
Potential Temperature Analysis for Mountainous Terrain
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Potential Temperature Analysis for Mountainous Terrain

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ABSTRACT

Potential temperature (θ) analysis supplies needed information that is not obtainable by other methods of graphical analysis. Terrain surface θ maps and large-scale θ cross sections are constructed by using data from weather stations, raobs, and aircraft soundings. Interpretation of the isentropes gives a fairly detailed picture of temperature, stability, and potential wind conditions at and above the surface in mountainous terrain. Applications include weather analyses for fire and pest control and studies of smoke dispersion.

1. Introduction

The trend toward intensified environmental management requires greater attention to the detail of wind, stability, temperature and humidity in the surface and friction layers of the atmosphere. Effectiveness and safety in such operations as air pollution control, forest and agricultural pest control, and open-area fire control are strongly affected by mesoscale and finer weather features. But where the terrain is mountainous, weather patterns are often complex and observations usually limited. The necessary information is not supplied by conventional meteorological analyses that use nearly horizontal surfaces, such as constant-pressure or constant-elevation surfaces. Instead, local atmospheric structure at and above the surface may be analyzed in terms of potential temperature—in the vertical by atmospheric cross sections and at the ground surface on a base map showing terrain contours.

2. Temperature and windflow in mountainous terrain

The complicating influence of mountainous terrain on weather conditions at the surface is most evident in windflow patterns. The blocking, deflecting, and channeling of windflow are obvious effects of rugged terrain. More subtle are the heat sources of varying size and elevation resulting from the uneven upthrust of the earth's surface. During clear summer days, heated mountains produce convective circulations in the first few thousand feet above the terrain as shown by Malkus (1955) for a Caribbean island and Schroeder (1961a) for a single ridge. But surface winds in mountainous terrain are a composite of 1) the flow pattern governed by the broad-scale pressure field in each horizontal layer of air intersecting terrain, 2) physical blocking and channeling by the terrain, and 3) local wind systems set up by heating and cooling of the terrain. The influence of each of these factors is strongly determined by the three-dimensional temperature structure.

During summer fair-weather patterns, local winds in mountainous terrain are greatly influenced by differences in temperature in the lower layers of the atmosphere. Surface air temperature varies with elevation, aspect, slope, extent and type of ground cover, as well as with the temperature and stability of the overlying air. These variations result in local density and pressure gradients that in turn produce complex wind patterns in the first 1000 ft or so above terrain.

Wind patterns in the Oregon Coast Ranges were investigated by Cramer.[1] In that study, station pressures observed at various elevations between sea level and 4000 ft were reduced for analysis of the 900-mb, 950-mb, and sea-level surfaces. With the predominantly summer fair-weather patterns sampled, it became apparent that mesoscale pressure patterns were closely related to temperature patterns in that mountainous area. Areas of highest temperature corresponded to the areas of lowest sea-level pressure. To analyze temperature directly, a method was required that would cancel out the effects of pressure (elevation) differences and produce values that could be meaningfully analyzed. Potential temperature was the logical parameter.

3. Method of potential temperature analysis

Air temperature can be readily converted to potential temperature.[2] The potential temperature of a parcel of

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[1] Cramer, O. P., 1960. Progress toward special tools for fire-weather analysis and forecasting in mountainous terrain. Paper presented at National Meeting, Amer. Meteor. Soc., Eugene, Ore., 15 June.

[2] Conversion from temperature and pressure to potential temperature may be accomplished by use of a thermodynamic diagram showing the graphical solution of $\theta = T(1000/p)^{R/c_p}$, where θ is potential temperature, T temperature (°K), p pressure (mb), R the gas constant for dry air, and c_p the specific heat of dry air at constant pressure.

unsaturated air changes only as heat is added or taken away, as by conduction at sunlit surfaces or at shaded, radiationally cooled surfaces. Thus, at any given pressure level, potential temperatures are comparable as temperatures; observations from different levels compare as indicators of temperature at a common level. The fact that observations in mountain areas are made at various elevations, a disadvantage in any other type of analysis, is an advantage for sampling and analysis of potential temperature and related conditions at the terrain surface in such areas.

