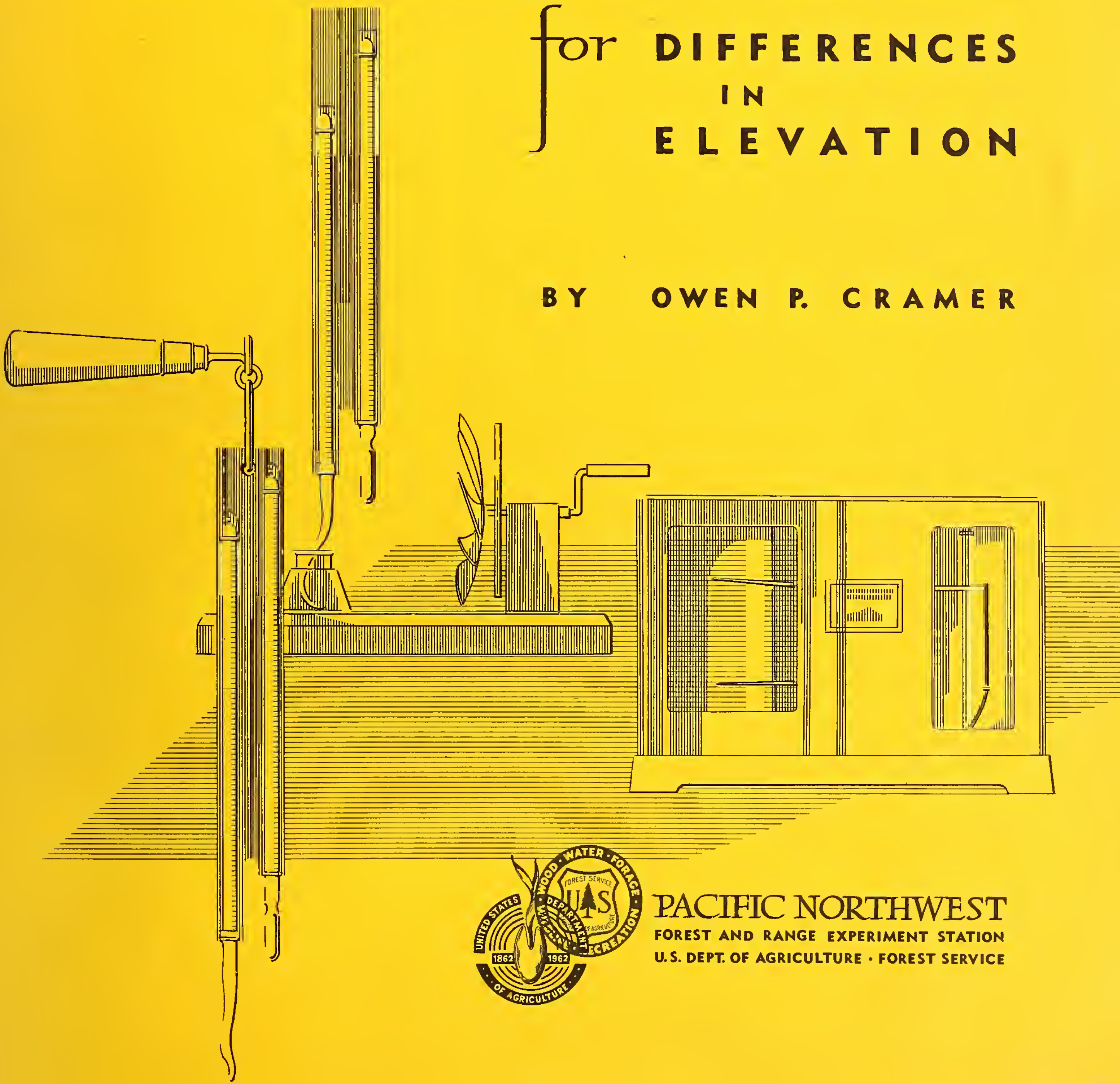
RESEARCH PAPER 43
JULY 1961

Adjustment of Relative Humidity and Temperature for DIFFERENCES IN ELEVATION

BY OWEN P. CRAMER



PACIFIC NORTHWEST
FOREST AND RANGE EXPERIMENT STATION
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SUMMARY

The variation of fire-weather elements in mountainous terrain is complex at any one time, and the patterns vary considerably with time. During periods of serious fire weather, this variation becomes important. Much information is obtainable by local interpretation of available forecasts and observations. Optimum use of available information requires some understanding of basic meteorological processes and also demands adequate tools for application of the principles.

This paper provides information about variation of midafternoon temperature and relative humidity in mountainous terrain and explains the use of two charts that help in estimating the amount of variation. For layers of air in contact with the surface, the charts make it possible to:

1. Determine the vertical extent of layers in which mixing is present (unstable layers) and of layers in which there is no mixing (stable layers).

2. Adjust temperature and humidity between elevations within mixed layers.

3. Predict afternoon valley temperatures and humidities from morning observations at peak stations.

4. Estimate humidities at any level within the mixed layer beneath cumulus clouds.

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by

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INTRODUCTION

Relative humidity is important in forest fire control. It influences the moisture content of fuels and thereby affects forest flammability. Relative humidity is consequently part of many fire-danger rating systems. It is used to indicate when fire weather is severe enough that logging operations are closed down to prevent fires. Predicted relative humidity is an essential ingredient for predicting fuel moisture.[1] Despite its uses, relative humidity is difficult to apply because its distribution is frequently complex. Observations and forecasts give clues to the distribution but cannot be fully utilized unless the principles of humidity and temperature variation are understood. These principles are most easily interpreted through the use of graphs.

Afternoon humidity and temperature[2] vary from one place to another in mountainous terrain, primarily because of elevation differences. Such variation is particularly marked where the terrain extends upward through two or more layers of air, each with its own temperature and humidity properties. Thus, peaks may sometimes be warmer and drier than valley stations, though the reverse is more usual. In completely mixed layers, temperature and humidity change with elevation in a regular manner--temperature decreasing with elevation and humidity increasing.

This paper discusses relative humidity, the vertical distribution of moisture in the air, and the effects of vertical temperature structure on stratification and mixing. Charts are presented with which predicted or observed relative humidity and temperature may be adjusted to different elevations under certain conditions.

1/ Cramer, Owen P. Predicting moisture content of fuel-moisture-indicator sticks in the Pacific Northwest. U.S. Forest Serv. Pac. NW. Forest & Range Expt. Sta. Res. Paper 41, 17 pp., illus. 1961. (Processed.)

2/ Temperatures and humidities discussed herein are measured by standard procedures in exposures fully open to the wind.

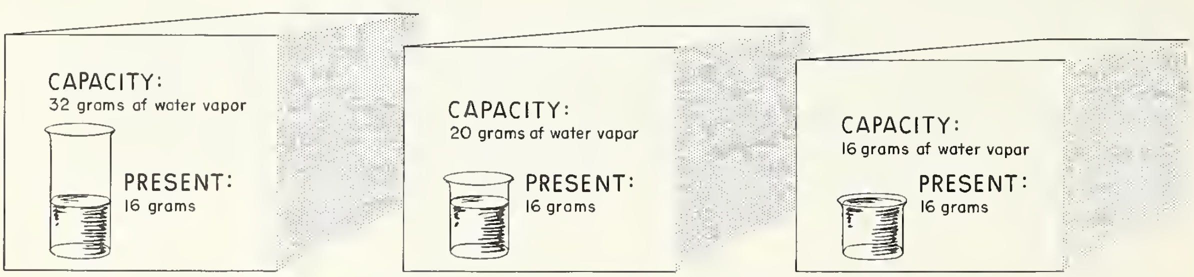
BASIC METEOROLOGICAL BACKGROUND

What Is Relative Humidity?

At each temperature, a given space can contain a certain maximum amount of water vapor. When this maximum amount of vapor is present, the space is saturated. Any additional moisture would condense and appear as dew or fog. The quantity of water vapor that saturates the space is not influenced by air pressure or even the presence of air but depends only on temperature. The higher the temperature, the more water vapor required for saturation. For every 20° F. increase in temperature, the water vapor capacity is approximately doubled.

The moisture present in air is usually described as weight of water vapor per kilogram of dry air. This description of atmospheric moisture is useful since the proportion of the mixture does not change with elevation (pressure) in thoroughly mixed air.

Relative humidity is a measure of the degree of water vapor saturation. At any temperature, relative humidity is the ratio, expressed in percent, of the water vapor actually present to that necessary for saturation (fig. 1). Thus, if 22 grams of water vapor will saturate a kilogram of dry air and only 11 grams are present, the relative humidity is 50 percent.



SPACES OCCUPIED BY 1,000 GRAMS OF DRY AIR

A. 50% RELATIVE HUMIDITY AT 91° F.   B. 80% RELATIVE HUMIDITY AT 77° F.   C. 100% RELATIVE HUMIDITY AT 70 1/2° F.

Interrelations of Relative Humidity, Temperature, and Elevation

Relative humidity varies with changes in temperature (fig. 1). It also varies with differences in the actual moisture content of the air (fig. 2). Since both temperature and moisture vary with elevation, relative humidity is difficult to describe for the wide ranges of temperature and elevation in an extensive mountain area.

