

Fog on the U.S. West Coast: A Review

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Abstract

Weather forecasts and warnings are the most important services provided by the meteorological profession. The effective development of forecasting methods rests upon comprehensive knowledge of the phenomena to be forecast. To help provide such knowledge, this review includes a chronological summary of pertinent information concerning fog on the U.S. west coast. There is increasing evidence that periods of dense fog at National Weather Service west coast stations fall within a 5- to 15-day sequence of synoptic events. Further, such sequences may be divided into four distinct phases: initial conditions, fog formation, fog development and extension, and stratus. A separate article will review West Coast fog forecasting approaches and present resulting methods.

1. Introduction

The U.S. west coast is a foggy area. According to a chart from the National Climatic Data Center reproduced in *USA Today* (1993), the entire segment of the West Coast from Los Angeles to Seattle is one of the three U.S. areas that experiences the most dense fog occurrences. The other two are the mountaintop area in the Appalachians and an area in central New England.

The chart is apparently based upon the amount of fog at first-order National Weather Service (NWS) stations. The three areas mentioned have the most days per year (some 60 days) when visibilities of one-quarter mile or less occur. An exception on the central California coast, surprisingly, is San Francisco where the number of days drops below 60. The coastal area from San Diego to Los Angeles, as does San Francisco, has fewer days of dense fog than 60 but still has more than 40 days.

West Coast fog is a marine fog. It is anchored to the sea. Although the coastal waters are cold year around, the fog is not always there. It is controlled by the changing coastal atmosphere.

After defining fog, this review will list pertinent information sources, will summarize some related climatological information, will indicate contributions to knowledge of West Coast fog in chronological order, and will describe how various contributions lead

to the conclusion that periods of West Coast dense fog fall within a 5- to 15-day sequence of synoptic events. Further, fog sequences may be subdivided into four phases of fog development. There is evidence that these phases occur along the U.S. west coast from San Diego northward through Oregon and possibly to the Canadian border.

a. Definition

Coastal fog forecasting is a different problem in different parts of the world. Unless otherwise designated, West Coast fog in this review will always refer to U.S. west coast fog from the Mexican to the Canadian borders. Fog will be defined as dense, moderate, or light according to whether the range of visibility is 0 to < 1 km, 1 to < 5 km, or 5 to < 11 km. If not otherwise specified, dense fog will be implied. The focus of the review will be upon cases involving dense fog. The definition of fog will not include the so-called California high fog or stratus.

b. Focus on fog, not stratus

Many writers do not differentiate between West Coast fog and stratus (e.g., Petterssen 1938; Gilliam 1962). By far the greatest number of studies are about stratus, and observations are made in the stratus season. However, it is apparent from the literature that the synoptic condition favoring a persisting stratus regime is different from the condition favoring new, dense fog formation. For stratus there is a strong but relatively quiescent inversion hovering above 400 m at coastal stations. For fog there is an unusually strong inversion with little moisture aloft varying day to day in height through levels below 400 m.

As will be discussed later, dense fog and stratus change thickness differently. New incidences of West Coast fog increase in thickness by upward growth until the thickness reaches 400 m. Stratus at the coast and offshore has a generally level top (usually above 400 m and near the inversion base), which varies little diurnally. Stratus varies in thickness by downward growth or recession (e.g., Byers 1930).

Fog and stratus have different seasons. If U.S. Army Air Force (AAF) (1944) statistics are correct, the West Coast dense fog season differs from the low-ceiling period. In San Diego, Oceanside, and San Francisco most dense fogs occur in winter from Sep-

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tember through March, while most low ceilings occur in summer from June through September. Stations farther inland have maxima of dense fogs and of low-ceiling periods, which coincide.

Unfortunately for fog research, many of the West Coast field experiments have been conducted in the stratus season, (e.g., Albrecht et al. 1988 and references therein) and thus have not provided much data of value in dense fog forecasting.

2. Literature

There is rich and varied literature pertaining to U.S. west coast fog and stratus. For example, Air Weather Service (1954) contains abstracts of 44 West Coast fog studies as well as 217 other fog and stratus studies. *The Proceedings of the Second American Meteorological Society Conference on Coastal Meteorology*, 1980, lists 25 West Coast fog papers. AMS publications—in particular, *Meteorological and Geostrophysical Abstracts (MGA)*—list many more.

a. Published references

When the MGA abstracts are searched from 1970 through 1992 for "forecast," there are 14 348 entries, for "fog" there are 1588, for "fog forecast" the number is 89, and when "West Coast" is added to the descriptors, the number drops to 9. Only 8 of the 89 and 1 of the 9 were chosen to be included in the reference list attached to this review. It is interesting that so few of the references listed would have been found in a computer search of the topic. Most have come to attention over the years through a long-time interest in the subject.

The abstracts do not seem to include M.S. theses or Ph.D. dissertations, and they include only an occasional institutional or contract research report. Articles contained in conference preprints or proceedings are apparently not retrieved unless the title of the conference fits the descriptors utilized.

Reviewing the refereed and the gray literatures with West Coast fog forecasting in mind, over 100 references were selected as being most useful. Twenty-two of these are dated 1980 or later; 5 were published in the last three years. Seventy were used for this background summary.

