4.5 HOT SPELLS AND THEIR ROLE IN FORECASTING WEATHER EVENTS ON THE U.S. WEST COAST

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1. INTRODUCTION

West coast weather events, which seem to have their initiations and therefore their forecasting influenced in a significant way by hot spells, include Kelvin waves, trapped waves, coastal surges, the synoptic evolution, south wind fronts, the Catalina Eddy, fog, and stratus. An exception is the low level jet which is terminated by a hot spell.

If the focus is on the land within ten to twenty km of the coast and an offshore band extending some 150 to 300 km from the coast, these events comprise an important portion of west coast weather. They all seem to require for their initiation a strong low marine inversion over a cold mixed layer, such as is found only after a hot spell. A hot spell will be described below.

Some references which point to this conclusion are the following. These references were not selected as the most definitive ones on the subjects listed. Rather, they were selected because they indicated a relationship between the phenomena discussed and hot spells. Arranged chronologically they are:

Fog at the San Diego Airport: For fog to form "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." (Leipper 1948, henceforth L48, etc.)

Fog in Oregon coastal waters: From aircraft observations over upwelled cold water: "Fog is in evidence if, during the preceding night, the wind veered to easterly or east northeasterly for several hours." (Meneely and Merritt 1973). This would likely be a warm wind.

Catalina Eddy: "This offshore flow may provide the initial mechanism for the start of the cyclonic cycle." (Rosenthal 1974). Offshore flow brings warm air.

Fog model: "Thus dry nearly adiabatic air overrunning a cold water surface fogs easily." (Oliver et al. 1978).

West coast fog at sea: "The warm air blowing over the cold sea surface establishes a surface-based inversion, creating conditions suitable for fog formation. The literature, however, does not provide an explanation of how the inversion is raised from the surface when the Santa Anas desist." (Pelié et al. 1979). These authors observed at sea how fog formation and growth brought about the existence and development of the unstable mixed layer. They supported the conceptual model described but not yet named LIBS (Leipper Inversion Based Statistics) in L48.

General comment: (Pertaining to the North coast): "---Interrupting the region's temperate weather are "heat waves" of high temperature and low humidity. These WARM SPELLS are usually associated with a northward extension of the central California "thermal" or "heat" trough into western Oregon and Washington and subsiding easterly flow across the Cascades. Maximum temperatures west of the Cascades can exceed 35 °C during these events. --The essential point is that large temperature drops and onshore surges are generally preceded by warming to temperatures that are above the mean for that time of the year.--" (Mass et al. 1986).

Surges and southerly winds: After screening satellite images of 23 surge events, Felsch and Whitlach (1993) concluded that " A potential stratus surge was identified if the 0000 UTC satellite image showed a stratus-free zone extending at least 60 n. mi. (111 km) offshore and 120 n. mi. (222 km) alongshore---" The clear area is indicative of a hot spell.

Fog extended along the coast; After many observations and wide literature reviews over a 47-year study "A forecaster may thus assume that most dense fogs at California coastal sites will follow offshore wind (hot spell) periods." and "There are strong indications that the LIBS method is applicable to situations along the California, Oregon and Washington coasts." (L95).

Surges and southerly winds: Offshore along the west coast "The transition from northerly to southerly winds often corresponds to the end of a coastal heat wave. --In all cases the surges were preceded by above normal temperatures over coastal sections of central California." (Archer and Reynolds 1996).

Northerly west coast synoptic evolution: "-the east Pacific high extends into southwestern Canada and the Pacific northwest. The result is offshore flow and subsidence along the mountainous west coast that produces a strengthening and coastal extension of the trough normally resident over the interior of southern and central California." (Mass and Bond 1996). The "synoptic evolution" described by these authors chiefly in terms of troughing and ridging related to heating seems to be almost identical to the LIBS fog sequence (L48,95) described primarily by different variables, namely the height and strength of the inversion

West coastal trapped event: At a buoy just offshore from San Francisco the air temperature "was much more extreme at buoy 26 where hot air advected from land out the San Francisco gap, causing sea-air temperature differences greater than of 10 °C in some locations. ---- With the wind reversal to southerlies, warmer air began moving over colder water, which formed a new SBL that began at the sea surface and grew upward." (Dorman 1997).

Coastal Model: The analysis of the pressure fields indicates that a cross-coast warm advection is a precursor to flow disturbances in the coastal region. (Work by the authors now in progress).

