Fog Forecasting Objectively in the California Coastal Area Using LIBS

DALE F. LEIPPER
Reno, Nevada

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ABSTRACT

Weather forecasts and warnings are the most important services provided by the meteorological profession. As one aspect of these services, a year-round fog forecasting objective is selected for California coastal sites and their surrounding areas, both alongshore and offshore. The effort was to provide a simple, straightforward forecasting method using primarily data from the coastal site, which might be supplemented and improved using the forecaster's experience, any new technology, and new results of research. The meteorological objective is to forecast light, moderate, and dense fog, the probability of each occurring, and the expected times of beginning and ending of each period of reduced visibility, both for terminals and for limited nearby areas. Forecasts of five days' duration are sought using a frequently observed sequence of synoptic events. Methods in use were reviewed. The synoptic approach, emphasizing sea–air relationships, has produced the most promising results at this time. This approach led to the method called LIBS (Leipper inversion base statistics), which is described in some detail. It is the only known method that attempts to meet the objective chosen. There are strong indications that the LIBS method is applicable to situations along the California, Oregon, and Washington coasts. Case studies are presented for Monterey, California. Further research is encouraged.

1. Introduction

A person newly interested in West Coast fog forecasting would be overwhelmed by the hundreds of pertinent publications, confused when he or she attempted to coordinate the subject matter, and disappointed when a good forecast method was not readily available.

Regarding present-day forecasts, Hosler (1992) states, "in spite of the considerable progress we have made in predicting day-to-day weather, . . . neither the accuracy, precision, nor usefulness has even approached what the person in the field, in the air, at sea, or in the street might feel was most useful." This is true of coastal fog forecasting as well.

Ballard et al. (1991) writes, "forecasting of the formation, evolution, and the dispersal of fog is one of the most difficult problems facing local forecasters in many parts of the world."

The fog forecaster has the difficult task of predicting the formation and dissipation of a cloud at a specific location, the time of its occurrence, its horizontal movements, its intensity, and the probability of its occurrence. An example is the fog bank approaching La Jolla, California (see Fig. 1). For forecasts of several days duration, the forecaster must utilize synoptic trends that are frequently observed.

Leipper inversion based statistics (LIBS) offers an approach to West Coast fog forecasting that overcomes some of the difficulties described.

Corresponding author address: Dr. Dale F. Leipper, 716 Terra Court, Reno, NV 89506.

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Because of the frequency and intensity of fog on the West Coast, fog forecasting is particularly important. Accurate fog forecasts there, at times, assist in the more efficient routing of countrywide air traffic and serve many other important functions.

a. The fog forecasting objective

Although there are many different ways in which an objective for a fog forecasting method could be described, the following has been chosen.

> The objective is to determine, for a given coastal site and the nearby area, including offshore, the most probable restricted visibility range likely to occur at any given time in the next five days, and also the probability that any more (or less) limited range of visibility might occur. It is sought to do this upon the basis of acceptable physical principles, using practical simplifications, climatology, and commonly observed sequences of day-to-day changes in the height of the inversion base (BI) and its strength over this coastal region. The method developed should be not only simple to use but should be such that its results may be improved by use of the experience of the forecaster, by the introduction of any new pertinent technology and by the results of the latest research.

The LIBS fog forecasting method for California coastal sites and nearby areas is based upon knowledge of West Coast fog, as summarized in Leipper (1994). Other approaches than LIBS to fog forecasting in this area were reviewed. They included climatology, persistence, theory, numerical methods, model output

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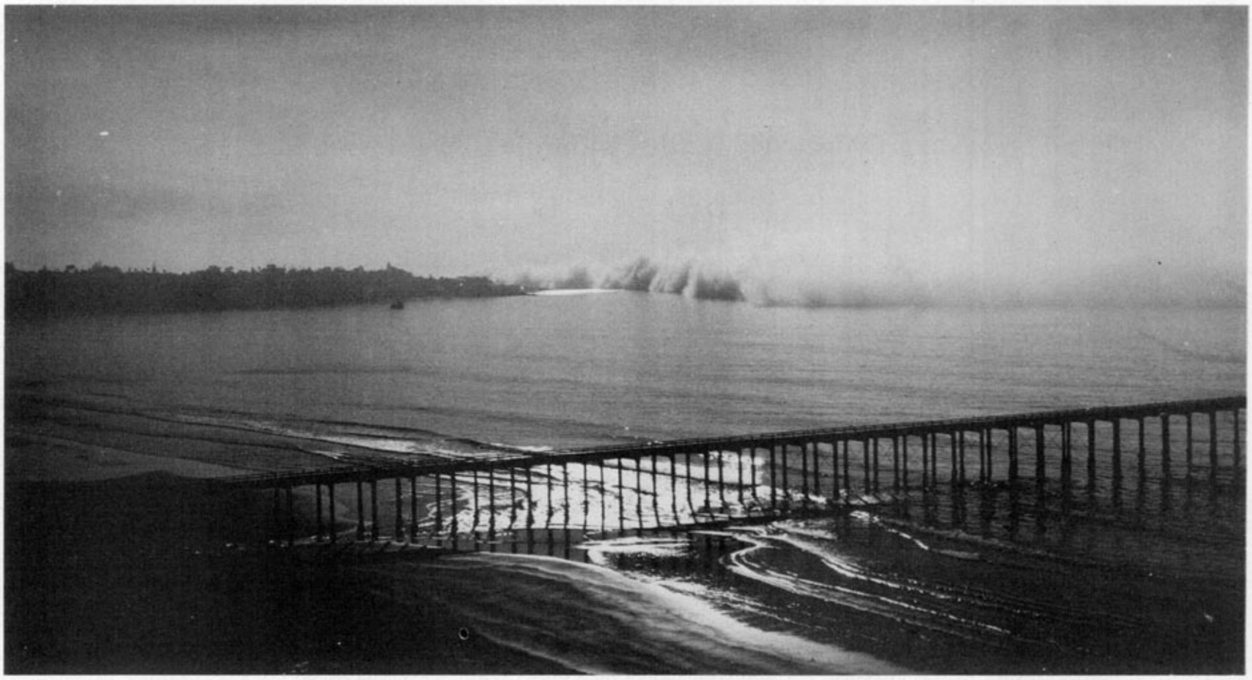

FIG. 1. Fog bank at La Jolla. A fog bank approaching shore in the late afternoon. Photographed from the campus of the Scripps Institution of Oceanography across the Scripps pier toward La Jolla (Leipper 1968). The date and time were not recorded. This type of fog bank is rare and can only occur in phase 1 of a fog sequence. It may occur after a period of offshore winds, when the base of a strong inversion has come down to the surface of the ocean, that is, when the air near the sea surface is 5° to 15°C or more warmer than the sea. It occurs at the time of day when the returning sea breeze is strongest.

statistics (MOS), synoptic evolution, an expert system, and onshore surging. In none of these approaches, other than the synoptic, was it attempted to meet an objective such as that stated here. Once the forecaster is familiar with LIBS, he or she can make fog forecasts easily and quickly.

b. *Definition of fog and site selection*

The useful ranges of visibility are those stated in Leipper (1994) for the three intensities of fog. Dense, moderate, and light fog are defined as fog having visibilities within the ranges of 0–1 km, >1–5 km, and >5–11 km, respectively. In miles, these ranges approximate 0–0.5, >0.5–3, and >3–7 miles.

The "site" in the objective may be taken as any California coastal location where the needed input data are available. The National Weather Service (NWS) west coastal stations are good sites. These stations are usually in positions somewhat protected or removed from the sea and not on the fully exposed open coast. The stations have the advantage of having good data for research, initialization, and verification of forecasts. They are also in locations where forecasts are of great interest. Their observation schedules often permit two-dimensional time series studies that are particularly important to fog forecasting. Forecasts for such stations will, of course, indicate some features of fog in the nearby area. The fog sequences are a real phenomena. A single sequence event may occasionally apply to the entire California coast.

c. *Development of the LIBS method*

The LIBS method came together over many years of analysis, experiment, and practice related to fog research on the West Coast. There were periods of intensive laboratory and field study, such as in the 1970s when as many as 81 research workers, representing some 15 institutions, were taking part in a 7-yr marine fog program. There are more recent developments in models and technologies, such as the eta small-grid model and the various kinds of remote sensing and recording equipment.

The LIBS method (Leipper 1980a) is an extension of the indices forecast approach (Leipper 1948). LIBS adds to the indices approach a means for forecasting for a period of five days, for specifying the intensity of fog and for predicting the time and probability of its occurrence in the area of a given site. The development utilized data from coastal land and nearshore sites within the sea-breeze regime along the California coast from San Diego to San Francisco. In some situations, LIBS can use onshore data alone to predict offshore fog.

It is the occasional west–east movement of the North Pacific anticyclone across the coastline and the circu-

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lation around it that leads to offshore winds. These winds in turn initiate West Coast fog development as they lower and strengthen the inversion. Fairly small changes in the winds may be a major factor in determining values of two fog forecasting indices, the BI range, and the heat index, which are to be discussed later.

Because the Pacific anticyclone changes only slowly and moves relatively systematically over a period of days, it usually provides a dependable feature of the weather upon which to base fog forecasts extending for as much as three to five days (Leipper 1980a).

Since there is a seasonal migration of the average position of the North Pacific anticyclone southward in the winter, the dense fogs occur at different locations along the approximately north–south coast. Thus, on the California coast north of Los Angeles, "the period of frequent fog is from July to October, and that of less frequent fog from December to May. On the lower coast—that is, from Los Angeles southward—the foggiest months are from December to February, and the least foggy from May to August" [Army Air Force (AAF) 1944].

Coastal sites studied in California included Leipper (1948) in the San Diego area and Leipper (1968) in the Los Angeles area. Dixon (1982), Rosenthal (1965, 1972), and others wrote about fog forecasting at Point Mugu, and a number of the listed additional references concerned fog in the Monterey area.