Potential temperature analysis immediately suggests isentropic analysis, but the application here is much different. Whereas isentropic analysis involves a surface of constant potential temperature, the surface of primary concern here is the terrain surface with which many isentropic surfaces may intersect. Rarely does an isentropic surface correspond to the shape of the land, particularly in mountainous terrain.

Use of potential temperature for synoptic-scale cross-section analysis has been a standard procedure for many years as has the analysis of isentropic surfaces. Potential temperature has also been used to describe finer temperature detail. Defant (1951) shows large-scale cross sections to illustrate the toposcale (Schroeder, 1961b) potential temperature structure associated with upslope and downslope winds. Toposcale deals with phenomena of 3 to 30 mi in size such as mountain and valley winds. Fosberg and Schroeder (1966) used horizontal analyses of "sea level temperature," an approximate potential temperature, to follow inland penetration of cool marine air in California. Potential temperature analyses in the form of the terrain surface map (*TSθ* map) and the cross section deserve broader use.

The preparation of potential temperature analyses is not difficult. In the mountainous terrain of the Pacific Northwest, surface observations in a 25-mi radius may represent an elevation range as great as 6000 ft. Rarely does a mountain station observe air pressure, but temperature readings are generally made and may be converted to potential temperature in one of two ways. One alternative is to determine the Fahrenheit potential temperature by multiplying station elevation in thousands of feet by 5.38F and adding this to the reported Fahrenheit temperature. The other procedure is to read the θ value from a thermodynamic diagram after converting station elevation to standard atmosphere pressure. Although neither procedure gives potential temperature precisely, the resulting values permit analyses of summer weather conditions that are indistinguishable from analyses of true potential temperature. These values are then plotted on terrain profile cross sections and on contour base maps at a scale of 1/1,000,000 or greater.

A few simple rules guide the analysis of these two types of charts. Cross-section transects were located to include a raob or aircraft sounding. Above the layer mixed by ground level heating, θ surfaces were assumed to be horizontal unless there was strong evidence to the contrary. Exceptions included meeting requirements for reasonable continuity, warm or cold air advection, or a frontal zone. The mixing layer was assumed to be dry adiabatic during midday and was indicated by vertical isentropes. During sunny summer days, a superadiabatic layer was assumed next to the surface. Cross-section analysis procedures have been detailed by Cramer and Lynott (1961).

On the *TSθ* map the isentropes have been found generally to parallel contours except in the vicinity of an atmospheric discontinuity. They are most likely to intersect contours during midday when the horizontal θ pattern in the deep-mixed dry adiabatic layer may reflect the temperature pattern in the air above. In early morning with little wind, the stable stratification of air layers in contact with the ground assures horizontal θ surfaces in contact with rising terrain. As heating progresses, the isentropes still tend to parallel contours as the heating effect also appears to be closely related to elevation. As the mixed layer deepens, the lowest cool layers disappear and the surface θ gradient decreases.

Turbulent mixing accompanying windiness tends to assure that the temperature observed at an exposed station is representative of the potential temperature of an appreciable layer of well-stirred air. During light winds, some allowance may need to be made for local influences. For example, temperatures at mountain-top stations will tend to be lower in the morning and higher in the afternoon than the free air temperature at the same elevation.

4. Interpreting the terrain-surface, potential-temperature map

The *TSθ* map is particularly useful in interpreting local surface wind patterns. Terrain contours on the base map not only define the shape of the terrain that has direct channeling and deflecting influence on flow, but also permit interpretation of the slope of the isentropes, and hence, estimation of the probability of density-induced flow, the basis for most local winds in mountainous terrain. In the usual hydrostatically stable situation, isentropes tend to parallel terrain contours, with coolest air on the bottom. Where isentropes cross contours, a horizontal density gradient is indicated and density flow is likely.

Though direction of flow is generally from cool toward warm, it also depends on such other factors as the broad-scale pressure pattern, stability, terrain constraints, and the presence of heating or cooling areas. Slope winds, for example, are produced by cooling or heating of the surface-air layer by the terrain. Terrain contour patterns indicate the steepness and orientation of a slope, and hence its tendency to produce sunny upslope or shaded downslope breezes. Wherever cool air can replace warmer air by horizontal or descending motion, flow tends to occur.

