Modification of the Marine Layer over Coastal Southern California

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ABSTRACT

The modification and eventual destruction of the marine layer by heating from below is documented by measuring the temperature and humidity fields in a vertical section from the coast of Southern California inland along the trajectory of the air. An instrumented light aircraft is used as the meteorological probe. The base of the temperature inversion near the top of the marine layer is seen to propagate downward into the marine layer as a result of the accumulation of convective debris at the top of the layer. At the inland extremity of the vertical section the marine air is observed to have warmed to the point where convective elements originating at the ground are able to escape the layer and rise into the warm dry air above. Implications of these results on the accumulation and distribution of air pollution are discussed.

1. Introduction

Coastal Southern California during most of the year is covered by a layer of marine air. This air arrives at the coastline about 1000 ft in depth with temperature and humidity characteristic of the sea surface over which it has been moving for many previous days. It is the relatively thin bottom layer of a large mass of air moving around the northeast end of the North Pacific subtropical anticyclone, an air mass which through marked subsidence has become warm and dry. Only its lowest layer, the marine layer, has exchanged heat and moisture with the sea surface and has thus become a cool humid film overlain by a deeper mass of warm dry air.

Upon arrival at the continental boundary the shallow marine layer is short-lived. Typically, in the course of its first day's travel across the land it becomes completely modified, mixed and stirred with the upper warm dry air and loses its identity. However, it lasts long enough to bestow upon the narrow coastal margin of the continent a benign climate and along with it an unwelcome air pollution problem. The same stability that traps the moisture at sea and insulates the marine layer from the hot dry air above, upon arrival over the land, traps all the air contaminants being released into the atmosphere at or near the surface.

Early research into the nature and behavior of the marine layer, notably that of Neiburger, was motivated by an interest in the comings and goings of fog and stratus in the coastal areas. Subsequent work on the subject, however, has been stimulated to a large extent by the need to understand better Los Angeles' polluted atmosphere. The work reported here[1] was so motivated and constitutes a detailed examination of the progressive modification and eventual destruction of the marine layer on a day when a strong, but not unusual, temperature inversion existed at the top of the marine layer.

The technique used was the determination of the temperature and humidity field of the lower atmosphere in a vertical section that extended from the coast inland along the path that the marine air moved. A light aircraft instrumented with a rapid response (0.02 sec) resistance thermometer and a hygrometer (radiosonde type sensor) was used to make the soundings. The vertical field of temperature and humidity in this vertical section then was examined as a representation of the progressive modification of the marine layer as it was submitted to the new and markedly different conditions at the lower boundary.

2. Observations

The Santa Clara River Valley, about 50 mi northwest of Los Angeles, was chosen as the site for the experiment because it constitutes a well-defined channel along which the marine air moves after it crosses the coastline. Fig.1

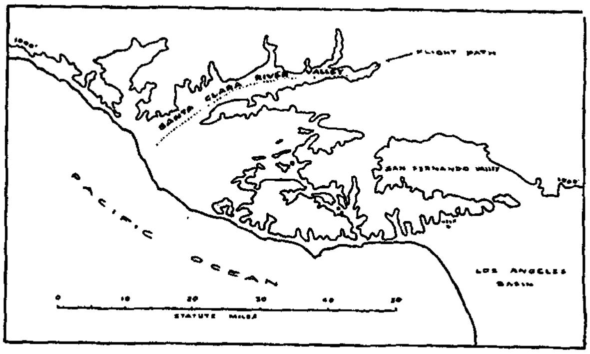

FIG. 1. Map of Santa Clara River Valley.

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[1] Supported by the U. S. Weather Bureau, Contract CWB-10087.

