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FOG DEVELOPMENT AT SAN DIEGO, CALIFORNIA

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INTRODUCTION

If true fog alone be considered—that is, suspended water particles which reduce horizontal visibility at the earth's surface to 1,000 meters (or ½ mile) or less—then fog at San Diego occurs nearly four times as frequently during the winter period, from October through April, as during the remaining months of the year (11, p. 34). Yet, of the many studies of California fog which have been made, none appears to be concerned directly with coastal fog in the winter period.

The fog situations during several winter periods were examined at Scripps Institution. Particular attention was paid to air mass characteristics at various altitudes relative to sea surface temperature. It became apparent that nearly all of the fog situations developed in a systematic manner over a period of days, and that the developments resulted from the effect of local influences upon a given set of initial conditions. The purpose of the following discussion is to describe this development, to present a model, and to give statistical evidence showing the pertinence of the concepts involved.

A MODEL DEVELOPMENT

A model has been devised to illustrate the manner in which fog situations develop in the San Diego area. The model is described in four different stages beginning with the initial conditions which are required if the development is to take place.

The dominant feature of the initial conditions is the presence over the sea of air which has a temperature higher than the sea surface temperature and which is relatively dry aloft. The high temperature of the air guarantees that an inversion will be formed at the surface to restrict the vertical movement of moisture and thus cause a thin lower layer of air to approach saturation. The dry air aloft permits

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rapid cooling of the surface layer and intensification of fog by radiation.

The initial conditions for fog formation may be brought about when the Pacific anticyclone pushes inland over northern California and causes a general easterly flow, so that the air arriving at San Diego has moved down the slope of 4,000-foot mountains. Air following such a path is necessarily warm and dry at San Diego. Out of 42 winter fogs

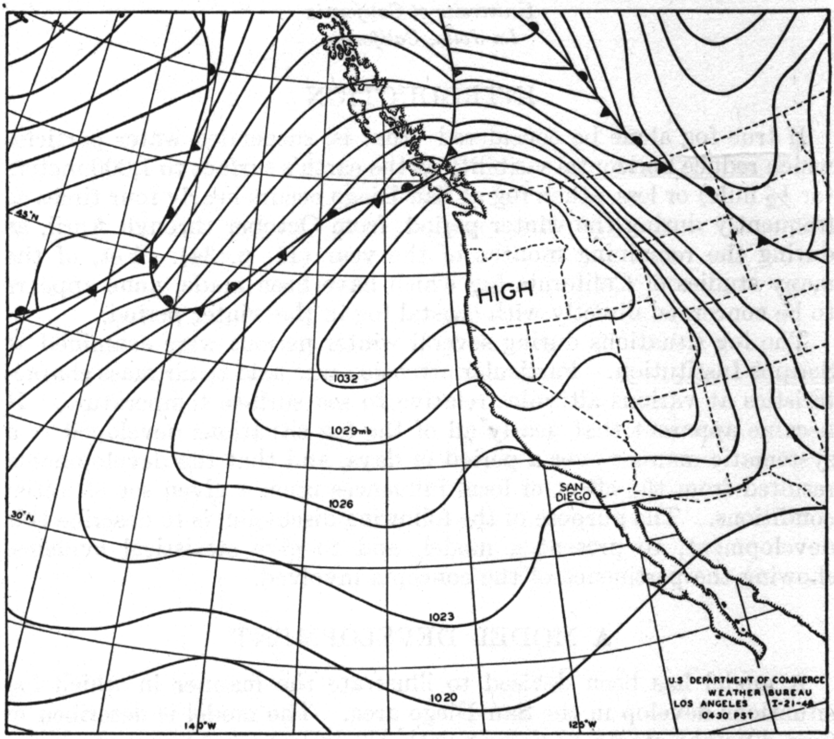

Figure 1. Weather map showing the type of synoptic situation which usually precedes winter fog at San Diego.

occurring in 1943 to 1945, 39 were preceded or accompanied by easterly winds aloft. The typical synoptic weather situation is shown in Fig. 1.

In the second stage of the fog development, the easterly air flow weakens as the high-pressure cell is divided into two parts, one on each side of the coastal mountains. Flow of warm dry subsiding air toward the sea decreases, and the locations of the high-pressure cells permit the air offshore from San Diego to remain in a relatively stagnant condition. The moisture content of the lower layers increases due to evaporation from the sea, and the heat content of these layers decreases due to conduction of heat downward (9). A surface inversion is formed, and the lowest air layers become nearly saturated at a temperature close to that of the underlying sea surface.

