UDC 551.553.11/.21:551.524.31(795)

Marine Air Penetration in Western Oregon: An Observational Study

LARS E. OLSSON [1]—*Department of Atmospheric Sciences, Oregon State University, Corvallis, Oreg.*

WILLIAM P. ELLIOTT—*School of Oceanography, Oregon State University, Corvallis, Oreg.*

SHENG-I HSU—*Department of Atmospheric Sciences, Oregon State University, Corvallis, Oreg.*

ABSTRACT—Intense daytime heating in an interior valley and cold upwelled water offshore combine to produce a strong horizontal temperature gradient and the development of a baroclinic field. This leads to an onshore component of the wind in the lower layers with the main features guided by the local topography. Penetration rates of 5 m/s were found. A layer of winds with an easterly component was also found between the low-level westerlies and an upper level westerly current. This easterly current showed signs of being a return flow and was found to have higher small-particle concentrations over the shore than either layer above or below it.

1. INTRODUCTION

Western Oregon is considered to be the region west of the crest of the Cascade Range. The crest of this range is about 150 km from the coast and parallel to it with an average elevation of about 2000 m and peaks to 4000 m. There is a lower range of mountains, the Coast Range, about 30–50 km east of the coast. This range, which also parallels the coast, has an average height of about 500 m and peaks to 1300 m. Between these ranges lies the Willamette Valley, where the majority of the population of Oregon lives. In summer, the weather is dominated by surface high pressure, which produces generally fair skies and north to northwesterly winds near the surface. An inversion aloft is present more than 75 percent of the time with a base between 1 and 2 km above the surface. Most of the industrial activity of the state takes place in the Willamette Valley, and in summer there is a great deal of agricultural burning. Holzworth (1972) has pointed to the region as having one of the highest potentials for urban air pollution in the nation. He based this assessment on low mixing heights coupled with high frequencies of light winds within the mixing layer. More complete discussions of the summer climate in Western Oregon can be found in Lowry (1963) and Schroeder et al. (1967).

The northerly winds off the coast produce intense oceanic upwelling, particularly in July and August, and this cold water surface, coupled with intense daytime heating of the valley, produces a strong east–west temperature gradient. A west–east pressure gradient develops across the Coast Range in response to the temperature gradient. This local pressure gradient, in combination with a differential frictional effect and the prevailing north-northwest winds, produces an onshore flow component that causes marine air to penetrate into the Willamette Valley through several passes and corridors through the Coast Range. This penetration of marine air into the valley is a significant feature of the local climate since it contributes to the ventilation of the valley and the dispersion of air pollutants. This marine air penetration is the subject of the study reported here.

This marine air penetration is generally spoken of as a sea breeze, but the circulation that produces it is a complex interaction of sea-breeze-type circulations and mountain–valley circulations. It is complicated by the presence of the marine inversion and the inversions aloft associated with the general synoptic patterns in the summer and early fall.

Several investigators (e.g., Lowry 1962, Schroeder et al. 1967, Fosberg and Schroeder 1966) have reported on sea-breeze observations along the west coast in connection with the effects of the marine air on fire-weather conditions. Schroeder et al. (1967) have described the west coast "monsoon," and Cramer and Lynott (1970) have analyzed the life cycle of a heat wave in western Oregon. Edinger (1959) and Viezee and Oblanas (1969) have reported on studies of the marine air inversion in California.

2. OBSERVATIONAL PROGRAM

During the summers of 1969 and 1970, several special observations were made of winds, temperatures, and aerosol concentrations aloft over western Oregon. These observations were supplemented by surface observations of winds, temperatures, and pressures. On two days, July 9 and 23, 1970, extensive measurements were made of the marine air penetration into the Willamette Valley through the Sheridan corridor west of Salem. This corridor is a

[1] Now at the Swedish Institute of Meteorology and Hydrology, Stockholm, Sweden

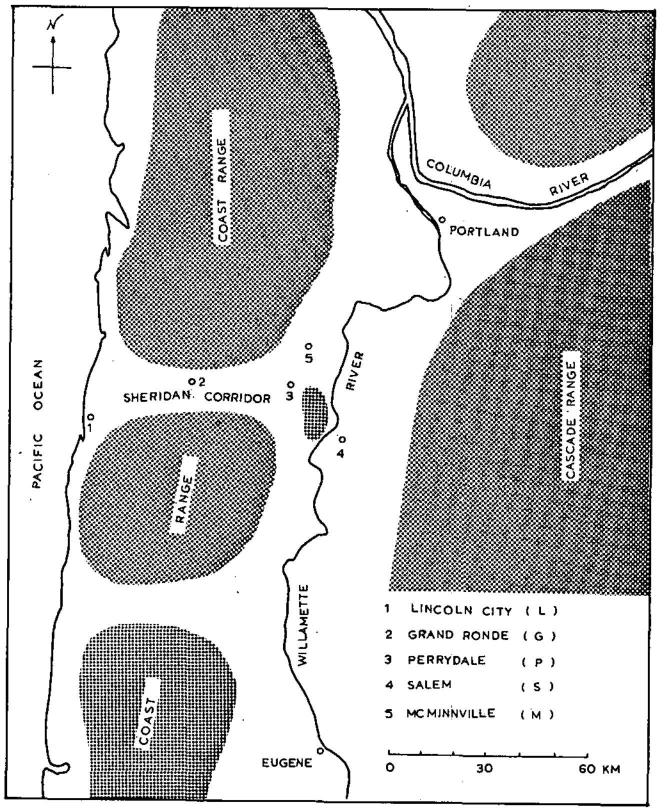

FIGURE 1.—Northwest Oregon.