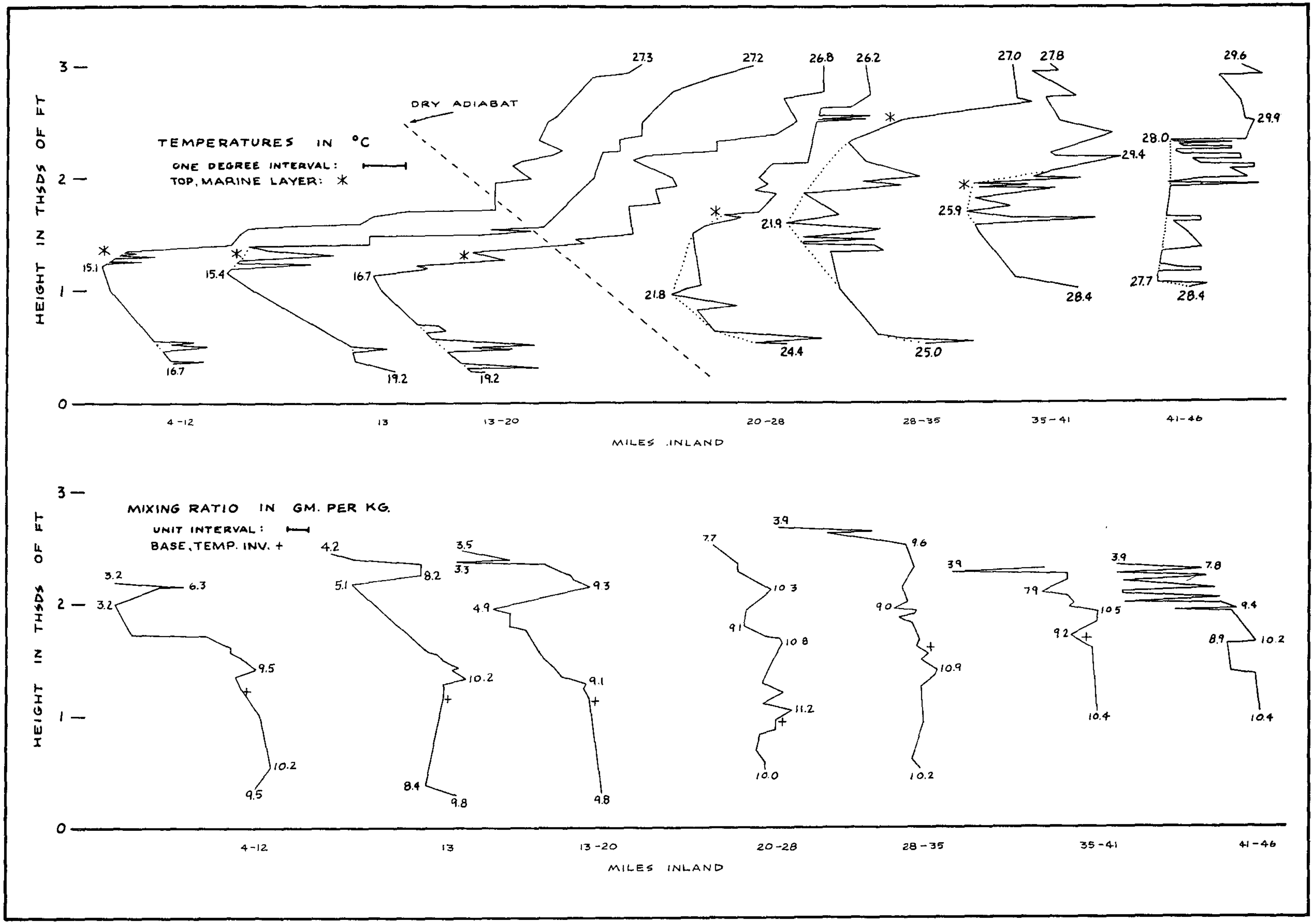

FIG. 2. Temperature and humidity soundings along the Santa Clara River Valley, distance from coast increasing from left to right.

is a map of the area. It was chosen also because the valley is an area of low population density covered mostly by fields and orchards where a light plane can make low passes with minimum hazard to life and property. Its narrowness, 2 or 3 mi, defines the marine air trajectory within relatively close limits so that one can be reasonably certain that the marine air is being sampled along its trajectory.

The measurements were taken 28 July 1961 using a flight pattern consisting of serial ascents and descents along the length of the Santa Clara River Valley. The dotted line in Fig. 1 denotes the path of the plane down the valley and in Fig. 3 the dash-dot line shows the plane's trajectory in a vertical section along the valley axis. The one completely vertical segment of the trajectory represents an ascent made while circling. All other legs were simple straight line ascents or descents at air speeds near 50 m $\sec^{-1}$ and vertical speeds of about 3 m $\sec^{-1}$. The measurements required one half hour to complete, 1300 to 1330 PST. A stratus overcast existed over the ocean and inland 4 mi, its edge defining the western limit of the observational area, which was completely clear of clouds.