In the third stage, the normal northwesterly airflow and seabreeze

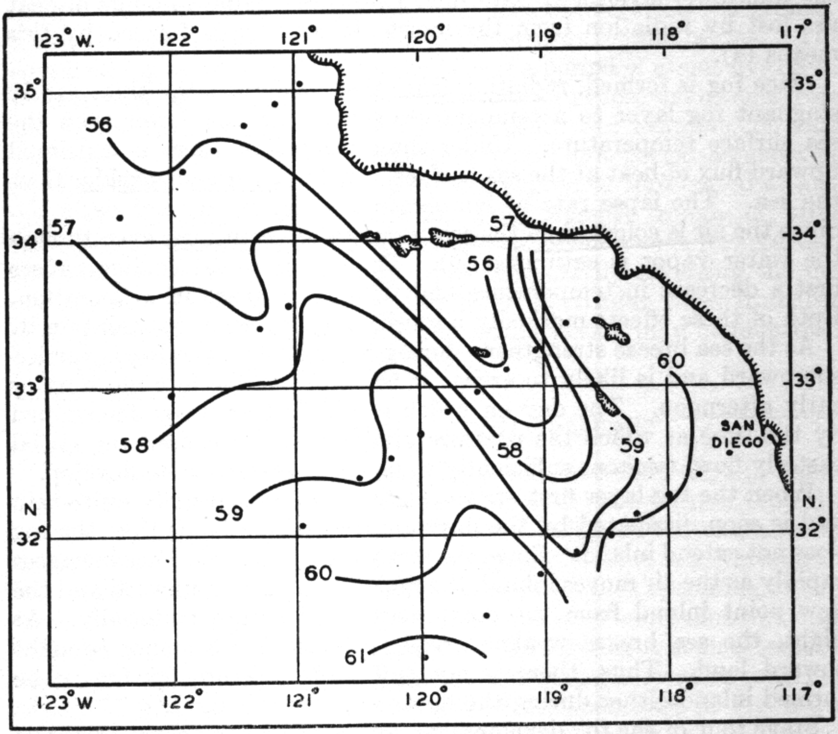

Figure 2. Sea surface isotherms in degrees Fahrenheit based upon a cruise of the E. W. Scripps, February 15 to 25, 1938. Observations were made where dots appear.

regime returns and fog forms. The details of formation cannot be described as yet, but observations indicate that formation occurs over regions of low sea surface temperature. Fig. 2 shows a tongue of relatively cold water which is consistently found in the same area. Fog formation is often observed here (1). Also, fog is often found along the coastline where observations during eight winter cruises by the buoy boat of the Scripps Institution have shown a band of water which is at times several degrees colder than the sea surface ten to fifteen miles offshore. In the situation shown in Fig. 2, the average sea surface temperature at Scripps pier near San Diego was 14.3C (57.8 F) and that offshore was 15.6C (60.0 F).

Changes in humidity and heat content which occur during flow of nearly saturated air across sea surface isotherms may cause the formation of fog. If these changes do not form fog, they appear to bring the thin lower layer of air into such a state that large amounts of heat are lost by radiation from the moist air, and fog is formed by this means (4).

Once fog is formed, radiation from the cloud cools the thin, nearly stagnant fog layer to a temperature several degrees lower than the sea surface temperature. Under these conditions there is continual upward flux of heat at the sea surface, but the air remains colder than the sea. The lapse rate of temperature is nearly dry adiabatic (7). Since the air is colder than the sea, evaporation continues even though the water vapor is saturated (9). Thus, radiational cooling causes first a decrease in temperature and then an increase in evaporation. Both of these effects markedly intensify fog and serve to maintain it.

As the sea breeze strengthens during the daytime, the fog is carried shoreward and is likely to arrive at the coast in the late morning or early afternoon. The day on which it will first arrive is determined by the time at which the pressure gradient, which caused the initial easterly flow, weakens sufficiently to permit a sea breeze to develop.

When the fog layer first arrives at the coast it is usually quite thin and is soon dissipated by the daytime heat of the land; thus the fog does not extend inland. Since the temperature at the surface increases rapidly as the air moves inland, the moisture is carried upward and the dew point inland from the coast does not increase materially. At night, the sea breeze weakens, and moisture is no longer brought toward land. Thus, there is not sufficient moisture for fog to be formed inland either during the day or during the night.

Stage four of the fog development occurs when the nearly adiabatic layer deepens to approximately 400 feet or more. The increasing westerly winds and sea breezes and the convection resulting from radiational cooling at the cloud top contribute to this deepening. Evaporation from the sea continues and the presence of the strong inversion still restricts the vertical movement of moisture, thus maintaining a high dew point in the marine layer (the nearly adiabatic moist layer). Fog is present over the sea both day and night. During the day the sea breeze carries the fog toward shore. The daytime radiation and conduction of heat from the land mass dissipate the fog as it approaches shore, but the nearly adiabatic layer, being deeper than in the previous stage, is not destroyed as rapidly. It retains its high moisture content in the form of vapor and moves inland. At night, the air over the land cools and fog is formed in the moist layer. As cooling continues, this fog may spread and join with the fog offshore.