In order to hold the review to a reasonable length, references have been used in three ways. There are complete quotations from only a few references. In many other cases, there is a short description or indication of the contents of the reference. Finally, there are some references that are used, as in a bibliography, to designate additional sources for information on important topics.

b. Gray literature

In compiling the review, every effort has been made to find references from the refereed literature. However, a major reason why the various pieces of West Coast fog knowledge have not come together prior to this review is that many of the significant ones have not appeared in the refereed literature.

Many climatological studies, reports containing aircraft and ship data (e.g., Calspan 1976), satellite imagery, descriptions of clear areas offshore and the fronts around them, and the relation of onshore observations to offshore fog have been described in reports of limited distribution. A number of these reports are listed among the references here and their important contributions are reviewed.

Among the valuable references not widely distributed are ten M.S. theses written at the Naval Postgraduate School (NPS) in Monterey, California. All of the authors of these theses are naval officers with some six years of naval experience, including time at sea. Their thesis work was the capstone of a two-year graduate curriculum in oceanography and meteorology. Many of the theses were done in conjunction with CEWCOM (Cooperative Experiment in West Coast Oceanography and Meteorology). Their contributions are significant. The theses are available at the NPS and each contains a listing of the distribution made. Distribution is unlimited and reproduction is authorized. The theses of students at other institutions such as San Jose State, UCLA (University of California at Los Angeles), and San Diego State are additional sources.

Manuscripts and papers listed as references but not readily available have been collected and will be offered for retention in the Reno Library of the Desert Research Institute. The Institute is a division of the University and Community College System of Nevada.

c. Information from field experiments

A number of extensive field experiments provide information useful in developing fog forecast methods. A recent history of California stratocumulus field experiments (Kloesel 1992) lists a number of events providing data relevant to West Coast fog. An article by Albrecht et al. (1988) adds information about the First International Satellite Cloud Climatology Project, Regional Experiment.

CEWCOM is a major set of experiments off the California coast, not listed by Kloesel, conducted between 1972 and 1982 under Naval Air Systems Command, U.S. Navy. The project was coordinated by Murray R. Schefer. The considerable extent of the program is described in CEWCOM (1977). This series of meso- and micrometeorological experiments involved a land and sea network of radiosonde observation (RAOB) stations, ships, aircraft, balloons, and kites.

Participants in CEWCOM included the Naval Postgraduate School, a number of other universities, several naval and civilian government laboratories, and several industrial research groups. Representatives of the groups met annually during the program. In 1975, for example, 81 scientists representing 31 institutions attended the meeting, representing the extent of this marine fog forecasting effort.

For a sampling of CEWCOM results, reference may be made to Pelié et al. (1979), Noonkester (1979), Backes (1977), Calspan (1974, 1976), and Arvin/Calspan (1983). The Pelié article summarizes the results of research cruises on a specially equipped vessel manned by experienced scientific personnel. Fifteen of the 25 fog papers in the *Proceedings of the AMS Second Conference on Coastal Meteorology* in Los Angeles in 1980 are from CEWCOM. These proceedings also contain a number of articles on the Marine Atmosphere Boundary Layer Experiments (MABLES).

Another earlier but highly significant set of experiments was that reported by Meneely and Merritt (1973). These authors related time sequences of satellite images of fog and clouds to patterns of sea surface temperature during nine upwelling events off Oregon.

3. Pertinent climatological information

a. Climatology overview

Willett (1928) gives a good worldwide picture of fog and haze. Renard (1976) includes a look at observation, analysis, climatology, and marine fog forecasting. Stevenson (1963) describes sea fogs on the coast of England. Ballard et al. (1991) fully analyzes the Haar of northwest Scotland. Palmer (1917), Byers (1930), and Patton (1956) give early descriptions of the fog off central California. Coast Pilot (1963 and other years) does this for the entire West Coast from a seaman's view. Petterssen (1938) deals mostly with stratus but provides useful general information on fog and writes from the vantage point of a forecaster.

In gathering climatic data pertinent to West Coast fog, some of the most intensive work was done during World War II (1940–45). Thus, there are a number of references from that era. Before that time, in the period from 1910 to 1940, which lacked radar and good ship-to-shore communication for weather data, there were a larger number of active light stations than there are now along the coast. Good records of dense fog were kept at these stations. One of the best articles utilizing data from light stations was published by Palmer (1917).

Checking with climatologists from California and

Oregon, no publications were found documenting any changes in the coastal-fog-related climate over the past 75 years. Conclusions about fog forecasting in this review are based upon fundamental physical variables and the relations between them. Such relations would not be affected by climatic changes nor would they be significantly changed by season or by geographic location.

Some climatological source materials are AAF (1944), which gives fog and low-ceiling frequencies along the Pacific coast; AWS (1954), which summarizes fog and stratus forecasting; Naval Weather Service Command, U.S. Navy, now NOC, Naval Oceanography Command (NWSC) (1971), which has sea surface temperature and visibility maps; NWSC (1974), which has meteorological records at stations; and Renard and Willms (1975), which covers North Pacific summer marine fog frequencies.

b. West Coast fog unique

The fog situation on the West Coast is unique. The major unique factor is the great strength of the low inversion (Blake 1948).

