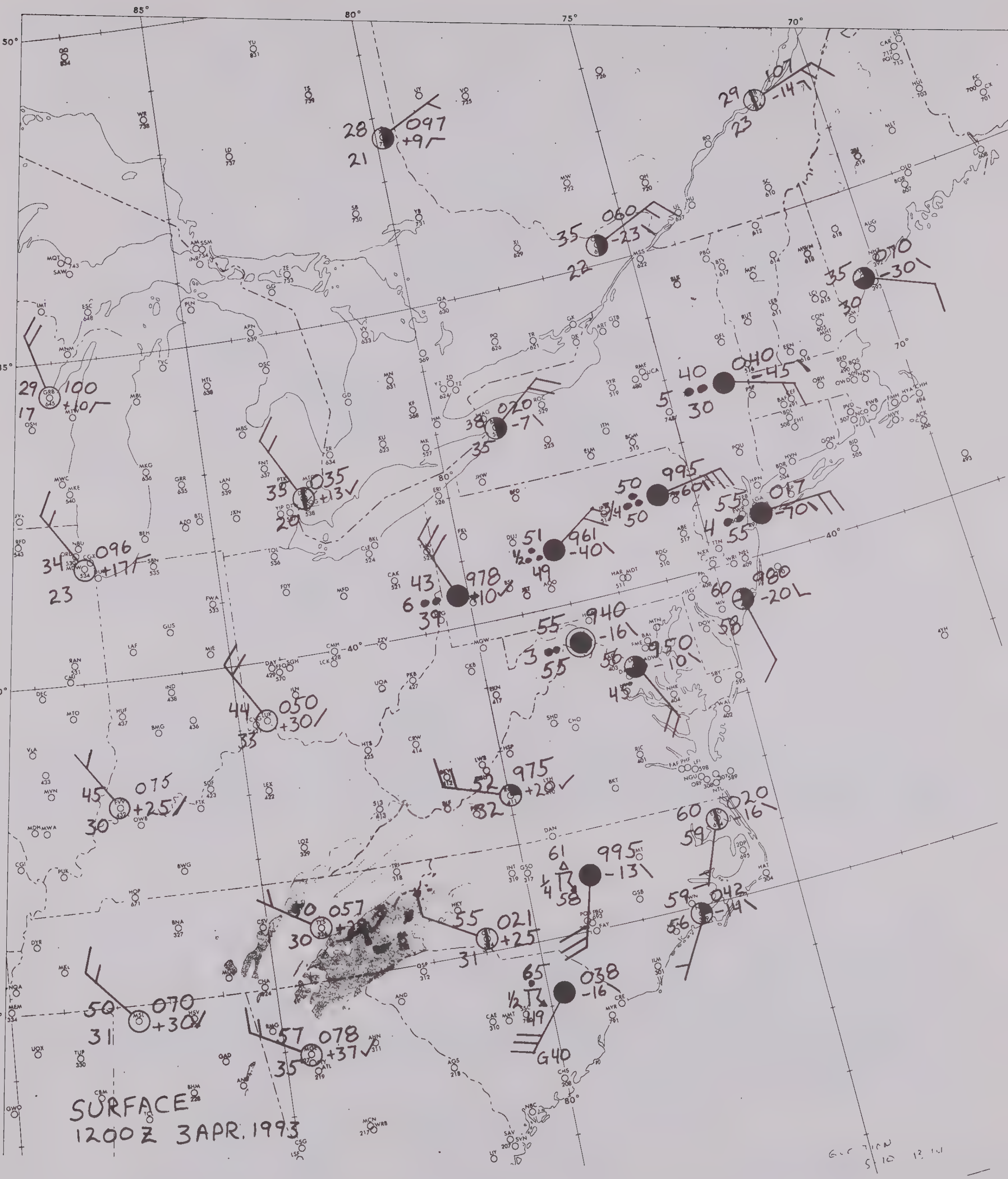
Current Weather Depiction

Between the temperature and the dew point on the station model, there is a space in which we put a symbol which depicts the weather at the station at the time of the observation. The visibility in miles is also plotted in this position. (See figure 5–10.)

The table in the appendix lists symbols for various weather phenomena that might be used to describe current weather conditions. Some of them are rarely used, but the symbols that depict various types and amounts of precipitation are quite commonly seen on surface weather maps. These include:

TABLE 5-1

Drizzle	Rain Shower	Freezing Rain
Rain	Snow Shower (flurry)	Freezing Drizzle (heavy)
Snow	Thunderstorm	Sleet



Precipitation intensities are shown by repetition of the symbols. For instance, * indicates light intermittent snow, ** indicates light continuous snow, *** means moderate snow, and **** means heavy snow. The same convention applies to the rain and drizzle symbols as well. Sometimes one of the weather symbols appears in the lower right-hand corner of the model. This symbol depicts the weather that has occurred in the past six hours. For example, suppose a station model was plotted in this manner:

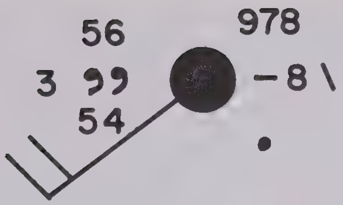


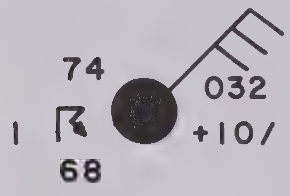
Figure 5–10

We would decode it as follows:

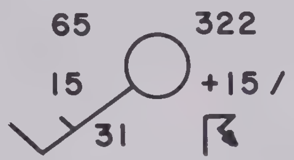
Sky overcast, temperature 56° F, dew point 54° F, wind from the southwest at 20 kts, sea-level barometric pressure is 997.8 mb, having fallen 0.8 mb in the last three (3) hours, visibility is 3 miles in light continuous drizzle, and there has been rain in the last 6 hours.

Problem 5–11

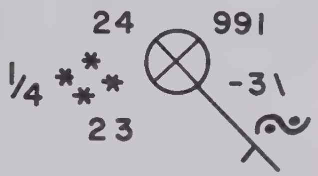
Putting together what we have learned about the station model, what is the weather at the following stations. Use the table in the appendix if necessary.



(a)



(b)



(c)

Sky Cover			
Wind Direction/ Velocity			
Temperature			
Dew Point			
Pressure (sea level)			
Pressure 3 hours ago			
Discontinuous, Continuous Fall, Rise			
Visibility			
Current Weather			
Weather in past 6 hours (if any)			

Problem 5–12

Plot a station model based on the following weather observation: Sky is obscured, wind calm, temperature 65°F, dew point 65°F, pressure is 1,000.0 mb and has not changed in the past 3 hours. The present visibility is ⅛ mile in fog. During the last 6 hours, there was a thunderstorm.

Extra-Tropical Cyclones

A look at plate 5–2 shows that the polar front is not a simple circular line that girdles the globe at a given latitude. Rather it is a very irregular zone moving around the northern hemisphere in a sinuous track. At irregular intervals, wavelike shapes may be seen. These waves are large storm systems with low pressures and cyclonic (counterclockwise) winds. The storm systems that exist on the polar front are not there by accident. The counterclockwise flow of wind about the storm performs a definite function. Southerly winds on the eastern side of the cyclone bring warm air north, while northerly winds to the west of the storm center bring cold air south. In this way, the atmosphere is attempting to equalize the temperature differential caused by uneven solar heating. See figure 5–11.

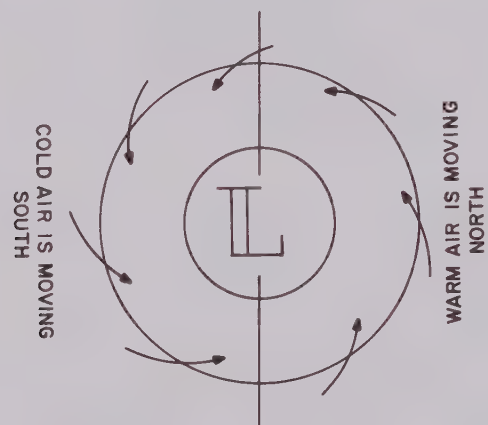


Figure 5–11

The life history of a typical extratropical cyclone might be something like this:

a. A cold front is moving to the southeast in the eastern United States. See figure 5–12a. (Note the map symbol for a cold front. The points indicate the direction of movement.)

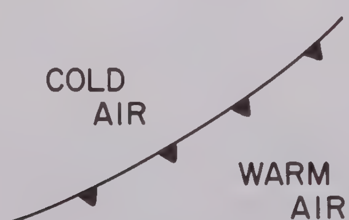


Figure 5–12a

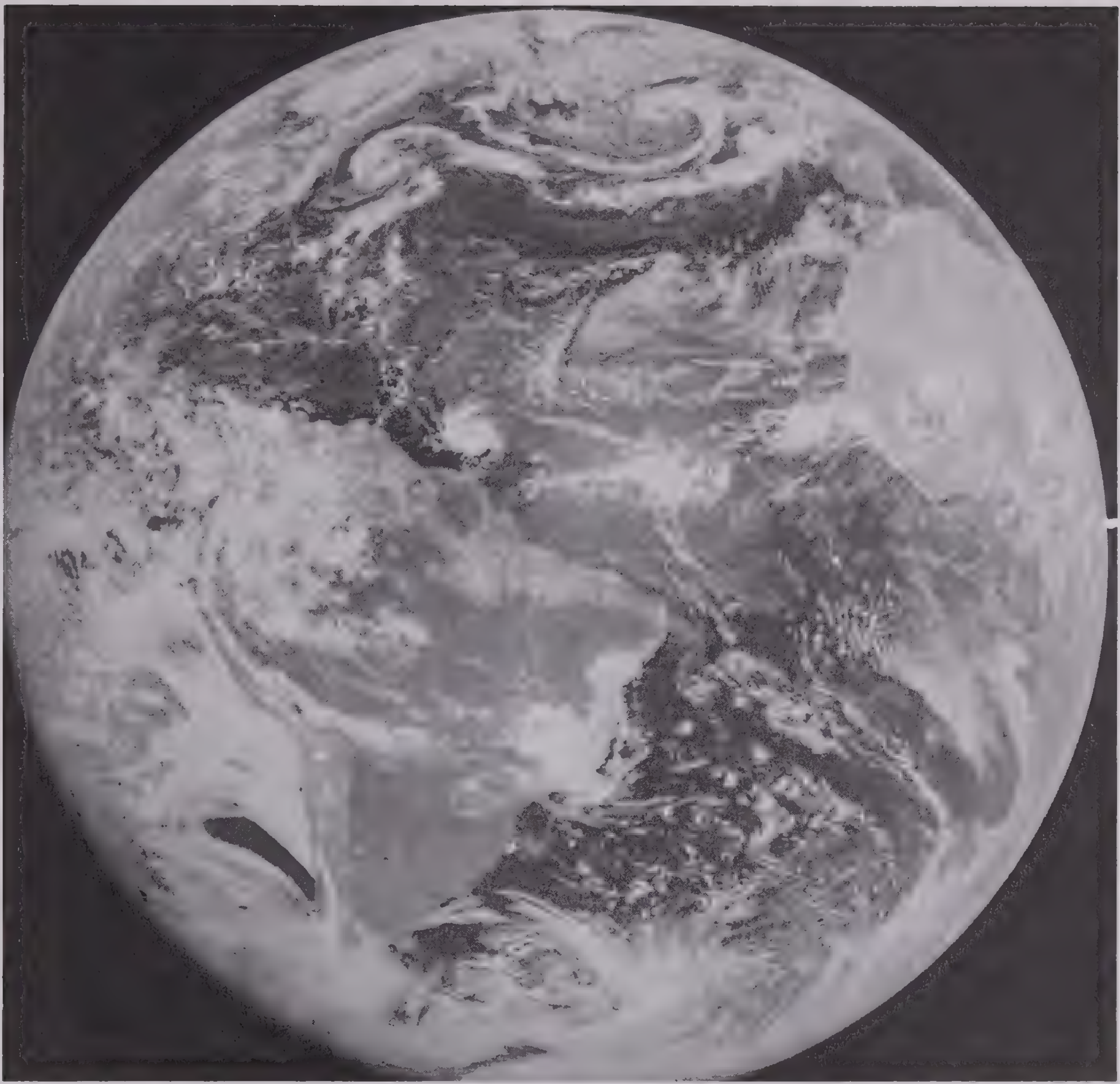


Plate 5–2

b. A localized area of low pressure forms at some point along the front. See figure 5–12b.

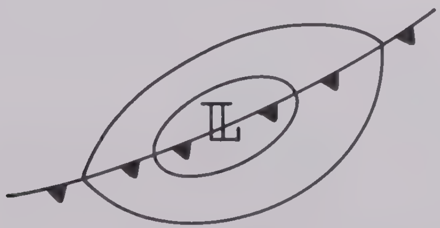


Figure 5–12b

(Why this happens will be discussed in a later exercise.) When this happens, a circular isobar pattern emerges and cyclonic flow develops around the weak low pressure system. The wind pattern around this low begins to move the cold air to the northwest of the low in a counterclockwise manner. (Figure 5–12c.)

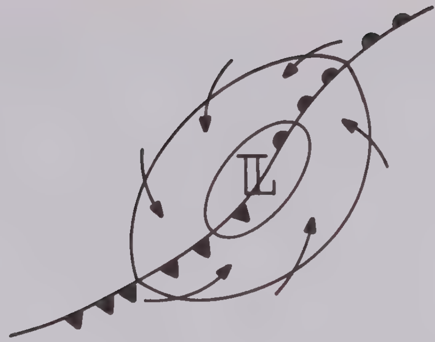
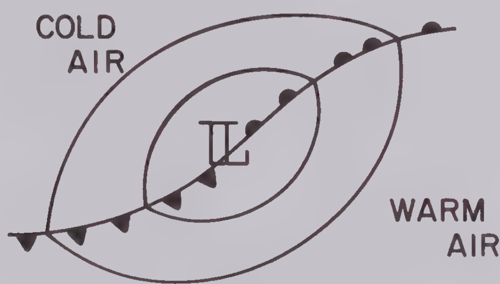


Figure 5–12c

Problem 5–13

At this point, show the movement of the fronts by placing arrows in the diagram as you did in number 7. Label the fronts (cold, warm, stationary), as appropriate.



The advancing cold air moves faster than the retreating cold air does. This causes a "wave" to form on the front. As this happens, the central pressure of the area gets lower and lower causing a larger pressure gradient and, therefore, stronger winds. See figure 5–13.

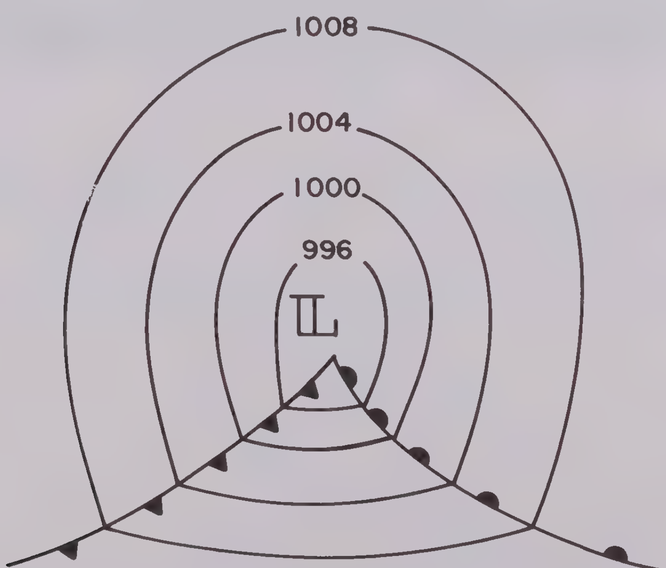


Figure 5–13

When the storm has reached this stage of maturity, it is convenient to label various sectors of the storm as cold, cool, and warm. The air behind the cold front is coming from the cold air mass. This area behind the cold front is called the cold sector. The section between the warm and cold fronts is the warm sector and the section on the cold air side of the warm front is called the "cool" sector. This nomenclature is useful in labeling cross sections and is illustrated in figure 5–14.

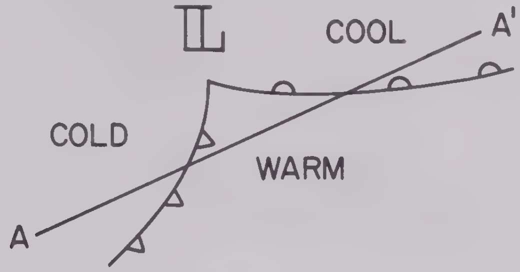


Figure 5–14

A vertical cross section along line A-A′ is shown in figure 5–15. Note: The vertical dimension is greatly exaggerated.

Figure 5–15

You can see that the slope of the cold front is greater than the slope of the warm front. This can be explained by friction. As the cold air advances (see arrow), the leading edge is retarded by surface friction and the slope is steeper than that of the retreating air which is held back by friction.

Because the cold front moves faster than the warm front, it overtakes the warm front near the center of the storm. When this happens, the cold air not only pushes the warm air aloft, it also displaces the cool air upward. This is called an occlusion. See figure 5–16. Notice that the warm air is no longer in contact with the surface of the ground, but has been pushed aloft. This lifting of the warm sector causes heavy precipitation in the vicinity of the occlusion. (Remember that lifting of moist air is the cause of

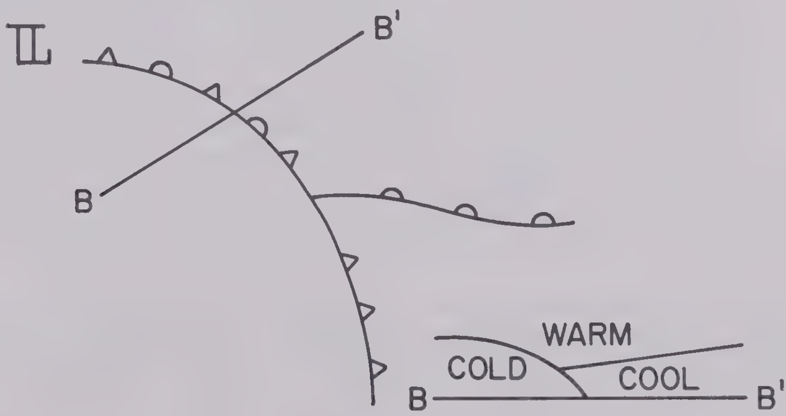


Figure 5–16

precipitation.) Once the occluded stage has been reached, the storm has begun to decay and while there is still heavy precipitation associated with it, this storm has lived its life cycle and the low pressure area will begin to fill and dissipate.

These storms which have areas of thousands of square miles, normally have a life span of 3–10 days. Often a front will have a whole family of storms each in a different stage of development (see plate 5–2). In figure 5–17 storm "A" is just beginning to form, "B" is a mature cyclone and "C" has occluded.

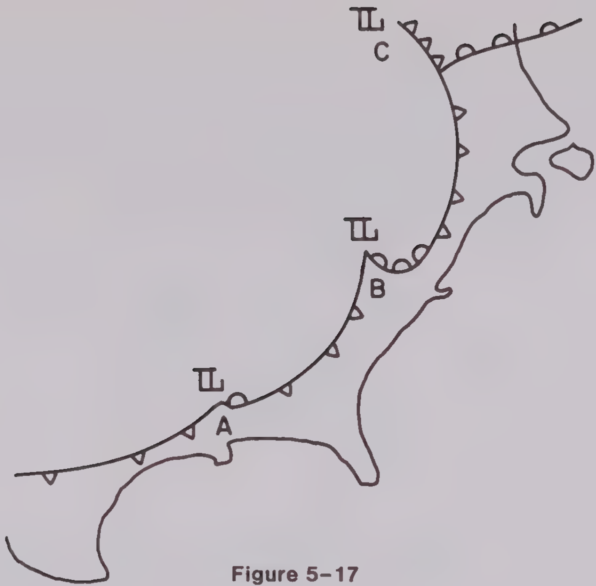


Figure 5–17

In the above figure, the storms are moving to the northeast along the front.

Problem 5–14

Using the plotted map you analyzed in problem 10, outline the regions of cloudiness by enclosing the areas of total cloudiness with a scalloped line:

Note that if you have several neighboring stations that are cloudy, the area in between them is probably cloudy. Your analysis should look something like this:

not like this:

Next shade in the areas of precipitation with a colored pencil.

Movement of Storms

While the winds in a storm system blow in a counterclockwise direction about the center, this motion is independent of the actual movement of the storm. The storm is moved by winds that exist in the middle of the troposphere. These winds form a river of air which circles the globe at velocities often in excess of 100 kts and gives us our best clue to future storm movement. However, there is a useful tool for forecasting the future position of a low pressure system. The pressure tendencies that show the change in pressure over a three hour period are used. A surface map has these tendencies plotted to the right of the station model. A meteorologist wishing to forecast storm movement would isopleth the pressure tendencies, drawing lines of 0, +1, +2, +3, etc., as well as −1, −2, and −3. Once this was done, he would predict that the future location of the storm would be in the area of the largest pressure falls.

Problem 5–15

Using the surface map dated April 3, 1993 on page 68, isopleth the pressure tendencies from (−4 to +4). Use an arrow to indicate the direction you think the storm will move. Remember that you must add a decimal point to the pressure tendencies (+5 becomes +.5; −17 becomes −1.7; etc.). Use intervals of one millibar.

Summary

Upon completion of this exercise, you should have a basic understanding of the extra-tropical cyclone. This particular meteorological phenomenon is an important source of atmospheric moisture in many parts of the globe. A significant amount of the rainfall that is measured in the eastern United States originates in these large storms and the fronts associated with them. It is important to note that the storms act as "giant heat exchangers," bringing cold air south and warm air north in an attempt to achieve thermal equilibrium.

UPPER AIR FLOW

Introduction

In the exercise concerning Fronts and Extratropical Cyclones, the discussion about the movement of storms was left to a later laboratory exercise. In this lesson, the mid-to-upper levels of the troposphere will be examined and the relationship between some surface weather phenomena and upper air flow patterns will be emphasized.

Constant Pressure Surfaces

Pressure is the one atmospheric variable that always decreases in the vertical. This means that if the pressure is 1,000 mb at the surface, then the pressure will be 999 mb just above the surface, 800 mb some distance farther up, and so on until the "top" of the atmosphere is reached. Because the top of the atmosphere is not a finite boundary, but rather blends into outer space, we will consider 100 mb as the "top" of our atmosphere. Therefore, if we were to look at a column of the atmosphere, it might appear like figure 6–1. Notice that the pressure changes quite rapidly with the height near the ground, and less rapidly near the top of the atmosphere. For those of you with a background in mathematics, it can be seen that the change of pressure with height is logarithmic.

You can see that the value of any pressure less than the surface must be present at some altitude above every point on the globe's surface. Thus we can choose any pressure value (less than about 1,000 mb) and find it in every column. If we connect all of the points with the same pressure, we form a surface on which the pressure is constant.

If the earth were a smooth, featureless sphere (such as billiard ball) and the atmosphere were isothermal (i.e., of equal temperature throughout), then the constant pressure surfaces would be concentric spheres surrounding the earth much like the layers of an onion. The height above the surface of a constant pressure surface—say, the 500 mb surface—would be everywhere equal. If we allow temperature variations to enter the scene, the picture changes somewhat. You will remember from earlier work that cold air is denser than warmer air. This would mean that if we had columns of air that had equal weight (i.e., pressure) and were of different average temperatures, the columns would be of different sizes.

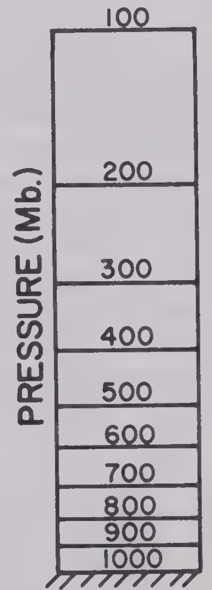


Figure 6–1

Problem 6–1

Here we have two columns of air. Each has a pressure at the surface of 1,010 mb. The average temperature of column A is 20° colder than the average temperature of column B. After looking at the height of the pressure surfaces in column B, would you say that the 500 mb surface would be higher or lower than the 500 mb surfaces in column A?

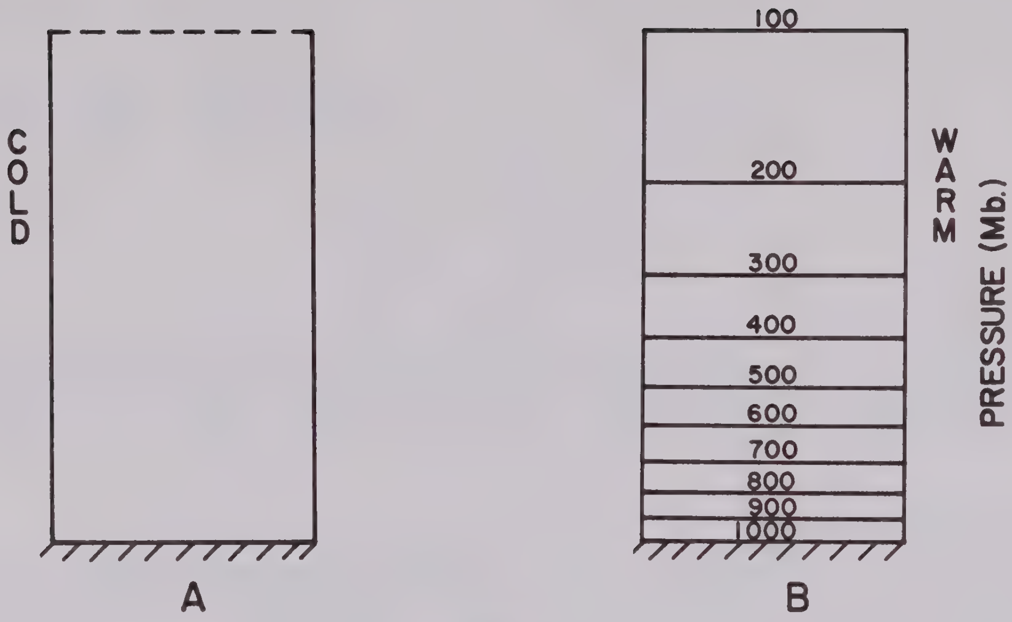


Figure 6-2

Draw in the pressure surface as you think they would appear in column A. Remember that *any* change in the heights of the pressure surfaces is proportionally shared by all the column. In other words, you should decide whether column B should be larger or smaller than column A, and then draw in the pressure surfaces accordingly. When you have done this, connect the two columns by drawing a line from the 100 mb surface of column A to the 100 mb surface of column B, etc. Now can you see that the lines you have drawn between the columns represent the constant pressure surfaces of 1,000 mb, 900 mb, 800 mb, . . . ,and 100 mb between the two points A and B? Suppose we take the same two columns of air and again the average temperature of column A is 20° colder than column B. We now measure the *height* above sea level of the constant pressure surfaces. Take the 500 mb surface for example. Suppose the height of the 500 mb surface at A is 5,400 meters and the height of the 500 mb surface at B is 5,640 meters above sea level. We could intersect the 500 mb surface with constant height levels at 60 meter intervals and note the intersection with dots (see figure 6–3.)

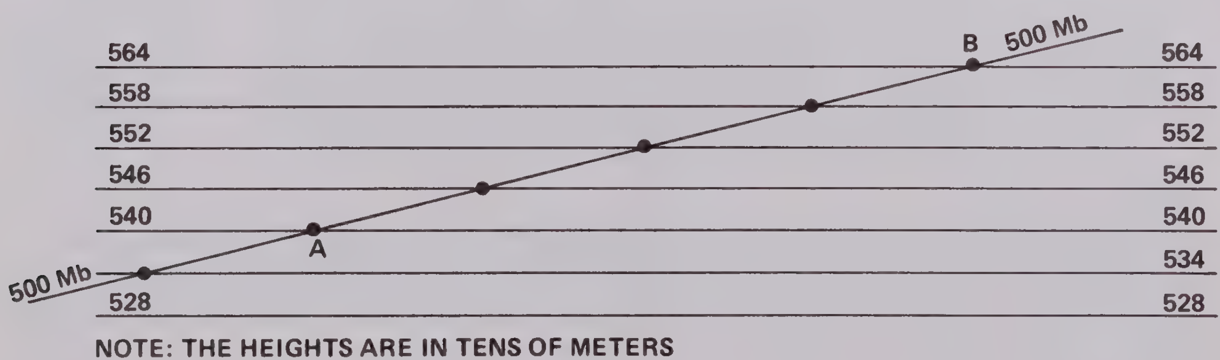


Figure 6–3

Now if we had two more stations, C and D positioned to the north of A and B respectively, and the average temperature of the column of air above C was 20° colder than A and the average temperature of the air above D was 20° colder than B, we would have something that might look like figure 6–4.

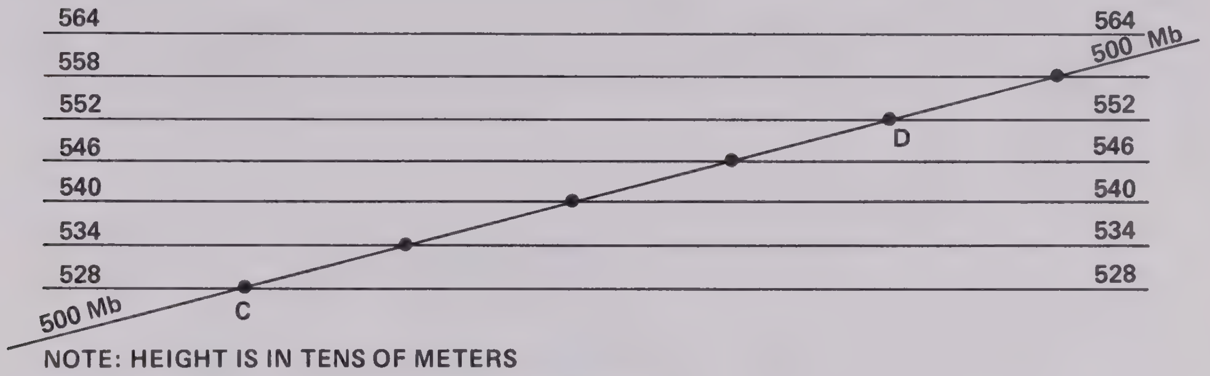
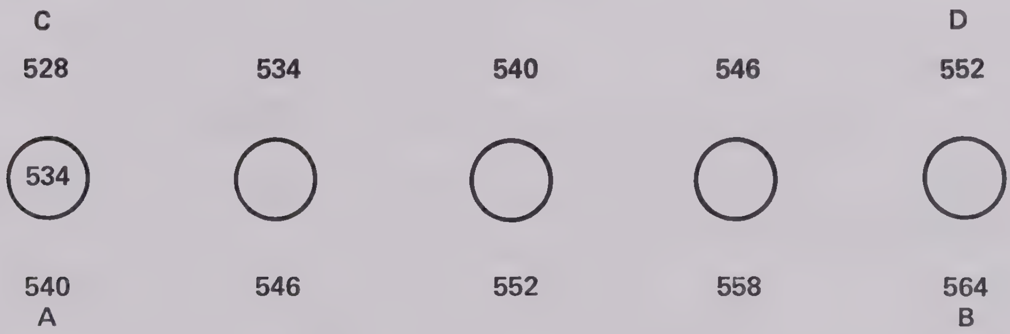


Figure 6–4

Transferring the above to a map view and plotting the heights of the "dots" we get the following field of numbers (in tens of meters).

Problem 6–2

Put in the heights of the 500 mb surface in the circles (use the data already plotted to infer the proper heights). Isopleth the field by drawing lines of constant height starting with 534 and using an interval of 6.



Problem 6–3

If the lines you drew in the field above were lines of constant height above sea level of the earth's surface (i.e., contour lines), how would you describe the surface shown above? (Give your answer in a form such as "A hill, a valley, a flat plain, a flat plain dipping to the east, etc.") It can be shown by the same analysis that the lines of intersection of constant pressure surfaces with a constant height plane are parallel to the height lines on a constant pressure surface.

For instance, figure 6–5 shows a cross section of the atmosphere showing the heights of 2 constant pressure surfaces, P_1 and P_2. The pressure of P_1 is less than that of P_2. If a line of constant height (h_1) is followed, it can be seen that the pressure is high at the start and reaches a minimum at point A′.

Following the constant pressure line (P_2) it is seen that the height is high at the start and reaches a minimum at point A (the same distance from the origin as point A′). Thus the patterns are identical.

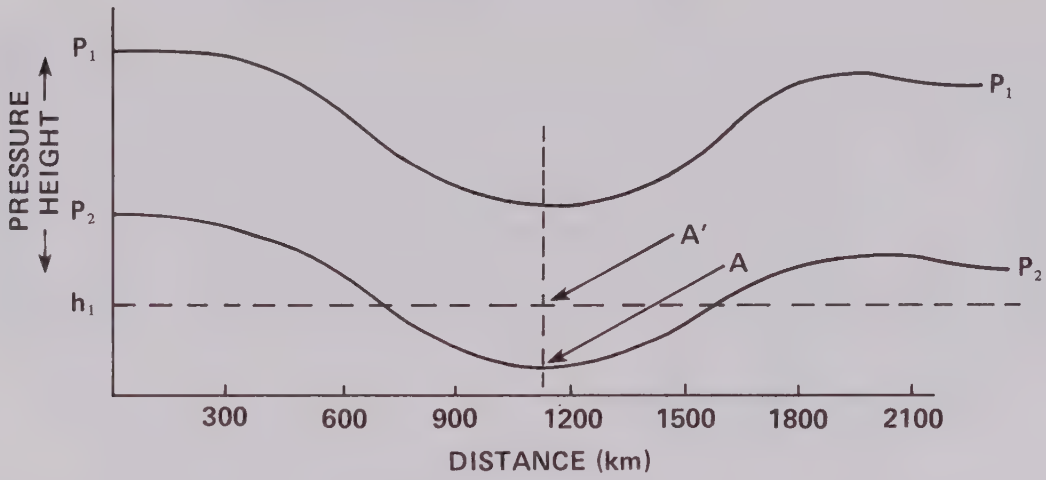
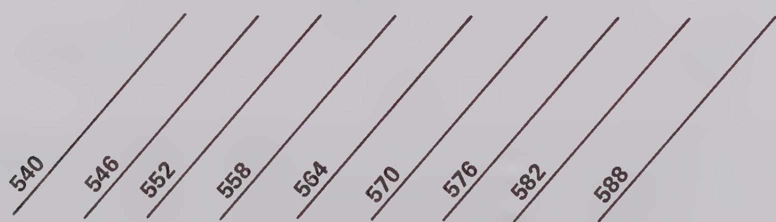


Figure 6–5

Problem 6–4

a. Given the following pressure field, draw arrows showing the direction of wind. (assume geostrophic, i.e., no friction, flow)

b. On the constant pressure surface below draw arrows showing the direction of the wind (again, assume geostrophic flow).



c. From the example, what can you say about the flow of air on a constant pressure surface as compared to a constant height surface?

Except for surface maps, meteorologists use constant pressure surfaces for weather maps. One of the several reasons for this is the fact that the difference in height between two constant pressure (or isobaric) surfaces is directly proportional to the mean temperature (adjusted for the amount of water vapor present) in the layer between the surfaces. In other words, if at any point the 600 mb layer was close to the 500 mb layer, then the mean temperature in that layer is colder than at any other point where the layers are farther apart.

Development of Troughs and Ridges in the Westerlies

If we imagine a billiard ball planet with a flat homogeneous surface, with an atmosphere having a temperature profile similar to that of the earth's, we would find that the constant pressure surfaces have a very simple orientation. Because it is colder in the north and warmer in the south, the surfaces would be closer together in the colder area and further apart in the warm equatorial zone. Taking a cross section from the North Pole to the equator and deforming it so it is flat (removing the curvature), we would get the result as shown in figure 6–6.

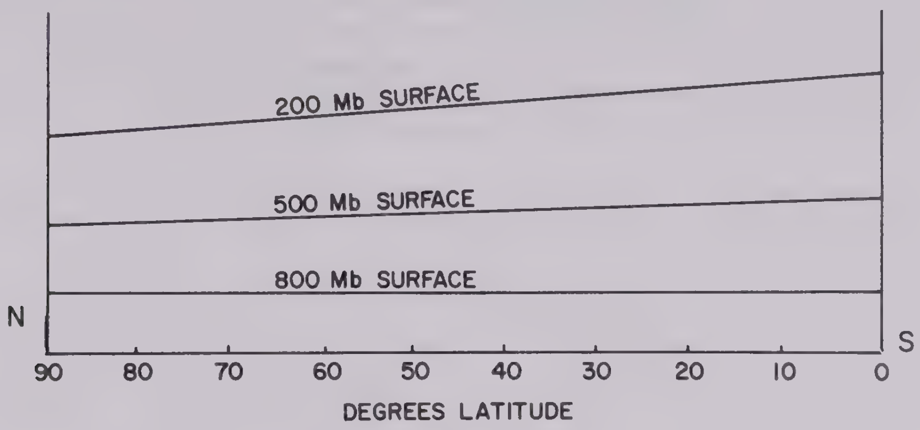


Figure 6–6

Now turning our attention to the 400 mb surface and considering it from above (i.e., a map view), we draw the height contours for the Western Hemisphere as shown in figure 6–7.

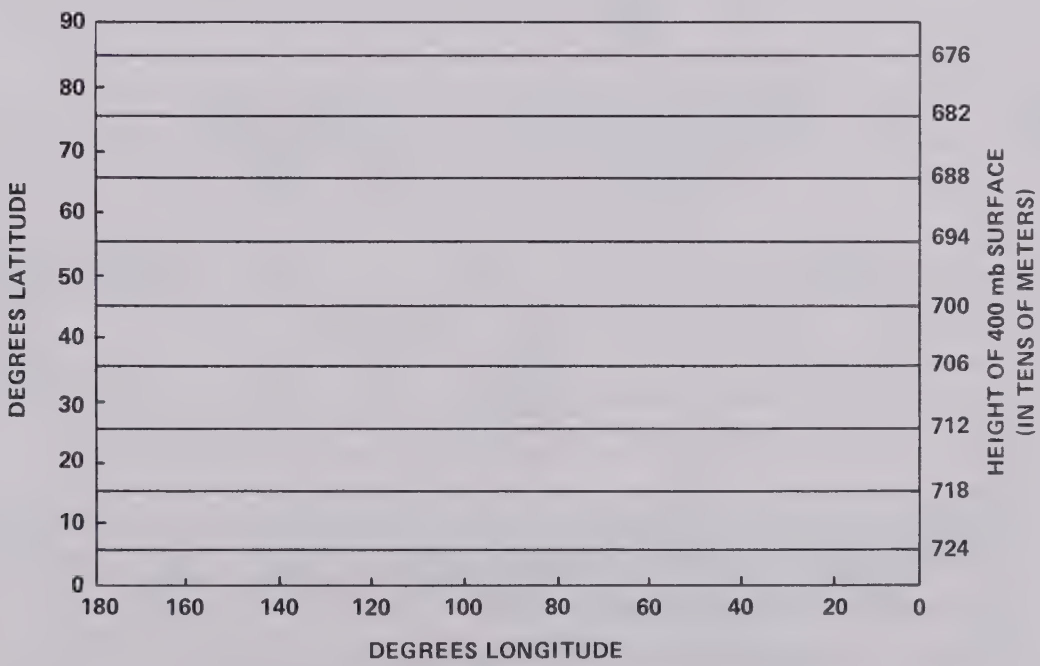


Figure 6–7

Note: The heights assigned to these lines are representative figures.

Problem 6–5

Draw arrows in figure 6–7 to show the direction of wind travel between 30° and 50° N latitude.

By adding continents and oceans to our hypothetical planet, we find some interesting patterns developing. Let's see if we can predict what these patterns would look like. If we start out with the temperature of the continents and oceans the same, our height contours would look very much like the ones drawn on the preceding map. However, when the winter season approaches, the land cools more quickly than the oceans. This can be inferred from our knowledge of our earth. In the cold months, temperatures over the continents are much colder than temperatures over the oceans. For example in February the average ocean temperatures off the east coast of North America range from 77°F near Key West to about 45°F in the New England coastal area. The temperatures in the middle of the continent are usually lower—near zero and below zero temperatures are not uncommon. From these temperature changes, we can infer that the heights of our 400 mb surface are lower over the continents than over the oceans. When we draw our height contours we would get a pattern like that shown in figure 6–8.

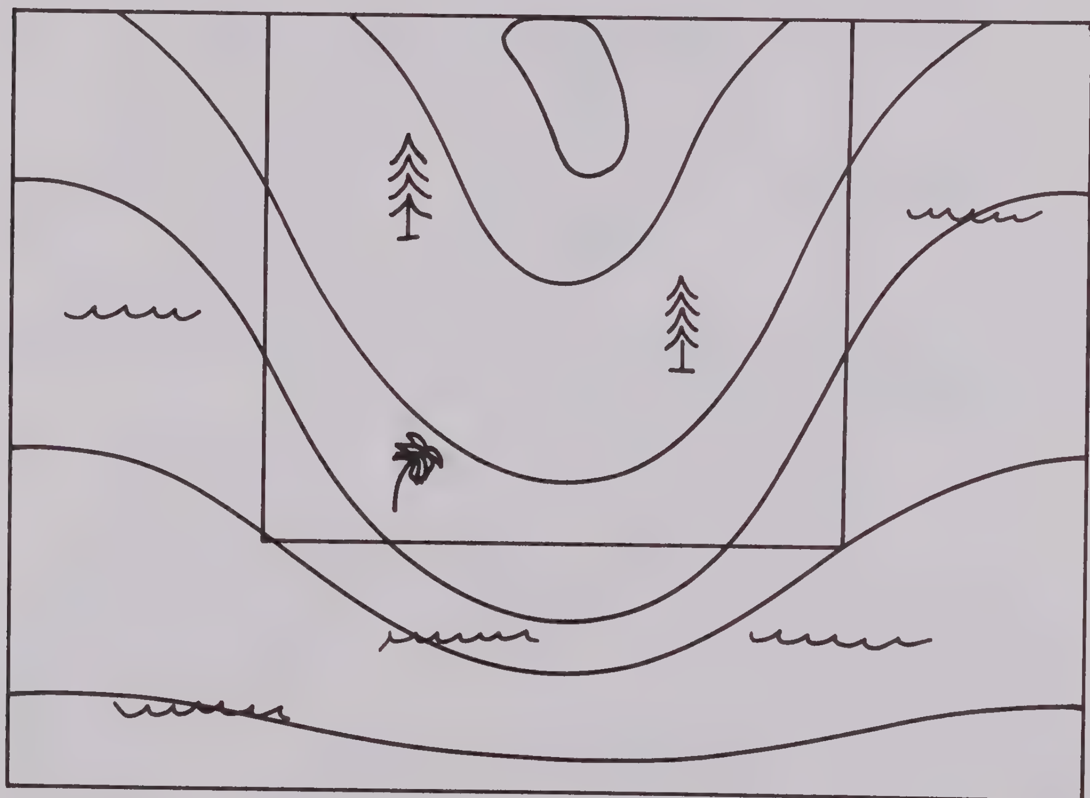


Figure 6–8

Problem 6–6

a. Draw the wind pattern in figure 6–8. (Notice that the lowest heights would correspond to the lowest pressure if the map were a constant height map rather than a constant pressure surface.)

b. Put a large "L" where the heights are lowest.

c. The wind is blowing (clockwise, counterclockwise), in the vicinity of the low.

The low area is called a "trough" on a constant pressure surface and the highs are called "ridges."

d. Mark the ridge(s) by putting an "H" where appropriate.

The Gradient Wind Concept

Where the geostrophic wind was discussed, you will remember that we only used the pressure gradient force and the Coriolis force in balance to produce our frictionless, unaccelerated wind. In an attempt to model the observed upper air winds more closely, meteorologists have turned to the *gradient wind,* which allows the curvature of flow to be taken into account.

The gradient wind is like the geostrophic wind in that it is frictionless, but it is not unaccelerated. There are two forces *not* in balance. The difference, directed inward, is the centripetal force, and is the force that makes the air turn in a circle.

The same forces act on the gradient wind as on the geostrophic wind. But, in the case of the gradient wind, the pressure gradient and Coriolis forces are not balanced. It is the imbalance of these two forces

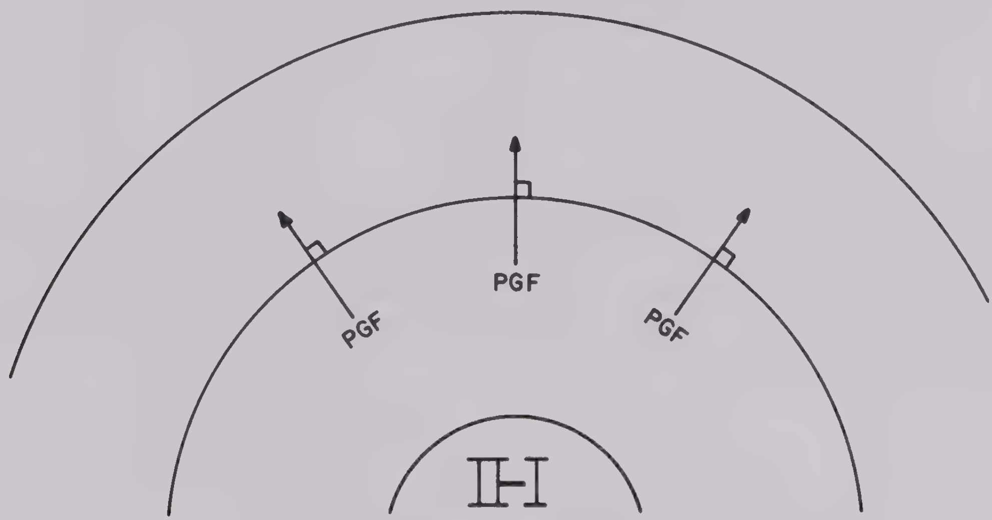
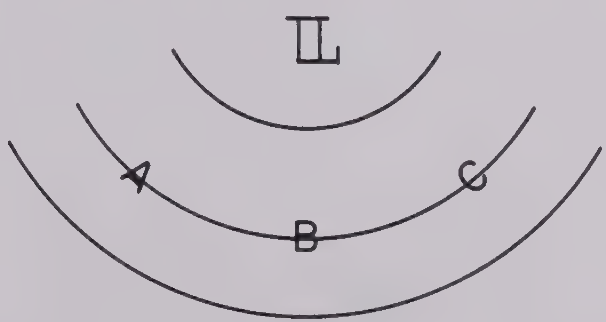


Figure 6-9

that cause the wind to curve in its flow. When height contours (and isobars) are curved, the pressure gradient force acts at right angles to the contours and is directed from high to low pressure. The arrows in figure 6–9 above indicate the direction of the pressure gradient force.

Problem 6–7

Draw in the pressure gradient force at points A,B, and C in this low pressure trough:



If we consider a parcel of air moving around a ridge on the 400 mb pressure surface and analyze the forces acting on that parcel, we can see just how the air is forced into a curved flow pattern. Because of inertia, a parcel of air in motion tries to move in a straight line (see figure 6–10).

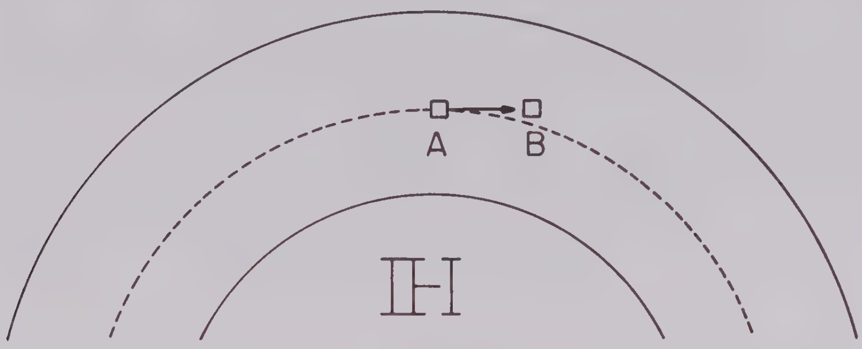


Figure 6–10

(To prove this to yourself, tie a weight to a piece of string. Swing the weight around your head. When you release the force—i.e., the string—what happens to the weight? Does it continue to curve around your head? Does it go in a straight line tangent to the circle?) Let's assume a parcel of air is moving in a straight line tangent to an arc midway between two contours on the 400 mb surface. Allowed to do this, the parcel moves away from the midpoint line (the dotted line in figure 6–10) and goes from point A to point B. Now let's examine the forces that are acting on the parcel at point B. Figure 6–11 is a blow up of point B in figure 6–10.

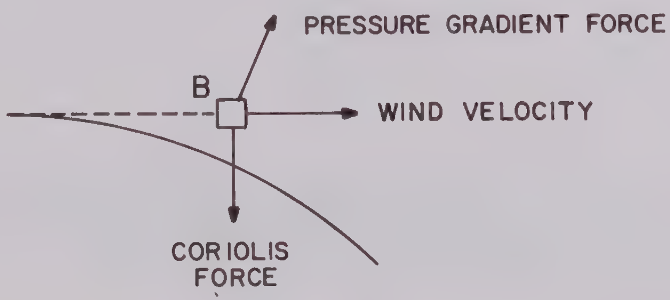


Figure 6–11

Note that the pressure gradient force has a component toward the direction of flow. This force has a net effect of increasing the velocity of the wind and thus increasing the Coriolis force. The increased Coriolis force acts on the wind and causes it to bend to the right so as to be once more parallel to the contours (figure 6–12).

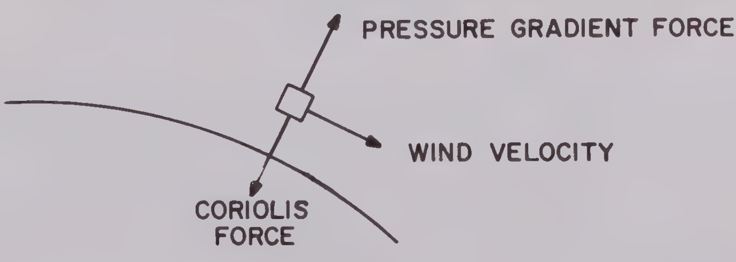
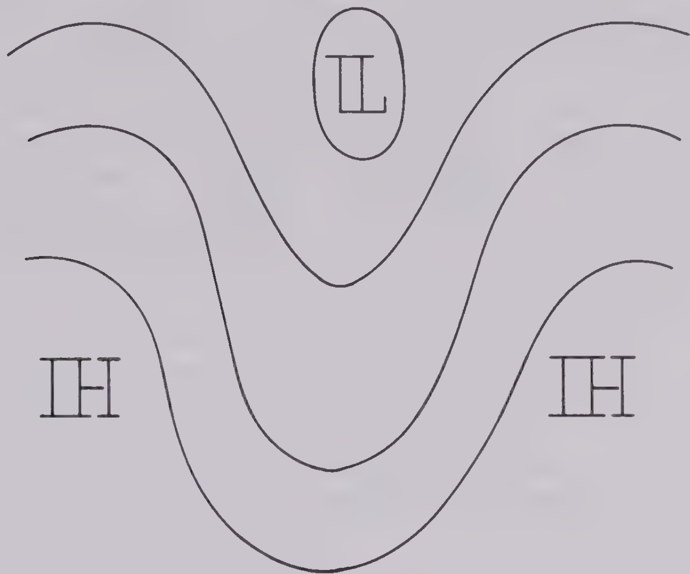


Figure 6–12

Because the wind is *faster* than the geostrophic wind would be for the same contour spacing, it is said to be *supergeostrophic*.