As the marine layer below the inversion continues to deepen, the point is reached where the mixing and cooling processes do not result in condensation throughout the entire layer. The upper portion is filled with water particles first and fog does not form on the ground. Thus, the fog sequence is ended and the stratus regime begins. The complete fog sequence usually extends over a period of about five days.

In the actual development of a particular situation, deviations from the above transformation may be observed. For example, on rare occasions the entire sequence may take place in a period as short as one day; a normal sequence may be interrupted or terminated at any stage by the passage of a front or an upper pressure trough; or, after the easterly winds have weakened and fog development has started, the winds may strengthen again, thus temporarily reversing the development. In spite of the deviations of particular cases from the model, nearly every case of fog in the winter period may be identified with the development described above.

AN OBSERVED DEVELOPMENT

In Fig. 3 are shown the soundings for seven successive days in January 1948. Sounding A shows the presence of dry air warmer than the sea to heights as great as 2,000 feet, which indicates the existence of stage one described in the model development. This is a warning of fog to come. The synoptic situation associated with the influx of this air is similar to that of Fig. 1, the time of the map being nine and one-half hours after the time of the sounding. Sounding A is an afternoon sounding which was used because the morning observation was not available on this day. The remainder of the soundings in Fig. 3 are early morning observations made at 24-hour intervals.

Sounding B shows that a surface inversion has formed and that the surface air temperature is lower than the sea surface temperature. This indicates that stage two occurred between soundings and that stage three exists. Fog arrived at the coastline at 1710 PST (Standard Time at 120° W) on the afternoon following the sounding, January 21. The air temperature in the fog as it arrived at the end of the Scripps pier, 16 miles north of San Diego, was 2.4 C lower than the sea surface temperature there. It was also lower than any known sea surface temperature in the near-by offshore area. Fog was observed at Lindbergh Field, San Diego, for 48 minutes beginning at 1820 PST. It retreated when the sea breeze, which had been WNW at 3 to 7 miles per hour, weakened and was replaced by S and E winds of 2 mph. The breakdown of the Pacific anticyclone into two cells occurred prior to 2235 PST, as shown by the synoptic weather map at that time.

Sounding C indicates the presence of a mixed layer below the inversion and is associated with fog at Lindbergh Field in the early morning and for a short period in the early evening. Careful measurements of sea surface and air temperatures were made at approximately half-

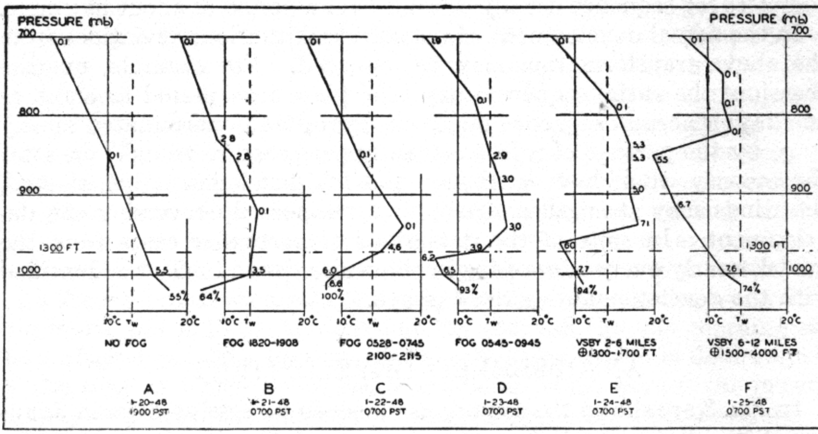

Figure 3. Soundings during the development of a fog situation, taken from radiosonde observations at North Island, San Diego, California. The number at the base of each sounding is the relative humidity. Other numbers along the soundings are specific humidities in grams per kilogram. Vertical lines are isotherms labeled at the base, and the dashed line, labeled T_w, is the sea surface temperature.

hour intervals in the fog at distances 0.2 to 5.0 miles from shore on this day. Air temperature was observed at heights of a few inches, five feet, thirty feet, and seventy feet above the sea surface. Between 0950 and 1317 PST, when the observations were made, every air temperature was lower than the sea surface temperature. The average difference was 2.3 C.