deep pass, approximately 10 km wide, between 1000 m high peaks in the Coastal Range. The pass, with a summit at about 200 m, opens into the Willamette Valley approximately 50 km inland. Pilot balloon measurements of the winds aloft were made along a line perpendicular to the coast through the pass at stations equipped with hygrothermographs and barographs. Air trajectories within the valley region were also studied with constant-level balloons (tetroons), which were tracked with light aircraft and a ground-based radio receiver system. Horizontal temperature profiles through the corridor and within the Willamette Valley were obtained with a thermometer mounted on an automobile. The location of the area studied and the observing sities are shown in figure 1.

Temperatures and small-particle counts aloft were measured from an aircraft. The temperature measurements were made with a recording portable EG&G system using a shielded sensor, Model 702.[2] The resulting temperature profiles were compared with the profiles from simultaneous radiosondes over Salem, and it was found that, although the absolute temperature might differ by as much as 2°C, primarily due to dynamic heating, the shapes of the profiles were approximately the same (Olsson et al. 1971). This means that stability as determined by either sounding technique would be the same for all practical purposes. A small-particle detector was used for measuring particle concentrations. This instrument counts all particles larger than 10^{-7} cm and has a range from 2×10^2 to 1×10^7 particles per cubic centimeter.

The profiles of the winds aloft were determined from single theodolite observations of 10- or 30-g balloons.

[2] Mention of a commercial product does not constitute an endorsement.

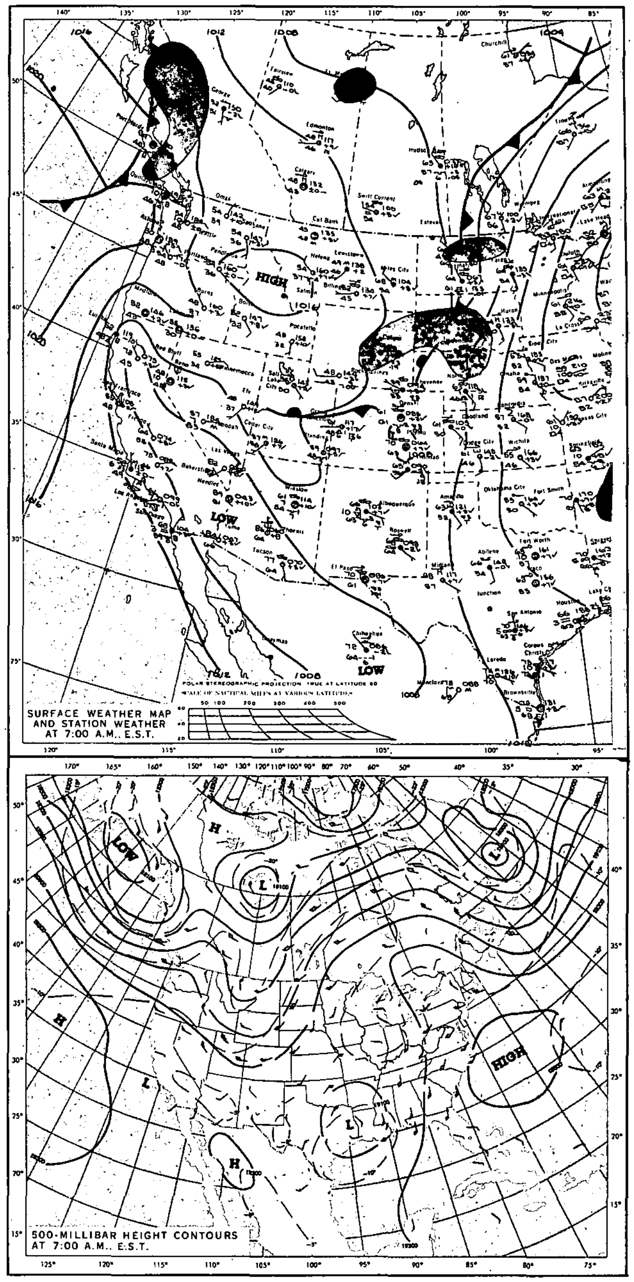

FIGURE 2.—Surface and 500-mb charts for 1200 GMT, July 23, 1970.

3. ANALYSIS AND DISCUSSION OF DATA

On July 23, 1970, extensive measurements were made of the marine air penetration west of Salem. On this day, high surface pressure prevailed off the Oregon coast with northerly gradient winds in the lowest 1500 m over the Willamette Valley. Skies were clear during the morning with high clouds observed during the afternoon and evening. Smoke reduced visibilities in the valley in the morning to about 6 mi. Light westerly winds were observed aloft in the afternoon and evening, as a weak low-pressure trough at 500 mb moved toward the Oregon coast. The 1200 GMT (0400 PST) surface and 500-mb charts for this day are shown in figure 2.