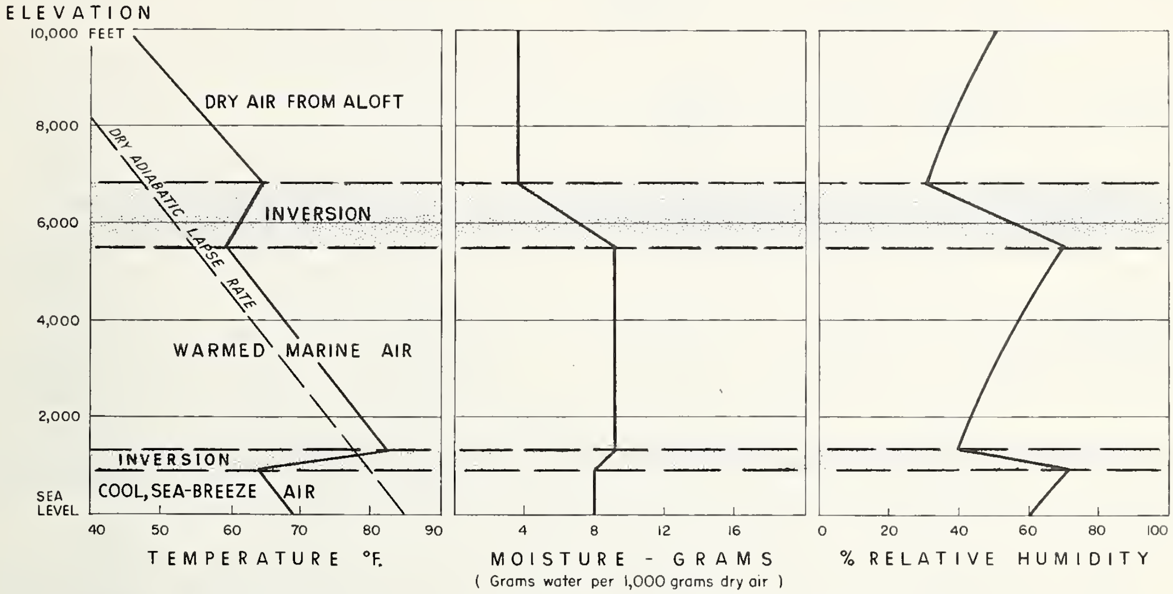


Figure 2.--Temperature, moisture, and relative humidity curves simulated for 4:30 p.m. at a station having a sea breeze. In this illustration, each of the three layers of air is mixed within itself, producing a constant proportion of moisture within each layer. Change in humidity within each layer is due entirely to temperature difference with elevation, which in each mixed layer is 5-1/2° F. per 1,000 feet elevation.

Fortunately, sometimes there is order in this apparent chaos. An orderly arrangement is found when heating at the surface or turbulent wind has so stirred the air that it is completely mixed through a substantial layer. Mixing usually occurs to a height of several thousand feet above the ground on most sunny summer afternoons. In mixed, nonsaturated air the temperature decreases with increase in elevation at a constant rate of 5-1/2° F. per 1,000 feet. Mixing is assumed in any layer through which such a temperature decrease is observed. The proportion of water vapor to air is constant in a mixed layer. Under such conditions, relative humidity varies in a regular manner with elevation. This is the basis for the aid presented later for converting relative humidity directly from one elevation to another.

How Temperature Affects Vertical Distribution of Moisture

Air motion distributes moisture vertically. Except where it is caused by mechanically induced turbulence, vertical motion depends upon existing difference of temperature with height in relation to the change in temperature that occurs from change in pressure as air moves vertically. The existing decrease of temperature with increase in height is called the temperature lapse rate. When the lapse rate is just 5-1/2° F. per 1,000 feet, it is exactly the same as the rate at which rising air cools from expansion, due to decreasing pressure with increase in height, and descending air heats from compression. This lapse rate is often used for comparison and is called the dry adiabatic rate. When such a lapse rate exists, slight horizontal differences in temperature will cause vertical motion (fig. 3). This occurs because a parcel of air warmer than its surroundings is lighter than the surrounding air and will rise. The reverse is true of a parcel cooler than its surroundings.

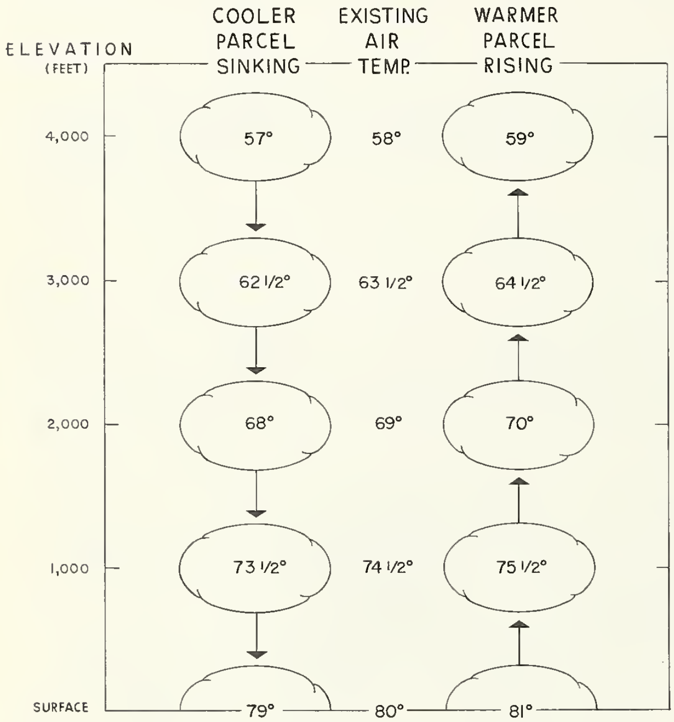
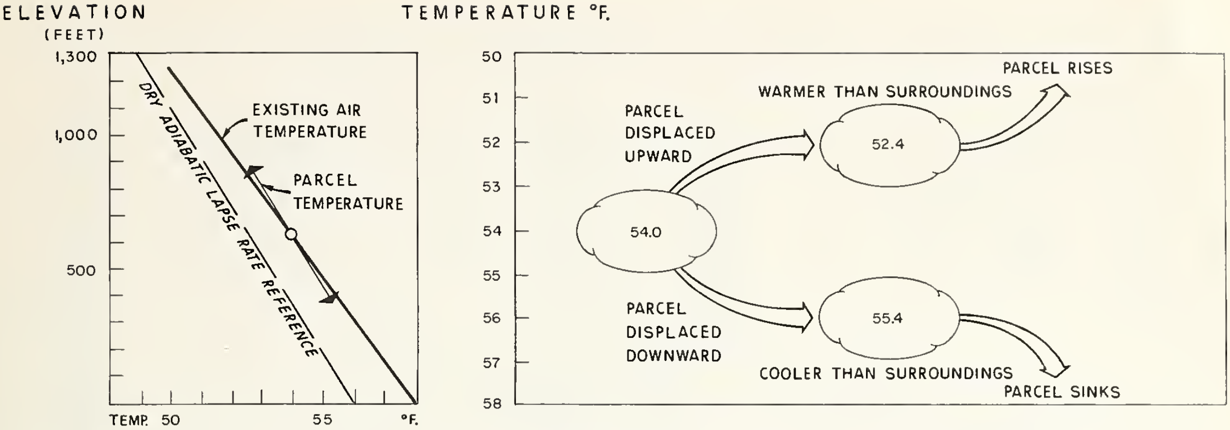


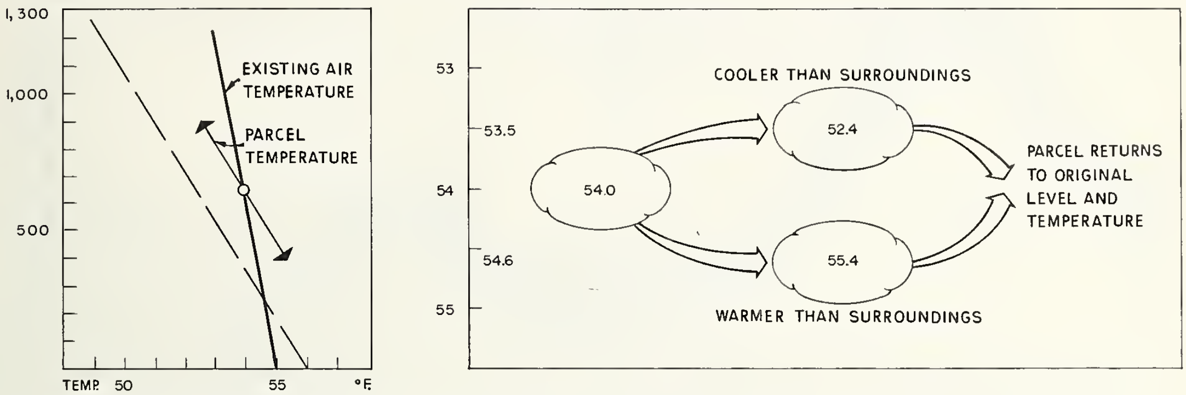
Figure 3. --Vertical motion supported by slight horizontal temperature differences in air with dry adiabatic lapse rate.

If the lapse rate is greater than dry adiabatic (unstable or superadiabatic), vertical motion is accelerated and mixing is assured (fig. 4a). If the lapse rate is just 5-1/2° F. per 1,000 feet (neutral or dry adiabatic), vertical motion has occurred or will occur and mixing may be assumed (fig. 4c). Vertical motion and mixing are suppressed by lapse rates less than dry adiabatic (stable) (fig. 4b).

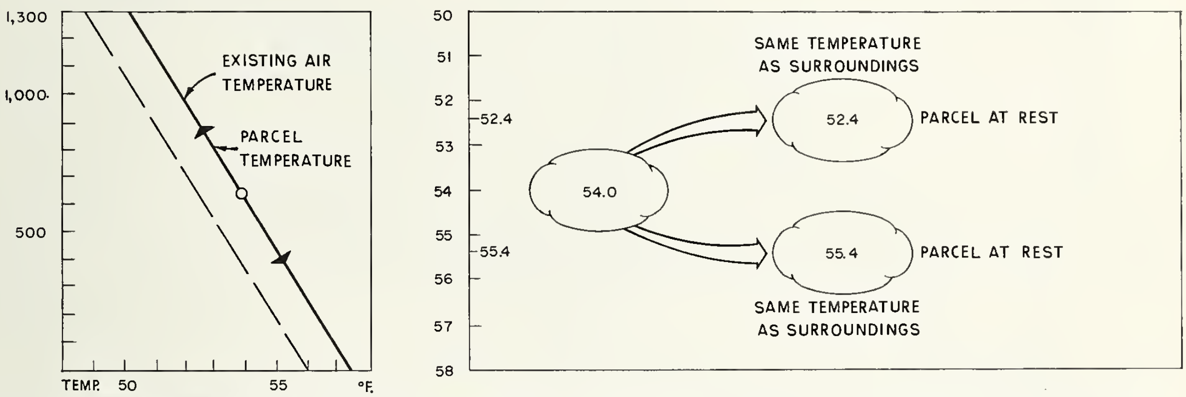
The lapse rate is variable. It varies from hour to hour and from day to day (fig. 5). Lapse rate may vary also from place to place, particularly where there are major differences in elevation between stations (fig. 6). Differences in temperature structure of different air layers and differences in the heating effects of the terrain below are responsible. Conditions existing must be carefully determined before the procedures to be described can be applied.