Problem 6–8

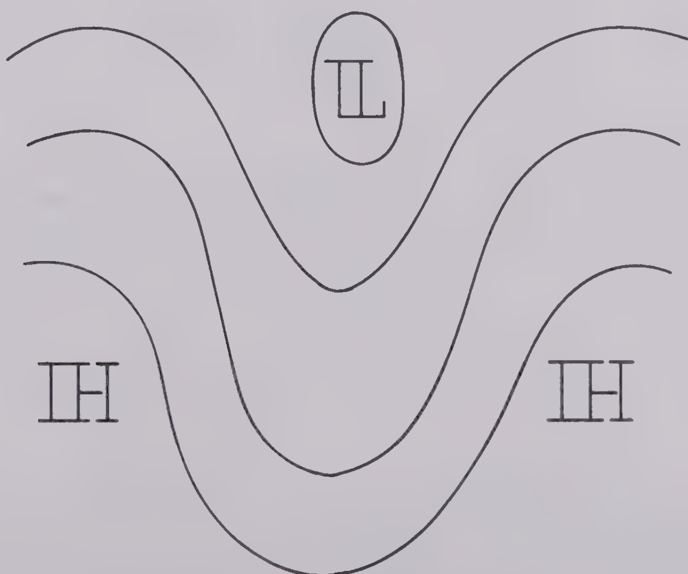
a. Here is a low pressure trough. Show how the forces would act on a parcel moving from left to right around the trough. Draw a figure similar to figure 6–11.



b. Is the flow supergeostrophic? Subgeostrophic?

Problem 6–9

Here is a typical long wave as it appears at 400 mb in the westerlies. Draw a circle around the area(s) of *supergeostrophic* flow and label them (it) with a plus. Draw a circle around area(s) of *subgeostrophic* flow and label them (it) with a minus sign. Label any areas of geostrophic flow with a zero.



Convergence and Divergence Aloft

If a superhighway is filled to capacity with traffic, all moving at the same speed—say 55 mph—and someone has to stop because of a blowout or a breakdown of some sort, what happens? Well, the slight constriction of one lane being blocked in the highway causes the whole traffic stream to back up. When this happens, the speed of the traffic upstream from the obstruction is limited to that speed at which the cars can bypass the stalled vehicle. Downstream, the traffic speeds up and the stream of cars becomes more stretched out and the cars are not as densely packed.

With this analogy in mind, let us turn our attention to the diagram in question 9. Here we have the air at the ridge blowing faster than the air in the trough. Between the two, we have converging parcels of air. In other words, the faster moving air parcels are moving into an area of slow moving ones. Unlike our highway, the 400 mb surface pictured here is not a solid surface and the air parcels can move in three dimensions. This allows the parcels to move in a vertical direction as well as horizontal ones. In the upper atmosphere then, the convergence causes the air parcels to be "squeezed" away from the area of convergence. Looking at the "stretched-out" or *divergent* pattern on the other side of the trough, we find just the opposite effect. Here, the air parcels are rising from lower levels to try to "fill in" the space caused by the "stretching out" of the parcels (just as the automobiles became more widely separated past the obstruction). Figure 6–13 is a side view of this. Notice that at the surface we have air *diverging* at the left of the diagram and *converging* at the right of the diagram. What kind of pressure pattern would you expect to find where there is convergence at the surface? What type of pattern would you expect to find where there is divergence at the surface?

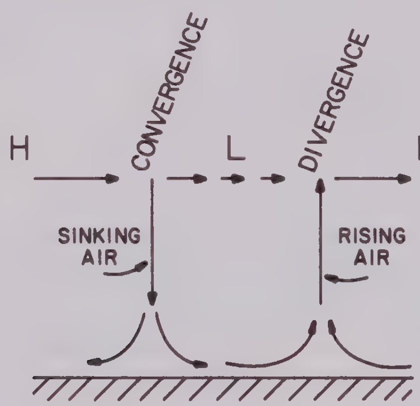
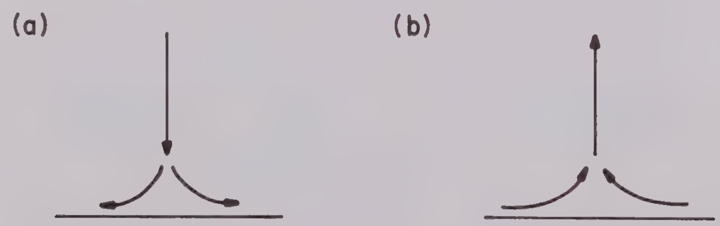


Figure 6–13

Problem 6–10

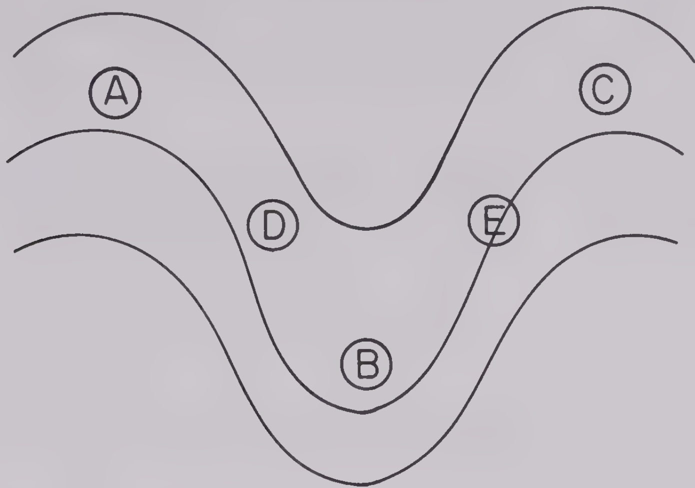
Label these diagrams as either low or high pressure systems by placing the appropriate letter on each one.



Putting this all together, we can see that where there is divergence aloft, there is convergence at the surface and where there is convergence aloft, there is divergence at the surface.

Problem 6–11

Referring to the map of the 400 mb surface below, answer the following questions.



a. the surface low would be found under point ____________.

b. downward flowing air would be found at point ____________.

c. the air is (faster, slower) at point A than at point B ____________.

d. point(s) ____________ are called ridge(s).

e. point(s) ____________ are called trough(s).

It is obvious from weather charts that the trough at upper altitudes is to the west of the surface low. This would indicate that the trough is inclined to the west as altitude is increased. To see how this looks, consider figure 6–14.

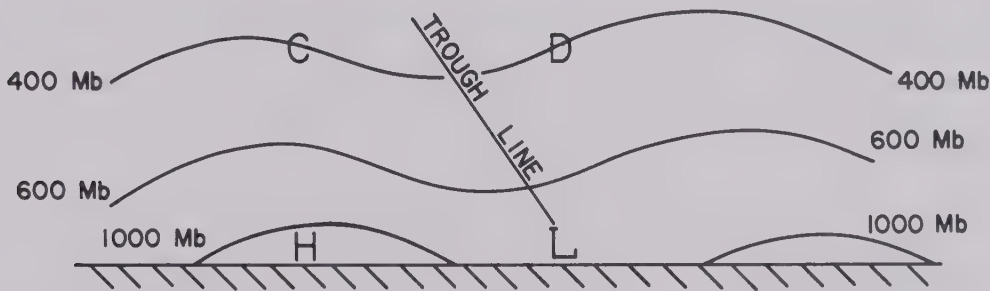


Figure 6–14

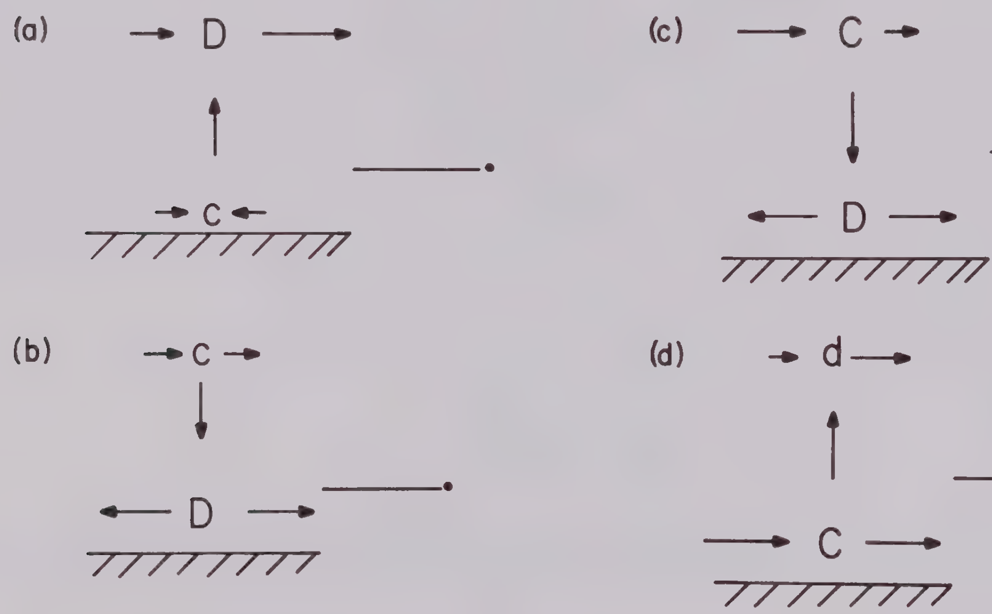
Notice that the convergence and divergence are positioned over the surface high and low.

Cyclogenesis

For any low pressure system to persist, there must be a mechanism for extracting mass from the column of air above the geographical position of the surface low. Because there is a constant influx of air from the regions of higher pressure surrounding the low pressure system, the only way the system can continue to exist over a period of time is to have more (or at least as much) mass (air) leaving the upper portion of the column than is coming in from the sides at lower levels. If the divergence in the upper troposphere is very strong, the convergence at the surface will increase until as much air is coming in at the bottom as is flowing out of the top. Likewise, if the divergence should weaken, then the incoming air will "fill up" the low, thus reducing the pressure gradient (and therefore the wind speed) so that the system will once more be in equilibrium with lower pressure in the system greater than it was before.

Problem 6–12

In this exercise, an upper case letter indicates strong convergence or divergence and a lower case letter indicates weak convergence or divergence. In each of the situations pictured below, forecast whether the *surface* system will strengthen, weaken, or remain steady for the next few hours.



The life cycle of an extratropical cyclone in the Northern Hemisphere can be depicted as is done in figure 6–15a, b, c, and d.

a. We start out with a weak trough in the westerlies. If there is a front extending northeast—southwest to the east of the trough, then the stage is set for the formation of a cyclone (cyclogenesis).

Figure 6–15a

b. The trough deepens and the divergence aloft east of the trough line causes a low pressure area to form on the front.

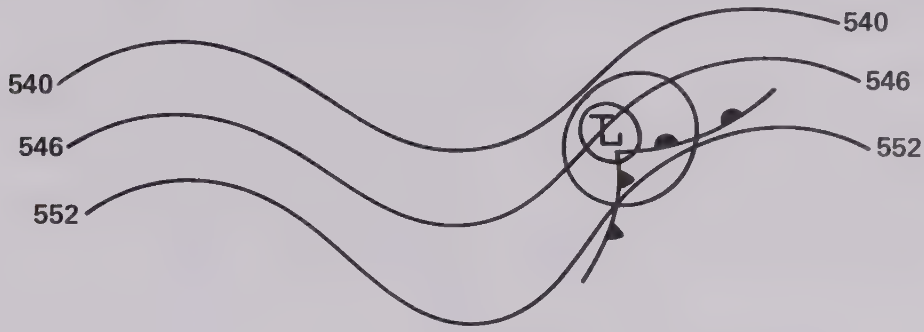


Figure 6–15b

c. As the trough continues to deepen, divergence aloft increases, deepening the surface low, and in an attempt to reach equilibrium, the surface convergence also increases.

Figure 6–15c

d. Propelled along by the "steering winds" (the wind flow in the vicinity of the 500 mb pressure surface), the storm moves northeastward. As it matures, it occludes—see exercise 6 for a review of this concept—and moves out from beneath the area of strongest divergence aloft.

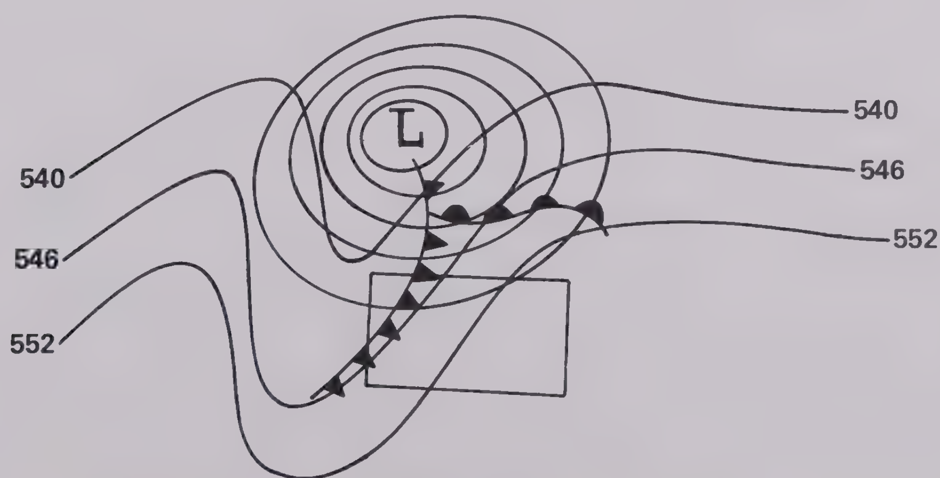
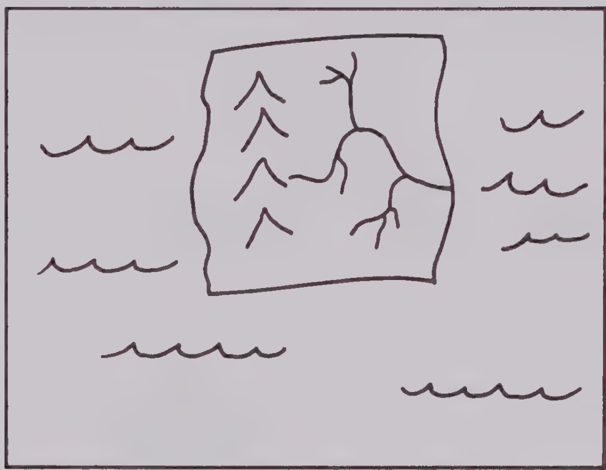


Figure 6–15d

At this point the storm is dying, but the area in the box is in a favorable position for a new storm to develop. As long as the trough remains in the same position relative to the front, one, two, or perhaps a family of storms will be spawned, move northeastward, mature, and finally dissipate.

Problem 6–13

On the simplified map below of a continent surrounded by an ocean, draw in the likely positions of long wave ridges and troughs in the westerlies (assume that it is winter). Draw an "L" in red to indicate where you would expect cyclogenesis.



Summary

In this exercise you have been introduced to the concepts of upper air flow and cyclogenesis. You should be familiar with the gradient wind, its relationship to the geostrophic wind, and its contribution to the convergence and divergence fields in the upper atmospheric flow. You should also understand how the surface weather patterns are connected to the convergence and divergence fields aloft.

The basic principles introduced in this exercise should enable you to better interpret the weather depictions in newspapers or on television. And if you understand these concepts, you will know a good deal more than the commentator who merely reads the forecasts.

VORTICITY AND DIVERGENCE

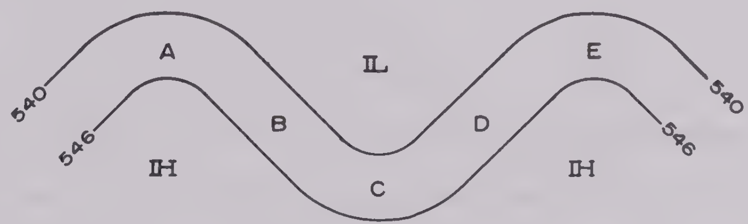
In the previous exercise, the effects of convergence and divergence on the surface pressure were discussed. It is clear that in order to estimate the amount that pressure will rise or fall at a given location during some future time, it is necessary to estimate accurately the net convergence or divergence of mass in a column above the location during that time period.

Because it is extremely difficult (if not impossible) to measure mass convergence (or divergence) with any degree of accuracy, a method had to be found which linked convergence and divergence to something that could be measured. Meteorologists discovered that the "spin" of the air could be related to convergence and divergence of the atmosphere. This "spin" is measured about a vertical axis and is called *vorticity*.

The Greek letter zeta (ζ) is used to represent vorticity. When the air is spinning in a counterclockwise manner in the northern hemisphere (as viewed from above) ζ is greater than zero (positive) and when it is spinning in a clockwise manner, ζ is less than zero (negative). If the flow is straight (no spin), there is no vorticity and ζ is equal to zero.

Problem 7–1

On the 500 mb chart below, evaluate the sign of ζ (positive, negative, or zero) at each point denoted by a letter. Label the points with a +, −, or 0 as appropriate.



Problem 7–2

a. Refer to the diagram in problem 7–1, and make the following matches.

1. Cyclonic flow	a. $\zeta < 0$
2. Anticyclonic flow	b. $\zeta = 0$
3. Straight flow	c. $\zeta > 0$

(note: > means "greater than" and < means "less than")

b. Surface lows have (positive, negative) vorticity.

c. Surface highs have (positive, negative) vorticity.

Problem 7–3

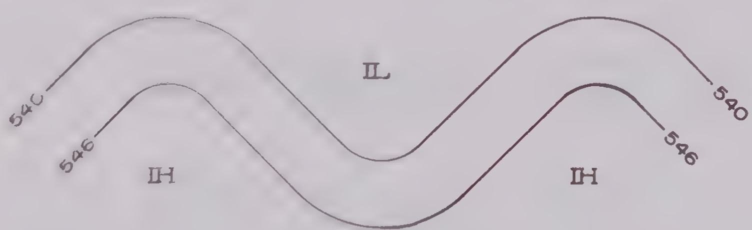
a. As a parcel of air moves from point A (on the diagram in problem 7–1) to point C, how does the vorticity of the parcel change?

b. How does the parcel's vorticity change as it moves from C to E?

Now look back to Exercise 6, Upper Air Flow, and review the areas of convergence and divergence with respect to the ridge and trough lines on a 500 mb wave.

Problem 7–4

Put a (−) where you would expect convergence and a (+) where you would expect divergence. (Note that convergence is considered to be the negative of divergence.)



Pausing for a moment to gather up all of the pieces, you should have discovered the following patterns:

1. As ζ increases with time following the parcel, air converges and as ζ decreases with time air diverges.
2. This can be explained by the following qualitative relationship:

$$\frac{\text{Change in vorticity}}{\text{Change in Time}} = -\text{ Divergence} \ .$$

In other words, if $\frac{\Delta\zeta}{\Delta t}$ (following the parcel) is positive, the air is converging (negative divergence). Also, if $\frac{\Delta\zeta}{\Delta t}$ is negative, then the air is diverging. A simple analogy is that of a skater spinning on ice. If the skater brings his/her hands closer to the axis of spin (i.e., convergence), the rate of spin (the vorticity) increases. As the hands move away from the axis of rotation (divergence) the rate of spin decreases.

3. Quantitatively, the more negative the vorticity becomes in a given time interval following the parcel as it flows through the wave, the greater the divergence of mass. Likewise the more positive the vorticity becomes in a given time interval, the greater the convergence of mass.

While the divergence of mass in the atmosphere cannot easily be measured, the vorticity, or spin, of the air can be calculated from wind measurements. These values can be plotted on a map and analyzed. Figure 7–1 is a map showing the 500 mb height contours as solid lines and contours of vorticity as dotted lines. This map is produced by the National Weather Service twice daily at 0000 Greenwich Mean Time (GMT) and 1200 GMT. These times correspond to 7 P.M. (EST) the night before and 7 A.M. EST, respectively.

The time system used in meteorology is Greenwich Mean Time (GMT), also known as Universal Time, Zulu Time or Z time. It is the time as measured on the prime meridian which runs through Greenwich, England. There is no A.M. or P.M. when using this time system. Rather, time is measured in units, tens, hundreds and thousands of hours with 0000 Z being midnight in Greenwich, England, 0600 Z is 6:00 A.M., 1200 Z is noon, 1800 Z is 6:00 P.M. and 2359 Z is one minute before midnight. To convert from Z time to Eastern Standard Time (EST) one must use the equation: EST = GMT − 500 hours. To convert to Central, Mountain or Pacific Standard Time subtract 600, 700 or 800 hours, respectively. Here are some examples:

1200 Z = 0700 EST = 7:00 A.M. EST
1820 Z = 1320 EST = 1:20 P.M. EST
2030 Z = 1530 EST = 3:30 P.M. EST
2300 Z = 1800 EST = 6:00 P.M. EST
0500 Z = 0000 EST = 12:00 A.M. EST

The last two examples may confuse you. To convert to EST from 0000, 0100, 0200, 0300 or 0400 Z when subtracting 500 hours the calculation goes past midnight into the previous day.

In meteorology it is the practice to abbreviate time on the hour to just the important digits. This is usually true for both writing and speaking. For example, instead of writing 1200 Z or saying "twelve-hundred Z" one would simply write 12 Z and say "twelve Z;" instead of 0200 Z, "zero-two-hundred Z," it would be 2 Z and "two Z."

So far the discussion has been limited to the spin of the air relative to the earth. This is called the "relative vorticity." However, the ground itself has spin caused by the rotation of the earth. This is numerically equal to the coriolis factor, f, which is expressed as:

$$f = 2\Omega \sin\phi$$

where Ω is the rotation of the earth in radians/second and ϕ is the latitude. Numerically, Ω is equal to 7.29×10^{-5} radians/sec, or .0000729 radians/sec.

Problem 7–5

Calculate the value of f for the following latitudes. The sin of each latitude is supplied.

	Latitude (ϕ)	**Sin ϕ**	**f**
a.	0°	0.0000	
b.	30°	.5000	
c.	45°	.7071	
d.	60°	.8660	
e.	90°	1.0000	

Absolute vorticity (ζ_a) is equal to the sum of the relative vorticity (ζ_r) and the coriolis parameter (f):

$$\zeta_a = (\zeta_r + f) \ .$$

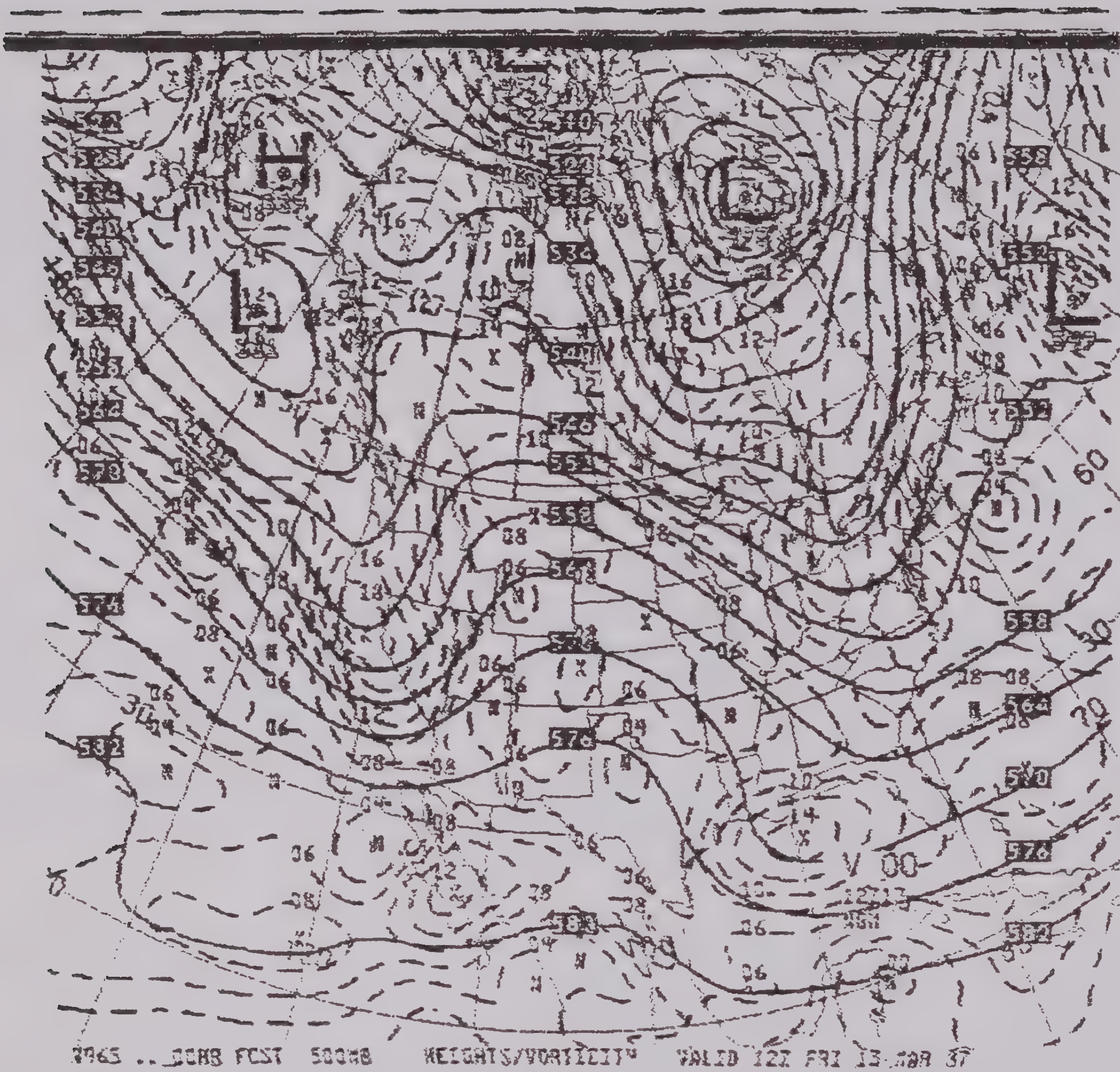


Figure 7–1. NGM analysis of 500 mb heights in decameters (———) and absolute vorticity × 10^{-5}/sec (----) for 12 z Friday, 13 March.

Problem 7–6

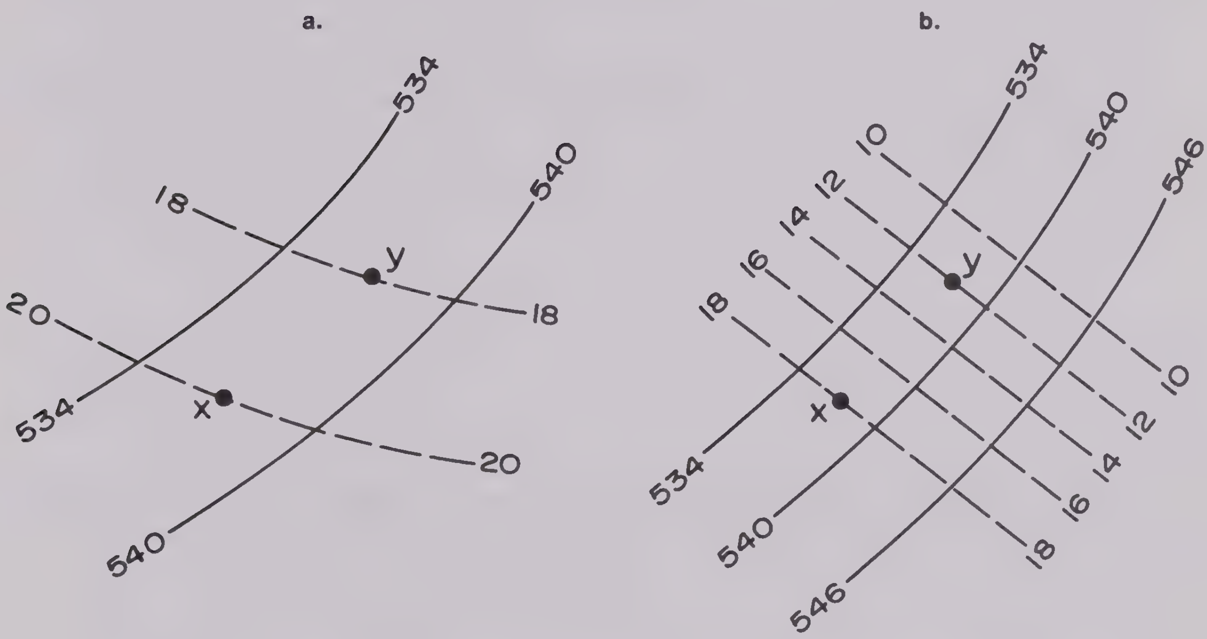
Assume a latitude of 45°N (sin 45 = .7071) and calculate the absolute vorticity (ζ_a) for each of the following relative vorticities:

	ζ_r	f	ζ_a
a.	2.3×10^{-5}/sec		
b.	-2.3×10^{-5}/sec		
c.	8×10^{-5}/sec		
d.	-4×10^{-5}/sec		

It should be noted here that except for the most unusual circumstances, ζ_a is positive. That is, even though ζ_r can be negative, f is always positive and of sufficient magnitude to make ζ_a always positive. Thus, in figure 7–1, the lines of equal vorticity are isopleths of absolute vorticity (ζ_a) and all values are positive. Notice that on the map in figure 7–1, some combinations of the solid contour lines and the dashed isopleths of constant ζ_a form polygons of various sizes.

Problem 7–7

a. In figure 7–2a, below, note that the solid contour lines are farther apart than the contour lines in figure 7–2b. In which figure are the winds the fastest? Why? (Note that as the contours are closer together, the pressure gradient, and hence the wind speed, increases.)



Figures 7–2a & b. Solid lines are 500 mb height contours, labeled in decameters and dashed lines are isopleths of absolute vorticity $\times$ 10 ^{5}/sec.

b. In figure 7–2b the dashed lines of constant vorticity are closer together than in figure 7–2a. If a parcel of air travels from x to y in figure 7–2a, how much does the vorticity change? (Remember that the units are given in 10^{-5}/sec, so that a line of constant vorticity labeled 18 is really 18×10^{-5}/sec.)

If a parcel were to travel from x to y in figure 7–2b, how much would the vorticity change?

c. If the distance xy is 100 km in both figures, the wind speed in figure 7–2a is 40 m/sec, and the wind speed in figure 7–2b is 60 m/sec, what is the rate of change of vorticity in each case? Remember that

$$\frac{\triangle \zeta_a}{\triangle t} = \frac{\zeta_a \text{ at y} - \zeta_a \text{at x}}{\text{time for parcel to travel xy}}\text{; and the time} = \frac{\text{Distance}}{\text{Speed}}$$

d. In both cases you would expect divergence/convergence. In which case would the divergence or convergence be the greatest?

e. What conclusions can you draw relating the size of the "boxes" and the amount of vorticity change with time?

Problem 7–8

In exercise 6, the relationship between the divergence (or convergence) of mass aloft and pressure change at the surface was introduced. State that relationship in two or three concise sentences.

Problem 7–9

Now summarize the relationship of the change of vorticity with time and the change of pressure at the surface. Limit your answer to about 100 words. (Include the relationship between the rate of change of vorticity and divergence and the relationship between divergence and surface pressure change.)

USE OF THE 500 mb HEIGHTS / VORTICITY MAP

This exercise is a continuation of Exercise 7. In that exercise, you were introduced to the relationship of the rate of change of the vorticity of a parcel with time and its relationship to the mass convergence or divergence in a column of air above a particular surface location. An important assumption is that a parcel of air remains between two adjacent contours from west to east as it moves across the earth. Thus, as the parcel moves through the wave(s) depicted on the 500 mb map, its vorticity will change as the curvature of the contours changes. In this exercise you will learn how to evaluate the relative amounts of vorticity change, following a parcel, by using the maps produced by the Nested Grid Model (NGM) of the National Weather Service.

In figure 8–1a, below, note that a maximum value of vorticity is depicted by the letter x and minimum value of vorticity by the letter n. The values of isopleths of vorticity are in units of 10^{-5}/sec and the contours are in decameters (dam). Thus, a vorticity isopleth labeled 18 is 18×10^{-5}/sec and a contour line labeled 570 is 5700 meters above mean sea-level.

Problem 8–1

If a parcel of air travels from A to B along the designated path (just to the south of the 546 contour in the Great Lakes Region in figure 8–1a), how will its vorticity change with time? (A solid line has been drawn at the trough axis. Notice that as the trough axis is passed, the sign of the vorticity change reverses.) Do not try to calculate the amount, just describe what happens.

The contours on a 500 mb map are the result of the sum of a number of waves of varying wave lengths. The most obvious wave in figure 8–1a is the wave with a ridge line along the west coast of the United States and a trough line on the Utah–Colorado border; a ridge line to the east of the trough is less obvious, however. The trough line across the Great Lakes referred to in problem 8–1 is part of a wave of much shorter wave length. These waves are called "short waves" by meteorologists. This short wave has become superimposed on the longer wave and has obscured the features of that longer wave.

Short waves travel from west to east in the upper air flow and the shorter the wave length, the faster the west to east progress. In other words, short waves *move through* the waves with longer wave lengths.

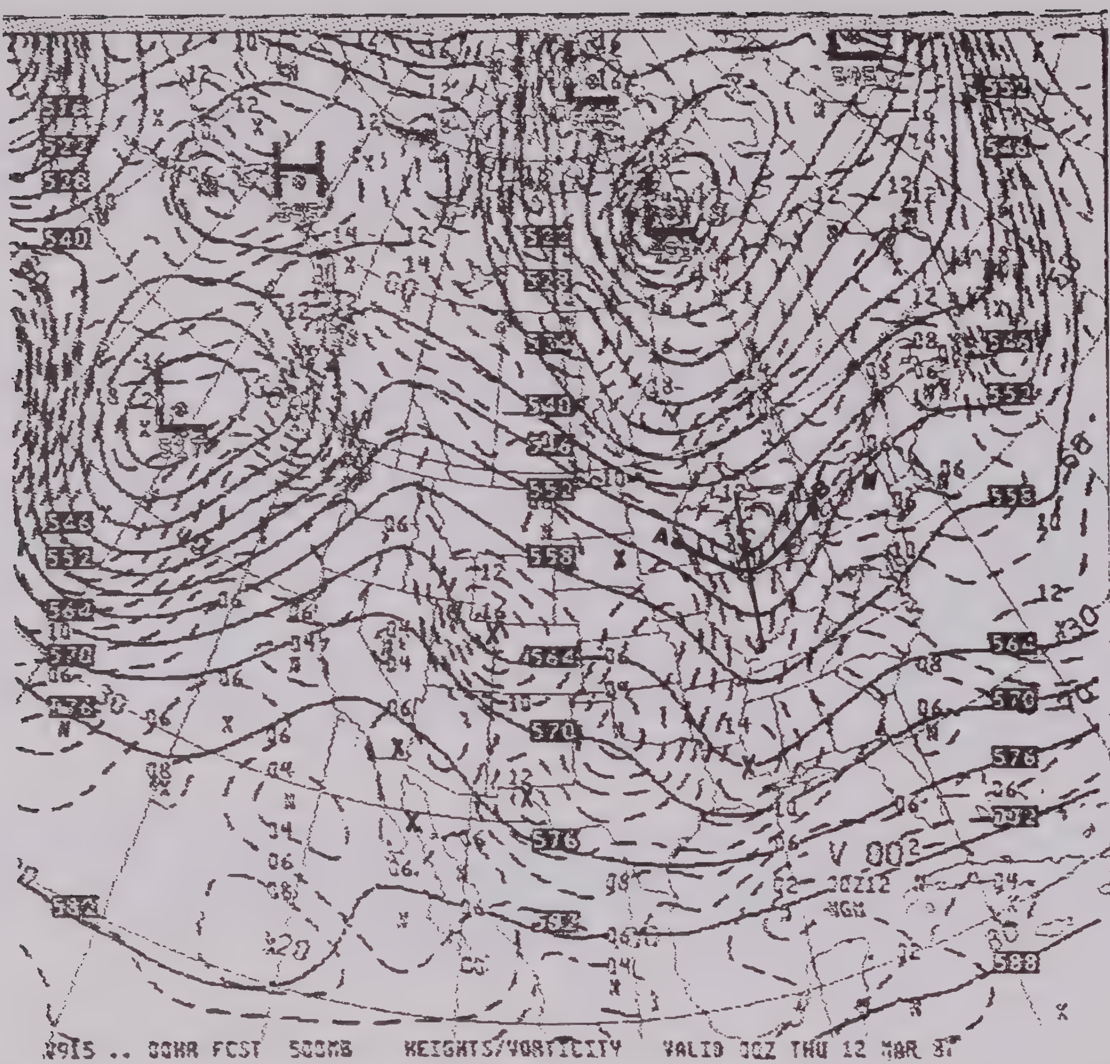


Figure 8–1a. NGM analysis of 500 mb heights in decameters (———) and absolute vorticity × 10^{-5}/sec (----) for 00 z Thursday, 12 March.

While the short wave over the Great Lakes is of sufficient magnitude to change the shape of the 500 mb contour field, other short waves are made evident only by an inspection of the vorticity field. For example, the vorticity maximum in Mexico (just south of El Paso, Texas) seen in figure 8–1a does not alter the 576 contour line to as great an extent as the 546 contour line is altered in the Great Lakes area. Identification of the short wave in Mexico is more easily inferred by the vorticity isopleths.

Problem 8–2

In the diagram on page 100, there are graphs of three waves of different wave lengths and amplitudes. The first wave (Wave 1) in this idealized situation is a stationary wave in mid-latitudes; the second wave (Wave A) is a short wave traveling through the stationary wave.

a. Add (or subtract, as necessary) the amplitude of the short wave to that of the longer wave for each of the points on the graph. Plot the new points on the same graph as Wave 1. Connect the points with a red line. The first three points have been plotted for you.

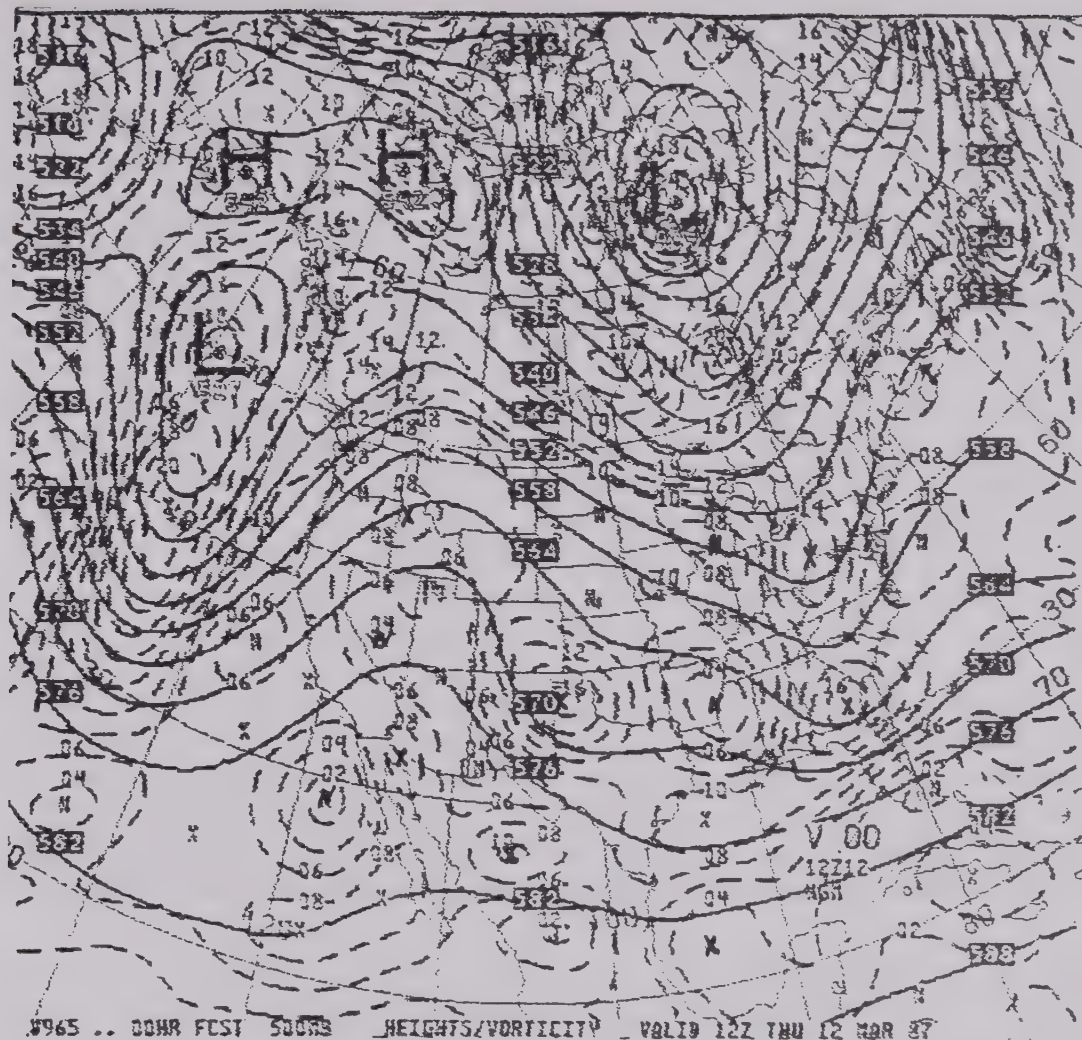


Figure 8–1b. NGM analysis of 500 mb heights in decameters (———) and absolute vorticity × 10^{-5}/sec (----) for 12 z Thursday, 12 March.

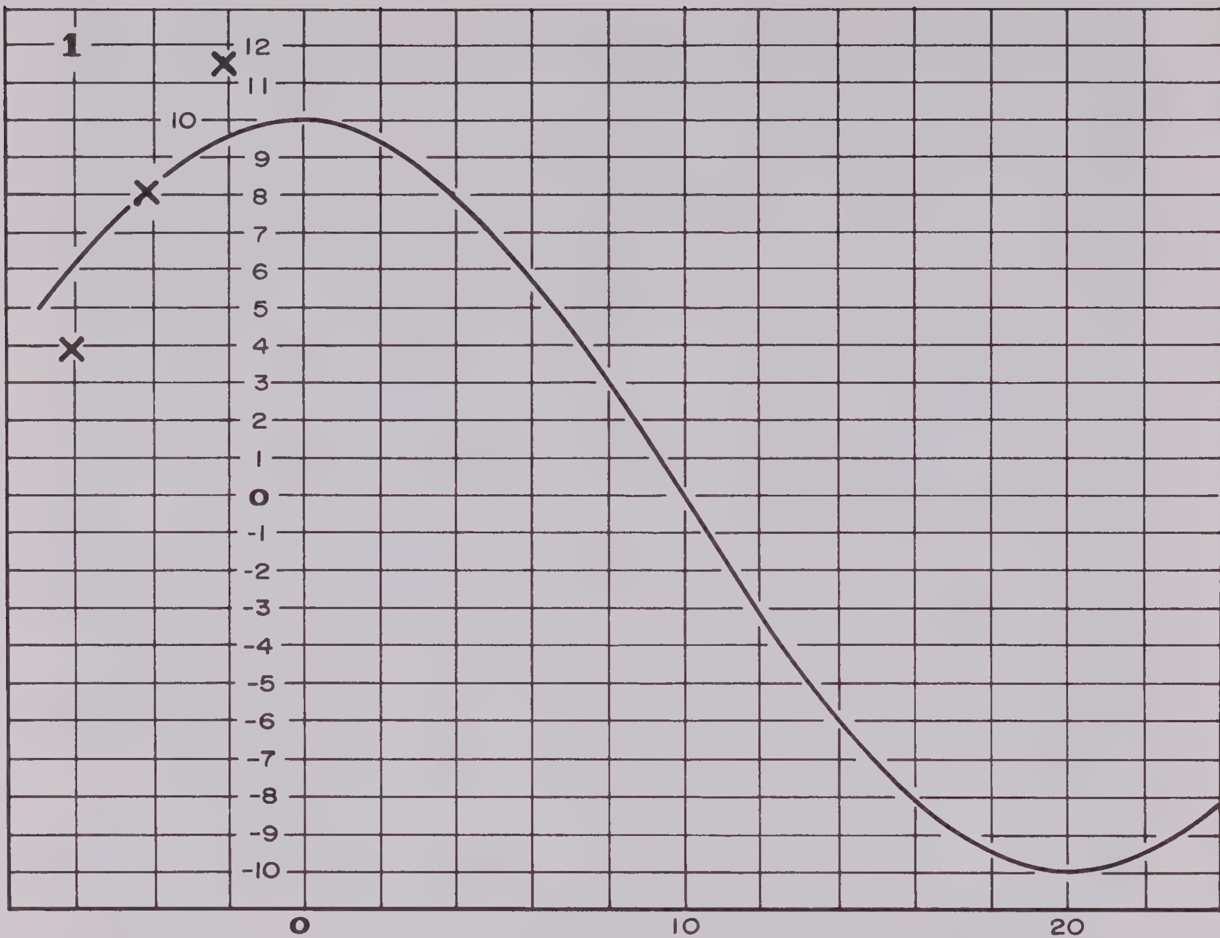
b. Wave B is the position of Wave A at some later time. Add (or subtract) the amplitude of Wave B to that of Wave 1 as was done with Wave A in a) above and connect the points with a blue line.

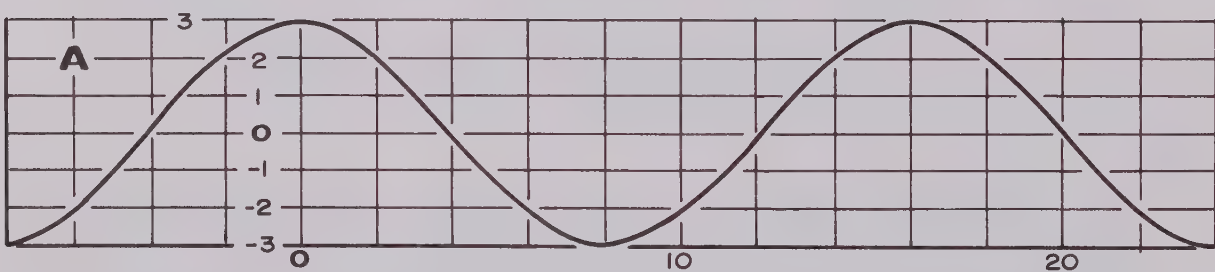
c. The red line and the blue line represent what the wave contours would look like at 2 different times. What will be the value of the combined waves at 20° on the longitude scale at some future time when the two troughs coincide?

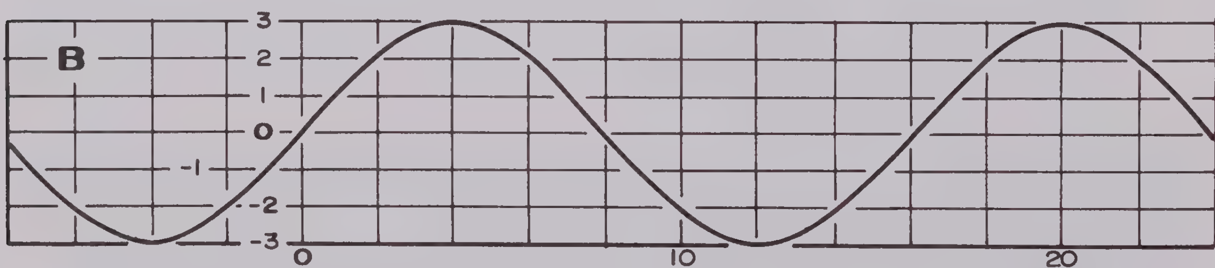
Problem 8–3

Figure 8–1b is an analysis of the 500 mb height/vorticity for 12Z, Thursday, 12 March, 1987. This map time is 12 hours later than that in figure 8–1a.

a. Where is the vorticity maximum located which was in Eastern Utah at 00Z, 12 March?


1
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
10
20


A
3
2
1
0
-1
-2
-3
0
10
20


B
3
2
1
0
-1
-2
-3
0
10
20

b. Keep in mind that short waves move faster than long waves. Can you explain where the vorticity maximum came from that is in Georgia at 12Z?

c. Where would you expect the vorticity maximum in problem 8–3b, above, to be located in 12 hours, i.e., at 00Z Friday, 13 March?

Problem 8–4

Refer to figure 8–2.

a. Draw a line from the vorticity maximum ("X") in northeastern corner of Kansas to the vorticity maximum south of Lake Superior. Then, connect that vorticity maximum to the one directly south of Hudson's Bay.

b. How does vorticity change with time following a parcel to the right (downwind) side of the line you have drawn in 8–4a? (Answer 8–4b and c in a qualitative sense as you did in Problem 8–1.)

c. How does vorticity change with time to the left of the line as you follow a parcel from left to right through the wave?

d. Where would you expect areas of convergence? Divergence?

e. What changes of surface pressure would you expect with time in the lower peninsula of Michigan?

