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the sharp smog bank and California fog development

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Abstract

Meteorological conditions associated with the observance of a sharp smog bank near Riverside, Calif., are compared with those previously shown to be related to the development of winter fogs in California. The conditions are similar. Thus, it is proposed that three simple indices found useful in the prediction of west coast fog be used also to predict situations favorable to the shallow, sharp-banked smogs which have been observed. The indices measure the influence of the sea surface temperature field upon air warmed in downslope flow associated with easterly winds in the area.

1. Introduction

In WEATHERWISE, Stephens (1965) discussed the appearance of a smog bank with a sharp vertical boundary near Riverside, Calif. He described the character of the boundary and discussed possible reasons for it. The description brought to mind a study of winter fogs near San Diego, Calif., in which the author, Leipper (1948), found fog banks also with sharp boundaries. These occurred in meteorological situations which may be similar to those associated with sharp smog banks such as Stephens observed. Knowledge of these situations may be useful in predicting the arrival of such banks. The meteorological sequences which are involved are highly dependent upon sea surface temperature.

Among the features mentioned by Stephens were the facts that the boundary of the smog bank was so sharp that it could be contained within the distance of a single city block, that it seemed to move mostly after mid-day, that there was considerable mixing under the inversion which overlies the smog, that the air ventilation was more effective on the clean side of the bank and that the bank seemed to break up at a certain point in space or after a certain traverse across land.

Stephens refers to the work of Edinger (1963), in which a single atmospheric section associated with fog and smog was analyzed. Although the observations were made in July (July 28, 1961), Edinger states that they were not typical of that season but represent a situation which probably occurs only some 10% of the time in summer. In particular, the gradient above the base of the inversion was unusually strong, being as great as 8.8C in 500 ft, comparable to certain winter conditions. He states that this situation, with the very strong inversion, is the condition having the highest pollution potential. In the case studied, the marine layer containing the smoggy air was approximately 1000 ft thick which he stated to be somewhat typical. Edinger mentioned that the lapse rate near the ground was superadiabatic and that there was very dry air above this, probably coming from the Pacific and subsiding to form the warm and dry overlying layers. He also mentioned that the sea breeze in general was deeper than the marine layer so that it carried with it both the marine layer and the overlying dry air when it approached shore. His study was concerned primarily with the changes which occur in these two layers after they cross the coast and move inland. He had no observations over the sea. He concluded that it took about 35 miles of traverse over land before the inversion was broken by heating from below, and he stated that the elimination of the inversion, that is, the reduction of the overall stability, was primarily due to such heating.

In a recent article by Schroeder *et al.* (1967), the literature on the main aspects of the marine air inversion on the Pacific Coast are summarized. They state that the steady transport of Pacific marine air inland is interrupted when the Pacific anticyclone moves onshore and that, when it again becomes centered offshore the reinvading marine air behaves much like a meso cold front. Under a discussion of needed research they mention that the principal problems associated with the sea breeze are related to its leading edge and the interaction with the synoptic-scale features and the steady transport of marine air inland. I believe the following description will cast some light on this interaction.

2. Similarity of fog and smog situations

Although the fog development sequence described in my paper of 1948 applied to winter-time situations in the three years studied, it is believed that the characteristics of certain stages of these fog situations in the winter were quite similar to those found by Edinger in the summer of 1961 and to those of the situation in which Stephens observed the sharp smog bank. The distinguishing characteristic was the presence of very warm dry air over the inversion and a very cold marine layer underlying it. The air above the inversion in such situations is often of the order of 10C warmer than the underlying sea—much warmer than in the normal stratus periods. Also, the marine layer is colder than usual. This combination results in the strongly stable situation described by both Edinger and Stephens as having high smog potential when it moves inland. In the San Diego area such situations were associated with fogs having sharp boundaries.