Many offshore field studies, some working as far northward as the latitude of Eureka, have tested the applicability offshore of the San Diego Indices and the presence of fog sequences with four phases, as in LIBS. Useful references for the ocean area off southern California are Noonkester (1979), Backes (1977), Leipper (1980b, 1982), Leipper et al. (1979), Dorman and Winant (1994), and Ueyoshi and Roads (1993). For the central California coast there are Peterson (1975), Van Patten (1980), and Evermann (1976). Farther north there are similar phenomena. A reference for Oregon is Meneely and Merritt (1973). Off the northern coast through Oregon and Washington, the results of Mass et al. (1986) and Mass and Albright (1987) are pertinent to the offshore aspects of the fog phases found to the south. These studies, which represent the entire west coast of the United States, indicate that the Indices and LIBS are useful in adjacent offshore areas.

In the inland direction, the height of the coastal inversion affects the access of the marine layer to nearby areas. This access is, in turn, related to the development of fog in those areas. Knowledge of coastal fog forecasting and also knowledge of coastal stratus are useful in inland fog forecasting. Mass et al. (1986) discuss the inland intrusion of cold moist air from coastal surges. Onshore surges or "marine pushes," which are almost identical to those situations found in phases 2 and 3 in California, have been described for Portland, Oregon, (Jannuzzi 1993) and for the entire Pacific Northwest coast (Mass et al. 1986; Mass and Albright 1987).

Due to the wide areal extent of the synoptic features involved (e.g., Beardsley 1976; Leipper 1980b), and due to the fact that heights of the inversion bases for use in forecasting fog are needed only within large vertical ranges, the nearest early morning RAOB can often be used as the initial sounding in making synoptic forecasts at a given site. The eta 80-km and smaller regional models and the Doppler radar instrumentation may soon provide better information on areal distribution of BI than is now available. However, although Oakland is some 150 km from Monterey, the similarity of coastal fog events from Monterey to Pillar Point as shown in Figs. 2 and 3 is a good indication that the Oakland RAOB provides for Monterey the information needed about the BI range and the heat index. The essential lower-level temperature features of the Oakland RAOB and the LIBS relations of these features to surface visibility ranges have been shown to agree with acoustically measured structures at Monterey over a 1-yr period and also with local test RAOBS made at Monterey (Arvin-Calspan 1983).

2. The LIBS method, general description

Fog forecasting, using LIBS, is considered in two parts (Leipper 1980a). The first is the 5-day forecast of the day to day, or nondiurnal, synoptic weather evolution or sequence, which is related to fog. The second is the statistical determination of the diurnal variation in visibility that is likely to occur in the predicted synoptic situation at a particular site. This determination includes the probability that fogs of different intensities will occur at the site, as well as the probable times of their occurrences.

Knowledge of West Coast fog, described by Leipper (1994), may be used to forecast the fog sequence day by day, objectively or with supplemental synoptic analysis. The 5–15-day fog sequence, its subdivision into four phases, the description of those phases, the relation between BI and visibility, and the variation of height of the inversion base through the sequences are described in that reference.

Changes in BI are often related to the strength of offshore winds. These winds are called by various names at different West Coast locations. The Santa Anas of Southern California are best known. A review of the 34 cases of dense fog in the Monterey area in 1973, when extended observation sites were available (Leipper 1980a), determined that all were associated with periods of days that included offshore winds as indicated by the isobaric patterns. In southern California, 39 of the 42 dense winter fogs that occurred at San Diego in the years studied were preceded or accompanied by easterly or northeasterly (offshore) winds (Leipper 1948). A forecaster may thus assume that most dense fogs at California coastal sites will follow

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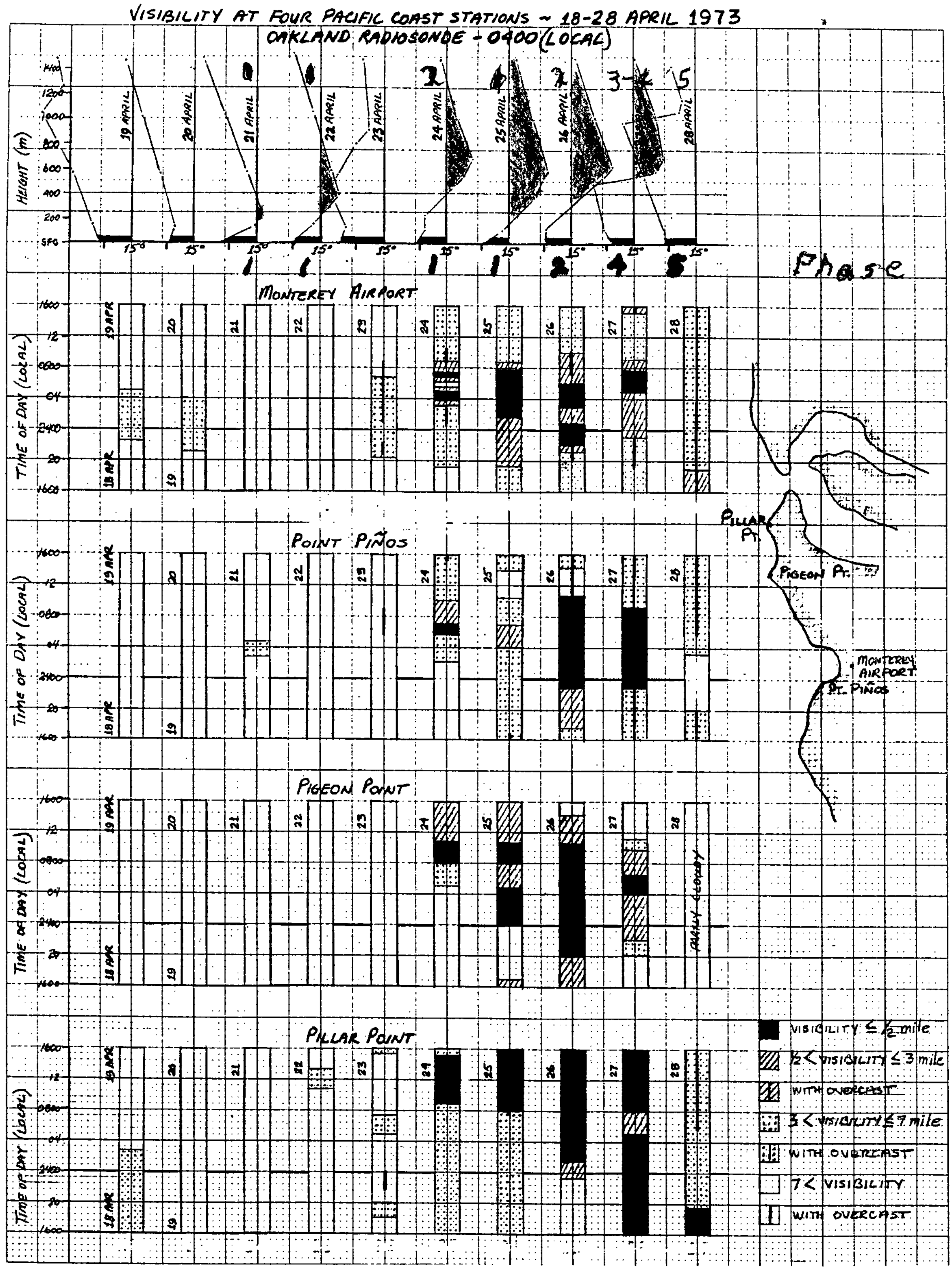

FIG. 2. Extract from a year of similar data in Beardsley (1976). Each vertical bar is a 24-h visibility and fog record; the darker the bar, the lower the visibility. The daily Oakland, California, RAOBS are plotted on a rectangular grid, with the 15°C as a common reference temperature. Three of the sites are on the open coast and the fourth is at the Monterey Airport. Reproduced from Leipper (1994).

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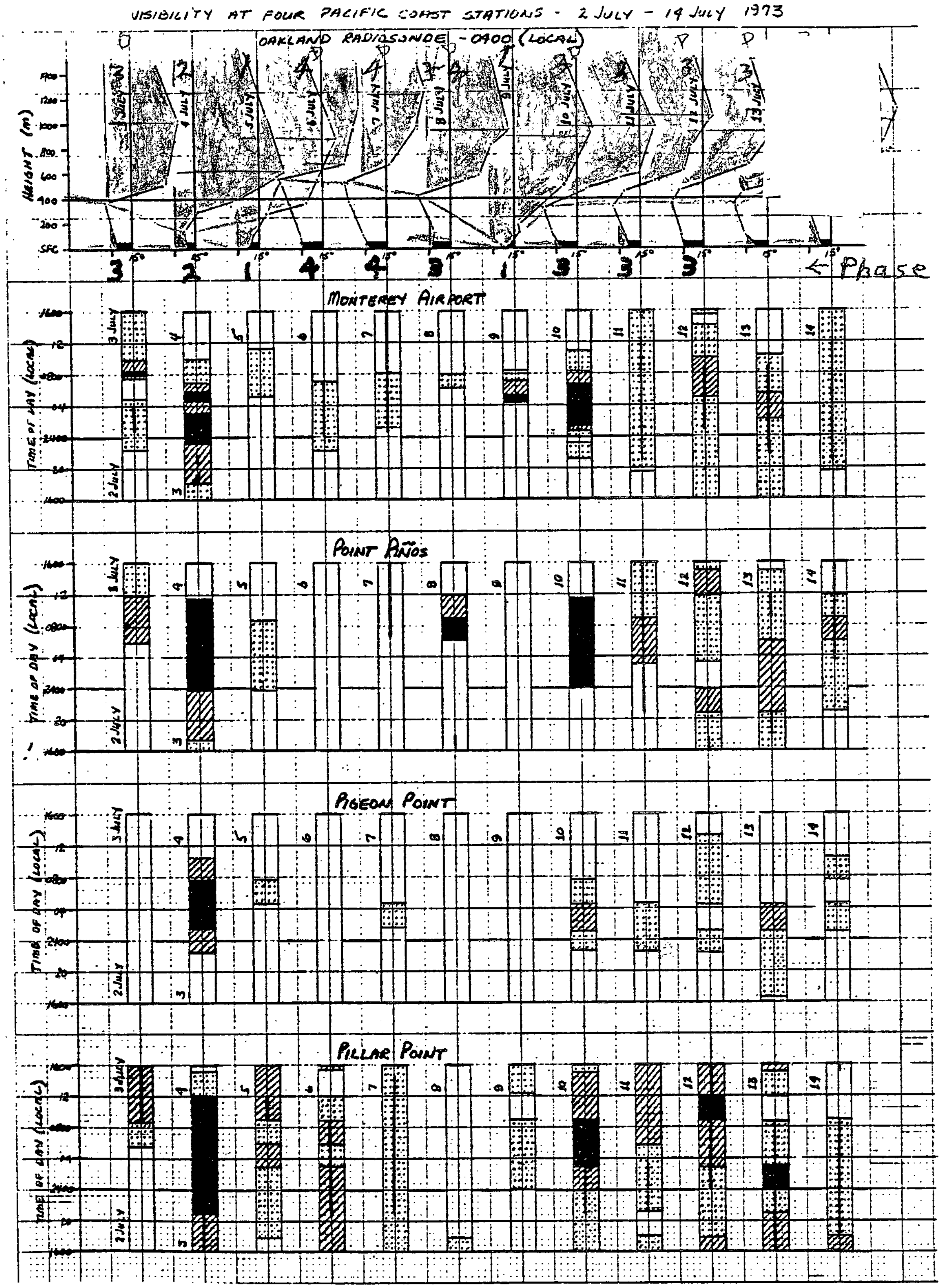

FIG. 3. Same as Fig. 2 except that the dates are 2–14 July 1973.