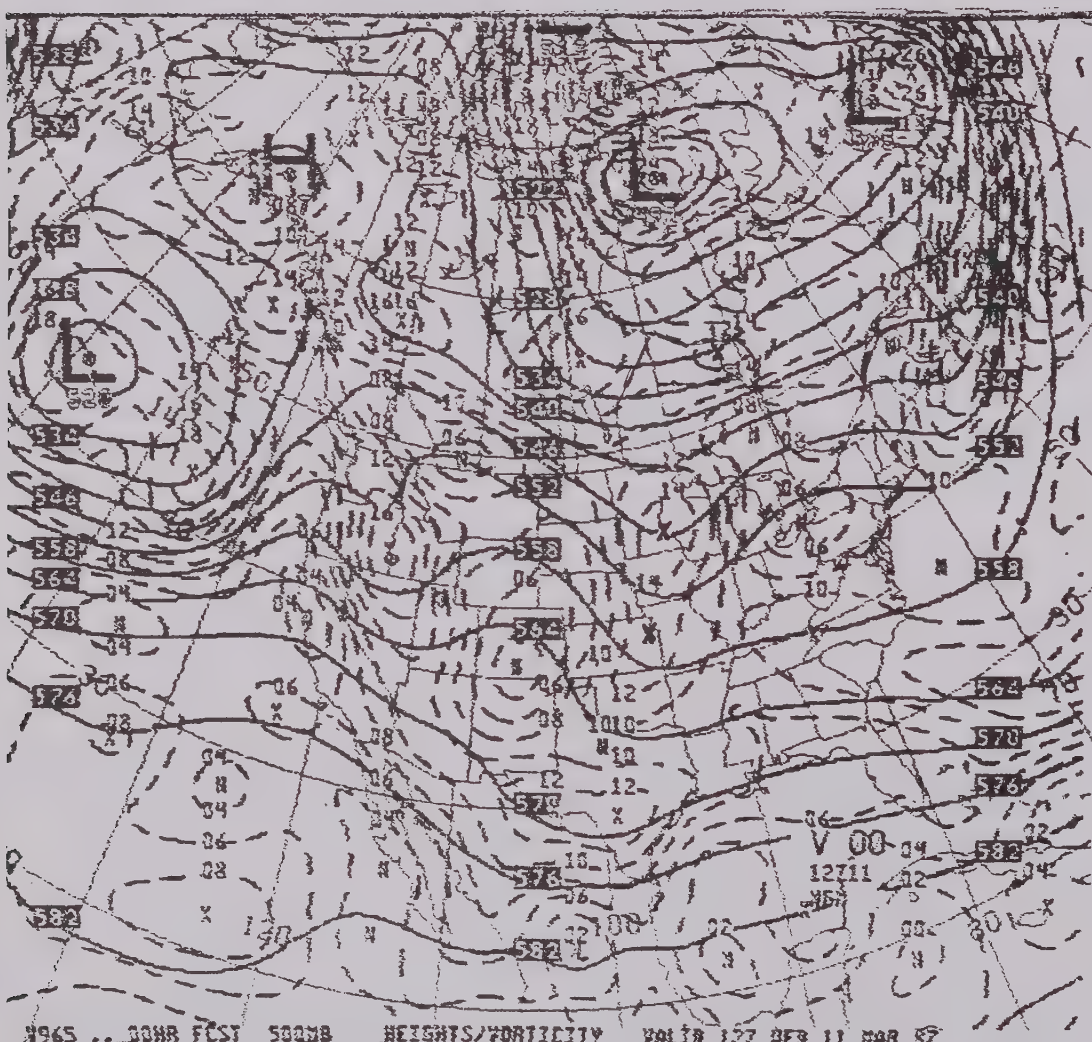


Figure 8–2. NGM analysis of 500 mb heights in decameters (———) and absolute vorticity $\times$ 10^{-5}/sec (----) for 12 z Wednesday, 11 March.

The line you drew in problem 8–4 is a line of *zero vorticity change.* This means that as you follow an air parcel through a wave, the point where the vorticity stops increasing with time and begins to decrease is a point of zero change. A simple analogy is that an automobile which is traveling foreward must come to a stop (however brief) before it can move to the rear. As you have seen, a trough in the 500 mb height field is one place to find a line of zero vorticity change. Are ridges also areas of zero vorticity change?

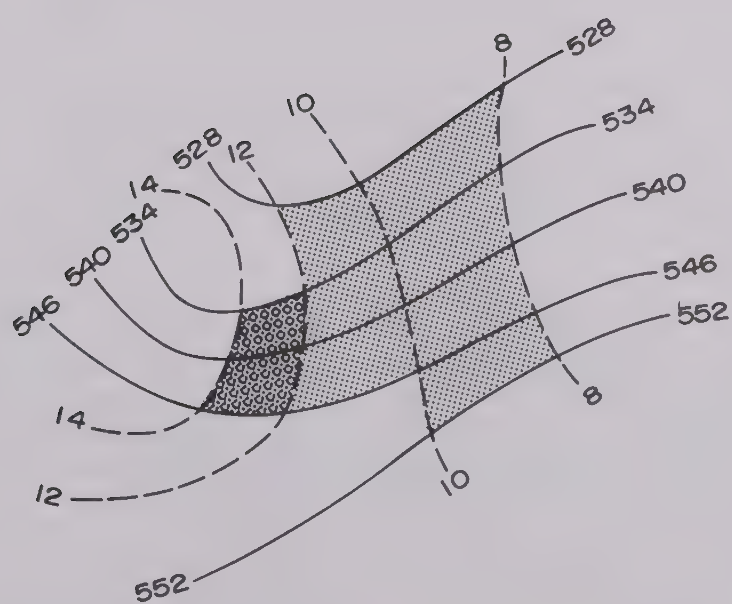
Problem 8–5

Find and draw a line of zero vorticity change in the Rocky Mountain states (refer to figure 8–2). There is another such area on the west coast. Draw a zero vorticity change line there.

To ascertain the magnitude of pressure change at the surface, it is necessary to calculate the rate of change of vorticity of a parcel as it travels through the wave. A "first guess" method of doing this is to inspect the size of the "boxes" that are formed by the height contours and the lines of equal absolute vorticity. (See exercise 7 for a review of this subject.)

Problem 8–6

Starting at the trough line (zero vorticity change line) that you drew in problem 8–4, lightly shade in red all of the *enclosed* "Boxes" where vorticity decreases with time. Then lightly shade in blue all the enclosed boxes where vorticity increases with time. Find the smallest box in the blue area and darken it in blue. What is the significance of these darkened areas? An example is provided below.



Summary

In Exercises 6, 7, and 8, you have been introduced to some of the physical processes that govern the flow in the upper portion of our atmosphere. You should be able to connect the various patterns at the 500 mb level with surface weather patterns. The concepts of convergence, divergence, and vorticity are fundamental in enabling you to form a three dimensional picture of the atmosphere and its motions.

THE THUNDERSTORM

Introduction

Estimations have been made that over 1,800 thunderstorms are in progress over the earth at any given moment. Few, if any, people are unfamiliar with this unique product of nature or the death and destruction which it sometimes brings. However, the thunderstorm can be a benefactor as well as a destroyer. Recall that in the winter the earth is tilted so that the north polar region receives little sunlight compared to the equator. This sets up a large temperature gradient (analogous to pressure gradient, temperature gradient equals $\frac{\text{change in temperature}}{\text{change in distance}}$) from the North Pole to the equator which in turn causes a large pressure gradient to exist in the Northern Hemisphere. Low pressure systems in the winter are usually very strong as a result of this temperature gradient and, therefore, become copious rain producers during their three to ten day meanderings across the country.

In the summer, however, the entire situation is very nearly reversed. The North Pole and the equator both receive much solar energy resulting in a weak temperature gradient. Pressure gradients are weaker and so, therefore, are cyclones. However, since summer is the main growing season for most crops, the much needed rain must come from somewhere. This is where the thunderstorm becomes important because these marvels of nature can produce as much precipitation in, say, 15 minutes in the summer as an intense low pressure system can in two days in the winter.

Factors That Can Change the Lapse Rate

Thunderstorms grow in an atmospheric environment where that lapse rate is unstable (see exercise 4). (For reference the stability-instability criteria are presented in the following table.) Therefore, for purposes of predicting the general location where thunderstorms may form, it is important to understand what can change the lapse rate.

Lapse Rate Criteria

Unstable	Lapse Rate > 1°C/100m
Stable	Lapse Rate < 1°C/100m
Neutral	Lapse Rate = 1 C/100m

"Differential Advection"

The environmental lapse rate can be changed by several processes. One of these processes is *differential advection:* for any two atmospheric layers, if the air aloft is replaced by warmer air while the lower level is replaced by cooler air, the lapse rate of the two layers will undergo an *increase in the stability;* conversely, if the upper layer becomes cooler through advection while warm air is advected into the lower layer, this will *increase the instability.* See figure 9–1a and 9–1b.

Figure 9–1a

Figure 9–1b

Figure 9–1. In figure 9-1a an unstable lapse rate has become stable. If the lapse rate was *already* stable it could be made *more* stable by this process. In figure 9-1b a stable lapse rate has been made unstable. If the lapse rate is *already* unstable it can become *more* unstable by this process.

Problem 9–1

Why can a thunderstorm only grow in an unstable atmosphere?

"Surface Heating and Cooling"

The atmospheric lapse rate can be changed not only by differential advection but also by surface *heating* or *cooling.* For example, on warm summer afternoons the ground absorbs much solar energy thus warming the lowest atmospheric layers (through conduction). This warming near the surface, while the upper atmosphere remains at about the same temperature, will *increase* the *instability* (decrease the stability).

The atmospheric lapse rate will become *more stable* when surface cooling occurs with either no corresponding changes in temperature in the upper layers or warming of the upper layers. For example, at night with clear skies and dry air, the surface loses a tremendous amount of heat to space causing the lower layers to cool to a temperature below that of the upper layer. This will increase the stability of the atmosphere.

Problem 9–2

Draw an early morning temperature sounding on the left. Illustrate the effects of surface heating on the sounding by drawing an afternoon sounding on the right. Draw the new sounding to show that the atmosphere is in such a state that thunderstorm clouds could grow. Assume that *only surface* heating affects the new sounding.

Problem 9–3

As you will read in the following section thunderstorms grow to very great heights (40,000–60,000 ft). However, photographs from satellites and airplanes (such as the one in figure 9–2) show that the growing clouds tend to flatten out at the top (the "anvil top"). Recalling what you learned about the vertical structure of the atmosphere in the Temperature Exercise, what might cause the thunderstorm cloud to cease to grow in the vertical and flatten out at the top as though it hit a "cap" or "lid"?

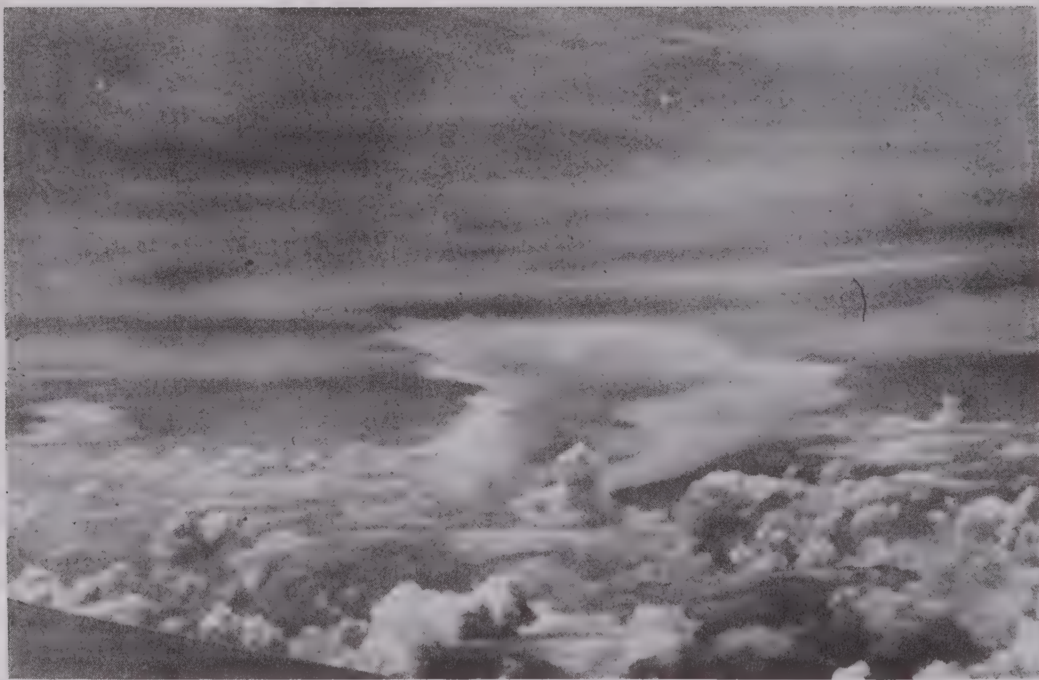


Figure 9–2

Stability Indices

The general stability or instability of the atmosphere over a location can be reduced to a single number. This number is called the *stability index.* In most cases it is computed by means of simple equations. Temperatures and/or dew points at various pressure levels are used as inputs to these equations. Stability indices have one main advantage: they are generally easy to compute and can, therefore, be computed for many stations in a relatively short period of time. Therefore, entire stability index maps can be computed quickly and used as a forecasting tool. However, they must be used with a knowledge of existing large scale weather features to be worthwhile. That is, one must know where the fronts are, the low pressure systems, mountains, etc., which could influence the production of thunderstorms. Used *alone* to forecast thunderstorms a stability index is practically worthless. The greatest advantage of a stability index is that it alerts the forecaster to those areas which have the *potential* for being thunderstorm sites.

Problem 9–4

There are several stability indices. One of the most used is the "K" index. It is computed by the following equation:

$K = T\ (850\ mb) + T_d\ (850\ mb) + T_d\ (700\ mb) - T\ (700\ mb) - T\ (500\ mb)$ where T and T_d refer to temperature and dew point, respectively, in °C.

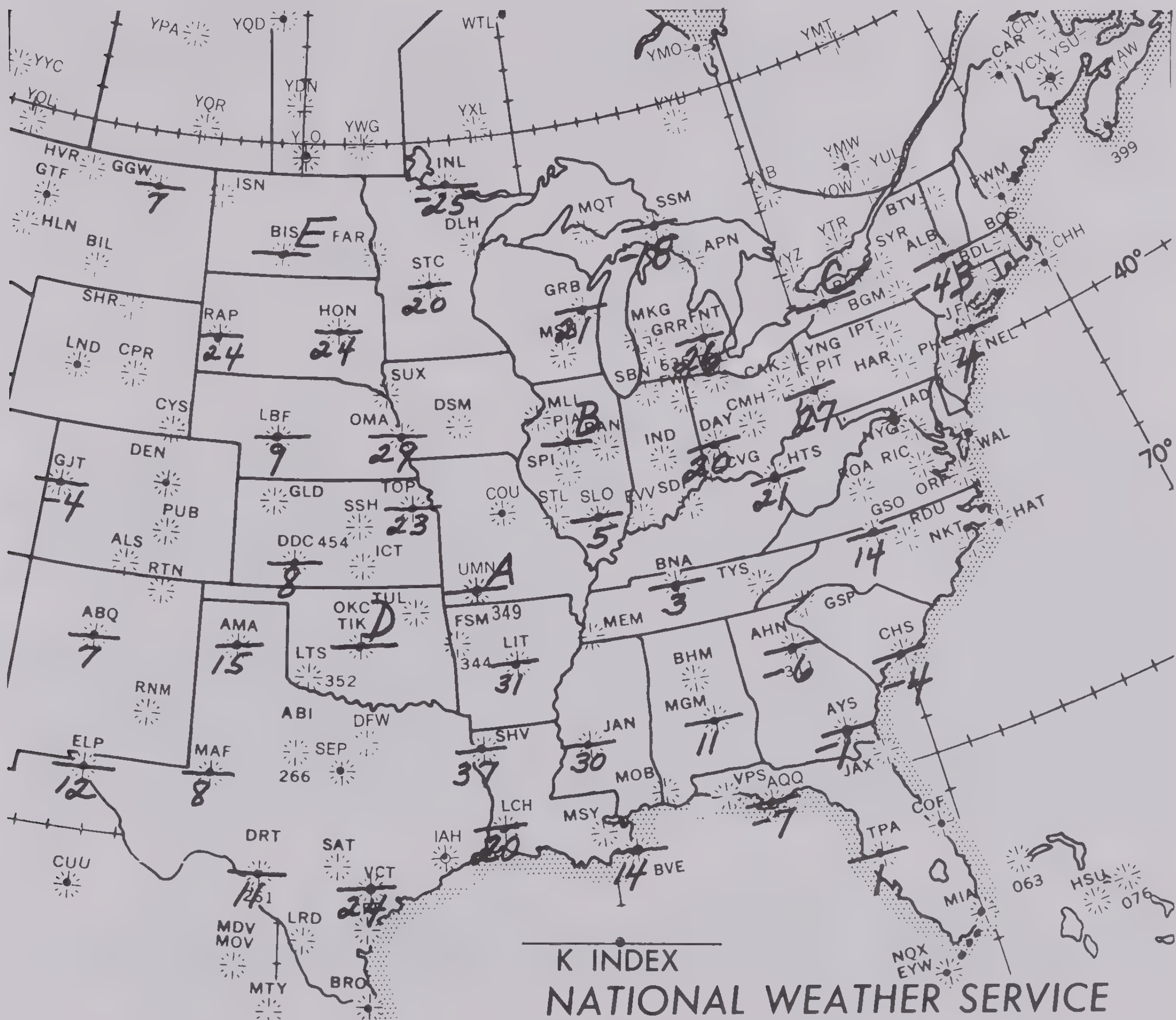
The critical values for the K index are:

$K > 22$ implies general air mass showers.

$K > 35$ implies that thundershowers are very likely. However, the K index does not do well predicting severe thunderstorm potential.

Compute the K index for the following five stations using the data given. Plot the K index on the map and analyze the map for every 10 units of K using $K = +10$ as a base. If you were a forecaster which areas would you investigate further for potential thunderstorm development? (You may find it helpful to shade in the areas where $K > 20$.)

	T(850)	T_d(850)	T_d(700)	T(700)	T(500)
A.	14.2	13.6	− 1.8	2.6	−16.6
B.	11.2	10.5	−27.4	2.6	−14.3
C.	2.2	−27.8	− 2.1	−2.1	−18.6
D.	12.8	4.8	− 7.0	3.0	−16.4
E.	−.5	− 1.3	− 9.2	−8.3	−23.7



Life Cycle of a Thunderstorm

The production of the thunderstorm is characterized by rapid lifting of warm, moist air, in an unstable environment, to great heights. This rapid lifting can be accomplished by differential heating, fronts, storms and terrain effects. Any one of these processes alone can cause enough lifting for the generation of thunderstorms. However, in many instances the most *severe* thunderstorms occur when two or more of the lifting mechanisms are working together.

Genesis

The first stage of the developing thunderstorm begins when differential heating causes warmed parcels of moist surface air to rise in an unstable environment (the lifting can be augmented by fronts, storms and/or the terrain). The response to this lifting is the appearance of fluffy, white cumulus clouds which form when the ascending parcels of air reach the condensation level (the altitude where the temperature of the air equals the dew point temperature of the parcel). The first cumulus clouds, however, are not likely to continue to "build" to form the giant *cumulonimbus* thunder clouds. Dry air, being fed into the cloud through the process of *entrainment,* mixes with the moist air of the cloud causing evaporation in a very brief time. However, with each cloud that evaporates due to entrainment, the atmosphere is left a bit more moist than previously. (Recall that evaporation increases the air's moisture content.) New parcels are continually rising behind the first one. Finally, entrainment is less effective in drying the parcel because relatively moist air is being fed into the cloud. The cloud now finds itself in an environment conducive to its growth.

In general, then, the first stage of growth of the thunderstorm cell begins with a general rising motion of the air. Successions of cumulus clouds appear and die until, finally, several form and do not dissipate. The fledgling thunderstorm, then, is actually an aggregate of cumulus clouds which overcome the hostilities of the environment and can continue to grow. (It is important to realize that the popular notion of a single parcel of air rising, condensing and finally going on to become a thunderstorm is, indeed, a fallacy. Careful observations have shown that the final product is actually made up of a collection of many smaller clouds.)

This discussion on the initial stage of the thunderstorm closes by noting that air is being fed into the storm from below and through the sides by entrainment all of the way to the top of the thunderstorm cells. The updrafts contained within the growing cloud cell carry liquid water upward at speeds of up to 25 mph past the freezing level where the liquid water freezes into snow and ice crystals. As these ice particles reach the upper levels of the cloud they encounter the increasingly fast winds of the prevailing westerlies. The ice crystals are blown down-wind to begin forming the "anvil top" that is the trademark of the thunderstorm.

Problem 9–5

What is entrainment? What are the effects of entrainment on the first cumulus clouds of the day? On the clouds later in the day? How might latent heat of condensation affect the growing clouds?

Maturity

The second, or mature, stage of the thunderstorm is observed at the surface with the onset of cool, gusty winds as the updraft is now joined by a strong downdraft. The downdraft is caused by the frictional drag of falling precipitation (rain, snow, ice) which has become too large and heavy to be suspended by the updraft. Like the updraft, the downdraft is also fed by air being entrained into the thunderstorm cell. However, where the updraft was sustained by heat released during condensation, the downdraft is fed by the cooling due to the evaporation of the falling precipitation.

The downdraft, however, is not usually present throughout the entire cell. For near the center of the cloud, the updraft is still pushing the air aloft at speeds of up to 70 mph. The thunderstorm top may now reach 60,000 feet with the ice crystals at this height being carried downwind to form the anvil-topped cumulonimbus.

Problem 9–6

How does latent heat of evaporation affect the downdraft?

The Gust Front

This is caused by the downdraft present in the mature stage of a thunderstorm. It occurs when rapidly sinking air hits the surface of the earth and spreads out in all directions. Because the thunderstorm is moving, the winds at the surface are moving fastest just ahead of the storm and slowest to the rear of it. This can be explained by considering that the forward velocity of the storm itself is added to the winds in advance of the storm and subtracted from those behind it. Because the air is generally unstable in the vicinity of a thunderstorm, it is colder than its environment when it is displaced downward (note—this is the opposite case of air being warmer than its environment when it is displaced upward). This causes the air to have negative bouyancy and it sinks of its own accord. As the air sinks it warms adiabatically, but remains *colder than the environment*. Evaporational cooling takes place as the air becomes unsaturated during its descent, further lowering the temperature. By the time the descending parcel of air reaches the ground, it is much colder than the air that is already at the surface. This cold air pushes ahead of the thunderstorm and acts as a mini-cold front which displaces the warm, moist air ahead of the storm aloft to form new clouds or enhance the growth of existing clouds. Figure 9–3 illustrates the effects of the gust front and plates 9–1 a, b, c, d show the gust front as seen by weather satellites.

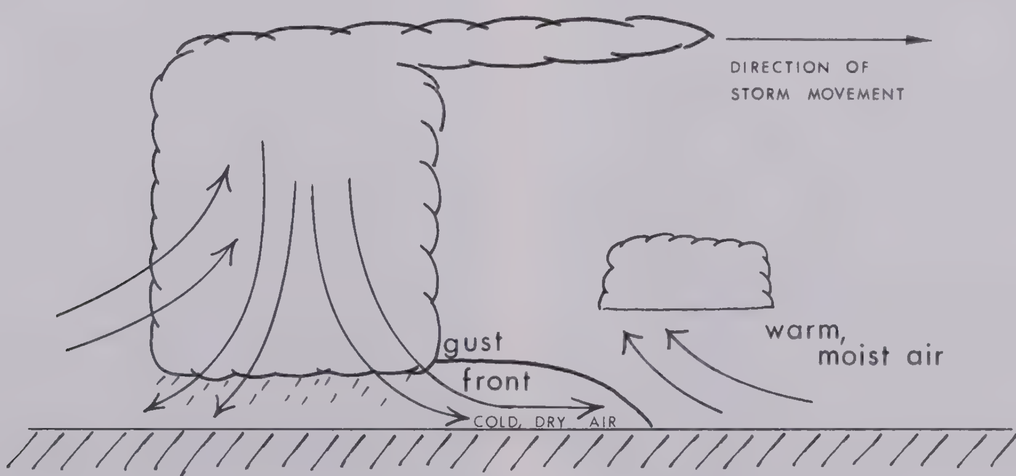


Figure 9–3

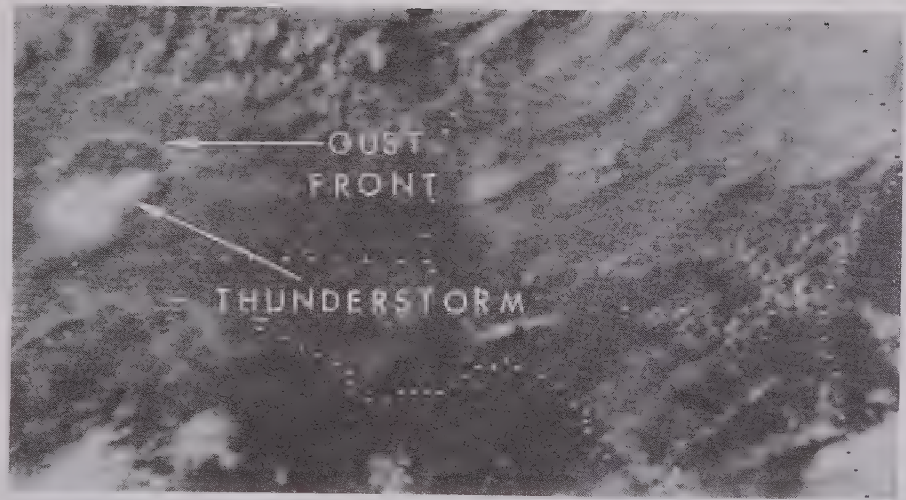


Plate 9–1a. This satellite photo shows a thunderstorm in southwest Alabama and its gust front spreading-out to the north. Clouds along the leading edge of the gust front are enhanced by the front's lifting action.

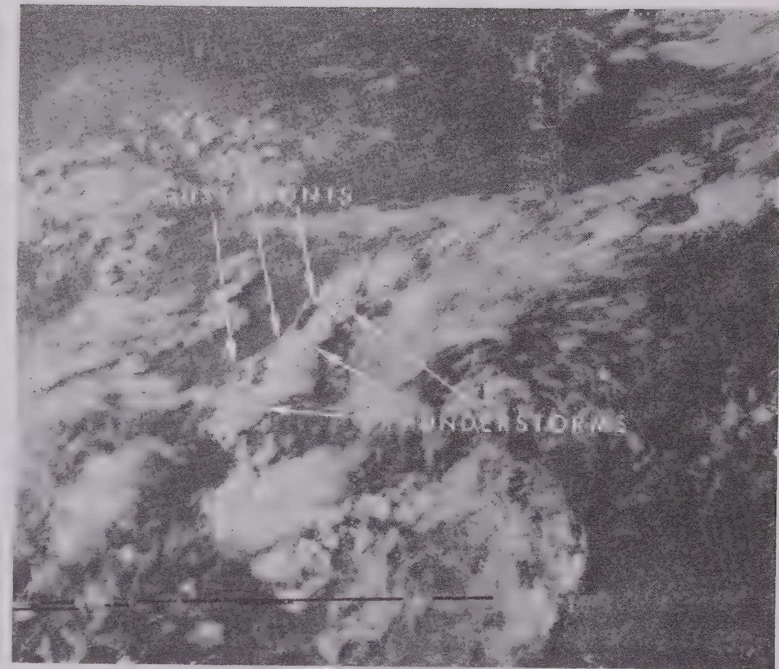


Plate 9–1b. A long line of thunderstorms extends from north-central Florida to east-central South Carolina. Gust fronts can be seen to the west of these storms curving northeast to southwest.

(1)

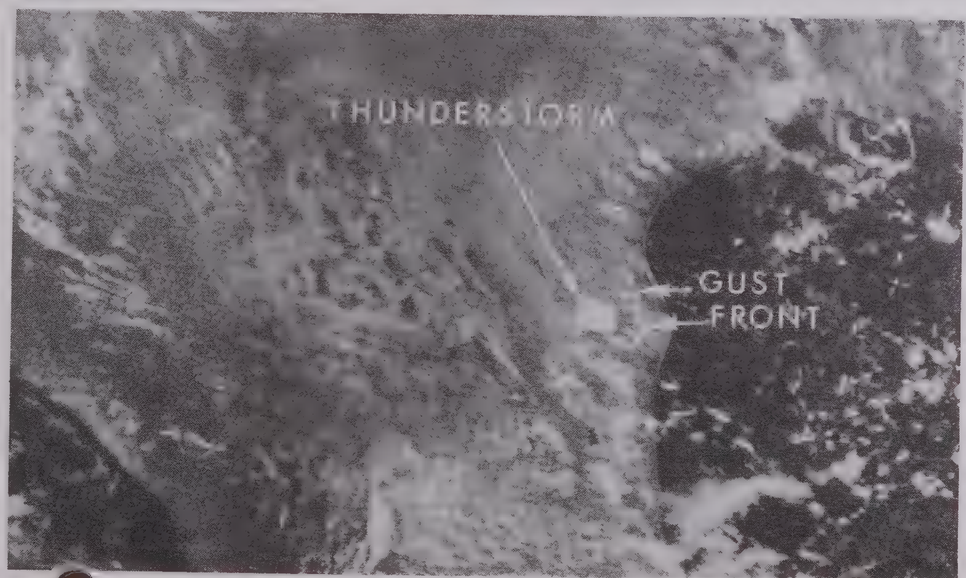
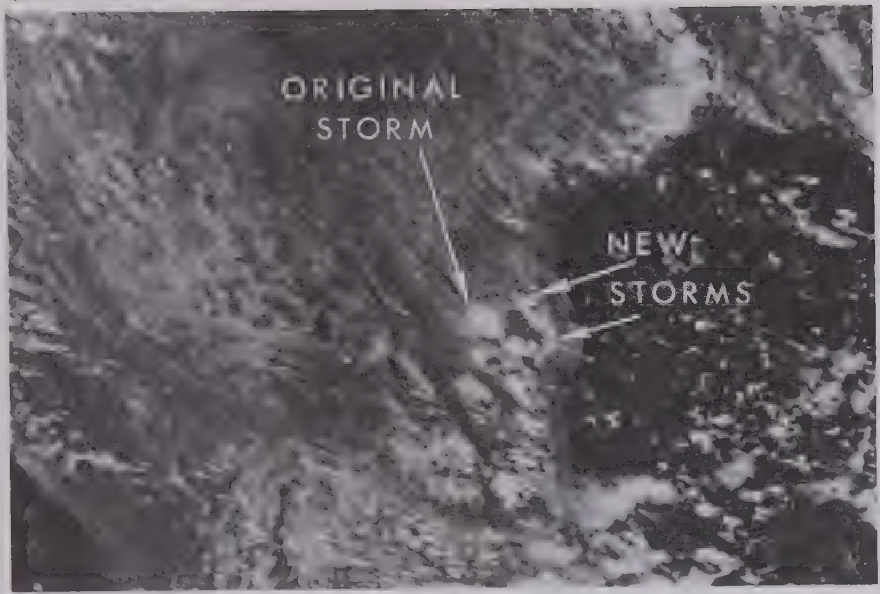


Plate 9–1c. This fascinating series of pictures show the gust front's ability to spawn new storms and *new* gust fronts. The first picture shows a gust front emanating from a thunderstorm along the Texas Gulf Coast. Small clouds near the storm have been dissipated but other clouds are growing on the front. The second picture shows the original storm dissipating and new storms forming on the gust front. In the third picture the new storms have developed and are producing a new gust front. The fourth picture shows that the original storm is just about gone. The second storm is diminishing. The new gust front is causing increased cloud growth ahead of it but dusk is moving in from the east. This will cut off the surface heating for these growing clouds and hence, new thunderstorms probably will not develop. Pictures are one hour apart from two to five o'clock in the afternoon Eastern daylight time.

(2)


ORIGINAL STORM
NEW STORMS

(3)


ORIGINAL STORM
STORMS
NEW GUST FRONT

(4)

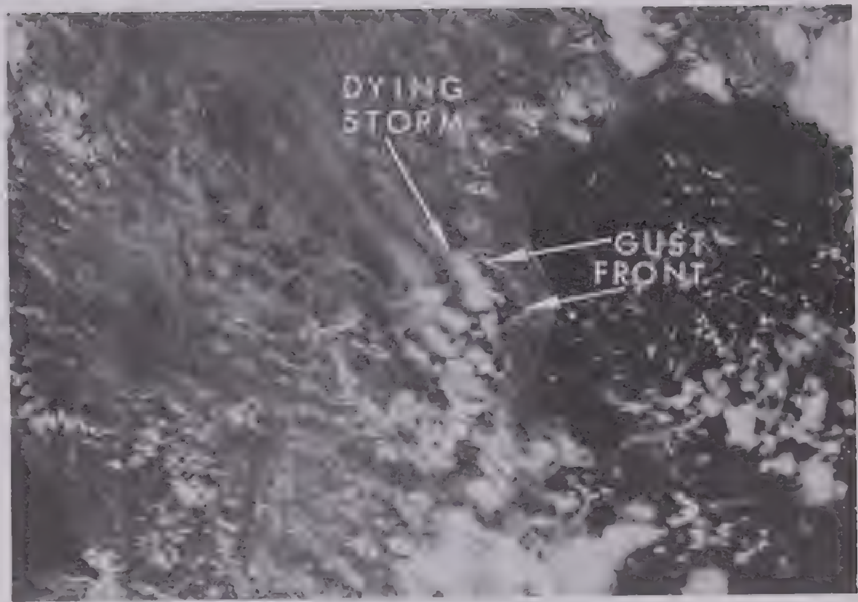

DYING STORM
GUST FRONT

Plate 9–1d. A long east-west gust front can be seen in this photo. The front is a remnant of storms which occurred earlier in the day.

Problem 9–7

What is the gust front? How is it formed? What are the capabilities of the gust front? Why?

Dissipation

The dissipating stage of the thunderstorm begins as the downdraft begins to overcome the updraft throughout the entire cell. The heavy rains are reduced to light showers as the cell exhausts its water supply while the latent heat of condensation, which gave energy and life to the storm, ends with the disappearance of the updraft. The strong winds and lightning diminish as the downward motion gradually breaks up the system.

Squall Lines

Squall lines are composed of individual thunderstorm cells which orient themselves in lines usually ahead of a cold front. The lines may be short and irregular or long and well-defined (as shown in plate 9–2). Much of the most severe weather from thunderstorms occurs during squall line situations.

The interesting feature of squall lines, however, is that they can advance at speeds *greater* than the speed of the front with which they are linked. The reason is that the gust fronts are advancing from the thunderstorm cells faster than the cold front is moving. This causes the new thunderstorms to regenerate far ahead of the cold front which initially triggered them.

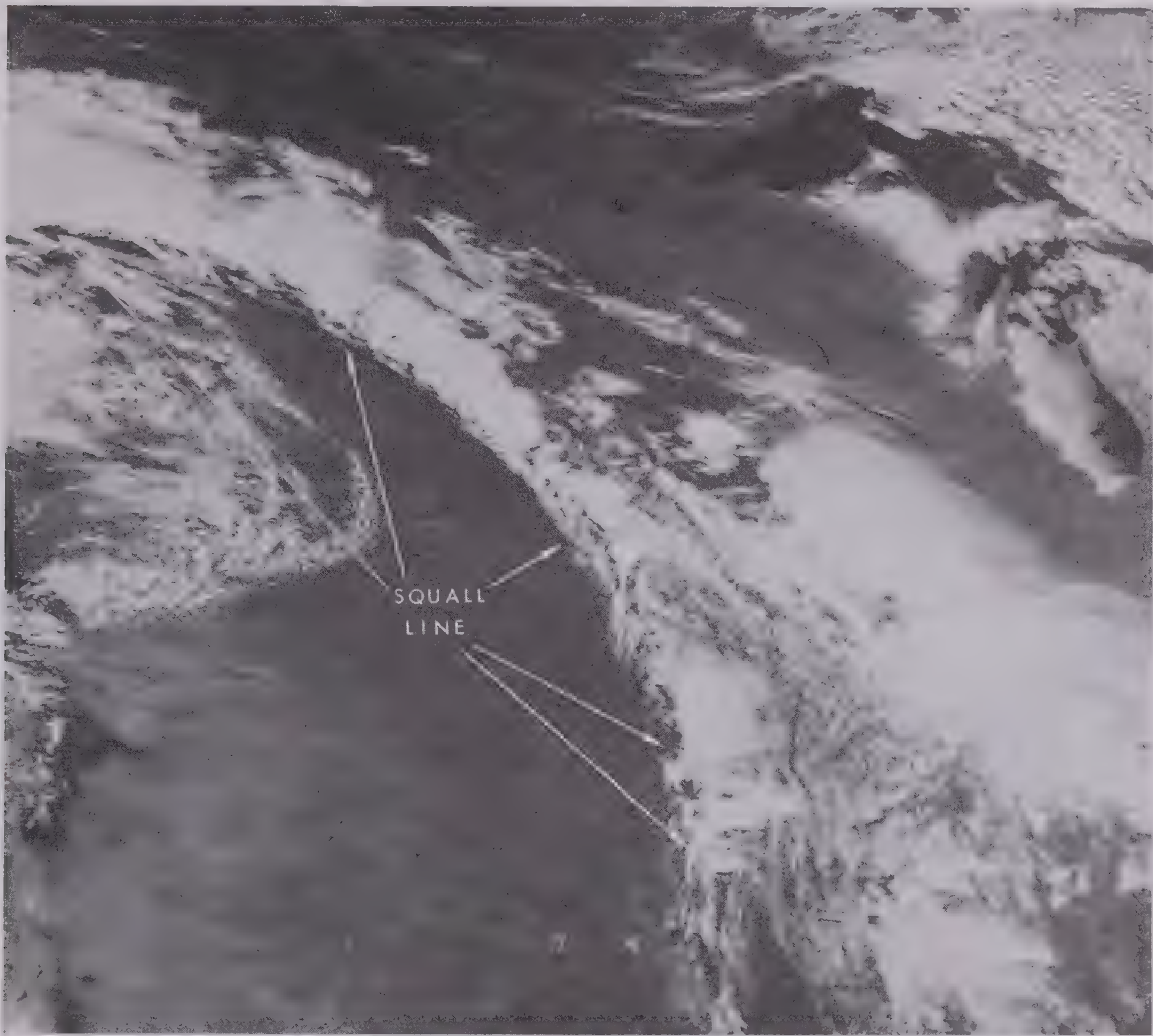


Plate 9–2. Numerous thunderstorms can be seen embedded in this long squall line in the midwest United States on May 6, 1975. Many tornadoes associated with the squall line caused several deaths and many injuries.

Forecasting Thunderstorms

Forecasting where thunderstorms will form is a difficult task. There are conventional data (such as knowing where the fronts are, where the moisture is, etc.) to be used by the forecaster and there is also what might be called "unconventional" data such as a knowledge of how the sea breeze works and how the terrain is shaped. Great progress is being made in the use of satellites in forecasting thunderstorms (pictures of growing cumulus clouds are extremely useful).

"Sea Breeze"

Recall from the Temperature Exercise that in the summer, bodies of water are colder than adjacent land masses. This gives rise to the sea breeze (as well as bay, river and lake breezes). As heating occurs during the day the air over the land becomes warm and light. This allows the cold air from the adjacent water to move towards the land. This produces the "sea breeze front." (See figure 9–4.) Like the gust front and large scale cold fronts, it causes lifting of the air and cloud production. Plate 9–3 shows an active sea breeze front in Florida. This satellite photo shows how the front has moved westward from the Atlantic Ocean producing clouds and thunderstorms inland from the shore.

Figure 9–4

Plate 9–3

Whenever land is adjacent to water, fronts of this type can develop and cause increased thunderstorm development. Plate 9–4 shows thunderstorms developing on the lake breeze west of Lake Michigan. Plate 9–5 shows developing thunderstorms on a "river breeze" front on the Altamaha River in Georgia.

Simply knowing what the sea breeze front is and how it works does not always mean that on any day thunderstorms will form on the front. If the air mass is very stable cloud growth will be severely restrained. If the prevailing wind is blowing against the front, the front might not develop and, therefore, cloud development might not take place or it might take place closer to shore than it would normally.

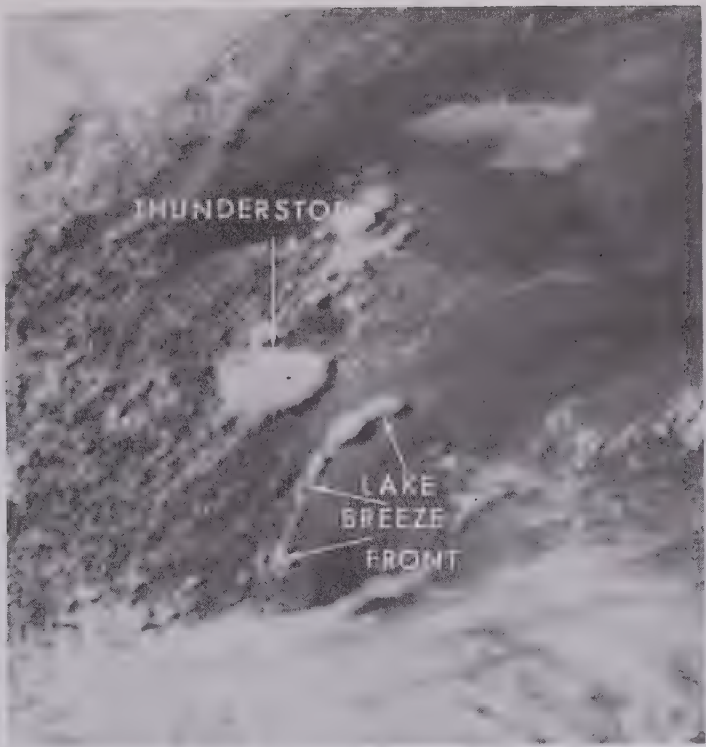


Plate 9–4

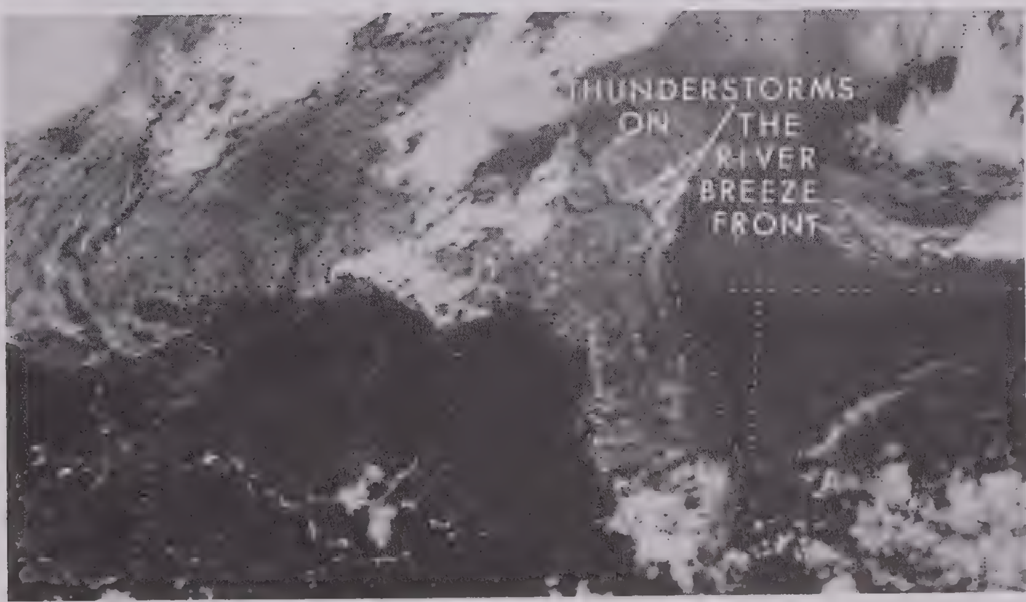


Plate 9–5

Problem 9–8

In plate 9–5 thunderstorms formed to the north of the Altamaha River. Can you think of why they did not form to the south?

Terrain

Terrain features affect the growth of clouds in some interesting ways. Notice in plate 9–4 how clouds have not formed over Lake Michigan and plate 9–5 how the Altamaha River is readily visible because it is outlined by clouds. Recall, again, that the air over bodies of water is cooler than surrounding land areas and what is needed to produce convective clouds is *warmth* from below.

In plate 9–6 the prevailing wind over Florida is from the east. Notice how cumulus clouds have built up from central Florida eastward but that over and to the west of Lake Okeechobee the sky is clear. No clouds have formed *over* the lake because it is cool. This air, cooled by the lake, moves westward, lowering the temperature of the air over the land.

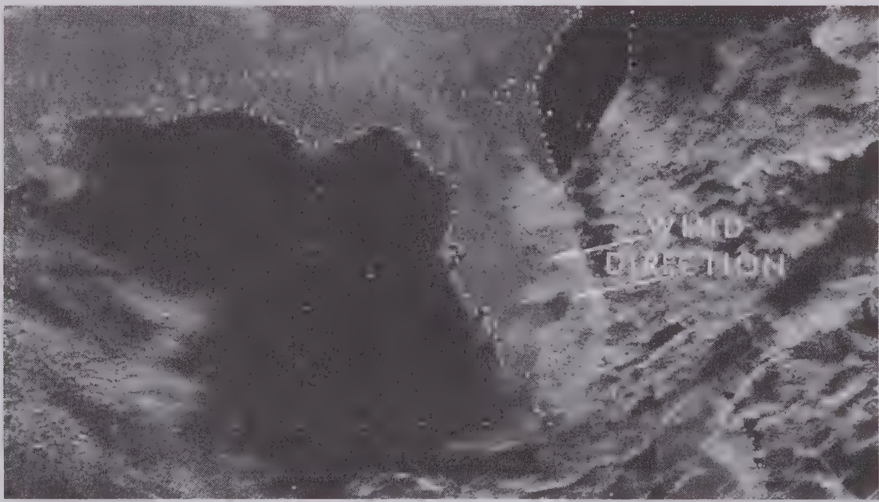


Plate 9–6

Problem 9–9

As shown in plate 9–6, cloud growth is inhibited west of Lake Okeechobee in south central Florida. What mechanism causes this lack of cloudiness? (Hint: consider the change in stability of the air masses on the east and west sides of the lake.)

The actual shape of a coastline plays a big role in the development of cumulus clouds. Consider a day on which the wind is relatively light or calm and a coastline like that shown in figure 9–5a. When the sea breeze comes on shore it arrives nearly perpendicular to the coast (figure 9–5b). In figure 9–5c notice how the sea breeze converges at points 1 and 3 but diverges at point 2. Recall from earlier exercises that surface convergence leads to upward motion and surface divergence leads to downward motion. Clouds then can be expected to form first at points 1 and 3 where there is convergence.

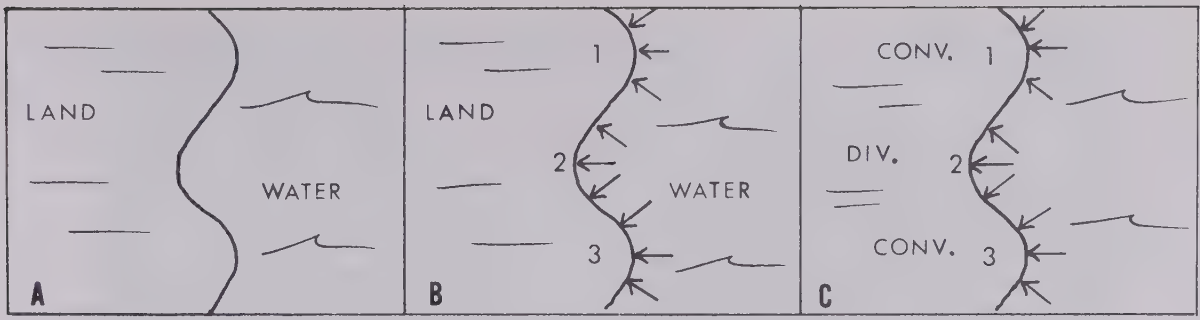
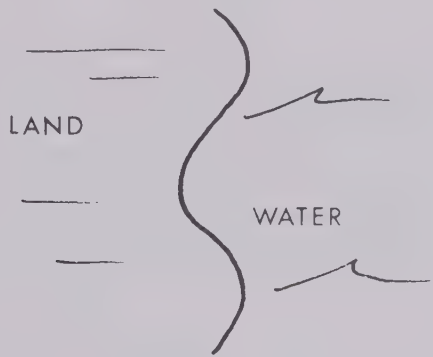


Figure 9–5

Problem 9–10

A coastline is shaped as shown. Assuming that during the day the only wind is from the sea breeze, where would clouds be most likely to form first? Why?



Cloud Mergers

Quite often thunderstorms develop at the *intersection* or *merge point* of two convective cloud lines. This is believed to occur because of the increased convergence and upward motion at the merge point. Satellite photos have been especially useful in early detection of where thunderstorms *may* form because cloud lines can be detected relatively easy on such photos.

Problem 9–11

In plate 9–1d point out two locations where cloud lines appear to be merging and hence might be thunderstorm sites. See plate 9–7 for the answer.

Lightning

Of all meteorological phenomena, lightning causes the greatest number of direct deaths. Snowstorms may cause more indirect deaths and tornadoes cause more property damage, but it is lightning, which strikes the earth about 100 times each second, that kills or injures about 400 Americans each year.

Lightning usually occurs during the mature stage of the thunderstorm. As the towering cumulonimbus cloud develops, complex energy exchanges occur and the interactions of electrically charged particles cause the production of a large and intense electric field within the cloud. The distribution of positive

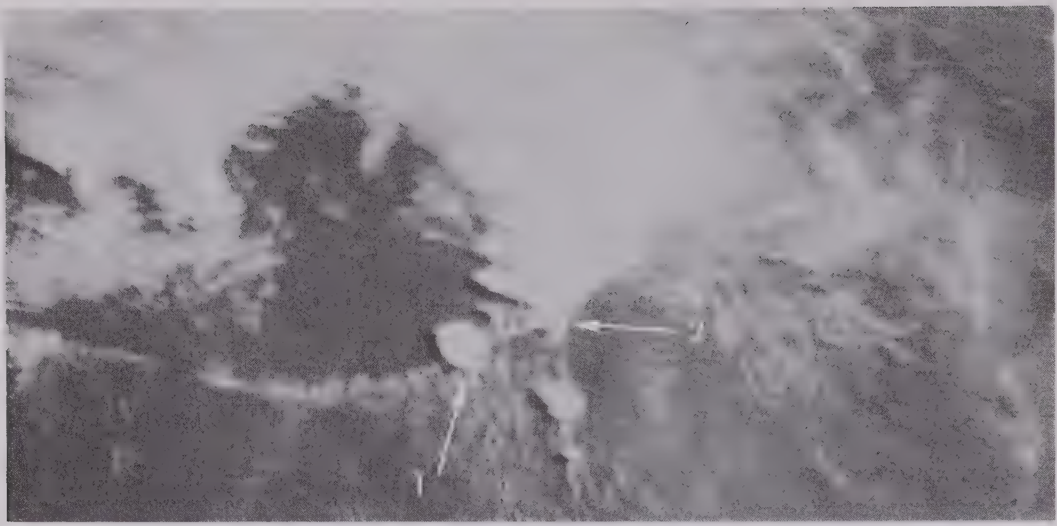


Plate 9–7

and negative charges within the cloud are shown in figure 9–6. Note that in the cloud's upper regions, where there is an abundance of frozen precipitation, the electric charge is positive, whereas, in the lower regions the charge is negative with a small area of positive charge. Unfortunately, no completely acceptable theory of the processes which lead to the electrification of the thunderstorm cell is available.