The second factor making West Coast fog unique is the presence of cool, upwelled water along the coast (e.g., Bakun et al. 1974; Meneely and Merritt 1973).

There are a few other regions in the world that have somewhat similar air, water, and topography situations in midlatitudes; “. . . circumstances are not substantially different in the stratus zones of western Morocco, the Ecuador–Peru–Chile, and the southwestern African coasts” (AWS 1954; Taljaard and Schumann 1940; Mass et al. 1986).

c. Sea fogs other than West Coast fogs

Most ocean fogs such as those of the northern North Pacific Ocean are different from West Coast fog since the northern ones are advective (Leipper 1945; Renard and Willms 1975; Jung 1983). They are not associated with the sharp, low-level coastal-type inversion. In the northern fogs, the relation of the dewpoint to the sea surface temperature is the most useful indicator for the forecaster. The dewpoint relation is determined by the air trajectory and by the oceanwide patterns of sea surface temperature.

d. The years differ

In West Coast fog occurrences the years differ, sometimes widely, from each other. At Point Loma near San Diego, the average year had 433 hours of fog while one year between 1950 and 1957 had 1291 hours. Farther north the differences are less, with the San Francisco lightship showing an average year of 1066 hours of fog with the maximum year in the 46-year record having 1674 hours (Coast Pilot 1963).

e. More fog at light stations

It should be noted from the records of fog, assumed to be dense fog, at lighthouse stations (Palmer 1917) that there are about five times as many hours of fog at these locations near the land-sea interface as there are at the National Weather Service, National Oceanic and Atmospheric Administration stations, which are usually somewhat inland along the West Coast. Point Reyes is exposed, and it recorded 1493 hours when the foghorn blew in an average year, while six other lighthouses south to Point Arguello all had more than 1000 hours. Los Angeles had 805 hours of dense fog at the light station and San Diego 423 (Coast Pilot 1963). On the other hand, the NWS stations at San Diego and San Francisco had only 15% as many days of fog as did Point Reyes. Eureka had 39% as many (AAF 1944).

f. Air-sea temperatures

The average West Coast sea surface temperatures are low due to upwelling. The lowest, in the range of 11° to 12°C (e.g., Bakun et al. 1974; Peterson 1975) are along the central California coast.

The average surface air temperatures at coastal stations at early morning RAOB (radiosonde observation) time tend to be within 1°C of the sea surface temperature (Diaz and Quayle 1980). Over the ocean, the air temperatures at the air-sea interface are equal to the sea surface temperature. Because of this, the strong inversions that occur are clearly much more the result of heating of the air, which often attains temperatures of 15° to 25°C, or even 30°C, rather than of cooling of the sea surface.

Contrary to a widely held opinion, it does not seem that the usual gradient of sea surface temperature nor the excess cooling caused by upwelling are critical to West Coast fog development after its initial shallow formation (Petterssen 1938; Meneely and Merritt 1973; Leipper 1982). The San Diego area has neither cold, upwelled water nor strong horizontal gradients of sea surface temperature but still had 40 dense fog sequences in a three-year period (Leipper 1947, 1948a).

Figure 1 shows an example where the air above the mixed layer but below 1000 m was warmed some 10°C by advection, but where the surface temperature remained within roughly 1°C of its original value. The daily observed winds below 1500 m, the map analysis, and the daily RAOBs for this event may be found in Leipper (1968). Many similar changes occur.

g. The coastal ranges and adiabatic heating

The coastal ranges extend, with only one break near San Francisco, along the entire West Coast from San Diego northward to Seattle. Since they vary in height from 500 m to as much as 2400 m, the adiabatic

heating that results from the downslope motion varies from approximately 5° to 24°C.

In offshore flow situations, the surface temperature at the crest of the range is already high (Blake 1948). The additional adiabatic heating of the air mass and the advection of that air onto the coast markedly strengthens and lowers the original subsidence inversion. It often replaces the entire column of air in the lowest 1000 m at the coast. At the same time, it displaces any moist air above the inversion (e.g., Leipper 1948a, 1968, 1982; Byers 1930).

The coastal mountain ranges, the occasional offshore flow, the cool ocean, the phases of fog development, and the relation of offshore fog to observations and forecasts made for coastal stations are strikingly similar along the entire U.S. west coast to the Canadian border (Leipper 1982; Meneely and Merritt 1973; Mass and Albright 1987).