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2. HOT SPELLS

On the U. S. west coast a hot spell as used in this article is a period such as is often associated with the well known Santa Ana downslope winds. Similar winds on other parts of the coast are known by different names such as Sundowner winds near Santa Barbara or the Brookings Effect at Brookings.

A hot spell on the west coast is a spell of warm weather made unusually warm by the flow across the coast line of desert air which has been further heated adiabatically by flow down the slopes of the coastal mountain range. The nighttime surface air at the coast during such a period may be 5 to 15 °C or more warmer than the adjacent sea surface. These hot spells occur frequently on segments of the coast from Baja California to British Columbia. They are particularly noticeable in the lowest 1,000 m of the coastal air column. They sometimes extend along the entire coast line.

In addition to the very high coastal air temperatures, the hot spells can be identified by the inland extension of the Pacific anticyclone which leads to the offshore downslope air flow, the geostrophic flow across the coast line indicated by the isobaric pattern, coastal visibilities of 20 to 50 miles, and offshore areas cleared of coastal clouds as seen in visible satellite images (in these areas the hot dry air has quite likely reached the sea surface forcing the strong inversion down to that level.) For an example, see Figs. 1 and 2.

As shown in Table 1, the inversion at Oakland 30.5 hours before the satellite image in Fig. 2 was surface based. In the intervening hours there was time for the inversion base to rise to 100 m or so at sea and for the surge and the fog wisps to develop.

3. THE INFLUENCE OF HOT SPELLS ON WEATHER

3.1. Creating great stability

Mass and Bond (1996), in discussing the synoptic evolution which they observed off the northern coast, state "Finally, it is obvious that without a lower tropospheric layer of some stability, orographically trapped coastal flows would not occur." An important question is "How does this stability come about?"

The west coastal stability is usually attributed to subsidence. However, subsidence alone cannot bring offshore air temperature high enough nor bring the base of the inversion low enough over the water to bring about fog formation. Neither can subsidence explain the kind of day to day variability observed in the height of the low inversion at the coast. Further, no indications of subsidence are observed at the coast in the lower 1000 m when advection is bringing in hot continental air to that layer.

The very warm air mass which is brought to the coast by advection will remain over the water when the easterly winds die down. There is nearly always a period of relatively calm weather then before the usual coastal winds return. During this period air mass modification by sea-air interaction is the major element of change.

3.2. Initiating a new mixed layer

When the very warm offshore flow reaches the sea surface, since the surface air temperature is brought quickly to the slowly changing sea surface temperature, a strong surface or near surface inversion is formed. Under this inversion a shallow layer of fog is formed (L48,95 and see below). Due to turbulent mixing which must be triggered by a wind shear at the interface of the shallow surface layer and the overlying hot air mass, the initially stable low-level inversion is eroded and the moisture flux from the surface penetrates upward. Condensation occurs and the layer of condensed moisture deepens. As soon as the fog layer is created, the longwave radiational cooling at the fog top enhances the mixing process. Consequently, the fog layer grows upwards as a mixed layer. Thus, offshore of the west coast, fog creates the mixed layer and not vice-versa. It provides an upper interface upon which the wave-related weather events listed above may occur.

The surface layer of the air mass is modified while the air above the new mixed layer remains near its original high temperature and moves very little in a vertical direction. Subsidence of this warm air may be ignored during this period since the cooling of the mixed layer and the associated increase in pressure act opposite to the processes initiated by the advection of the hot air mass.

Although the downslope winds across the coast line may be of short duration and not given great attention, their effects in creating a new mixed layer may be felt for several days afterward.