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offshore wind periods. Occasional frontal, stratus lowering, or radiation fogs may be exceptions, but these often follow much of the same synoptic fog sequence as LIBS (Peterson 1975; Arvin-Calspan 1983).

In a typical fog sequence, the BI is brought to zero by a strong offshore, downslope wind. When this wind dies, the BI increases gradually through three additional phases. The four phases of a typical fog sequence then are the initial conditions, fog formation, fog growth and extension, and stratus.

Briefly, phase 1 has strong offshore winds; a semi-ovular clear area offshore; zero or near-zero BI; and hot, dry air with very high visibilities ashore. The zero BI is present over the sea when the air temperature (Ta) is greater than the water temperature (Tw). A difference of 5°C or more is a good precursor of fog. The low inversion may not show at a land RAOB site where the surface temperature may be abnormally high, but its presence offshore at the same time is critical to fog formation.

Phase 2 has shallow, cold, dense, often patchy fog at sea approaching the coast in wide bands, possibly touching the coast in midafternoon. Here, BI is between 0 and 250 m.

Phase 3 has deeper, more widespread, less dense fog at sea and more encroachment over land. Here, BI is between 250 and 400 m.

Phase 4 has no fog ashore but a low stratus overcast. Here, BI is 400 to 800 m.

As a measure of the strength of the inversion, a second index, other than BI as already described, is found to be useful. It is what will be called the "heat index." This is the amount by which the temperature of the warmest air in the lowest 1000 m at the site area exceeds the sea surface temperature at the coast. The value of Tw is indicated in Figs. 2 and 3 by the left end of horizontal bars at zero height.

The shaded areas in Figs. 2 and 3 show an anomaly, Ta > 15°C, and, although such plots are not essential in making the LIBS forecast, they are helpful in visualizing the sequence progression. The rectangular plot is used instead of a Skew *T* diagram because it is simple to plot and easy to read, and because subsidence is not significant at these low levels in coastal fog situations.

The marine push and the rising moisture index often can be recognized in Figs. 2 and 3 by the haze appearing in the late afternoon on a day before a fog event. Phases 1 and 4 are shown by clear days and stratus days, respectively. Phases 2 and 3 are best identified by the BI range, with fog occurrence, or by the areal distribution of fog and clear areas offshore shown on remote sensing images. The airflow in phases 2 and 3 is a delicate balance between offshore flow, sea breeze, and seasonal geostrophic flow. Also, intense circulations such as the Catalina Eddy and the marine push may develop offshore in these phases. Phase 1 has strong offshore flow and phase 4 is the prevailing seasonal flow.

The forecast based upon the fog sequence gives the general synoptic situation for each day of the forecast period. The hour by hour terminal visibility forecasts within each of these days will be obtained by using a procedure to be outlined later. The focus here is on the 5-day sequence of synoptic situations.

Table 1 of Leipper (1994) shows that from the day of lowest BI in a sequence, the average BI increases systematically. However, the increase in individual cases may be at a greater rate than the average increase.

Fog forms at sea when the BI is at or near zero. It increases in depth systematically up to 400 m, making it predictable by the LIBS method. It is not agreed upon whether the fog formation in phase 1 is by water-vapor-driven convection (Telford and Chai 1984, 1993), by radiation and mixing (e.g., Ackerman et al. 1993), or by cooling or heating from below (Leipper 1982). However, fog creates the mixed layer and not vice versa.

The 400-m guideline for depth of west coast fully developed fog and stratus banks can be checked by observations in time plots of ceilings and cloud tops such as shown by Blake (1948) for San Diego, Lea (1964) for Point Mugu, and Cole (1964) for Monterey. The guideline has been used in West Coast fog forecasting since 1948.

These 5-day forecasts are not dependent upon local synoptic climatology. The procedure is applicable at any site on the California coast, with the possible exception of the coast influenced by the Catalina Eddy (Ueyoshi and Roads 1993).

3. Procedure for the LIBS objective 5-day forecast

a. The no-fog forecast

As long as the air below 1000 m is colder than the sea, no fog is to be forecast for the shore station for the next several days. Before fog forms, it is necessary that an offshore wind develop to create a strong, low inversion. Then sea–air interaction must form the fog. After that, the sea breeze regime must redevelop to bring the fog ashore. This total development would nearly always take several days or more. Meantime, no fog is forecast.

b. The beginning of a fog sequence

Predict the beginning of a fog sequence when the initial conditions are observed or predicted. The prefog indications (i.e., the initial conditions) of the beginning of a fog sequence are an extension inland of the Pacific anticyclone, a strong offshore component in the geostrophic wind, an unusual warming relative to the sea surface in the lower 1000 m of the atmosphere at the coast; visibilities of 20 to 50 miles, and a growing semi-ovular clear area off the coast.

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TABLE 1. Ranges of the height of the inversion base and the associated phases of fog development.

BI Range	0 m	>0–250	>250–400	>400–800	>800
Phase Number	1	2	3	4	5 (extension)

c. The successive days of the sequence

Before any fog occurs, the forecaster, given strong initial conditions, could predict with some confidence that, for a coastal location, there will be several days (24-h periods beginning at 1600 LT) of foggy weather within the next week, that the high temperatures will be replaced by lower temperatures in fog, that on the first day of fog it will probably be very dense but patchy and it might occur briefly just as the offshore wind eases off, that the second day the fog will be less dense but more highly probable and less patchy, that the third and fourth days the fog will be still less dense and not so highly probable, and that the fog may lift to become stratus. As is well recognized, meteorological forecasts of five days have some uncertainly. Other than LIBS, the author believes there is no west coast fog forecasting approach for variable conditions that can be used with as much confidence.

The day to day forecast is a forecast of the synoptic situation as represented on successive days by the phase of the fog sequence that is predicted for that day.

To make a purely objective fog forecast, it is assumed that the typical sequence will occur as indicated in Tables 1 and 2.

d. Deviations from the typical sequence

If the developing weather deviates from the typical sequence progression of Table 2, the BI range for forecasts must be determined by other means. One way is to predict a positive trend starting at the most recent observed value of the BI. The recommended rate is 200 m day^{-1}, which is on the low side. A strengthening of the offshore wind component could reverse this rising trend of the BI. The early morning predicted BI range determines the phase of the fog sequence (see Table 1) associated with it. The phase description for the forecast value of the BI range (Leipper 1994) then becomes the forecast of the synoptic situation for that 24-h period. The period begins at 1600 LT (UTC-7 in summer) on the afternoon of the calendar day before the predicted early morning BI range.

The 6-day objective forecast would be from line 2 in Table 2. In lines 3 and 4, this table includes the observed values in two case studies of fog sequences.

e. Additional considerations

The day to day synoptic forecast may be thrown off the usual rate of sequence progression by unusual changes in the offshore wind component. The flow may not be strong enough to heat the lower atmosphere to a temperature above the sea temperature. A renewed strengthening of the offshore flow may reverse the direction of the sequence or slow its progression. Changes in the wind sometimes are not detectable except by their effect upon the fog indices, the BI and the heat index. A frontal passage or other unusual synoptic event may interrupt or end the sequence.

For a forecast utilizing synoptic experience and skill, the forecaster could do two specific things. First, he could attempt to predict the day the offshore wind will cease (the offshore wind period may be only one day or as many as six days, rather than the assumed 2-day period of the objective forecast). Second, he could predict, for any good reason, a different rate of change in the increasing BI range. The average rate seems to be the same in all seasons.

The BI range, both physically and statistically, relates well to the diurnal range of surface air temperature, the probability of fog, the intensity of pollutants, and other variations that take place in the mixed layer (e.g., Lockhart 1935; Petterssen 1938; Leipper 1980a; Telford and Chai 1984; Telford and Keck 1988; Arvin–Calspan 1983; Eddington 1992). The strong inversion under dry, very warm air guarantees that there will be no precipitation to affect visibility. Thus, the statistics relating BI and visibility include air pollution effects. They are not affected by precipitation. The LIBS visibilities quite likely represent the true measured visibilities.

Of value in forecasting BI range for fog is the fact that after studying a full year of variation, Peterson (1975) found essentially what Blake (1948) found for stratus regimes: "the graphs for maximum daily surface temperature in the inland valley and maximum temperature at the top of the inversion at the coast displayed patterns in their increases and decreases so closely related that, except for the difference in the absolute temperatures, one could be used in lieu of the other." Further, variations of these two quantities are

TABLE 2. Days of a typical fog sequence with associated heights of the BI and the phase of fog development; a forecast guide with two case examples.

Day of sequence	1, 2	3	4	5	6
BI forecast height (m)	0	200	400	600	800
Typical phase	1	2	3	4	5
24–28 April 1973	1	2	4	5	
24–28 June 1993	1	2	3	4 est	

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directly related to variations in the BI (Blake 1948; Leipper 1980b). These correlations may provide a means for prediction of BI at the coast using the eta or a similar regional model and inland data.