Usually the earth carries a negative electrical charge. But as the thunderstorm cell passes over an area, the negatively charged base of the cell induces a positive charge directly below and for several miles around the cloud. See figure 9–7.

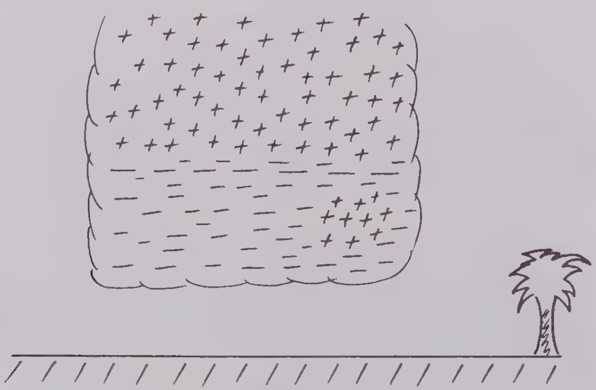


Figure 9–6

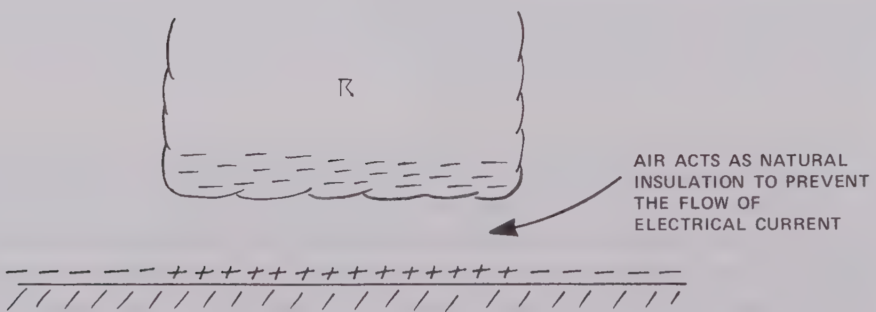


Figure 9–7

In order to establish a flow of electricity between the positive and negative charges, electrical current frequently flows upward from the positively charged ground to the negatively charged cloud via buildings, trees or other high objects which are relatively good conductors of electricity.

Air is not a good conductor of electrical current and the layer of air between the cloud and the ground insulates the cloud and ground charges. This natural insulation prevents the flow of current unless the electrical charge becomes great enough to overcome the air insulation. When this difference in electrical charges becomes great enough, lightning occurs. Lightning, therefore, represents a flow of electrical current from a negatively charged source to a source that is postively charged. The lightning discharge can be between two clouds, within one cloud, from cloud to ground and from ground to cloud if tall structures are involved.

The typical lightning stroke that is usually observed in thunderstorms, rather than being a solitary event, is actually a sequence of several occurrences happening so rapidly that usually all we see is the final product.

See figure 9–8. The sequence begins when a negatively charged path with a radius of about four inches begins to advance from the cloud to the ground. This initial burst is known as the *pilot leader* and it advances toward the earth at speeds of up to 2,000,000 mph. The pilot leader initially moves only about 35 feet before it pauses. During this pause it receives a recharge of energy from the cloud and then begins another journey of about 35 feet at about the same speed. These successive jumps are known as *step leaders* to distinguish them from the pilot leader which is the initial surge. The step leader advances to about 15 to 150 feet from the earth's surface. At this point positively charged particles advance from the surface to the step leader. The earth and the cloud are now joined by a path of electricity and up this path rushes a *return stroke* which energizes the atoms and molecules of the air and illuminates the branches of the descending step leader. The return stroke travels upward at speeds approaching the speed of light: over 200,000,000 mph. The return stroke serves to discharge (neutralize) the opposing charges between cloud and ground. But the initial return stroke only discharges about the lowest 300 feet of the cloud. The drama continues then, when secondary returns, called *dart leaders,* discharge higher and higher regions of the negatively charged portion of the cloud. The number of dart leaders varies but the average is three to four. The elapsed time from pilot leader to final dart leader is about one second.

The lightning discharge can take many forms. The most common form is streak lightning, commonly called a lightning bolt, which may be a single line or multiple lines extending from the cloud to the ground. Sheet lightning is simply a bright flash of light seen often as a thunderstorm is approaching and for some time after one has passed. The flashes cover a broad area and are caused by discharges from cloud to cloud. Heat lightning is usually seen during the hot summer months and is believed to be the reflection of lightning from thunderstorms occurring beyond the horizon.

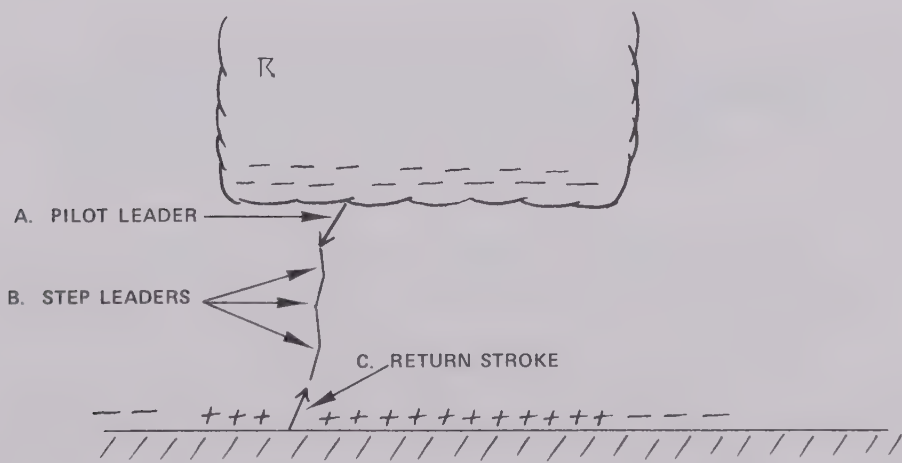


Figure 9–8

Problem 9–12

What are the individual components of a lightning discharge from cloud to ground? Why is it wise to stay away from trees or other tall objects during a thunderstorm?

Thunder

Thunder is a direct effect of lightning. Recall that when the air is heated, expansion occurs. Around the lightning discharge the temperature of the air approaches 15,000°C. (Two and one-half times the sun's surface temperature!) This heating causes rapid expansion of the air and this expansion simulates a violent explosion which we call thunder.

Sometimes thunder is heard as a sharp crack when you are close to the lightning discharge. Most of the time, however, low, persistent rumblings are heard. It is interesting to note the causes of the latter type:

a. The observer is not equidistant from all parts of the lightning stroke. Take the simple example of a perfectly straight lightning bolt. The thunder caused by the heating of the air closest to the observer (that is, near the ground) would reach him before the thunder caused by heating of the air farther away (that is, higher up towards the cloud).

b. However, lightning discharges are rarely straight. Therefore, with a crooked path the thunder occurring closest to the observer will reach him first, that further away will reach him later. Hence, as with "a," this leads to a rumbling sound.

c. Many times there occurs a succession of discharges. This leads, obviously, to a succession of thundering rumbles.

d. The sound heard from the thunder also can be reflected off of buildings and mountains, etc., similar to echoes, which again can cause rumbling sounds.

Problem 9–13

Sound travels at a speed of about one-fifth of a mile per second. If the lightning "explosion" occurs at the instant you see the lightning how can you determine how far the lightning occurrence was away from you?

Hail

Hail consists of roughly spherical lumps of ice and snow which usually fall from very active thunderstorms. These lumps of ice may range in size from that of a small marble to larger than a baseball. Damage due to hailstorms averages about five million dollars annually in the United States with 80% of the damage due to crop destruction. The scourge of all crops, it has frequently been known as the "white plague."

See figure 9–9. The initial hailstone, or embryo, begins as rain in the lower layers of the thunderstorm cell. The updrafts present in severe thunderstorms move the raindrop to higher and colder portions of the cloud. This region can be seen in figure 9–9 as the embryo formation region (EFR). The updrafts in this region must be relatively weak in order to allow the embryo sufficient time to grow into large particles. The EFR must be situated below the −40 degree Celsius level so that there is supercooled water available for embryo growth. When the embryos have formed and grown in the EFR, they fall into the main updraft region of the cloud known as the hail growth zone (HGZ). Here, updrafts must be in the 10 to 15 meter per second range in order to support the hailstone and to prevent it from falling to the ground prematurely. There also must be a good supply of supercooled water available to the hailstone for continued growth. Once the hailstone has grown to a sufficiently large size, it falls to the ground in the hail cascade region.

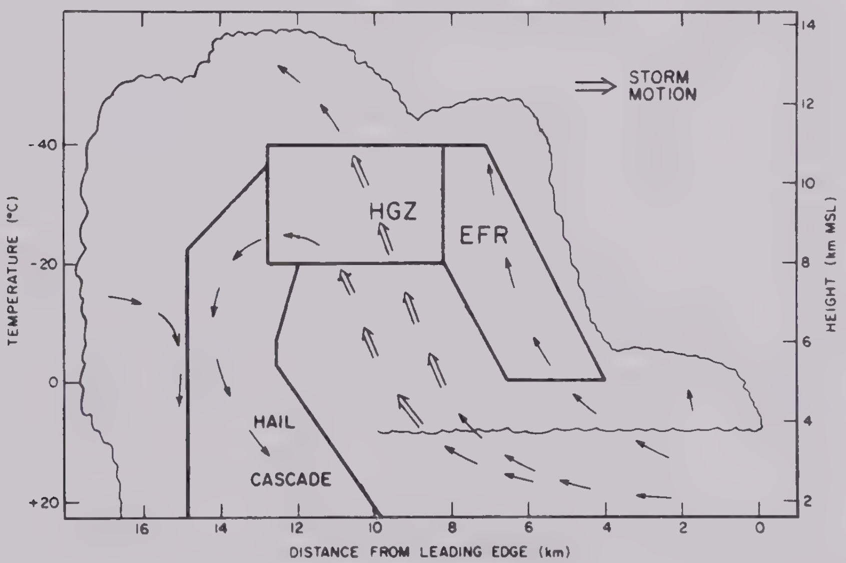


Figure 9–9. Cross section of a multi-cellular hailstorm showing the embryo formation region (EFR), hail growth zone (HGZ), and the hail fallout zone. The updrafts and downdrafts are indicated by arrows. (After Kenneth C. Young, "A Numerical Examination of Some Hail Suppression Concepts" AMERICAN METEOROLOGICAL SOCIETY MONOGRAPH #38, 1978).

The strength of the updraft in the HGZ is important in determining the size of the hailstone. An updraft of 60 mph will support a one inch diameter hailstone and a 120 mph updraft will support a three inch diameter hailstone.

Summary

In this exercise you have seen how differential advection and surface heating or cooling can cause changes in the lapse rate. You were also introduced to a useful tool for a "first guess" forecast of severe weather—the stability index. You have seen that a thunderstorm goes through three stages of development—cumulus, mature and a dissipation stage and you have learned of the unique abilities of the gust front. Terrain, the sea breeze and merging cloud lines all affect the development of thunderstorms and you've seen that satellite photos are invaluable in analyzing these events. Lastly, you were shown how lightning, thunder and hail develop within the storm.

AIR POLLUTION

Introduction

That phenomena which we call air pollution is a very complex thing. So complex that an investigator would have difficulty getting people living in different parts of the country to agree on just what the term "air pollution" really means. If you were to ask a citizen of Los Angeles, for example, just what air pollution is, his answer would most probably be, "smog." Likewise, a habitant of New York would most likely consider sulphur dioxide (SO_2) as air pollution. Ore dust in Stuebenville, Ohio, smoke in Gary, Indiana, acid mists in Northern Europe—all of these can be considered as air pollution. Surprisingly enough, Mother Nature is also a contributor to air pollution. The Blue Ridge Mountains and the Great Smokey Mountains in the eastern United States probably received their name from the bluish-grey haze that seems to hang over them. This haze is often the result of sunlight reacting on evaporated hydrocarbons which produces smog. The hydrocarbons are the products of the various species of pine trees which are found in the area. So you see, air pollution can be many things. Perhaps what should concern us is not the type of air pollution or the source but the weather conditions that can concentrate the pollutants to such an extent that discomfort or illness can result.

The atmosphere, happily, has a built-in mechanism for self-cleansing. If you have ever noticed how clear and sparkling the air appears after a rain, you have seen this cleansing action at work. Given the fact that the atmosphere can rid itself of pollution, do you think we are in any danger of overloading the atmosphere with foreign material?

As an exercise, let's calculate the amount of atmosphere the planet earth contains. From the pressure exercise, we already know that hydrostatic pressure is the weight per unit area of the fluid (in this case the atmosphere) over that area in question. Assuming that the average pressure over the whole globe (at sea level) is 15 pounds/in^2, we can multiply that pressure by the surface area of the earth in square inches to get the total weight of the atmosphere.

Problem 10–1

Use these data to compute the total weight of the atmosphere.

Area of a sphere $= 4\pi \times R^2$

$\pi \sim 3.1416$

R of earth $\sim$ 4,000 miles

ft/mile = 5,280 ft^2/mile^2 = 5,280 × 5,280 = 27,878,400

in^2/ft^2 = 144

________________________ lbs.

Give your answer in tons.

________________________ tons

Problem 10–2

If 30,000,000 tons of particulate matter is put in the air each year in the United States (a reasonable estimate for 1970), how great a concentration of pollution would this be? Assume that the pollution is mixed evenly throughout the atmosphere. Express your answer in *parts per billion.*

You can see that the atmosphere is so large that it can easily accommodate very large amounts of foreign matter without becoming overloaded. Why then are we concerned with atmospheric pollution?

When we figured out the tremendous powers of dilution that the atmosphere has we assumed that the pollutant was evenly distributed throughout the whole atmosphere. This was an erroneous assumption. Normally, atmospheric pollution tends to be concentrated in certain areas and be diluted in others. The key to whether the atmosphere dilutes or concentrates its load of pollution lies in the stability of the air. (For a review of stability, see the exercise on clouds and the precipitation process.)

When the atmosphere is unstable, vertical movements of the air are enhanced. This allows mixing of the pollutant with the atmosphere to take place. If, on the other hand, there is a stable layer (an inversion) in the lower atmosphere, pollution is trapped below that layer and is concentrated—sometimes to a dangerous level.

Nocturnal Inversions

After sunset, the earth cools by radiation. The lower layers of the atmosphere are cooled by their proximity to the cooling ground. As the night progresses, the earth gets colder and colder until the lowest temperature is reached near dawn. A series of temperature versus height diagrams (fig. 10–1) show this process:

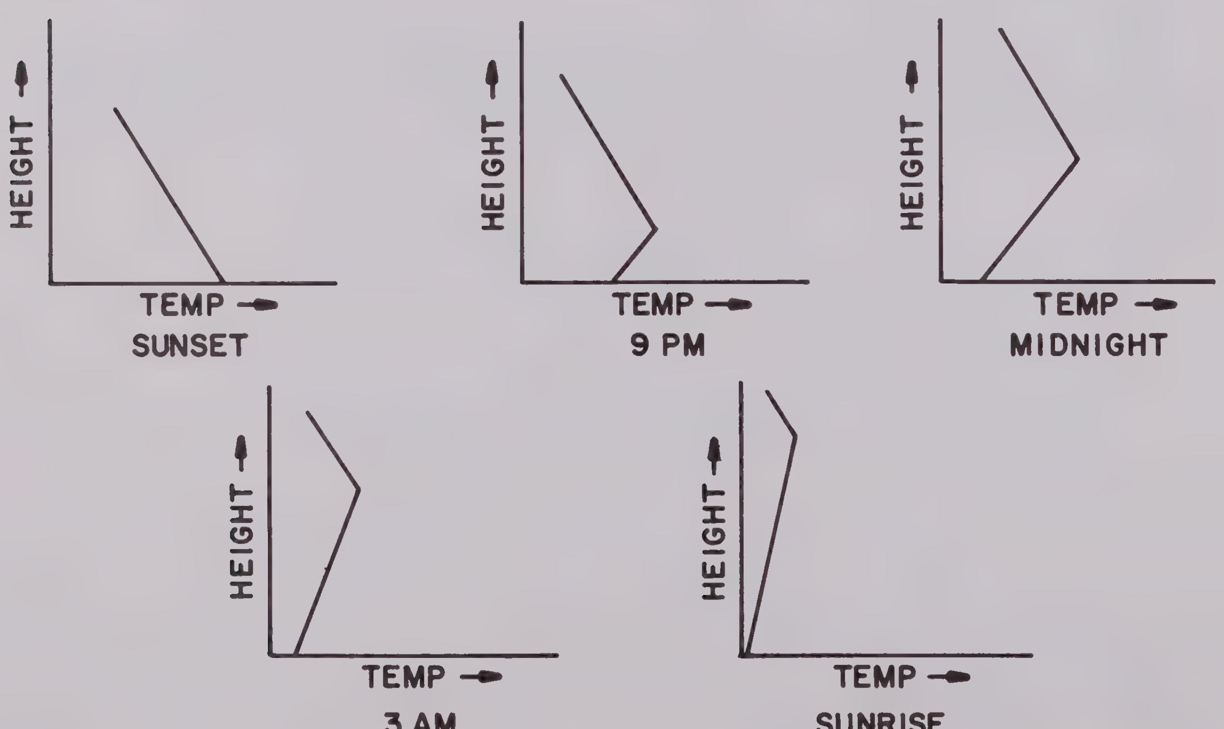


Figure 10–1

Problem 10–3

That portion of the temperature vs. height curve (i.e. the environmental lapse rate) which warms withheight is called a(n) ________________ and the air in this layer is ________________ .

At this time, lets review the effect that a stable lapse rate has on vertical motion.

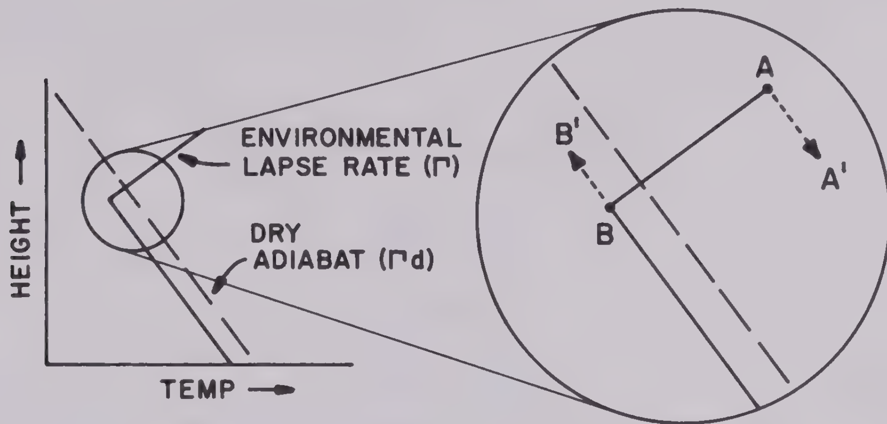


Figure 10–2

If air at point A (see insert, figure 10–2) is caused to move downward to point A′, it will be considerably warmer than the air around it. (Remember that dry air warms or cools at the dry adiabatic lapse rate of 10°C/km when it is forced downward or lifted. See exercise four for a discussion of the adiabatic assumptions.) When warm air and cool air exist side by side at the same pressure, the warm air is less dense than the air around it and, therefore, will try to rise back to its original position. The effect is much the same as if you were to try to push a cork to the bottom of a pail of water. As soon as you released the downward pressure on the cork, it would immediately pop back to the surface. Likewise if air at point B were lifted to B′ the air would be much colder than the air around it and, for that reason, heavier. The air would then sink back to its starting point. Because of this, a stable layer acts to suppress vertical motions and acts as a sort of "boundary" between less stable air above and/or below.

The Effects of Stability on "Point Source" Pollution

One of the problems often encountered by air pollution engineers is point source pollution. A good example of this type of pollution is the stack of an isolated power plant. Air pollution engineers must take local climate into account when they design a power plant. For example, suppose the proposed plant site was to be in a mountain valley as shown in the cross-section drawing, figure 10–3.

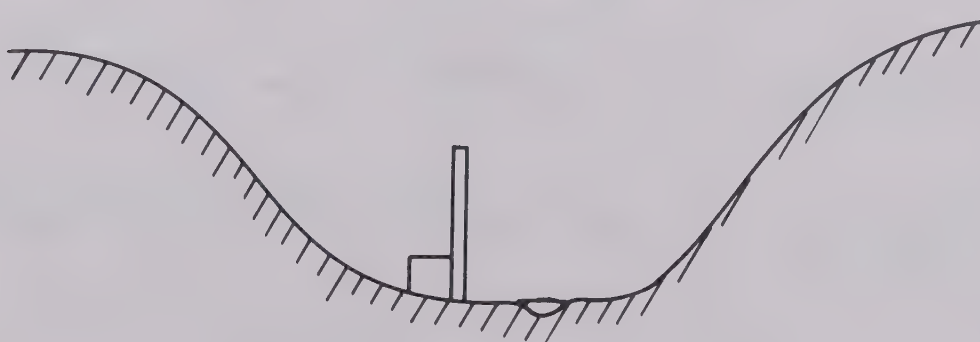


Figure 10–3

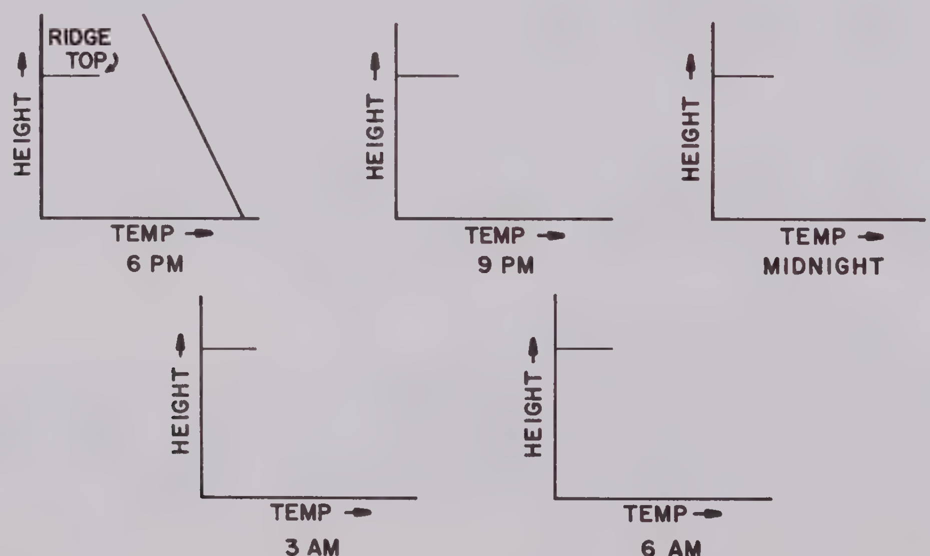
What could happen is this:

During the night, the sides and bottom of the valley chill because of radiative cooling. The cold ground cools the thin layer of air in contact with it. This layer of cold air is more dense than the air immediately above the ground layer, so it tends to slip down the slope. The cold air tends to pool in the valley and by dawn has filled it up (fig. 10–4).

Figure 10–4

Problem 10–4

Draw the temperature-height profile you would expect to see if you made a series of temperature measurements in a valley at 9 P.M., midnight, 3 A.M., and 6 A.M. Assume sunset is at 6 P.M. and sunrise is at 6 A.M. The 6 P.M. sounding is provided for a reference.



Assuming the same initial (sundown) sounding as in the nocturnal inversion, is this series of soundings different or similar?

Problem 10–5

Where do you think it would be best to locate a power plant—at the floor of the valley or at the top of the adjacent ridge? Why?

As you can see, inversions caused either by nocturnal cooling or terrain effects (or both) could cause pollution problems.

Plume Behavior

Different environmental lapse rates can cause different behaviors of smoke stack plumes. For instance, a stable lapse rate allows smoke to diffuse horizontally but inhibits vertical motion. Viewed from the top and side, it would look like this (figure 10–5):

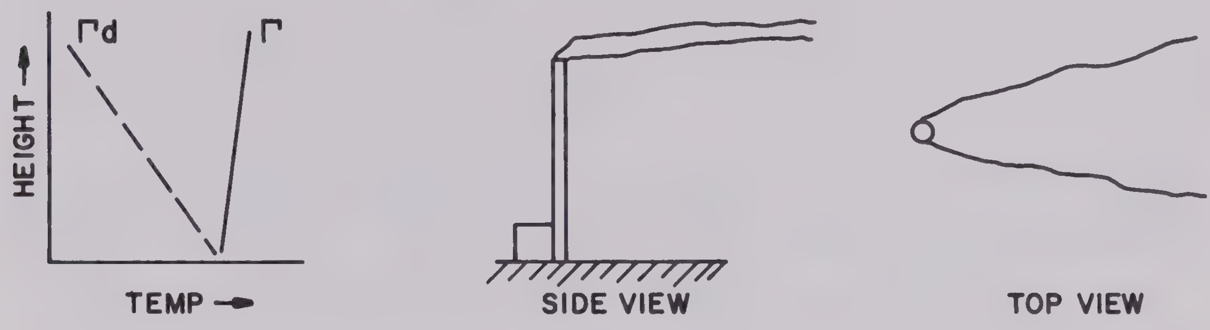


Figure 10–5

This type of plume is called a "fanning" plume. Now suppose that the lapse rate was a neutral one. A neutral lapse rate allows the plume to spread out equally in all directions, growing larger (and more diluted) as it is carried downwind from its source (the stack). Here is what the side view of a smoke plume in a neutral lapse rate looks like:

Problem 10–6

Draw the top view.

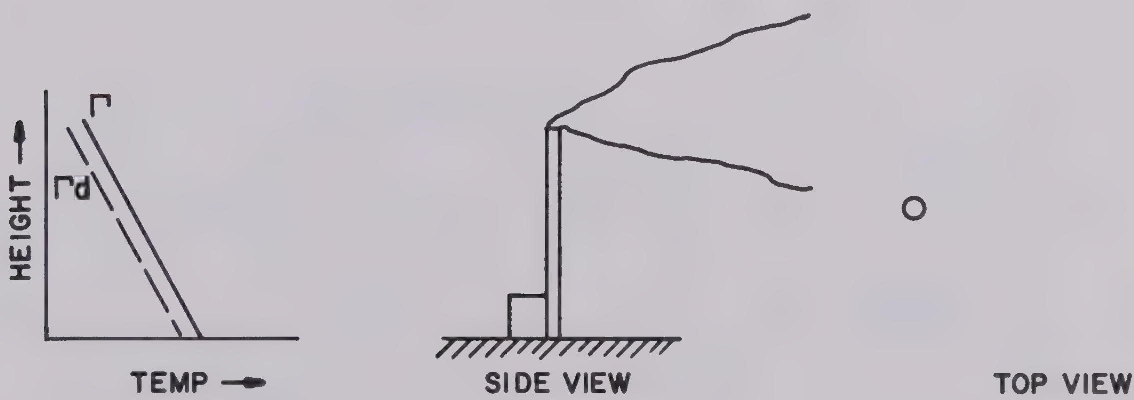


Figure 10–6

This is called a "coning" plume (figure 10–6).

Problem 10–7

Even though "fanning" and "coning" plumes occur in stable and neutral layers respectively, they are not considered to be major causes of pollution at the ground level. Why is this so?

When the atmosphere is unstable, vertical motion is enhanced and rapid mixing of the pollution with the atmosphere occurs. However, if the mixing is strong enough, stack gases are sometimes carried down to the ground level close to the source (figure 10–7).

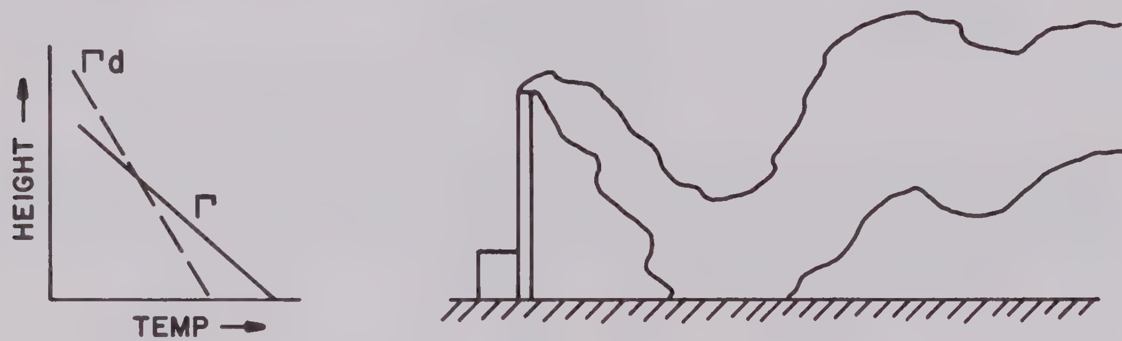


Figure 10–7

A plume that behaves this way is called a "looping" plume. Again, this type of plume is not significant as far as ground level pollution is concerned.

Thus far, we have talked of plumes that result from stable, neutral, and unstable lapse rates. Because Mother Nature is not necessarily simple, we find lapse rates such as have been already discussed very infrequently indeed. What is more common is a mixture of the types of lapse rates already discussed. We have already discussed the nighttime inversion, so let's see just what happens to such a lapse rate after the sun comes up in the morning. Our nocturnal inversion might look like figure 10–8. The coldest air is near the ground and temperature increases with height until the top of the inversion is reached.

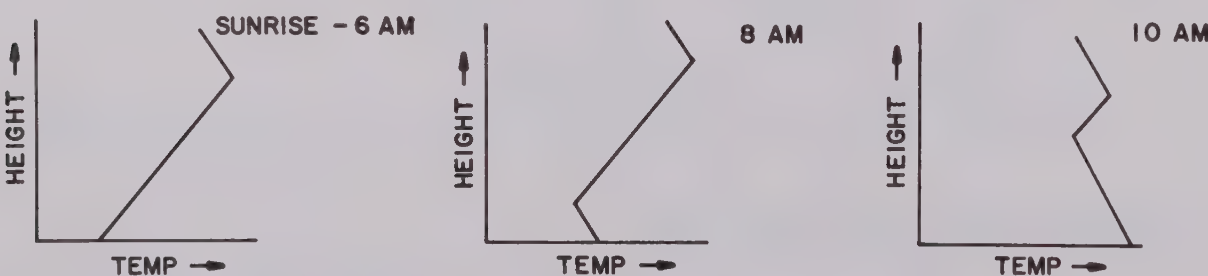


Figure 10–8

Then, above the zone of nocturnal cooling, the atmosphere again cools with height. After sunrise the ground begins to heat up, warming the air just above it. As the heating continues, the mixed (i.e., heated) layer becomes more unstable and the layer becomes deeper. What effect does a lapse rate, such as we see in the 10 A.M. diagram, have on plume behavior? A lot depends on the depth of the mixed layer. If the mixed layer is deeper than the height of the stack, the following behavior would apply: The inversion layer would act as a bottle cap trapping the pollutant below it (figure 10–9). The neutral (or unstable, as the case may be) layer below the inversion would promote vertical movements in the layer causing the trapped pollution to reach ground level. This type of plume is called a "fumigating" plume, and is a cause of air pollution events that could be damaging to plant and animal health. Normally, such an atmospheric condition is transient and by midday the sun has warmed up the lower atmosphere enough to completely destroy the inversion layer. Sometimes, however, a cloud deck moves in during the mid-morning which prevents further surface heating and allows the inversion layer to persist throughout the day much to the discomfort of the region's inhabitants.

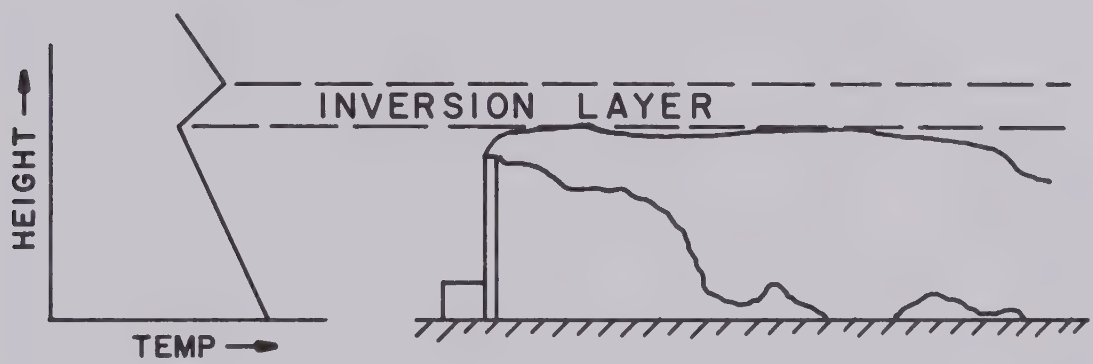


Figure 10–9

Sometimes there is the case where the inversion is very shallow. When this happens, the temperature profile looks like this (figure 10–10):

Note that in this case, the smoke plume is prevented from reaching the ground by the inversion layer *below* it (figure 10–10). (Recall that the stable layer prevents air from sinking through it from above as well as trapping air and pollution below it.) This type of plume is called a "lofting" plume. This is the least polluting of all plume types. Because of this, people who design power plants attempt to place the smoke stack outlet above the most common height of the nocturnal inversions. Almost all of the modern power plants have extremely tall stacks.

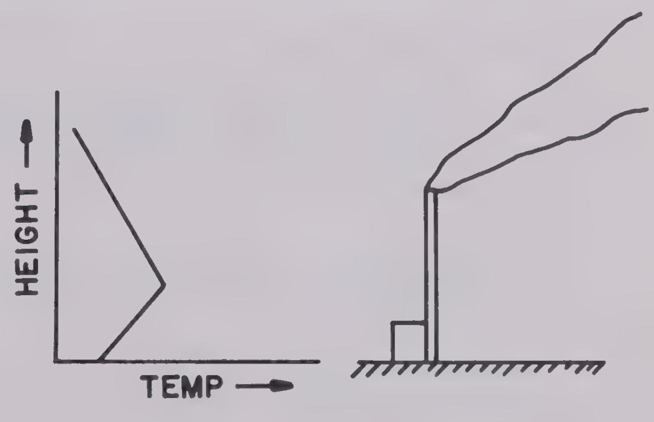
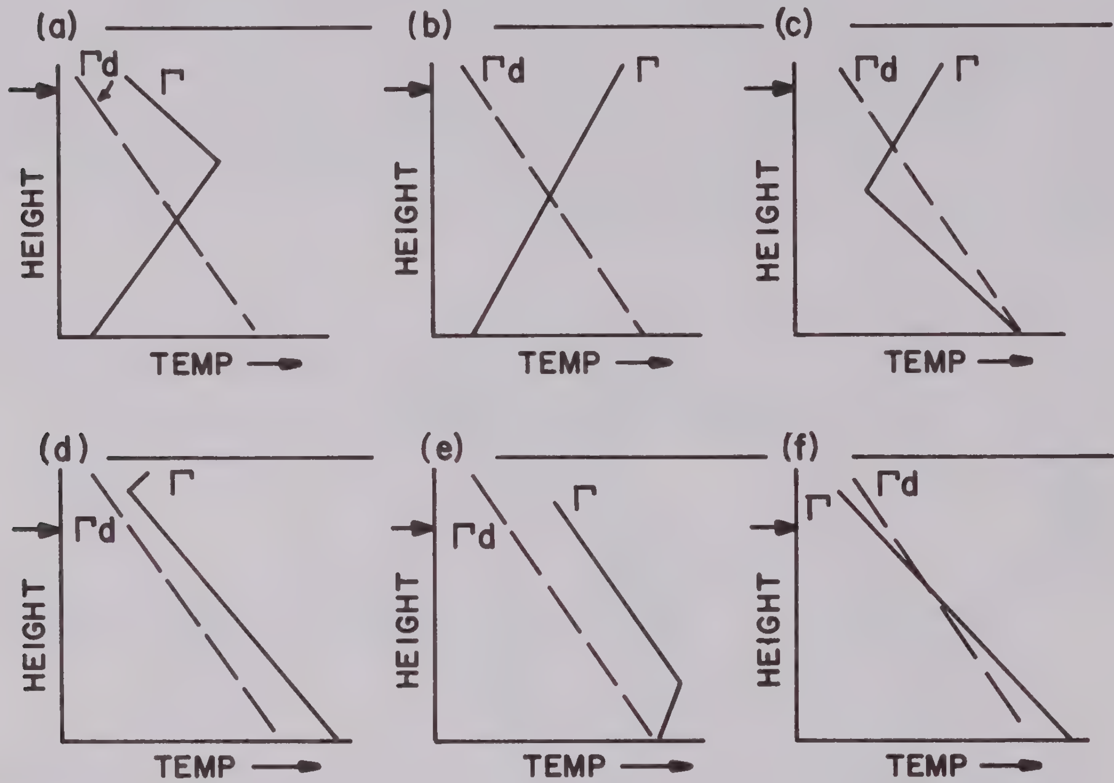


Figure 10–10

Problem 10–8

Here are several environmental lapse rates. The dry adiabatic lapse rate is indicated by a dashed line. The stack height is depicted by an arrow on the height axis. Identify the type of plume that you would expect to find for each atmospheric lapse rate.



Large Scale Pollution Events

Up to this point, our attention has been focused on isolated point sources. Unfortunately, most places that have a pollution problem are affected by many such point sources in a fairly confined area. When weather and topography combine to favor a large scale pollution event, the results can be dramatic indeed. (see plate 10–1.)

Problem 10–9

From what you have learned in the previous sections, where do you think the most likely place would be for a pollution episode?

a. Mountain top
b. Isolated rural valley
c. Industrial valley
d. Mixed farm and forest land

Why?

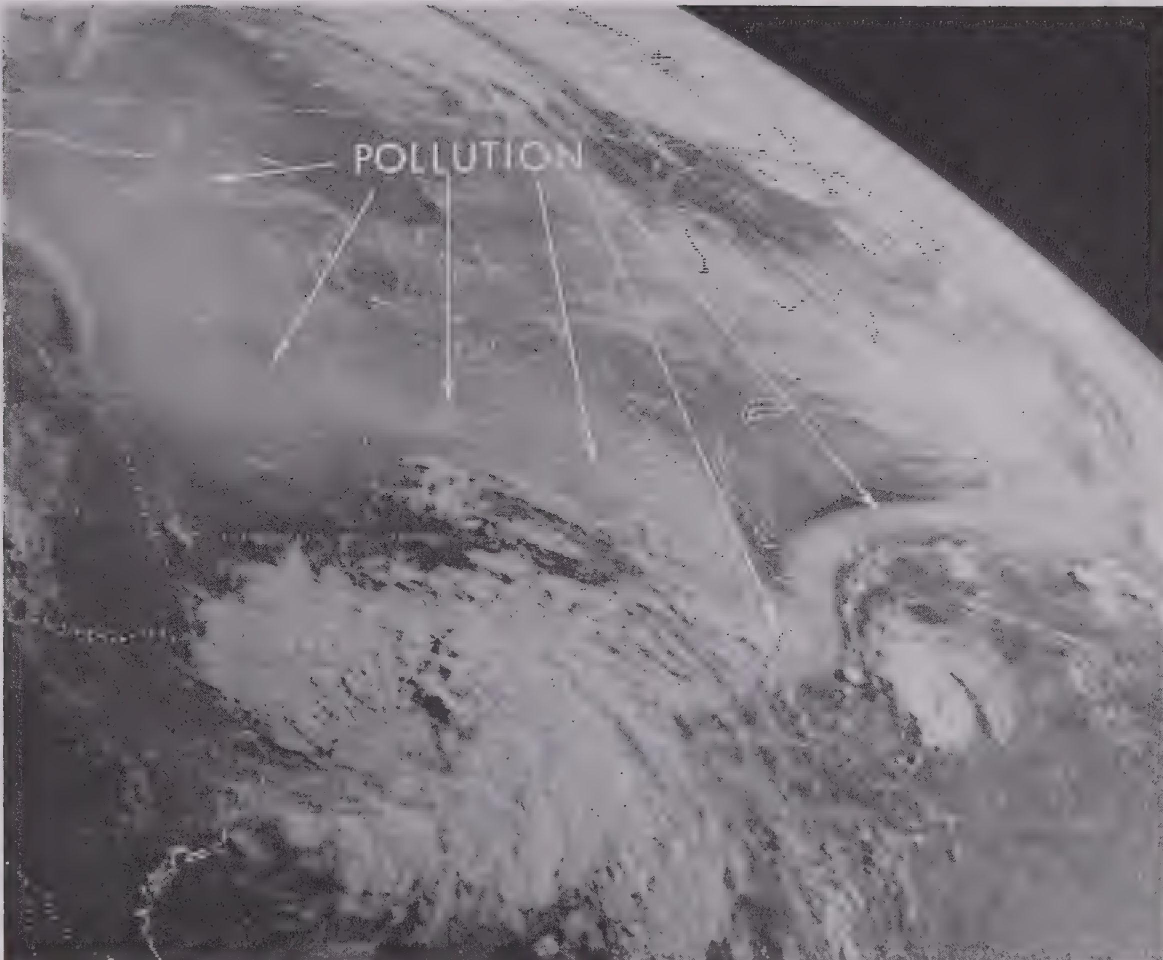


Plate 10–1

Problem 10–10

What kind of weather would contribute most to a large scale pollution episode?

a. Stable
b. Unstable

Why?

Large scale pollution events are caused by area sources of pollution (cities, industrial complexes, etc.) and by large scale weather phenomena. How do these large scale weather systems effect stability?

Looking back to exercise 3 (pressure), we recall that pressure is not linear with height. It is, in fact, logarithmic. Instead of the *height-temperature* diagram you are used to, we will now see what happens when we diagram the lifting or sinking of air on a *pressure*-temperature diagram (figure 10–11).

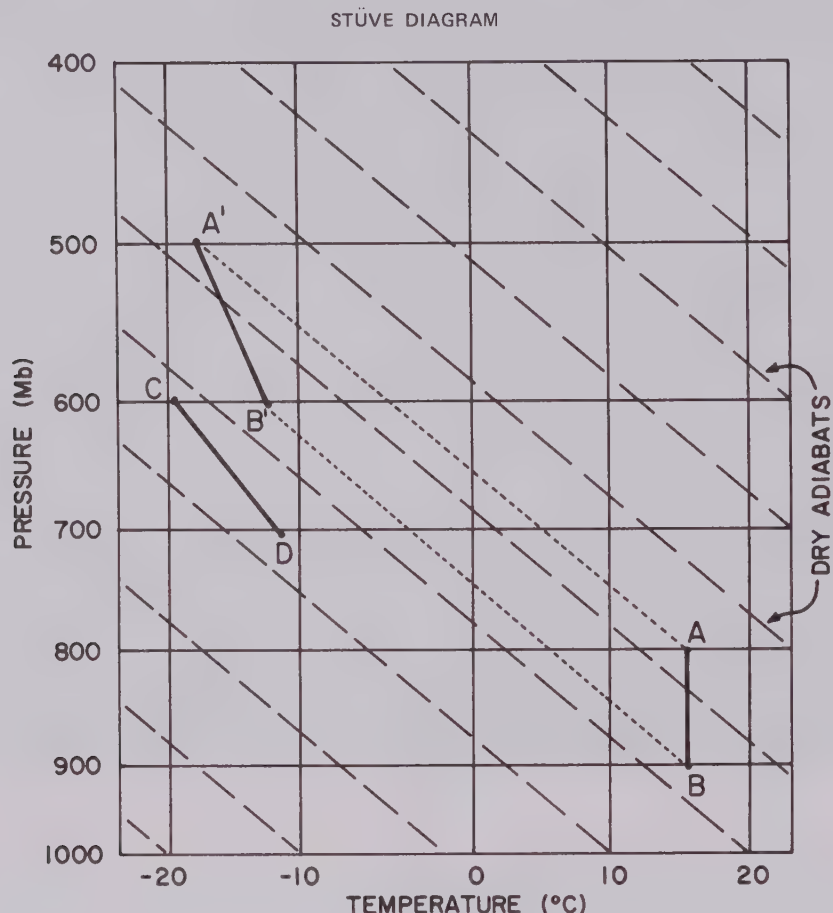


Figure 10–11

The y-axis on this diagram is not strictly a logarithm of P but P raised to a power of .288. This allows the dry adiabats to remain straight lines as in examples in earlier exercises. In figure 10–11 we have taken a layer of air 100 mb thick that is isothermal (see point A at 800 mb and point B at 900 mb). If this air is lifted, it will cool along the adiabats (dotted lines) until it reaches points A′ and B′ on the diagram. Because the *distance* from 500 mb to 600 mb is greater than the distance from 800 to 600 mb, the lapse rate of the lifted layer of air must change.

Problem 10–11

Look again at the lapse rate of the lifted layer (A′ to B′). Is it

a. More stable

b. Less stable

than the lapse rate of the original layer (A to B)?

Problem 10–12

Take the layer of air depicted by C D in figure 10–11 and cause it to descend to the 900 to 1,000 mb layer.

In other words, force it to the surface.

a. What happens to its stability?

b. Under what circumstances in nature does this sort of sinking air occur on a very large scale?

c. From this we can conclude that large scale air pollution episodes occur during __________ (fair, stormy) weather.

Summary

This exercise should have given you some insight into the awesome size of our atmosphere. You should also be aware of the great capability of the atmosphere to cleanse itself of impurities. Only when unfavorable weather conditions combine with large amounts of pollution do we get major air pollution events. On a smaller scale, local weather conditions (nocturnal inversions, for example) can combine with certain types of terrain to produce localized problems.

DISPERSION METEOROLOGY I

Introduction

If you were the president of a large oil company and wanted to develop a new refinery in, let's say, Ohio, you would have to comply with complex laws requiring you to protect the air quality of your proposed project region. One of the first things you would have your staff do is determine how much pollution your facility would emit. Once you determine this, you'll need to know where the pollution will go; that is, how the pollution will be dispersed. Not only will you have to know how the pollution will be dispersed, but what times of the year, even what times of the day will the pollution be dispersed most readily. The purpose of this and the following exercise is to present and discuss those parameters that comprise the study of dispersion meteorology.

In simplest terms, dispersion meteorology provides an evaluation of the capability of the atmosphere to disperse airborne effluents. The four basic parameters that comprise the study of dispersion meteorology include atmospheric stability, surface winds, mixing heights and inversions, and mixing layer wind speeds. The topography of a region also plays an important role. Dispersion potential tends to be poorest in valleys, especially where the ends are restricted, and best on hilltops or other exposed locations.

An understanding of the dispersion potential of a region makes it possible to estimate the impact of existing and proposed sources of ground level and elevated emissions of pollutants. For areas that are plagued with poor dispersion conditions, seemingly insignificant sources of pollution can result in excessive concentrations over large areas. Conversely, areas experiencing extremely good dispersion conditions lend themselves to most types of land and industrial development. We wish to make it clear at the outset that the dispersion meteorological parameters discussed in this exercise are differentiated from the climatological variables, such as temperature, precipitation, humidity and pressure, discussed previously. Though measurements of temperature at various heights can be used to determine atmospheric stability, and high and low pressure systems contribute to the formation of inversions, *by themselves* these variables do not have a direct impact on the dispersion of particulate or gaseous emissions.

Finally, you'll notice that several of the parameters we'll discuss here, most noticeably stability and inversions, were discussed in previous exercises. Our purpose in doing this is certainly not to confuse but, rather, to show that certain meteorological concepts have multiple uses. For example, a discussion of stability can be used to show not only why thunderstorms form but also to discuss how pollution from an industrial facility may be dispersed.

Only atmospheric stability as it relates to dispersion meteorology will be discussed in this first exercise. The next exercise, Dispersion Meteorology II, will present information on surface winds, inversions and mixing heights, and mixing layer winds.

Atmospheric Stability

One way the ability of the atmosphere to disperse air pollutants can be discussed is in terms of atmospheric stability. Previous exercises have shown that the atmosphere is typically referred to as being stable, unstable, or neutral. For purposes of our dispersion analysis, we generally expect stable atmospheric conditions to occur at night as cold air accumulates close to the surface and drains to lower elevations. Under such conditions, dispersion, both horizontally and vertically, is inhibited and wind speeds tend to be very light.

Dust emissions, such as those associated with mining activities or from vehicle travel along an unpaved road will have a maximum impact under stable, light wind speed conditions. However, emissions also tended to be lighter in the absence of strong surface wind speeds. Emissions from a tall power plant stack, on the other hand, are buoyant, because they are warm, and will tend to stay aloft and intact with minimal surface impact. Emissions from a short stack, such as those from a house chimney on a cold winter night, tend to stay close to the surface.

An unstable atmosphere occurs during periods of intense surface heating induced by strong solar radiation during the daylight hours. This results in good atmospheric mixing in the lower layers of the atmosphere. This mixing occurs primarily as a result of convective activity which creates extensive vertical displacement of air as warm parcels of air rise from the surface and displace cooler parcels of air at ambient temperatures aloft. Such conditions result in the rapid mixing or dispersion of airborne effluents. This is generally advantageous for the dispersion of air contaminants emitted near the surface such as those associated with dust releases from mining or construction activities. However, pollutants emitted by buoyant, elevated plumes can have a maximum impact at the surface under these conditions.

Neutral atmospheric stability is indicative of a windy, well-mixed atmosphere. Such conditions result from mechanical turbulence associated with mixing induced by either strong winds and/or surface roughness effects such as proximity to rugged terrain or among buildings in an urban environment. Neutral conditions also dominate in the absence of strong surface heating or nighttime radiational cooling. These conditions are generally associated with cloudy skies.

Neutral atmospheric stability does not generally result in maximum source-related pollutant concentrations. In the case of mining activities, the presence of neutral atmospheric conditions results in an unclear picture. Dispersion under such conditions is generally good due to good mechanical mixing and brisk wind speeds. However, these same strong wind speeds also increase the rate of emission of particulate matter (dust). In the case of a buoyant plume, neutral conditions do not generally represent a worst-case scenario although moderate ground-level concentrations can result at intermediate downwind distances from the source.

In summary, the effect of atmospheric stability on the dispersion of airborne effluents is strongly dependent on the height at which the pollution is released. Unstable conditions generally occur during periods of high positive net radiation (toward the earth's surface) and low wind speeds, while neutral conditions generally develop because of cloudy skies and/or high wind speeds. Therefore, in simplest terms, we can make the broad assumption that unstable conditions occur only during the day, stable conditions only occur at night, and neutral conditions can occur during either the day or night.

Problem 11–1

As operator of a large power plant, you may have to supply additional electricity to the regional power network at any time during a specific day of the week. You will have to run your equipment at a greater than normal capacity to accomplish your task. During what period of the day will you best be able to do this to minimize ground level pollution? Why? All of your emissions are emitted from a tall stack.