A.--Unstable lapse rate--greater than dry adiabatic--vertical motion accelerated--mixing occurs.



B.--Stable lapse rate--less than dry adiabatic--vertical motion suppressed--no mixing occurs.



C.--Neutral lapse rate--dry adiabatic--vertical motion tolerated--mixing has or will occur.

Figure 4.--Effects of lapse rates on vertically displaced parcels of air. Parcel starts at same temperature in each instance and is displaced the same vertical distance. The differing lapse rates of the surrounding air are shown by the heavy solid line in the left-hand diagrams and the side scale in the right-hand diagrams. The dashed reference line in the left diagrams is the dry adiabatic lapse rate of 5-1/2° F. per 1,000 feet of elevation.

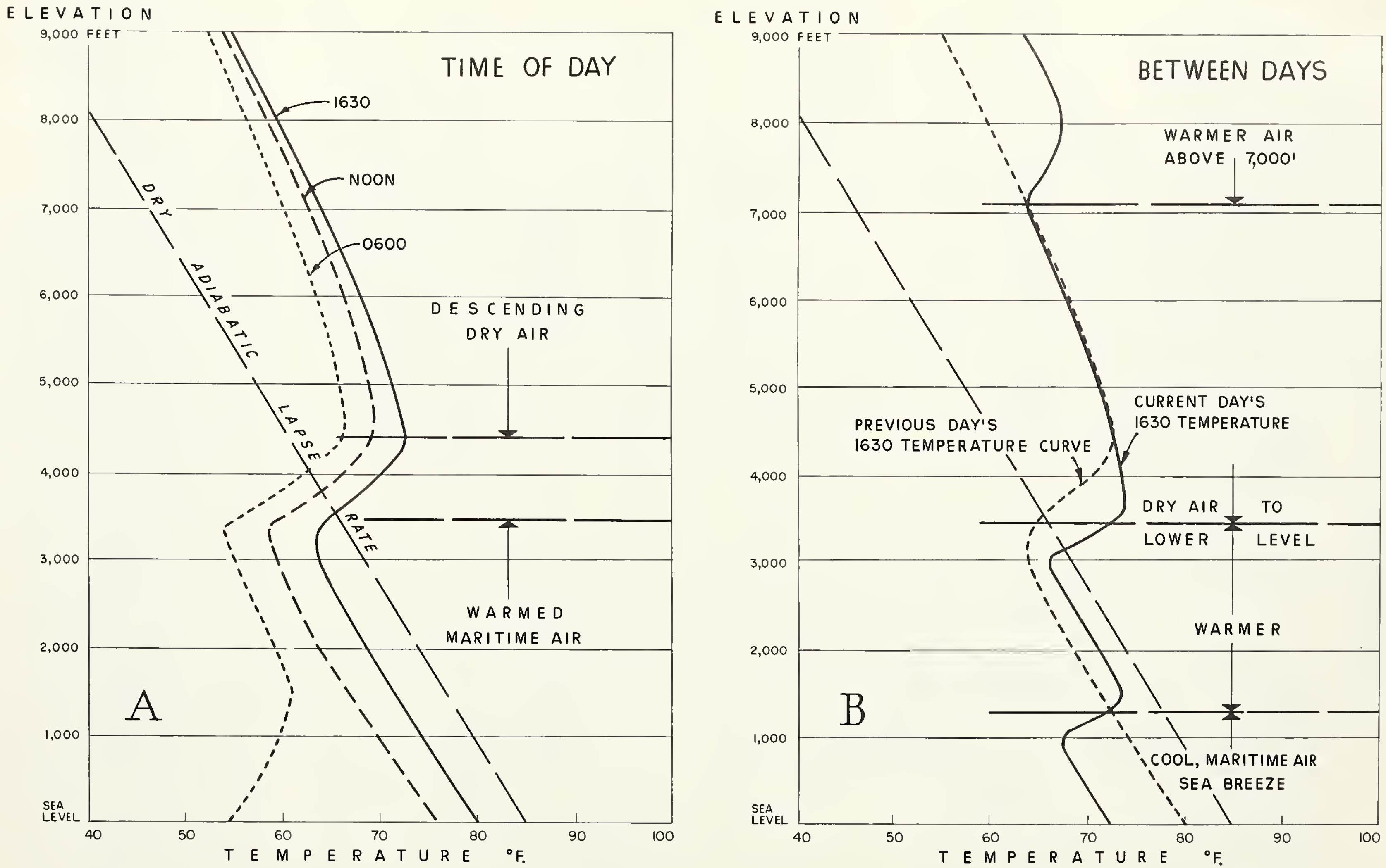
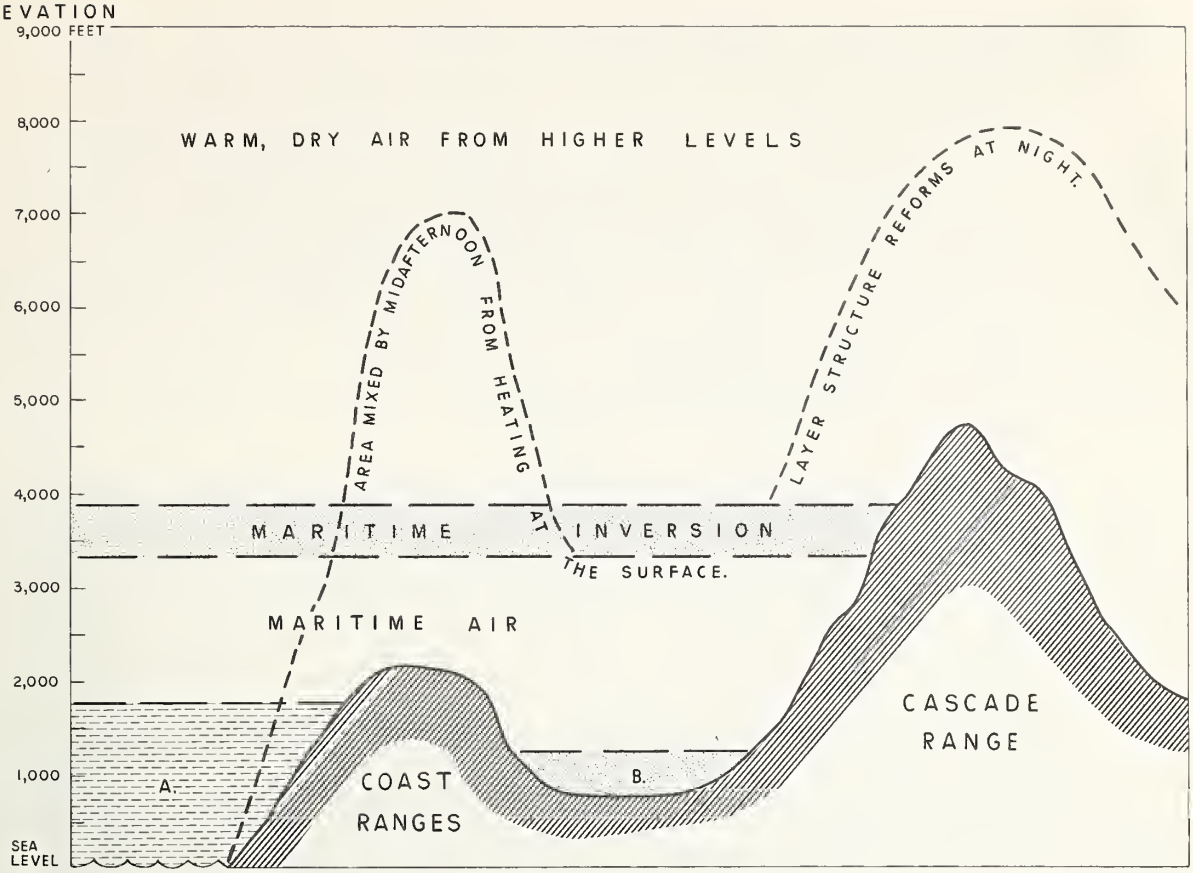


Figure 5.--Temperature-elevation (lapse rate) curves illustrating change in temperature at various heights; A, with time of day, and B, between days. Dashed straight line is reference dry adiabatic lapse rate of 5-1/2° F. per 1,000 feet elevation.



A. COOL, MARITIME AIR often foggy

B. COOL AIR from nighttime rodiotion ond cool oir droinoge from the slopes forming o nocturnol inversion.

Figure 6.--Typical strata of air over western Oregon and western Washington on a summer morning.

TEMPERATURE ESTIMATES

When moisture is evenly distributed, as within mixed layers, relative humidity may be graphically adjusted between elevations within such layers. To do this, mixed layers must be identified. This is done by analysis of the vertical temperature structure.

Certain typical variations of the surface mixing layer need to be considered. Its depth varies with elevation of the country over which it forms, being greatest over the high country. Horizontal temperature differences may consequently be expected within the mixing layer between mountains and lowlands. Temperature also varies in the surface layer with distance from the coast. To minimize error from horizontal temperature gradient, stations compared should be no more than 20 miles apart. Considerably less east-west leeway is advisable close to the coast in the lower 3,500 feet. In general, there will be more leeway along or within a mountain range than across it and parallel to the coast than at right angles to it.

Determining Temperature Structure from Reported Values--Use of Chart I

Vertical distribution of temperature may be determined from either observed or predicted values for specific elevations. Temperatures, observed simultaneously at all points, are plotted on Chart I (fig. 7) opposite their elevations.[3/] If the observations fall in a line parallel to one of the sloping lines, a dry adiabatic lapse rate is indicated and the layer is assumed to be mixed. If the slope is flatter than the sloping lines on the chart, a greater than adiabatic lapse rate is present and mixing is assured.