A description of the regional inversion base height pattern is given by Neiburger et al. (1961). There are other studies pertinent to BI forecasting (Edinger 1963; Lea 1964; Lilly 1968; McClure 1974; Rosenthal 1965, 1972; Stephens 1965; Telford and Chai 1984; Telford and Keck 1988; Oliver et al. 1978; Leipper 1980b; Backes 1977; Venkatram 1986). A comprehensive summary of factors affecting BI in situations such as those on the West Coast is contained in Melas and Kambezidis (1992).

4. Background for the 24-h procedure

The BI controls the diurnal variation of visibility. For the hour to hour visibility determinations with a given BI range (or phase) and for preparation of fog forecast worksheets, each BI range is considered separately. Only days after the strong offshore winds have ceased and that have Ta > Tw at some level below 1000 m are involved. Sea–air interaction then becomes a major factor. The average beginning and ending times of fogs of different intensities are determined for the site selected. The visibility statistics for that phase or BI range may then be presented as a line in a table made for the particular site as in Table 3. The number of cases of fog compared to the total number of days with the same BI provides an indication of probability of occurrence. Table 3 indicates a method for organizing the synoptic climatology for other sites that have different influences on diurnal variation of visibility than does Monterey. For West Coast sites, the diurnal statistics with a given BI may not turn out to be greatly different from each other.

Graphical representations of data compiled, as in the table referred to above, are included here as worksheets (see Fig. 4). Use of the worksheets will be illustrated under the LIBS 24-h forecast procedure. The times for beginning and ending of light fog are variable and not restricted to the average bar length shown in the worksheets (see Table 3).

Although Figs. 2 and 3 show the hourly visibility for three coastal stations as well as Monterey Airport, it is important to remember that the visibility data represented on the worksheets (Fig. 4) are for the Monterey Airport, where the data for the statistics were collected.

This LIBS procedure is for making objective hourly terminal forecasts in segments of 24 hours or less for a chosen site. As mentioned, the 24-h segments begin at 1600 LT each day. They are based upon the concept that given the height range of the BI, the associated diurnal variation of visibility in the fog ranges is determined by synoptic climatology as represented on worksheets. The associated RAOB is that forecast to occur the next morning.

5. Procedure for the LIBS operational 24-h fog forecast

a. Check for the no-fog situation

If the 5-day sequence forecast has not been made, observe the most recent early morning RAOB representing the area in which the site lies. If the air at all levels below 1000 m is colder than the sea surface and no strong offshore component of wind is expected that day, or if the relative humidity at 10 000 feet is over 40%, then no fog will be forecast.

b. Check for fog sequence initial conditions

If there is a strong offshore component of the geostrophic wind, there is a good chance that a fog se-

TABLE 3. Visibility frequencies versus height of the BI, air warmer then the sea, Monterey Airport, California, April–November 1973.

Number days	Height BI (m)	Percent of days with visibility			Midtime of occurring fog			Average duration (hours)		
		0–0.5	0–3	0–7	0–0.5	0–3	0–7	0–0.5	0–3	0–7
69	0	28 (19)[a]	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	12.0	20.0
35	250–400	34 (12)	71 (25)	97 (34)	01–08 04–06[b]	01–09 04–05	anytime	3.5	7.6	19.5
53	400–800	6 (3)	40 (21)	89 (47)	02–09	21–10 00–06	anytime	4.7[c]	8.3	15.6
79	over 800	3 (2)	6 (5)	27 (21)						

[a] Number of days it occurred.
[b] Most occurrences were in this interval.
[c] This very seldom occurs (3 times).
Reproduced from Leipper (1994).

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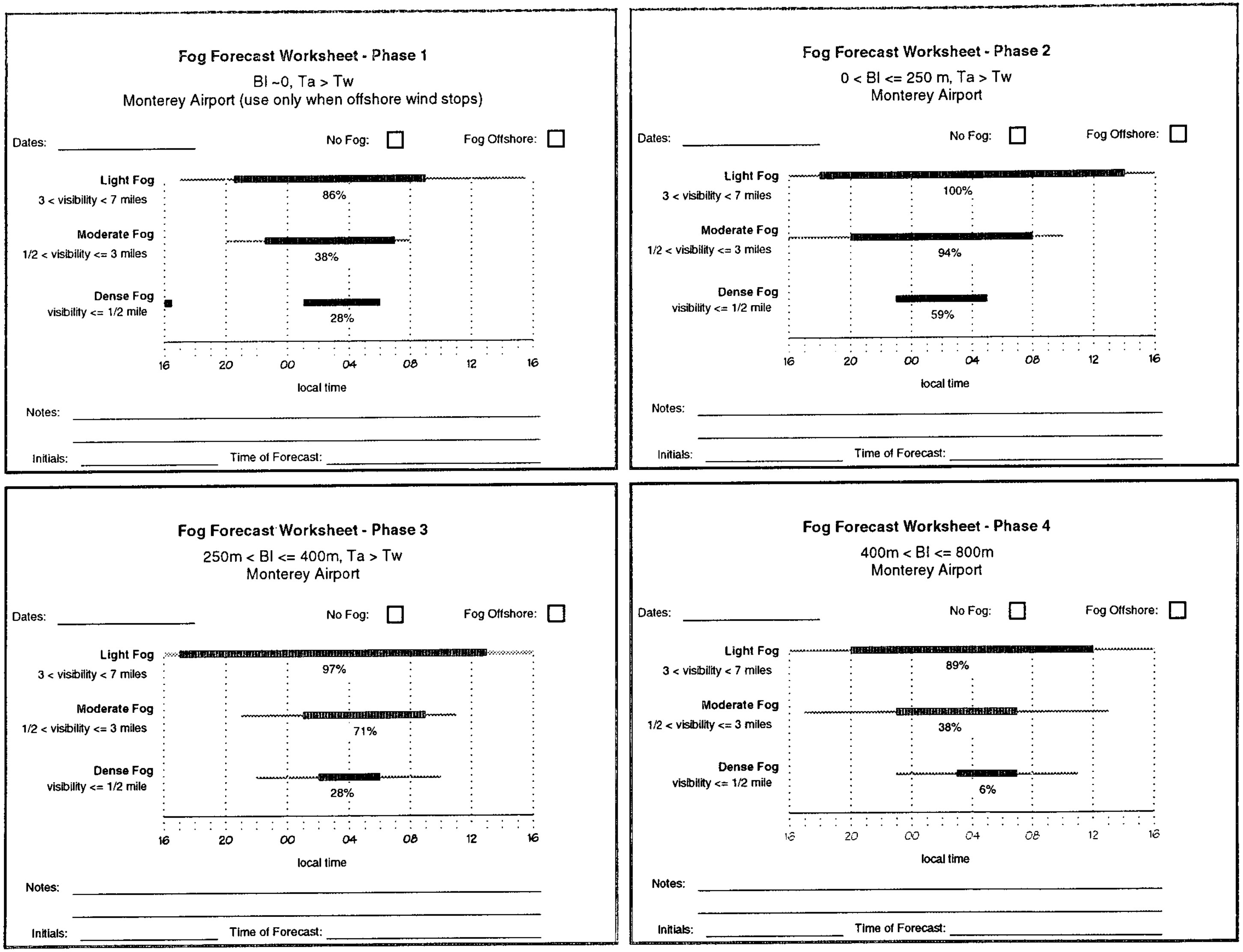

FIG. 4. Worksheets for the LIBS 24-h fog forecasts at Monterey Airport. These are graphical forms representing synoptic climatology values from the lines of Table 3. Probability of occurrence during the 24-h period is entered. The horizontal bars represent the expected duration of fog and its beginning and ending times. Here, Ta is the temperature of the warmest air in the lower 1000 m; Tw is sea surface temperature. Persistence, climatological, and verification data may be entered when available. The forecast may be modified accordingly, if necessary.

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quence may be starting. Check the morning RAOB. If air at some level below 1000 m is warmer than the sea, and the relative humidity of the air at 10 000 feet is less than 40%, fog may occur. In this situation, a LIBS 24-h forecast should be made. This LIBS procedure is used for that purpose.

c. Objectively determine expected BI range

If the 5-day sequence forecast has been made and is progressing as expected, select the range into which the BI will fall for the coming morning from Table 2, which shows the usual progression of BI in a fog sequence (0, >0–250 m, >250–400 m, >400–800 m, or BI > 800 m).

d. Check the fog guide lines

Apply the forecast BI range and surface moisture criterion as described by Leipper (1948), that is, if the forecast BI is less than 400 m and the afternoon dewpoint is higher than (Tw − 5°C), fog may occur and the LIBS 24-h forecast procedure should be continued. Otherwise, predict no fog.

e. Select the appropriate worksheet

To make a LIBS 24-h forecast for the Monterey Airport, if it is decided that fog may occur, the predicted BI range determines which worksheet from Fig. 4 is to be used. It should be noted that the vertical axis on the worksheets is not a visibility scale but rather consists of three independent lines, each representing one fog intensity and the corresponding visibility range. The ends of each bar show the average times of beginning and ending.

Figure 4 contains one worksheet for each predicted range of BI except BI > 800 m. Each of these worksheets indicates the fog intensity to be forecast for the coming 24 hours at that site under the synoptic situation (range of BI) expected to occur. Judgment should be used if deviations from the statistical forecast seem indicated. Probabilities should be noted. Changes in probability are often the most significant changes from phase to phase. Case studies (hindcasts) are presented below for Monterey. For BI of 800 m or more, called phase 5 by extension, there is no worksheet, but the probability of dense fog is 3%, moderate fog is 6%, and light fog is 27%, while the strong inversion exists (see Table 3).

f. Verification

The observed values from the forecast period may be entered on the forecast worksheet as they become available for updating the forecast or for partial verification. Also, on this worksheet, the previous day's observed visibility values may be entered, if desired, for persistence comparisons. By use of the applicable worksheets, additional days may be forecast as far ahead as the range of BI can be forecast.

g. Nearby offshore area forecast

To forecast for nearby offshore areas, use the predicted BI range to determine the associated typical phase within the fog sequence (see Table 1). Each phase corresponds to one of the characteristic forecast periods, that is, one of the worksheets in Fig. 4. The phases, as described in Leipper (1994) and reviewed briefly above, outline expected features of the patterns of foggy, clear, and cloudy areas offshore that may be expected with the different BI ranges applicable to that area.

This concludes the 24-h procedure.