Fig. 2 shows the plotted temperature and mixing-ratio soundings that were obtained. They are arranged so that the distance from the coastline increases from left to right. The position of the plane during each sounding is given in terms of distance inland directly below each curve. These plotted curves are slight simplifications of the actual records, consisting of points on the continuous records where significant changes in the traces occur. Differences between the plotted soundings and the actual recorded temperatures and mixing ratios were kept to a small fraction of a degree C or a gm per kgm.

The most striking feature of the temperature structure is the great stability at the base of the inversion near the coast, almost 9C increase through a 500-ft layer, and the progressive decay of this temperature contrast to one of less than 2C at the most inland station. It is apparent that this marked modification of the stability of the inversion layer during the air's 45 mi journey up the valley is largely a result of the marked warming of the marine layer, 16.7C to 28.4C, during its transit inland.

The more detailed structure of the individual soundings reveals conspicuous excursions away from an otherwise smooth temperature curve in the sub-inversion layer, especially at the more coastal locations. At stations farther inland this appears to be the case also, although the increase in number and magnitude of such deviations makes the smooth environmental curve more difficult to discern there. It is significant that the fluctuations in temperature are not distributed on both the positive and negative sides of the environmental state but are confined to the positive. One might conclude that two types of air are being encountered: a cool environment and intrusions of warmed air having temperature excesses of 1 or 2C over the environment. Myrup[2] noted this sort of structure, but on a smaller

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[2] Edinger and Myrup, 1961: Observations of the thermal structure of convection. Final Report for U. S. Department of Commerce, Weather Bureau Contract No. CWB-10087, Department of Meteorology, U.C.L.A., 94 pp.

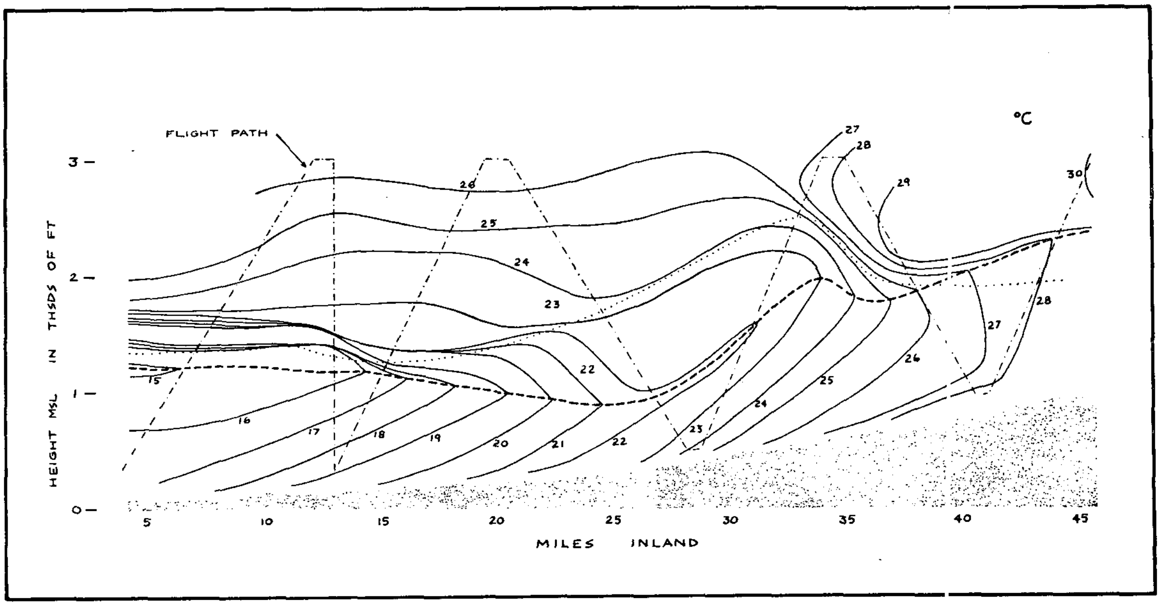

FIG. 3. Temperature field (Celsius) analyzed in the vertical cross section along the axis of the Santa Clara River Valley. Path of aircraft shown as dash-dot line. Top of marine layer indicated as dotted line, base of inversion as a dashed line.

scale in morning air over a desert dry lake bed, using data taken with the same equipment on the day prior to this experiment.

