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Reprinted from Preprint Volume: First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone, May 10-14, 1982; The Hague, Netherlands. Published by the American Meteorological Society, Boston, Mass.

WEST COAST MARINE FOG; A WARM OR A COLD WATER PHENOMENON?

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1. INTRODUCTION

For the past four or more decades and up to the present time, various research papers and widely used textbooks in general meteorology and forecasting state that almost all sea fog is advection fog caused by cooling of warm moist air moving over a colder surface. Although the concept is applied over all ocean areas, many writers give the northwesterly winds flowing over the cold upwelled water off the California coast and the coastal fog so often found there as a specific example.

On the other hand, for more than sixty years, some fogs have been reported at sea which were colder than the sea and thus were being heated rather than cooled from below. In 1947, it was concluded that saturation could not be reached and fog could not be formed by cooling from below alone, since both atmospheric moisture and heat are lost through turbulent processes at comparable rates, Emmons and Montgomery (1947).

2. ACCEPTING COOLING FROM BELOW

Byers (1930) writes about California fogs, "In relating conditions of the ocean it will be assumed that the fog is formed over the ocean by a condensation of water vapor in saturated air passing over a cold water surface of the ocean, a hypothesis accepted by the majority of meteorologists." He makes reference to Palmer (1917), Hurd (1927), Wright (1916), and McEwen (1912).

Over the years and up to the present time, most textbooks and many research articles describe sea fog formation in this same fashion. Some typical references include: Taylor (1917), Willett (1928), Sverdrup (1942), Petterssen (1958), Stevenson (1963), Renard (1976), Kotsch (1977), Noonkester (1979) and Anthes et al. (1981). From this sampling, it is apparent that a significant group of meteorologists interested in fog at sea and in coastal fog in particular have found and do find the concept of fog formation by cooling of warm, moist air from below to be helpful to them.

3. QUESTIONING OR MODIFYING THE CONCEPT OF COOLING FROM BELOW

Some of the references in this section present observations of marine fog having air temperatures lower than those of the underlying sea surface. This is evidence against fog formation by cooling from below. Other references give evidence resulting from various types of analysis that factors in addition to surface cooling are involved in the formation of West coast marine fog. Some of these pieces of evidence seem unrelated and at times even contradictory to each other. They are summarized in this section without comment, the hope being that many of them can later be integrated into a descriptive physical model which will provide an answer to the warm and cold water question.

3.1 General

In 10% of Taylor's (1917) observations of sea fog, specifically those made when there was insufficient wind to carry his kite aloft, the sea temperature was higher than the air temperature. From this evidence he concluded, "...possibly cold air blowing over warmer water may also give rise to fog."

Under the heading of 'Cooling from Below', discussing fogs along the West coast, Petterssen (1940) cautions, "The air that moves in over the colder water will be cooled from below and might well produce fog but, in that case, the air ought to be stable, and not unstable, as it actually is. This cooling effect of the sea cannot be the direct cause of the fog, for it is frequently observed in San Diego that fogs form with the air current from the northwest. The air would then be heated and not cooled from below."

Emmons and Montgomery (1947) supported by Emmons (1947), on the basis of extensive observations of warm air moving over cooler water, firmly conclude that, "...fog can form next to a cold surface only when there is further cooling by radiation directly from the air or when saturation is not required." This marked the beginning of a new era of consideration.

Leipper (1948), describing a proposed physical model of sequential fog and stratus development in the San Diego area stated, "The details of formation cannot be described as yet, but observations indicate that formation occurs over regions of low sea surface temperature. He added that, "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." When this has happened, there can no longer be cooling from below. He made observations at three elevations up to 70 feet in fog between the coast and five miles offshore and found for this shallow fog that all of the air temperatures measured averaged 2.3 C colder than any sea surface in the vicinity, thus verifying the importance of radiative cooling in such fogs. Indices for use in forecasting were described. Leipper (1968) applied the model 100 miles farther north, showed pictures of the shallow fog and described how this, "...

creates a super-adiabatic layer.... The mixing which occurs within this layer causes the fog layer to increase gradually in depth from day to day," and how it eventually became a stratus regime.

For practical forecasting, Rosenthal (1972) gave the opinion that, "It can be argued (and often is) that a warmer sea surface enhances stratus formation by decreasing stability, adding moisture, and stimulating limited convection within the marine layer, or that a cooler sea surface enhances stratus formation by cooling marine layer air below its condensation temperature. Until this conflict of underlying theory is resolved, it is not possible to predict changes in stratus due to changes in the temperature of the ocean surface...."