6. Case studies

a. Selecting sequences for case studies

Sample hindcasts could be made readily for any day at Monterey. However, the selection of a fog sequence of several days would add considerable interest over single-day cases. One valuable set of observations made in the research-intensive 1970s was that set included in Beardsley (1976). The collection includes regular and special observations, both on the coast and offshore, for most days of 1973. Figures 2 and 3 reproduce 10-day samples of these data. Also, Oakland RAOB data, which are applicable for the area, and hourly visibility data are included, not only for the Monterey Airport but also for three nearby (within 150 km) coastal sites. The 23–28 April 1973 period was chosen for a case study.

The 1973 sequence is applicable at the nearby sites. Comparing visibilities at the four sites in Fig. 2, when there is foggy weather or stratus at one site, there is almost always foggy weather or stratus at the others. This means that the Monterey Airport forecast usually may be applicable at these other locations. The timing and intensity are very similar from place to place, although the locations are quite different. These facts support the conclusion that the BI indicated at Oakland may be used over a coastal region extending to Monterey.

There are slight differences between the fogs at the four sites in Fig. 2. Pillar Point has the most dense fog. Its duration increases steadily from 24 to 27 April. Monterey Airport, being more protected from the sea, has the shortest periods of dense fog. All four sites have stratus on 28 April, with fog only at Pilar Point on four hours at the end of that 24-h period. As mentioned, similar comparisons have been carried out through most of the days in a full year.

The 1973 case study was based almost entirely upon shore-based data. The surface weather maps for this case study are reproduced in Fig. 5. There are many days without fog at Monterey. In the foggiest months, there are only two or three fog sequences.

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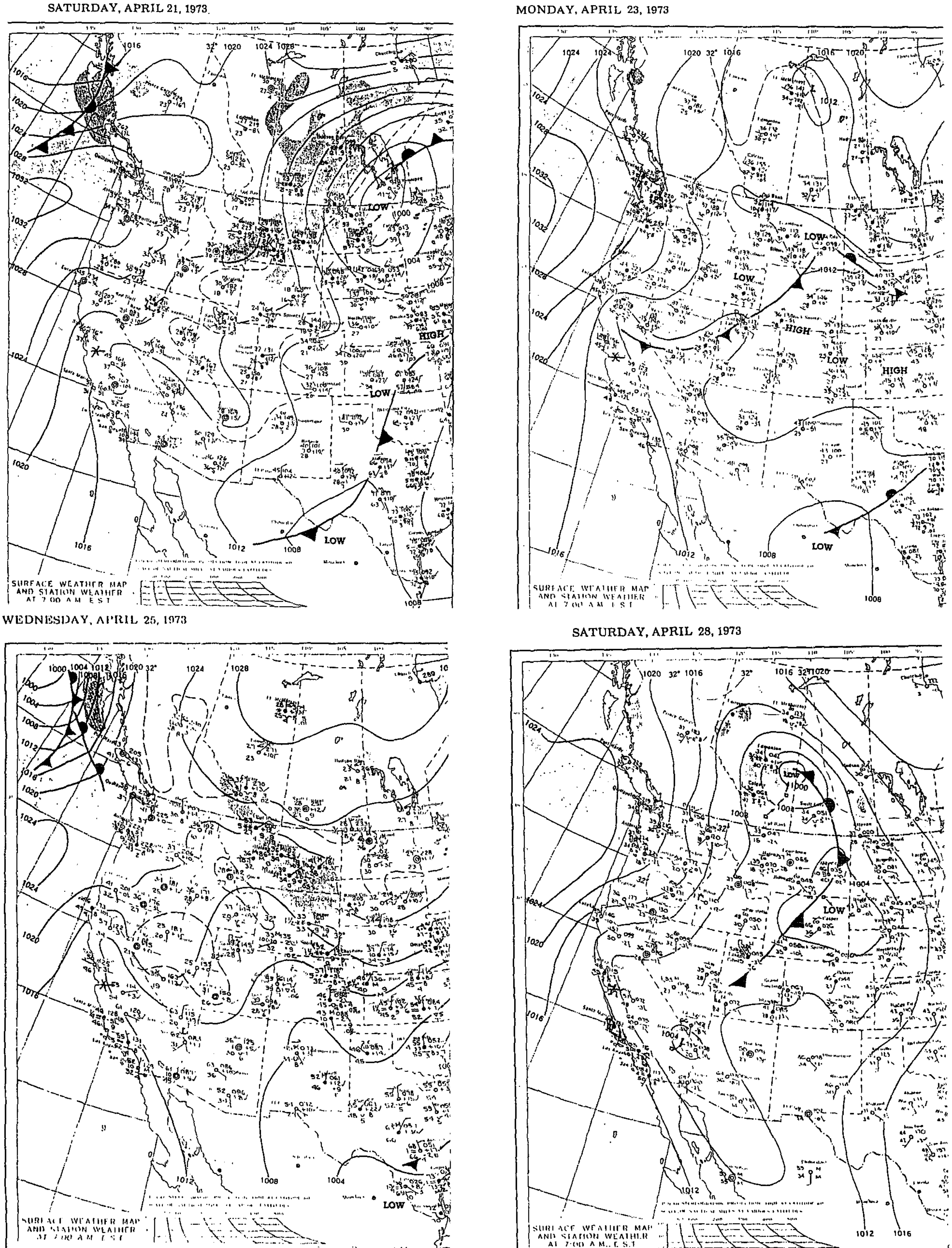

FIG. 5. Surface weather maps for the April 1973 case study from the files of the National Weather Service. The * indicates the Monterey area. Of particular concern is the offshore component of the geostrophic wind at Monterey.

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For a more recent case study, the year 1993 was chosen. A different approach to this LIBS case study was taken. It will indicate some of LIBS useful aspects. Fewer hourly observations were available from Monterey Airport in 1993 than in 1973, and none was available from the three coastal sites. On the other hand, an advantage of 1993 over 1973 was the availability of daily satellite images in 1993.

Expected fog sequences in 1993 were picked by surveying the NWS daily published surface weather maps for the year and choosing two synoptic situations typical of the initial fog phase. These were situations where there was a strong offshore geostrophic wind component at the latitude of Monterey. One situation selected was 23 June 1993 and one on 14 November. Fog sequences were expected to follow. Thus, it was expected that the LIBS procedure would be pertinent, and the 6-day period 23–28 June 1993 was selected for a case study in that year. (It was soon obvious that the November sequence was not going to develop. The air did not become warmer than the sea.)

b. Case study of April 1973 fog sequence

Some of the changes in successive RAOBS of this sequence, as shown in Fig. 2, are explained by changes in isobaric patterns on readily available weather maps. The lowering of the BI and the variation in the heat index seem to depend primarily upon the strength of the offshore geostrophic wind component. The increases in the BI seem to be the result of airmass modification over the sea.

No 500-mb maps are shown here since the essential features related to the sequence can be described readily. Looking at the NWS daily published 500-mb charts, the North Pacific anticyclone shows an intrusion into Washington at 0700 on 21 April, the first day of the sequence. On the next day, it extends inland no farther but has moved south over Oregon. By 23 April it has moved farther south with the inland extension broadened out and isobars running parallel to all of the California coast. This pattern holds until 25 April when a col forms offshore from California and persists through 26 and 27 April. On 28 April, the last day of the sequence, the normal pattern returns.

Four 0700 LT surface maps within the sequence period are shown in Fig. 5 for 21, 23, 25, and 28 April 1973. These four maps show about all that can be derived from readily available surface synoptic maps to aid in forecasting the progression of the fog sequence. Their value for this purpose is quite limited. On the other hand, the BI and the heat index do change considerably and are thus more useful in similar situations.

As shown by the RAOBS in Fig. 2, by 21 April there had been three days of warming in the Monterey area with an offshore geostrophic wind component. The air in the lower 1000 m is still colder than the sea on 21 April. The warming continues through 22 April but, as shown on the map for 23 April and the RAOB for that day, a cold front disrupted the warming trend. This was only temporary.

The RAOB for 24 April shows that the warming trend had recovered from the frontal disruption and that air above 400 m is now warmer than the sea. From 600 to 800 m it is some 8°C warmer. Phase 1 of the fog sequence now begins. The map for 25 April shows that the California thermal low has reasserted itself northward past Monterey, while the RAOB for that day shows the most warm air (the highest heat index) in the sequence, as well the strongest and lowest BI. These three phenomena go together.

From 25 to 28 April, the BI gradually increases through fog sequence phases 2 and 3. Then the isobars at the coast parallel the coast and the higher BI (over 800 m), phase 5, shown on the RAOB, are associated with partly cloudy weather and stratus at all four stations.

The changes in BI and in the heat index are traced much more easily than are the synoptic map changes. From Fig. 2, consider the day to day sequence in which all of the following cases, 23–28 April, are included. All of the BI ranges fall into a natural sequence: first, no air warmer than the sea, then air becoming warmer than the sea and BI near 0 (two days), and BI > 0–250 m, >250–400, and >400–800 on successive days. The orderly progression of categories gives some hope of aiding in prediction of the BI ranges. Careful monitoring of the winds with regard to offshore components will help to predict changes in the BI range and heat indices.

Study of remote imagery now available from satellites also will illustrate the progression through the four fog phases of the fog sequence and thus will improve forecasts. Images were not available for the 1973 sequence. However, Fig. 7 presents examples from the 23–28 June 1993 fog sequence, which shows images during the different phases.

c. Other sequences in 1973

Between April and November of 1973, there were some 20 other fog sequences when LIBS might be used. Some of these were incomplete sequences, or ones not ideal, as might be expected in any meteorological phenomenon. As mentioned, the most common cause of deviations from the ideal progression in a sequence is unusual variation in the offshore component of the geostrophic wind. These changes are difficult to observe but they noticeably affect the BI and heat indices.

Figure 3 is a July sample from the Beardsley (1976) data, which is characteristic of the summer period. At this time, the air above the BI is almost always warmer than the sea and the inversion is strong and low. Figure 3 shows a large heat index, one that changes within the period. The BI came below 400 m twice in Fig. 3 and there was dense fog at Monterey associated with each

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descent. In each instance, except the one time on 10 July at Pigeon Point, dense fog also occurred at each of the three sites on the open coast. As expected, there was stratus instead of fog when the BI was over 400 m, even slightly over.