At 0400 PST, the Salem rawinsonde indicated a strong nocturnal inversion in the lowest 100 m with isothermal conditions up to 1000 m where a strong but thin subsidence

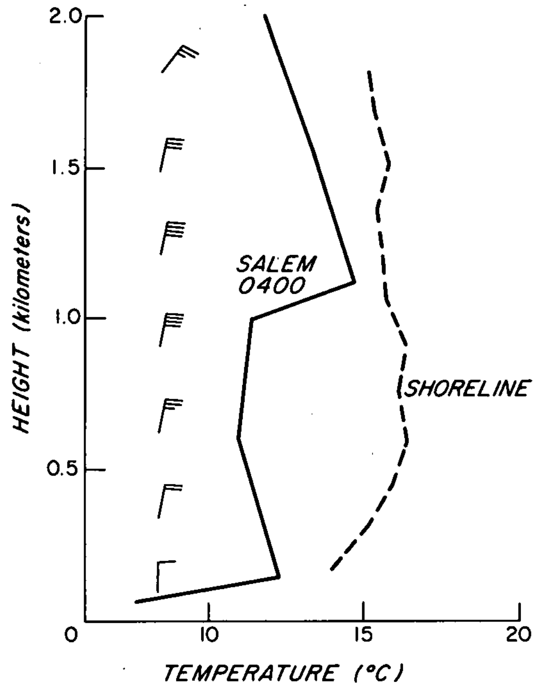

FIGURE 3.—Temperature soundings on the morning of July 23, 1970.

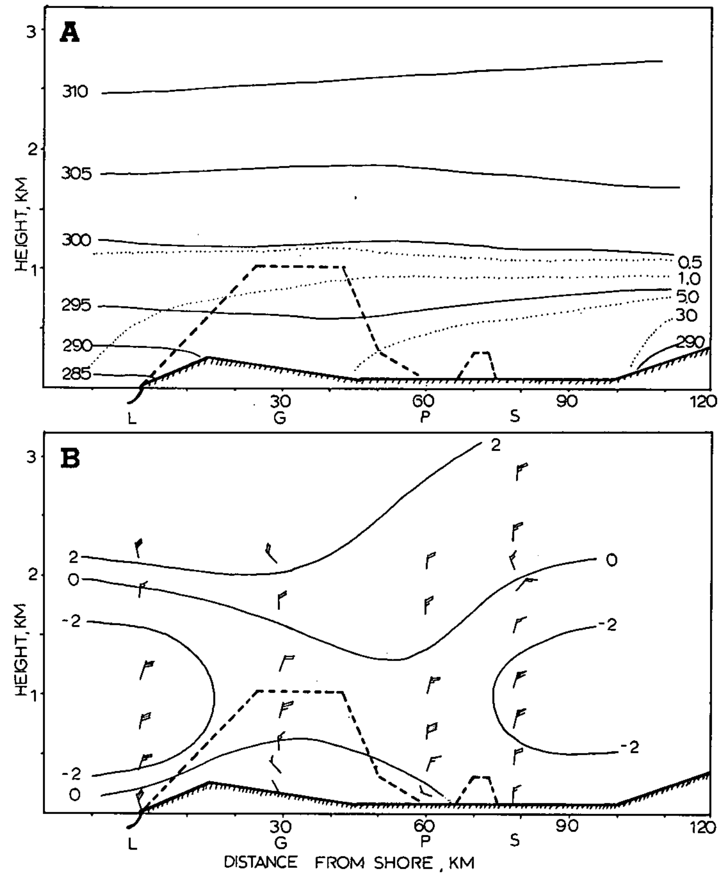

FIGURE 4.—(A) potential temperature (°K, thin solid line) and small-particle concentration (10^3 cm^{-3}, dotted line) and (B) wind observations aloft (one full barb equals 2 m/s) and isotach analysis of east-west component (m/s, negative values indicate easterly component) for 0700–0900 PST, July 23, 1970. Topography through Sheridan Corridor and the Coast Range on either side of the corridor are indicated by heavy solid lines and heavy dashed lines, respectively.

inversion was based (fig. 3). The winds were light and from the north-northeast below 2500 m and northwest above. Temperature profiles just offshore at 0730 PST, as determined by aircraft, showed an inversion in the lowest 500 m with isothermal conditions from 500 m to at least 2000 m. Particle counts were low, less than 10^3 cm^{-3} below 1100 m with a significant decrease above that level.

Our observations began at 0700 PST. Stable conditions prevailed over the area in the early morning with the most stable region over the coastal waters (fig. 4A). Particle counts were still low with the exception of the extreme Eastern portion at the base of the Cascades. (The high concentrations here result from the return flow of pollution from the previous day brought down with the downslope winds of the Cascades. We observed this effect on other occasions.) The wind flow shows a shallow layer of north-northwest winds overlain by a layer of north-northeast above which is another north-northwest layer (fig. 4B).