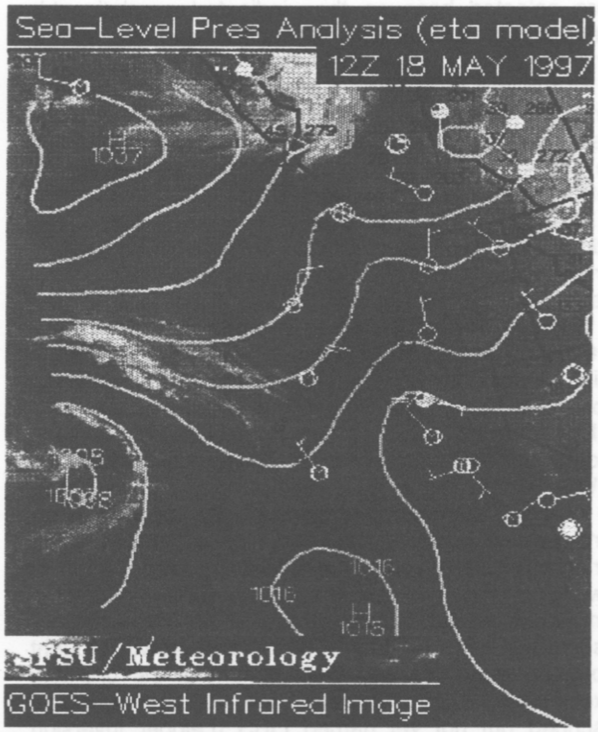

Fig.1. Sea-level pressure analysis, predicted by the eta model, of the weather conditions associated with an offshore flow. The high pressure cell extends inland north of the U.S. coast. Cross-coast isobars indicate offshore winds over the Washington, Oregon and northern California coasts.

Note that in Fig. 1 the coastal winds do not reflect in either strength or direction the offshore flow indicated by the isobaric pattern. It is suggested that the flow down the coastal mountains leads to a vertical divergence of the air mass which destroys the general lower level flow pattern.

4. FORECASTING THE WEATHER EVENTS

The hypothesis is that only when the inland heating is augmented by the adiabatic heating of the downslope flow does the coastal air become stable enough and the coastal inversion low enough to bring about a situation allowing the occurrence of the events listed in Section 1. This situation follows a hot spell (described in Section 2.)

If this hypothesis is correct, the LIBS five day fog forecasting system (L95) may be used to predict when the synoptic situation will occur. Briefly, the hot spell is an initial condition required for the LIBS sequence to begin. The initial condition need not be forecast but may be observed. When it occurs fog will soon form offshore and two or three days later (usually) conditions alongshore will be favorable for the occurrence of the wave-type weather events and/or a surge.

The LIBS five day forecast is based upon a sequence of increasing inversion heights which follow the given set of initial conditions. The sequence is identified by the various stages of the growing mixed layer.

After a comprehensive study of 23 observed surges, Felsch and Whitlatch (1993) were led to assume that "a surge would not develop if stratus was observed along the entire central California coast line at 0000 UTC." They also state "surges did not occur ---when the inversion was too high, too weak, or nonexistent." Apparently the formation is most probable with an inversion approximately 250 m in height. This is in phases 2 and 3 of the LIBS forecast sequence. The same appears to be true for Kevin waves, trapped waves, south wind fronts and the Catalina Eddy. However, fog forms with the lowest inversions and grows in depth to 400 m or so. Stratus occurs when the inversion lifts above this level.

It appears that in some two cases per month of offshore flow the inversion is brought to the sea surface and a new mixed layer develops and grows as described. (L96). It is this growing mixed layer which is favorable to the coastal weather phenomena mentioned. When the layer reaches some 400 m in depth, a balance of processes affecting the cloud depth is reached (Oliver et al., 1978) and the inversion seems no longer favorable for the various disturbances other than stratus.

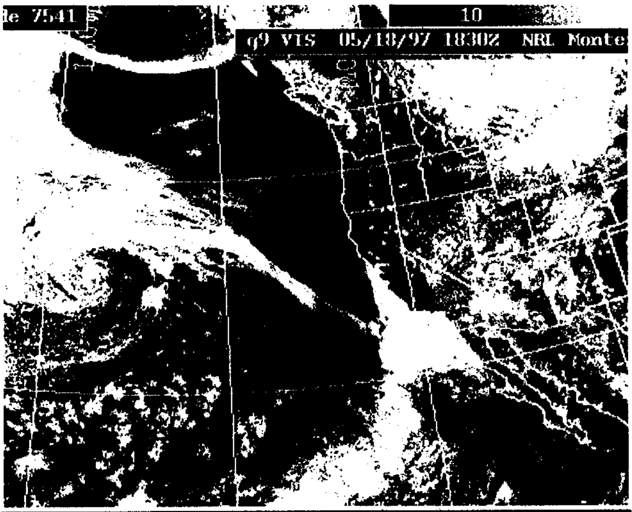

Fig. 2. Satellite image in the visible part of the spectrum showing the area initialy cleared by the hot offshore winds indicated, for example, some 6 hours earlier in Fig. 1. At the southern coastal part of this clear area a surge has formed and west of the state of Washington wisps of what is believed to be new shallow fog are appearing.