Turning our attention now to the mixing-ratio curves, we find in all cases a layer next to the ground through which the water vapor is more or less homogeneously distributed with a mixing ratio of about 10 gm per kgm. This layer is 1000 to 1500 ft deep. A trend from the coast inland is detectable at the lowest levels, the observed values at the ground increasing from 9.5 gm per kgm at the coast to 10.4 gm per kgm at the most easterly station. There appears to be a fairly distinct second moist layer aloft at the more coastal stations separated from the lower homogeneous layer by a very dry stratum. Actually, it is in the sounding nearest the coast that the driest air is encountered, 3.2 gm per kgm, in the center of this dry layer.

No deviations in the moisture curves, similar to the departures from the environmental state observed in temperature soundings, are detected in the homogeneously moist layer. Deviations do occur in the layers above but here they are not particularly numerous or striking except at the most inland station where the sounding indicates five wet and dry cycles confined in an upper layer 500 ft thick, values changing abruptly between 4 and 8 gm per kgm.

3. Analysis

In order to synthesize these observations, the continuous fields of temperature and moisture were constructed in the vertical plane along the axis of the valley. Before the temperature analysis could be accomplished a decision had to be made whether or not the temperature field should be reconstructed in the same detail that the soundings provided, faithfully indicating each intrusion of warm air in the cooler sub-inversion environment. To analyze the field in this detail one would have to make a judgment as to the general shape of these intrusions. Actually the only evidence as to physical configuration was a single dimension, that of the distance through the volume along the flight path, a line inclined slightly to the horizontal at a 1 in 20 slope. It was decided that within the marine layer, defined as the homogeneously moist layer, only the temperatures of the environmental state would be considered. A more meticulous analysis would have to await more sophisticated probing of the marine layer capable of sensing the shapes of the warm air intrusions. Fig. 3 shows the temperature field constructed according to this convention.

An analogous convention was not a requirement for the analysis of the moisture field, the warm intrusions having a moisture content not detectably different from that of their environment. Fig. 4 shows this field. At the most easterly sounding in the cross-section where marked rapid changes were recorded, the isolines of mixing ratio were analyzed as oscillating in the vertical coordinate to suggest that the stratification of moisture was no longer horizontal there but considerably tortured due to convection that was distorting the top of the marine layer.

Making a comparison of the fields of temperature and moisture one is immediately struck by the fact that the base of the inversion does not coincide with the top

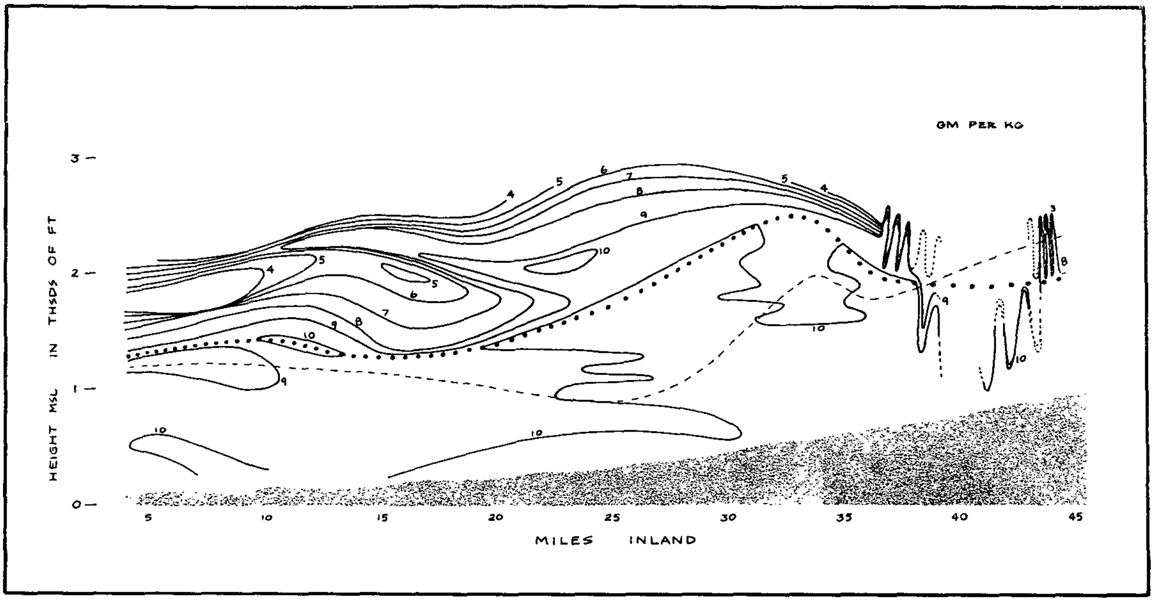

FIG. 4. Humidity field (mixing ratio in gm per kgm) analyzed in the vertical cross-section along the axis of the Santa Clara River Valley. Top of marine layer shown as dotted line, base of inversion as a dashed line.