Roach et al. (1973), in a careful study of radiation fog over land, used infra-red transmission properties to define optically thin (fog formation) and optically thick (fog and stratus maintenance) phases in the life of a fog. Based upon their observations, they stated, "The transition between each phase usually lasted a few minutes" and that, "...mesoscale dimensions (say up to 100 km) imply that the vertical structure of the atmosphere is the main factor in fog development. Likewise Riehl and Augstein (1973), working in a different area conclude that, "... synoptic-scale flow and divergence patterns appear to play a key role in determining low cloud formation over the sea, overriding in importance even the interface processes."

Simon (1977) wrote of, "...stratus that form in air which is cooled by the upwelled water adjacent to the coast." He brought in horizontal velocity divergence and radiative cooling and heating as well.

Pelié et al. (1979) present the results of observations made in fog situations over a period of years from the R/V ACANIA of the Naval Postgraduate School operating along the California coast. They concluded, "...the clear air upwind of the fog-stratus system advects over cold water where it is 'conditioned' for fog formation, i.e. surface air is cooled, stabilized, and moistened." They believed that most fogs which they observed were, "Triggered by patches of warm water...." Their data support the importance of radiation after fog is formed and the instability and growth of the mixed layer in these circumstances. They noted that, for one particular case, "Within the fog, air temperature did not respond to changes in the sea surface temperature."

3.2 Theory, Including Numerical Models

Fleagle (1953), supported by Fleagle et al. (1952) discusses and quantifies the role of radiation in fog formation, which had been pointed out by Emmons and Montgomery to be a critical factor over a cold water surface. He suggests the name 'cold surface fog' to replace 'sea fog' and 'advection fog'. He gives an example where the air is 10 C warmer than the sea (a difference which can occur off the California coast) and shows that the air above approximately 70 cm is cooled by radiation so that fog forms. He points out that, "After fog has formed, the physical processes are altered greatly", mentioning that the fog then acts essentially as a blackbody radiating surface and that latent heat released by condensation introduces a new factor. He also stated that, "It is extremely difficult to make accurate observations which may be used to test..." his fog formation theory, but he had some data.

Several PBL models are directed toward the particular West coast fog problem. Some of these, together with their limitations and some of their implications, are summarized below.

In his model of cloud topped mixed layers under a strong inversion, Lilly (1968) considered a constant divergence rate, a given upper level stability, a radiative cooling rate and other parameters assumed typical of California coastal conditions. As one of his results, he stated, "The sea surface temperature is predicted to be slightly cooler than that of the air near the surface," thus supporting cooling from below. He emphasized the importance of the initial fog formation when he stated that his model, in a sense, "...only pushes the problem back one step and substitutes the question of origin of the cloud layer which must be present at the time subsidence begins." In discussing difficulties, he said, "The interaction of large scale atmospheric properties and thermal convection is a principal unsolved problem in the development of forecast and/or general circulation models." Once the initial fog is created, Lilly conjectures, "...the strong inversions typical of the so-called 'mixed layer' of coastal California and similar regions are necessarily maintained by a low cloud layer..." in a manner which he described.

Barker (1977) describes a two dimensional numerical model which uses existing mesoscale features of the type found along the California coast along with numerical products of the Fleet Numerical Oceanography Center. With the advection of warm moist air over colder water, the model shows, "In agreement with Emmons and Montgomery (1947), heat is removed by turbulent and radiant transport, while moisture is removed only by turbulent transport. This tends to generate higher humidities and eventual saturation. Once fog is formed, heat and moisture losses increase dramatically....Several experiments were conducted to test the persistence of fog as it advected over water 2 C warmer than that upstream. In each case, the result was the same; fog dissipated instantly as soon as the warmer water was reached." This last result differs from results of Oliver, et al. (1978).

Oliver et al. (1978) address a second order closure model to the type of situation in which West coast marine fog is found. They conclude, for an example where turbulence dominates, that, "...cold air with high relative humidity overrunning a warm surface will tend to fog." As another example of their model's application, they used a stable, steady boundary layer running over constant temperature water to be incident on a region of linearly increasing surface temperature. Contrary to the results given by Barker's (1977) model, they show that fog forms and deepens and that, "The early stages of a temperature inversion formation at the top of the fog bank are also in evidence." The model shows that fog may exist over a warm surface. Their work pointed to the pivotal role played by radiation in fog formation. In a special case where there is a solar driven diurnal cycle existing about a mean boundary layer state, they show the type of changes which may be expected in the boundary layer and in the stratus cloud.