By early afternoon (figs. 5A, 5B), the air over the valley had become nearly adiabatic with a superadiabatic region just east of the Coast Range. Over the water, however, the air was still stable due to the cold, upwelled water. A layer of stratus clouds formed with a base at about 500 m over the beach at this time forcing the pibal observation site 7 km inland. The top of the mixed layer is well defined by the gradient of small-particle concentration and coincides with the 300°K potential temperature surface over most of the region. The highest particle concentration is above the superadiabatic region, which also coincides with the leading edge of the marine air at this time.

The associated wind field (fig. 5B) shows strong westerly flow through the corridor but much less so over the beach and in the main part of the valley. The westerlies extend the highest above the Coast Range; above them, there is a layer with an easterly component also at greatest elevation over the mountains.

By late afternoon, the marine air had penetrated farther inland (figs. 6A, 6B). The lapse rate over the valley was still almost adiabatic while still stable over the coast. The top of the mixed layer is still well defined by the particle concentration, but there is a slight increase in particle concentration over the coastal area. We believe these particles were carried over the mountains in the layer with an easterly component sometime earlier in the day. There is a general decrease in particle concentration through the corridor as the cleaner air from the sea advances. The zone of maximum westerly flow has moved farther east and increased in magnitude. The layers of westerly and easterly flows are still highest over the mountains.

The general flow over the valley was northerly for most of the day. A tetroon released at McMinnville airport at 0930 PST and tracked for 4 hr by aircraft followed a generally southward course with excursions toward both the west and east. After noon, when the tetroon was well south of the study area, it experienced strong vertical currents in excess of 200 cm/s at elevations below 900 m,

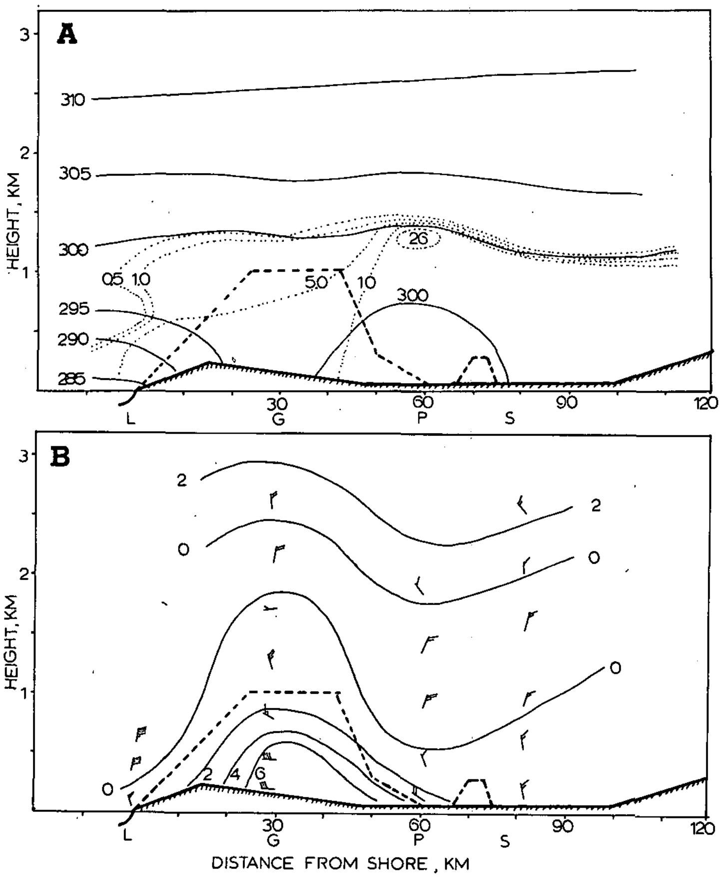

FIGURE 5.—Same as figure 4 for 1200–1400 PST.

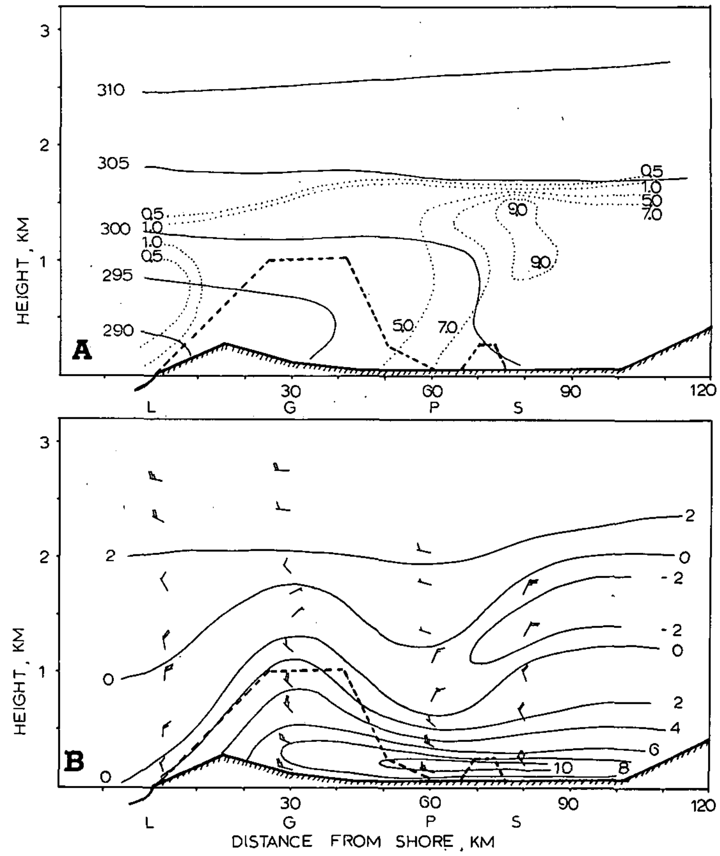

FIGURE 6.—Same as figure 4 for 1600–1800 PST.