It would appear from the fog studies that an initial condition required for the development of a sharp fog or smog bank would be the presence over the southern California coast of air which is extremely warm and dry from the near-surface and upward. Although warming aloft might be due to subsidence out over the Pacific, our data indicated that the most extreme heating occurs at the lower levels as the result of downslope motion. This happens when the Pacific anticyclone pushes inland north of Los Angeles and the winds called Santa Anas blow toward San Diego and Los Angeles from the east, warming adiabatically in the 4000-ft descent from the mountains. In such situations there should be extremely good visibility and no fog or smog inland along the coast. For comparison, the synoptic situation which existed on the day before one sharp smog bank was observed by Stephens is shown in Fig. 1. It shows the high extending inland. This is quite similar to the synoptic pattern which precedes sharp fog banks at San Diego, Leipper (1948), and fog did occur there after this.

3. Fog development at San Diego

We shall consider now the development of a fog situation in southern California. Later, we will relate features of this development to the Los Angeles smog bank situation. The fog situation begins to develop when the dry air, adiabatically warmed, becomes stationary over the sea. It soon becomes nearly saturated with moisture in a thin layer at the surface. The great overall stability holds the moisture near the surface. When the east winds die down and the normal north-westerly regime begins, fog is created in the thin surface layer at sea as the warm, nearly saturated air moves over the cold tongue of the surface water which is known to exist offshore. Thus, fog is created by cooling from below. However, once the white cloud is formed, so much incoming radiation is reflected from the top and so much heat is radiated by the cloud itself that observations show the fog layer cooling to a temperature lower than that of any ocean surface in the vicinity.

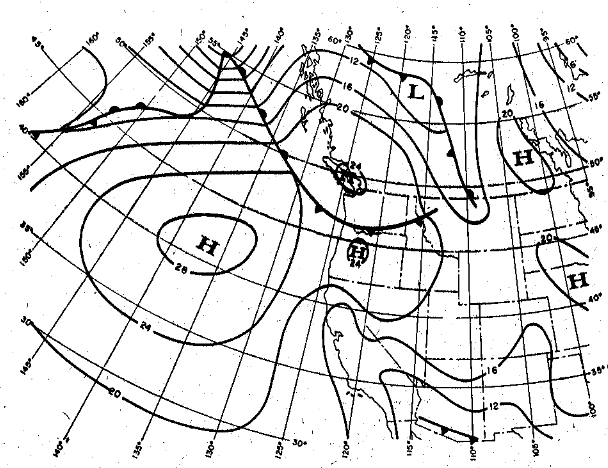

Fig. 1. Weather map (0000Z, 1 October 1961) for the west coast area one day before a sharp smog bank was observed near Riverside, Calif.

Once the fog is formed at sea and the fog layer becomes cooler than the ocean surface due to radiation, there is heating from below and cooling continues from the top of the fog layer. This creates a super-adiabatic layer such as that observed by Edinger. The mixing which occurs within this layer causes the fog layer to increase gradually in depth from day to day. When the normal sea breeze regime returns, the strongest onshore winds occur at the time of day when the sea breeze blows. Late afternoon is thus the most probable time when any fog bank existing offshore would be blown towards shore. Fig. 2 is a photograph of a fog bank approaching the coast in late afternoon as observed across the pier of the Scripps Institution of Oceanography looking toward La Jolla. The sharpness of this bank is apparent. It is this feature which first led to the belief that a similar development might be related to the sharp smog bank described by Stephens.

On the first day that the thin fog bank moves toward the coast, it is quite likely to break up at the coast. The heat of the land is sufficient to dissipate a thin fog and the associated shallow inversion before it can travel far. Fig. 3 shows the shallowness of one of these afternoon fogs. The deck level of Scripps' pier, which appears in the picture, is 18 ft above the sea surface. The true fog is mostly confined to a layer below this level.