3.3 Climatology

Altough climatologies of marine fog generally show, as stated by Köppen, that most fog at sea is co-located with the cold water, the area offshore from Southern California may be an exception. The Naval Weather Service Command (1971) Climatological Study shows offshore visibilities of less than one half mile to occur in all months of the year from San Diego--latitude 32.5 N--to latitude 35 N. Rather than having a maximum over the coldest water, the greatest number of low visibilities occurred in all months of the year in a band along shore extending less than 240 km from the coastline, a band often occupied by a tongue of warm water. At all latitudes, California fog occurs offshore in significant amounts in all months of the year.

4. ANALYSIS

4.1 A General Conclusion

It is not completely obvious from the foregoing whether West coast marine fog is a cold water or a warm water phenomenon. However, the instability of the fog layer, Petterssen (1938) and the observations of fog after formation at air temperatures lower than any nearby sea surface temperature, Taylor (1917), Leipper (1948) and Pelié et al. (1979) can be explained by net radiational cooling of the shallow fog layer overlain by a dry air column, Baker (1977), Fleagle (1953), Oliveret al. (1978). This removes the strongest arguments for the fog being a warm water phenomenon. There remain the observations of Pelié et al. (1979) that warm water seems to trigger fog formation but, for this to happen, they state that the air must be 'conditioned' and indicate that the conditioning occurs over cold water. Thus, the indications are that West coast marine fog formation is a cold water phenomenon. After formation, radiational cooling becomes a much more significant factor during a period of fog growth and the influence of the sea surface temperatures becomes relatively less.

To fully answer the question of west coast fog and warm or cold water, a decision must be made as to how the fog forms. This does not appear to be clear from the literature. It is believed that a descriptive physical framework can be presented which will be internally consistent and capable of accommodating most of the observations, concepts and conclusions referenced above. The framework will need to provide for the changing roles of subsidence, advection, turbulence and radiation as they interact over the nearshore waters of the West coast.

4.2 A Physical Framework, Basic Characteristics

A suitable framework should have several important characteristics. First, it should take recognition of the fact that coastal fog is part of a sequence of events of synoptic scale occurring over a period of days or even weeks, Taylor (1917), Leipper (1948), Pelié et al. (1979). Diurnal changes which are superimposed upon the longer term trends of the day-to-day sequence are important but are somewhat better undersood, e.g. Petterssen (1938), Oliver et al. (1978), and are not featured here. Also, at a given location they are to a large extent determined by the broad synoptic scale situation.

Another important characteristic of a good framework for West coast marine fog development is that it should provide for four distinctive phases within the fog-stratus sequence. Lack of such distinction seems to be at the root of much of the confusion about this type of fog. The four markedly different regimes, based upon considerations such as those of Fleagle (1953), Lilly (1968) Barker (1977), Oliver et al. (1979), are: 1) Initial Conditions, 2) Initial Fog Formation, 3) The Period of Fog Growth, and 4) The Stratus Period.

The framework to be acceptable must apply for a narrow band some 240 km in width of unique coastal character but, at the same time, it must recognize that the governing synoptic influences of subsidence and advection may extend hundreds of km along the coastline in any given fog sequence, Blake (1928), Byers (1930), Leipper (1980).

Finally, the framework must add something to the present understanding of the West coast marine fog phenomenon. The framework proposed does attempt to add several improvements: 1) It provides a way to coordinate and integrate many of the concepts, conclusions and observations found in the literature about this complex phenomenon; 2) It suggests a breakdown of the phenomenon into four more readily analyzed phases; 3) It offers an hypothesis for the role of the sea surface temperature in fog formation; and 4) It presents a strong emphasis on the role of the offshore drift of warm, dry air and the way that it influences coastal fog formation by creating stability over the cold ocean and permitting unusual radiational cooling of the boundary layer in the atmosphere. These four contributions will be apparent in the description of the four phases of west coast fog.

4.3 A Physical Framework, the Four Phases

4.3.1 Phase 1. Initial Conditions: The essential features of this phase are the presence along the coastline of an area of generally low sea surface temperature overlaid by a column of air which is warmer (5 C to 10 C or more) and of low relative humidity (below 40%). This combination may occur only occasionally and is associated with a period of clear days or, in stratus season, by a 'hole in the stratus' at the coast, Rosenthal (1972). The clear air is the result of seaward movement of warm, dry air which has undergone subsidence in an inland extension of the Pacific anticyclone, Leipper (1948). The source of this type of air column, but not its characteristics, has been controversial. However, presently available satellite imagery utilized together with rawinsonde data available at the coast and geostrophic flow as indicated on synoptic surface maps, leaves little question about the origin or the path of the air.