Sloping isentropes and accompanying density flow may be expected in several situations. Where there is advection of air of a different potential temperature than ambient, isentropes tend to slope and cross streamlines. The sea breeze, downslope drainage wind, glacier winds, and the thundersquall are examples of cool air advection. Isentrope slope will be greatest in zones of discontinuity, and flow will appear to be across isentropes. Actually, each parcel of air tends to move at constant θ, causing the θ-gradient pattern to move along with the wind. The position, orientation, and pattern of isentropes on an analysis give clues to likely and unlikely air motion due to the temperature, and resulting density gradients.

A sample *TSθ* analysis with cool marine air moving inland through two passes of the Oregon Coast Ranges (Fig. 1) shows that the flow is generally from cool to warm, the equivalent of from high toward low pressure. The high country (⩾ 2000 ft) rises into air about 10K warmer than the cool air moving into the valleys from the coast. The lower elevation flow of cool stable air is channeled somewhat by the terrain. The cool air is advancing as a wedge, as may be noted by the slope of isentropes, e.g., 300K at around 2500 ft on the west descends to a few hundred feet at Corvallis. The flow is parallel to the gradient, or perpendicular to the isen-

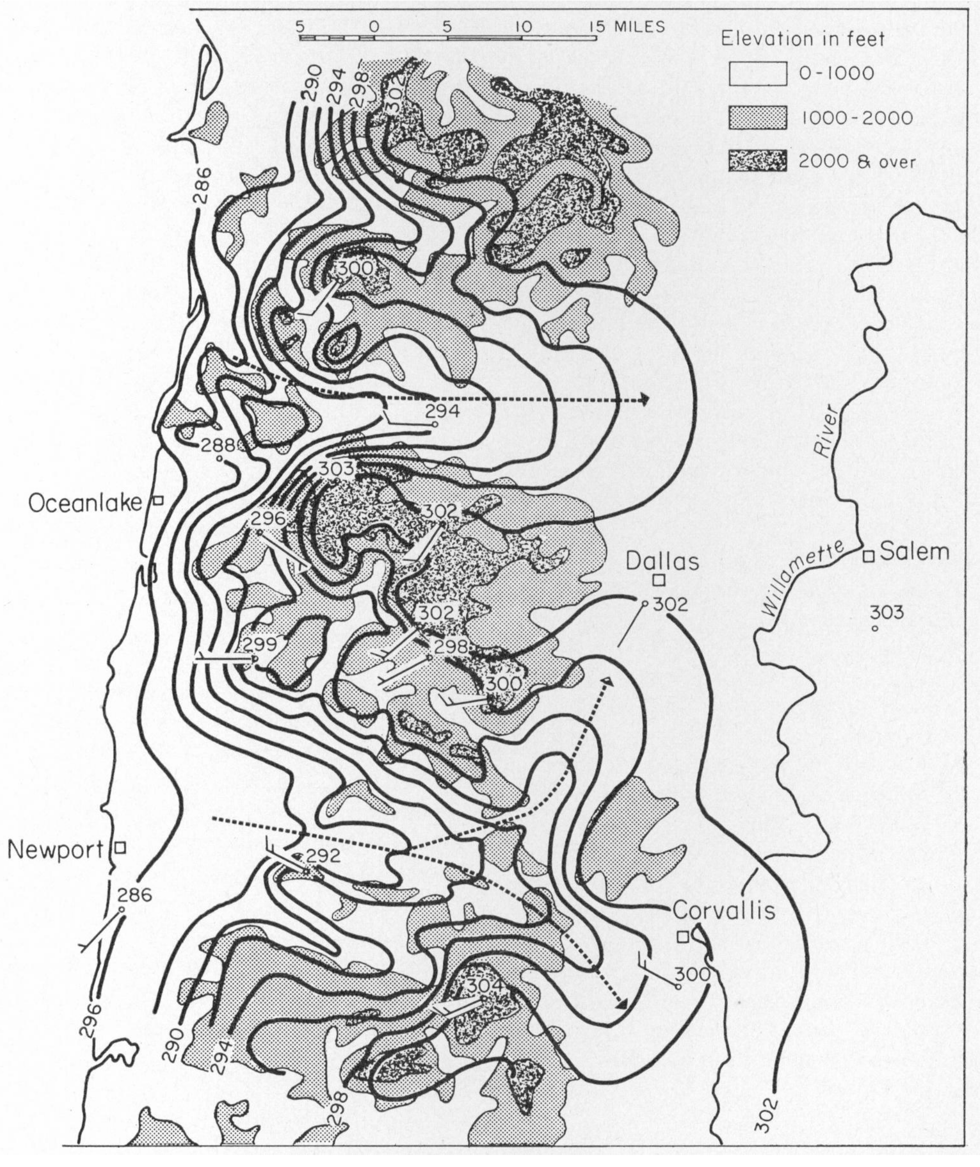

FIG. 1. *TSθ* map of onshore flow of cool marine air through passes in Oregon Coast Ranges at 1615 PST 22 August 1956. Highest θ values are at high elevation or in the interior. Isentropes are drawn for each 2K.