Fig. 4 shows schematically a development of such a fog situation in southern California. In Fig. 4-1 the winds blowing off the land carry warm air out to sea over cool and warm water areas. Influenced by the underlying sea, the very lowest air layers become nearly saturated at air temperatures near those of the water. In Fig. 4-2 the east winds have stopped, the sea breezes have begun and some of the warmer moist air is cooled to fog formation when it moves back over the tongue of cool water. In Fig. 4-3, in the later afternoon, the thin fog bank is carried towards shore by the returning sea breeze but is dissipated upward by the heat of the land when it reaches the coast. The inversion is broken and the moist layer is dispersed. In this situation moisture does not move inland. When the sea breeze stops that day, the fog bank retreats toward the sea, as in Fig. 4-4.

As time goes on, the unstable fog layer (with a strong inversion above it) increases in thickness due to convection within it and is again carried towards shore with the afternoon sea breeze. Eventually the fog reaches a thickness such that it cannot be dissipated at the coast but may move inland. Fig. 4-5, with the inversion unbroken, shows such a situation. At this stage, there may be enough heating from below to evaporate the fog particles but not enough to break the inversion. It is just prior to this stage of the development which is proposed to be related to the appearance of sharp smog banks.

With continued convection throughout the fog layer as days go by, the layer is thickened further and it eventually reaches a thickness beyond which there is insufficient cooling to create a full layer of fog. This thickness is apparently about 1300 ft at San Diego. At greater

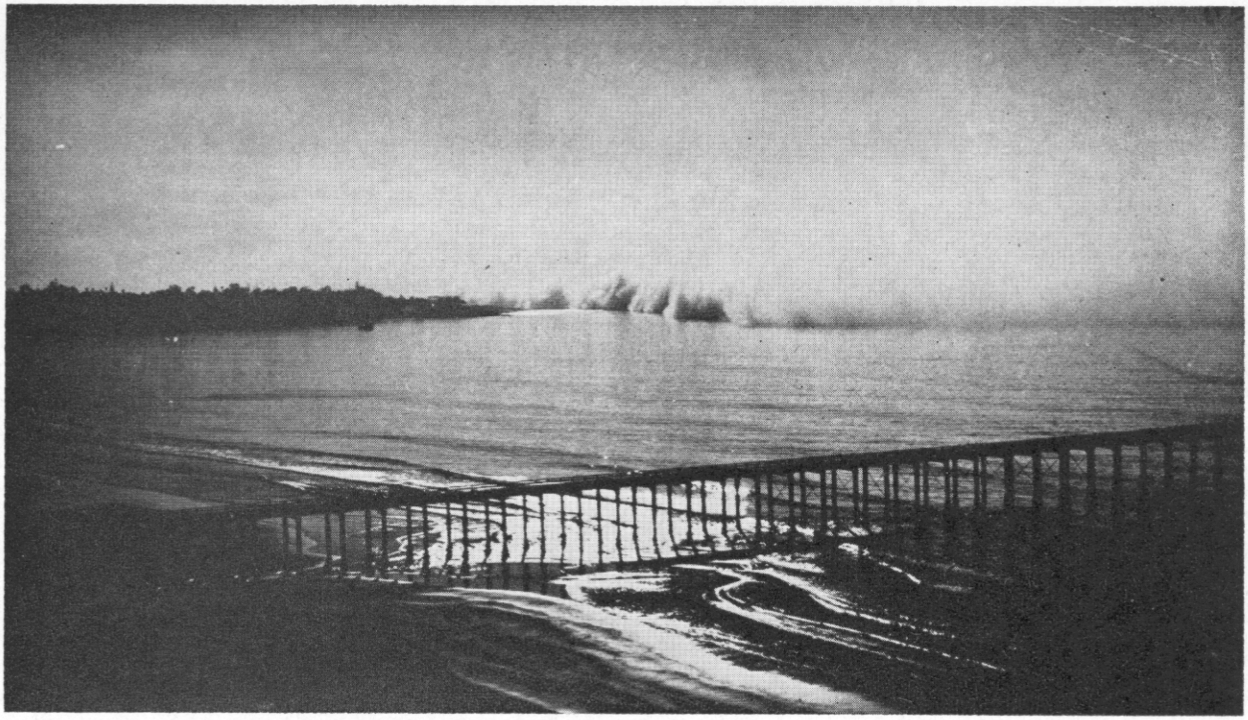

FIG. 2. Photograph of a sharp fog bank approaching La Jolla, Calif.