With this type of offshore drift, the inversion base comes down to the surface along the coast, Patton (1956), Rosenthal (1972). As Blake (1928) noted, inversions of more than 5 C are almost certain to be followed by fog or low clouds at any time of the year along much of the California coast.

Considering the importance of the large positive air-sea temperature diffence, little attention has been given to it. This importance arises from the stability of the strong surface inversion which must exist offshore under these circumstances and from the dryness of the air column which, as mentioned, allows increased radiational cooling from the surface boundary layer, Barker (1977). The presence of the surface inversion offshore, in the absence of direct observations of the vertical temperature structure, may be inferred with some confidence by noting the clear areas in satellite imagery and by comparing the temperature of the air as it drifts seaward along the coast with the nearby general level of the sea surface temperature. It may be assumed that the air at the surface will come to the temperature of the underlying sea and from this information a decision may be made as to whether or not this establishes a strong surface inversion offshore.

4.3.2 Phase 2. Initial Fog Formation: This is the onset of fog in the day-to-day fog-stratus sequence. It is not the simple reformation of fog caused by regular diurnal changes in 'conditioned' air. It is the transition from a non-foggy period of days to a foggy period.

It is hypothesized that initial fog formation on this coast may come about in two ways. First, it may occur as advection-radiation fog when a moist wedge of northwesterly surface winds cross to the cold coastal waters under the warm, dry air column listed as a necessary initial condition. Second it may form as radiation fog offshore in the quiet flow period between the cessation of the offshore drift and the renewal of the prevailing northwesterly winds. (As a special case, when a shallow marine layer extends inland in winter, radiation fog may form there and spread across the coast.)

Barker (1977) presents a numerical example which is applicable to the first type of initial fog formation, the advection-radiation type. This details how fog could be formed by advection over sea surface temperature gradients of magnitudes similar to those occurring off portions of the California coast, providing that the important cooling contribution of radiation is considered. He shows that dryer air, such as is found off California at times, allows considerably more radiational cooling of the boundary layer and thus encourages fog formation more than the usual moist marine columns.

For the oceans as a whole, although fog cannot form solely by cooling from below, it is apparent that there is often enough radiational cooling in addition to turbulent effects to bring about fog formation through a combination of the processes. The only new consideration for the practical forecaster is the need to anticipate any high moisture levels in the upper atmosphere which might reduce the net radiational cooling of the surface layers.

The second type of initial fog formation off the west coast is similar to that proposed by Leipper (1948) with improvements based upon research results reported by various authors since that time. It might be called a radiation fog forming at sea (or occasionally onshore) in the presence of the unique initial conditions as found at times off the California and similar coasts. This type of formation occurs when the seaward drift of the warm, dry air ceases, leaving the offshore situation described under initial conditions. There occurs a short stagnant period before the prevailing northwesterly surface winds begin to rebuild to their usual strength. In this period, the strong surface stability allows the thin surface layer of air to become 'conditioned' for fog over the cool surface water, i.e. it's temperature decreases and it's moisture content increases, Petterssen (1938), Pelié et al. (1979). When the air begins to move again, turbulence is initiated and this, together with the net influence of radiation processes, leads to fog formation. The radiation is particularly effective because the overlying air column is dry, having originated through subsidence. Initial formation may occur in a short time and it is very difficult to obtain fully descriptive observations, Fleagle (1953), Roach et al. (1973).

This sea radiation fog is similar to what Byers (1959) calls land and sea fog except that the air drifting offshore to set up the initial conditions is dry, not moist. The moisture off California must result from evaporation from the sea. This could come about and the moisture could be retained in a thin lower layer in the presence of the unusually strong surface temperature inversion described.

It is hypothesized that the band of fog off the West coast is formed there primarily because this is the band where warm, dry continental air may drift offshore at times. The dry air permits the upward flux of radiational heat to increase and the high temperature of the air when cooled at the sea surface leads to the strong and very low or surface inversions required for fog formation. The sea surface temperature determines the air temperature at the base of the inversion and the saturation vapor pressure at that temperature determines the moisture content of the surface layer. Neither the exact value of the sea surface temperature nor the gradients may be critical to this type of fog formation as long as the sea surface is significantly cooler than the overlying air.

4.3.3 Phase 3. The Period of Fog Growth: This is the period when the base of the inversion is lower than some 400 m. It is the highly convective phase. It is the time when patchy fog occurs. It is the period when the sea breeze tendency may bring fog toward the coast during the heat of the day.