of the marine layer (homogeneous moist layer). To aid the reader in making this comparison the base of the inversion on both analyses is entered as a dashed line and the top of the marine layer as a dotted line. Near the coast the disparity is relatively small, the marine layer being only 100 to 150 ft deeper, but midway up the valley, 25 mi inland, the marine layer is almost 1000 ft deeper. At the very eastern end of the section the difference between the two decreases rapidly, passes through zero at 38 mi inland and changes sign, the marine layer becoming shallower than the sub-inversion layer over the last 7 mi of the section.

Though the top of the marine layer does not coincide with the base of the inversion, it does coincide closely with the level of maximum stability everywhere except over the most easterly 7 mi of the section.

The moisture field above the marine layer reveals two interesting features, the dry tongue and moist tongue above it. The dry tongue is observed to be driest and deepest at the coast becoming progressively moister and shallower with increasing distance inland. The upper moist tongue, on the other hand, is deepest and moistest inland becoming shallower and drier toward the coast.

So, several distinct types of air are detected. There appears to be a natural separation based on moisture distribution, into two basic layers: one having a nearly homogeneous distribution of moisture, called the marine layer, and a layer above it, drier with a heterogeneous distribution of moisture. Then, the lower of these two layers, the marine layer, may be divided into three sub-types: a superadiabatic layer next to the ground, an inversion layer beneath the top of the marine layer and the many small warm intrusions found imbedded in both.

How does this complex thermal configuration of the marine layer come about? Clearly the moisture cannot be mixed up into the inversion layer without affecting the inversion, because the mixing motions redistribute heat as well as moisture maintaining always an inversion at their upper boundary. To propagate the inversion downward into the marine layer, on the other hand, a process must be invoked that redistributes heat but not moisture. Such a process exists. Since the moisture distribution is uniform within the marine layer, convective motions, *confined* to this layer, will be incapable of redistributing moisture though they very effectively transport heat.

Considering the warm intrusions imbedded in the marine air to be buoyant convective elements of some sort rising through the layer after being heated through contact with the ground, let us investigate what their effect should be on the vertical temperature structure. It is clear that some of them reach the top of the marine layer since they are observed at all levels within the marine layer. Though they impart some of their excess heat to the environmental air through small scale mixing motions (as a matter of fact, enough to raise the environmental temperature by 12C in 35 mi), many are vigorous enough to reach the top with 1 or 2C excess in temperature. However, this excess is not sufficient to allow them to penetrate the strong stable layer that exists at the top of the marine layer. So the convective elements must stop there, still buoyant with respect to the marine layer but having negative buoyancy with respect to the drier, much warmer, air above. Here they remain,