4. Historical perspective

a. Long-term programs

The model output statistics work of Renard et al. (1980) and the Leipper (1948a, 1980a) inversion-based statistics (LIBS) approach showed systematic

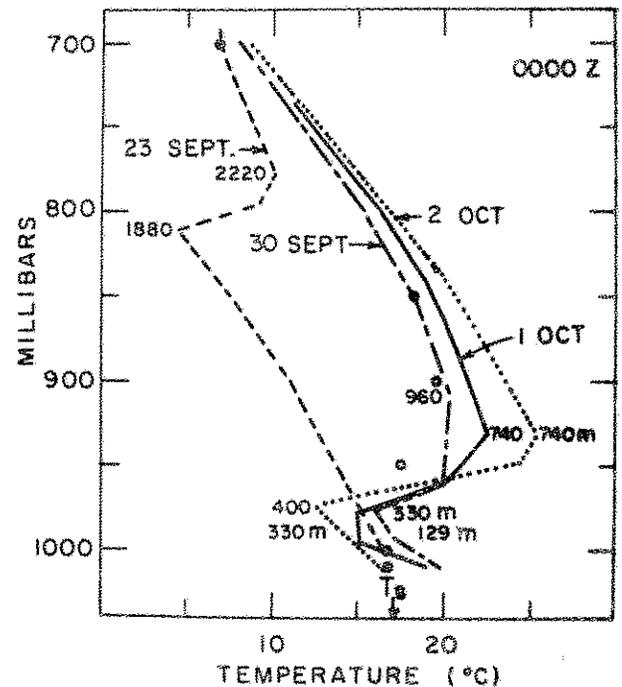


FIG. 1. Change in temperature structure following a period of easterly winds at Santa Monica, California. The surface temperature remained near the sea surface temperature while, over a 7-day period, the air above 400 m warmed by approximately 10°C creating and greatly strengthening a low inversion—details in Leipper (1968).

progress toward developing usable, coastwide databases for fog research. Caispan carried out a nine-year program (Arvin/Caispan 1983) that produced a large amount of observational data, analysis, and informational support for further work. The studies at Point Mugu by Rosenthal (1965, 1974), Lea (1964), and Lee (1979) have been ongoing for years with useful results. Another long-term series of studies reported in publications, which are more on the theoretical side, but based upon field studies, are those of Teleford and Chai (1984) and others at the Desert Research Institute. The STABLE (Sutro Tower Atmospheric Boundary Layer Experiment) (Miller 1975) is another intensive initiative. It was followed by MABLES (e.g., Van Patten 1980).

b. Pertinent contributions (arranged chronologically)

1) BLAKE (1928)

In describing one strong inversion observed at San Diego, Blake wrote, "How else, except by dynamically heated descending air, are we able to account for the excessively low relative humidity . . . ?" Also, ". . . the inversion layer is usually the result of subsidence of air from the interior of the continent brought to the California coast by the high-level anticyclone . . ." In this, "brought to" are the significant words, that is, advection.

Blake also stated, ". . . marked inversions ($> 5^{\circ}\text{C}$) are almost certain to be followed by fog or low clouds every month of the year."

2) BYERS (1930)

Writing about the central California coast, Byers found that haze traced the limits of penetration of sea air and that it appeared before fog. He said the average thickness of fog was 400 m.

3) PETERSSSEN (1938)

Petterssen found that radiation from the fog top led to instability through the fog layer. He stated that it is, "of crucial significance to be able to forecast whether the inversion is going to rise or lower."

4) BLAKE (1948)

Blake had, at this time, served 50 years as forecaster for NWS in San Diego. He tells how the phenomena associated with the San Diego coastal fogs and stratus are widespread and uniform. He states that the only acceptable explanation is in, "the subtropical Pacific and the North American anticyclones."

Then, "under normal summer (stratus) conditions, inversion height, temperatures aloft, and maximum surface temperatures throughout the whole of southern California and Arizona were closely related." Also, ". . . not only is the march of surface temperature

closely tied in with pressure trends aloft, but that is also connected with the rise and fall of the inversion as well." His graphs show the average 400-m thickness of the cloud layer.

5) LEIPPER (1948A)

The author offers a physical model of West Coast fog development in the San Diego area. It utilizes the lowering of the inversion by offshore winds, the growth of the unstable fog layer by radiational cooling at the top (see Table 1), the 1300-ft average thickness for fully developed fog, and four stages of fog development.

6) FLEAGLE (1953)

This is a useful theory of fog formation.

7) ROSENTHALL (1974)

This produced an extensive satellite imagery study of diurnal stratus variability.

8) MENEELY AND MERRITT (1973)

The writers, as mentioned above, reported on aircraft and satellite observations of nine events off the Oregon coast. They were struck by a sequence of cloud patterns over the coastal waters that repeated itself from event to event. This sequence turns out to be almost identical to the sequence of events observed in fog developments off the California coast.

9) WHEELER (1974) TO BACKES (1977)

Within this period, six Naval Postgraduate School theses by Leipper students Wheeler (1974), Misciasci (1974), Peterson (1975), Evermann (1976), Beardsley (1976), and Backes (1977) were on the subject of West Coast fog. Of four other Naval Postgraduate School students working on fog projects, McConnell (1975), Koziara et al. (1983), and Renard and Willms (1975) were advised by Professor Renard, and McClure (1974) was Professor Taylor's student. These studies provided tests and extensions of the fog development process and its potential applications.