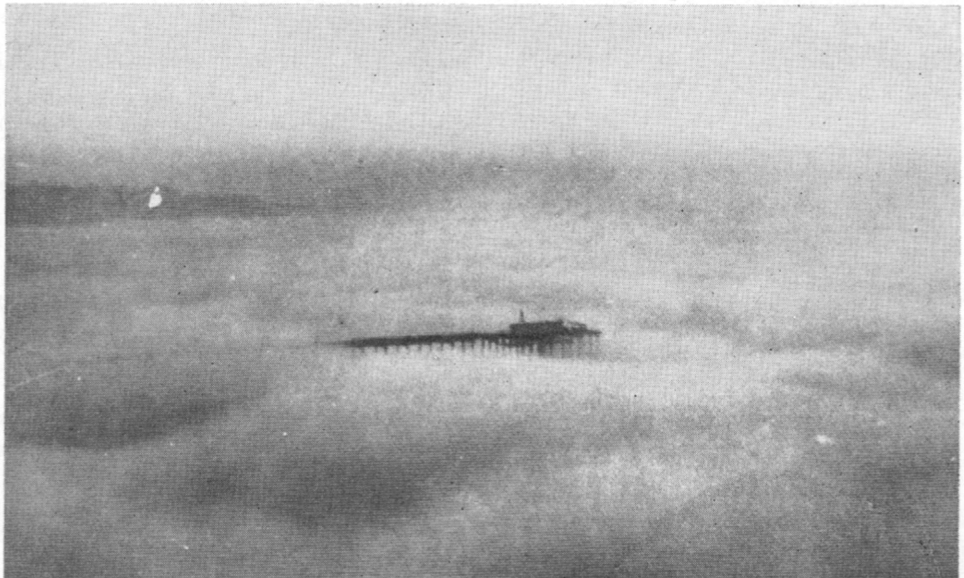

FIG. 3. Photograph of the Scripps Pier showing above a thin fog layer.

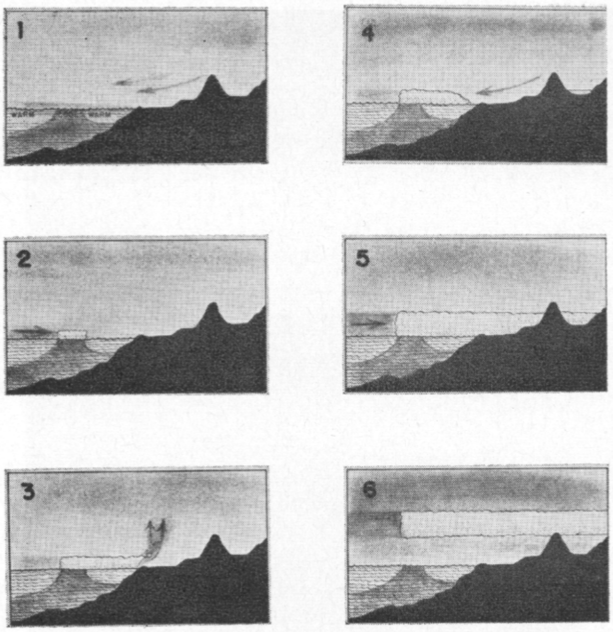

FIG. 4. Six steps illustrating schematically the development of fog along the southern California coast.