indicating strong convective activity below the inversion base. The path of this tetroon is shown in figure 7.

A second tetroon was released from the McMinnville airport at 1620 PST and moved south-southwest at an average speed of 6.5 m/s at elevations between 1100 and 1220 m. This tetroon was lost at 1700 PST near Perrydale, about 15 km south-southwest of the launch site, as its trajectory became unstable. Vertical updrafts in excess of 50 cm/s were experienced by the tetroon before it was lost. The turbulence associated with the vertical currents affecting the tetroon was also noted by the tracking aircraft crew. A further discussion of these tetroon flights (and their trajectories) can be found in Olsson et al. (1971).

By examining the wind component perpendicular to the leading edge of the penetrating marine air, we were able to estimate convergence and associated vertical velocities. The component along the boundary was ignored. This crude method gave convergence values in excess of $20\times 10^{-4}s^{-1}$ with associated vertical updrafts in excess of 40 cm/s. These values are in good agreement with those measured by the tetroon and are of the same order as those found in a lake-breeze regime by Lyons and Olsson (1972).

During the afternoon, an automobile with a temperature sensor mounted on its outside was driven from McMinnville to the coast and back between 1325 and 1553 PST. On the return trip from the coast, the wind direction was noted in a very qualitative manner. The overall temperature gradient was about 13°C over approximately 80 km. (The trip takes about 1 hr and 20 min.) This temperature gradient was not uniform, however; there were preferred regions of relatively sharp change in temperature not always related to obvious wind changes. The temperature increased 5°C in the first 6 km inland then increased about 2° in 3 km centered about 20 km inland. At about 40 km from the coast, the temperature began to increase again although the wind remained westerly. The wind remained westerly for about 19 km while the temperature increased another 3° to almost 29°C, an overall increase of 13°C from the coast. At this point, the car came to a 2-mi wide calm zone. It was virtually impossible to detect any wind even by throwing grass in the air. Beyond this, definite light northeast winds were found, and they increased to the McMinnville airport, some 8 km farther northeast. We were thus able to locate a zone of converging surface winds about 3 km wide with a fair degree of accuracy, but at this time there was little temperature contrast across this zone.

Two hours later, using the same techniques, we found the convergence zone in essentially the same place (by auto odometer). There was still no temperature contrast across the calm zone, but, immediately to the west in the west wind regime, there was now a 4°C decrease in 8 km (fig. 8).