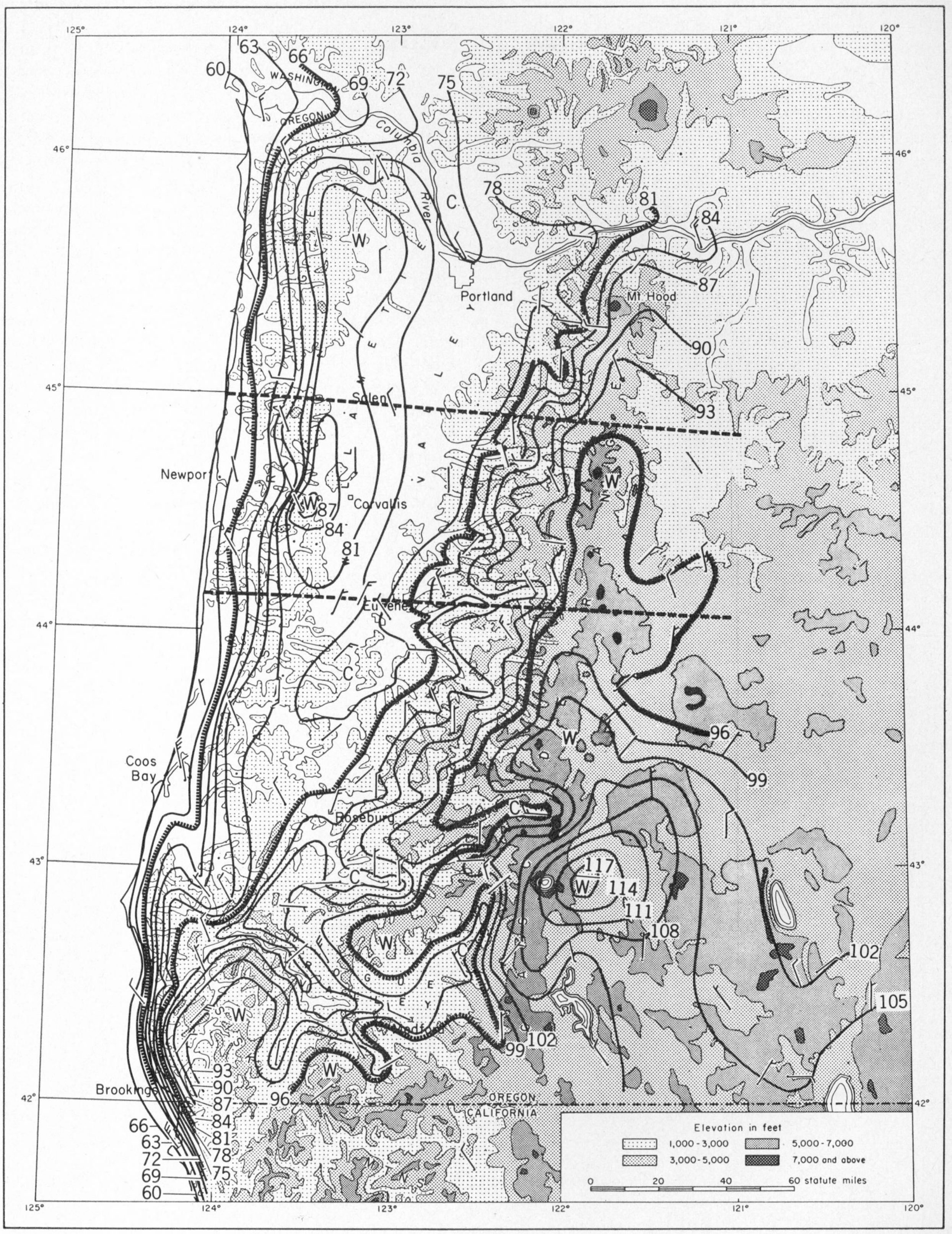

FIG. 2. Western Oregon $TS\theta$ map at 1600 PST 2 July 1960. Isentropes are drawn for each 3F. Dashed lines indicate zone represented in cross section (Fig. 4).

tropes at the leading edge, and the isentropes are moving with the wind as they would with a cold front.

Advection of cool air, shown by wind at large angles to the isentropes, is limited to the lower Columbia Valley, Coos Bay on the coast and, possibly, the southern Willamette Valley (Fig. 2). Flow is generally parallel to the isentropes along the coast with some deflection toward warm air or low pressure. On the west side of the Cascades, the flow is more directly from cool toward warm, up the canyons and the slopes as is reasonable on a sunny summer afternoon. Due primarily to terrain restraints, strongest winds are generally parallel to the isentropes in southwest Oregon where the θ gradients are most pronounced.

5. Interpreting the potential temperature cross section

To form a detailed picture of mountain area weather conditions, it is necessary to consider the vertical extent and characteristics of air layers in contact with or influencing the surface. The cross section depicts such typical features as the surface superadiabatic layer, the mixed layer, the height of the lowest stable layer, residual stable layers in valleys, the marine or nocturnal inversions, and on a large scale, heated convective plumes over ridges and peaks. It is particularly useful in combination with the $TS\theta$ map for showing depth and properties of any layer for which the $TS\theta$ map shows the lateral extent of surface contact.

In regions of frequently stratified air masses with inversions, as along our Pacific Coast, surface weather can vary considerably under the influence of contrasting strata. Wind velocity, gustiness, temperature, humidity, and pollution load may vary between strata. Such surface conditions are important in fire-weather forecasting for fire-danger rating and forest fire-control operations.

The cross section helps to indicate the potential for up- and downslope motion. On sunlit slopes, θ values are highest next to the slope and flow trends to be up the slope. Downward flow would be expected on cooling slopes with lowest θ values next to the slope. Upslope wind on a sunny slope may be limited by an inversion, or, if it reaches the summit, may continue upward as a thermal if the θ values are higher than those of the air above; if the θ values are lower, the original upslope wind may descend the far side of the ridge, depending also on air temperature on the far side of the ridge. Air flowing down a slope will descend until it meets cooler air that, for example, may fill the valley below. The warmer downslope air will tend to flow out over the top of the cooler, more dense air.

In the steady state, flow is parallel to the isentropes. In a zone of horizontal θ gradient or a discontinuity zone, the θ pattern is likely to be moving with the wind. In a layer where θ decreases with height (as in the superadiabatic surface layer) or in a layer of constant θ (as in the mixing layer), upward and downward turbulent motion may be expected.