Problem 11–2

You are the operator of a large coal mine in northeastern Wyoming. To gain access to the coal, you have to remove several feet of soil that lies on top of it. (This material is typically called overburden.) The first step in doing this is to set-off an explosion to loosen the overburden. Since an explosion raises a considerable amount of dust, and you have to minimize dust emissions, what period of the day is it best to set-off your blasts? Why?

Measurements

Atmospheric stability can be measured using several types of instruments. As shown in previous exercises, stability can be assessed by determining how temperature changes with height. Obviously, then, if you had a very tall structure, such as a tower or a stack, you could put a thermometer near the bottom and one near the top. A measurement of the change in temperature with height would give you the lapse rate and you could determine if the atmosphere was stable, unstable or neutral. This method is commonly referred to as the delta T method since it relies on a change, or difference, in temperature with height. The Greek letter delta (Δ) is used to refer to a change or difference between two values.

The ΔT method is excellent and very reliable but it is only useful if the temperature sensors are at least 100 feet (30 meters) apart. Since it is not always possible to place instruments on structures this high, other methods of determining stability have been developed. One of these is the sigma-theta ($\sigma\theta$) method. The Greek letter sigma (σ) refers to standard deviation, a statistical analysis for determining the variability within a set of values. The Greek letter theta (θ) refers to the horizontal wind direction (that is, north, south, east, west, etc.).

Computations of $\sigma\theta$ have been correlated to the unstable, neutral and stable categories by several air pollution research scientists. $\sigma\theta$ can be determined in several ways including a statistical method and by means of an electronic calculation. The statistical method treats discrete wind direction values (such as 180°, 185°, 170°, etc.) as a data sample for which the standard deviation is then computed. The resulting value is then compared to a number which has been found to correspond to the unstable, neutral and stable categories. The electronic method uses a special circuit, attached to a wind vane, which performs the tedious computations of standard deviation automatically. Output from the electronic circuit are direct values of $\sigma\theta$ which are compared to the corresponding unstable, neutral and stable values.

Other instruments used for monitoring stability include a net radiometer and an acoustic sounder. Recall that we can consider unstable conditions to occur during periods when the earths surface is being strongly heated by the sun. Stable conditions can be expected when terrestrial heat is escaping to space. A net radiometer is a device used for measuring the difference between incoming and outgoing radiation using a very sensitive sensor. The strength of the incoming or outgoing radiation provides a measure of the stability of the atmosphere when the net radiometer measurements are combined with wind speed values in an empirical formula.

An acoustic sounder, sometimes referred to as acoustic radar or Doppler acoustic sounder, is a device which emits a brief pulse of sound energy at a particular frequency vertically into the lower atmosphere. The pulse echoes back from atmospheric "scatterers" to an antenna receiver located near the sound transmitter. The atmospheric scatterers are caused by temperature differences in the air or by mechanical (that is, wind driven) turbulence. If the scatterers are moving away from the antenna, the echo will be at a lower sound frequency than the transmitted pulse. If the scatterers are moving toward the antenna, the echo will be at a frequency higher than the transmitted signal. This change in frequency is called the Doppler Effect.

The acoustic sounder can yield considerable information on temperature and wind patterns aloft. A careful analysis of the data obtained by the instrument will show the difference between echoes caused by temperature variations, and those caused by wind speed or direction differences. Typically, temperature, or thermal echoes indicate an unstable atmosphere. Echoes caused by wind anomalies, also known as shear echoes, typically characterize a stable atmosphere. A neutral atmosphere may be present when either type of echo is heard. A careful analysis of other meteorological data must be made by the analyst to accurately categorize the various stability classes.

The Star Method

The instrumentation for monitoring stability, discussed above, is relatively expensive and is typically used in remote locations where trained meteorologists are not present, or at facilities where personnel are engaged in activities other than the hour by hour monitoring of the weather. The National Climatic Center (NCC) in Asheville, North Carolina utilizes a stability computation method which does not require special instruments but, rather, relies solely on the hourly weather observations made by meteorologists at National Weather Service (NWS) stations. Recall from the Introduction that we can consider unstable conditions as occurring primarily during periods of strong surface heating and low wind speeds, and that stable conditions usually occur when the earth's heat is escaping to space (high negative net radiation) and winds are light. Also, neutral conditions, it was said, can occur when it is cloudy and/or windy. The NCC method, then, utilizes observations of cloud cover, made hourly by the stations weather observer, coupled with the wind speed observed when the sky observation was made.

The data produced from the cloud cover and wind speed observations are referred to as STAR (for Stability Array) data. Historical STAR data are extremely useful because they can be obtained quickly from the NCC and they are relatively inexpensive. In addition, rather than simply considering the atmosphere as unstable, neutral, or stable, much more accurate classifications can be determined. Table 11–1 presents seven stability classes which can be calculated using the STAR method. More definitive information such as this is required for the sensitive computer modeling that must be done to accurately determine where pollution from an industrial facility will travel.

TABLE 11–1
Stability Classifications Available from the NCC Star Method

Class	Name
1	Extremely unstable
2	Unstable
3	Slightly unstable
4	Neutral
5	Slightly stable
6	Stable
7	Extremely stable

Table 11–2 shows how to determine stability based upon net radiation and wind speed. Net radiation refers to all incoming solar radiation or all outgoing terrestrial radiation or a combination of both. It is expressed in table 11–2 as a Net Radiation Index (NRI). The NRI is determined by the following method:

TABLE 11-2
Stability Class as Determined from Net Radiation and Wind Speed

Wind Speed (Knots)	Net Radiation Index 4	3	2	1	0	−1	−2
0–1	1	1	2	3	4	6	7
2–3	1	2	2	3	4	6	7
4–5	1	2	3	4	4	5	6
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8–9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
12 or more	3	4	4	4	4	4	4

1. If the total cloud cover is 10/10 (sky is completely overcast) and the ceiling is less than 7000 feet (2134 meters), the NRI is 0.
2. For night-time (for this method night is defined as the period from one hour before sunset to one hour after sunrise):
   a. If the total cloud cover is 4/10 or less, the NRI is −2.
   b. If the total cloud cover is greater than 4/10, the NRI is −1.
3. For daytime:
   a. Since atmospheric stability during the day depends on how much solar energy the earth receives and, since this depends on the angle at which the suns rays strike the earth (the angle of the sun above the horizon), you must first determine the Insolation Class Number based on solar altitude from table 11–3.

TABLE 11-3
Insolation Class Number Based on Solar Altitude

If Solar Altitude is:	Insolation Is Classified as:	And the Insolation Class No. Is:
Greater than 60°	Strong	4
Greater than 35° but less than or equal to 60°	Moderate	3
Greater than 15° but less than or equal to 35°	Slight	2
Less than or equal to 15°	Weak	1

   b. Now that you have the Insolation Class Number, it must be modified to take cloud cover into account. If total cloud cover is less than or equal to 5/10 the NRI equals the Insolation Class Number.
   c. If cloud cover is more than 5/10, modify the Insolation Class Number by the following six steps:
      1. If the ceiling is less than 7000 feet (2134 meters), subtract 2;
      2. If the ceiling is between 7000 and 16000 feet (2134–4878 meters), subtract 1;
      3. If the sky is completely overcast (10/10 cloud cover) and the ceiling is greater than 7000 feet (2134 meters), subtract 1;
      4. If 1, 2 or 3 do not apply, no modification is needed;

5. If your modification gives you a number equal to 0, let the modified Insolation Class Number equal 1;
6. Once you have completed steps 1–5, use the NRI in table 11–2 corresponding to your modified Insolation Class Number.

To properly use the STAR method to determine stability, you will need to understand the term ceiling. Ceiling, or ceiling height, is defined to be the distance between the surface and the layer of clouds that covers the sky by more than 5/10. Therefore, when you look at the sky and see multiple layers of clouds you will have to estimate which layer covers the sky by more than 5/10 and approximately how high it is to determine the ceiling.

Now let's look at some examples. (All examples apply to mid-latitude stations.)

Example 1

It is 10 o'clock at night. You study the sky and determine that there are only a few clouds since you can see many stars. Therefore, you conclude that the sky is nearly clear (less than or equal to 4/10 cloud cover). There is no wind.

Answer

From step 2a, the Net Radiation Index is equal to −2. From table 11–2, an NRI of −2 and calm winds yield a stability class equal to 7, extremely stable.

Example 2

It is 10 o'clock in the morning in December. The sky is completely overcast with very low clouds. (It's one of those days when it looks like it's going to rain any minute.) You conclude that the ceiling height is less than 7000 feet. The winds are blowing at about 10 knots.

Answer

You can't see the sun but, in winter at 10 a.m. you know that its going to be at an angle between 35° and 60°. From table 11–3, the Insolation Class Number is 3. Step 3c tells you to modify this number if cloud cover is more than 5/10. Step 3c1 applies here, so you subtract 2 from the Insolation Class Number. The modified number now equals 1. You set this equal to the NRI. From table 11–2, an NRI of 1 with 10 knot winds yields a stability class equal to 4, Neutral.

Example 3

It is noon in the summer. Skies are clear and there is no wind.

Answer

The sun is almost overhead at this time of the year at mid-day. Therefore, the solar altitude is greater than 60° and, from table 11–3, the Insolation Class Number equals 4. Step 3b shows that no modification is necessary since the cloud cover is less than 5/10. Therefore, set the NRI to the Insolation Class Number. Table 11–2 shows that an NRI equal to 4 with calm winds yields a stability class of 1, Extremely Unstable.

Example 4

It is about two hours before sunset in the winter. Rain clouds are dissipating, the sky is bright with the last rays of the sun but the sky is still covered quite heavily with clouds. You conclude that cloud cover is greater than 5/10. There are a few low rain clouds left but mostly there are higher clouds but not the very high wispy clouds called cirrus. You determine that the ceiling height is more than 7000 feet but less than 16,000 feet. Winds are strong behind the departing rain storm—probably about 15 knots.

Answer

Since this is still a daytime condition, you must determine the Insolation Class Number. At this time of day in the winter, the sun is very low in the sky. We'll assume here that, according to table 11–3, insolation is weak (solar altitude less than 15°) and the Insolation Class Number equals 1. Step 3c says we must modify this number because cloud cover is greater than 5/10. Because of our ceiling determination, we use step 3c2. The modified number now equals 0. However, step 3c5 says that if the modified number is less than 1, we must make it equal to 1. Now, from table 11–2, an NRI of 1 with winds greater than 12 knot, yields a stability class of 4, Neutral.

Example 5

It is just after sunset. You have the same sky conditions as noted in Example 4 *except* that the winds are only blowing at about 5 knots.

Answer

Because it is just after sunset, follow step 2. Specifically, because cloud cover is more than 4/10, use step 2b which sets the NRI equal to −1. From table 11–2, an NRI of −1 with winds of 5 knots yields a stability class equal to 5, Slightly Stable.

Problem 11–3

Go back to table 11–2 and enclose, by use of a solid line, all of the Stability Class numbers corresponding to the unstable category (that is, Classes 1, 2 and 3). Do the same for the neutral category (Class 4) and the stable categories (classes 5, 6 and 7). Does the atmosphere become more or less unstable as wind speed increases? Does it become more or less stable as wind speed increases?

Problem 11–4

According to the STAR Method, when is the only time atmospheric stability can be neutral with calm, or nearly calm winds (3 knots or less)?

Problem 11–5

From table 11–2, we see that the NRI depends on insolation. As insolation becomes weaker, does the atmosphere become more unstable or more stable when winds are light?

Problem 11–6

It is just before sunrise. Skies are clear and winds are calm. What is the stability class?

Problem 11–7

It is 1 o'clock in the afternoon in summer. High clouds (higher than 16,000 feet) from an approaching thunderstorms cover the sky. Winds are calm. What is the stability?

Problem 11–8

It is midnight. Skies are overcast and the winds are 10 knots. What is the stability?

Problem 11–9

Determine a set of conditions that would yield a stability class of 6, Stable.

Problem 11–10

Determine a set of conditions that would yield a stability class of 3, Slightly Unstable.

Problem 11–11

In Example 2, how would you describe the stability class if the winds were calm?

Problem 11–12

Make two stability observations on two different days. Record all of your data and results below. (You can estimate cloud cover and ceiling height yourself or by contacting your campus weather station or nearest NWS station. Wind speed data can be obtained similarly or by listening to your local radio weather report.)

Observation 1		**Observation 2**	
Date		Date	
Time		Time	
Weather		Weather	
Cloud Cover		Cloud Cover	
Ceiling		Ceiling	
Winds		Winds	
Stability		Stability	

Problem 11–13

If you were driving along an unpaved road during the stability conditions you observed in Observation 1 of Problem 11–12, would you expect the dust you generated to be readily dispersed or to linger above the roadway for awhile? What about during Observation 2?

STAR data for nearly every NWS station in the U.S. are available from the NCC. The NCC takes the observations from the stations, processes them in a computer using the methodology you just learned and prepares extensive data tabulations of stability for different wind conditions and for different times of year. These data can be purchased from the NCC and summarized in the form of bar charts to simplify analysis.

The seasonal and annual stability data shown in figures 11–1 and 11–2 were prepared from STAR data for Greensboro, North Carolina and Miles City, Montana. The Greensboro data show that neutral conditions predominate (41% of the time) during the annual period. Seasonally, neutral conditions occur most often in winter (56%) and least often in summer (27%). Stable conditions occur about 38% of the time during the year. A stable atmosphere is observed most often in the fall (43%) and least often in winter (35%). Unstable conditions are observed most often in summer (35%) and least often in winter (9%). During a given 12–month period, we can expect unstable conditions to occur about 21% of the time at Greensboro.

Problem 11–14

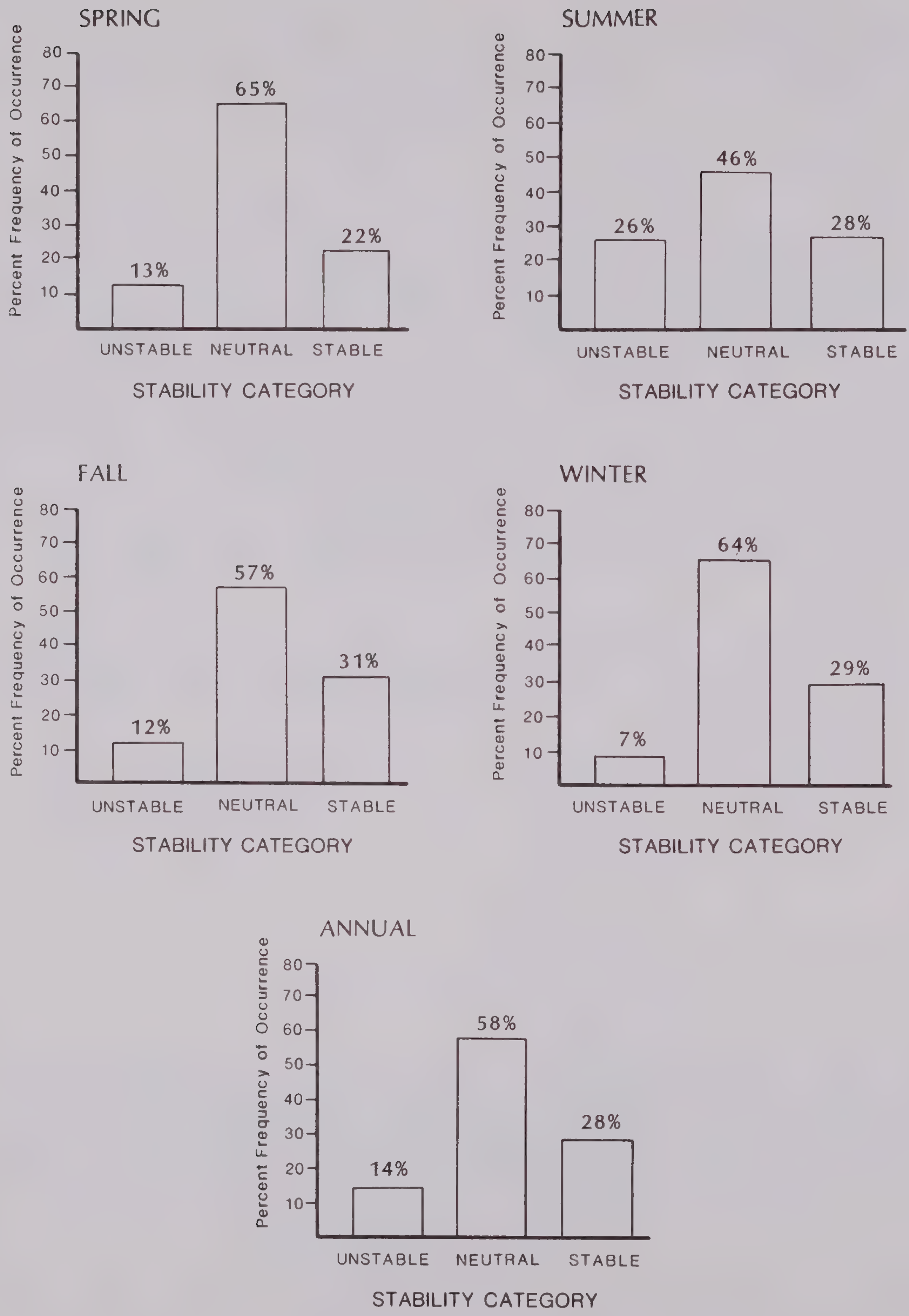
Average cloud cover data for Greensboro are given in table 11–4. Using these data, why do you think neutral conditions occur most often in the winter?

Problem 11–15

You've learned that the STAR Method assumes that stable conditions occur only at night. You've also learned that stable conditions occur during periods when terrestrial radiation can readily escape to space. Terrestrial radiation cannot escape readily, however, when there are clouds present because the clouds act like a "blanket" to keep the terrestrial heat near the earth. Knowing all this, and using table 11–4, why do you think stable conditions occur least often in the winter at Greensboro?

Seasonal and Annual Stability Distributions
Greensboro, North Carolina

Figure 11-1



Seasonal and Annual Stability Distributions
Miles City, Montana

Figure 11-2

TABLE 11–4
Average Cloud Cover Data for Greensboro, North Carolina

Season	Average Cloud Cover (in Tenths)
Winter	6.1
Spring	5.7
Summer	6.0
Fall	5.1
Annual	5.8

Problem 11–16

Why do you think unstable conditions predominate in summer at Greensboro?

Problem 11–17

Write a brief summary, similar to the one given for Greensboro, for the Miles City, Montana data given in figure 11–2.

Problem 11–18

Table 11–5 presents average cloud cover data for Miles City. Which are the two cloudiest seasons of the year? How do these data compare with the maximum seasonal occurrences of stable conditions?

TABLE 11–5
Average Cloud Cover Data for Miles City, Montana

Season	Average Cloud Cover (in Tenths)
Winter	6.8
Spring	6.7
Summer	4.5
Fall	5.7
Annual	5.9

Problem 11–19

Stable conditions occur most often in the fall at Miles City (31% of the time) but summer is the season when cloud cover is lowest for the year. Since the STAR Method relies on cloud cover and winds, what can you surmise about the winds in the fall as compared to summer based on the occurrence of stable conditions?

Problem 11–20

Figures 11–1 and 11–2 show that, annually, neutral conditions occur 17% more often at Miles City than at Greensboro. Tables 11–4 and 11–5 show, however, that average annual cloud cover is about the same at both stations. What can you say about the average annual wind speed at Miles City that would explain why neutral conditions occur more often there?

Summary

Dispersion meteorology is a specialized segment of the science of meteorology that allows one to determine how pollution will be mixed in the atmosphere and where it will go. The dispersion of pollutants depends on several factors. One of the most important is atmospheric stability. This exercise, the first of two on dispersion meteorology, introduced you to the concept of stability as it relates to pollution studies.

Stability is not a terribly complicated topic. It is simply a measure of the atmosphere's ability to "mix itself up" and thus allow material traveling in the atmosphere to disperse. There are basically three stability classes: unstable, neutral and stable, which can be subdivided even further for detailed computer analysis. As used in this exercise, we've discussed stability in a manner that is different from the discussion in other exercises. Don't be confused, however. The overall concept is still the same. Because it is such a broad and important physical process, it can be related to thunderstorm development as well as the movement of pollution.

The other topics that comprise dispersion meteorology are discussed in the next exercise. By the time you finish Exercise 12, you should have a good understanding for the factors that dictate pollution transport, and for the role of the meteorologist who must try to predict what areas may be affected by the emissions from a proposed industrial development.

DISPERSION METEOROLOGY II

The previous exercise presented the principles and purposes of dispersion meteorology analysis. It also discussed the concept of atmospheric stability and how it relates to the process of dispersing pollution in the atmosphere. This exercise continues that discussion with the presentation of sections on surface winds, mixing heights and inversions, and mixing layer wind speeds.

Surface Winds

The distribution of the prevailing surface winds is important from the viewpoint of both climatology and dispersion meteorology. The preferred direction of wind flow plays an important role, for example, in the location of areas experiencing increased rainfall amounts due to orographic lifting. The prevailing winds also dictate local and regional transport characteristics for pollutants. In this section, surface winds are distinguished from upper level winds which will be discussed in the section on mixing layer winds.

There are a variety of instruments available for monitoring wind speed and direction. The most common methods use the simple three cup anemometer and wind vane. The typical anemometer consists of three small cups attached to a vertical drive shaft. The cup assembly and drive shaft rotate as the winds flows past the sensor. When this happens, a small assembly, called a light beam chopper, alternately masks and exposes a sensitive circuit to a miniature light source. The sensor responds to the light striking it and produces an electrical impulse which corresponds to the wind speed.

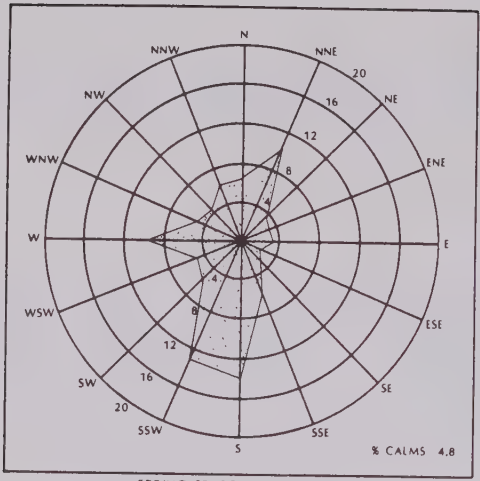
Other wind speed sensors have a configuration like an airplane propeller. Wind speed in some of these units is proportional to the number of revolutions that the propeller turns in a given period of time. In other units, the rotation of the propeller generates an alternating electrical current that is proportional to the wind speed.

Wind direction is typically measured by a counter-balanced wind vane that always points into the wind. As the vane rotates, the vertical shaft revolves around a precision electrical assembly. A small electrical voltage is produced which corresponds to the various directions from 0° to 359°.

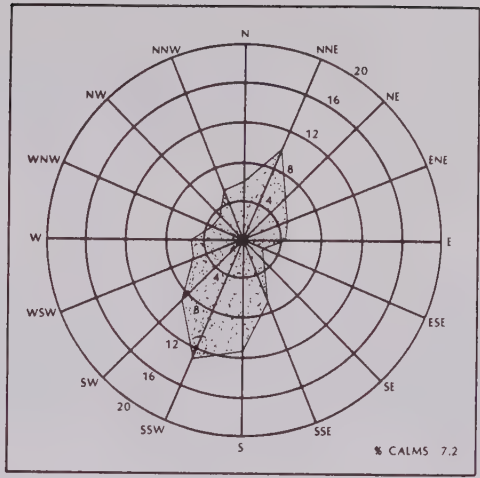
Vertical wind direction is occasionally measured simultaneously with horizontal direction by means of an instrument called a bivane. Sensor operation is similar to that described above. A bivane can be used to monitor atmospheric stability since it provides a measure of the up and down motion of the atmosphere. It is only occasionally used in air pollution studies.

Wind data are best presented through the use of wind roses. Wind roses provide a graphical representation of the frequency of occurrence of winds from each of the sixteen cardinal directions for specified averaging periods. Typical averaging periods for dispersion meteorology studies are seasonally and annually.

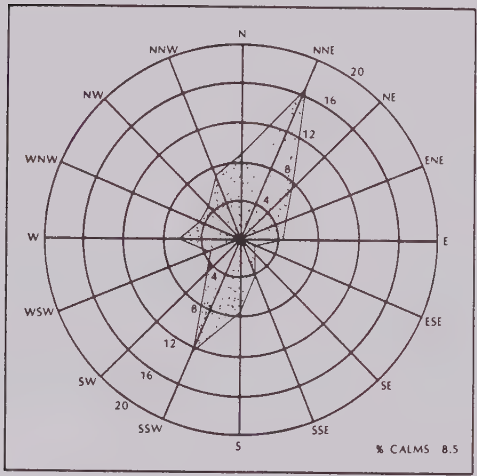
Figure 12–1 presents an annual wind rose for Greensboro, North Carolina along with wind roses for the spring, summer and fall seasons. The annual wind rose was prepared from the data given on page 153.



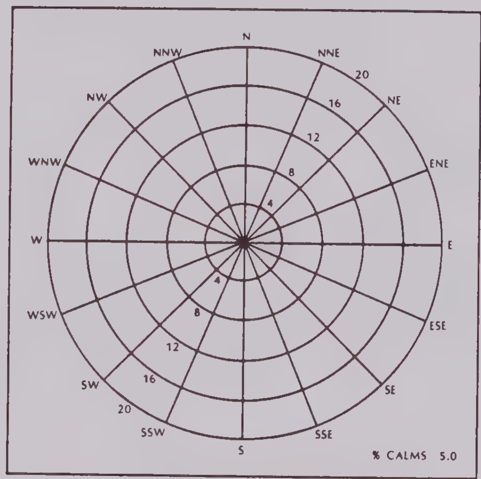
SPRING SEASON WIND ROSE



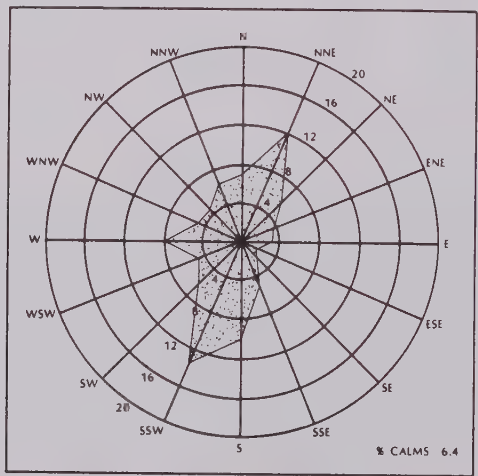
SUMMER SEASON WIND ROSE



FALL SEASON WIND ROSE



WINTER SEASON WIND ROSE



ANNUAL WIND ROSE

SEASONAL AND ANNUAL WIND ROSE DISTRIBUTION
Greensboro, North Carolina

Figure 12-1

Direction	Frequency of Occurrence	Direction	Frequency of Occurrence
N	7.0%	S	10.1%
NNE	12.2%	SSW	13.5%
NE	5.9%	SW	6.1%
ENE	3.9%	WSW	5.0%
E	3.5%	W	8.0%
ESE	1.8%	WNW	7.0%
SE	2.1%	NW	4.9%
SSE	5.0%	NNW	6.2%

"Frequency of occurrence" refers to how often the wind occurred from a given direction during the period of time that the data were collected. For example, figure 12–1 was completed from data collected over a five-year period. On the annual wind rose, we can say that during the five year period of record, north and west-northwest winds were observed 7.0% of the time. South-southeast winds were noted 5.0% of the time while west winds occurred 8% of the time.

Problem 12–1

Based on the data given above and presented on the annual wind rose in figure 12–1, from which two directions does the wind flow most often at Greensboro? From which two directions does the wind flow least often?

Problem 12–2

Winter season wind direction data for Greensboro are given below. Plot these data on the blank wind rose in figure 12–1.

Direction	Frequency of Occurrence	Direction	Frequency of Occurrence
N	6.2%	S	6.2%
NNE	13.2%	SSW	15.7%
NE	5.3%	SW	6.1%
ENE	2.1%	WSW	5.1%
E	2.0%	W	10.0%
ESE	1.0%	WNW	7.2%
SE	0.8%	NW	7.0%
SSE	3.7%	NNW	7.5%

Problem 12–3

Table 12–1 presents average seasonal and annual wind speed data for Greensboro. Which two seasons have the highest average wind speed? During these seasons, from which two directions is the wind speed strongest? Knowing what you do about synoptic scale weather systems, why do you think wind speeds are strongest during these seasons?

TABLE 12–1
Mean Seasonal and Annual Wind Speed (MPH) Greensboro, North Carolina

Direction	Winter	Spring	Summer	Fall	Annual
N	7.5	8.0	6.0	6.9	7.1
NNE	9.0	9.0	7.1	7.8	8.3
NE	8.3	8.3	7.1	6.9	7.5
ENE	6.2	6.9	5.9	6.0	6.2
E	5.3	6.4	5.8	6.1	5.9
ESE	5.8	6.7	6.0	6.0	6.1
SE	6.2	6.8	6.4	6.0	6.4
SSE	6.9	7.6	6.6	6.8	7.0
S	7.5	8.2	6.7	6.3	7.4
SSW	8.3	8.2	6.7	6.9	7.6
SW	8.4	8.4	6.7	6.9	7.6
WSW	8.6	8.5	6.6	7.7	7.8
W	10.0	10.1	7.0	7.8	9.0
WNW	11.0	9.9	7.0	8.3	9.4
NW	9.2	8.9	6.2	7.9	8.3
NNW	8.2	7.8	6.3	7.4	7.5
Calms	5.0%	4.8%	7.2%	8.5%	6.4%
Average	8.0	7.9	6.1	6.6	7.1

Problem 12–4

Figure 11–1 in the previous exercise showed that neutral stability occurs most often in the winter at Greensboro. Do the data in table 12–1 (and your answer to the previous question) substantiate this? Why?

Problem 12–5

According to table 12–1, during what season of the year are calm winds most prevalent at Greensboro? Is this consistent with the data in figure 11–1 in the previous exercise which showed that stable conditions occur most frequently during the fall at Greensboro?

Figure 12–2 presents a different type of computer generated wind rose for Miles City, Montana. These "telescopic" wind roses combine wind speed and wind direction data within the same graphical representation. Note that a key to the wind speed data is given in the upper right hand corner of each plot while data on calms are given in the upper left corner.

The seasonal and annual wind roses for Miles City can be explained through an understanding of the manner in which high and low pressure systems migrate through the region. Normally, high pressure systems, with a clockwise circulation of air around the center of the system, enter Montana either from the northwest or the west. As the system moves eastward or southeastward, the clockwise circulation around the high will cause a predominance of northwesterly flow in this area. As the systems progress eastward, the return southerly flow is generally from a south-southeasterly direction. Low pressure systems, on the other hand, usually migrate along an easterly track located south of the state. The counterclockwise circulation of air around the low pressure system causes a generally south-southeasterly flow of air into eastern Montana. The spring and summer wind roses generally show a slightly lower frequency of occurrence of south-southeasterly winds in this region indicating that storms (low pressure systems) are not as common during these seasons.

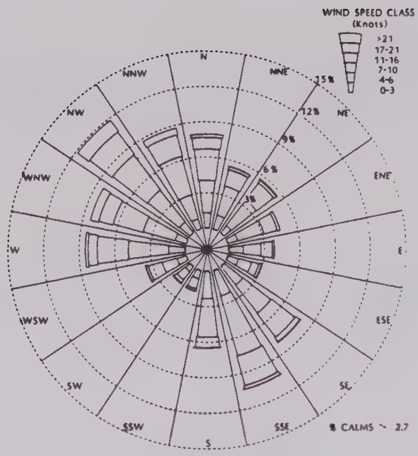
Problem 12–6

During what season of the year do calm winds occur least often at Miles City? Do you think neutral stability conditions may also occur most often during this season? Check figure 11–2 in the previous exercise to find out.

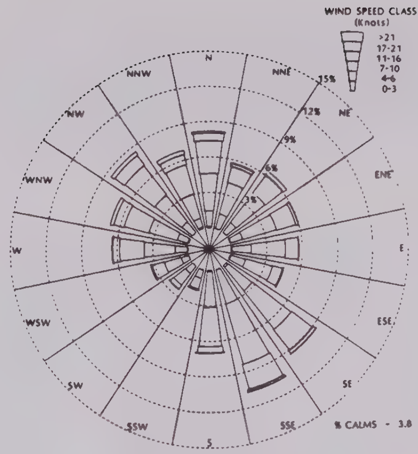
Mixing Heights and Inversions

Atmospheric stability provides a quantitative measure of the ability of the atmosphere to mix and disperse pollutants, but gives no indication of the vertical extent of this mixing. Even the most unstable atmosphere can be capped by a relatively stable layer aloft which limits the volume of air available for the mixing of airborne pollutants. The height above the surface of this limiting layer is defined as the mixing height. The mixing depth, then, is the layer of atmosphere between the surface and the stable air aloft through which relatively vigorous vertical mixing can occur.

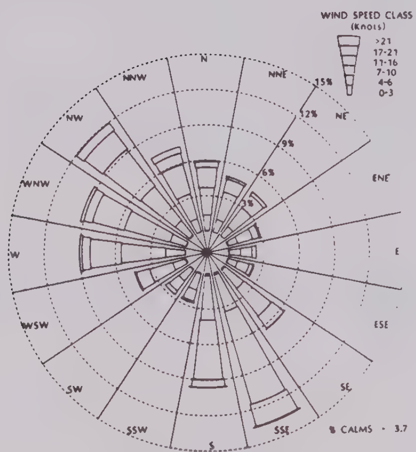
The level of the mixing height is calculated from routine measurements of surface and upper air temperatures and is generally not measured directly. Data to determine the presence and strength of an inversion and the depth of the mixing layer are collected twice daily through the use of radiosondes. As discussed in Exercise 1, radiosondes are instrument packages carried aloft by large, helium-filled balloons.



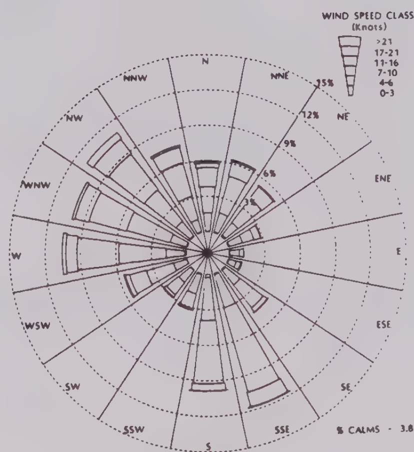
SPRING SEASON WIND ROSE



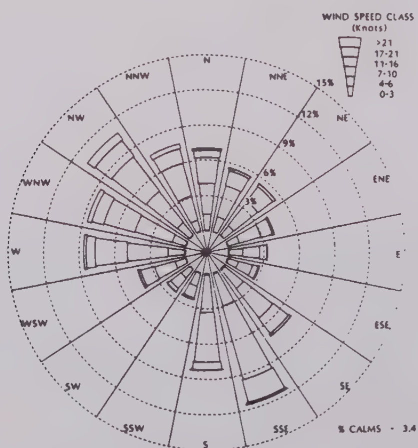
SUMMER SEASON WIND ROSE



FALL SEASON WIND ROSE



WINTER SEASON WIND ROSE



ANNUAL WIND ROSE

SEASONAL AND ANNUAL WIND ROSE DISTRIBUTIONS
Miles City, Montana

Figure 12–2

Exercises 4 and 9 discussed the fact that temperature normally decreases with height at a rate of 1°C for every 100 meters of elevation. This is referred to as the lapse rate. Layers of the atmosphere through which the temperature decreases at a slower rate or actually increases with height are called stable, with the latter condition known as an inversion. Air that is being lifted from the surface generally cools at the normal lapse rate. If a rising air parcel encounters an inversion or stable layer, it is then colder than the surrounding air and sinks back down to the bottom of the inversion. In this way, inversions serve to limit the volume of air available for the mixing of pollutants released at or near the surface.

The type and frequency of occurrence of temperature inversions play an important role in the overall description of the dispersion meteorology of a region. Basically, surface-based inversions result in a layer of stable air close to the ground usually with very light wind speeds. This type of situation tends to maximize the impact from both nonbuoyant, ground-level sources and elevated sources such as power facilities, refineries, etc. Elevated inversions, on the other hand, limit the depth of the atmosphere within which pollutants can be mixed and dispersed. This type of inversion has less of an impact on ground-level emissions though the impact from elevated sources may still be significant.

A typical diurnal scenario finds mixing heights to be lowest during the early morning hours due to the presence of a surface or low-level inversion. As surface heating progresses during the morning, the surface inversion is eroded and finally dissipated. However, an elevated subsidence inversion (usually attendant with the presence of high pressure systems) often exists at higher levels. Thus, as the mixing height increases, it is usually still limited, although to a much lesser degree, by the presence of the elevated inversion. For this reason, mixing heights are generally calculated for both the morning and afternoon periods.

Let's look at an example. Table 12–2 presents mixing layer heights for the Greensboro, North Carolina region for the morning and afternoon, and for each season and the annual period.

TABLE 12–2
Mean Seasonal and Annual Mixing Heights for Greensboro, North Carolina

Period	Morning		Afternoon	
	Feet	Meters	Feet	Meters
Winter	1574	480	3247	990
Spring	1607	490	5789	1765
Summer	1460	445	5609	1710
Fall	1115	340	4362	1330
Annual	1443	440	4756	1450

Mean annual morning mixing heights in this region are approximately 33 percent of their afternoon averages, 1443 feet versus 4756 feet. The low morning values result from the formation of intense inversions on mostly clear nights. These inversions severely limit the depth of the atmosphere through which ground-based emissions can be mixed.

On a seasonal basis, morning mixing heights are greatest in spring (1607 feet) and lowest in fall (1115 feet). The fall minimum is the result of the relatively low cloud cover at this time of year. Spring sky conditions are among the cloudiest for the year. Cloud cover at night restricts the formation of nocturnal inversions near the surface thus allowing the mixing height to develop at a higher latitude than when the sky is clear.

Afternoon mixing heights are lowest in winter (3247 feet) and highest in spring (5789 feet) and summer (5609 feet). Reduced heating in winter does not allow the evening inversions to disperse as rapidly or to rise to a higher altitude. In spring and summer, as the days become longer, increased solar heating not only disperses the nocturnal inversions more rapidly but also pushes the inversion to a higher altitude. Additionally, high pressure systems, which promote upper air inversions, become stronger and more prevalent during these seasons.

Finally, seasonal variations in the mean morning mixing height are not as great as they are for the mean afternoon mixing height. The largest seasonal difference during the afternoon is about 2550 feet between spring and winter, while the smallest seasonal difference during the morning is only about 490 feet between spring and fall. This is directly attributable to the wide variation in solar radiation between spring and winter and to the small difference in solar radiation between spring and fall. At night the only two variables affecting mixing heights are wind speed and cloud cover, whereas during the day the insolation effect usually exceeds the influence of winds and clouds. This is especially true during the spring and summer when the days become long and the solar angle is large.

Table 12–3 presents mixing height data for Miles City, Montana. Mean annual morning mixing heights in this region are approximately one-fifth of their afternoon averages (1148 feet versus 5906 feet). These low morning values are the result of the formation of intense radiation inversions on mostly clear nights. These radiation inversions severely limit the depth of the atmosphere through which ground-based emissions can be mixed. The data presented in table 12–3, show that morning mixing heights do not exhibit the same seasonal pattern as the afternoon mixing heights (that is, maximum in summer, minimum in winter). Rather, morning mixing heights are generally highest in the spring and lowest during the fall. This is due to the fact that the amount of cloud cover during the spring months is among the highest for the year while fall values of cloud cover are among the lowest. Wind speeds also tend to be lower during the fall. Cloud cover restricts the formation of nocturnal inversions, acting essentially as a blanket to prevent terrestrial heat from escaping to space, thus keeping the surface warm. In addition, seasonal variations from the annual morning mean are not as great as they are for the afternoon mean. The seasonal difference during the afternoon is about 4921 feet (between spring and winter) while the seasonal difference during the morning is only about 492 feet (between spring and fall).

TABLE 12–3
Mean Seasonal and Annual Mixing Height Data for Miles City, Montana

Period	Morning		Afternoon	
	Feet	Meters	Feet	Meters
Winter	984	300	2953	900
Spring	1312	400	7874	2400
Summer	984	300	9187	2800
Fall	820	250	5250	1600
Annual	1148	350	5906	1800

Problem 12–7

Explain the concept of mixing depth. How is the mixing height determined? Why is a knowledge of mixing depth important?

Problem 12–8

From the data in tables 12–2 and 12–3, what period of the day is best for the dispersal of pollutants from a source of emissions near the surface? Why? Would you expect the same answer if the emissions were coming from a very tall stack? (Refer back to the Introduction to Exercise 10.)

We can supplement our understanding of the dispersion potential of a region by analyzing the inversion data directly. Table 12–4 presents the frequency of occurrence of inversions at Greensboro for 7:00 A.M. EST and for 7:00 P.M. EST. The data are presented as a percent frequency of occurrence for inversions with varying base heights.

Since 7:00 A.M. is slightly before sunrise in this region during the winter and slightly after sunrise in summer, the presence of surface-based, nocturnal inversions would be expected during all seasons at this time with a slightly higher percentage expected in winter. The data presented in table 12–4 show a high frequency of occurrence of surface inversions during all seasons of the year with a maximum occurrence in fall (74.4%). The high frequency of occurrence of surface-based inversions during this season is a direct result of the frequent occurrence of clear skies and calm winds which occur at this time of the morning. The minimum frequence of occurrence of surface-based inversions occurs during summer (60.3%). This diminished frequency of surface-based inversions is the result of the early sunrise in this season which results in surface heating that degrades surface-based inversions before the 7:00 A.M. observation is taken.

As the sun rises and surface heating increases, mixing increases at the surface and the early morning, surface-based inversions decay and become elevated inversions or dissipate completely. The data presented in table 12–4 show that the majority of the late afternoon inversion base heights occur above the surface. Surface-based inversions are observed most often in fall (48.7%) and least frequently in summer (8.2%). These data indicate that in summer, vigorous heating is still occurring at 7:00 P.M. while, in fall, the sun has begun to set at this time and surface inversions begin to form. The maximum occurrence of evening surface-based inversions does not occur in winter (when the sun is well below the horizon at 7:00 P.M.) because of increased winter cloudiness which inhibits the formation of surface inversions.

TABLE 12–4

Frequency of Inversion Occurrence (Percent) at Greensboro, North Carolina

Morning (7 A.M. EST)					
Base of Inversion (Meters)	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Surface	62.6	62.6	60.3	74.4	64.9
1–500	17.3	17.0	14.4	9.9	14.6
501–1000	9.1	6.3	4.2	4.5	6.0
1001–2000	6.2	5.6	3.5	3.4	4.7
2001–3000	1.6	1.9	2.8	1.9	2.0
Total	96.8	93.3	85.2	94.1	92.2
Afternoon (7 P.M. EST)					
Surface	44.3	10.4	8.2	48.7	27.7
1–500	12.4	6.5	6.3	4.4	7.4
501–1000	14.8	6.5	3.3	5.8	7.6
1001–2000	16.9	19.5	12.5	17.6	16.7
2001–3000	5.1	18.1	15.3	7.7	11.6
Total	93.5	61.0	45.6	84.2	71.0

Inversions with bases below 3000 meters (9843 feet) were most frequently observed during winter (93.5%) and least often noted in summer (45.6%). The *relatively* high incidence of surface inversions in winter and the vigorous mixing which occurs in summer account for these results.

On an annual basis, surface-based inversions were observed about 40 percent less often in late afternoon (27.7%) than in the morning (64.9%). Overall, inversions within the categories noted in table 12–4 were recorded about 22 percent more often at 7:00 A.M. (92.2%) than at 7:00 P.M. (71.0%).

Problem 12–9

Table 12–5 presents inversion data for Miles City, Montana for both the morning and afternoon periods. Referring to the morning (5 A.M. MST) inversion data, what is the percent frequency of occurrence of surface-based inversions during each season? What season has the highest frequency of occurrence of surface-based inversions in the morning? Why? Which season has the lowest frequency? Why? Are the data in table 11–5 in the previous exercise of any help in answering these questions?

TABLE 12–5
Frequency of Inversion Occurrence (Percent) at Miles City, Montana

Morning (7 A.M. EST)					
Base of Inversion (Meters)	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Surface	72.5	70.3	92.4	79.6	78.7
1–500	13.7	9.5	3.0	6.2	8.2
501–1000	5.8	6.1	1.1	4.4	4.4
1001–2000	4.4	6.3	1.8	4.9	4.3
2001–3000	0.4	2.4	0.4	1.9	1.2
Total	96.8	94.6	98.7	97.0	96.8
Afternoon (7 P.M. EST)					
Surface	36.9	7.0	16.1	23.0	21.4
1–500	22.6	6.8	2.0	6.7	9.6
501–1000	7.6	9.8	2.4	10.0	7.4
1001–2000	8.7	17.3	14.8	16.0	14.2
2001–3000	7.1	11.8	7.2	11.0	9.3
Total	82.9	52.7	42.5	66.7	61.9

Problem 12–10

Referring to the afternoon data in table 12–5, why do you think there is a lower frequency of occurrence of surface-based inversions at this time during all seasons?

Problem 12–11

The *total* number of inversions in the afternoon at Miles City is lowest for the year in summer. Why?

Mixing Layer Wind Speeds

The average wind speed through the mixing layer is calculated for the morning and afternoon hours using winds aloft data from radiosondes. These wind speeds, together with information on mixing heights, provide additional data to describe the dispersion potential of a region. Moderate to high wind speeds coupled with deep mixing depths provide a large volume of air in which mixing can readily occur. Very low wind speeds with shallow mixing layers severely limit the dispersion of airborne pollutants.

Mean mixing layer wind speed data for Greensboro are shown in table 12–6. These data show that, on an annual basis, the average mixing layer wind speeds over Greensboro in the morning are about 11 mph. Mixing layer wind speeds increase to 14 mph during the afternoon. A limited amount of seasonal variation is observed in the mean morning mixing layer wind speeds. The strongest morning wind speeds occur in winter and spring (12 mph) while the lowest wind speed occurs in summer (9 mph). Strongest afternoon wind speeds also occur in spring (17 mph). Afternoon mixing layer wind speeds slow to approximately two-thirds of the spring value in summer (11 mph).

TABLE 12–6
Mean Seasonal and Annual Mixing Layer Wind Speeds for Greensboro, North Carolina

Period	Morning		Afternoon	
	Miles/Hour	Meters/Sec	Miles/Hour	Meters/Sec
Winter	12	5.4	15	6.8
Spring	12	5.4	17	7.6
Summer	9	4.0	11	4.9
Fall	10	4.5	13	5.8
Annual	11	4.9	14	6.3

Problem 12–12

Mixing layer wind speed data for Miles City are shown in table 12–7. Write a brief narrative summary for these data as was given for the Greensboro data above.

TABLE 12–7
Mean Seasonal and Annual Mixing Layer Wind Speeds for Miles City, Montana

Period	Morning		Afternoon	
	Miles/Hour	Meters/Sec	Miles/Hour	Meters/Sec
Winter	12	5.4	14	6.3
Spring	13	5.8	18	8.1
Summer	10	4.5	14	6.3
Fall	10	4.5	16	7.2
Annual	11	4.9	16	7.2

Summary and Final Problems

All meteorological analyses, whether for forecasting or pollution problems or any one of numerous other studies, require the computation and interpretation of a considerable amount of data. Dispersion studies are not unique but, as you have probably seen in this and the previous exercise, many items have to be considered to develop a credible dispersion analysis. Studies like this do not occur infrequently. Rather, they are part of an important segment of the science of meteorology that tries to provide industrial developers with the information necessary to develop projects in an environmentally safe manner.

These two exercises introduced the concepts of atmospheric stability, surface winds, mixing heights and inversions, and mixing layer wind speeds as they relate to dispersion studies. An assessment of stability provides information on how well "mixed" the atmosphere is. Stable conditions are generally unfavorable for pollutant dispersal. Unstable and neutral conditions are more acceptable but the winds attendant with neutral stability may cause the generation of surface dust while the rapid vertical movement associated with an unstable atmosphere may promote unpleasant impacts at the earth's surface from tall stacks.

Surface wind analyses are important from the standpoint of where pollution will go and how fast it may get there. The study of mixing heights and inversions further refines the analysis by giving additional information on the volume of atmosphere available for pollution to be dispersed. Finally, mixing layer wind speed data further enhance the analysis by helping to show how rapidly pollutants may be dispersed within the mixing layer.

One important facet of dispersion meteorology that was only briefly discussed in the Introduction to the previous exercise, but which is vitally important, is terrain. Hills, valleys, mountains, canyons, etc. all have to be carefully analyzed in any dispersion analysis because of the effect that they can have on the movement of pollution. Consideration of terrain greatly refines any dispersion analysis. Though the effect of land features was not discussed here, because of the numerous varieties of terrain and their associated influences, you should be aware of the importance of terrain in the overall analysis of the dispersion problem.

The problems to follow will require that you consider all of the dispersion information in this and the previous exercise. The problems represent practical situations that you, as a consulting meteorologist, might be faced with if you were advising the company for which you worked.

Problem 12–13

You are the president of a large mining company that is planning to develop surface mining operations in both Miles City, Montana and Greensboro, North Carolina. Operations at the facilities will involve blasting, digging, and removal of the minerals. This will generate much dust. There will also be dust generated from the movement of trucks hauling material over unpaved roads. At both locations, rank the seasons to show when pollutant dispersal will likely be most and least favorable. It will be helpful to list all of the dispersion parameters and show when each is most and least favorable before analyzing the data as a whole and making your final decision.

Problem 12–14

Your company will be operating power plants in both Miles City and Greensboro. They are plants fueled by coal. Usually, fossil-fueled power plants are heavy emitters when they first begin operations. What season of the year would be best to start-up the plants at both locations? Does your answer differ from your answer to the previous question? (Each stack is 100 meters (330 feet) high.)

Problem 12–15

You are the operator of nuclear power plants in both Miles City and Greensboro. A minor accident, which released a small amount of radioactive gas, occurred at both plants in the last year. At Miles City, the accident occurred in the fall and, at Greensboro, the accident occurred in the winter. Both releases occurred at a height of about 30 meters (100 feet). Based on your analysis of each location's dispersion meteorology, which region was most unfavorably impacted? Don't forget to consider wind direction. (Note: You can make this analysis more complete by obtaining maps of the areas and trying to determine if any nearby towns were affected.)