After further exploration with the automobile we found

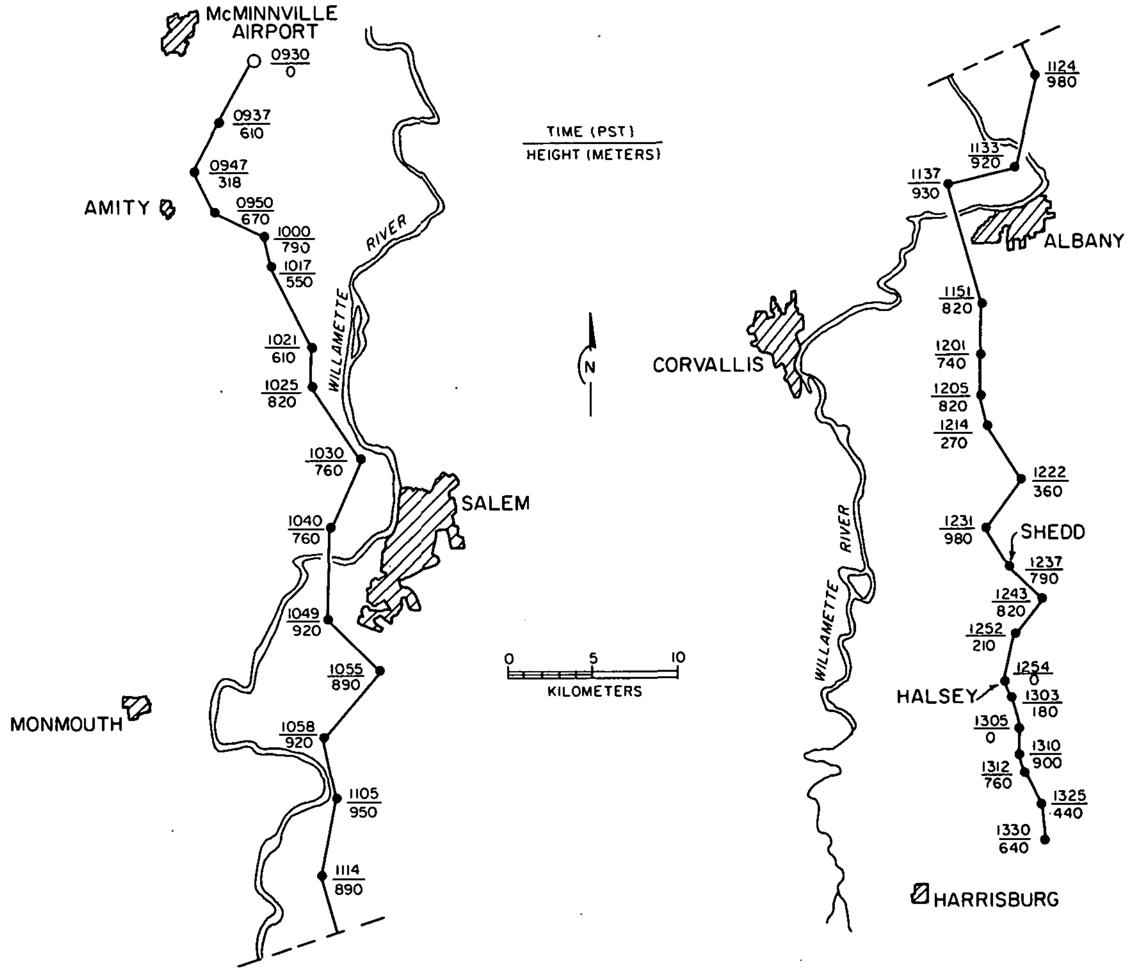

FIGURE 7.—Tetroon trajectory for release at 0930 PST.

this zone intersecting another highway about 8 km southeast of the intersection described above and approximately half way between McMinnville and Perrydale. In this region, the wind shifted from northeasterly to westerly and a temperature contrast of 3°C over 0.5 km was found across the convergence zone. Neither part of the convergence zone had any obvious cloud patterns associated with it despite the fact that simple continuity considerations would indicate a vertical speed of the order of 100 cm/s. This convergence zone has also been observed on other occasions and is indeed suggested in the mean afternoon wind rose from McMinnville for July–September.

The schematic diagram (fig. 9) shows a reconstruction of this situation (with other observations added). The marine air does not spread out equally upon emerging from the Sheridan corridor but rather turns to the south, and an apparent front lies in the northwest–southeast direction, turning perhaps more north–south in the main valley. A vertical cross section through the leading edge of the penetrating marine air is presented in figure 10.

Temperatures recorded at Grand Ronde, Perrydale, and Salem and times of marked wind direction shifts at the surface are presented in figure 11. The surface winds at Grand Ronde were actually calm during the morning

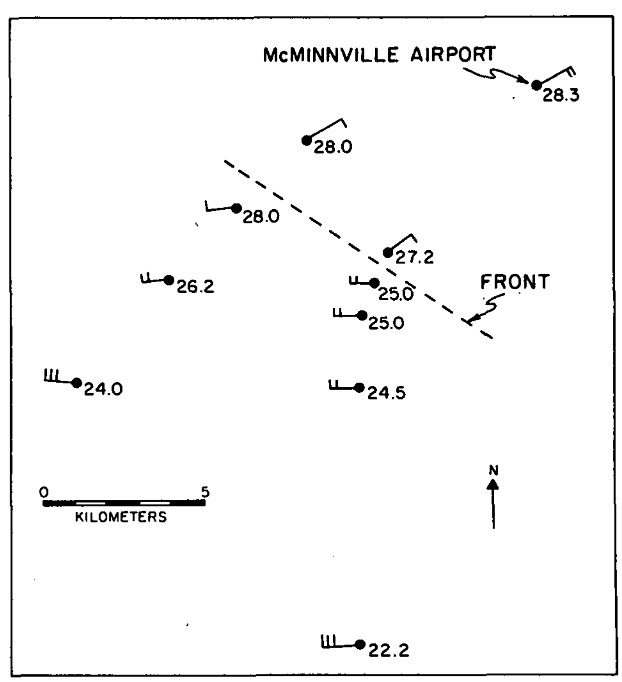

FIGURE 8.—Winds and temperatures (°C), as measured from auto, near the "front". The elapsed time for these observations was about 1 hr.

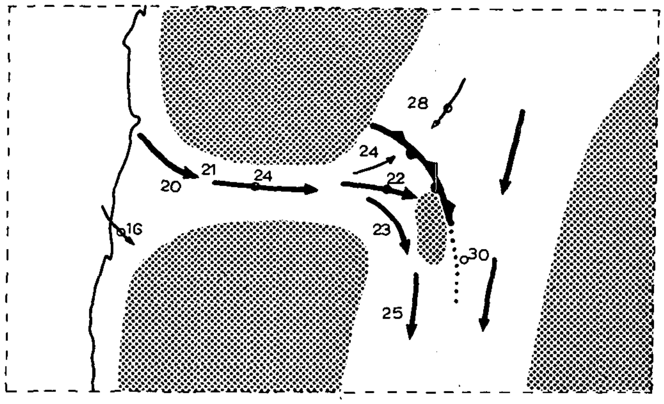

FIGURE 9.—Temperatures (°C) and surface air flow through Sheridan Corridor in the late afternoon on July 23, 1970.