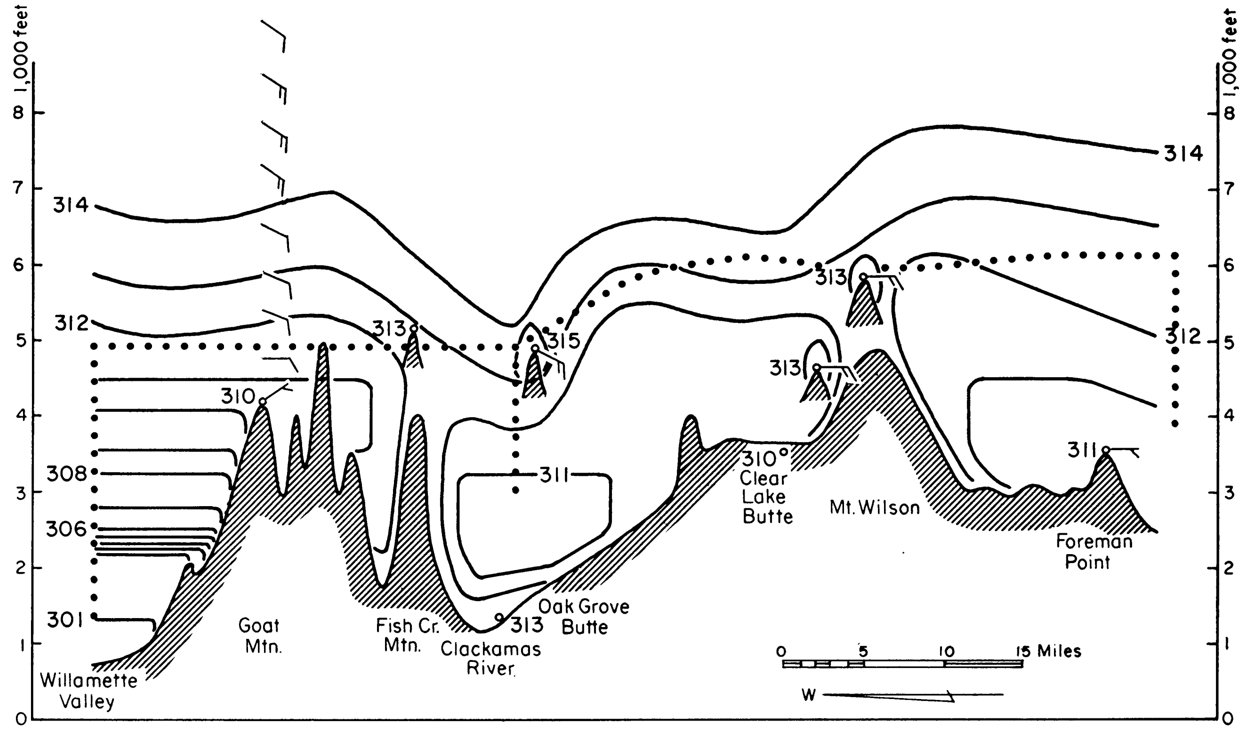

FIG. 3. Atmospheric potential temperature (°K) cross section over the northern Oregon Cascades at 1400 PST 8 August 1963. Instrumented aircraft route is shown by dotted line. Note warm plumes over peak stations.