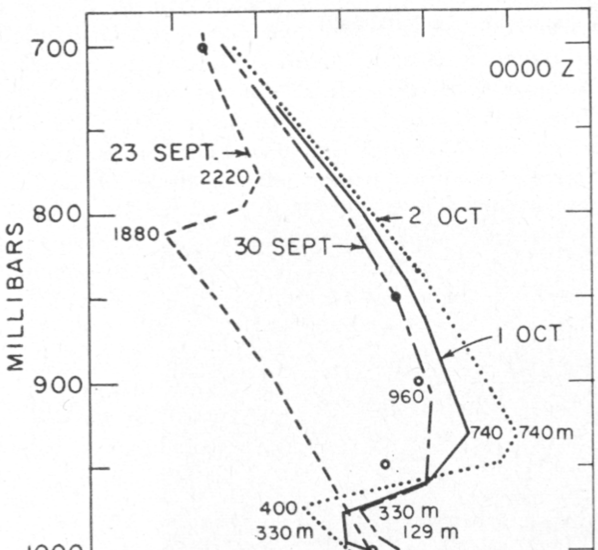

FIG. 6. Comparison of atmospheric temperature structures on four selected days, Santa Monica, Calif. Open circles are 7-yr averages 1958–64. T_s is the sea surface temperature.

thicknesses there is stratus overhead, but a layer with no fog near the ground as shown schematically in Fig. 4-6. Of course, the pollutants may remain in lowest levels of the marine layer even though the fog has not formed there.

This fog development sequence seems to take place frequently in winter. With the approach of summer,

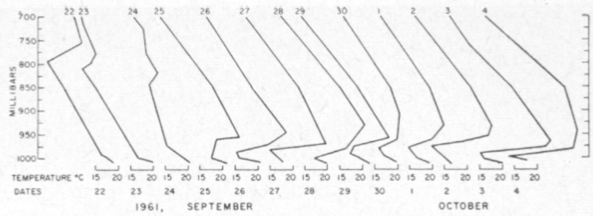

FIG. 5. Daily sequence of atmospheric temperature soundings at Santa Monica, Calif. (0000Z). September–October, 1961.

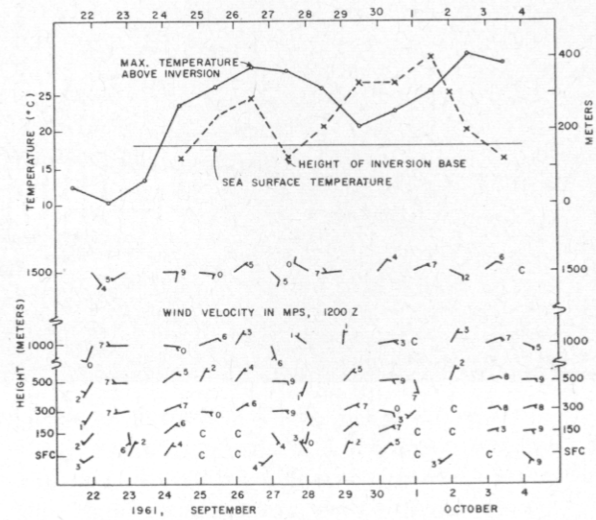

FIG. 7. Early morning winds and features of offshore atmospheric temperature structure indicated by late afternoon soundings. (Santa Monica, Calif.)

however, a fog situation may develop and move through various stages to the stage illustrated in Fig. 4-6. Then, this stage may persist for several weeks or more at a time, giving the steady stratus overcast which is common along the west coast. Sharp smog banks would not be expected in this stage.

It would appear then that the situation most favorable to the sharp smog banks such as that described by Stephens would occur between these stages of development illustrated by Figs. 4-3 and 4-5. The marine layer would have to be thick enough to maintain itself while it, together with its overlying inversion, was carried inland by the afternoon sea breeze but it would have to be thin enough to concentrate the dense and polluted air within sharp boundaries.