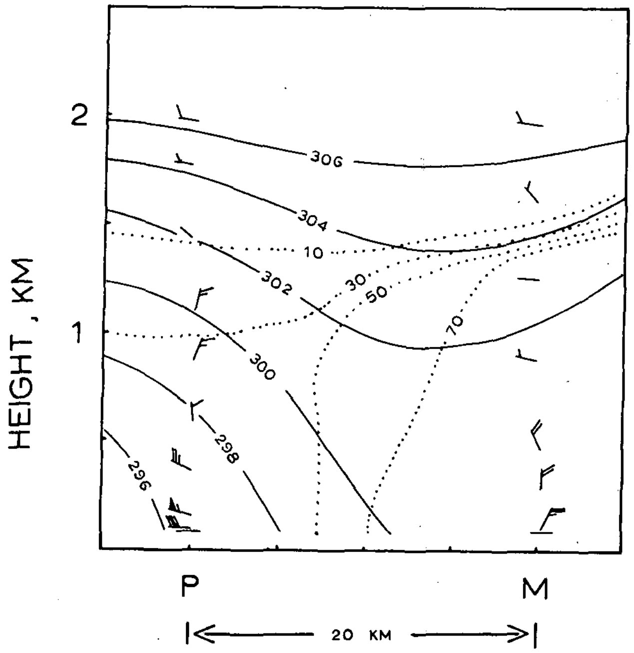

FIGURE 10.—Cross section of potential temperature (°K, solid line), particle concentration ($10^3 cm^{-3}$, dotted line) and winds between Perrydale (P) and McMinnville (M) at about 1700 PST.

with a surge of west winds and an associated marked leveling of the temperature between 1100 and 1200 PST. The wind shift and associated leveling of the temperature at Perrydale occurred shortly after 1300 PST, suggesting that the leading edge of marine air penetrated at a rate of approximately 5 m/s. This high rate of penetration is about twice that observed for a lake breeze by Lyons and Olsson (1972) and could possibly be due to the channeling effect through the Sheridan corridor. The windshift at Salem and McMinnville and associated temperature changes were less pronounced as they occurred late in the afternoon in air that had a relatively long trajectory over land allowing for considerable modification in its characteristics.

Pressures recorded during the day show that, while a significant difference (10 mb) developed between the Coast Range and the valley, the gradient within the valley is almost negligible. The maximum pressure gradient was

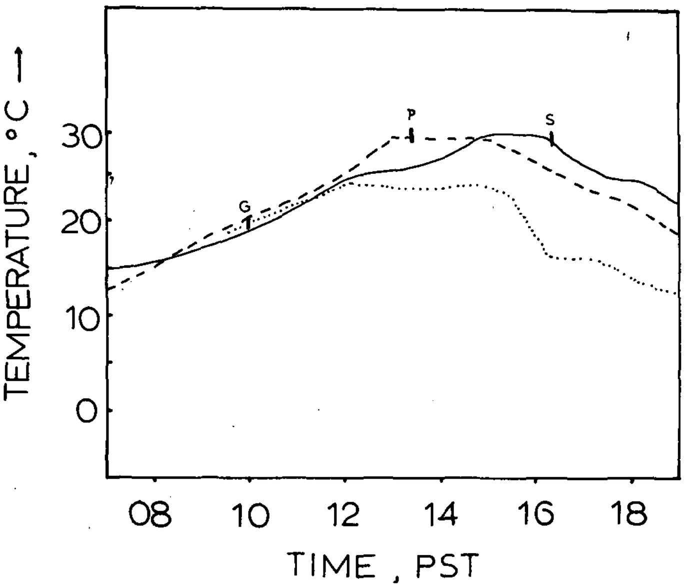

FIGURE 11.—Temperature vs. time at Salem (solid line), Perrydale (dashed line), and Grand Ronde (dotted line). Vertical bars indicate time of surface wind shift at each station.

found at about 1000 PST. Using the objective method for estimating the likelihood of a sea breeze developed by Lowry (1962) and pressure and maximum temperature differences across the Coast Range of 10 mb and 14°C, respectively, we obtained an empirical probability of 1.0, for a sea breeze on July 23, 1970.

4. SUMMARY

Marine air penetration into the interior valleys along the west coast of the United States is of major importance in determining the climate in those areas. This penetration is caused by a complex interaction between the sea breeze, various topographic winds, and the prevailing north-northwest gradient wind in the summer and early fall. Synoptic conditions conducive to the development of these mesoscale circulations prevail on more than 75 percent of the days during this period (Mathews 1971). The observed coastal air circulations seem to have characteristics that are quite different from those observed over other coastal regions (Lyons and Olsson 1972, Hsu 1970). Based on special observations of winds, temperatures, and particle counts and on studies of climatological data, the following characteristics of the coastal air circulation are suggested.