WEATHER RADAR

Introduction

History of Weather Radar

Radar, an acronym for *RA*dio *D*ectection *A*nd *R*anging was first used for military purposes during World War II. Detection of aircraft and ships could be made when the radar transmitter emitted a burst of electromagnetic energy and this was then reflected from the object back to the radar receiver. Unfortunately, not only targets of military interest were revealed in this manner but also meteorological phenomena such as rain showers and thunderstorms. Although these were a nuisance, it was realized that meteorological use might be made of radar to locate and analyze weather features. After World War II the United States Weather Bureau (now the Weather Service) began to modify military radar sets to better analyze meteorological phenomena. However, it was not until 1959 that an operational system for meteorological application was put into large scale use. This system, the Weather Surveillance Radar System, is still in use today.

The weather radar system is established nationwide (see table 13–1). Most sites are manned 24 hours a day by observers who are trained to operate this powerful and sensitive system, recognize and interpret the data that they see and disseminate it to the public.

TABLE 13–1
National Weather Service Radar Network

Brunswick, Me.	Detroit, Mich.	Huron, S.D.
Chatham, Mass.	Cincinnati, Ohio	Grand Island, Neb.
Buffalo, N.Y.	Evansville, Ind.	Garden City, Kans.
New York, N.Y.	Bristol, Tenn.	Wichita, Kans.
Atlantic City, N.J.	Nashville, Tenn.	Oklahoma City, Okla.
Patuxent Naval Air Station, Md.	Memphis, Tenn.	Amarillo, Tex.
Pittsburgh, Pa.	Centreville, Ala.	Midland, Tex.
Hatteras, N.C.	Jackson, Miss.	Stephenville, Tex.
Wilmington, N.C.	Slidell, La.	Hondo, Tex.
Charleston, S.C.	Lake Charles, La.	Galveston, Tex.
Atlanta, Ga.	Neenah, Wis.	Brownsville, Tex.
Waycross, Ga.	Marseilles, Ill.	Limon, Colo.
Daytona Beach, Fla.	Minneapolis, Minn.	Albuquerque, N.M.
Tampa, Fla.	Des Moines, Ia.	Medford, Ore.
Miami, Fla.	Kansas City, Mo.	Missoula, Mont.
Key West, Fla.	St. Louis, Mo.	Salt Lake City, Utah
Appalachicola, Fla.	Monett, Mo.	Auburn, Wash.
Pensacola, Fla.	Little Rock, Ark.	Sacramento, Cal.
		Palmdale, Cal.

Purpose of Weather Radar

First and foremost weather radar is used as an analysis and forecasting tool useful in the zero to six hour time period. (Short range forecasts such as this are frequently called **nowcasts.**) Radar can be used not only to simply *detect* precipitation areas but it can also be used to determine and monitor the *severity* of precipitation areas and thunderstorms. A precipitation area may become a tornado area within 30 minutes and, since the Weather Service radars provide new data constantly the intensity, speed and direction of movement of such severe weather features can be monitored closely and early warnings issued to the public as such severe weather situations develop.

Radar can also be used as an after-the-fact research tool. Research now going on is attempting to correlate radar data and satellite data to the actual amount of precipitation that falls from a weather system. Advances have already been made in correlating radar observations with rainfall rates.

Equipment

Components of Weather Radar

There are four main components of the radar system: the transmitter, the antenna, the receiver and the scope.

The *transmitter* transforms signals coming into it into electromagnetic waves of a particular frequency which are then transmitted through the *antenna* in a specific direction. Upon coming in contact with an object, the waves (energy) are scattered ("echoed") back toward the antenna. (The antenna is used for both sending and receiving signals.) The received energy is passed through the *receiver* which amplifies the signal (which has since been weakened somewhat) and presents it on the radar *scope*. The scope is a cathode ray tube similar to a television tube.

Radar as a Listening Device

The principle behind the working of the radar is quite simple. It is a listening device that monitors its own echo.

In a cave or canyon would you yell and hear your echo, sound waves travel outward from your mouth in all directions. Some of the sound is reflected off of certain parts of the cave and back to your ear. Your brain then indicates that sound has been heard. The echo usually sounds fainter than your yell.

The radar "yells" not sound waves but electromagnetic waves which travel at the speed of light, 186,000 miles per second (*much* faster than sound waves). The energy travels out in the antenna beam. Some of the energy is lost if there is no object to scatter it. The scattered energy, upon returning to the antenna, is very much weaker than when it left the transmitter. When it returns to the antenna (your ear) the energy is passed to the scope (your brain) indicating that an object has been located after having been amplified in the receiver, something that isn't done in you.

The Plan Position Indicator and the Range Height Indicator

What does the operator actually see on the scope? Well, it depends on which of several types of information he is seeking. Two kinds of scopes currently in use are the Plan Position Indicator (PPI) and the Range Height Indicator (RHI).

The PPI indicates direction and distance on a circular screen. The circle is divided into 12 thirty degree increments ($12 \times 30° = 360°$: the circumference of a circle). Direction measured in this sense is called *azimuth*. Equally spaced concentric circles within the larger circle indicate distance (*range*). (The circles are 25 miles apart.) A rotating straight line, called the *sweep line,* rotates at the same speed as the antenna (see figure 13–1). The radar installation is located at the center of the circle. An echo usually remains visible on the "scope" for about 20 seconds.

Problem 13–1

Give the azimuth and range of echoes 1 and 2 on the PPI scope in figure 13–1.

	Azimuth	*Range*
1.		
2.		

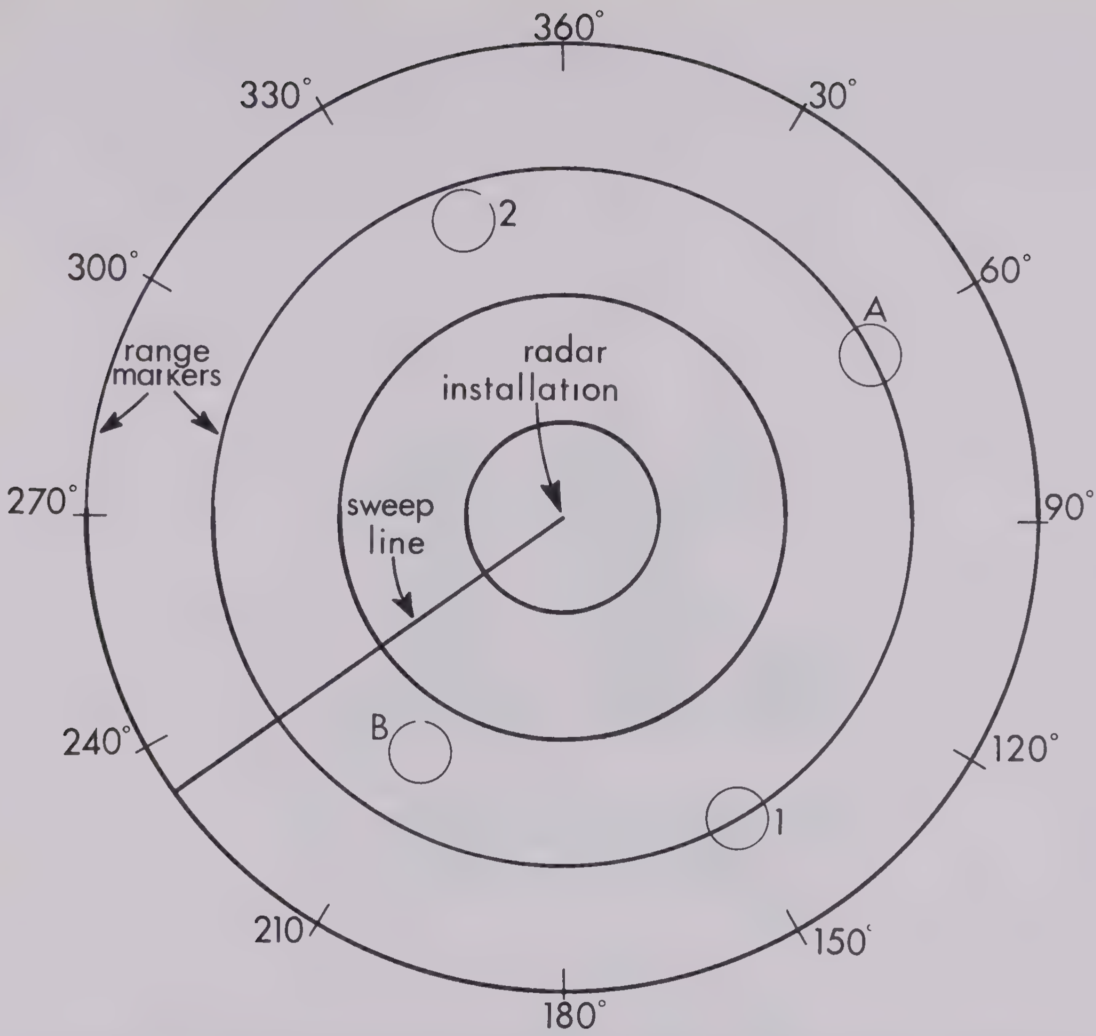


Figure 13–1. *The PPI Scope.* In this example echo A is located at azimuth 60°, range 75 miles. Echo B is located at azimuth 210°, range 60 miles.

The radar antenna usually rotates horizontally about a vertical axis at a fixed tilt above the horizontal when the PPI is in use. What if a thunderstorm appears and the operator wishes to know to what altitude it extends? (The height of a thunderstorm top is strongly correlated to the thunderstorm's intensity.) He can then turn on the Range Height Indicator (RHI). This stops the horizontal motion of the antenna and switches it to vertical motion. Now a vertical profile of the echo can be attained with distance from the radar measured on the X-axis and height in thousands of feet on the Y-axis. (See figure 13–2 for an example of an RHI display.)

Problem 13–2

Give the height and range of the echoes at points A and B on figure 13–2.

a. Height __________ Range __________

b. Height __________ Range __________

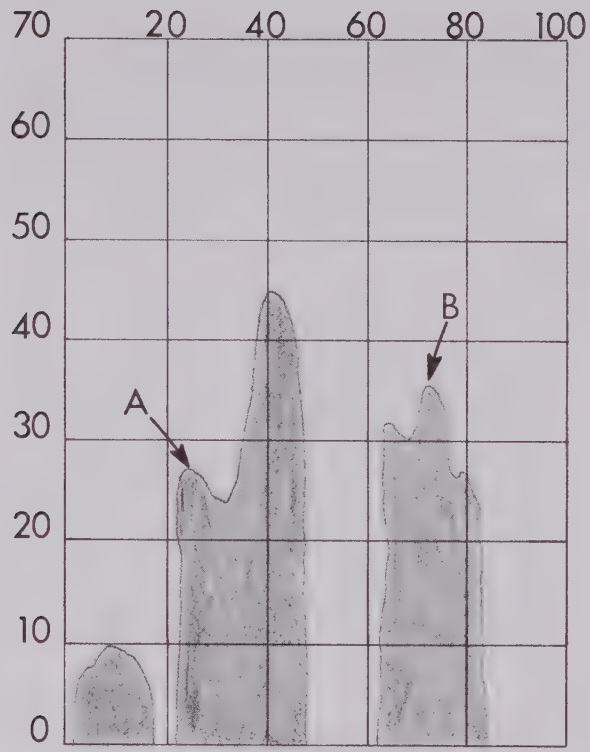


Figure 13–2. *The RHI.* Example of how showers might appear on the RHI. Horizontal lines indicate altitude in thousands of feet. Vertical lines are range markers in miles. In this example the height of the echo at 41 miles is 45,000 feet. At 10 miles range there is an echo with a height of 10,000 feet.

The Weather Bureau Radar Remote System

With the development of radar for weather applications the problem of getting this valuable data to as many users as possible arose. For this purpose the Weather Bureau Radar Remote (WBRR) System was developed. This system allows for the nearly instantaneous transmission of radar pictures by means of a modified television camera focused on the actual PPI display. It is transmitted over regular telephone lines to anyone who may need to use such data. Users are typically government and private forecast agencies. Reception on the user's end can be in two forms: the first is a device similar to a television set which shows the actual scanning of the radar indicator. The second mode of reception is through the use of a facsimile recorder. This device produces a *still* picture on paper (a picture of the radar scope without showing the sweep line). One of the main advantages of this type of reception is that a *record* can be made of the radar information for study at a later time.

An added feature of the WBRR is the operator's ability to comment on what is appearing on his scope. He can, in effect, "write" on the scope that a precipitation system is increasing or decreasing in size or intensity or that an echo is rain, snow or a severe thunderstorm. These remarks are then shown on the user's receiving device.

It is important to note here that the WBRR is not the *only* way to receive radar data (other ways will be shown later) but it is the fastest way.

The Video Integrator and Processor

The Video Integrator and Processor (VIP) is a separate device added to the radar console. The VIP analyzes the incoming radar signal and correlates it to six previously selected rainfall-rate categories. When the VIP is switched "on" it automatically provides for constant monitoring of the intensities of precipitation echoes. This is done through the use of six contouring color shades (see table 13–2). The VIP is best illustrated through the use of figures; therefore, see figure 13–3.

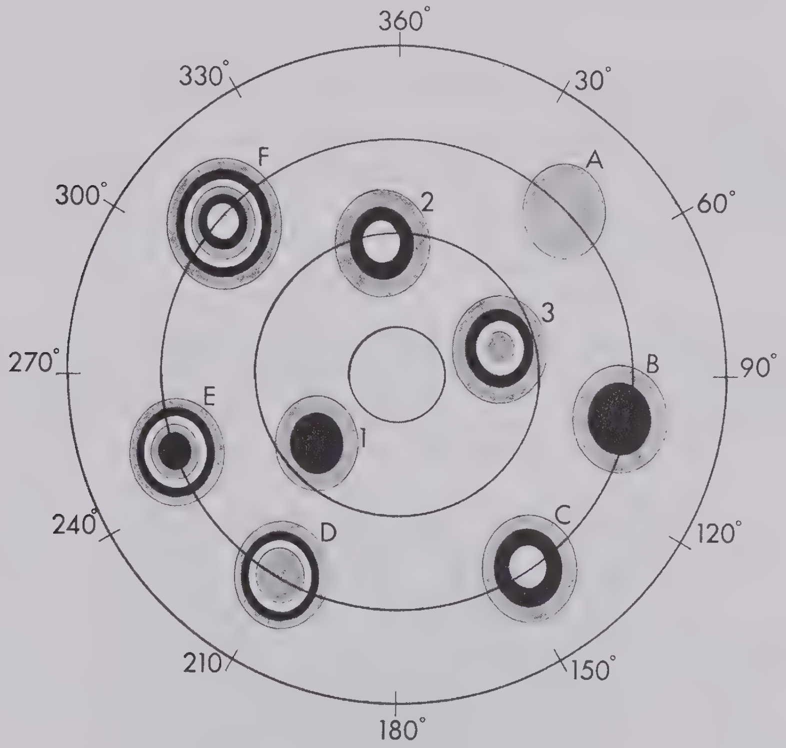


Figure 13–3. *The Six VIP Levels.* Echo "A" illustrates a level 1 echo (gray). Echo "B" illustrates a level 2 echo (black) within a level 1 echo. Echo "C" illustrates a level 3 echo (white) within a level 2 echo within a level 1 echo. Echo "D" illustrates a level 4 echo (gray) within a level 3 echo within a level 2 echo within a level 1 echo. Echo "E" illustrates a level 5 echo (black) within a level 4 echo within a level 3 echo within a level 2 echo within a level 1 echo. Echo "F" illustrates a level 6 echo (white) within a level 5 echo within a level 4 echo within a level 3 echo within a level 2 echo within a level 1 echo.

TABLE 13–2
VIP Levels as Would Be Seen on the WBRR

Color Shade	VIP Level	Rainfall Rate	Precipitation Is Termed
Gray	1	< .1 in. per hr.	Light
Black	2	.1 to .5 in. per hr.	Moderate
White	3	.5 to 1.0 in. per hr.	Heavy
Gray	4	1.0 to 2.0 in. per hr.	Very heavy
Black	5	2.0 to 5.0 in. per hr.	Intense
White	6	> 5.0 in. per hr.	Extreme

It is important to note that the VIP levels go "in order." That is, there cannot be a level 3 echo without a level 2 echo and a level 1 echo, etc. Just as if you were climbing a mountain: you can't go past the 200 feet marker without first passing the 100 feet marker and the 50 feet marker.

The VIP is an important adjunct to the Weather Radar System. It is especially useful in thunderstorm situations. For here the intensity of a convective-type echo can be closely watched and inferences on the other aspects of thunderstorms (lightning, winds) can be made by a trained forecaster from the VIP intensity-level categories since it has been found that the higher the VIP level, the more severe the thunderstorm.

Problem 13–3

Of echoes 1, 2 and 3 in figure 13–3 give the azimuth, range and intensity of the echoes with the lowest and highest VIP levels on the scope.

Highest Level Echo: Azimuth: ________ Range: ________ Intensity: ________

Lowest Level Echo: Azimuth: ________ Range: ________ Intensity: ________

The Radar Beam

The waves of electromagnetic energy emitted by the radar transmitter travel at the speed of light, 186,000 miles/second. In a vacuum, these waves would travel in a straight line but in our atmosphere due to changes in the density of the air, that is, changes in temperature and moisture, the radar beam is slightly curved. The amount of curvature depends on the atmospheric lapse rates of temperature and moisture. Many different lapse rates can occur within the path of the radar beam and it is impossible to know just how much the beam is being curved. Because of this each radar set is calibrated to a standard atmospheric lapse rate and, therefore, the beam is presumed to have a standard curvature.

If the beam stays closer to the ground, meaning that the curvature is *greater* than "normal," "superrefraction" exists. If the curvature is *less* than "normal," that is, straighter than it should be, "subrefraction" exists (see figure 13–4). Any deviation from the "standard" of the lapse rates of temperature and moisture causes erroneous positioning of the echo. Horizontal distance is usually not effected too greatly, but vertical height can be affected substantially. Sometimes a true target is missed altogether and sometimes targets show up where none should exist.

For example, in figure 13–4 the normal beam would detect both echoes A and B. The subrefracted beam would detect echo A but miss echo B whereas the superrefracted beam would also miss echo B but now the city will appear as an echo.

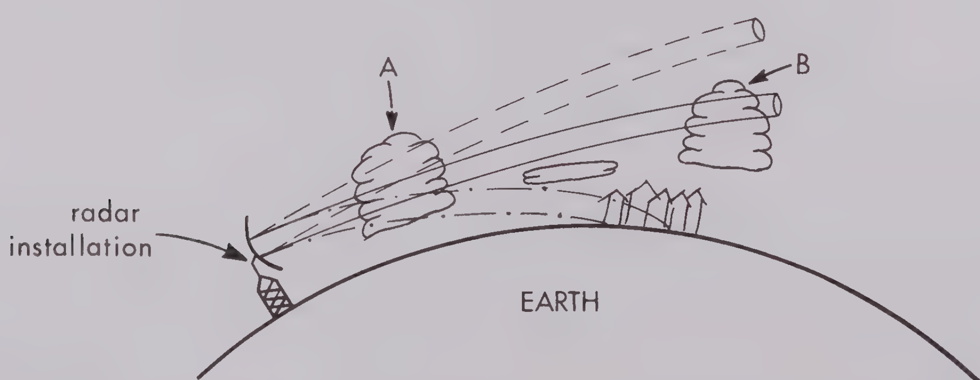


Figure 13-4. *Normal Beam Propagation, Subrefraction, Superrefraction.* The solid line depicts the path of the "normal" beam. The dashed line shows subrefraction (beam too straight). The dash-dot line shows superrefraction (beam too curved).

Problem 13–4

Is it possible for it to be raining within the range of the radar beam and, yet, no echo is seen on the scope? Explain your answer.

Superrefraction usually occurs when the radar beam is trapped below an inversion. In this situation ground targets, cities, mountains, etc. (called anomalous propagation or AP), rather than aerial targets, may fill all or part of the scope. If skies are clear it is easy to recognize AP, but should precipitation echoes be mixed in with the AP it can be difficult to separate the two echoes.

Figure 13–5 depicts an actual occurrence of anomalous propagation as seen on the PPI. In the figure much of the scope appears to be covered with level 2 echoes. You will notice, however, that the radar operator has annotated the scope "NON-PCPN" which means "nonprecipitation" echoes or AP. This picture was received early in the morning on a clear day when there was an inversion based at the surface. The radar beam, then, is superrefracted as shown in figure 13–4 and echoes other than the precipitation are being received.

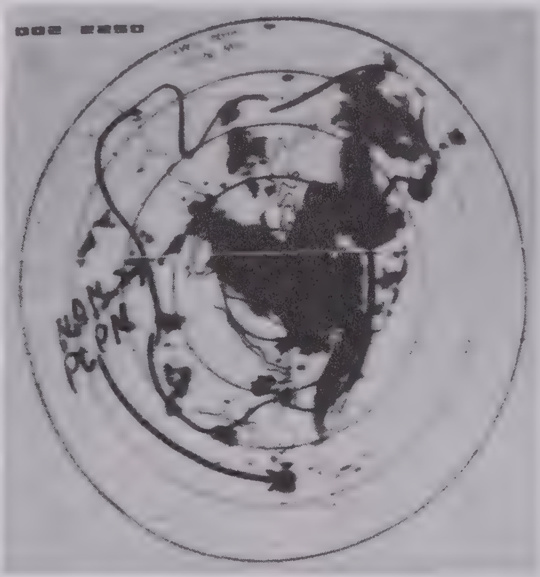


Figure 13–5

Targets—What the Radar "Sees"

Most Weather Service radars are built to detect objects of raindrop size (raindrops have a radius between ½ and 1½mm). Obviously, then, buildings, trees, mountains, etc., are "fair game" for the radar to detect. When the radar detects such objects it is said that "ground clutter" is being detected. The distance from the radar station that ground clutter is detected depends on the intensity of superrefraction.

Each weather radar PPI has a distinguishing ground clutter pattern. These are objects near to the stations which almost always show up on the radar display.

Meteorological Targets—Clouds

Weather Surveillance Radars normally do not "see" clouds. This does not mean that a cloud droplet, with a radius one-hundred times smaller than a raindrop, does not intercept some of the radar beam; it does. But, by the time the energy reflected by the cloud droplet is returned to the radar receiver, it is too weak to show up on the indicator.

Rain

Rain, other than in convective showers, usually produces a rather indistinct echo pattern that changes shape and intensity rather slowly. Figure 13–6 shows echoes associated with a winter low pressure system.

Figure 13–6

Raindrop size has an effect on the amount of energy reflected back to the receiver—the larger the drop the more energy that is reflected and, therefore, the stronger the echo. Studies have shown that there is a correlation between raindrop size and rainfall rate. Other studies have shown that the stronger the echoes the more severe the turbulence associated with the precipitation area.

Snow

Echoes from snow are much weaker than echoes from rain. This is because the snowflake reflects less energy than a raindrop. While snow echoes do appear on the PPI, the extent of the snow area may actually be much larger due to the weakness of the returning echo (see figure 13–7).

Squall Lines and Hail

As you learned in the Thunderstorm Exercise, squall lines are lines of thunderstorms. On radar, rather than being featureless like a large scale rain echo, squall line showers usually show rapid changes in shape and intensity. The Video Integrator and Processor is invaluable to the user who seeks to analyze the severity of thunderstorms whether individually or in a squall line (recall that the VIP analyzes the intensity of the reflected signal).

In previous sections it was pointed out that the intensity of the echo corresponds with the severity of turbulence in thunderstorms (the rapid and erratic vertical motions). And, as was also pointed out in the Thunderstorm Exercise, the strongest thunderstorms have the most intense vertical velocities (60 mph or more).

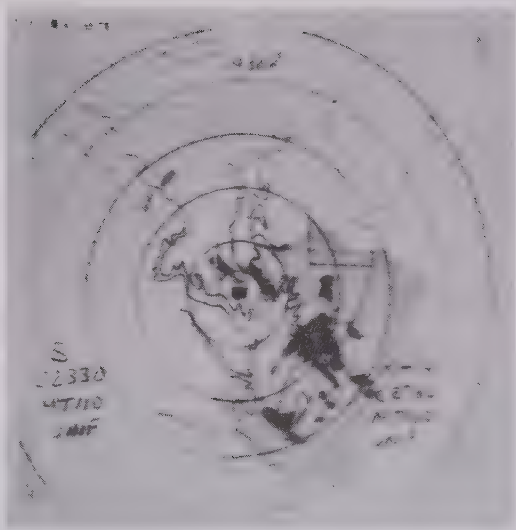


Figure 13-7. The grayish echo pattern over southeastern Maryland is from snow. The darker echoes within the snow echoes are rain showers.

As you saw in table 2 and figure 13–3, the VIP contours the echo patterns showing which echoes are most intense, hence, severe. This, therefore, makes the most severe portions of a squall line readily identifiable. It also makes it convenient to the user to monitor the squall line for abrupt intensification or dissipation of individual thunderstorms.

On the radar, the squall line usually appears as a line of echoes. VIP levels of individual storms can be noticed and rapid changes in the VIP levels can be seen during a relatively short time. Figure 13–8 depicts squall lines on radar and the use of the VIP in analyzing them.

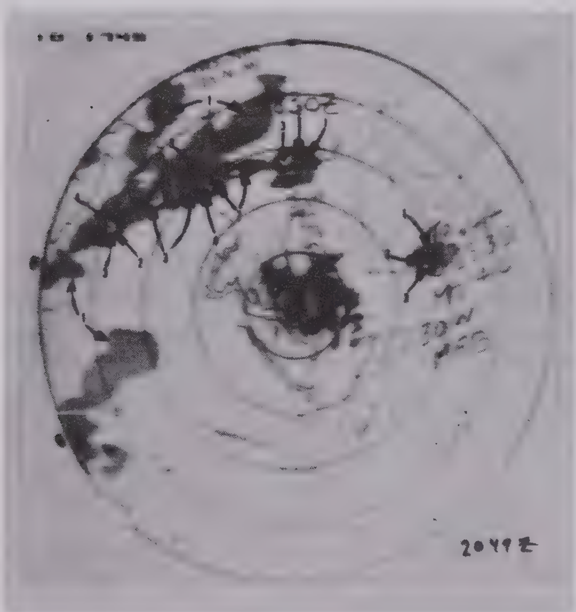


Figure 13–8a. Shows a northeast to southwest squall line across central Maryland and Virginia. Arrows indicate the location of the numbered VIP levels. Where is the most intense part of the squall line at this time?

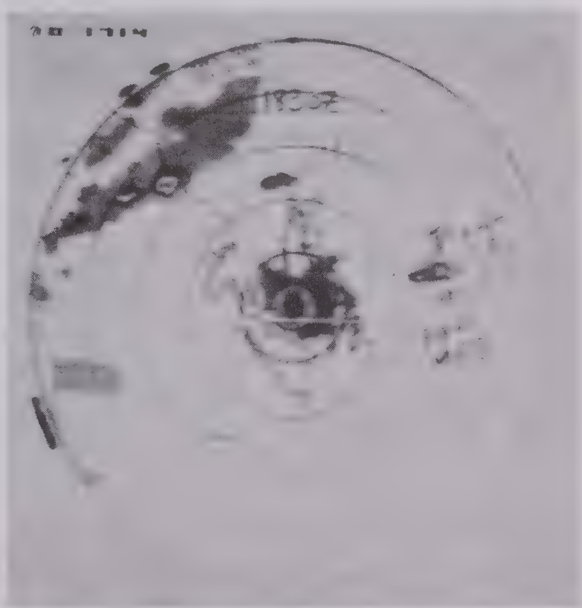
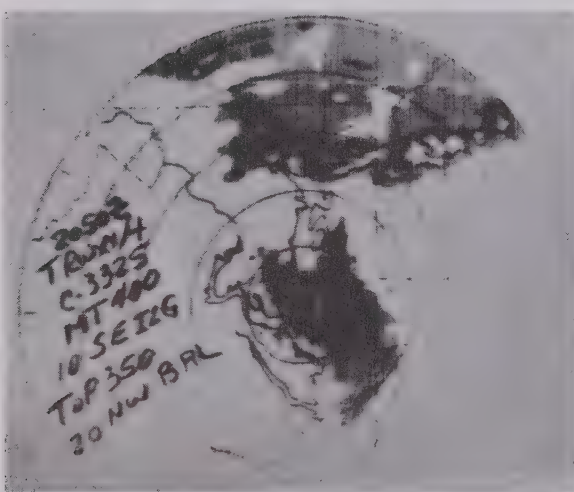


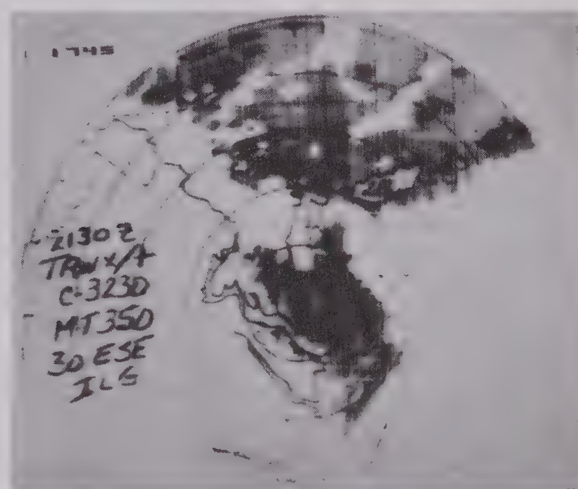
Figure 13–8b. Shows the same squall line 20 minutes *earlier.* Can you see how the squall line has grown and (most of all) *intensified* by analyzing the VIP levels?

Problem 13–5

Picture A was received 24 minutes *prior* to Picture B. Analyze the squall line intensity showing which echoes have intensified and which have weakened. Do this by drawing arrows to the echoes in 5b and writing I or W near the arrow. How much rain would you expect from the most intense section of the squall line?



A



B

Hail is usually associated with violent thunderstorms. Hailstones produce an intense echo because they have a water coating and are much larger than the average raindrop. This makes hail a good reflector.

Radar Range for Meteorological Targets

The question of just how far away the radar beam can detect targets cannot be answered with definite preciseness. Recall in past sections that the radar beam does not always travel in a "normal" path. Atmospheric conditions can cause it to travel too straight or too curved thus causing the beam to entirely miss objects by "going over" them or not even reaching a target. (Refer back to figure 13–4.) Also, the character of the target can affect the range. That is, a very low precipitating cloud can be missed by the radar beam whereas a very high thunderstorm, very far away may be detected. (Note the cloud between echoes A and B in figure 13–4. Even a normal beam can miss a low target.) Table 13–3 lists the normal range and the best range for various weather phenomena.

TABLE 13–3
Radar Range for Meteorological Targets

Target	Best Range	Normal Range
Rain	75 miles	150 miles
Thunderstorms	85 miles	200 miles
Severe thunderstorms (very high tops)	100 miles	250 miles
Snow	60 miles	85 miles

Measurements

As previously stated, direction and height of an echo are shown by the PPI and RHI, respectively. Distance of the echo from the radar is computed electronically by the simple expression: distance equals rate multiplied by time. For the radar this is: distance to echo equals 186,000 mi/sec multiplied by the number of seconds it takes energy pulse to return to receiver multiplied by ½. The ½ is a factor because reception of an echo implies a roundtrip of the radar pulse. One-half of this is the distance to the echo.)

Movement

Movement of an echo is determined by the user simply referring to previous pictures. It is necessary, however, to stipulate whether the echoes are cells, areas or lines.

Areas and lines are made up of cells but reporting the movement of areas and lines can be a bit confusing because the area or line may move in a direction that is different than the direction of movement of the cells comprising it. (Figure 13–9 illustrates this apparent anomaly.) To determine the movement of the area it is necessary to pick a point as close as possible to the center of the area and refer to that point on succeeding pictures. Line movement can only be perpendicular to the orientation of the line. That is, a north-south line can only move east-west; and an east-west line only moves north-south, etc. (Refer to figure 13–9.)

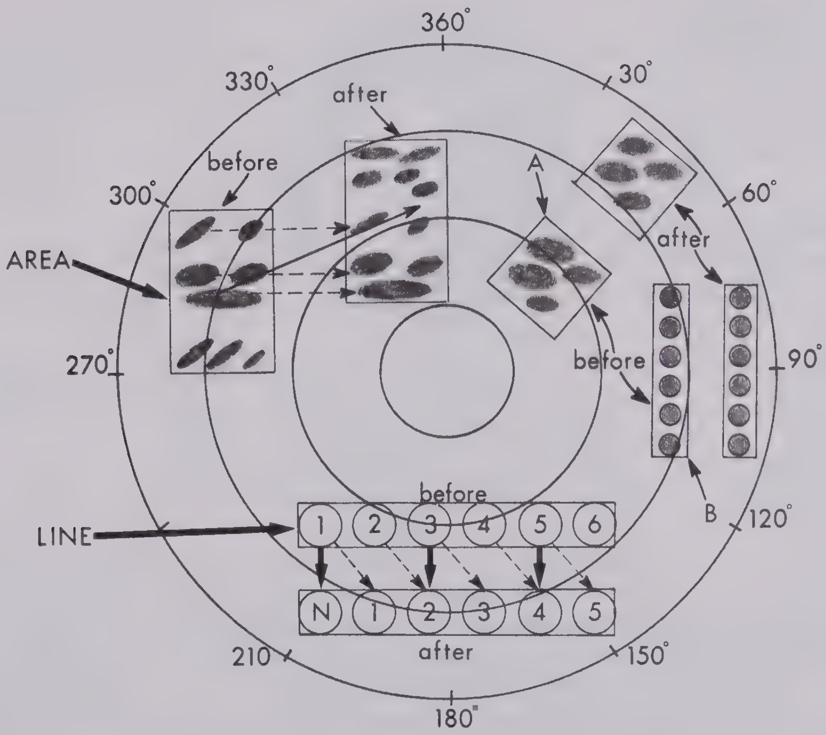


Figure 13–9. *Movement of an Area and Movement of a Line.* Two PPI displays superimposed. Rectangles in the northwest quadrant outline "**areas**" of cells. Solid arrow indicates movement of the area (towards northeast). Dotted arrows indicate movement of the cells within the area (towards the east). Note that the lower three cells have dissipated while new cells form in the upper portion of the area. Rectangles to the south illustrate two successive positions of a line of echoes. The line moves to the south. The echoes, however, move toward the southeast. Note that echo 6 has dissipated and echo N is new.

Problem 13–6

Indicate by arrows the movement of the area A and line B in figure 13–9. From what direction have the line and area come? (That is, from 360° (north) or from 270° (west).) Give a numerical answer.

Intensity

As already mentioned, intensity of an echo return is related to rainfall rate. Advanced electronic techniques enable the radar operator to determine the intensity of echoes. Echo intensity is related to the amount of energy reflected from the target and from this the rainfall rate can be calculated. Table 13–4 shows the radar intensity symbol which the operator would annotate on the scope, the rainfall rate corresponding to this intensity and how the *surface* observation of the precipitation would be termed. Also included are the corresponding VIP levels. (Don't be confused thinking that the VIP can only determine intensities. It does not. The VIP is an adjunct to the rest of the radar unit. It contours the echoes and permits easy identification of intense portions of the cell. The VIP is not always "on," however. It does not need to be always on especially in many instances of widespread rain or snow situations from large low pressure systems. The rain may be quite substantial, of course, but the echoes may change little in intensity over a long period of time.)

TABLE 13–4

Rainfall Intensity Symbol and Term	Rainfall Rate	Surface Observation Is Called	VIP Level
− Weak	< 0.1 in. per hr.	Light	1
(No symbol) Moderate	0.1 to 0.5 in. per hr.	Moderate	2
+ Strong	0.5 to 1.0 in. per hr.	Heavy	3
++ Very strong	1.0 to 2.0 in. per hr.	Heavy	4
X Intense	2.0 to 5.0 in. per hr.	Heavy	5
XX Extreme	> 5.0 in. per hr.	Heavy	6

The rainfall rate data given in table 13–4 do not necessarily correspond to the amount of rain collected by a rain gauge under the echo. For example, a strong echo implies a rainfall rate of .5 to 1.0 in./hr, but for several reasons this does not mean that ½ in. to 1 in. will fall into a rain gauge: (1) The radar beam detects the precipitation at some distance above the ground and due to evaporation of the droplet as it falls or the wind blowing the droplet away from the gauge *less* than the theoretical amount may actually reach the ground. (2) The beam looks at a *large* portion of the echo at one particular *instant*. The rain gauge collects rain over a period of time and the collecting area is less than a square foot.

Reporting Radar Echoes

Operators of radar installations are required to make two types of reports. One is the Radar Report (RAREP) and the other is a Narrative Report. Both types of reports are sent to users via teletypewriter.

The RAREP

The Radar Report is used principally by National Weather Service Forecast Offices and private forecasting services. It consists of all pertinent information about all of the echoes observed on the indicator. The reports are made each hour at 35 minutes past the hour. If the need arises (as it does in severe weather instances) special reports are made at other times.

All of the weather echoes present are classified as cells, areas or lines. Reporting is done in accordance with the RAREP code. Figure 13–10 is an explanation of the RAREP code along with a sample report. Numbered items in the RAREP explanation are further discussed below.

CONDENSED EXPLANATION OF RAREP (SD) CODE

LOCATION IDENTIFIER	TIME OF REPORT	CHARACTER OF ECHOES	WEATHER AND INTENSITY	INTENSITY TENDENCY	LOCATION AND DIMENSIONS OF ECHOES	MOVEMENT	ECHO TOPS	REMARKS
EVV	1640Z	AREA 6	TRW+A	/+	4/125 221/115 100W	2715 CELLS 2325	MT 550 at 310/45	3/4 INCH HAIL 310/45

DECODED REPORT

Evansville Indiana hourly Radar Report (RAREP) taken at 1640Z An area 6 tenths covered with echoes, containing thunderstorms producing heavy rainshowers and occasional hail at the surface These echoes are increasing in intensity. Area extends from 4° 125 nautical miles to 221° 115 nautical miles, is 100 nautical miles wide The area is moving from 270° at 15 knots, the cells within the area from 230° at 25 knots Maximum top of the detectable moisture is 55,000 feet MSL at 310° 45 nautical miles. Hail ¾ inch in diameter was reported with this echo.

The above report is for the echo area in the radarscope picture. The slash mark (/) is used to separate the intensity of the echo from the intensity tendency

TIME OF REPORT

Time of observation (24-hour clock) in Greenwich Mean Time. Observations are normally taken at 40 minutes past each hour. When a special observation is taken, the contraction SPL is placed between the Time of Report and Character of Echoes.

CHARACTER OF ECHOES

CHARACTER	DEFINITION	CONTRACTION
Isolated echo	Independent convective echo	CELL
1. Area	A grouping of related or similar echoes	AREA
2. Line	Related or similar echoes forming a line at least 30 miles long with a length to width ratio of at least 5 to 1	LN
Stratified elevated echo	Precipitation aloft	LYR
Spiral band area	Curved lines of echoes, including wall cloud, which occur in connection with hurricanes, tropical storms, and typhoons	SPRL BAND AREA

3. NOTE Echo coverage in tenths within an area, line or elevated echo is given by the number which immediately follows the word or contraction describing the character of the echoes For example, AREA6 means that echoes cover 6 tenths of the outlined area

PRECIPITATION SYMBOLS

IP ICE PELLETS	SW SNOW SHOWERS	ZR FREEZING RAIN
L DRIZZLE	T THUNDERSTORMS	ZL FREEZING DRIZZLE
RW RAIN SHOWERS	S SNOW	
R RAIN	A HAIL	

INTENSITY

LIGHT	–	VERY HEAVY	++	UNKNOWN	U
MODERATE	NO SIGN	INTENSE	X		
HEAVY	+	EXTREME	XX		

INTENSITY TREND 4.

TREND	CONTRACTION
Increasing	+
Unchanging	NC
Decreasing	–
New	NEW

The intensity trend is evaluated in terms of a net change in the characteristic intensity equal to approximately one intensity category (light to moderate) during a specified time period, which is one hour for lines and areas and fifteen minutes for cells

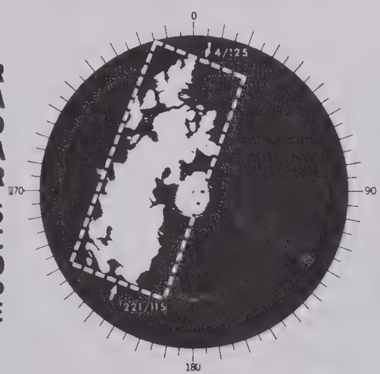
DIMENSIONS OF ECHOES

Width (W) or diameter (D) are reported in nautical miles The average width of lines and rectangular areas, and the average diameter of cells and roughly circular areas, are reported.

MOVEMENT Past 15 min.

Direction, to nearest ten degrees from which, and speed in knots with which, the echo is moving. Both cell and system movement are reported when available Line movement is reported in terms of the component perpendicular to the axis.

RADAR SCOPE



ECHO PATTERN

LOCATION OF ECHOES

1. Locations of echoes are relative to the radar position. The azimuth in degrees true, and the distance in nautical miles, to salient points of the echoes are given.
2. If the echoes are arranged in a line, the azimuth and distance will be given to as many points along the axis of the line as are necessary to establish its shape.
3. If an irregularly shaped area is covered by echoes, the azimuth and range to salient points on the perimeter of the area will be reported as necessary to reconstruct the shape and size of the echo area.
4. If an area of echoes of roughly circular shape is observed, or if a single echo such as a thunderstorm cell is observed, the azimuth and range to the center of the area or cell will be reported.

5. **ECHO TOPS**

Maximum height of detectable moisture, in hundreds of feet above mean sea level. Tops are not reported beyond 125 nautical mile range.

UNUSUAL ECHO FORMATIONS

Certain types of severe storms produce distinctive patterns on the radar scope. For example, the hook-shaped echo associated with tornadoes and the spiral bands with hurricanes. The bright band is a narrow horizontal layer of intensified radar signal a short distance below the 0°C isotherm (Melting level). Unusual echo formations will be reported in remarks.

6. **OPERATIONAL STATUS**

STATUS	CONTRACTION
(1) Equipment performance normal on PPI scan; echoes not observed	PPINE
(2) Equipment out of service for preventive maintenance resulting in loss of PPI presentation (The contraction is followed by a date-time group to indicate the estimated time when operation will be resumed.)	PPIOM
(3) Observation omitted for a reason other than those above, or not available.	PPINA
(4) Radar not operating on RHI mode; echo altitude measurements not available.	RHINO

A contraction pertaining to the operational status of the equipment is sent as required by the table above. In the above list, "PPI" refers to the radarscope (Plan Position Indicator); the additional letters refer to "no echo" (NE).

GENERAL NOTES

SD (Storm Detection)—Radar Report (RAREP) Identifier Identifies the message as a RAREP

When the report contains an important change in echo patterns, or some other special criteria given in the **Weather Radar Manual**, Part A has been met, it is designated as a special (SPL).

Intensity of precipitation at distances exceeding 125 nautical miles from a WSR-57 or other radar of similar sensitivity, or 75 miles from other radars, will be reported as unknown (U). Intensities of snow, hail, drizzle, and ice pellets are not reported.

One rainfall intensity category is selected to characterize each reported echo system. For convective systems, it is the maximum intensity in the system. For other systems, it is the intensity predominant in horizontal extent.

Persisting echoes are indicated in remarks

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION NOAA U.S. DEPARTMENT OF COMMERCE

U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE
SILVER SPRING, MD. 20910

Figure 13–10

1. An area is a group of echoes. Defining the boundaries of an area can be confusing. To report the pattern the operator "encloses" the area by imaginary lines and reports the azimuth and range of points of intersection of the lines.

Here is how the area, the western-most area in figure 13–9, would be reported: 300/99 310/75 270/55 270/85, which says "area is 300°, 99 miles; 310°, 75 miles; 270°, 55 miles; 270°, 85 miles." Notice that the points are reported clockwise around the area.

Problem 13–7

Report the original position of Area A in figure 13–9 according to the RAREP code.

The example in figure 13–10 shows the area enclosed by a rectangle. The endpoints of an imaginary line through the middle of the area are given along with an average width of the area.

2. Lines are reported in the same way as the area example given in figure 13–10. For example, the southernmost line in figure 13–9 would be reported as: 212/87 148/87 12W which says that a line extends from 212°, 87 miles to 148°, 87 miles and the line is 12 miles wide.

3. Within the defined area or line it is important to know the echo coverage. It is reported in tenths. For example, in figure 13–9 the westernmost area would be reported as "AREA 5" indicating that the area is five-tenths filled with echoes.

4. It is also necessary to know how the intensity of the echoes are changing. Referring back to table 13–4 if the echo has increased in intensity by one or more categories it is termed "increasing"; decreased by one or more—"decreasing"; remained the same—"no change"; if the echo has recently appeared—"new."

5. Maximum heights of echoes are reported. In convective weather situations, this is especially important because the maximum top of an echo is strongly correlated with the severity of the surface weather. Maximum tops (MT) are reported in thousands of feet with the two trailing zeroes dropped. The azimuth and range of the maximum top are reported also.

6. The operational status, when needed, is reported immediately after the time. For example: If the Pittsburgh PPI at 1435Z (see below) shows no echoes, the report would read: PIT 1435 PPINE—This means "Plan Position Indicator—NO ECHOES"

The RAREP is rather easy to understand. It just takes familiarization with the code. Below are five examples.

RAREP and Decoded Reports

(See figure 13–11 for the NHK PPI scope to go with the examples.)

1. NHK 1435 LN6 TRW++/+ 10/100 60/50 30W 2715 CELLS 2425 MT 400 AT 50/50

This is the Patuxent River Naval Air Station radar report for 1435 Z. (To convert from Z time to Eastern Standard Time subtract 500 hours. That is, 1435 Z is 9:35 EST.) It says that a line 6/10 covered with echoes containing very strong thunderstorms, which have been increasing in intensity during the past hour, extends from 10°, 100 miles to 60°, 50 miles and is 30 miles wide. The line is moving from 270° at 15 kts. However, cells are moving from 240° at 25 kts. Maximum top of the echoes is 40,000 feet at 50°, 50 miles.

2. NHK 1835 AREA 4 RW—/— 360/50 360/25 270/25 330/50 2120 CELLS 2425 MT 120 AT 330/25

This is the radar report at 1835 Z. An area 4/10 covered with echoes containing light rain showers has been decreasing in intensity during the past hour. The area extends from 360°, 50 miles to 360°, 25 miles to 270°, 25 miles to 330°, 50 miles. Area movement is from 210° at 20 kts. Cells, though, are moving from 240° at 25 kts. Maximum top of echoes is 12,000 feet at 330°, 25 miles.

3. NHK 1635 AREA 9 SW+ZR/— 300/75 240/75 50W 3010 CELLS 2725 TOPS 100 UNIFORM

Patuxent River N.A.S. at 1635 Z: an area 9/10 covered with echoes extends to 25 miles on both sides of a line whose endpoints are 300°, 75 miles and 240°, 75 miles. The echoes are from heavy snow showers and moderate freezing rain. The echoes are decreasing in intensity. The area is moving from 300° at 10 kts. Cells are moving from 270° at 25 kts. There is no maximum top, rather the tops are at a uniform height of 10,000 feet.

4. NHK 2035 PPIOM

This radar report for 2035 Z says that the NHK PPI display is not available for presentation because the radar system is out for maintenance.

5. NHK 1235 LN 4 TRWU/NEW 360/80 330/75 20W 3415 CELLS 3320 MT 500 AT 335/75 AND 355/69

The radar report for 1235 Z: a line 4/10 covered with echoes consisting of thundershowers but of unknown intensity has appeared within the past hour (hence, "NEW"). The echoes extend 10 miles on both sides of a line whose endpoints are at 360°, 80 miles and 330°, 75 miles. The line is moving from 340° at 15 kts. though cells are moving from 330° at 20 kts. (Notice that, since the operator reports movement, the echoes have been on the scope for at least 15 minutes.) Maximum tops of 50,000 feet are at two locations 335°, 75 miles and 355°, 69 miles.

Figure 13–11

If you look back at the various figures which are reproductions of actual WBRR facsimile pictures, you will notice that the comments written on the scope by the radar operator are really an abbreviated form of the RAREP. For example, the remarks in figure 13–7 would be decoded as: at 1430 Z (top of page) the echoes are composed of moderate snow (lighter echoes) with individual cells moving from 230°

at 30 kts. Tops are uniform ("UNIF") at 11,000 feet. Also, echoes of light rain are observed (darker echoes) showing no change in intensity. Cells are moving from 230° at 36 kts. Tops of most of the echoes extend to 16,000 feet (thus indicating that the tops are at a uniform height).

Problem 13–8

If you need assistance with the following refer to figure 13–10 and paragraphs 1–5. Decode the following RAREPS.

1. PIT 1735 AREA 9 TRWXX/NC 10/50 60/75 60/50 360/25 2435 CELLS 2740 MT 600 AT 40/50
2. PIT 1935 AREA 2 SW−/+ 330/75 360/70 330/30 2715 CELLS 2715 TOPS UNIFORM 110
3. PIT 2035 LN 7 TRW/− 330/70 270/50 50W 2735 CELLS 2120 MT 520 AT 300/60
4. PIT 2135 PPINA
5. PIT 0645 AREA 8 RW−IP−/+ 180/50 300/25 60W 2415 CELLS 2405 MT 110 AT 240/35

Narrative Reports

Narrative radar reports are issued for the specific area around the radar installation. They are not as detailed as the RAREP, being used mainly by the news media for issuance to the public. That is, rather than azimuth and range being reported, geographical features such as cities, mountains, rivers, etc., are mentioned and specific coverage and intensities are not as precise. These are issued when the RAREP is issued.

Here is an example of a narrative report and its associated RAREP. See the NHK PPI in figure 13–12.

RAREP:

NHK 2045 AREA 8 TRW/+ 330/100 270/50 260/110 3015 CELLS 2220 MT 450 AT 300/75 AREA 3 RW−/− 75/44 102/55 15W 2705 CELLS 2805 MT 200 AT 90/45

Narrative Report:

Washington, D.C. Weather Service 1500 EST

At three p.m. Patuxent River radar showed a large area of moderate thundershowers extending from just southwest of Charlottesville northeastward to the Pennsylvania border near Hagerstown and then southward to Fredricksburg. This line is moving from the northwest at 23 mph. The eastern shore is free of precipitation except for a small area of light showers in the Salisbury area.