In sounding D the mixed layer has deepened but is still only 1,000 feet thick. On this day, which is typical of stage four in the model development, fog at Lindbergh Field formed at 0545 PST and lasted four hours. On the following day, January 24, the mixed layer became too deep for fog to form; visibilities were from two to six miles, and an overcast persisted all day with ceiling height from 1,300 to 1,700 feet. Thus the sequence ended. On the day represented by sounding F the highest temperature above the inversion had dropped below the sea surface temperature and the inversion base was too high to permit fog formation. Visibilities continued to improve and were from six to twelve miles. The sky remained overcast with ceilings from 1,500 to 4,000 feet.

NONDIURNAL INDICES OF FOG

In order to characterize the stage of the fog situation development where fog may be expected at Lindbergh Field, three nondiurnal indices have been defined. Each element used in determining values of the indices is measured at a given time of day. Thus diurnal variations do not affect the index values. So that a day would usually include both the formation and dissipation time of fog, a 'fog day' was defined as the period from 1630 PST on one calendar day through 1629 on the following calendar day. The indices for a given fog day are:

1. Height of the Inversion Base: The height above which the air temperature increases with height at the most rapid rate on the North Island (San Diego) morning raob (radiosonde observation).
2. Temperature Index: The quantity ($T_a - T_w$) where, if an inversion exists with base below 3,000 feet, T_a is highest air temperature above the inversion base on the morning raob or, if no inversion exists with base below 3,000 feet, T_a is the surface air temperature on the morning raob; T_w is the sea surface temperature at the end of the Scripps pier.[2]
3. Moisture Index: The quantity ($DP_{1630} - T_w$) where DP_{1630} is the surface dew point at Lindbergh Field at 1630 PST and T_w is the sea surface temperature on the preceding fog day.

Values of the three nondiurnal fog indices have been determined for each day of the period 1943 through 1945, when data were available. It was observed that most days on which fog occurred were days when the indices had values lying within certain ranges. Limits were placed on these ranges after a study of the variations. The ranges, determined to be favorable to fog, were: for height of inversion base, 0 to 1,300 feet; for temperature index, any positive value; for moisture index, any positive value or any negative value between 0 and −5 C.

The index ranges selected as favorable to fog in the winter period have been found to be applicable also to fogs which develop in the summer period. However, in summer the synoptic weather features

[2] Regular sea surface temperature observations are not made closer to San Diego than the Scripps pier; however, selected observations have shown that the temperature at the pier is usually representative of the coastal regions closer to San Diego and in San Diego Bay.

which bring dry warm air over the sea and cause the inversion base to lower into the range favorable for fog may be different than in winter. Blake (2) has shown large-scale zonal subsidence to be an important process.

In the period 1943–1945 there were 222 days when all three indices were favorable to fog; on 62 of these days (28%) fog (*i. e.*, visibility ½ mile or less) occurred. There were 825 days which did not favor fog because at least one index was unfavorable; on 23 of these days (2.8%) fog occurred. Thus, the percentage of fog occurrences on days defined by the indices as favorable to fog was ten times as great as the percentage of occurrences on unfavorable days. Furthermore, on the 23 days when fog occurred with unfavorable conditions existing at normal times for the determination of index values, linear interpolation (or allowance for observational error) shows that the indices were probably favorable at the time of fog formation. There was one exception, when a period of fog lasted only 40 minutes; this was associated with rapidly falling pressure and was followed by rain and strong frontal activity.

For practical purposes it may be stated that fog will not form at Lindbergh Field on a given day unless the three nondiurnal indices are favorable. These indices thus provide a necessary but not sufficient condition for fog formation. If the conditions are to become sufficient, other considerations must be employed. One which shows considerable promise is an evaluation of the effect of moisture in the atmosphere above the inversion base. In 1943, for example, there were 96 days favoring fog and 32 days when fog occurred. In that year, one when reliable moisture data were available, it was found that 47% of the 64 days favorable to fog but with no fog occurring were days when the moisture content aloft was high, as indicated by the mixing ratio at 10,000 feet being 3.5 grams per kilogram or greater. If 1943 is a typical year, then fog will form on 48% of the days having the three nondiurnal indices favorable and also having a mixing ratio at 10,000 feet less than 3.5. On the majority of the remainder of such days there will be a low overcast or a fog bank at sea.

The indices have been plotted against time over a three-year period. It appears that they vary in a relatively slow and consistent manner which may be forecast, and that they may be of value in day-by-day fog forecasting for Lindbergh Field. Since fog formation, wherever it may occur, is controlled by some of the same factors and processes which operate at San Diego, it may be possible to apply similar reasoning and indices to other locations.

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SUMMARY

A model illustrating the manner in which fog situations develop in the winter period in the San Diego area is presented. The importance of the role played by sea surface temperature is stressed. An observed example of the development is described. Nondiurnal indices are defined, these serving as criteria to aid in determining whether or not fog will form at Lindbergh Field, San Diego, on a given day in either summer or winter.

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