As mentioned, Beardsley (1976) presented most of the days of 1973 in the same form as the samples shown in Figs. 2 and 3. Shading in the heat index on these other days and then surveying them and the station hourlies with LIBS in mind provides a fairly complete case study for each day represented. The sea surface temperature for each day is indicated at the left end of the black bar at the zero height. The variation from one sequence to another is apparent, as is the manner in which the heat index and the BI are related to the progression of each sequence. There are obvious differences between the behavior of the LIBS indices in different seasons. Comparison of Figs. 2 and 3 provides examples of these differences. When the air is warmer than the sea, the 400-m height is shown to be a practical dividing line between days having fog and those having stratus.

d. Case studies of 24-h forecasts in April 1973

Each of the 24-h case studies in 1973 was made using the LIBS 24-h procedure as described above. The 24-h segment (fog day?) begins at 1600 LT and carries two dates, that of the calendar day on which the visibility forecast begins and that of the next calendar day. The RAOB forecast is made for the early morning of the second date, that is, about 12 hours after the visibility forecast begins.

The 24-h forecasts for each of five days in the 1993 sequence will be described in some detail later. Because of this, the forecasts for April 1973 have been made without detailed explanation. The results for 1973 are indicated on the verification worksheets. Readers may judge for themselves as to the success of the LIBS forecasts (see Fig. 8).

In these 24-h case studies for 1973, the observed BI ranges were obtained from Fig. 2. These values determined the proper worksheet to use, selected from Fig. 4. Data for making the forecasts (hindcasts) and the verifications were obtained from Fig. 2.

Verification of the hourly visibility forecast is made by plotting the observed hourly visibilities for the period covered by the forecast and comparing them directly to the hourly values forecast on the worksheet.

e. Case study of the 5-day objective fog forecast in June 1993

In preparing the 1993 case study of a fog sequence, the order in which it was possible to obtain the input data and information provided an opportunity to test some of the concepts involved in LIBS. This testing is described below.

As mentioned, the dates of 23–28 June were selected as probably being a fog sequence suitable for a case study. After there had been opportunity to review the daily surface maps (see Fig. 6), the hourly observations for Monterey Airport were obtained from the Western Regional Climate Center satellite link. Looking at the hourlies, many additional indications of the fog sequence were found. As for visibility, the days of 23, 24, and 25 April were unusually clear. Visibilities on the last two of these days were from 30 to 55 miles. Temperatures rose to a very unusual 84°F on 24 June and to 82°F on 25 June. The extremely good visibilities and the unusually hot weather were strong signs that the area was under the influence of a downslope, offshore wind. The daily maximum dewpoints rose slowly from 52°F to 54°F to 56°F from 23 to 25 June, indicating some return of marine air with a slight sea breeze at the surface. The surface winds were generally from the northwest quadrant at less than 10 knots. The strong offshore geostrophic wind, indicated by the surface isobaric pattern, had no significant reflection in the surface observations. All of this fits well with fog sequence phase 1.

A decision must be made by the forecaster as to when the fog sequence will begin. The unusually high maximum surface temperature and the high heat index (11.3) (see Table 4) on 24 June, together with the 1601 satellite image (Fig. 7) showing a good semiovular clear area offshore indicated that 24 June would be a good choice for the first day in a sequence. It was selected. This choice establishes a sequence that is a 5-day forecast as laid out in Table 2.

The hourly observations for the next 5 days show how well the 5-day objective forecast worked out. Unfortunately, in 1993, observations are no longer available for this Monterey Airfield site after 2300 LT and before 0600 LT. These are the hours when fog occurrence is most probable, as may be seen on the worksheets (e.g., see Fig. 8). However, there was fog in other hours on 26 and 27 June. Moderate fog was reported on the 0600 LT observations in both periods. The fogs extended into the mornings.

From the surface observations of visibility variations alone, by LIBS relationships, it was deduced that the BI on 24 and 25 April was near zero, on 26 April it was from 0 to 250 m, and on 27 April it was between 250 and 400 m. Stratus with rising ceilings was observed on 28 April and, again from the surface hourlies, it was deduced from LIBS relationships that the BI on that day would be over 400 m. These deductions, except for the last day when there was no RAOB, were shown to be correct by RAOBs obtained later.

Still from the hourlies, when the observation schedules resumed at 0600 LT, the visibilities on the 26 April were 1.5 miles in fog, and on 27 April were 2 to 5 miles (a fog bank had been sighted for much of the previous day, west through north). On 28 April, visibilities were 10 miles, with broken clouds at 800 to 1100 ft. This is

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THURSDAY, JUNE 24, 1993 FRIDAY, JUNE 25, 1993

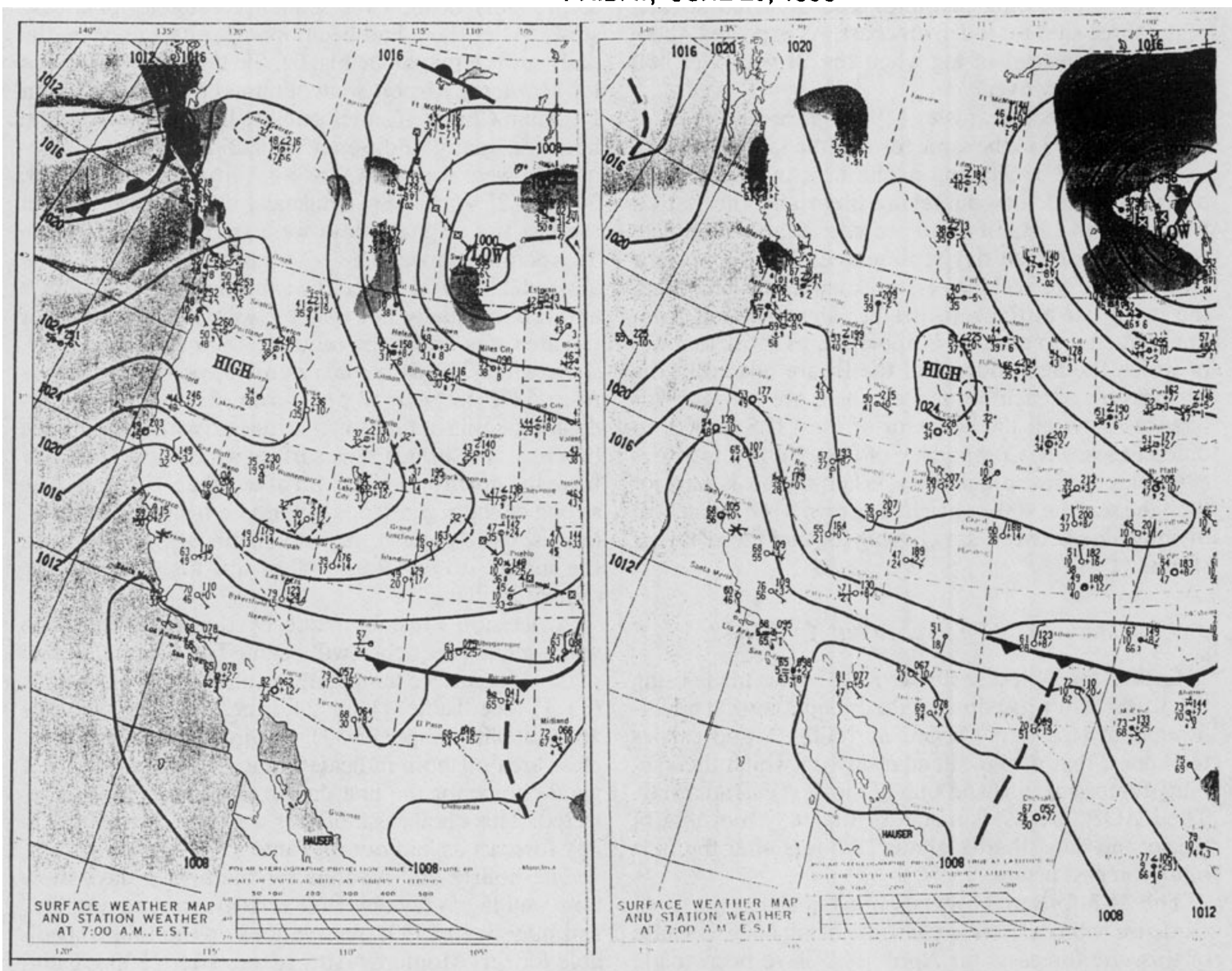

FIG. 6. Surface weather maps for the June 1993 case study.

the sequence of visibilities to be expected from phases 2 to 3 to 4 of LIBS, that is, nearly dense fog to moderate fog to stratus overcast.

On 26, 27, and 28 June, the hourlies showed the surface winds were 360° to 310°. They shifted more westerly to 310° to 240° on the 27 and 28 June. Speeds for these days were a little greater than they were on the preceding three days, being mostly between 8 and 10 kz but rising as high as 15 in the evening of 28 June. The relatively small changes in surface winds are not utilized in the LIBS method. Other hourly observations, as described, do support the concept of a fog sequence.

Next, the RAOBS for the sequence period were obtained. They were extracted from copies of the historical National Climatic Data Center (NCDC) Upper Air Data tapes at the Western Regional Climate Center. With the data now at hand, it would be possible to prepare a graphical presentation in the form of Fig. 2. However, a simple table (see Table 4), will contain the elements of the RAOB data essential to check the objective 5-day forecast that had been made on 24 June.

From the early morning RAOBS, Table 4 was prepared. In this table, Ta is the highest air temperature below 1000 m. The sea surface temperature was taken to be 14°F. The relative humidities are in percent at 3300-m altitude. The winds are at 1000-m height. Directions are in degrees, with north being 000° or 360°, and speeds are in knots.