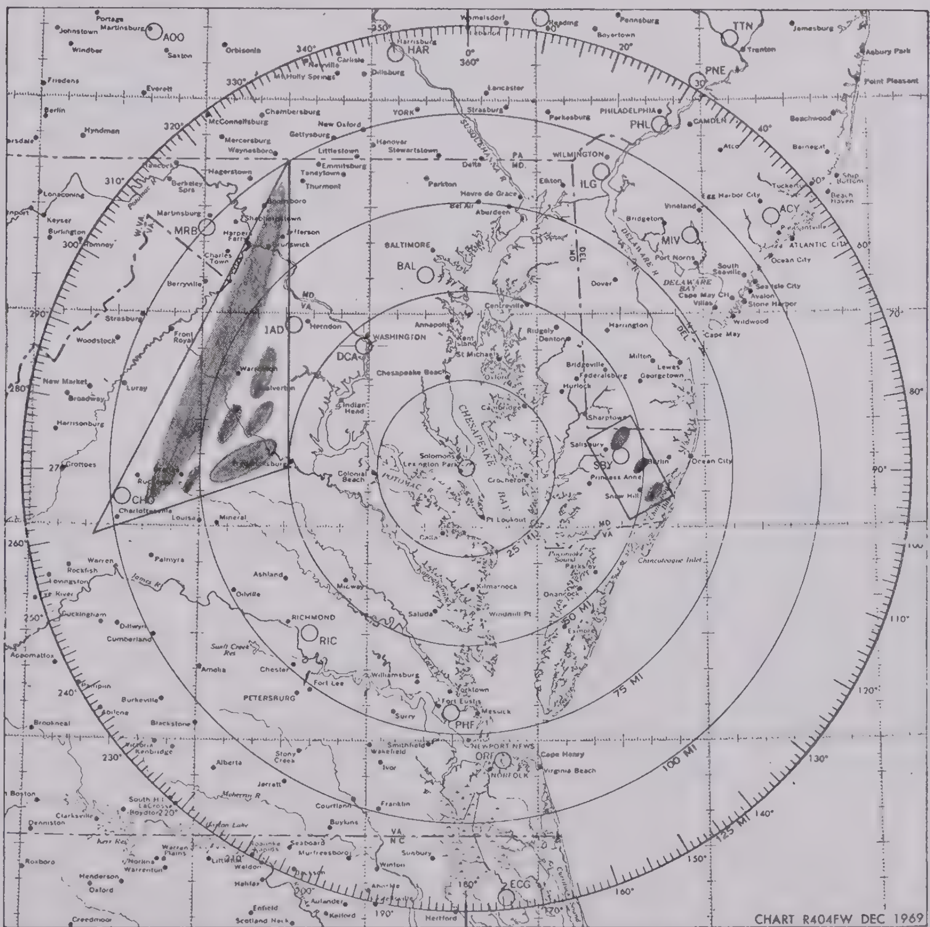


Figure 13–12

Problem 13–9

Decode and draw this RAREP on the map provided. Then, write a narrative report.

NYC 0635 AREA 7 SWIP/NC 360/50 270/20 290/60 2925 CELLS 3015 TOPS UNIFORM 110 AREA 3 R−/− 215/30 215/50 30W 270/20 CELLS 260/15 MT 200 AT 190/30

Summary

There is a nationwide radar system manned 24 hours daily to detect and monitor the weather. Information obtained is analyzed and used in the forecasting process and later provides data for useful research.

The components of the radar transmit electromagnetic waves and receive reflections from meteorological targets. However, in certain situations the radar beam can be superrefracted or subrefracted, missing targets altogether or picking up ground clutter.

Another component of the radar is the scope. The Plan Position Indicator shows the echoes' direction and distance, and the Range Height Indicator depicts the heights and distance of echoes. An auxiliary device, the Video Integrator and Processor, monitors the intensities of precipitation by the use of contoured color levels.

To send radar information to forecasters the Weather Bureau Radar Remote System was established to transmit the radar scope data instantaneously to a video set or a facsimile recorder.

Radar Reports are sent via teletype hourly to forecasters to be analyzed and Narrative Reports are sent to newscasters for public information.

WEATHER FORECASTING I

Introduction

History of Weather Forecasting

Near the turn of the century the weather forecasting agency now known as the National Weather Service was part of the United States Signal Service. On any given day six men worked in preparing the necessary weather charts for the one man who made the forecasts for the United States. Forecasts were made three times a day. Seventy-five observations were received in the offices of the Signal Service for each forecast and the six map plotters and analyzers prepared these seven charts:

1. a surface map showing pressure, temperature and the wind at each station;
2. a dew point map;
3. an "upper air" map which indicated the type of cloud over each station and its direction of motion;
4. a map on which pressure was analyzed (i.e., isobars drawn);
5. a map on which temperature was analyzed (i.e., isotherms drawn);
6. a map on which was plotted the eight hour pressure change for each station;
7. a similar map showing the 24 hour pressure change.

The maps were completely plotted and analyzed two hours after the observations were taken and the forecasts were issued by the one man who did the forecasting a mere 20 minutes later.

Today, the National Weather Service (NWS) employs hundreds of men and women throughout the country. Thousands of observations are taken each day in order to prepare the over 200 computer and hand drawn weather charts which are sent to public and private forecast offices. Thousands of forecasts of numerous variety are made from these data each day.

In a way, it is misleading to think of the National Weather Service as the direct counterpart of the United States Signal Service. The National Weather Service is just one agency of the vast Department of Commerce organization, the National Oceanic and Atmospheric Administration (NOAA). Of the agencies in NOAA which are included in the "Atmospheric" division not all of them work *directly* to improve the quality of weather forecasting. Indirectly, though, whether by designing new sensing instruments, learning how to better use satellite data or expanding the capabilities of the computer the ultimate goal is to improve the quality of weather forecasting.

Previous to the late 1950s weather forecasting was done solely by individuals working with the weather charts which they had prepared. These completely "man-made" forecasts were good with a high degree of accuracy obtained quite often. With the advent of computer plotting, analyzing and forecasting it was hoped that the "machine-made" forecasts would be of a consistently better quality. This was not the case, however, and the reasons why the computer often erred on forecasts will be taken up later. To put it simply, the man-made forecasts were good and the machine-made forecasts were good, but it has been found that, consistently, the best forecasts are made when the forecaster uses the computer products, studies, refines and questions them, and then prepares a forecast based on *his* knowledge *and* the computer guidance. This method of forecasting is sometimes called the "man-machine mix" and it has yielded the best results to the immense problem of weather forecasting.

The National Weather Service

The National Weather Service (NWS), with headquarters in Silver Spring, Maryland, is the parent governmental organization for agencies which specialize not only in meteorological activities but also hydrologic, oceanographic and climatological services. NWS engages in research and development and vast technical training activities.

The meteorological organization of NWS includes: the National Meteorological Center (NMC) in Camp Springs, Maryland, the National Severe Storm Forecast Center in Kansas City, Missouri, the Hurricane Warning Centers in San Francisco, California and Honolulu, Hawaii, and the National Hurricane Center and the Regional Center for Tropical Meteorology, both in Miami, Florida. Also in the organization are Weather Service Forecast Offices (WSFO) and Weather Service Offices (WSO).

Our interest here is with NMC, the WSFO's and the WSO's.

National Meteorological Center

Every day NMC receives at its offices in the World Weather Building in Camp Springs, Maryland 39,000 land observations, 2,500 ship observations, 2,500 upper-atmosphere sounding reports and 3,500 aircraft reports from all over the world, as well as an immense amount of cloud photographs and temperature and moisture data from weather satellites.

The data, centrally processed in the form of computer and hand-drawn maps and written reports and the prepared forecasts, are then transmitted to public and private forecasters all over the world.

To fulfill these vast responsibilities NMC has four subdivisions:

The Forecast Division uses computerized and manual techniques to prepare maps and forecasts;

The Automation Division operates the NMC computers and tests new techniques to automate NMC operations;

The Development Division conducts research and development into new types of computer weather prediction;

The Long Range Prediction Group prepares monthly weather "outlooks" and develops techniques to improve weather prediction past the current five day forecasting period.

Weather Service Forecast Offices

There are 52 WSFO's in the United States and Puerto Rico (see table 14–1). These offices are the main "field" forecast centers. They are responsible for issuing forecasts and warnings within their assigned states and portions of states. Each WSFO issues a state and area forecast twice daily for a time period of 48 hours. Five-day weather outlooks are issued once a day. Weather warnings and specialized forecasts are also issued for their areas of responsibility.

Weather Service Offices

The WSO's (approximately 250 throughout the country) are smaller than the WSFO's. The Weather Service Offices issue forecasts to meet the requirements of their localities. Their main responsibility is to issue local forecasts which are adapted from the area forecasts made at the WSFO. They also have important weather warning and communication responsibilities.

Problem 14–1

What are the differences between the WSFO's and WSO's? Which WSFO is nearest your home? Your school?

TABLE 14–1
National Weather Service Forecast Offices

Albany	Fort Worth	Omaha
Albuquerque	Great Falls	Philadelphia
Anchorage	Honolulu	Phoenix
Atlanta	Indianapolis	Pittsburgh
Birmingham	Jackson, Miss.	Portland, Me.
Bismarck	Juneau	Portland, Ore.
Boise	Little Rock	Raleigh
Boston	Los Angeles	Reno
Buffalo	Louisville	Salt Lake City
Charleston, W. Va.	Lubbock	San Antonio
Cheyenne	Memphis	San Francisco
Chicago	Miami	San Juan
Cleveland	Milwaukee	Seattle
Columbia	Minneapolis	Sioux Falls
Denver	New Orleans	St. Louis
Des Moines	New York	Topeka
Detroit	Oklahoma City	Washington, D.C.
Fairbanks		

Tools Used for Forecasting the Weather

Most of the maps produced by NMC can be separated into two categories: analyses and prognoses (that is, forecasts—"progs" for short). In this section we'll discuss some of the many analyses. Most of the progs are made by computer and are referred to as "numerical guidance" which will be discussed in the following section.

Before discussing the maps, review the section on Greenwich meantime (GMT) in Exercise 7.

Analyses

Any map on which isopleths have been drawn pertaining to meteorological data on the map (temperature, dew point, etc.) is said to have been analyzed. The meteorological information may be actual observed data or it may be information forecasted by the computer. In order to differentiate between the two types we will say that: "A map on which isopleths have been drawn pertaining to *observed* data is called an **analysis.**" (The actual data may or may not be included on the map.)

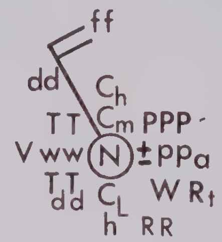
There are many meteorological parameters which can be analyzed and many types of analyses. For convenience we'll start at the surface and work our way up.

Surface Maps

The surface map is one of the most important maps used by the meteorologist for it shows him what the weather is like throughout the country. "Has the rain in Ohio moved into Pennsylvania yet? Is a low forming in the Gulf of Mexico? What are the winds like behind the front in Michigan?" These and an infinite variety of other questions can be asked and answered by the use of the surface map.

There are actually several types of surface maps. Probably the most frequently used is the surface map for the North American area. The purpose of this map is to depict the important synoptic weather features over North America. This map is prepared from observations taken eight times a day every three hours beginning at 0000 Z. The individual hours for which this map is prepared (0 Z, 3 Z, 6 Z, . . . 21 Z) are known as "synoptic time." That is, this is when the observations are taken and a "snapshot" of the surface weather is prepared. (The code used to transmit this surface data is known as the "synoptic code.") The weather observations are taken at each station, coded and sent via teletypewriter to NMC in Camp Springs, Maryland. The data used to be plotted by hand. However, since late 1975 the data have been plotted entirely by computer. Pressure is analyzed in intervals of four millibars. The isobars are labeled by two digit numbers. Since surface pressure is usually between 960 mb and 1,050 mb, a particular isobar is decoded by this method: if the isobar is labeled 00 to 50 put a "10" in front of the two digits; if the isobar is labeled 60 to 99 put a "9" in front of the two digits. Fronts are also drawn on the map. Pressure centers are indicated by an H or L signifying the location of Highs and Lows, respectively. The value of the central pressure of the system is plotted near the H or L and is also signified by a two digit number (decoded the same as the isobars). This pressure value is then underlined to indicate that it is a central pressure.

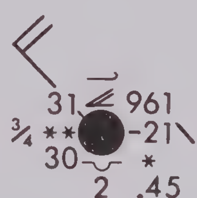
The station model, which you learned about in previous exercises, is actually an abbreviated form of the station model used for the NMC surface analyses. For the sake of completeness, here is the entire model showing all of the data that *can* be contained in it.



where:

ff	Wind speed
N	Total amount of clouds
TT	Temperature
V	Visibility
ww	Present weather
T_dT_d	Dew point
C_L	Type of low clouds
h	Height of low cloud base
RR	Amount of precipitation during the last 6 hours
R_t	Time precipitation began or ended
±	Indicates if pressure is higher or lower than 3 hours ago
PP	Indicates the amount of pressure change
a	Pressure tendency
W	Past weather
PPP	Sea level pressure
C_m	Type of middle clouds
C_h	Type of high clouds
dd	Wind direction

And here is an example:



where:

Temperature: 31°F
Wind: NW at 20 kts.
Total clouds: overcast
Visibility: ¾ mile
Dew point: 30°F
High clouds: cirrus
Present weather: light snow

Low clouds: strato cumulus
Low cloud bases: 300–599 feet
Pressure tendency: −2.1 mb falling steadily
Precipitation last 6 hours: .45 inches
Middle clouds: altostratus
Pressure: 996.1 mb
Past weather: snow

The chart on the inside of the back cover shows the various symbols, and their definitions, that could go on the model.

Figure 14–1 shows an actual North American surface map as produced by NMC. (Please turn to the foldout map at the end of this book.)

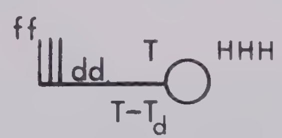
Another surface analysis produced by NMC is the Northern Hemisphere map. This map is produced every six hours beginning at 0000 Z and contains data for the entire Northern Hemisphere.

Problem 14–2

Decode stations F and G in figure 14–1. Where is the center of the system with the highest surface pressure? The lowest? What are the values of the isobars through Pennsylvania?

Upper Air Maps

A wide variety of upper air maps are produced each day by NMC. Some of the maps have the actual observed data plotted on them along with an analysis of the data. Some of the maps just have an analysis of one or more particular parameters and the data are left off. Nearly all of the upper air maps are plotted and analyzed by computer. The data used for the upper air maps come generally from radiosonde observations, aircraft reports and satellite observations. All of the maps are issued twice daily from data received from the 0 Z and 12 Z radiosonde launchings. At these two times throughout the world balloons bearing instrument packages are launched and tracked by ground observers. The data received are then coded and sent via teletype to the NMC computers. For those maps on which the data are plotted the following upper air station model is used:



T is the temperature at the particular pressure surface in degrees Celsius. $T - T_d$ is the dew point depression in degrees Celsius. (The station circle is darkened if $T - T_d$ is less than 5°C. If $T - T_d$ is greater than 30°C an X is plotted here.) HHH refers to the height in meters at which the particular pressure level was encountered. The dd refers to the wind direction and ff to wind speed (same plotting as for surface model); if the wind is missing M is placed in the lower right quadrant; if the wind is calm LV is placed in the lower right quadrant.

Centers of upper level anticyclonic and cyclonic circulations are labeled by an H or L, respectively.

The purpose of all of the upper air maps is to give the forecaster a picture of what is happening in the upper atmosphere. For whatever is happening aloft will eventually make its presence known at the surface.

500 mb Analysis

Two separate 500 mb maps are prepared twice a day. The first is the North American 500 mb analysis extending from the North Pole to as far south as southern Mexico and including the adjacent ocean areas. On these maps, both 500 mb heights and temperatures are analyzed. Height contours are solid lines drawn for each 60 meters of height and are labeled in decameters ("tens-of-meters"). Temperature is analyzed using dashed lines. On the 500 mb map, the heights shown in the station model are in decameters. (In other words, to determine the height do as you would for the contours—put a zero at the end of the three given numbers.) Also plotted on the station model is the 500 mb height change for the last 12 hours. This, too, is in decameters (that is, the trailing zero is omitted) and it is plotted in the lower right hand quadrant of the model. See figure 14–2 for a North American 500 mb map.

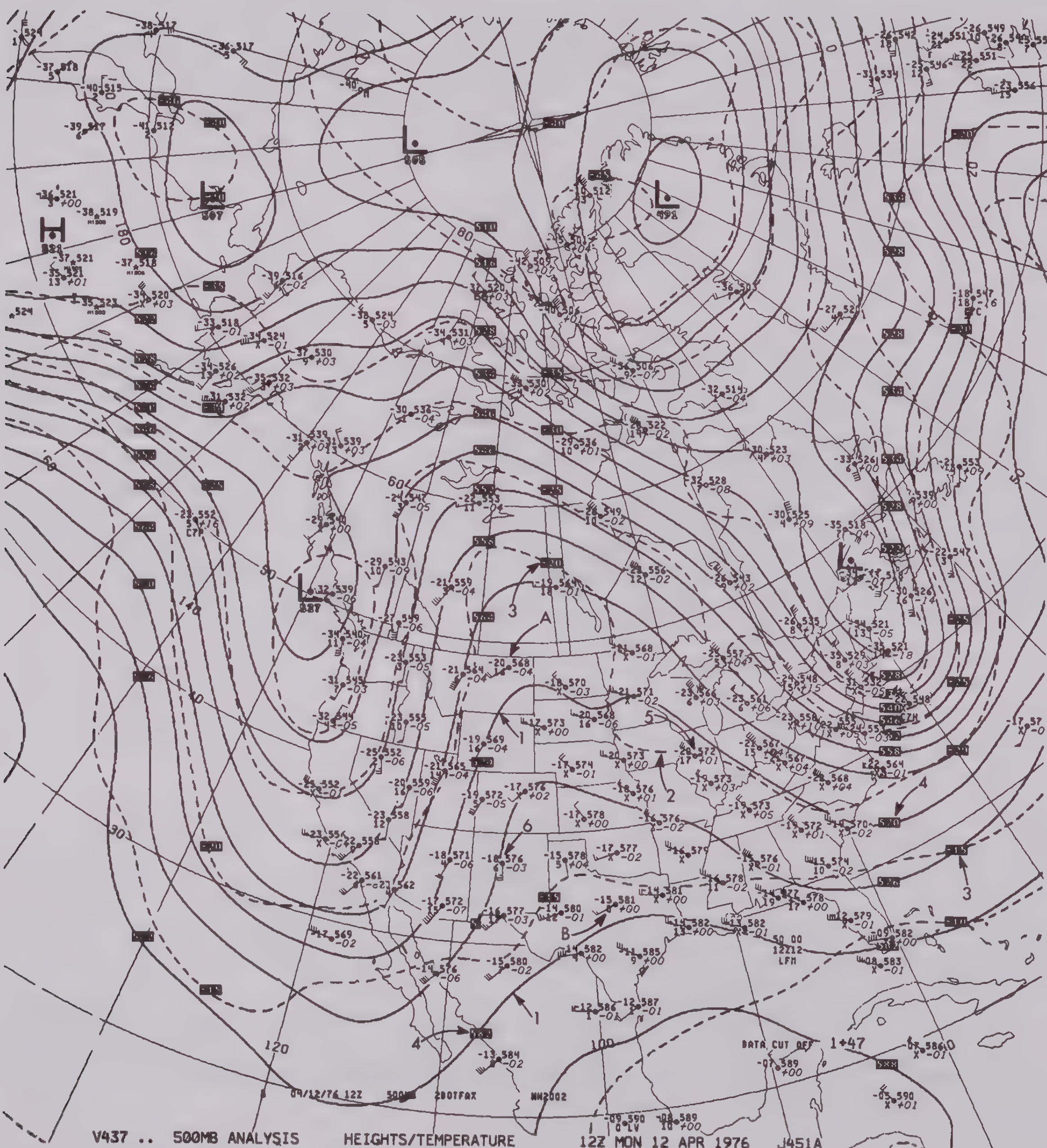


Figure 14–2. *500 mb Map—North America.* (1) Solid lines are contours (60 meter intervals), (2) dotted lines are isotherms (5°C intervals), (3) isotherm label, (4) contour label (trailing zero is omitted, read height in meters), (5) this station report, decoded, is: T = −20°C, T − T_d = 17°C, height of 500 mb level over this station is 5,720 meters, the 500 mb level has *risen* by 10 meters during the past 12 hours, winds are northwest at 25 kts., (6) this station report, decoded, is: T = −18°C, T − T_d = 6°C, height of 500 mb level over this station is 5,760 meters, the 500 mb level has fallen 30 meters during the past 12 hours, the wind is from the south at 25 kts.

The second type of 500 mb analysis includes North America, northern Asia and Europe and the northern Atlantic and Pacific Oceans.

Problem 14–3

Decode stations A and B in figure 14–2. What is the value of the contour line drawn through South Carolina? What does it mean?

Also plotted and analyzed twice each day by NMC are a variety of upper air maps for the following levels: 850 mb, 700 mb, 300 mb, 250 mb and 200 mb.

Other Maps

The synoptic code, which was mentioned above, conveys a great deal of surface weather data. From these data several additional maps are plotted. These maps are not really analyses nor are they prognoses; therefore, they are listed here under "other maps." All of these maps contain data for the United States and southern Canada and they are all plotted by hand: a Maximum Temperature chart, a Minimum Temperature chart, Six and Twenty-four Hour Precipitation Amount charts and an Observed Snow Cover chart. Also plotted twice each day is a Composite Moisture chart which includes a Stability Index map, a Precipitable Water map and maps on which are plotted the average relative humidity from the surface to 500 mb and the height of the freezing level.

Radar Summary Chart

In the Weather Radar Exercise you learned about the RAREP or Radar Report. Fourteen times a day all of these reports from all over the country are plotted on a map which then becomes the *United States Radar Summary Chart*. The purpose of this chart is to present the current large scale and small scale precipitation pattern across the country.

Numerical Guidance

In previous sections the computer has been mentioned as being a valuable tool for the meteorologist. Computers perform the tasks of plotting maps and then analyzing them thereby freeing the meteorologist from these tasks in order that he may spend his time doing other useful things. So far that is all the computer has been mentioned as doing: plotting some numbers and drawing lines on a map. In this section we'll explore the vastly more complex task the computer does: predicting the weather.

Mathematical and Physical Models of the Atmosphere

Equations can be written for almost any activity or process that takes place in the universe. In the atmosphere, many physical processes can occur at any time: the movement of the air in any one, or all, of the three dimensions (north-south, east-west, up-down), the temperature can become warmer or colder, the amount of moisture in the air can increase or decrease, the pressure at any location can rise or fall. In all, seven equations are needed to completely describe the state of the atmosphere at any *given* time. In order to forecast the weather we will want to know how each of the meteorological variables contained in the equations is changing *with time.*

For example, you are probably familiar with the equation **distance = rate × time:**

Let's say you are going on a trip by auto. You will be traveling at a rate of 50 mph. Can you use this equation to predict where you will be in five hours from the time you leave? Two hours? Fifteen hours? Yes, of course you can. Just put in the hours you will be traveling and multiply by the rate. You now know how your distance will be varying as the time varies.

Let us say now that you are actually interested in predicting how much money you will spend on your trip. Your costs will include food, fuel and lodging. Before you leave you want to predict how much money you'll need. Since you don't as yet know how much your meals will cost or fuel or lodging, you begin to make some assumptions. You assume, say, that meals will cost $5.00 each (if you eat three times a day this is $15.00)—your food equation is **money for meals = $15.00 × time** (number of days of travel); you assume that gas is $1.29 per gallon and that you'll need twenty gallons per day—your fuel equation is **money for fuel = 25.80 × time** (number of days of travel); finally, you assume that you can find a room for $30 per night—your lodging equation is **money for lodging = $30 × time.** What you have done is constructed a **model** to compute the cost of your journey. Actually, you have constructed a **"numerical model,"** numerical because you are using mathematics.

Note two things: you have had to make some assumptions and all of your equations involve the variable "time." You can use your "model" to predict your cost for one day's travel or for as many days as you like. But will your prediction be correct?

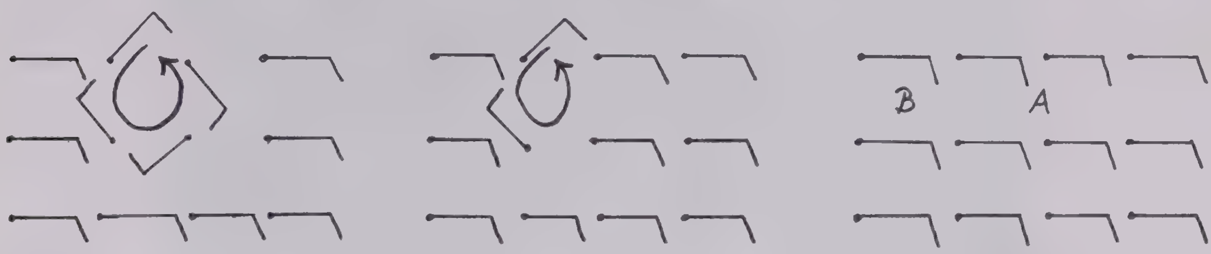
Numerical models of the atmosphere are infinitely more complex than this very simple example. The equations of the atmosphere each contain many terms and the atmospheric models don't simply multiply these terms by "time." The seven equations of the atmosphere are each solved for many, many locations (called "grid points") and for several levels in the atmosphere. To begin the computations, data are needed for the equations. These data, observations of the wind, temperature, moisture and pressure structure of the atmosphere which are obtained from surface reports, radiosondes, and satellites, are then fed into the equations. The equations are then solved and new values of the wind, temperature, etc., are found, but these values are for some *time* in the *future*. That is, *predictions* of the meteorological variables have been made. (In other words, the meteorological variables *change with time*.) We say that the equations have been solved for some time "increment" (usually 10 minutes). These new "data" are then fed into the original equations, time is incremented and another set of values to describe the state of the atmosphere is found. This process continues and can be stopped at any time to produce a forecast but it is usually stopped at 12, 24, 36 and 48 hours to produce 12, 24, 36 and 48 hour forecast maps.

The computer is used not because a man cannot solve the equations but because he cannot solve them fast enough. For in order to make just a 24 hour forecast for the Northern Hemisphere, more than *300 million* calculations need to be performed.

Since computers are doing the weather forecasting, and computers can't make mistakes, all of the forecasts should be perfect forecasts, right? Wrong. All the computer does is perform mathematical calculations. If any facet of the atmospheric model is incorrect or if the data that are being fed into the model are incorrect, the forecasts will be less than perfect. In other words, the model may look great on the drawing board but "will it fly?" Here are some of the things that can cause a computer forecast to go awry:

Assumptions: In our very simple example of trying to predict how much your trip would cost some assumptions had to be made. To model the atmosphere certain assumptions must be made. But what if the assumptions are incorrect? If this is the case, the actual results may be minor or they may be disastrous. Say on your trip you can't find a motel room for $30. Instead, you have to pay $35 or $40. You may not go broke but your spending prediction will be in error. But a small, incorrect assumption can mushroom: Suppose you can't find a motel room at all on the road on which you're traveling. Rather, you have to get off the main road and drive 20 miles out of the way to find a room. But these rooms are $50 a night, the only restaurant sells meals for $10 and the nearby gas station pumps gas for $1.50 per gallon. Now your prediction is more than "a little off." Assumptions made in the atmospheric model may be correct for one day and incorrect for another day depending on the weather situation.

Resolution: In the previous section it was said that the equations of the atmosphere are solved for many locations and that these locations are called grid points. These grid points are roughly 120 miles apart. Therefore, in order for the model to properly "pick-up" (resolve) a weather system, that system would have to be at least 120 miles "large." Large low pressure systems which cover thousands of square miles can be resolved quite well by the model. But small systems, called mesoscale systems, perhaps just 30 or 40 miles in extent can cause inclement weather when good weather was predicted by the model.



The dots, grid points, in the above diagram are about 120 miles apart. In the left diagram one could easily picture a LOW within the cyclonic circulation pattern depicted. In the center diagram, the system is smaller but cyclonic winds can be inferred. In the last diagram the winds are uniform *at the grid points*. The weather at A in the third diagram may be much different than the weather at B because of a system too small to be resolved by the model.

The problem of resolution brings up an important problem for weather forecasting. Even though thousands and thousands of bits of data are received each day, the observation network is still insufficient, especially the upper air network. More observations are needed and bigger and faster computers need to be developed to handle the increased calculations which will then need to be performed to generate computerized forecasts.

Terrain: The surface of the earth is not uniform. The terrain almost always affects the weather. Certain terrain features (for example, the oceans, the Rocky Mountains, the Appalachians) are "built into" the model but the earth's surface varies almost infinitely and not every terrain anomaly can be taken into account in the model. But, whether mountains are present to cause the air to rise, lakes in the way causing it to move faster (because of less friction) or forests to cause it to move more slowly (because of increased friction) there is some effect on the weather and not all of these effects can be predicted.

Finally, not all numerical models behave the same way. Specifically, there are three operational synoptic or large scale numerical weather prediction models in use by NMC and they vary in the way that the equations are used and in their engineering (for example, the distance between grid points). One of the models works best at the latitude of the polar jet stream but it doesn't forecast 500 mb lows very well; another model takes too long to forecast surface low pressure systems but it works well in forecasting 500 mb lows in certain parts of the country; and the third model forecasts the development and position of surface lows very well but it keeps 500 mb lows too far south and moves them slower than the "real" atmosphere is doing.

There are other quirks to the models and because of the complexity of the math and physics it is often unclear why a model is performing the way it is. All of this serves to make the process of forecasting the weather more difficult. "To believe the model or not to believe" is a dilemma that forecasters always have to face.

Problem 14–4

Briefly explain the resolution problem in numerical weather prediction.

Plate 14–1. This photo shows a small scale cyclonic circulation in a deck of low clouds off the California coast. This system is only about 12 miles in diameter—far below the resolution of the numerical models. (Photo courtesy of NASA)

The NGM

There are three synoptic scale numerical weather prediction models "run" on the NMC computers each day. We will explore only one of the models: the Nested Grid Model or NGM.

As with the other models the NGM is produced twice daily from 00 Z and 12 Z data. Output products from the NGM are numerous. Each 00 Z and 12 Z NGM "package" consists of: an *analysis* map of 500 mb heights and surface to 500 mb average relative humidity, an *analysis* map of 500 mb heights and 500 mb vorticity and 12, 24, 36 and 48 hour *forecast* maps of each of the following: a surface pressure map and 1,000 mb to 500 mb thickness map, a precipitation and 700 mb vertical velocity map, a 700 mb heights and surface to 500 mb average relative humidity map and a 500 mb heights and 500 mb vorticity map. The complete NGM forecast package consists of 18 maps: two analyses and four forecast maps for four time periods (12, 24, 36, 48 hours). Since the depiction of the various maps doesn't change, only the 12 hour forecast maps will be shown here. Each map is for the United States, Canada, the adjacent oceans and most of Mexico.

Refer to figure 14–3 maps 1 through 3.

Problem 14–5

On map 1 of figure 14–3 color red in the area of highest forecast relative humidity (i.e., > 90%). Which way is the 700 mb surface forecast to slope over Washington (i.e., from N to S, E to W)?

On map 2 where is the highest forecast surface pressure in the United States? The lowest? What are the values of the two thickness lines going through Minnesota? Is it forecast to be warmer (in the 1,000 mb to 500 mb layer) in southern or northern Minnesota?

On map 3 where is precipitation forecasted to fall in the United States? How much? Where is the *most* precipitation forecasted to fall?

Satellites

The first weather satellites were launched in 1960. Since that time great advances have been made in satellite photography and communications. Today there are four satellites in orbit being used primarily for meteorology: Geostationary Orbiting Environmental Satellites, East and West (GOES-East, GOES-West) and National Oceanic and Atmospheric Administration Satellites (NOAA-7 and NOAA-8).

The GOES satellites are in stationary orbit 23,300 miles above the equator situated over 75° W longitude and 135° W longitude, respectively. Twenty-four hours a day, every half-hour they provide pictures of the earth as seen in plates 14–2 to 14–4 and throughout this manual. The photos from these two satellites are primarily used for weather forecasting and research. NOAA-7 and 8 is a polar orbiting satellite and provides views of the entire globe (see plate 14–5). NOAA-7 and 8 photos are used primarily for research.

The GOES satellites provide pictures of four miles resolution in the infrared spectrum and one-half to two miles resolution in the visible spectrum. The satellites' infrared sensors detect heat with the coldest surfaces being white in the photographs and warmest surfaces appearing black. Various shades of gray depict temperatures in between the coldest and warmest. The full disk pictures provide the large scale view of the earth with smaller scale views obtainable as the resolution improves to one-half mile. That is, the smallest object that can be seen would have to be at least one-half mile large.

The signals from the satellites are originally received at Wallops Island, Virginia. After certain electronic manipulations, the signal is sent to Suitland, Maryland to the headquarters of the National Environmental Satellite Data and Information Service and from there it can be transmitted to various users throughout the country equipped with receivers to produce satellite photographs.

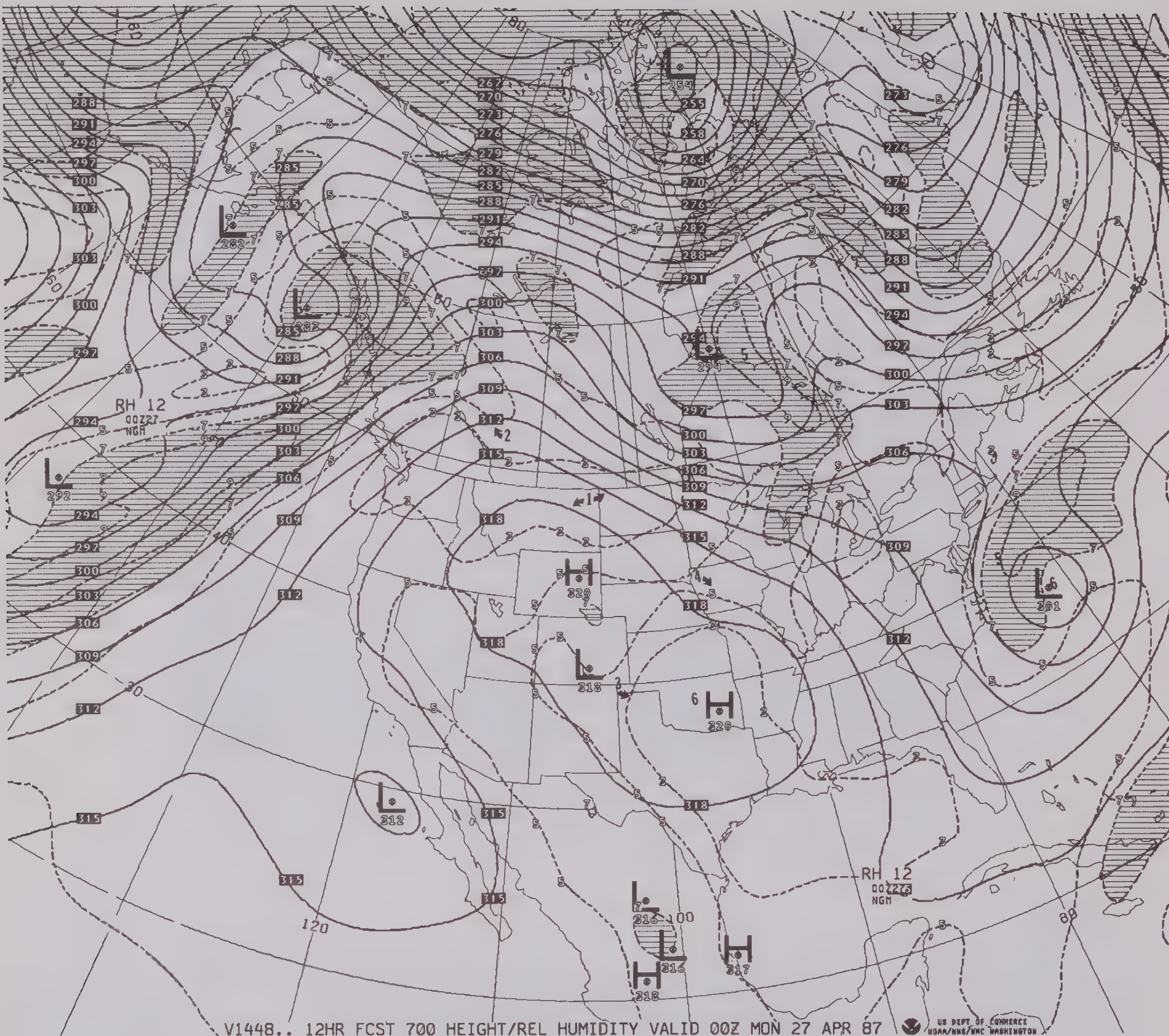
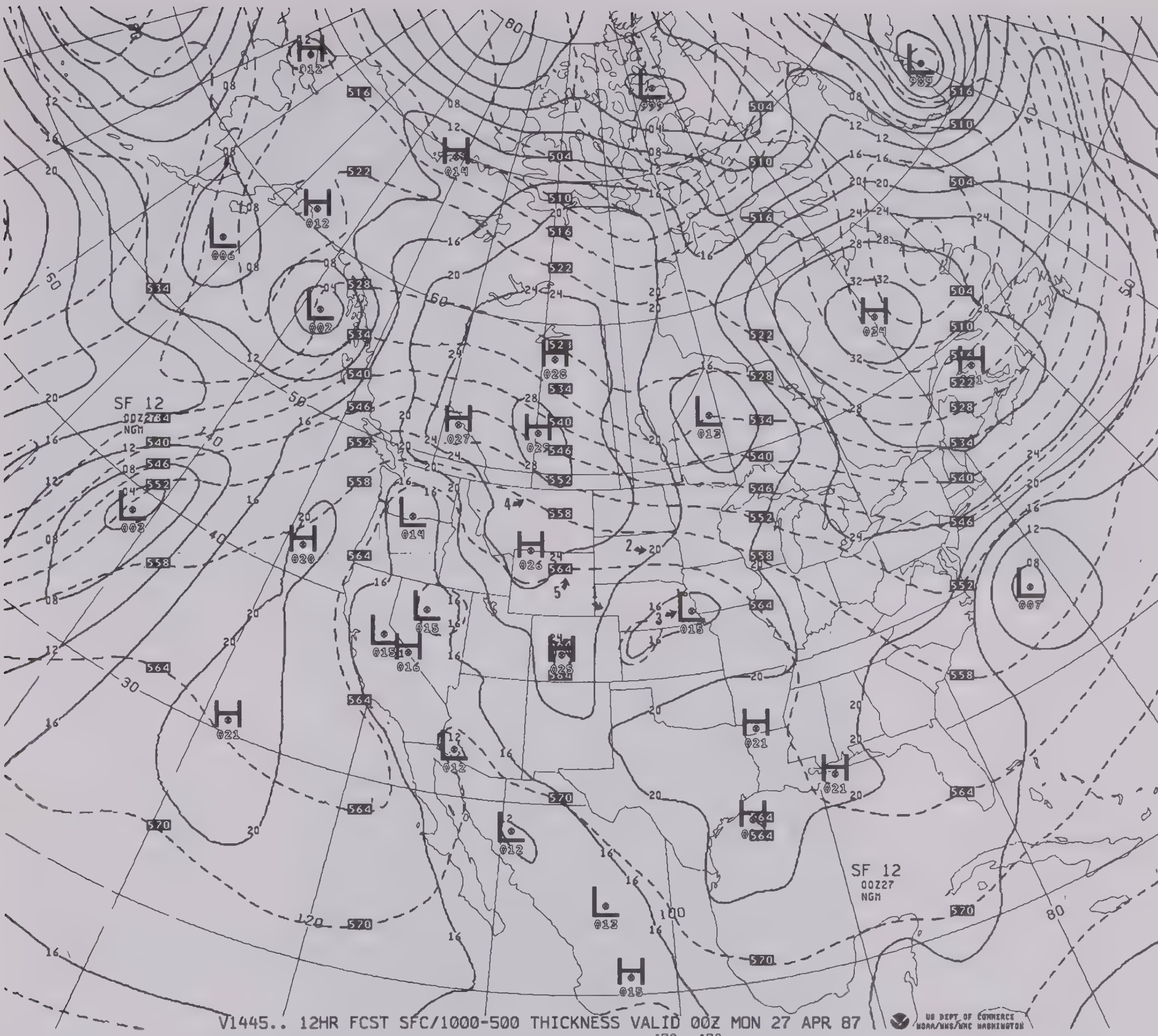


Figure 14–3 Map 1. *NGM 12 Hour Forecast of 700 mb Heights and Surface to 500 mb Mean Relative Humidity.* (a) solid lines—700 mb height contours drawn at 30 meter intervals, (2) height contour label—height of the 700 mb contour in decameters (tens of meter), (3) dotted lines—isopleths of relative humidity drawn at 20% intervals (10, 30, 50, 70, 90%), (4) relative humidity isopleth label—tens of percent, (5) shaded area—relative humidity greater than 70%, (6) H or L—indicate centers of 700 mb highs and lows.



Job No. 403340 03

Figure 14–3 Map 2. *NGM 12 Hour Forecast of Surface Pressure and 1,000 mb to 500 mb Thickness.* (1) solid lines—surface isobars drawn at 4 mb intervals, (2) surface isobar label—hundred and thousands digit omitted, (3) H or L indicate centers of surface high or low pressure centers, the value of the central pressure is below the H or L and is written in millibars with the thousands digit omitted, (4) dotted lines—isopleths of 1,000 mb to 500 mb thickness drawn at 60 meter intervals, (5) thickness line label—value in decameters.

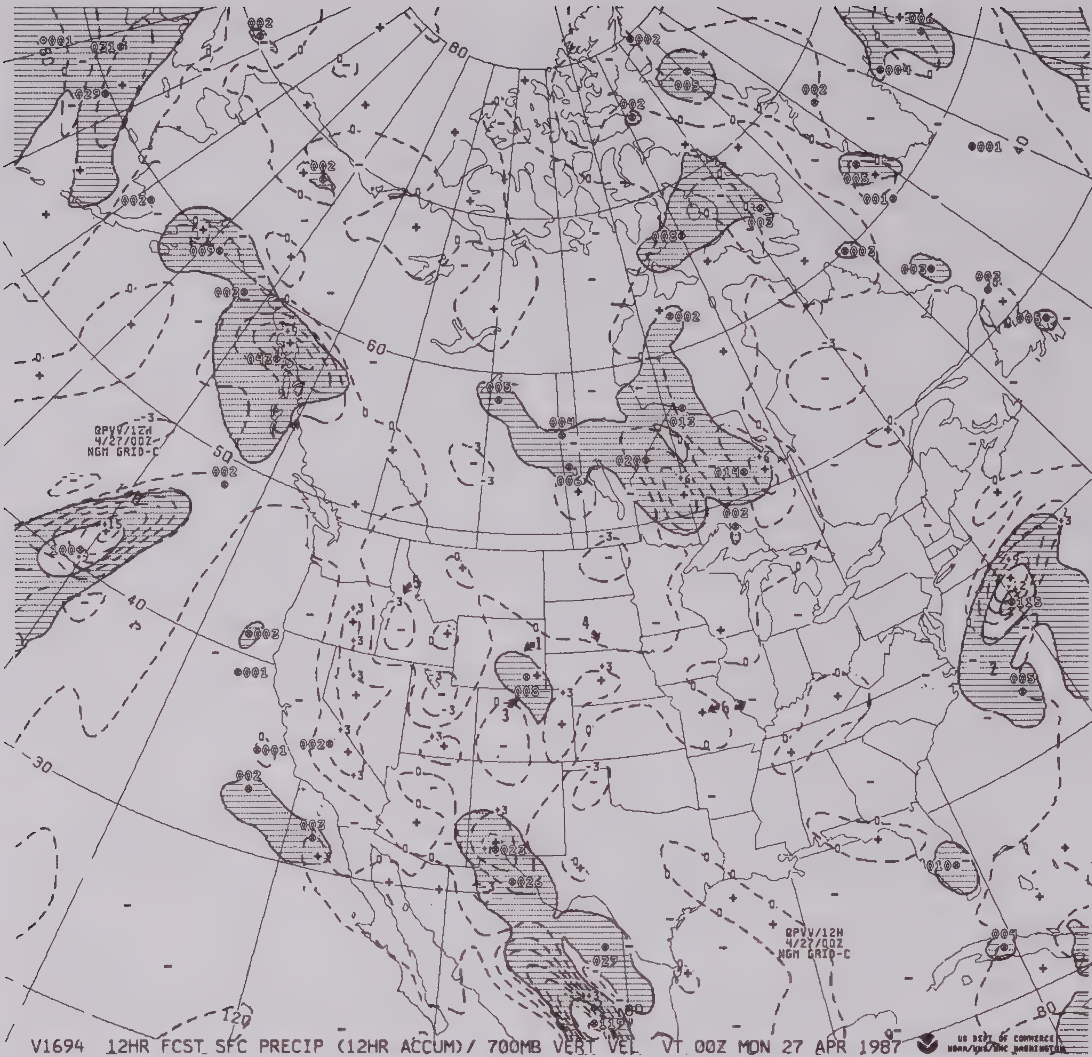
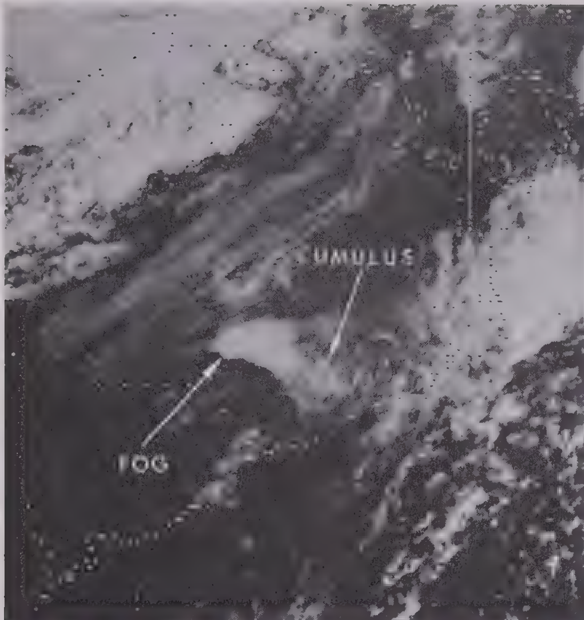
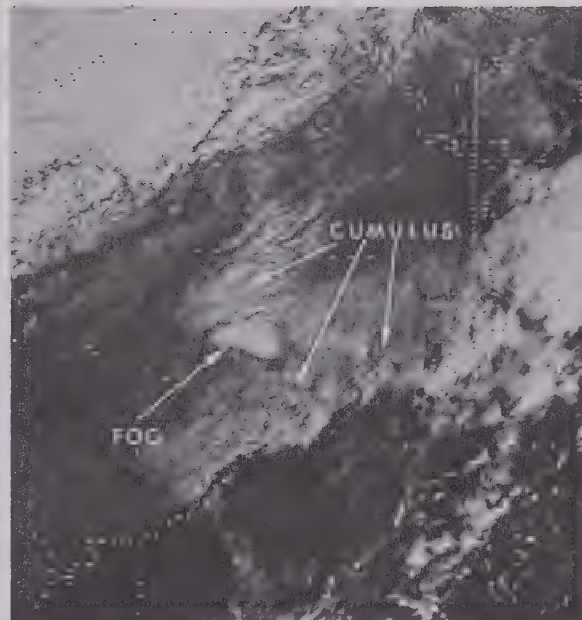


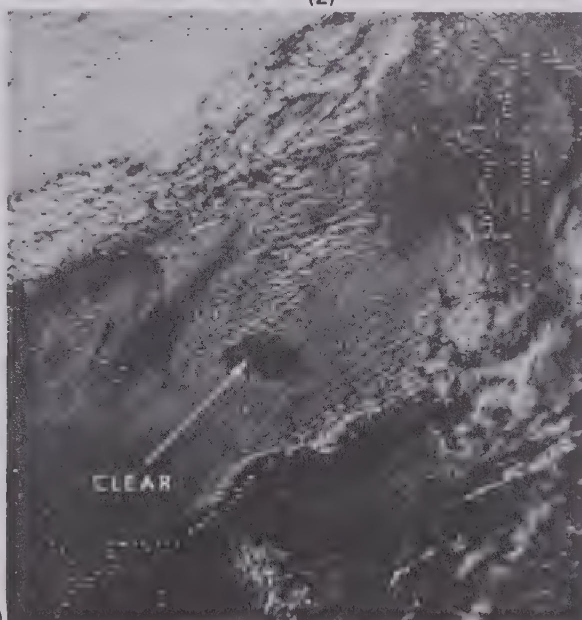
Figure 14–3 Map 3. *NGM 12 Hour Forecast of Precipitation and 700 mb Vertical Velocity.* (1) solid lines—isopleths of precipitation, cumulative during the *past* 12 hours. Isopleths are not labeled. The units are inches and they are drawn as follows: .01″, .50″, 1.00″, 1.50″, 2.00″ . . . (2) shaded areas—indicate cumulative precipitation between .01″ and .5″, 1.0″ and 1.5″, 2.0″ and 2.5″, etc. That is, after the .01″ to .5″ values the whole unit to half unit is shaded but the half unit to whole unit is *not* shaded, (3) the central value of the precipitation maxima are given in hundredths of an inch, (4) dotted lines—isopleths of vertical velocity, units are cm/sec drawn for every 2 cm/sec, (5) vertical velocity isopleth label— + indicates upward motion, − indicates down motion, (6) centers of upward (+) and downward (−) motion.



(1)



(2)



(3)

Plate 14–2. The cooling effect of fog is vividly seen in these ½ mile resolution SMS-1 photos. The area of interest is in central North Carolina. The first picture shows the large fog area at midmorning, 9:30 A.M. EST. Cumulus clouds can be seen forming to the east as the sun heats the surface and convection begins. The second picture, two hours later at 12:30 P.M., shows that cumulus clouds are much more widespread as heating continues. The sun is also having an effect on the fog area as it begins to burn-off the fog from the outside to the inside. Notice that immediately around the fog area there are no clouds. This is because the ground in this area has not warmed enough (because of the fog) for convection to begin. In the third picture, two hours later at 2:30 P.M., the fog area has completely dissipated but its effects are still present resulting in an almost circular clear area amidst several thousand square miles of cumulus.