10) CEWCOM (1977) AND PELIÉ ET AL. (1979)

This program from 1972 to 1983 produced many reports, theses, and publications. One part of the program was a series of seven cruises through 30 fog events that led to excellent descriptions of what happens offshore after a Santa Ana-type wind blows, as well as in other situations. CEWCOM observations and research provided detailed measurements in the levels below 20 m and coordinated them with synoptic information and observations. It reported on the surface inversions offshore, the initial formation of fog over warm water, the importance of radiation after fog formation, and the decreasing control of fog, as it

deepens, by sea surface temperature. It verified the average 400-m fog depth limitation.

11) OLIVER ET AL. (1978)

This was a turbulent-advective description of fog and low clouds using second-order closure. It found the 400-m thickness reasonable.

12) LEIPPER (1980A, 1980B, 1982)

These were three articles written for presentation at AMS conferences. They were an attempt to show the geographically widespread nature of the fog phases, to describe the Leipper inversion-based statistics (LIBS) forecasting system developed for Monterey, and to show that only the areal average temperature and not the gradient of sea surface temperature was involved in West Coast fog after its initial fog formation, apparently over warm water, in the lowest few meters over the sea.

13) ARVIN/CALSPAN (1983)

This was a project report concerning the final two years of work done by Calspan on West Coast and other marine fog since about 1972. It included the Pelié et al. (1973) article. It described the attempt to rate five numerical models and five nonnumerical models in their ability to forecast marine fog. Unfortunately, Eugene Mack, the key full-time person involved in most of this work, did not live to see it carried on.

14) TELEFORD AND CHAI (1984), TELEFORD AND KECK (1988)

These authors presented detailed analyses of the formation of cold fog in warm, dry air over colder water. The mechanism is water vapor-driven convection.

15) DORMAN (1985)

Dorman found indications of coastally trapped Kelvin waves and an explanation for the "Point Arguello eddy."

16) MASS AND ALBRIGHT (1987)

This is a good exposition of topographically trapped waves on the top of the atmospheric boundary layer from the Mexican Baja Peninsula to British Columbia in Canada. Such waves or surges are apparently closely related to phases 2 and 3 of West Coast fog development. Mass et al. (1986) gives a good description of a case of offshore fog on the U.S. west coast. Further work on these surges, with application in the Point Mugu area, was done by Eddington et al. (1992).

17) PEAK AND TAG (1989)

This was an effort to apply artificial intelligence in an expert system to predict marine fog. A similar system was published by Tremant (1989).

18) 1990-93

There are six references listed that were published during this period. None of them provide fog forecasting systems but they are helpful in understanding fog.

5. Sequences

a. Fog studies show sequences

There is strong evidence that a sequence exists in the variations of BI (height of the base of the inversion) through a fog development (e.g., Taylor 1917; Leipper 1948a; Backes 1977; Leipper et al. 1979; Leipper 1980a). The length of the sequences may vary from 5 to 15 days and it averages about 9 days (Table 1).

b. Spectra indicate sequences

In studying atmospheric spectra at San Francisco, Van Patten (1980) found that there were 10-day peaks in the wind and in the temperature spectra above the inversion base and that the primary variance was in the east-west component of the wind. He wrote that "This implies that the influx of marine air near San Francisco has a 10-day cycle." This supports the fog sequence concept.

c. Fog cycles indicate sequences

An interesting and detailed description of fog "cycles," including fog photographs for central California, may be found in Gilliam (1962). He discusses the relationship of the cycles to the "Pacific high."

6. The four phases

a. Overview of fog phases

The four phases are subdivisions of the West Coast fog sequence based upon the physical processes that are occurring. Four different stages were first described for the San Diego area by Leipper (1948a). They have since been called phases and found useful in the offshore area north to Point Conception (34.4°N) (Pelié et al. 1979; Backes 1977), in the area off the central California coast (Pelié et al. 1979; Peterson 1975), and off the Oregon coast (Meneely and Merritt 1973). Although there are slight differences in defining the extent of the individual phases, the use in all references has been essentially the same (Leipper 1982).

As in all meteorological phenomena, the sequences and their four phases show considerable independence and individuality but the basic family characteristics are present in nearly all events.

Progress through the four phases is a conceptual-physical model of the same type as the Norwegian frontal model, which has been useful to forecasters,

TABLE 1. Average height (BI) of the early morning inversion at Oakland during fog-related sequences, 1973.

Sequence day	-4	-3	-2	-1	0	1	2	3	4	5
Average BI (m)	782	570	393	325	65	199	389	406	537	594
No. of cases	6	27	31	34	34	34	31	21	14	7

although it cannot be put into a numerical model (e.g., Keyser and Uccellini 1987).

Of references listed concerning West Coast fog phases, the most complete and easily obtainable descriptive one is Leipper (1982). For practical utilization of the phases see Leipper (1980a). The most informative onshore data collections are Peterson (1975), Beardsley (1976), and Leipper (1948b, 1968). The most useful offshore data are reported by Pelié et al. (1979), Meneely and Merritt (1973), Leipper et al. (1979), and Backes (1977).