It is seen from Table 4 that the observed BI values, 6 m (taken to be zero offshore) for 23–24 June agreed with the satellite image of a clear area on 24 June. No fog formation showed. On 25 June, the morning RAOB showed a 6-m inversion, but later in the day at 1600 LT, the satellite image showed patchy fog indicating that the inversion was no longer zero offshore but that phase 2 had started. The BI was 133 m for 26 June and 337 m for 27 June. Both fall within the ranges deduced from surface observations in the fog sequence

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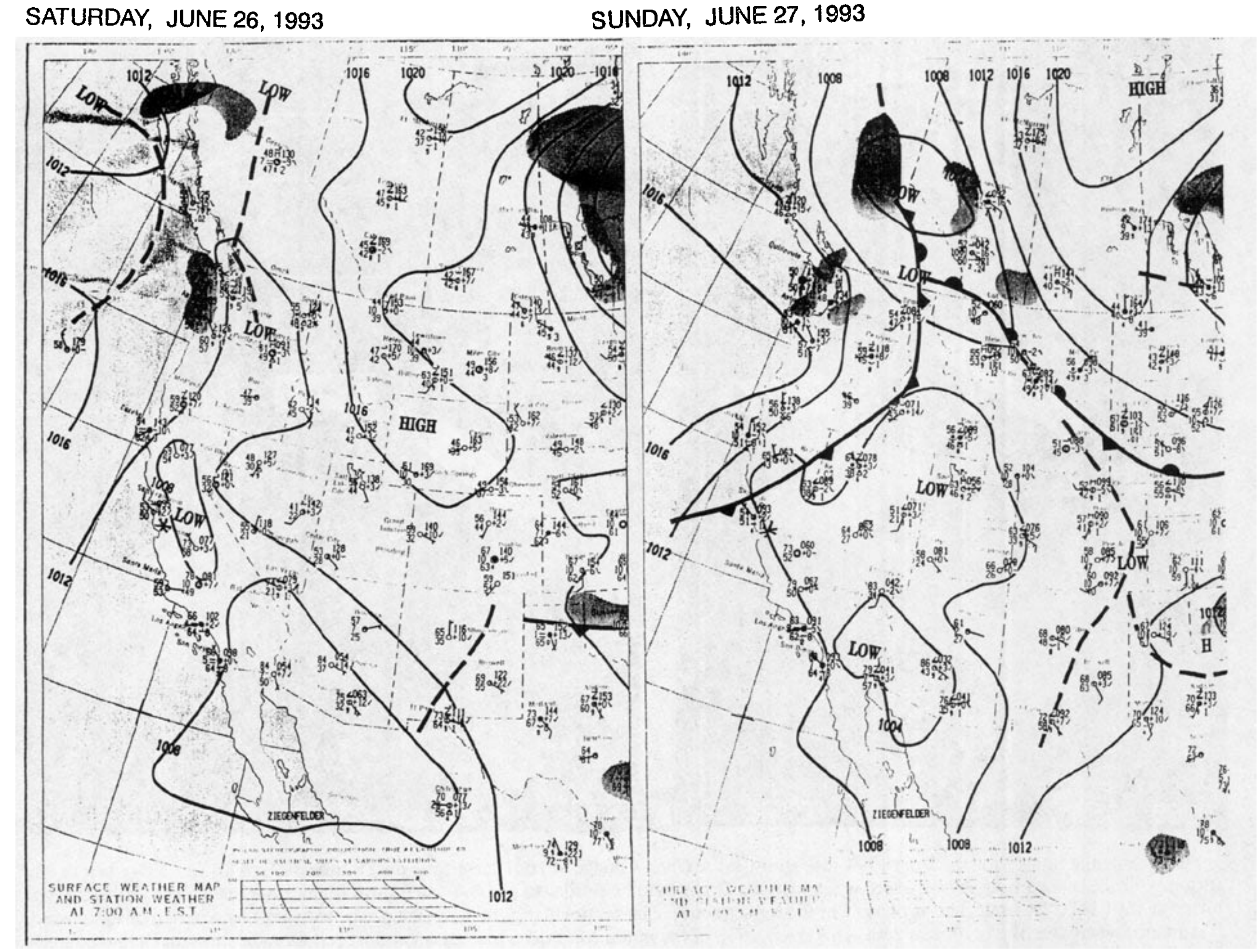

FIG. 6. (*Continued*)

above. The satellite image for 27 June, which is not reproduced here, showed no fog offshore in the Monterey area. It appeared that an offshore wind was blowing again and clearing the nearshore area.

The final set of data obtained were once a day remote visual images from the *GOES-7* satellite. These tell the whole story of development by phases. Figure 7a is on 21 June before there was any sign of a fog sequence coming. The clouds show no outstanding organizational patterns. Figure 7b shows phase 1 of the sequence on 24 June at 1601 LT. The semiovular pattern of clear sky is the offshore area swept by the strong downslope, offshore winds, where the BI is zero or near zero. Figure 7c is phase 2 of the sequence at 1601 LT on 25 June. Here the fog has formed, is patchy, and is approaching shore in pointed bands along the California and Oregon coasts. Figure 7d is phase 3 of the sequence on 26 June at 1601 LT, where the southern band of

TABLE 4. Summary of Oakland RAOB data from the June 1993 fog sequence dates.

Date 1993	Local time (UTC-7)	BI & Phase	Heat index (Ta-14)	RH% 3300 m	Wind speed at 1000 m, knots	Direction
23 June	0415	6 m	6.1	28	10	090
24 June	0415	6 m Ph1	11.3	20	13	021
25 June	0415	6 m Ph1	15.1	20	5	045
26 June	0404	133 m Ph2	13.5	22	5	296
27 June	0414	337 m Ph3	11.6	31	7	298

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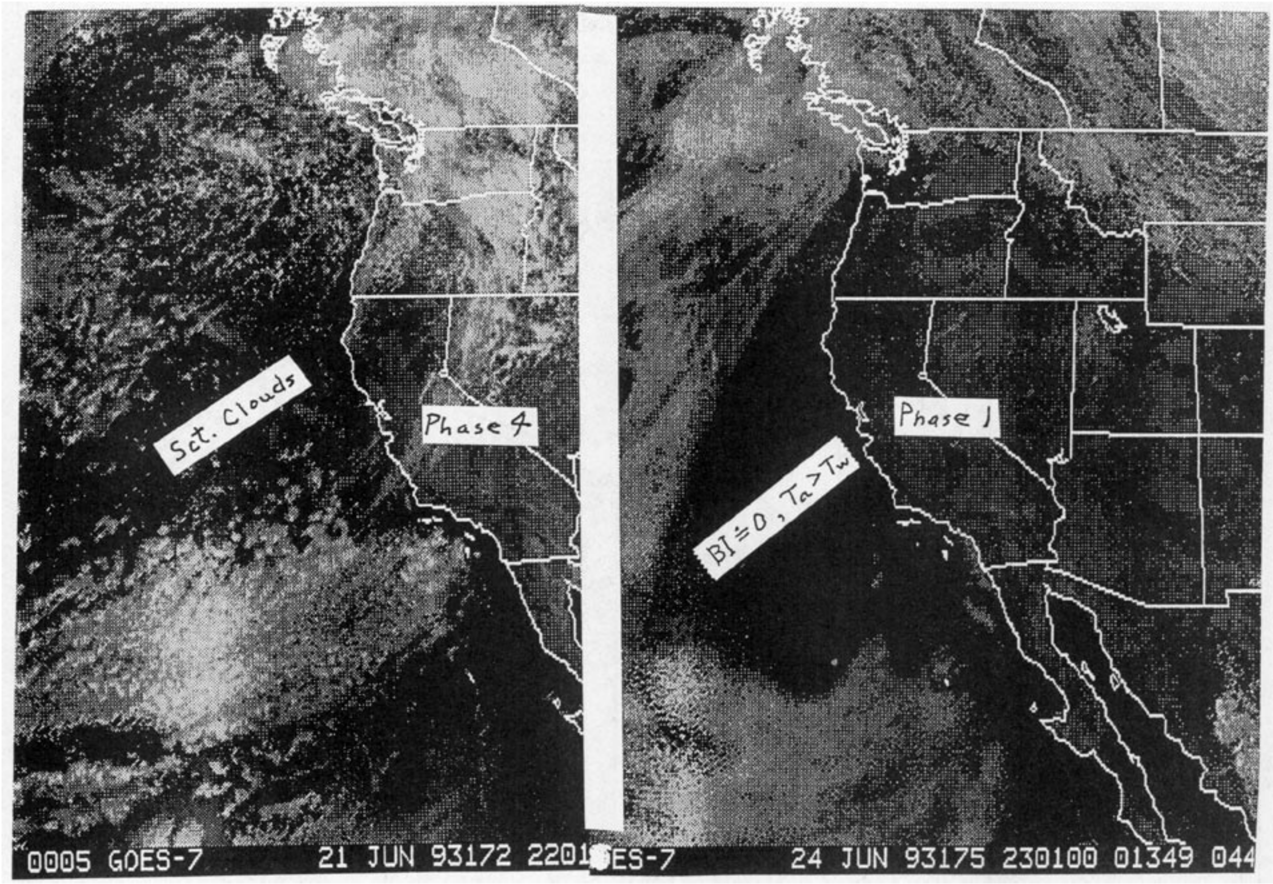

FIG. 7. Satellite images for the June 1993 case study. (a) A *Goes-7* image at 1601 local time on 21 June 1993. This was a day before any strong evidence of a coming fog sequence was apparent. This would be similar to phase 4 when the sequence has ended. (b) The same type image at 1601 UTC 24 June. This is phase 1 of the fog sequence. The semiovular clear area offshore is that swept by a strong offshore wind. It is an area where the BI is at or near zero. This is a portion of the initial conditions that are an almost certain indication that a fog sequence is to follow. (c) Shows 1601 UTC 25 June. It represents phase 2, the formation of fog with bands approaching the coast. (d) Shows 1601 UTC 26 June. This is a phase 3 example, fog growth and extension.

fog has deepened and spread. It came ashore at Monterey that night and the next.

With the decreasing number of available hourly station observations of visibility, increasing reliance will be placed upon what is known about fog development and the observation of it by remote imaging. Networks of automatic stations or buoys at sea do not as yet report visibility. Thus, the ground truth available in the 1970s, especially at sea, such as in Backes (1977), established ground truth relationships to remote images and descriptions of offshore fog distributions that now may be used in the absence of such coverage. For example, the satellite images of 16–19 June indicate a second fog sequence in that month.

The June 1993 case study of a sequence was centered around Monterey Airport because forecast worksheets had been developed for that station. The satellite images for 24 June, notably the large extent of the semiovular feature, indicate that the same sequence probably led to coastal fog from south of San Diego to north of Oregon. Day by day, fog or no fog might have been forecast for several days on any part of that coast using Table 2 and local heat index values.