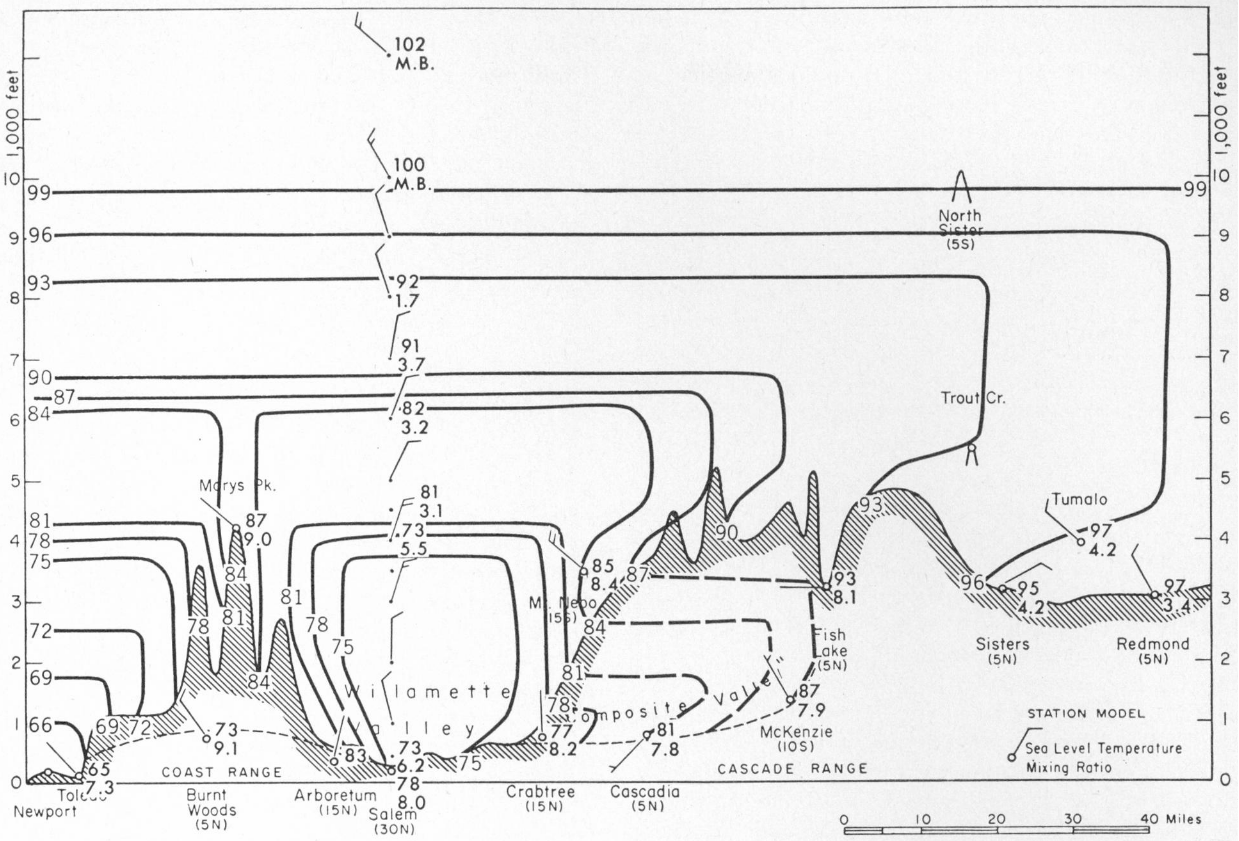

Fig. 4. East-west potential temperature cross section at 1600 PST 2 July 1960 from the Pacific Ocean across the Cascade Mountains.

A midafternoon cross section across the Cascade Range (Fig. 3), based on aircraft and surface observations, illustrates the contrast in temperature and stability conditions between the interior of the Range and the Willamette Valley. This particular situation shows terrain-induced wave motions in an easterly flow which was apparently strong enough to keep the cool marine air from reaching the Clackamas Basin.

On a broader base, Fig. 4 shows the transition of air mass properties from the coast into eastern Oregon. Of interest are the two inversions over western Oregon, the lower stable air along the coast, the break in the lower inversion over the Coast Ranges, the mixing layer between the surface and the top of the vertical isentropes, the absence of inversions east of the Cascade summit, and the greater depth of unstable air east of the Cascades. When taken together, the cross section (Fig. 4) and the $TS\theta$ map (Fig. 2) for the same synoptic time present a fairly detailed picture of temperature, stability, and potential wind conditions. For example, cool air to considerable height flowing up the central Willamette Valley is in contrast with the considerably warmer air on both sides of the valley. Although the mixing level in the center of the Willamette Valley is 3500 ft, it is 6000 ft over the central Coast Ranges and western Cascades. Upslope wind components would be expected on sunny exposures.