5. DEVELOPMENT OF THE WAVE INTERFACE

5.1. Overview

The development which leads to the relationship with the wave-related west coast weather events can be described in at least three ways. Firstly is by the conceptual fog model, the fog sequence (L48,68,94,95); secondly, by an extensive series of research cruises summarized below (Pelié et al. 1979); and finally, by analysis and modeling in the work of Oliver et al. (1978) and preliminary modeling work summarized in the following text.

As mentioned above, a tie between the hot spells and the various coastal events is indicated time after time when articles by various authors state that the event described seems to take place after a coastal heat wave. As far as is known, explanations for the tie have not been attempted. The desire in this presentation is to bring out the strong indications of a relationship between the west coastal weather events and the development of the coastal inversion in the fog sequence.

Although there are many indications in the literature that hot spells precede numerous weather events on the west coast, only a few articles satisfactorily describe the origin of the stability needed and the formation and growth of the mixed layer. These are essential for the occurrence of the weather events listed above. These articles (L48,94; Pelié et al. 1979; and Oliver et al. 1978) are not widely referenced nor are they used in any recent numerical models of west coast weather. The first of these is a conceptual model found useful in forecasting, the second is an intensive series of observations at sea in pertinent situations and the third is a set of analytical and modeling studies.

5.2. The conceptual model

In the fog sequence of the conceptual model it is the set of initial synoptic conditions which bring about the situations in which the various events may occur. These situations come about when the common northwesterly wind off the coast is disrupted. This may happen several times in one month. The disruptions may last only a short time but they make possible many of the events listed above. The wind disruptions are often not noted in the climatic wind summaries. The summer of 1997 has been unusual in that few of these situations have occurred along the central California coast and therefore few of the weather events listed have occurred there e. g., Los Angeles has been unusually smog free.

What happens to establish the initial conditions is that the Pacific anticyclone extends inland eliminating the usual northwesterly winds offshore. This leads to hot dry winds such as the Santa Anas which move down the coastal mountain range and carry their hot dry air out over the cool coastal ocean. (L48,94). This brings about a band clear of clouds along the coast or "holes" in the clouds off the coast as described for example by Rosenthal (1974). This is a band where there will be great stability in the near surface layer. As mentioned, these are believed to be the same events, described in terms of different variables, given as the setting for the "synoptic evolution" on the northwest coast by Mass and Bond (1996).

What seems not to be generally recognized is that the clear areas offshore must have a strong surface or near surface inversion since the air above the surface is unusually warm and the surface air temperature must become immediately equal to the relatively unchanging sea surface temperature.

Such a synoptic situation is described in the results of a nine day field experiment involving ships, balloons, aircraft, and shore stations which are indicated in Fig. 3 of Leipper (1994). This experiment covered an area between the southern California coast and the offshore islands.

5.3. Observations at sea

In the 1970s, the Naval Air Systems Command sponsored a seven year study of west coast fog involving some 90 scientists representing a broad combination of universities and research laboratories. A major activity in this program was a series of seven cruises off the west coast extending from San Diego on the south to Arcata on the north and out to sea for as much as 500 km (Pelié et al. 1979). These cruises over the years encountered 30 cases of fog.

The vessel Acania of the Naval Postgraduate School at Monterey was equipped with an observation tower and the best instrumentation available. The scientific crews consisted of broadly experienced meteorologists and observers (some are listed as coauthors in the Pelié reference), mostly from Calspan Corporation. Their observational results are believed to be by far the most definitive available on west coast fog formation at sea to the present date.

The Naval Postgraduate School-Calspan cruises supplied detailed observations from the sea surface to a height of 20 m, in addition to RAOBs (radiosonde observations). Observations from aircraft cannot give such information since they seldom fly lower than 60 m. The objective of the Acania cruises was to observe just how new fog did form in the clear area at sea and specifically to test the LIBS conceptual model. They met this objective well by making careful and repeated measurements in 30 fog events. Their results included the following:

1. "---surface-based inversions were observed, in complete agreement with the aforementioned (F48) hypothesis. There was no "destruction" of the inversion by Santa Ana type winds as often stated, for example by Simon (1977) and others. Dorman (1988) has observed that a shallow mixed layer does exist on the open coast at times when no inversion is shown on the coastal RAOB.