A simple compiled description of the four phases of West Coast fog development, incorporating more recent knowledge, follows (also see Table 2).

b. Phase 1: The initial conditions

The base of the inversion (BI) is at near zero offshore. The air column at the coast in the lower 1000 m is unusually hot and dry (also, there is less than 3.5 g kg⁻¹ at 3000 m). The North Pacific high has extended inland. There is a surface inversion at sea (the air at some elevation is warmer than the sea by more

than 5°C), but there may be no strong inversion showing on coastal RAOBs because of the east winds and the resultant high surface temperatures on land. This phase begins when the prevailing north-northwesterly winds offshore are interrupted by the strong off-shore flow. The sea breeze is completely overcome. A clear area appears alongshore and grows seaward.

c. Phase 2: Fog formation

The BI is between near zero and 250 m. This phase is a relatively calm period after the offshore winds decrease. The heat low begins to penetrate the high pressure area from the south along the coast. Haze appears (Peterson 1975). Some patchy fog forms. A shallow, unstable, mixed layer of fog develops at sea and gradually becomes deeper. Because of strong radiation from the fog top, the layer is colder than the sea. The onshore morning RAOB still may not show the mixed layer. The fog may come ashore briefly, occasionally in the afternoon with the sea breeze (Leipper 1968; Mass et al. 1986). A wedge of

TABLE 2. Visibility frequencies versus height of the base of the inversion (BI), air warmer than the sea, Monterey Airport, California, April through November 1973.

No. days	Ht of BI (m)	Percent of days with vsby			Midtime of occurring fog			Avg. duration (h)		
		0-0.5 mi	0-3 mi	0-7 mi	0-0.5 mi	0-3 mi	0-7 mi	0-0.5 mi	0-3 mi	0-7 mi
69	0	28% (19)*	38 (26)	86 (59)	03-04	00-12	anytime	5.1	8.6	12.8
17	0-250	59 (10)	94 (16)	100 (17)	02-03	00-04	anytime	6.1	12	20
35	250-400	34 (12)	71 (25)	97 (34)	01-08 04-06*	01-09 04-05	anytime	3.5	7.6	19.5
53	400-800	6 (3)	40 (21)	89 (47)	02-09 00-06	21-10	anytime	4.7**	8.3	15.6
79	Over 800	3 (2)	6 (5)	27 (21)						

*Number of days it occurred. **Most occurrences were in this interval. **This very seldom occurs (three times).