Immediately upon fog formation as described in phase 2, the balance of factors shifts markedly, Fleagle (1953), Barker (1977). Radiational cooling through the dry air above becomes the dominating influence upon the fog. The fog grows vertically and horizontally. It becomes as much as several degrees colder than the sea as a result of the cooling by radiation. This leads to heating from below and to instability as first described by Petterssen (1938). A mixed layer is created by the opposing heating and cooling processes, Leipper (1948), Fleagle (1953).

The creation of the mixed layer through convection leaves the initial warm, dry air mass above the boundary layer unmodified and it then becomes the top of the 'capping inversion', Lilly (1968). This capping inversion is strengthened by the radiational cooling of the boundary layer.

The 'mixed layer' deepens as the result of the strong convective action. The surface fog may lift with diurnal heating during this phase and the ceiling may be expected to be near the lifting condensation level, Petterssen (1938). The ceiling may lower with night-time cooling and become fog, e.g. Noonkester (1979), Pelié et al. (1979).

Early in phase 3, the fog layer becomes 'optically thick' as described by Roach et al. (1973). Its new radiational properties enable it to move over areas of higher sea surface temperature without dissipating, Leipper (1948), Pelié et al. (1979), Oliver et al. (1978) although it should be mentioned that Barker's (1977) computation disagrees.

It is noteworthy that, in this framework, the 'mixed layer' is created by fog formation rather than vice versa. Also, the 'capping inversion' is the result of boundary layer modifications brought about by fog formation. The strength of the inversion and the rate that the depth of the 'mixed layer' increases in the absence of synoptic scale events are primarily a function of the initial air-sea temperature difference.

4.3.4 Phase 4. The Stratus Period: This is the period when a strong inversion still exists but when the height of the inversion base has risen above 400 m. With such heights, surface fog will seldom be observed, e.g. Leipper (1948), Oliver et al. (1979).

Radiative processes affecting the boundary layer now will have come closely into balance with turbulent processes and the potential temperature of the boundary layer will have increased to a value near that of the sea surface temperature, Lilly (1968). In the absence of mesoscale influences such as subsidence and advection, models such as those of Oliver et al. (1979) may give good indication of diurnal changes in the cloud layer. The cloud has become more stratiform and the lifting condensation level is no longer as dependable in determining ceilings. The influence of the sea surface temperature is still important in the balance of forces which exists but the atmosphere cannot respond as quickly to it as when the cloud layer was low and shallow.

In the summer, as is well known, the stratus period may last for weeks with no clearing and no initial surface fog formation. During such periods, the behavior of the cloud layer is largely governed by diurnal effects and by gradual changes in the amount of subsidence occurring. The height of the boundary layer--the height of the inversion base--, because of the nature of subsidence, is closely tied to air temperature maxima inland and to the maximum air temperature found at the top of the inversion, Leipper (1980).

5. SUMMARY

West coast marine fog appears to be a cold water phenomenon. This is so because it may form as an advection-radiation fog over cold coastal waters when a wedge of marine air moves in under a warm dry coastal atmosphere; or it may form over the generally cold coastal waters as a radiation fog. This latter formation occurs when there is a warm, dry column of air and when a strong surface inversion suppresses surface turbulence. The boundary layer then may be 'conditioned' for fog and fog will form when some movement begins and when the resulting turbulence is enhanced by radiational cooling. Observed fogs colder than the sea are explained as fogs which were cooled after formation by radiational cooling through a dry upper atmosphere.

6. ACKNOWLEDGMENTS

The research which led to this report has been sponsored by the Naval Air Systems Command through the Naval Environmental Prediction Research Facility and the Naval Postgraduate School Departments of Meteorology and of Oceanography. The helpful advice of C. N. K. Mooers, R. J. Renard, R. G. Paquette, R. L. Elsberry, E. Barker, and J. Rosenthal is greatly appreciated.

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8. NOTE ON MODELS

Numerical models may give some insight into certain aspects of West coast marine fog development. Large scale models are required to deal with the subsidence and advection involved. However, these models normally cannot provide resolution which is sufficient to describe changes known to occur in the narrow coastal band, some 240 km in width, which is of interest.

Planetary boundary layer (PBL) models are mostly concerned with changes within and at the boundaries of the 'mixed layer'. Driedonks and Tennekes (1981) review the difficulties in using such models. They indicate, "There is a great variety of possible parameterizations of the PBL of increasing complexity," and state that further experiments are needed to test the various parameterizations. The assumptions and boundary conditions used in creating such models are of critical importance and, since choices of these may differ appreciably in the West coast fog situation, model results may be expected to differ from each other. In a sense, the problem of the practical forecaster is to help feed the proper boundary conditions and assumptions to the modellers.