2. Fog first formed in patches or streaks. At this stage, the gradient of SST appeared to be important. This was also noted by Meneely and Merritt (1973). The fog then spreads to form a broader and deeper layer. [It is at this stage that the top of the fog layer between the surface and some 250 m provides a good base for the development of waves and surges. This is stage 2 of the LIBS fog forecasting sequence (L95). The extent of the hot spell along the coast indicates whether the situation favors trapped waves in shorter segments, or surges, in longer segments. The inversion height usually keeps increasing beyond this stage 2. It is suggested that the weather events listed above may not occur after the inversion reaches a height of some 400 m and the fog lifts into stratus. The statement above by Felsch and Whitlach indicates this.]

3. After formation when the fog was still a thin layer it became colder than the sea by 1 or 2 °C. This led to heating from below which, combined with cooling by radiation from the fog itself, led to mixing and strong instability within the layer i.e., "the unstable marine boundary layer along the west coast is frequently formed by the lifting of the surface based inversion by radiation from fog liquid water."- (Petterssen 1938). As the fog layer deepened (beyond 20 m or so) it became less dependent upon the gradient of sea surface temperature. Upon reaching a depth of approximately 400 m there was no longer fog at the surface.

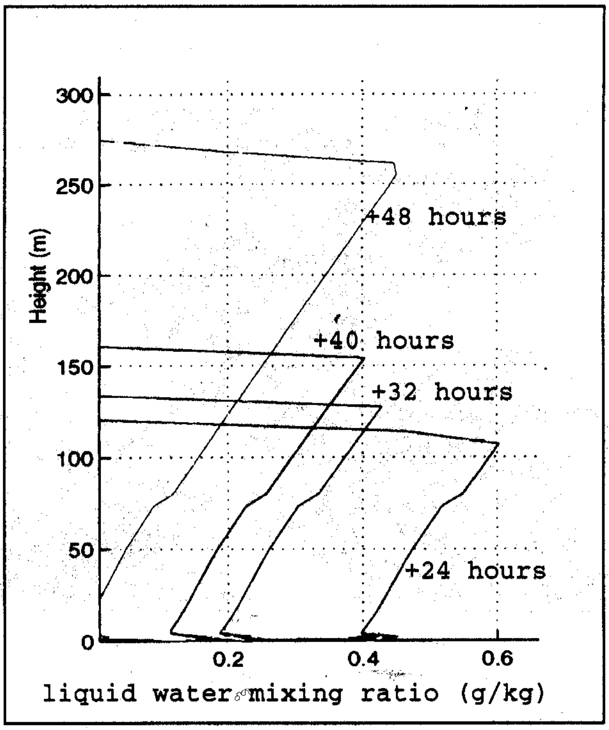

Fig. 3 Modeled vertical profiles of liquid water mixing ratio at eight hour intervals during the two day simulation.

5.4. Simulations of an idealized fog event based on coastal radiosonde measurements on 17 May 1997

1) **Observed properties of the hot spell event on 17 May 1997**

Data from the radiosonde measurements at Oakland, California, on 17 May 1997 at 1200 UTC, represents conditions for a typical hot spell event on land near the coast, see Table 1. There are no known atmospheric structure observations offshore on this date. However, since the circulation shown in Fig. 1 would carry the coastal air mass offshore, the coastal RAOB is a good representation of the structure offshore. Field studies have supported such a conclusion in similar situations. At the sea surface the air temperature would be quickly modified by the ocean. The sea surface temperature at this time was between 14 and 16 °C.

Although the vertical resolution of radiosonde measurements is quite coarse, some basic features of the hot spell event are clearly indicated in Table 1. This event preceded a surge case, observed next day, and previously shown in Fig. 2.

During the hot spell event, there would be a shallow marine boundary layer above the sea surface with relatively high humidity and stability, and low wind speeds. An elevated layer, created by offshore advection of the hot air mass, extends approximately between the top of the shallow marine layer and the 2400-2500 m level. The hot air layer was less stable, drier and with larger wind speeds than the near-surface marine layer. Another important difference indicating the origin of the air mass was in the wind direction. Winds at Oakland in the lower layer were northwesterly and turning clockwise, while winds in the hot air layer were northeasterly at this time. Based on this characteristic case, we constructed an idealized numerical experiment. Some of preliminary results are presented in the next subsection.

2) **Simulations of the hot spell event and formation of the coastal fog**

Leipper (1948) postulated that the warm surface air advected over the cold upwelling ocean is then cooled and creates a surface-based inversion. The mechanisms of fog formation and lifting of the surface-based inversion are still not completely known. Pelié et al. (1979) analyzed the results from different offshore field programs and discussed some of the main observed features of fog and stratus formation over the California coastal waters. There are some important effects such as the moisture flux (Telford and Chai 1984, 1993), turbulent mixing (Rodhe 1962), radiative processes (L48, Arvin-Calspan 1983), and interaction between turbulent and radiative effects (Oliver et al. 1978).