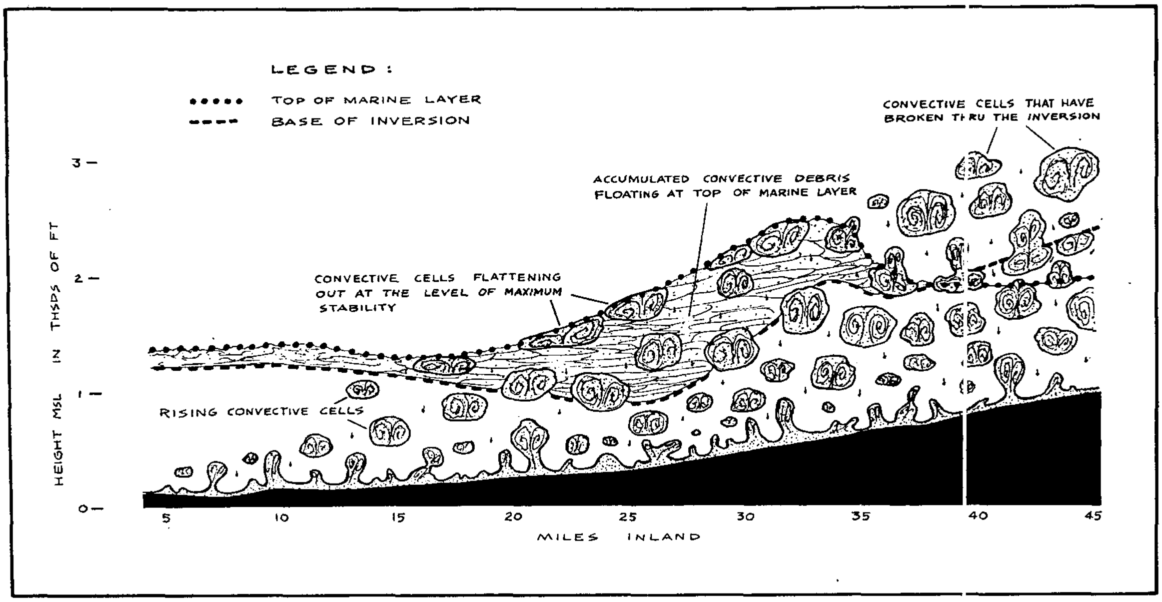

FIG. 5. Schematic diagram of convective motions within the marine layer. Top of marine layer indicated as dotted line, base of inversion as a dashed line.

gradually losing their excess heat to their surroundings by way of small scale mixing motions. In this way, a layer of warm air is formed at the top of the marine layer, the final resting place of all convective cells strong enough to reach this level.

The accumulation of this convective debris continues as the marine air moves inland from the coast creating a deepening upper warm layer through which an inverted lapse rate exists, and so the base of the inversion migrates downward into the interior of the marine layer. Only when the marine layer has been heated sufficiently to practically destroy the stability at its upper boundary are the convective cells able to escape the marine layer and end the accumulation of convective debris.

Fig. 5 is a schematic diagram illustrating this process. The shapes of the convective cells are arbitrarily shown as roughly spherical, although, as pointed out earlier, there is nothing in the data that prescribes this configuration. The rapid decrease in the depth of the marine layer observed in the most easterly (inland) portion of the diagram is associated with the transport of marine air in convective cells up into the dry layer above, here where the stability has finally been reduced to the point where it can no longer prevent loss of marine air vertically. These upward penetrations of marine air are associated with downward penetrations of dry air, this situation giving rise to the lively oscillations from 4 gm per kgm to 8 gm per kgm in the upper part of the most easterly sounding and indicated in the analyzed moisture field by the violent vertical oscillations of the isolines in this region. This is the only area where the base of the inversion is higher than the top of the marine layer.

Considering now the complex configuration of the moisture field above the marine layer, the seat of the driest air anywhere near the observational area is probably out at sea, strange as they may seem, in the strong inversion layer produced by subsidence in the Eastern Pacific subtropical anticylcone. The air aloft over the adjacent desert areas is not as dry by virtue of moisture brought in at low levels by the daytime on-shore winds and mixed to upper levels by vigorous desert convective activity. The upper dry tongue, therefore, probably comes from the Pacific. Such advection is not unlikely during the daytime since, typically, the sea-breeze is considerably deeper than the marine layer, advecting in the lower portion of the very dry inversion layer along with the marine layer. Advection might also explain the existence of the moist layer aloft if one could establish the existence of an upper return circulation in the sea-breeze in this case. Unfortunately, the required wind data are not available.

4. Interpretation

In the case investigated, mixing motions are observed to transform the thermal configuration of the marine layer from near neutral stability (at the coast) to complex and more stable configurations (inland). Typically, mixing motions are observed to have just the opposite effect, transforming complex thermal stratification into near neutral conditions. The essential feature that sets this case apart appears to be the simultaneous existence of two heat transfer processes of opposite effect, gradient diffusion and bulk convection, in which the buoyancy effects of the convection completely dominate the customarily effective gradient diffusion. This domination is possible in the marine layer apparently as long as its lower boundary is a good heat source and its upper boundary is a layer nearly impervious to convection.

The effectiveness of bulk convection even in the case of much weaker convection over the ocean may be indicated by the weak inversion based 150 ft below the top of the marine layer at the most coastal sounding. Unfortunately, the actual existence of this inversion layer at sea was not established by observations. Furthermore, it is possible that some convective debris of continental origin could already have accumulated here, 4 mi inland of the coast.