6. Applications of potential temperature analyses

$TS\theta$ maps and θ cross-section analyses at the mesoscale have proved valuable for investigations of several kinds of local weather conditions in Oregon. In addition to the study of Coast Ranges winds, these procedures have proved useful in the study of: 1) a meso cold front in the Cascades, 2) a heat wave in western Oregon, 3) influences on dispersion of smoke from mountain area sources, 4) temperature-related wind patterns in the Cascades, and 5) area mean temperature in mountain forecast areas. These applications of potential temperature analyses are briefly described below.

a. Mesosystem fronts

Mesoscale systems may produce temperature discontinuities that can be studied through potential temperature analyses. The sea breeze would seem to be ideally suited to such treatment. The thunderstorm-related mesoscale cold front, though usually traced through the marked pressure change that accompanies it, may also be indicated by potential temperature gradient analysis. This assumes that the cool air of the advancing edge of the thunderstorm high is in contact with the terrain surface. A zone of closely packed, steeply sloping isentropes indicates a discontinuity zone, such as a front, and implies a pressure gradient. A front aloft, surfacing in high country, may have similar properties. Such thermal discontinuities are usually much less obvious, particularly in mountain areas if temperature observations are analyzed directly.

b. Heat wave study

Potential temperature analysis of a heat wave over western Oregon (Cramer and Lynott, 1970) revealed that day-to-day summer weather patterns were greatly influenced by the interplay of stratified airmass characteristics, mountainous terrain, and proximity to the cool ocean (Figs. 2 and 4). The θ analysis was much more meaningful and useful than the pressure analysis alone.

c. Smoke dispersion

The cross section and $TS\theta$ maps provide an excellent base on which to evaluate trajectory and dispersion of aerosols such as sprays, dusts and smoke. For this purpose, potential temperature may be considered a fairly conservative tracer of air motion if cooling or heating sources and condensing clouds are not dominant. Knowledge of the presence of stable layers that will restrict vertical motion permits direct appraisal of potential smoke plume rise or descent into a valley. With such information, intermittent solid-waste burning might be limited to weather conditions favorable for smoke dispersal. Particularly in mountainous terrain, dispersion potential varies greatly from one source to another, from day to day, and even with time of day, depending on elevation of origin, heat and volume of plume, and thermal and motion properties of the air layer into which the plume is introduced.

d. Mountain winds

Cross sections, with enough data, may also provide a base for the study of wave and lee slope phenomena (Ryan, 1969). In stable air, in the absence of cool or warm air advection, isentropes may be used as streamlines to depict such flow phenomena as lee-slope surfacing and lee rotors, and to provide some clue to areas of surface flow reversal, and ascending and descending flow beneath wave motions.

e. Temperature analysis

Evaluation of temperature in mountainous terrain is in itself a problem when readings are taken at various elevations. A potential temperature analysis, at least during the warmer hours of fair summer days, may be considerably simpler. For the specific problem of determining the mean mid-afternoon temperature of a fire-weather forecast zone extending 20 by 40 mi, the mean potential temperature of the area may be interpolated directly from a $TS\theta$ analysis. This mean value may, in turn, be converted to temperature at the mean or other elevation of the area for rating the fire danger.

Potential temperature analysis may also be used for study of maximum temperatures in a mountainous area. Early morning potential temperatures from peak stations are helpful in forecasting maximum temperatures at valley stations, particularly during periods of subsidence in area remote from radiosonde observations.

7. Conclusions

Particularly applicable to mountainous areas, the information provided by analyses of potential temperature in atmospheric cross sections and at the terrain surface may be summarized as follows:

1) Extent of stratification. The analyses show the horizontal and vertical extent of terrain under the influence of several air strata, each with different properties. Thus, there may be terrain above and terrain below a maritime or nocturnal inversion.

2) Logical analysis of temperature, wind, and other elements reported by stations at various elevations. The three-dimensional approach is particularly important in mountain areas where observations from a variety of elevations are likely to result in a confusing two-dimensional analysis.

3) Possibilities for density flow. Areas susceptible to the sea breeze or mountain and valley winds become evident by emphasis of surface temperature pattern in relation to terrain shape. This information is particularly useful in summer with its flat pressure patterns and light winds aloft.

4) Local flow patterns in areas of wide height range. Here a horizontal analysis for any given level is unrepresentative of much of the area. Further, the complexities and weaknesses of pressure reduction through various imaginary layers of air are avoided.

5) Conditions controlling vertical motions. The three-dimensional potential temperature structure provides a basis for judging likely and unlikely windflow patterns and air trajectories. The analyses are helpful in the prediction and analysis of aerosol plume behavior.

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