Visible Indicators of Temperature Structure

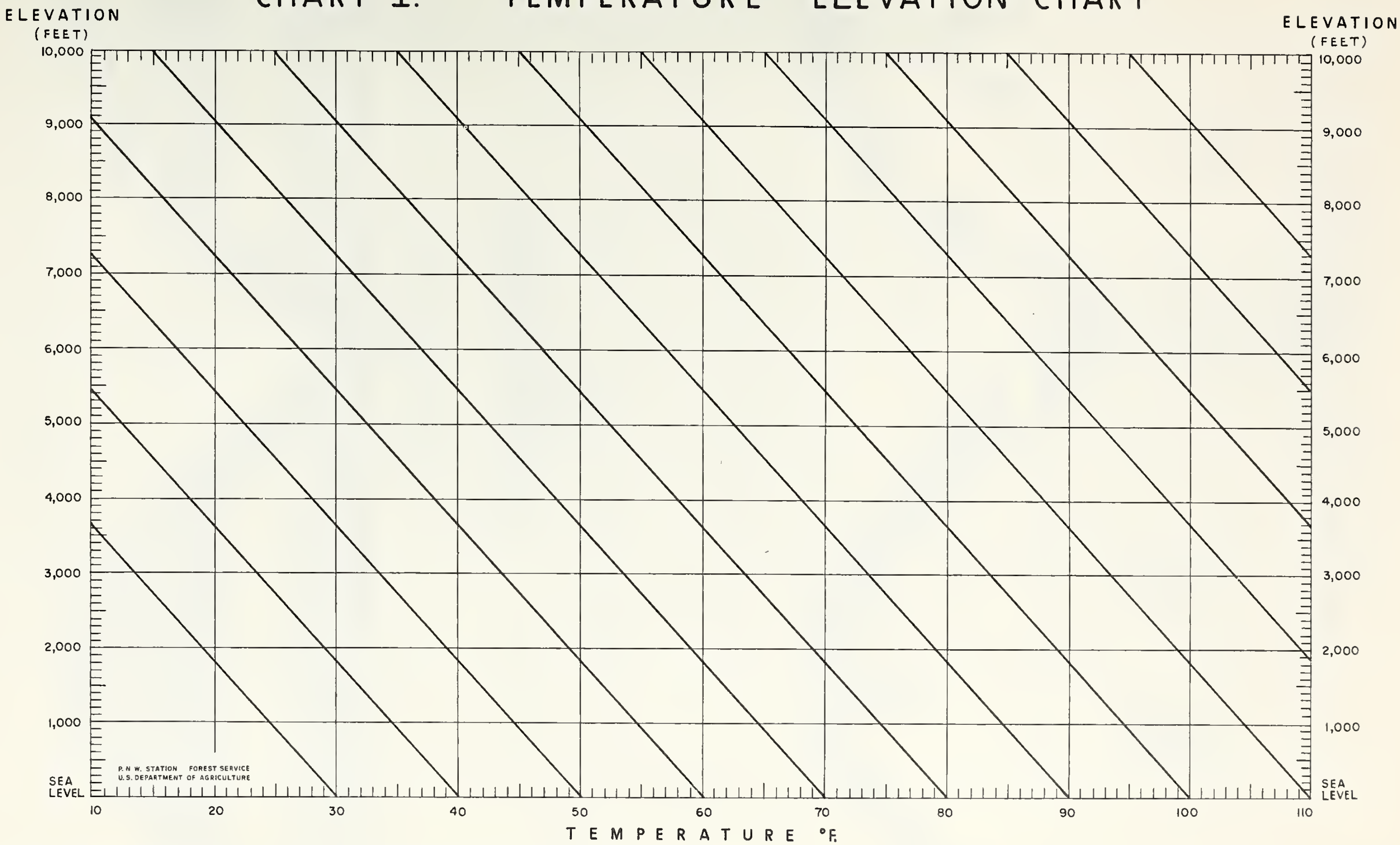
Since temperature observations may not always be available, sometimes it may be necessary to resort to careful interpretation of the visible indicators of temperature structure, and the resulting vertical motion and mixing. Care must be used in applying the indicators only to the layers in which they occur, since indicators of mixing and no mixing may be present in the same vicinity but in different layers.

Indicators of unstable lapse rate and presence of vertical mixing.--When mixing occurs, smoke, haze, and dust are not concentrated in the lower levels of the mixed layer but become evenly distributed vertically with no horizontal layers (fig. 8). Visibility at all levels tends to be equally good. Clouds of smoke and dust may be caught in rising or descending currents, or may just drift apart vertically. If rising portions of the mixing air reach saturation, cumulus type clouds will form. These clouds will have flat bases at a common level. Dust devils indicate a highly unstable lapse rate near the ground. Temperature and humidity may be adjusted between elevations within any layer for which the above indicators of mixing are present.

Indicators of stable lapse rate and absence of vertical mixing.--Where vertical mixing is not occurring, smoke, haze, and dust concentrate in the lower levels where they often form horizontal layers (fig. 9). Visible horizontal layers also form near the base of an inversion layer, i.e., a layer through which the temperature increases with elevation. Valley fog and stratus clouds commonly form beneath an inversion layer and indicate stable lapse rates at and immediately above the levels where they are present. Low cumulus clouds form flat tops at an inversion. In layers having indications of stratification, a stable lapse rate exists and vertical motion may be assumed to be absent. Within such layers, relative humidity and temperature cannot be reliably adjusted between elevations.

[3/] For routine local use of Charts I and II (pp. 9 and 13), the elevations of the usual stations from which observations are received and for which predictions are made should be marked and identified. The charts should then be placed under a transparent cover on which the current temperatures or humidities may be plotted and later erased.

CHART I. TEMPERATURE - ELEVATION CHART



SLOPING LINES REPRESENT DRY ADIABATIC LAPSE RATE -- 5 1/2°F. PER 1,000 FEET ELEVATION

Figure 7.

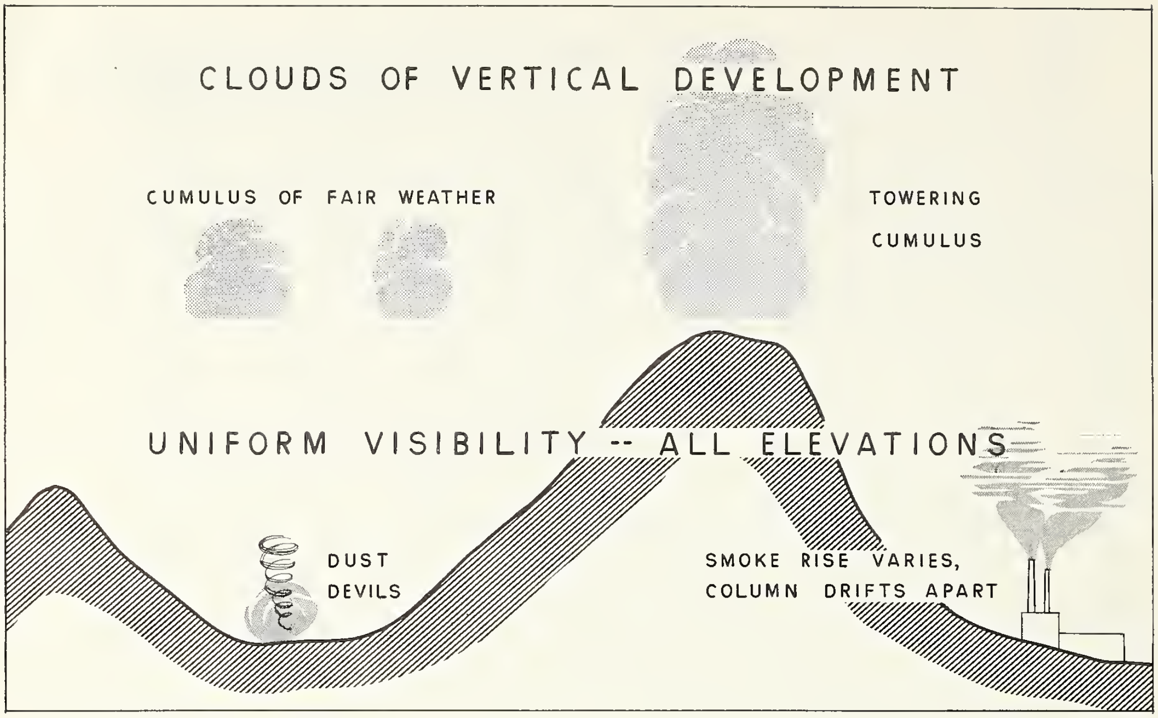


Figure 8. --Indicators of unstable air.