VISIBILITY AT FOUR PACIFIC COAST STATIONS ~ 18-28 APRIL 1973

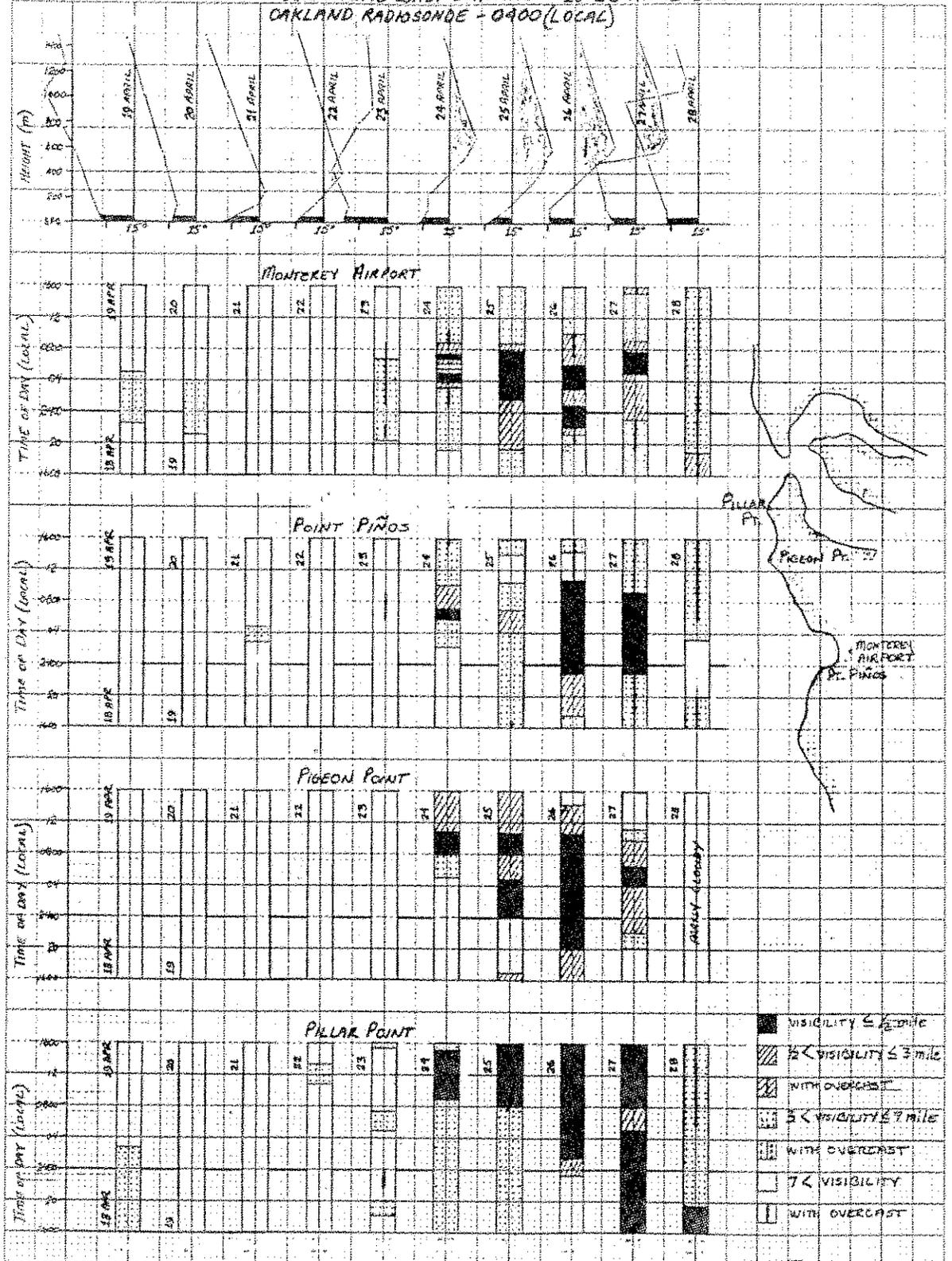


Fig. 2. A data display format for onshore data. Extracted from a year of such data in Beardsley (1976). Each vertical bar is a 24-h visibility record, the darker the bar the lower the visibility. The daily ROADS are plotted on a rectangular grid with 15°C as a common reference temperature. Three of the stations are on the open coast and the fourth is at the Monterey Airfield.

fog appears in the south on the west side of the heat low (e.g., Pellié et al. 1979; Peterson 1975; Backes 1977) and moves northward along the coast. This may bring a change similar to a frontal movement with large wind shifts and large (5°C or more) temperature changes (Mass and Albright 1987). An extensive clear area remains offshore and west of the wedge.

d. Phase 3: Fog growth and extension

The BI at a coastal station is between 250 and 400 m. For stations experiencing fog in phase 2, the fog may intensify and persist for a longer time in phase 3. At other stations the fog may appear for the first time. The northward-building heat low penetrates the Pacific high at the coast. The wedge of fog moves northward along the coast. Patchy fog forms and spreads along the coast in the formerly clear area offshore, possibly by means of a coastal surge action. The mixed layer becomes deeper and the surface temperature of the layer increases toward the sea temperature. The sea breeze begins to return and some higher relative humidities are observed at the surface at coastal stations in the afternoon. Fog occurs at coastal weather stations, usually at night. Winds are gusty as fog approaches. The north-northwesterlies offshore begin to return from the north in almost frontal form (Schroeder et al. 1967; Evermann 1976).

e. Phase 4: Stratus

The BI goes above 400 m. Upwelling begins again with the full return of the north-northwesterlies offshore. The usual pattern of widespread stratiform clouds returns. Nighttime ceilings will often be 400 m lower than the BI. Daytime ceilings may be higher by as much as 400 m or the sky may become clear as the stratus dissipates from the cloud base upward. There is no more dense fog at the coastal station unless the BI again drops below 400 m.

a year at Monterey (Leipper 1948b; Beardsley 1976). Figure 2 is a 10-day sample of the plots that were made for the full year at Monterey. The RAOB plots are shaded to represent the excess of temperature over a fixed reference value. The changes are seen to be related to the daily variations in the offshore component of the geostrophic wind and to the satellite imagery of clear areas and clouds. The stronger the offshore wind component, the higher the air temperature, the larger the shaded area, and, usually, the lower the BI. Also, the higher the coastal air temperature and the better the visibility outside and above the dense fog, the colder and more dense the fog.

Since subsidence is not an important factor in the surface layers at the coast, the only significant changes in temperature are those due to horizontal