The intense daytime surface heating, primarily of the interior valley floor, coupled with cold water upwelling offshore produces a strong temperature gradient across the Coast Range. This gradient may frequently exceed 15°C/100 km and results in the development of a baroclinic field as a perturbation on the prevailing stable synoptic pressure pattern. The resulting surface pressure differential across the Coast Range frequently reaches 10 mb by midmorning. This strong pressure gradient, coupled with differential surface friction between land and water, gives rise to an onshore component in the prevailing alongshore gradient wind. The topographic features of the Coast Range are of major importance in determining the trajectories of the air because of an inversion aloft associated with subsidence in the prevailing high-pressure synoptic regime and reinforced by the stable marine air penetrating onshore. The marine air tends to be channeled through the gaps in the Coast Range and may, by late afternoon, interact with the upslope wind on the western slope of the Cascade Range, causing marine air penetration of more than 100 km.

As a result of this channeling, the rate of penetration of the leading edge of the marine air, as well as the wind speed, is higher (about 5 m/s higher) than in a classical sea-breeze circulation. The zone of maximum westerly winds seems to penetrate inland as the afternoon progresses. Pronounced convergence, in excess of $20\times10^{-4}s^{-1}$ resulting in calculated vertical velocities exceeding 40 cm/s, occurs along the leading edge. Cold front characteristics are most pronounced to the northeast as the marine air is confronted by warm valley air. Due to the prevailing northerly gradient wind in the valley and longer overland trajectories resulting in air mass modification, these frontal characteristics do not exist to the south of the gap in the valley.

As the day progresses, a layer of winds with an easterly component develops above the layer of westerly winds. From noon on, these layers have their greatest vertical extent at the same longitude as the mountains, even though the measurements were made above the gap in the mountains. The effect of the mountain barrier is felt even above the gaps. The easterly flow is usually found near the base of the inversion but is sometimes evident above the base. It is not clear at present whether this flow is a return flow in a sea-breeze-type circulation or part of some larger scale circulation pattern resembling a helical motion in the northerly winds.

ACKNOWLEDGMENTS

We would like to thank Richard Egami, Robert Nelson, and a number of students for valuable help in the data gathering phase of the work. The research was sponsored by the Columbia-Willamette Air Pollution Authority and the National Science Foundation under Grants GA1618 and GA31141.

REFERENCES

Cramer, Owen P., and Lynott, Robert E., "Mesoscale Analysis of a Heat Wave in Western Oregon," *Journal of Applied Meteorology*, Vol. 9, No. 5, Oct. **1970**, pp. 740–759.

Edinger, James G., "Changes in the Depth of the Marine Layer Over the Los Angeles Basin," *Journal of Meteorology*, Vol. 16, No. 3, June **1959**, pp. 219–226.

Fosberg, Michael A., and Schroeder, Mark J., "Marine Air Penetration in Central California," *Journal of Applied Meteorology*, Vol. 5, No. 5, Oct. **1966**, pp. 573–589.

Holzworth, G. C., "Mixing Heights, Wind Speeds and Potential for Urban Air Pollution Throughout the Contiguous United States," U.S. Environmental Protection Agency, Office of Air Programs *Publication* No. AP–101, Research Triangle Park, N. C., Jan. **1972**, 118 pp.

Hsu, Shih-Ang, "Coastal Air-Circulation System, Observations and Empirical Model," *Monthly Weather Review*, Vol. 98, No. 7, July **1970**, pp. 487–509.

Lowry, William P., "The Sea Breeze of Northwest Oregon and its Influence on Forestry Operation," Ph.D. thesis at Oregon State University, Corvallis, June **1962**, 216 pp.

Lowry, William P., "Observations of Atmospheric Structure During Summer in a Coastal Mountain Basin in Northwest Oregon," *Journal of Applied Meteorology*, Vol. 2, No. 6, Dec. **1963**, pp. 713–721.

Lyons, W. A., and Olsson, L. E, "Mesoscale Air Pollution Transport in the Chicago Lake Breeze," *Journal of the Air Pollution Control Association*, Vol. 22, No. 11, Nov. **1972**, pp. 876–881.

Mathews, M. D., "Synoptic Climatology of Oregon," *Technical Report* #71–5, Department of Atmospheric Sciences, Oregon State University, Corvallis **1971**, 49 pp.

Olsson, L. E., Tuft, W. L., Elliott, W. P., and Egami, R., "The Study of the Natural Ventilation of the Columbia-Willamette Valley: II," *Technical Report* #71–2, Department of Atmospheric Sciences, Oregon State University, Corvallis, Apr. **1971**, 164 pp.

Schroeder, J. J., Fosberg, M. A., Cramer, O. P., and O'dell, C. A., "Marine Air Invasion of the Pacific Coast. A Problem Analysis," *Bulletin of the American Meteorological Society*, Vol. 48, No. 11, Nov. **1967**, pp. 802–808.

Viezee, William and Oblanas, John, "Lidar-observed Haze Layers Associated With Thermal Structure in the Lower Atmosphere," *Journal of Applied Meteorology*, Vol. 8, No. 3, June **1969**, pp. 369–375.

[Received July 5, 1972; revised March 2, 1973]