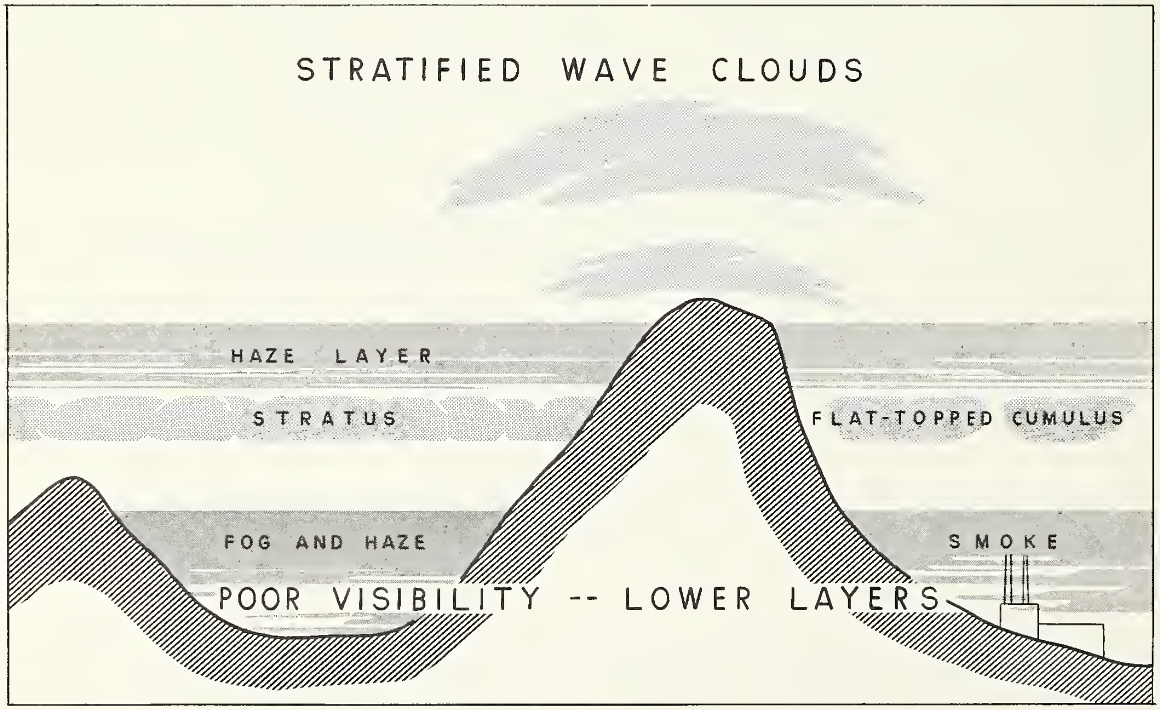


Figure 9. --Indicators of stable air.

Predicting Maximum Temperatures at Valley Stations from Observed Morning Temperatures at Peak Stations

Nighttime cooling is less at peak stations than at valley stations. Consequently, morning temperatures at peak stations are better indicators of temperatures later in the day when both peak and valley stations lie within the same mixed layer. On Chart I (fig. 7), starting at the peak station's elevation and morning temperature, the sloping lines are paralleled to the valley elevation, and the temperature is read. To this is added the expected increase in temperature during the day at the mountain station. This may be judged on the basis of the forecast and the previous day's observations of morning and maximum temperatures. The sum is the expected maximum temperature at the valley station (fig. 10, left side).

RELATIVE HUMIDITY ESTIMATES

Adjustment of Relative Humidity to Different Elevations--Use of Chart II

Where there is vertical mixing, Chart II may be used to adjust relative humidity for elevation (fig. 11). On that chart, the intersection of the humidity (horizontal scale) and its elevation (vertical scale) is found.[4] From this point, the sloping lines are paralleled to the desired elevation. The humidity at the new elevation is read from the horizontal scale. For example, relative humidity of 58 percent at 2,600 feet becomes 50 percent at 1,600 feet (fig. 12).

Humidities for elevations above or below a mixed layer cannot be accurately estimated by this method. Rough approximations of humidities between mixed layers, as for example within an inversion, may be obtained graphically as shown in figure 13. This should be done only with comparatively thin, unmixed layers between elevations for which humidities are available.

Estimating Relative Humidity in the Mixed Layer Below Cumulus Clouds

Cumulus clouds are the tops of columns of rising warm air cooled to saturation by the ascent. The common base level of cumulus is the elevation of 100-percent relative humidity in the mixed air. The humidity at any other elevation may be determined by following down the appropriate curve on Chart II from 100 percent at the cloud-base elevation. Elevation of the cloud base may be determined where clouds touch a peak, or it may be estimated (fig. 14). For example, if cumulus cloud bases are estimated at 5,500 feet, the humidity at 2,500 feet would be about 62 percent.

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[4] See footnote 3, p. 8.

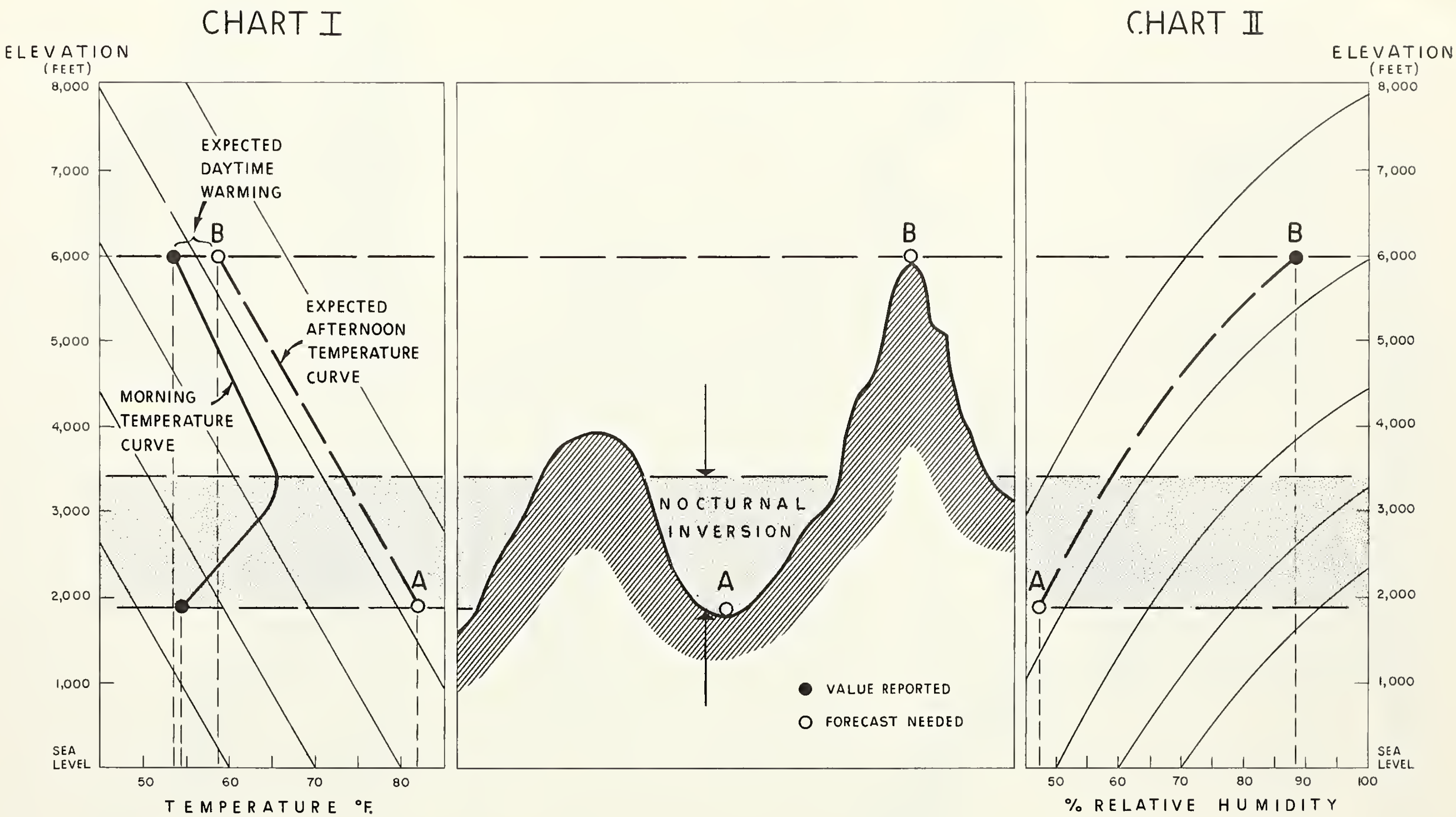
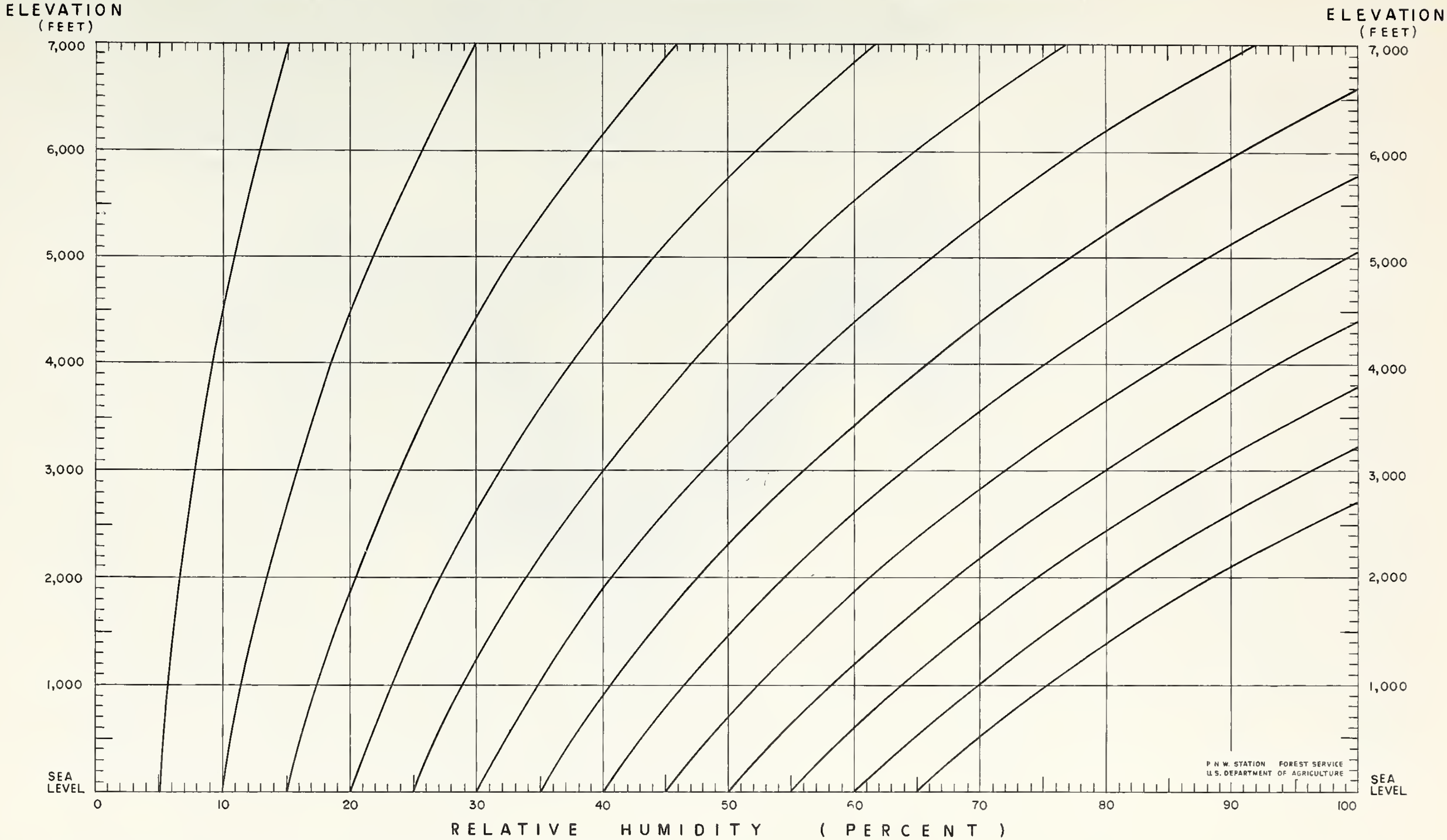