Before satellites photographed the earth, fog areas like this may have gone completely unnoticed if there were no surface observations within its boundaries. More important that just recognizing the fog is knowing that these fog areas will be cooler than the clear areas surrounding them, thus allowing forecasters to more accurately predict where thunderstorms will form because of differential heating effects. (See the Thunderstorm Exercise) (Photo courtesy of NOAA)

Plate 14–3. These three SMS-1½ mile resolution visible pictures taken July 3, 1975 show a squall line moving southward from northern New York. The first picture shows the squall line already developed at 9:30 A.M. EST. This line of thunderstorms roared out of New York into Pennsylvania and Maryland. The second picture, 1:30 P.M. EST, shows the line moving into central Pennsylvania. Note the cauliflowerlike group of thunderstorms along the line's front edge just east of the center of Pennsylvania. This indicates extremely vigorous convection. The third picture, 3:30 P.M. EST, shows the lumpiness of the thunderstorm cells all along the leading edge of the squall line. (The solid white clouds in Pennsylvania and New Jersey, becoming almost transparent in New York, are very high cirrus clouds blowing off from the tops of the thunderstorm.) Note also the sharp southern boundary of the squall line. This is the arc cloud formed by the downdrafts from the thunderstorms. Research has shown that rapidly moving squall lines such as this one, with intense convection along the leading edge of the arc, produce very strong low-level winds. And, indeed, this was the case with this squall line, with winds gusting to 35 and 40 kts and as high as 60 kts along the path of the storms. Research such as this, with such strong implications for forecasting (actually nowcasting), could not have been done before satellite data were available.

WBRR radar pictures for this storm are shown in problem 5 of the Weather Radar Exercise. (Photo courtesy of NOAA)

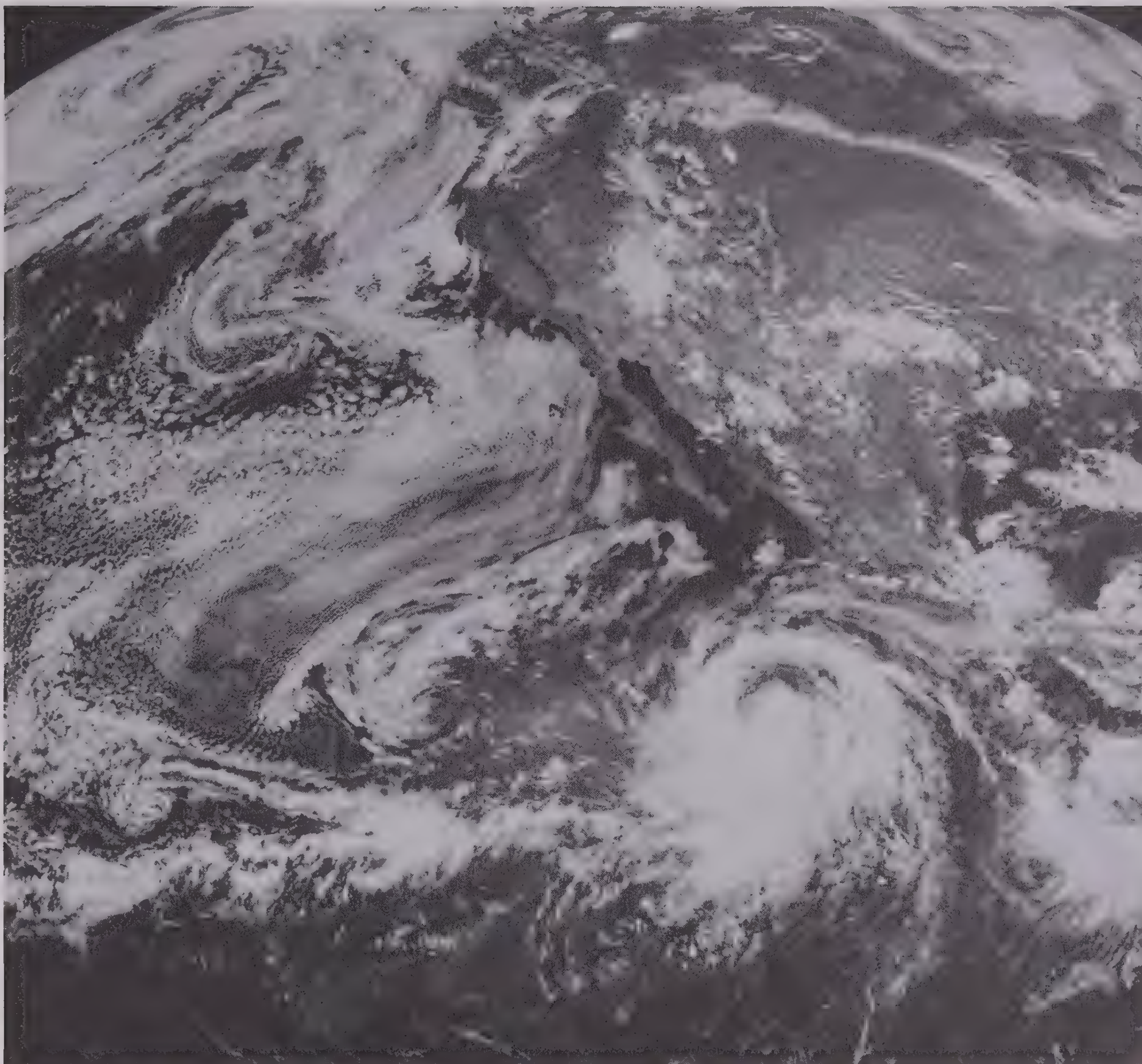


Plate 14–4. *A Melange of Whirls.* This SMS-2 photo, taken at 1945 Z on July 3, 1975, shows a variety of cloud whirls of all sizes. How many can you pick out? (Baja California is in the center of the picture, the Great Lakes are in the upper right and Alaska is under the cloud mass in the upper left.) (Photo courtesy of NOAA)

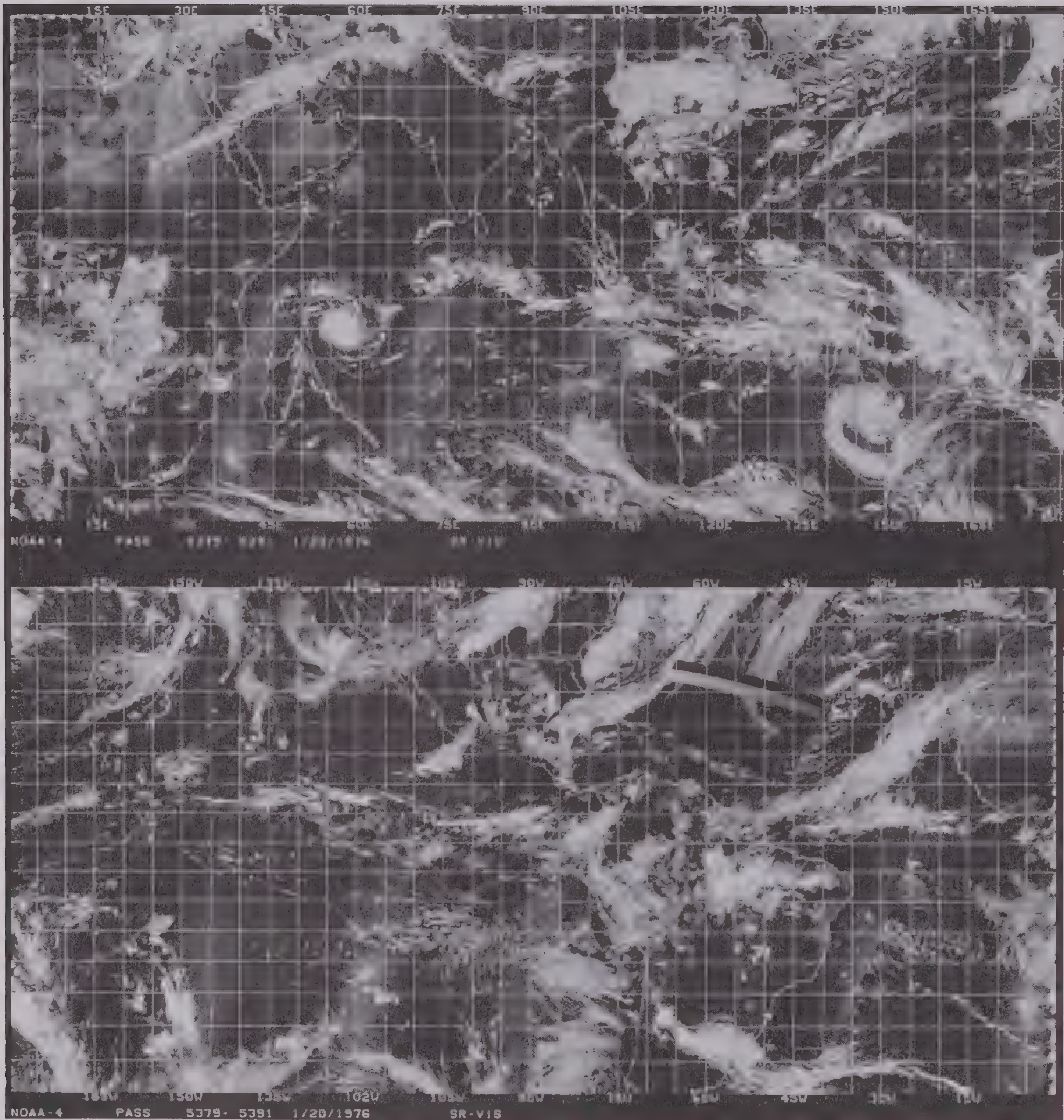


Plate 14–5. *A View from NOAA-4.* These two photos comprise a mosaic of the entire equatorial belt of the earth. Neither picture is actually one single photo. Rather, since NOAA-4 is a polar orbiting satellite, it photographs a swath of the earth with each pass from pole to pole. The finished product is composed by fitting all the pieces together to form the mosaic. About 11 passes were needed to complete each of these two pictures on which the Inter-Tropical Convergence Zone (ITCZ) is readily seen meandering near the equator. Also identifiable: a hurricane at 10°S, 57°E; sun glint (the sun reflecting off of the ocean) at 30°S, 37°W, and a variety of fronts, low pressure systems and other unusual cloud formations.

Apart from giving the forecaster the ability to detect rapidly developing weather features and to correlate observed cloud patterns to weather events with which their patterns are known to be associated, satellite data also serve as input data for the numerical models. Upper air moisture distribution can be inferred from cloudy versus clear areas on the photos, and wind direction and speed can be determined from viewing clouds on successive pictures. Upper air temperatures can be found from electronic analysis of infrared cloud photos. All of these data are then fed into the models to provide information in areas where observation stations are sparse or nonexistent.

The use of satellites is increasing constantly. New satellites are being planned and new ways to use the products obtained from current satellites are constantly being developed.

Problem 14–6

Which of the satellites that are currently in orbit are used for operational forecasting? Which are used for research? What is the difference between the satellites' infrared and visible sensors? What is the best resolution that can be obtained from the two satellites used for forecasting?

Problem 14–7

In plate 14–2(3) why is there a clear spot among the cumulus clouds in North Carolina?

Communications

Once the observations at a station are taken how do they get to the people and computers who draw the maps and make the forecasts? And, once the forecasts and maps are prepared how do they get to the users? This section will look at the four main communication methods currently in use.

Teletype

The teletype has already been mentioned as being used for communications of observed data. It is also used for communications of forecasts, both computerized (since some of the computer forecasts come out in numerical as well as mapped form) and manmade local and regional forecasts (see figure 14–4). The teletype can be used in any of three ways: since it is a typewriter-transmission device, the operator can sit at the keyboard and transmit as he types; or, he can prepare a punched-paper tape before transmission, then, when he wishes to transmit he can feed the paper tape through the machine and the message is sent. Even if he's a good typist, using the tape is quite a bit faster than transmitting while typing. The third way the machine is used is to let a computer do all the work. In most cases forecasts and observations are sent (by teletype) directly into the NMC computer in Camp Springs, Maryland. Once it has collected all of the forecasts and data, the computer then transmits the data to other teletypes. Teletype communication is done via regular telephone lines.

Facsimile

Facsimile machines are used to receive maps from NMC. As with the teletype, communication is via telephone lines. Facsimile maps, or "fax" maps, are drawn by the machine on specially moistened paper. The "ink" used to draw the maps is actually a weak electrical current which "burns" an image on the paper. The maps are not received in completed form all at once. That is, a completed map doesn't spew forth from the machine. Rather, the maps are received at a rather slow rate. A surface map, for example, takes about seven minutes to be completely received. Facsimile machines are the primary way forecast and observation maps get from NMC to various users.

Cathode Ray Tubes

Within the last few years many teletypes have been replaced with Cathode Ray Tubes or CRT's. These televisionlike devices are used both for transmission and reception of data and forecasts. Forecasts can be composed and, when satisfied with the results, the forecaster can push certain keys on the keyboard which send the product to a master computer in Suitland, Maryland for storage. Anyone who wishes to know the forecast types a request code and the computer replies by writing the forecast on the screen. Data, both mapped and coded, as well as forecasts and a variety of other products can be retrieved from the computer in this request-reply manner. With the increasing use of sophisticated electronics, the use of CRT's has expanded and they have produced a minor revolution in the weather forecasting field.

AFOS

Facsimile transmission of NMC weather maps currently takes between five and ten minutes. Imagine a system that produces a map in 15 *seconds*. Teletype transmission of written material is currently done at the rate of about 100 words per minute. Imagine a system which produces the same material at *3,000* words per minute; a system which will automatically check data for errors as they are received. AFOS, the Automation of Field Operation and Services, performs all of these jobs and many more.

Modern communications and computer technology were fully applied to the science of weather forecasting with this system which was developed in the late 1960's and early 1970's. The first AFOS units were delivered to selected Weather Service Forecast Offices in July 1977 with total implementation into most of the WSFOs and many of the WSOs in 1981.

Each AFOS system consists of two primary units: a minicomputer which collects data, checks and processes the data and then communicates these data to the forecaster and other AFOS systems; and, a console unit consisting of several televisionlike displays (which replaced the facsimile machine and teletype) controlled by a typewriter keyboard to compose and transmit messages. Each AFOS system is linked by means of a nationwide, 11,260 mile communications circuit. Any system is able to transmit a

```
ZCZC WBC997
FPUS1 KWBC 202210
WBC FP1 202210

DC01
DC AND VICINITY
MILD WITH A CHANCE OF SHOWERS OR THUNDERSHOWERS LATE TONIGHT AND
LIKELY ON SUNDAY. LOWS TONIGHT 50 TO 55. HIGHS SUNDAY 60 TO 66
BUT TURNING COOLER DURING THE AFTERNOON. WINDY AND COLDER WITH
PARTLY CLOUDY SKIES SUNDAY NIGHT. LOWS 32 TO 38. BREEZY AND COOL
WITH MOSTLY SUNNY SKIES MONDAY. HIGHS 48 TO 53. THE CHANCE OF
RAIN IS 50 PERCENT TONIGHT 70 PERCENT SUNDAY AND 10 PERCENT
SUNDAY NIGHT. WINDS SOUTHWESTERLY 10 TO 20 MPH SHIFTING TO
NORTHWEST SUNDAY AFTERNOON.$$

THE NATIONAL WEATHER SERVICE FORECASTS THE POTOMAC AT LITTLE
FALLS TO FALL FROM ITS PRESENT STAGE OF 4.4 FEET TO 4.2 FEET
SUNDAY.

EXPLANATION
A COLD FRONT IN THE MISSISSIPPI VALLEY THIS AFTERNOON WILL MOVE
THROUGH THE APPALACHIANS BY SUNDAY AFTERNOON AND BE ALONG THE
SOUTHEAST VIRGINIA COAST BY SUNDAY EVENING. SHOWERS AND A FEW
THUNDERSHOWERS WILL SPREAD OVER THE THREE STATE AREA IN ADVANCE
OF THE FRONT. MILD TEMPERATURES THROUGH SUNDAY BUT TURNING COOLER
FROM THE WEST SUNDAY AFTERNOON AND EVENING AS THE FRONT PASSES.
HIGH PRESSURE IN SOUTHERN CANADA WILL MOVE SOUTHEAST INTO THE
LOWER OHIO VALLEY BY MONDAY BRINGING COLDER WEATHER OVER THE
REGION WITH FREEZING TEMPERATURES IN THE MOUNTAINS BY MONDAY
MORNING.
```

Figure 14–4

message to any other system on the circuit within one minute. AFOS has eliminated most of the communication delays which occurred in the past, especially during large, severe-weather outbreaks, and relieved the forecaster of most of the nonforecasting chores he used to perform.

By improving communications and freeing the forecaster to *forecast* rather than tear teletype and fax machine paper, as well as giving him access to a tremendous amount of weather data in seconds, AFOS provides a level of forecasting and communications reliability which the public and meteorology had never seen before.

Summary

Weather forecasting is a complex task. Many factors combine to make the forecaster's job a difficult one. First of all, just the size of the atmosphere can be intimidating. Roaring winds, fierce storms, calm areas, and clear areas appear and disappear within the atmospheric "donut" and sometimes seem to defy logic. Secondly, the amount of data received each day which are at the forecaster's disposal can never be fully studied nor completely comprehended *in time* to prepare his many daily forecasts. And what of the data that are received and transmitted to the computer? Many times if a communication error is made (a + that should have been a − , a 1.1 that should have been an 11) entire prog packages can be in error. From balloon launch to computer output there are many places where errors can be made. Even if errors are not made, can the forecaster believe the computer? Are the assumptions correct, is the math correct, what of the terrain and what of the small scale systems which all too often destroy a forecast? Before you chastise the weather service the next time your picnic is rained out when clear skies were forecast, consider the above problems. Weather forecasting *is* a difficult job.

WEATHER FORECASTING II

Introduction

In this exercise, you will learn how to actually analyze weather maps. These maps are the basic tool of the weather forecaster. To review the station model, reread the portion of exercises 3 and 5 concerning the station model and how it is plotted. Appendix A will also be useful in helping to decode any symbols. The portion of exercise 5 concerning the location of fronts will be of help to you also.

The Surface Map

This map is a depiction of the surface weather conditions at a given time (exercise 14 will give you a review discussion of this and other maps used in this exercise). Figure 15–1 is an analyzed surface weather map dated 0000 Z, March 3, 1971. Pay special attention to the manner in which the isobars are labeled. The isobars are solid lines labeled at the ends of the lines (or at the top of a closed circle).

Note that the isobars never touch or cross each other. If they did, this would mean that the same place would have more than one pressure at the same time. This, of course, cannot happen.

Problem 15–1

Using the surface map dated 0000 Z, 3 March 1971 as a model, analyze the pressure and temperature fields on the plotted surface map dated 1200 Z, 3 March 1971.

First locate any fronts that may be on the map. Use wind shifts, temperature gradients, and dew points as aids. A careful look at the 0000 Z, 3 March 1971 map may be of help to you here. Draw in the fronts lightly in pencil. Note: The pressures have been plotted on these surface maps in a nonstandard manner. The last figure has been omitted. For example, 97 means a pressure of 997 mb and 04 means a pressure of 1,004 mb.

Next, draw the isobars as solid black lines and the isotherms as red lines. Be sure to label your isobars and isotherms the same way as in the example. Hint: for this and all other maps you analyze, use a number 2 pencil, well-sharpened, and sketch in your lines very lightly. When you are sure of your analysis—and only then—darken or color your lines.

Use 1,000 mb as a base isobar and draw isobars at 4 mb intervals. Draw isotherms at 5°F intervals using 0°F as a base isotherm. Again, refer to the example map if this is not clear.

When you have completed your isobar and isotherm analyses, kink the isobars toward higher pressure (see exercise 5 for a review of this) at the cold and warm fronts. Darken in the fronts with blue (for cold fronts) and red (for warm fronts) pencil lines. Now indicate the steady rain area by shading with green pencil. Be sure to include only the areas of *steady* rainfall (refer to Appendix A for the symbols depicting steady precipitation). Now do the same, using blue pencil, for the regions experiencing steady snowfall. Foggy areas should be shaded in with yellow pencil.

Finally, put a large blue "H" in the areas of high pressure and a red "L" in any low pressure areas.

The 500 mb map dated 0000 Z, 3 March 1971 has been analyzed for you (figure 15–2). The 500 mb station model was discussed in exercise 14. The 500 mb maps that have been plotted in this exercise record the dew point temperature not the dew point depression. It is felt that this makes the map more easily understood by the nonprofessional viewer. Note that the winds at 500 mb closely parallel the contours instead of crossing them at an angle as they do at the surface.

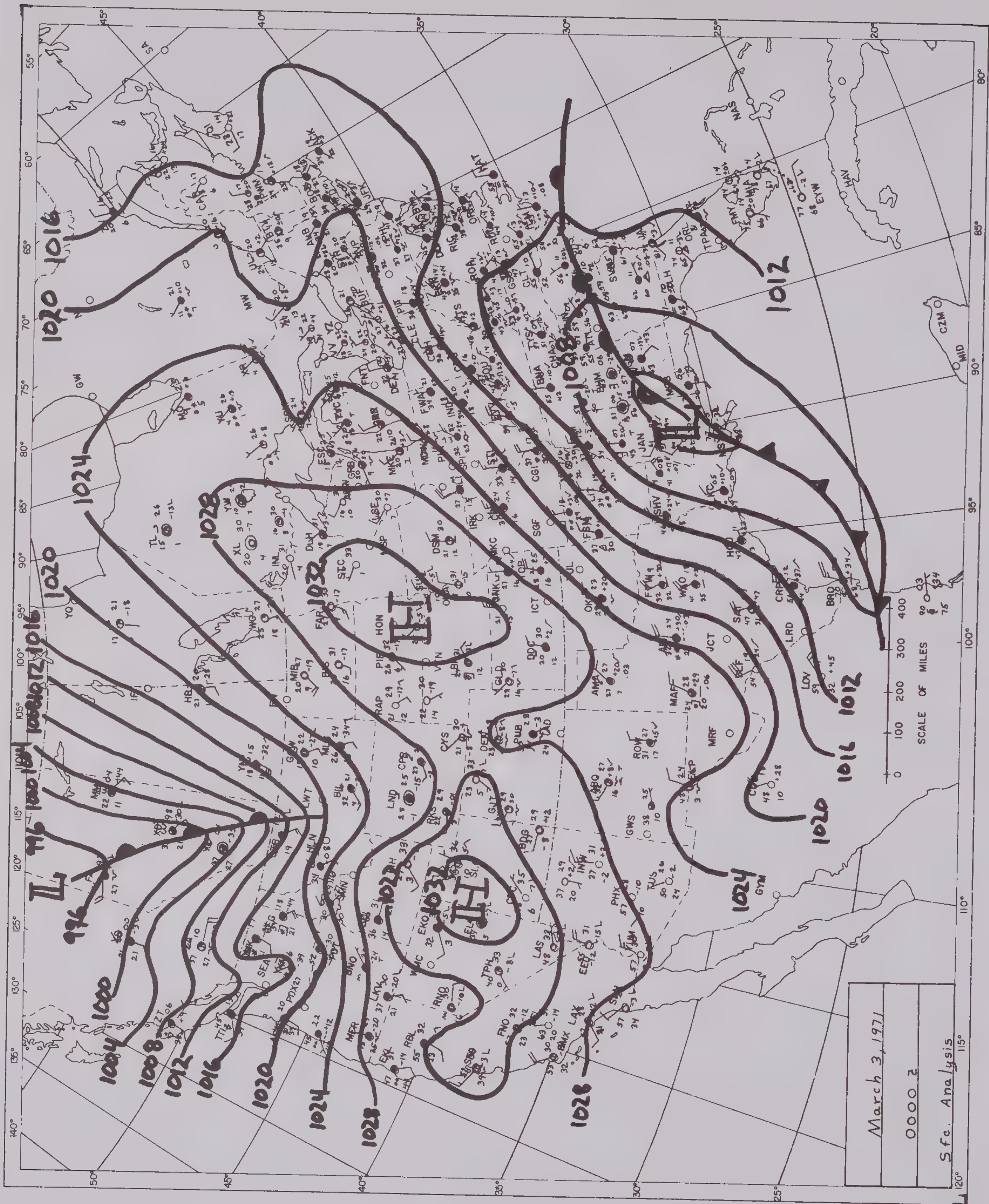
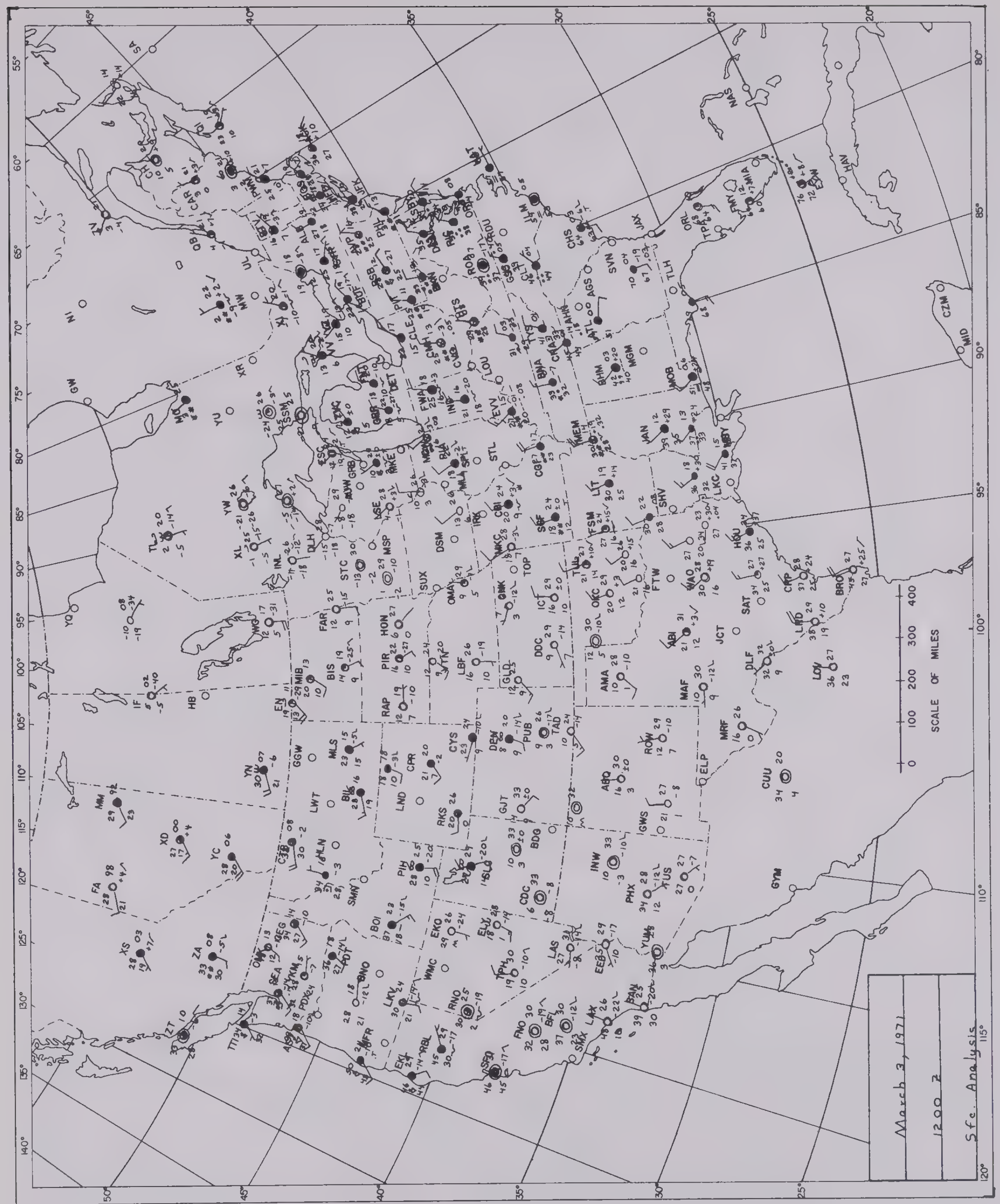
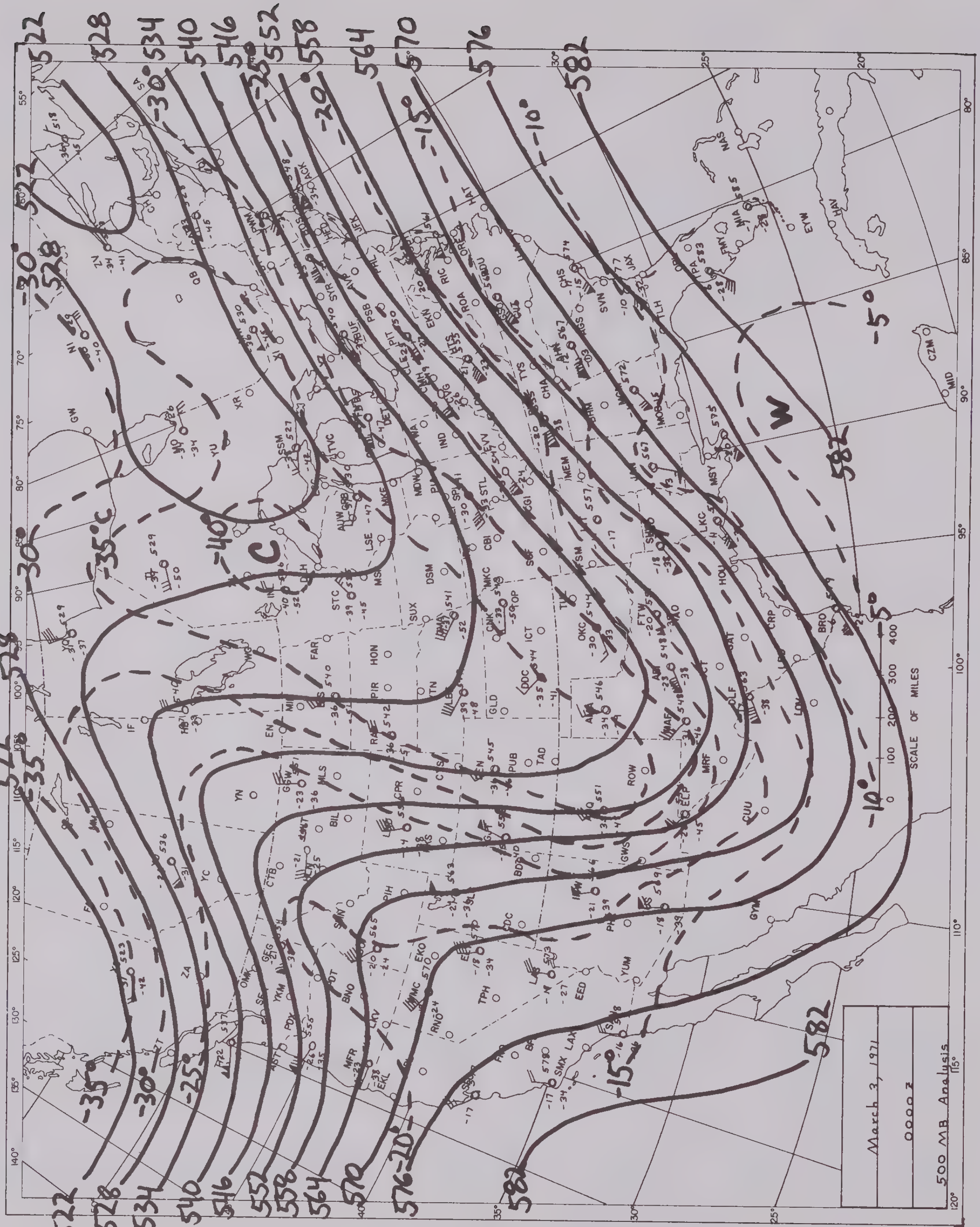


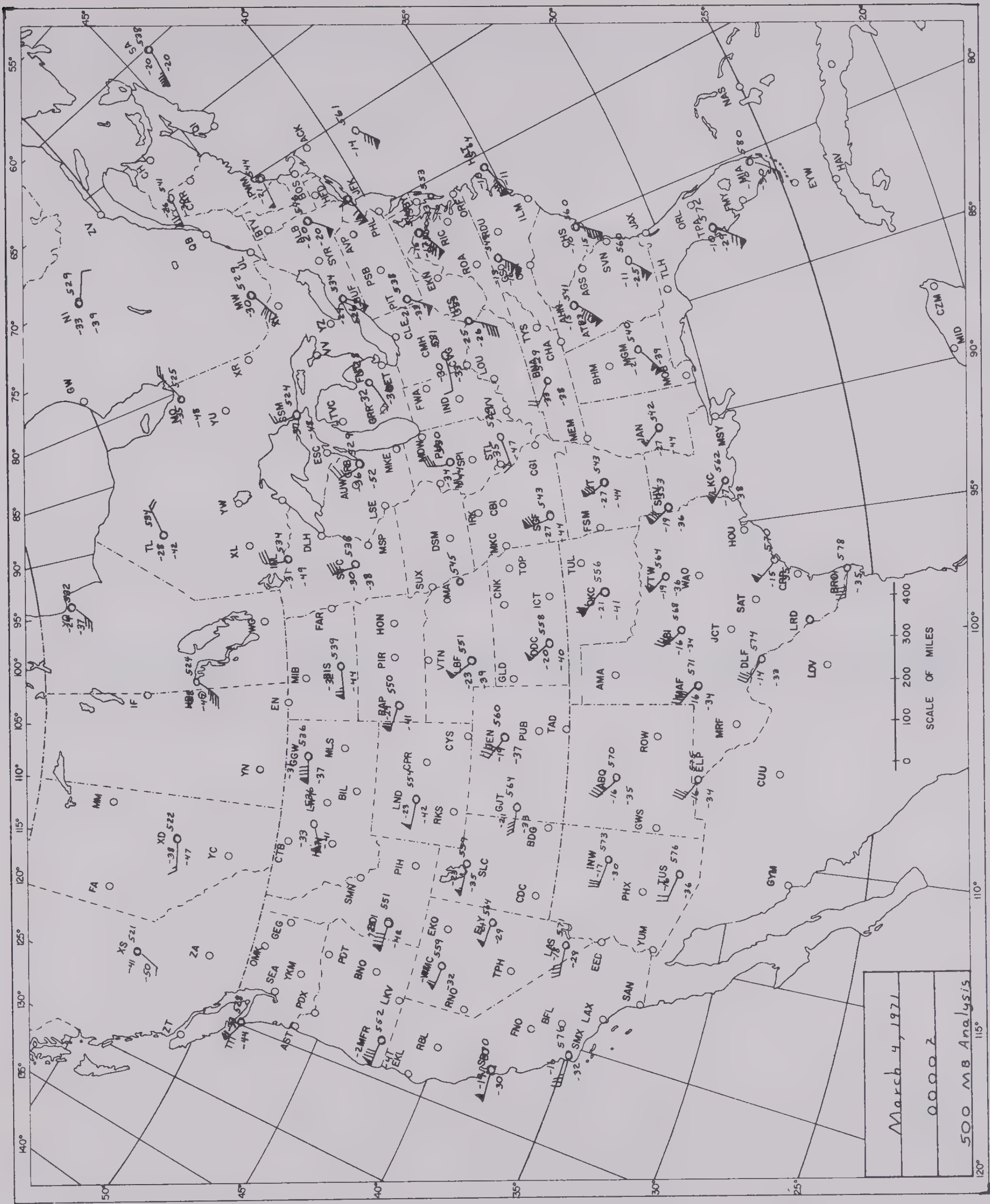
Figure 15-1


March 3, 1971
1200 Z
Sfc. Analysis
SCALE OF MILES



Copyright 1976 by John A. Dutton and Robert E. Livezey.

Figure 15–2


March 4, 1971
0000 Z
500 MB Analysis
SCALE OF MILES
0 100 200 300 400

Problem 15–2

Draw the contours of the 500 mb surface on the plotted map dated 0000 Z, 4 March 1971. These contours should be drawn at 60 meter intervals (i.e., 534, 540, 546, 552, etc.). As with the surface map use a number 2 pencil and draw your lines lightly until you are sure you have them the way you want them. Using a red pencil draw in the isotherms using a 5° centigrade interval (−50°, −55°, etc.). Label the coldest air with a blue "C" and the warmest air with a red "W." Locate the troughs and ridges (see exercise 6 for a review of troughs and ridges) and draw a blue dashed line along the ridge axis and a red dashed line along the trough axis.

Now plot with green X's the position of the surface lows at 0000 Z, 3 March 1971 and at 1200 Z, 3 March 1971. What can you say about the relationship of the movement of surface low-pressure systems and the winds of the upper atmosphere?

Problem 15–3

Referring to the plotted and analyzed surface maps, on which side of the cold front do you find the lowest dew points?

Problem 15–4

Where would you expect to find the coldest nighttime temperatures?

Problem 15–5

Why are the winds at 500 mb blowing almost parallel to the contours, but the surface winds cross the isobars at an angle?

Summary

By now you should have a basic understanding of the atmosphere and its most interesting phenomenon, the weather. An appreciation of the processes which affect your everyday life will help you make those important decisions: "Do I carry an umbrella today? Can we plan for a picnic tomorrow? What are the chances of a good weekend at the beach?" These and other weather related questions should be easier to answer now that you can apply the basic knowledge gained in this course to the various newspaper weather maps, radio and television forecasts, and the rules of thumb concerning the weather that abound in day to day existence.

BIBLIOGRAPHY

Ahrens, C. Donald. *Meteorology Today.* St. Paul, MN: West Publishing Company, 1982.

Anthes, R. A.; Cahir, John J., Fraser, Alister B., and Panofsky, Hans A.. *The Atmosphere.* 3rd ed. Columbus, OH: Charles E. Merrill Publishing Co., 1981.

Battan, Louis J. *The Nature of Violent Storms.* Garden City, NJ: Doubleday and Co., Inc., 1961.

Byers, Horace R. *General Meteorology.* New York, NY: McGraw-Hill Book Company, 1959.

Gedzelman, Stanley D. *The Science and Wonders of the Atmosphere,* New York, NY, John Wiley & Sons, 1980.

Holtzworth, George C. *Mixing Weights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States,* Research Triangle Park, NC, Environmental Protection Agency, 1972.

Huschke, Ralph E., Editor, *Glossary of Meteorology,* Boston, MA, American Meteorological Society, 1959.

Kotsch, William J. *Weather for the Mariner,* 3rd Ed. Annapolis, MD, Naval Institute Press, 1983.

Miller, Albert, Thompson, Jack C., Peterson, Richard E., and Haragan, Donald R. *Elements of Meteorology,* Fourth Ed., Columbus, OH. Charles E. Merrill Publishing Co., 1983.

Neuberger, Hans and Cahir, John J. *Principles of Climatology,* New York, NY. Holt, Rinehart and Winston, 1969.

Riehl, H. *Introduction to the Atmosphere,* New York, NY. McGraw-Hill Book Company, 1972.

Scorer, Richard. Clouds of the World: A Complete Color Encyclopedia, North Pompet, VT: David and Chodes, 1972.

This is by no means a complete listing of the many excellent books written on the subject of basic meteorology, but rather a sampling to be used as a reference if necessary.

In addition to the above books, you can learn more about meteorology from the following:

1. The Superintendent of Documents, Washington, D.C., publishes a number of interesting meteorology charts and brochures. You can get a list of these publications and their cost by writing to the

   Superintendent of Documents
   U.S.Government Printing Office
   Washington, D.C.

   and requesting a list of meteorological publications.

2. All of the meteorological data collected in the U.S. are archived by the National Climatic Center (NCC) in Asheville, NC. You can contact them by mail or by phone at 704/259–0682 for information on average weather conditions for cities throughout the U.S. and also for a wide variety of dispersion meteorology data.

3. The American Meteorological Society is a national organization which represents meteorologists and those interested in the science of meteorology. Membership information is available by writing to the AMS at 45 Beacon Street, Boston, MA 02108. Student memberships are available.

4. The National Weather Association is an organization whose aim is to provide a forum for the discussion of topics of interest to the *operational* meteorological community. The association also seeks to represent those interests and to influence events which may lead to improved weather products and service to users. For further information write to:

   The National Weather Association
   4400 Stamp Hill Road, Room 404
   Temple Hills, MD 20748

5. The Helen Dwight Reed Foundation in association with The American Meteorological Society publishes the magazine "Weatherwise" which contains a wide variety of articles pertaining to meteorology. For subscription information write to:

   Heldref Publications
   4000 Albermarle St. NW
   Washington, DC 20016

STATION MODEL AND EXPLANATION OF WEATHER CODE FIGURES AND SYMBOLS

§The symbol is not plotted for "ww" when "00" is reported. When "01, 02, or 03" is reported for "ww", the symbol is plotted on the station circle.
†Refers to "hail" only. ††Refers to "soft hail", "small hail", and "hail".

ww — Present weather

00 Cloud development NOT observed or NOT observable during past hour.§	01 Clouds generally dissolving or becoming less developed during past hour §	02 State of sky on the whole unchanged during past hour.§	03 Clouds generally forming or developing during past hour.§	04 Visibility reduced by smoke.	05 Haze.	06 Widespread dust in suspension in the air, NOT raised by wind, at time of observation.	07 Dust or sand raised by wind, at time of ob.	08 Well developed dust devil(s) within past hr.	09 Duststorm or sandstorm within sight of or at station during past hour.
10 Light fog.	11 Patches of shallow fog at station, NOT deeper than 6 feet on land.	12 More or less continuous shallow fog at station, NOT deeper than 6 feet on land.	13 Lightning visible, no thunder heard.	14 Precipitation within sight, but NOT reaching the ground.	15 Precipitation within sight, reaching the ground, but distant from station.	16 Precipitation within sight, reaching the ground, near to but NOT at station.	17 Thunder heard, but no precipitation at the station.	18 Squall(s) within sight during past hour.	19 Funnel cloud(s) within sight during past hour.
20 Drizzle (NOT freezing and NOT falling as showers) during past hour, but NOT at time of ob.	21 Rain (NOT freezing and NOT falling as showers) during past hr., but NOT at time of ob.	22 Snow (NOT falling as showers) during past hr., but NOT at time of ob.	23 Rain and snow (NOT falling as showers) during past hour, but NOT at time of observation.	24 Freezing drizzle or freezing rain (NOT falling as showers) during past hour, but NOT at time of observation.	25 Showers of rain during past hour, but NOT at time of observation.	26 Showers of snow, or of rain and snow during past hour, but NOT at time of observation.	27 Showers of hail, or of hail and rain, during past hour, but NOT at time of observation.	28 Fog during past hour, but NOT at time of ob.	29 Thunderstorm (with or without precipitation) during past hour, but NOT at time of ob.
30 Slight or moderate duststorm or sandstorm, has decreased during past hour.	31 Slight or moderate duststorm or sandstorm, no appreciable change during past hour	32 Slight or moderate duststorm or sandstorm, has increased during past hour.	33 Severe duststorm or sandstorm, has decreased during past hr.	34 Severe duststorm or sandstorm, no appreciable change during past hour.	35 Severe duststorm or sandstorm, has increased during past hour.	36 Slight or moderate drifting snow, generally low.	37 Heavy drifting snow, generally low.	38 Slight or moderate drifting snow, generally high.	39 Heavy drifting snow, generally high.
40 Fog at distance at time of ob., but NOT at station during past hour.	41 Fog in patches.	42 Fog, sky discernible, has become thinner during past hour.	43 Fog, sky NOT discernible, has become thinner during past hour.	44 Fog, sky discernible, no appreciable change during past hour.	45 Fog, sky NOT discernible, no appreciable change during past hour.	46 Fog, sky discernible, has begun or become thicker during past hr.	47 Fog, sky NOT discernible, has begun or become thicker during past hour.	48 Fog, depositing rime, sky discernible.	49 Fog, depositing rime, sky NOT discernible.
50 Intermittent drizzle (NOT freezing) slight at time of observation.	51 Continuous drizzle (NOT freezing) slight at time of observation.	52 Intermittent drizzle (NOT freezing) moderate at time of ob.	53 Continuous drizzle (NOT freezing), moderate at time of ob.	54 Intermittent drizzle (NOT freezing), thick at time of observation.	55 Continuous drizzle (NOT freezing), thick at time of observation.	56 Slight freezing drizzle.	57 Moderate or thick freezing drizzle.	58 Drizzle and rain, slight.	59 Drizzle and rain, moderate or heavy.
60 Intermittent rain (NOT freezing), slight at time of observation.	61 Continuous rain (NOT freezing), slight at time of observation.	62 Intermittent rain (NOT freezing), moderate at time of ob.	63 Continuous rain (NOT freezing), moderate at time of observation.	64 Intermittent rain (NOT freezing), heavy at time of observation.	65 Continuous rain (NOT freezing), heavy at time of observation.	66 Slight freezing rain.	67 Moderate or heavy freezing rain.	68 Rain or drizzle and snow, slight.	69 Rain or drizzle and snow, mod'te or heavy.
70 Intermittent fall of snow flakes, slight at time of observation.	71 Continuous fall of snowflakes, slight at time of observation.	72 Intermittent fall of snow flakes, moderate at time of observation.	73 Continuous fall of snowflakes, moderate at time of observation.	74 Intermittent fall of snow flakes, heavy at time of observation.	75 Continuous fall of snowflakes, heavy at time of observation.	76 Ice needles (with or without fog).	77 Granular snow (with or without fog).	78 Isolated starlike snow crystals (with or without fog).	79 Ice pellets (sleet, U. S. definition).
80 Slight rain shower(s).	81 Moderate or heavy rain shower(s).	82 Violent rain shower(s).	83 Slight shower(s) of rain and snow mixed.	84 Moderate or heavy shower(s) of rain and snow mixed.	85 Slight snow shower(s).	86 Moderate or heavy snow shower(s).	87 Slight shower(s) of soft or small hail with or without rain or rain and snow mixed.	88 Moderate or heavy shower(s) of soft or small hail with or without rain or rain and snow mixed.	89 Slight shower(s) of hail††, with or without rain or rain and snow mixed, not associated with thunder.
90 Moderate or heavy shower(s) of hail††, with or without rain or rain and snow mixed, not associated with thunder.	91 Slight rain at time of ob.; thunderstorm during past hour, but NOT at time of observation.	92 Moderate or heavy rain at time of ob.; thunderstorm during past hour, but NOT at time of observation.	93 Slight snow or rain and snow mixed or hail† at time of observ.; thunderstorm during past hour, but not at time of observation.	94 Mod. or heavy snow, or rain and snow mixed or hail† at time of ob.; thunderstorm during past hour, but NOT at time of observation.	95 Slight or mod. thunderstorm without hail†, but with rain and/or snow at time of ob.	96 Slight or mod. thunderstorm, with hail† at time of observation.	97 Heavy thunderstorm, without hail†, but with rain and/or snow at time of observation.	98 Thunderstorm combined with duststorm or sandstorm at time of ob.	99 Heavy thunderstorm with hail† at time of ob.

Cloud, past weather, cloud amount and barometer codes

Code	C_L Clouds of type C_L	C_M Clouds of type C_M	C_H Cloud of type C_H	C Type of cloud	W Past Weather	N Total amount all clouds	a Barometer characteristic
0	No Sc, St, Cu, or Cb clouds.	No Ac, As or Ns clouds.	No Ci, Cc, or Cs clouds.	Ci	Cloud covering ½ or less of sky throughout the period.	No clouds.	Rising, then falling. Now higher than, or the same as, 3 hours ago.
1	Ragged Cu, other than bad weather, or Cu with little vertical development and seemingly flattened, or both.	As, the greatest part of which is semitransparent through which the sun or moon may be faintly visible as through ground glass.	Filaments, strands, or hooks of Ci, not increasing.	Cc	Cloud covering more than ½ of sky during part of period and covering ½ or less during part of period.	One-tenth or less, but not zero.	Rising, then steady; or rising, then rising more slowly. Now higher than 3 hours ago.
2	Cu of considerable development, generally towering, with or without other Cu or Sc; bases all at same level.	As, the greatest part of which is sufficiently dense to hide the sun or moon, or Ns.	Dense Ci in patches or twisted sheaves, usually not increasing; or Ci with towers or battlements or resembling cumuliform tufts.	Cs	Cloud covering more than ½ of sky throughout the period.	Two- or three-tenths.	Rising (steady or unsteadily). Now higher than 3 hours ago.
3	Cb with tops lacking clear-cut outlines, but are clearly not fibrous, cirriform, or anvil shaped; Cu, Sc, or St may be present.	Ac (most of layer is semitransparent) other than crenelated or in cumuliform tufts; cloud elements change but slowly with all bases at a single level.	Ci, often anvil-shaped, derived from or associated with Cb.	Ac	Sandstorm, or duststorm, or drifting or blowing snow.	Four-tenths.	Falling or steady, then rising; or rising, then rising more rapidly. Now higher than 3 hours ago.
4	Sc formed by spreading out of Cu; Cu may be present also.	Patches of semitransparent Ac which are at one or more levels; cloud elements are continuously changing.	Ci, book-shaped and/or filaments, spreading over the sky and generally becoming denser as a whole.	As	Fog, or thick haze.	Five-tenths.	Steady. Same as 3 hours ago.
5	Sc not formed by spreading out of Cu.	Semitransparent Ac in bands or Ac in one more or less continuous layer gradually spreading over sky and usually thickening as a whole; the layer may be opaque or a double sheet.	Ci, often in converging bands, and Cs or Cs alone but increasing and growing denser as a whole; the continuous veil not exceeding 45° above horizon.	Ns	Drizzle.	Six-tenths.	Falling, then rising. Now lower than, or the same as, 3 hours ago.
6	St in a more or less continuous layer and/or ragged shreds, but no Fs of bad weather.	Ac formed by the spreading out of Cu.	Ci, often in converging bands, and Cs or Cs alone but increasing and growing denser as a whole; the continuous veil exceeds 45° above horizon but sky not totally covered.	Sc	Rain.	Seven-or-eight-tenths.	Falling, then steady; or falling, then falling more slowly. Now lower than 3 hours ago.
7	Fs and/or Fc of bad weather (scud) usually under As and Ns.	Double-layered Ac or an opaque layer of Ac, not increasing over the sky; or Ac coexisting with As or Ns or with both.	Veil of Cs completely covering the sky.	St	Snow, or rain and snow mixed, or ice pellets (sleet).	Nine-tenths or more, but not ten-tenths.	Falling (steadily or unsteadily). Now lower than 3 hours ago.
8	Cu and Sc (not formed by spreading out of Cu); base of Cu at a different level than base of Sc.	Ac with sprouts in the form of small towers or battlements or Ac having the appearance of cumuliform tufts.	Cs not increasing and not completely covering the sky.	Cu	Shower(s).	Ten-tenths.	Steady or rising, then falling; or falling, then falling more rapidly. Now lower than 3 hours ago.
9	Cb having a clearly fibrous (cirriform) top, often anvil-shaped, with or without Cu, Sc, St, or scud.	Ac, generally at several layers in a chaotic sky, dense Cirrus is usually present.	Cc alone or Cc accompanied by Ci and/or Cs, but Cc is the predominant cirriform cloud.	Cb	Thunderstorm, with or without precipitation.	Sky obscured, or cloud amount cannot be estimated.	Indicator figure. Regionally agreed elements and NOT "pp" are reported by the next two code figures.

Second Edition

A Basic Meteorology Exercise Manual

Carl R. Chelius
Hank J. Frentz

KENDALL/HUNT PUBLISHING COMPANY
Dubuque, Iowa

ISBN 0-8403-3340-4