What implications does this more detailed analysis of the nature of convection within the marine layer have for the accumulation of air pollution? To answer one must first recognize that this particular marine layer, observed from 1300 to 1330 PST, 28 July 1961, is at some variance with the mean or even the typical situation. The typical sounding as given by Neiburger, Johnson and Chien (1961) has a much less sharp inversion, the temperature increasing by 7.5C in 3250 ft (0.23C per 100 ft), than in this case in which the temperature rises 8.8C in only 500 ft (1.76C per 100 ft). A review of the Santa Monica radiosonde observations indicates, however, that inversions of this sharpness are not unusual. A rough estimate of their frequency of occurrence might be 10 per cent of the July cases.

This class of marine layers is of particular significance for air contamination studies since it is just this sort of marine layer that has the highest pollution potential. If one agrees that pollution, like heat, has its sources at the ground one might reason that the temperature and pollution distributions should be related. The buoyant masses of warmed air rising through the marine layer should be richer in pollution than the cooler environment. The warm convective debris at the top of the marine layer, and incidentally above the base of the temperature inversion, should have higher pollution concentrations than the environmental air below it.

This means that the time-honored expedient of equating the base of the inversion to the top of the polluted air does not apply in this important case. The best alternative short of actually measuring the vertical distribution of pollution is to designate as the top of the pollution the base of the layer of maximum stability, the layer having the maximum inverted lapse rate. This is the location of the transition zone between the moist marine air and the dry air mass above, a thin layer only 100 ft thick at the coast in the case studied here.

To date very little data have been obtained concerning the vertical distribution of air contaminants against which to check these inferences. However, the very sparse observations that have been made of the vertical distribution of pollution over Los Angeles tend to confirm them. Blimp soundings made by the Air Pollution Foundation[3] indicate that the highest concentrations of the oxides of nitrogen are found near the base of the inversion, the effect being most pronounced for those cases having the strongest inversions. Visual observations made during the 1957 investigation of the shape of the top of the polluted layer[4] indicate that on the average the top of the polluted layer is 500 ft above the base of the inversion.

The above mentioned 1957 investigation (Edinger, 1959) also pointed out the important role that mixing between the marine layer and the upper dry layer at their interface plays in diluting and deepening the marine layer (marine layer then defined as the sub-inversion layer). In the case studied here, the unusually strong stability at the interface minimizes that mixing between the two layers and consequently minimizes also the "deepening" effect. The important dilution of the marine air thus is delayed until it has been heated by daytime travel over 35 mi of terrain, at which time the stability of the interface has at last been reduced to the point where buoyant masses of air are able to penetrate up into the warm dry upper layer. Any mixing of the layers that precedes this rather sudden rupture of the interface is due to much smaller scale turbulent motions probably contained in the layer of convective debris just below the interface. Their influence is detected possibly as the progressive weakening of the upper dry tongue with increasing distance inland.

Much more must be done before we really understand the lively modification of the marine layer as it invades the continent. To this end the sort of investigation discussed here might be improved in several respects: 1) observations of the wind in the vertical section should be included; 2) the vertical section should be extended out to sea to describe accurately the initial conditions prior to modification; and 3) the attempt should be made to obtain moisture measurements with a time response (0.02 sec) comparable to that of the temperature probe so that micro-scale investigations of the mixing motions at the interface could be made.

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REFERENCES

Edinger, J. G., 1959: Changes in the depth of the marine layer over the Los Angeles Basin. *J. Meteor.*, **16**, 219–226.

Neiburger, M., D. S. Johnson and C. Chien, 1961: Studies of the structure of the atmosphere over the Eastern Pacific Ocean in summer, I. The inversion over the Eastern North Pacific Ocean. *University of California Publications in Meteorology*, Vol. 1, No. 1, pp. 1–58.

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[3] Renzetti, N. A., 1954: An aerometric survey of the Los Angeles Basin, Report No. 7, Air Pollution Foundation, 333 pp.

[4] Edinger, J. G., 1958: Research problems on the meteorology of Los Angeles air pollution. Final Report for U. S. Department of Commerce, Weather Bureau Contract No. CWB-9309, Department of Meteorology, U.C.L.A., 46 pp.