Figure 10.--Use of morning observation at peak stations to indicate afternoon temperature and relative humidity at valley stations. Valley below 3,400 feet is filled with night accumulation of cold air--nocturnal inversion. Considerably less cooling has occurred above this level. Heating and resultant mixing will destroy the inversion on a sunny summer afternoon. Approximate expected temperature and humidity curves are determined from adjusted morning observed values at the peak station.

CHART II. RELATIVE HUMIDITY - ELEVATION CHART

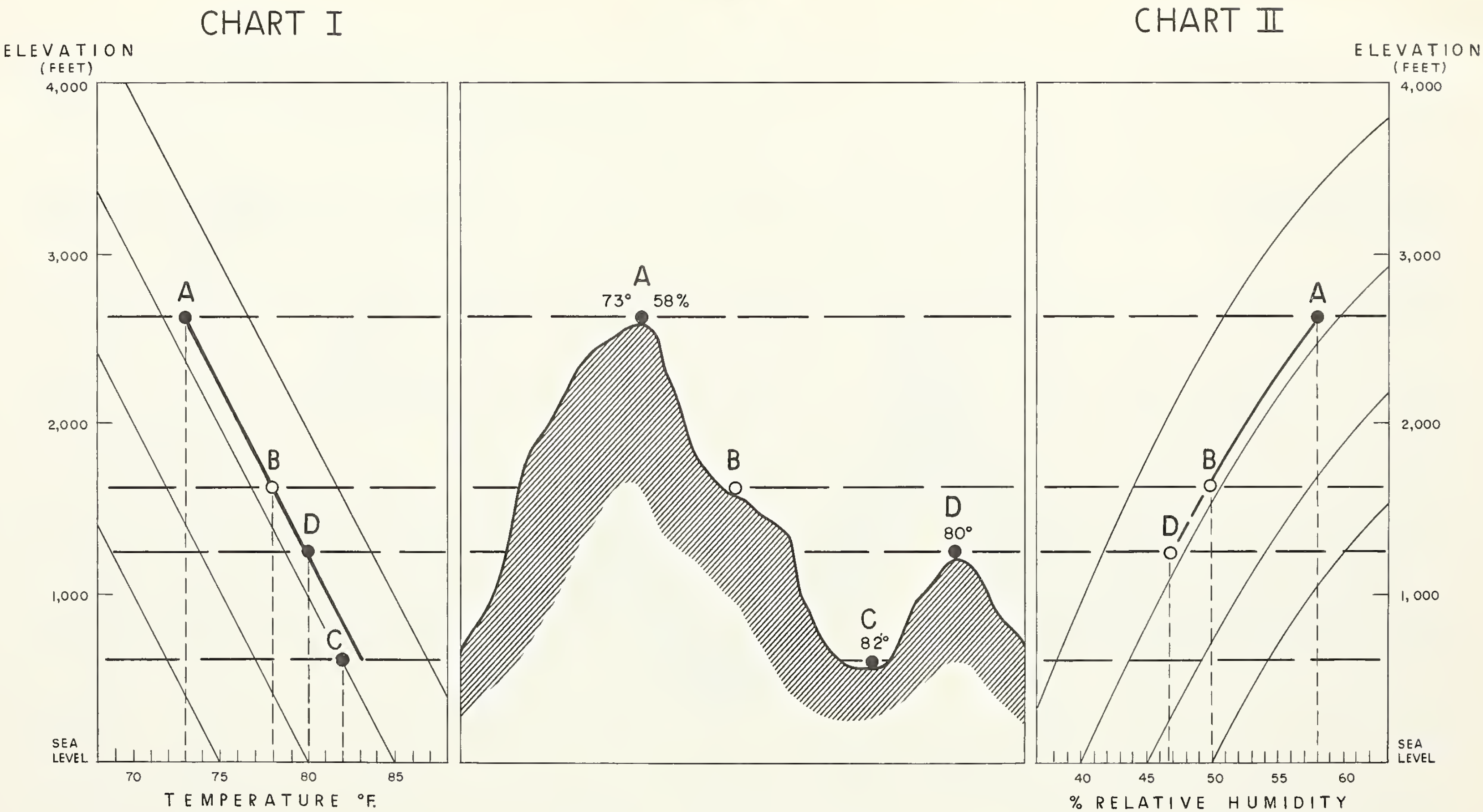


FOR MIXED LAYERS AND LAPSE RATE OF 5 1/2°F. PER 1,000 FEET ELEVATION

BASED ON MIXING RATIO VALUES AND U.S. STANDARD ATMOSPHERE PRESSURE ALTITUDES FROM PSEUDO-ADIABATIC DIAGRAM WB 1147, ASSUMING SEA-LEVEL TEMPERATURE OF 90°F.

SLOPING CURVES REPRESENT CONSTANT MOISTURE CONTENT.

Figure 11.



B. TEMPERATURE CHECK.
AIR IS MIXED BETWEEN A AND D, BUT NOT BETWEEN D AND C. B IS WITHIN A MIXED LAYER. ESTIMATED TEMPERATURE AT B IS 78°.

A. LOCATION OF REPORTING STATIONS ● AND LOCATION OF STATION FOR WHICH FORECAST IS NEEDED O. OBSERVED TEMPERATURES AND HUMIDITY FOR A ARE SHOWN.

C. HUMIDITY FOR A, 58%, IS EXTENDED IN MIXED LAYER TO B. ESTIMATED HUMIDITY AT B IS 50%. HUMIDITY AT D, ALSO WITHIN MIXING LAYER, MAY BE SIMILARLY ESTIMATED, BUT NOT C.

Figure 12. --Estimation of relative humidity within a mixed layer for a station from which no observations are available.

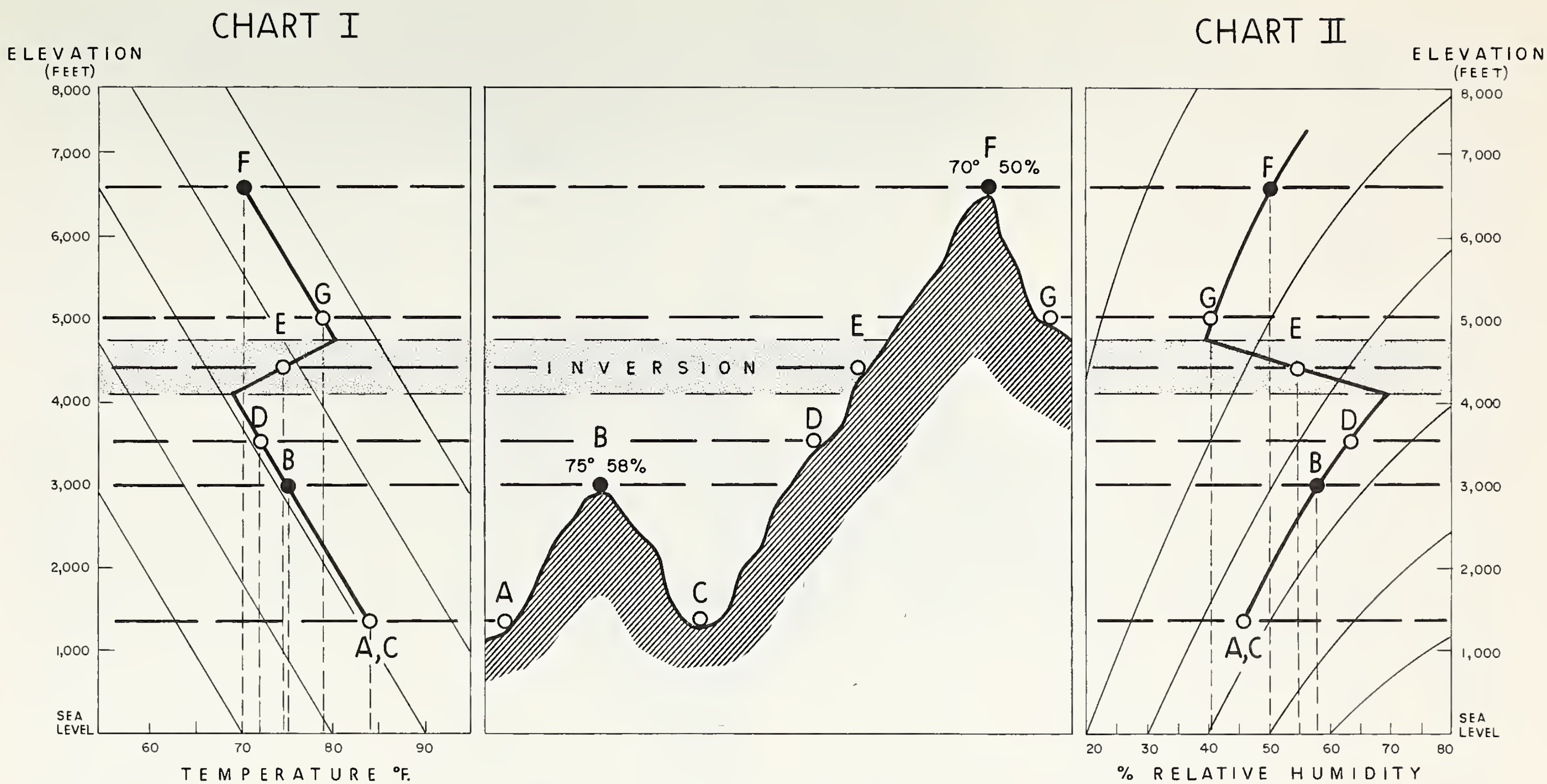


Figure 13.--Prediction of relative humidity in two mixed layers separated by an inversion. Forecast calls for midafternoon temperatures and humidities of 70° and 50% at F and 75° and 58% at B. An inversion is predicted between 4,000 and 4,800 feet.