4. The smog bank and associated meteorological features

The meteorological situation associated with the particular sharp smog bank described by Stephens is presented in Figs. 5, 6 and 7. The upper air soundings for 22 and 23 September, Fig. 5, show air temperatures dropping off rapidly with height and an inversion base near 800 mb. Afternoon soundings were used because they are most representative of conditions over the sea, being obtained near the end of the daily sea breeze flow from offshore. On the 25th considerable warming is indicated below 800 mb. This warming continues until the 28th when temperatures at 740-m height are more than 8C higher than at the surface. This strong overall stability remains through 4 October. The low inversion which forms on September 25th is forced lower until the 28th, the day of greatest warming aloft. The thin mixed layer then begins to increase gradually in height and continues growing from the 28th to 2 October. This is the period which corresponds to the fog development sequence of Fig. 4 between 4-4 and 4-5. The lowest surface temperature occurred on the 27th which would be indicative of fog formation offshore and its associated cooling after formation. The sharp smog bank was observed by Stephens late on 2 October. The soundings indicate that a mixed layer thickness of 400 m was required to allow the inversion to move inland that far without being broken by heating from below.

The soundings for 3 and 4 October show further heating at the height of the inversion top and an associated lowering of the inversion base. Thus, the development sequence appeared to be starting once more.

The time changes in the upper air temperatures are shown in another way in Fig. 6. Here the data are superimposed on the same coordinates for four selected days. It is interesting to note that, while the air became successively warmer above the inversion on 30 September, 1 and 2 October, the air below the inversion cooled through this same period. Both tendencies serve to strengthen the inversion.

In Fig. 7 are shown the winds for the period of the Stephens' smog illustrated in Fig. 5. Also shown are the heights of the inversion bases and the temperatures of the sea and of the warmest air. The early morning winds were used because there is no sea breeze at this time and the easterly down-slope flows are best indicated. The soundings of Fig. 5, on the other hand, were for the evening hours to best represent offshore conditions. These hours were also used for air temperatures and inversion heights in Fig. 7.

On 24 September easterly flow can be seen at all levels, Fig. 7. These are the winds which led to the warming indicated on 25 September. Similar warming also occurred with the east winds beginning 30 September.

5. Indices for fog and smog

Progress of the development of California fogs (and probably also of smogs) can be followed by reference to several simple indices, Leipper (1948). The indices are made up of data obtained from the morning radiosondes used together with the coastal water temperature and the surface dew point in the marine layer. This dew point may be obtained on the coast if it is measured during the period when the sea breeze is blowing. If the fog indices are indeed applicable to smog, then for the thickest smog to occur, the base of the inversion would be below some 1300 ft. The difference between the temperature of the warmest dry air above the inversion and the coastal sea surface temperature, called the temperature index, would have to be positive, and finally, the moisture index, which is the difference between the afternoon dew point and the coastal water temperature, would have to be such that the dew point was within 5C of the sea surface temperature or higher. The sharp smog bank should be expected on a day when the air is much warmer than the sea and after a thin coastal fog bank had approached shore in the late afternoon on a preceding day but was dissipated at the shore line. It should occur at the time of day when there is the strongest on-shore circulation, namely, the late afternoon when the sea breeze is strongest. The advance warning of such a smog bank (one or more days prior to it) should be the presence of dry air much warmer than the sea in the lowest layers over the Los Angeles area with winds blowing from the east. On a day shortly after the easterly flow ceased, the sharp smog bank might be expected.

The key feature of the dry warm air is that it must be closer to the surface and warmer relative to the sea than is usual in the California stratus situation. As stated, it is believed that this occurs with strong downslope easterly winds which drive the marine layer out to sea and require that a new one be formed under the warm dry air. The new inversion must start necessarily as a thin marine layer but when it approaches the coast it must be thick enough to survive some transport across the warm land. Thus, the smog bank would be expected between the day when fog first arrives at the coast and a day that a thicker marine layer moves inland and cannot be broken by heating from below.

The point at which the sharp smog bank will be dissipated can be estimated from the surface temperature. When the temperature at the ground reaches a value high enough that vertical convection will force itself entirely through the inversion, the smog will dissipate. The surface temperature required is one such that the temperature decreased adiabatically from this ground value would exceed the temperature at the top of the inversion, thus allowing the heated air and their surface pollutants to rise vertically beyond this point.

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