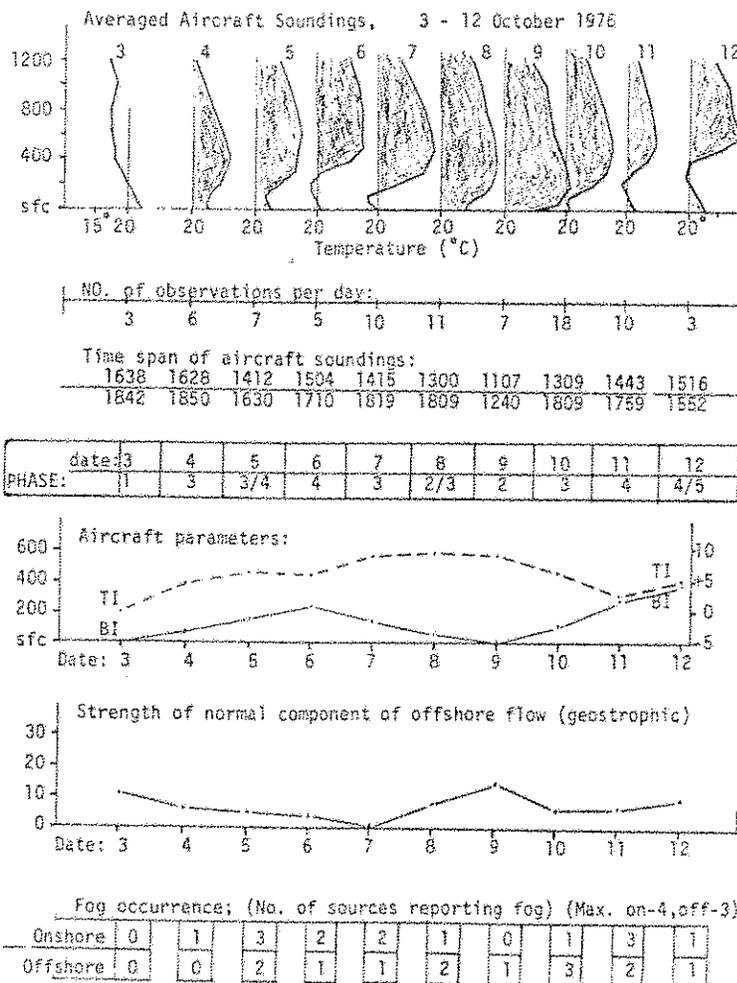


FIG. 3. A data display format for offshore and island data. Extracted from Backes (1977). The fog sequence of 3-12 October 1976 including a sequence reversal to phase 2 on 7 October. The area is located between the coast of southern California and the offshore islands. This entire area was under the same synoptic influence, an offshore wind, and the subsequent fog phases.

advection. Simple rectangular plots of RAOB temperature against height were chosen to best show the effects of this advection on temperature at the lower levels in Fig. 2.

The phases of development are indicated in Fig. 2 by the value of the BI on a given day and by the shaded representation of the visibility ranges. The darker the segment on the vertical 24-h plots, the lower the visibility in those hours. In this figure, haze usually precedes fog, and stratus follows it as shown by observations represented on the vertical bars.

b. Offshore and island data

Figure 3 represents the display of data for an area offshore from southern California where several island stations and many aircraft locations were involved (Leipper 1980b). The aircraft was instrumented and flown by Ralph Markson (Backes 1977).

The RAOBs in Fig. 3 are drawn similarly to those in Fig. 2. All of the aircraft and ship soundings and all of the coastal and island stations were in an area determined throughout to be under the same synoptic influence (Leipper 1980b). The phases of fog development were determined by the BI ranges. There were four onshore stations and three offshore ones.

c. An unusual area

Backes (1977) remarks that Point Arguello (34.4°N) seemed almost decoupled in one set of observed fog phases. Rosenthal (1974), Edinger (1963), Dorman (1985), and Eddington et al. (1992) describe the Catalina eddy in the same general area.

Even in this part of the coast, Rosenthal (1974) states, "This offshore flow may provide the initial mechanism for the start of the cyclonic cycle" there. Offshore flow is first phase of the fog sequence. Rosenthal's description and satellite imagery includes a cloud wedge similar to that of the second and third phases of the fog sequence. The tip of the wedge is turned westward when it approaches Point Conception (34.4°N) and it becomes a part of the eddy instead of being able to move on northward as the wedge does along other parts of the coast (Dorman 1985). Thus, even this irregular part of the coast may follow the usual fog development.

8. Topographically trapped waves or surges

There is growing evidence that the fog sequences observed off southern and central California, and off the Oregon coast, may also occur along the entire West Coast.

One indication of north-south extent is the pres-

ence of topographically trapped waves or surges at the BI level. Mass and Albright (1987) indicate that these waves range over the U.S. west coast from Baja California to British Columbia. Such surges may only be observed where there is a two-layer system. The top of the mixed layer, created in phases 2 and 3 of the fog sequence, makes an ideal boundary for such waves. The illustrations in the Mass and Albright reference are similar to the fog phase 3 in showing a cloud wedge. Also, they use the word "sequence."

9. Summary

This review is a summary of more than 70 publications. How to summarize a summary is the question.

There are several concepts, observations, and theoretical conclusions useful in understanding West Coast fog that have carried through the years: the advection of warm air down the coastal range slopes provides the strong, low inversion and dry air aloft needed for dense fog to form over the cool coastal waters; the average depth of fully developed fog or stratus clouds is 400 m; observations and theory show that radiation from the newly formed fog top is the major factor in creating an unstable layer that grows and creates the deeper mixed layer; and a newer result that indicates that surges on the interface between the fog layer and the warm air above it may greatly affect the manner in which the fog is distributed along the coast. These conclusions serve as a basis for West Coast fog forecasting, a subject to be reviewed in a separate article submitted to *Weather and Forecasting*.

The literature concerning U.S. west coast fog shows that there remain many confusing aspects of the phenomenon such as just how fog is formed offshore; differences of opinion such as what makes the inversion rise and fall and whether or not there is any subsidence at the coast; questions such as exactly what is the role of the sea surface temperature; what forces drive coastally trapped waves and surges; and complex problems such as those involving the interactions among turbulent processes, radiation, advection, subsidence, and convection. The challenge is to resolve these questions or to make decisions about them in order to establish a fog forecasting system that a forecaster can understand and operationally use, and to which a research meteorologist may relate in an objective manner.

Some of the remaining questions may be answered if priorities stated by the AMS Council (1992) for the next decade are followed. These priorities call for forecasting models that include, "... ability to represent properly the interaction between mesoscale sys-

tems and cloud microphysical processes involving latent heat release."

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