The probable temperature curve is plotted on Chart I within each mixing layer. Probable humidity curve extended within each layer on Chart II. Humidities and temperatures for the other stations may now be estimated. Humidity and temperature for elevations within an unmixed layer may be approximated as for E.

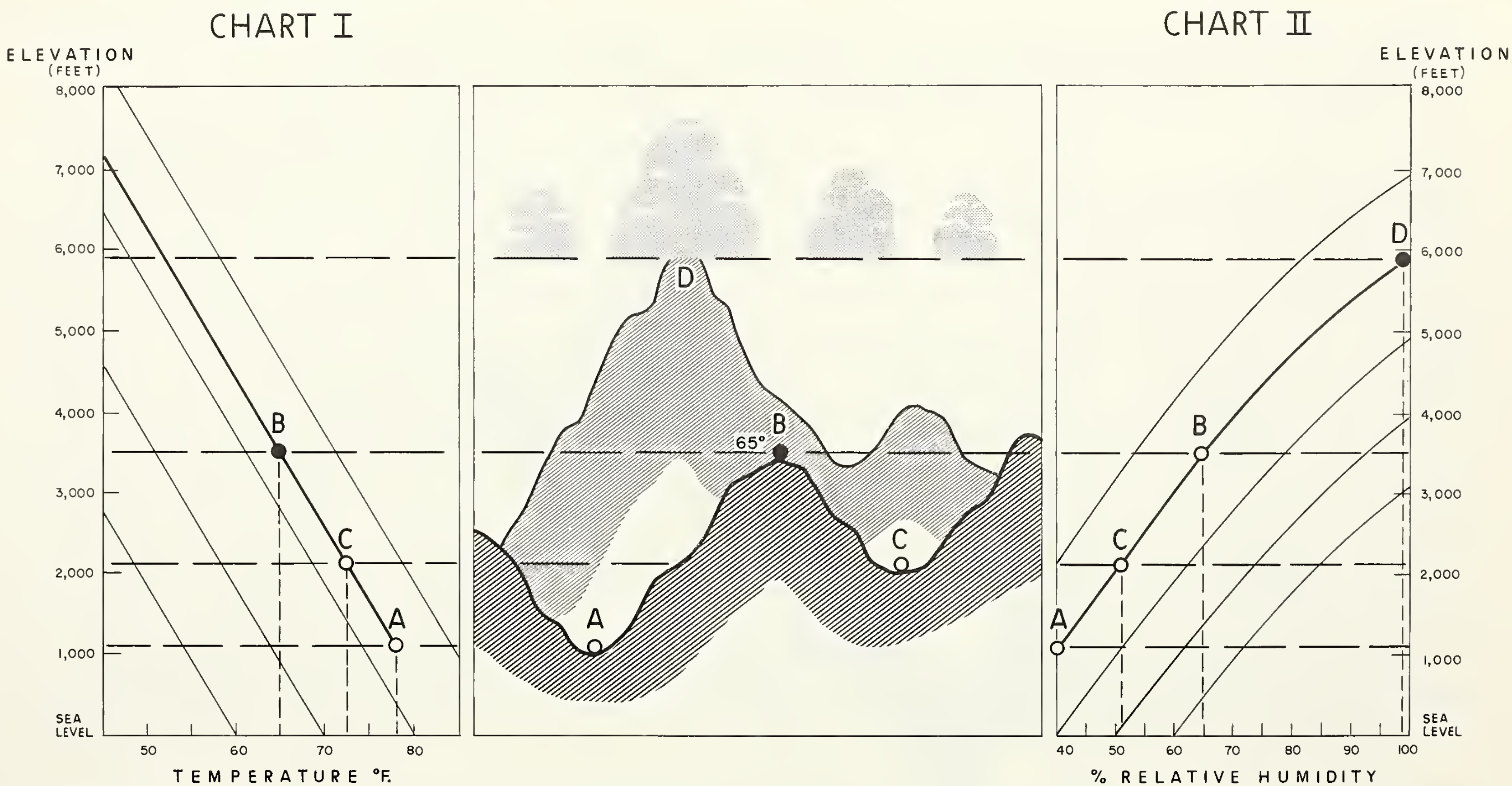


Figure 14.--Estimating relative humidity when cumulus clouds are present. Base of the cumulus intersects peak D at 5,900 feet. Cloud type indicates unstable air below, and cloud base indicates elevation of 100% relative humidity. This fixes location of the humidity curve for the unstable layer. Humidities for any other station, such as A, B, or C, may be determined from the curve. Similarly, elevation of cloud base could be determined from a surface relative humidity. Although cloud type indicates a dry adiabatic lapse rate, position of temperature curve on Chart I must be determined by an observation at some station such as B.

Conversely, if the humidity is known at a given elevation and cumulus clouds are present, the elevation of the cloud base can be estimated by paralleling the curved lines from the known point to saturation at the right-hand margin.

Predicting Afternoon Minimum Humidities in Valley Areas from Morning Observed Humidities at Peak Stations

It is often warmer and drier at peak stations early in the morning than at valley stations. By afternoon, however, warming in the lower layers frequently produces convective mixing between valley bottom and peak levels. The morning moisture at the peak approximates the moisture expected by afternoon throughout the mixed layer and hence at lower elevations. Two sources of error are recognized: (1) no allowance is made for increase in temperature, and (2) the lower layers may have a higher moisture content. Effects of these two errors on the humidity of the afternoon mixed layer will usually be compensating.

From the peak humidity-elevation point, the sloping lines on Chart II are paralleled to the desired valley-station elevation and the humidity scale is read (fig. 10, right side). This assumes mixing between peak and valley and does not apply where an inversion prevents valley air and peak-level air from mixing. Yesterday's maximum temperatures plotted on Chart I show whether mixing has been occurring between the two levels. Depth of this mixing layer changes from day to day and frequently does not extend much more than 3,000 to 4,000 feet above the valleys.

AIRMASS PROPERTIES THAT AFFECT TEMPERATURE AND MOISTURE

Many properties of the atmosphere vary from day to day and from place to place. Much of this variation is due to changes from one airmass to another airmass with different properties. More gradual change may be due to modification of an airmass in place. Those who attempt to adjust temperature and relative humidity from one elevation to another should know something about typical airmasses and how they are modified and thus change temperature and moisture distribution.

Description of Airmasses

The most common reason for day-to-day change in atmospheric moisture and temperature structure is a change in type of airmass. An extensive portion of the atmosphere with distinctive properties of temperature, moisture, and stability is called an airmass. These distinctive properties are acquired by prolonged passage or stagnation over a portion of the earth's surface. Such areas, referred to as source regions, provide names for the airmasses. Tropical air comes from low latitudes and is hot, while polar air comes from northern latitudes and is cool. Maritime air comes from an ocean source region and carries considerable moisture, whereas continental air comes from over land and is dry. Airmasses are designated by combinations of these source names. Tropical continental air is hot and dry and forms over the interior southwestern United States. In contrast, polar maritime air, which is cool and wet, reaches the Pacific Coast from the northern Pacific. Tropical maritime air that reaches the Northwest may originate in either the tropical eastern Pacific or in the Gulf of Mexico and may bring with it considerable thunderstorm activity.

As the winds change direction, they bring different airmasses over an area. Transition from one airmass to another may be gradual or more or less abrupt where the transition is marked by a front. Temperature and humidity may be expected to change in the transition zone, often abruptly through a front.

How Airmasses Are Modified

Typical airmasses have acquired their properties in layers several miles thick. These properties may be modified as they move, particularly in the lower layers. Airmasses moving northward become cooler while those moving southward become warmer. Passage over a mountain range such as the Cascades may produce marked changes in temperature and humidity (fig. 15). Air ascending the windward side cools by expansion during ascent. If it is moist, condensation and precipitation may occur. Condensation of moisture liberates heat, partially counteracting cooling during further ascent; and precipitation reduces the moisture content. Later, as the air descends on the leeward side, it warms at the dry adiabatic rate (5-1/2° F. per 1,000 feet elevation). The air on the leeward side is warmer and drier than at the same level on the windward side because it has lost moisture and has been heated by condensation during the ascent. Without condensation, temperatures and humidities would be identical for any elevation on both sides of the ridge.

An important modification process takes place within the typical high-pressure center. The characteristic vertical motion of air within a high is downward. This brings air to lower elevations from very high altitudes, where low temperatures prevent it from holding appreciable moisture. As it sinks, it warms at the dry adiabatic rate. This process is called subsidence and may occur over several states at once. Subsiding air is observed at high elevations first and may or may not reach the valley bottoms. Downslope winds on the lee sides of mountain ranges produce similar drying and warming effects. Some of the lowest humidities observed at the surface have resulted from combined subsidence and downslope winds. These two processes often combine during the Oregon and Washington east winds and the California Santa Ana.