In order to investigate particular roles of different processes influencing fog formation after the hot spell events, we performed a numerical experiment. We applied a 1D higher-order turbulence-closure model (Koracin and Rogers 1990, Rogers and Koracin 1992) to an idealized case of a hot spell event. The initial conditions were constructed based on the Oakland radiosonde described in the previous section.

Date:1200Z 17 MAY 97.Station: OAK.WMO ident:72493 Latitude:37.73. Longitude:-122.22.Elevation: 3.00

PRES	HGHT	TEMP	RH	DIR	SPD
mb	m	C	%	deg	knt
1012	3	19.2	85	310	3
1009	29	21.6	60	319	4
1000	107	23.6	57	345	6
975	330	27.0	37	46	12
954	522	27.0	37	52	13
925	794	24.8	41	60	14
850	1528	19.4	37	40	12
761	2466	12.4	30	338	10
700	3159	6.2	39	305	11
580	4666	-6.7	68	260	14
556	4995	-8.9	44	247	14

Table 1. Upper air data measured at Oakland on 17 May 1997 at 1200 UTC

The model grid consisted of 180 vertical points from the sea surface to 1200 m. The details on the model setup, initial and boundary conditions will be presented elsewhere. According to preliminary results, fog initially forms in the shallow near-surface marine layer (less than 100 m deep) capped by the hot, dry air mass. Limited vertical extension of the marine layer effectively prevents the outflow of moisture and initiates relatively fast saturation over the cold upwelling waters.

Once fog forms,. radiative cooling at the fog top becomes a significant cause of mixing within the fog layer. Moisture from the surface is then efficiently transported upward and the fog layer increases in depth. The initial u wind component was 3 m/s within the first hundred meters of the shallow marine boundary layer which was characterized by high humidity. The hot air mass was initialized with a temperature discontinuity of 10 °C at the top of the marine layer and u wind component of -5 m/s (offshore). The hot air mass was assumed to be well mixed and with low humidity. For the model, It extended to 400 m ASL.

The fog is simulated first in the moist and cool shallow marine layer and its evolution is significantly determined by radiative processes and the generation of turbulence within the fog layer. After one day the fog penetrates into the layer of hot air and then the growth is faster due to efficient turbulent transport of near-surface moisture and the distribution of the cooling processes. Evaporative cooling may also contribute to the generation of turbulence, while shortwave heating slows the upward growth of the fog layer. Fig. 3 shows modeled vertical profiles of the liquid water mixing ratio at eight-hour intervals during the second day of simulation and illustrates this discussion.

Preliminary analysis of the simulation results indicates that the mechanical generation of turbulence due to wind shear within the shallow marine layer and the wind direction shear at the interface between the hot spell and marine layer, as well as the longwave cooling at the fog top are the main determinants for fog penetration into the hot air mass and further growth.

6. SUMMARY

On the basis of observations and statements in numerous articles by authors of west coastal studies, it is believed that hot spells on the U. S. west coast play a significant role in the initiation of many west coast weather events. These events include Kelvin waves, trapped waves, coastal surges, south wind fronts, the synoptic evolution, the Catalina Eddy, fog, and stratus.

If this indicated role is correct, the LIBS five day fog forecasting system (Lr 1995) may be used to predict when the synoptic situation will be favorable for the occurrence of many of the events which mark west coastal weather. The LIBS system is now being tested at the National Weather Service Forecast Office in Monterey,

.To review, there are two aspects of the synoptic situation associated with hot spells which lead to the occurrence of the weather events listed. Firstly, when the offshore flow during a hot spell reaches a segment of the coast line, the marine layer over this segment is replaced by hot dry air and an alongshore pressure gradient is established. Secondly, when the hot dry air moves offshore the surface air temperature is immediately brought to the lower sea surface temperature and a strong surface or near surface atmospheric inversion is formed. Fog forms under this inversion and grows in depth. It is the top interface of this growing mixed layer which provides a surface upon which the wave phenomena may occur. The alongshore pressure gradient may give rise to surges and south wind events.

The simulation studies using the hot spell model indicated that turbulence due to wind shear and longwave radiational cooling are the primary factors which are relevant to the required initial fog formation and growth.

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