Stratification of Airmasses

Usually the air structure overhead is not typical of a single airmass but is more like a stack of horizontal layers, each with its own airmass properties (fig. 9). Winds, usually varying with height, bring these layers from differing sources. Thus, these layers determine the pattern of temperature, humidity, and wind in mountainous terrain. Intelligent use of fire-weather information in mountainous terrain requires awareness of air stratification. Degree of

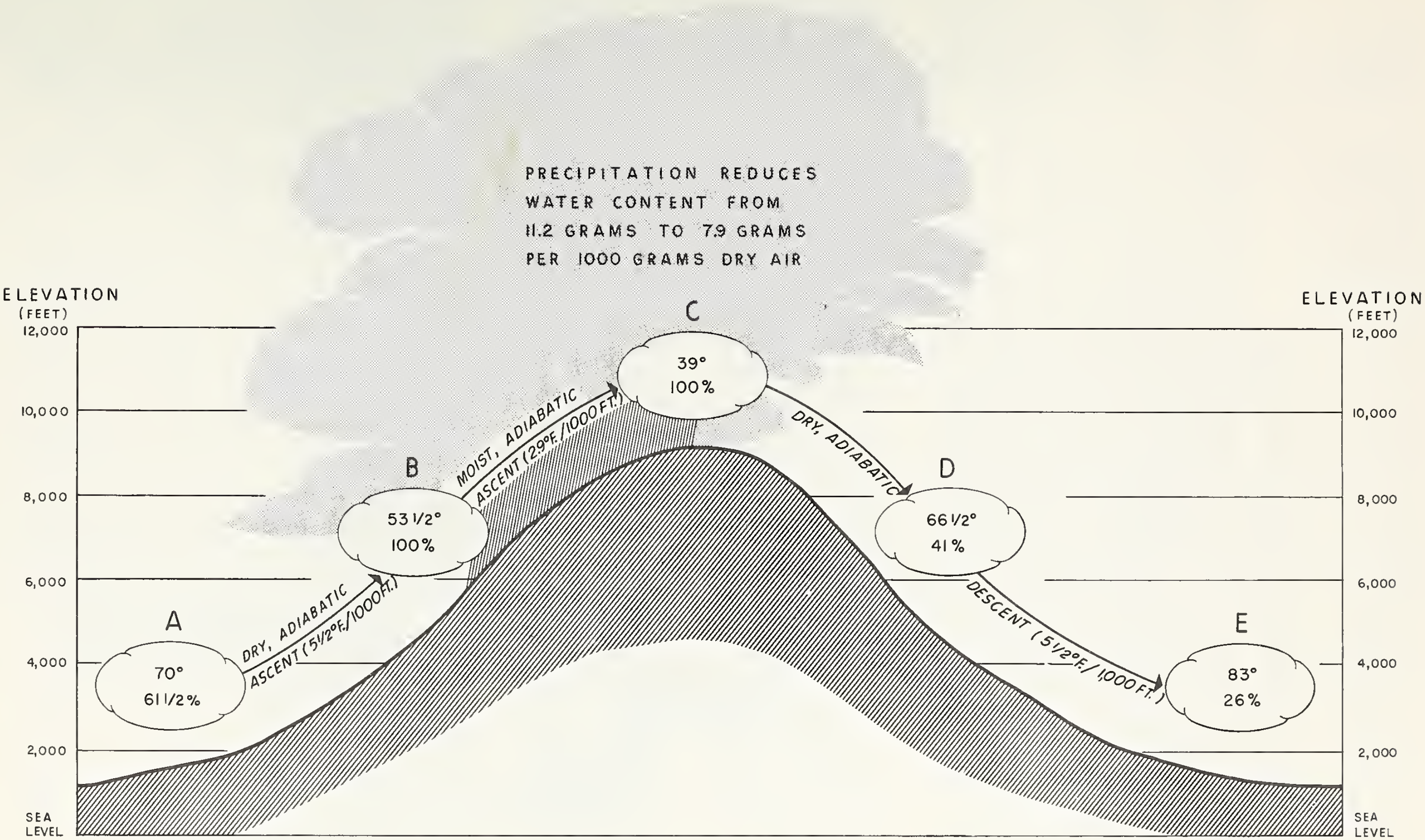


Figure 15.--Modification of a maritime airmass passing over a major mountain range. Air ascends slope from A, cooling to saturation at B. Between B and C, cooling is less rapid due to the liberation of heat by condensation, and water is removed by precipitation. At C descent begins and adiabatic warming causes dissipation of the clouds. From C to E warming occurs at the dry adiabatic rate.

stratification is most readily indicated by the vertical temperature structure. Chart I will be useful in determining the presence, vertical extent, and characteristics of individual layers.

Typical Oregon and Washington Summer Airmasses

Although stratification varies considerably between day and night and also differs from one day to another, west of the Cascade crest in Oregon and Washington there are commonly three distinct layers in contact with the terrain at various elevations during summer fair weather. The lowest layer is maritime air which is comparatively cool and moist. It may extend upward to 5,000 feet, though this will vary considerably. The temperature and, consequently, humidity within this layer change from night to day with the greatest changes near the ground and the least at the top of the layer. The lapse rate within this layer also varies greatly from day to night, but is usually dry adiabatic during midafternoon on sunny days. Along the coast the lower portion of this layer is cool and often foggy and is carried into Coast Range valleys at night by the sea breeze.

Above the maritime air is a transition layer between lower and higher layers. When the contrast is great, the layer may be an inversion. This transition layer, often called the maritime inversion, is most pronounced in the morning and, with sufficient warming in the layer below, may actually disappear in the afternoon. When present, this inversion layer prevents mixing of air above and below it and thus separates possibly contrasting humidity and wind regimes.

The uppermost of these three layers varies much less from day to night than the lower layers. Low humidity and a lapse rate slightly less than dry adiabatic are characteristic. This air usually originates at high elevations within the Pacific high-pressure cell and may gradually descend to lower elevations over a period of several days under subsidence conditions. Within this layer westerly winds may bring low humidities to mountain stations.

Daytime heating from the ground produces a mixing layer of some depth on every sunny summer day. On some days the mixing layer extends above the usual level of the inversion. During periods of pronounced sea breeze that brings cool air from the ocean, only a shallow mixing layer may form at lower elevations. At the same time, a deeper mixing layer may form over terrain that extends above the cool air (fig. 16). Temperature reports and Chart I can aid in identifying this condition.

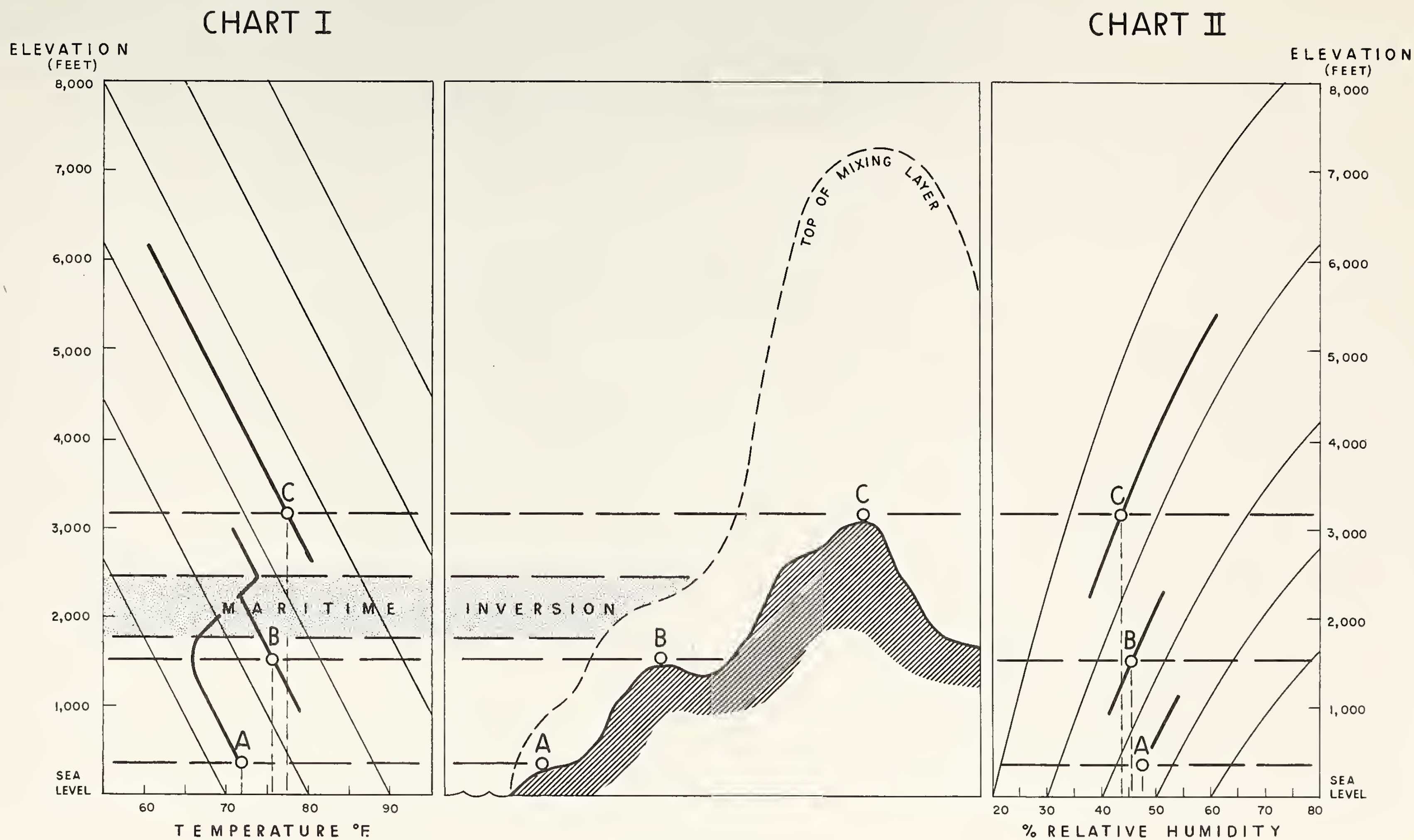


Figure 16.--Variation in depth of mixing layer with distance from the coast and with elevation. Temperature and humidity curves are not continuous but represent conditions at different distances from the ocean.

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