The above consideration of the June 1993 fog sequence is offered as a case study of a sequence, an example of the application of a 5-day objective forecasting method for West Coast fog.

f. Case studies of objective 24-h forecasts in June 1993

These case studies will be based upon BI ranges of the objective forecast sequence as described in Table 2. This means that all of the forecasts (hindcasts) are just as they would be if they had been made at the same time on the first day of the sequence. Together they make up a 5-day hour by hour forecast. The primary decision of the forecaster is which forecast 24-h period should be named as the first period of the sequence. This depends upon the ceasing of the offshore flow and

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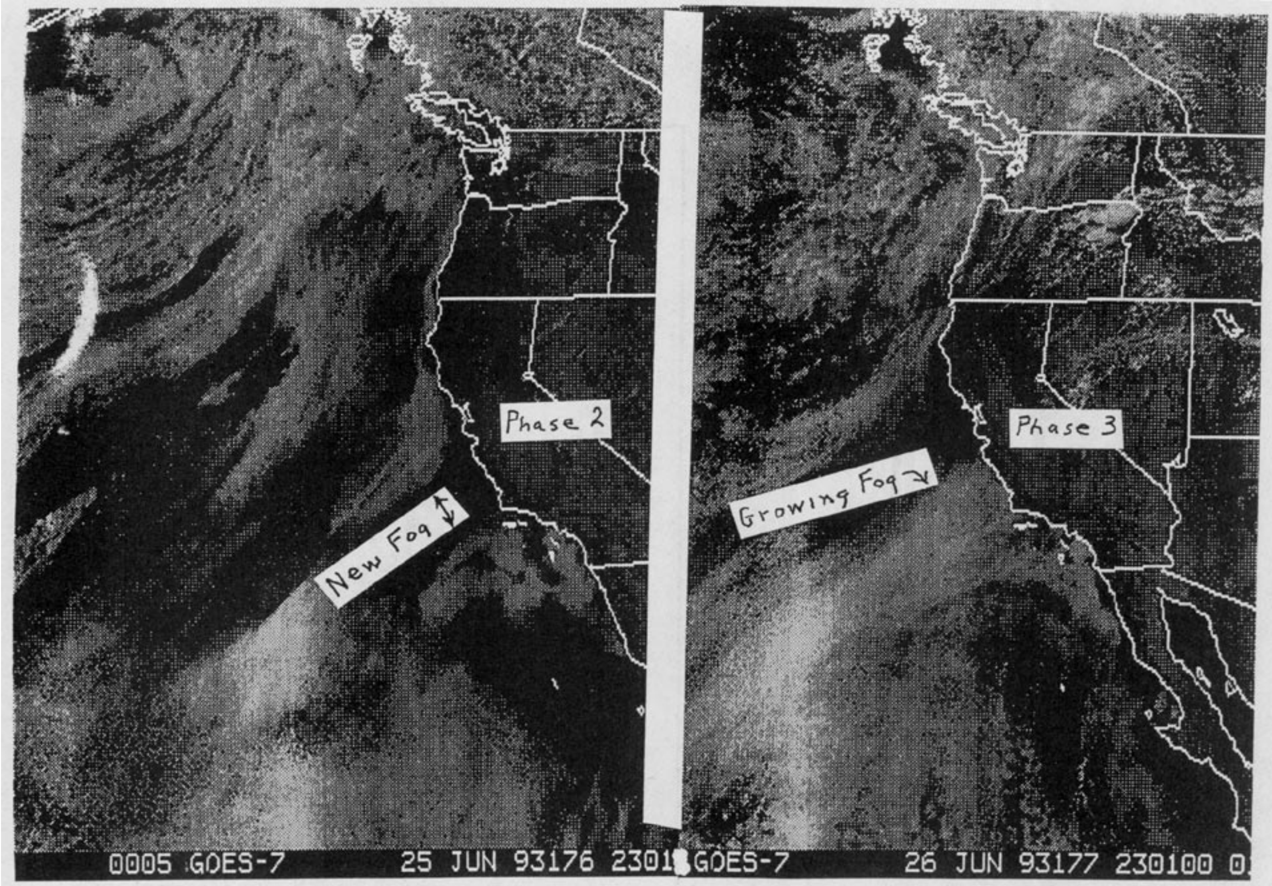

FIG. 7. (*Continued*)

reaching the maximum value of the heat index. On this basis, 24 June was set as the first day of the sequence in this case. With the sequence thus determined and followed as in Table 2, the 24-h forecasts were made period by period. The plots of the visibilities observed later are shown by vertical lines in Fig. 9 for comparison with the visibilities forecast, which are represented by the horizontal lines.

1) CASE 1, 24–25 JUNE 1993

This is the first period in phase 1 (see Table 2). The worksheet would not be used because the offshore wind apparently was remaining strong. The satellite image at 1601 LT 24 June (see Fig. 7b) showed clearly that the initial conditions for a sequence were being established. Thus, in the 24-h period beginning at 1600 LT (UTC-7) on the 24 June, the forecast would be for no fog. This was because the heat index had been high, (6.1) on 23 June (see Table 4) but growing rapidly, showing that the strong offshore wind flow was continuing.

It turned out that the BI on 24 June was still 6 m (0 at sea assumed). On the hourlies, the visibility at Monterey never dropped below 30 miles. Unusually high visibilities are to be expected just before the first dense fog. There was no fog, unless it occurred during the period between 2100 and 0600 LT when there were no hourlies, which was unlikely in this synoptic situation.

2) CASE 2, 25–26 JUNE 1993

This was the second period of the objective sequence and phase 1 is assumed still in effect (see Table 2). The observed BI on the morning of 25 June had still been 0. The satellite image for 1601 LT 25 June (see Fig. 7c) shows that patches and bands of fog had formed offshore and were approaching shore. The worksheet for zero BI at Oakland (phase 1) was used. The forecast was for fog to occur. The probabilities were for light fog 86%, moderate fog 38%, and dense fog 28%, according to the worksheet.

It turned out that the observed BI on 25 June was still zero. Fog did not come in as forecast unless it came in between 2300 LT 25 June and 0600 LT 27 June, its most probable time. For the hourlies, there was no fog verification to enter on the worksheet (see Fig. 9a), which would show any observed visibilities in the fog ranges superimposed on the forecast values.

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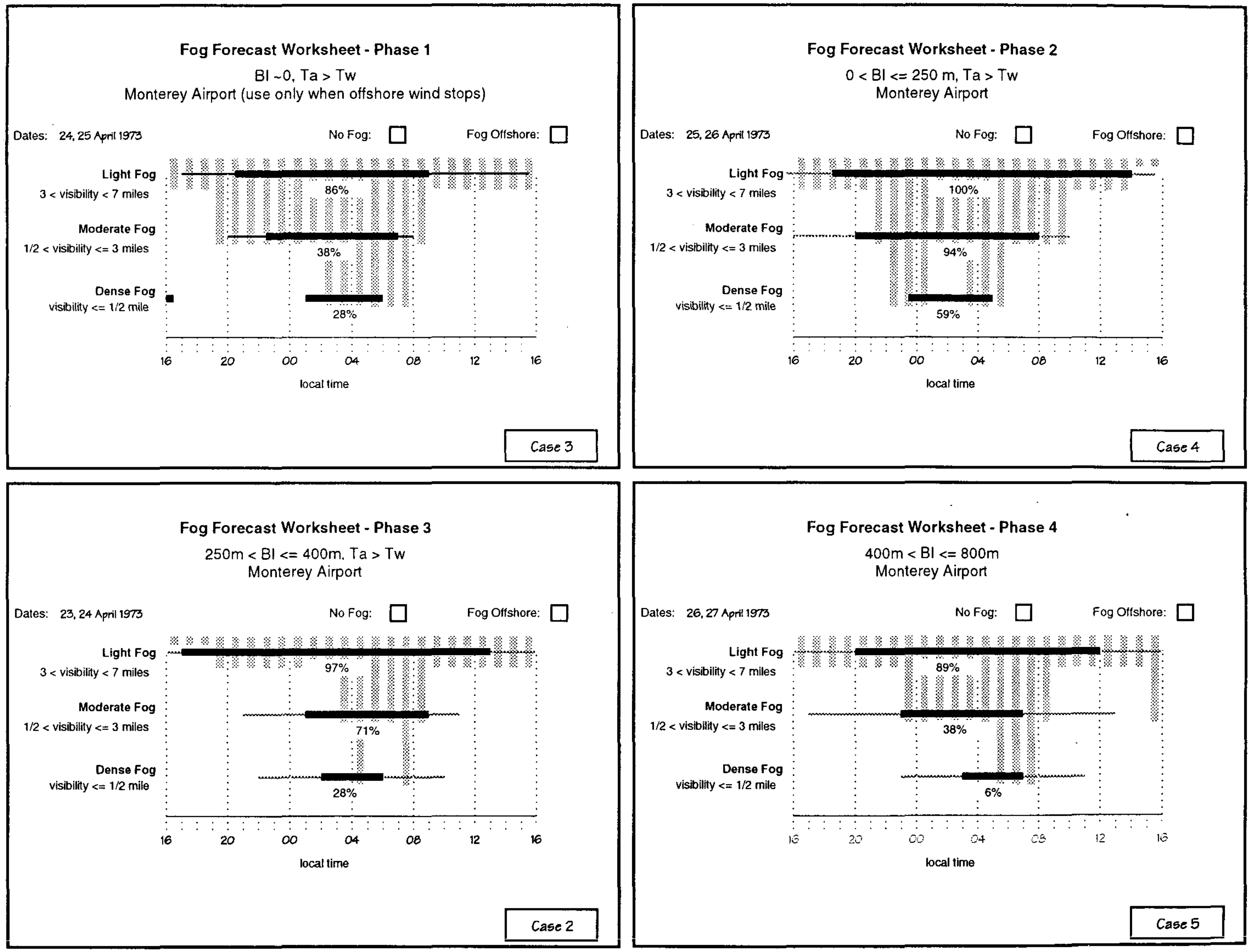

FIG. 8. Case study 24-h hindcasts for 1973 as given on the worksheets and the corresponding observed visibilities as recorded in the Monterey Airport hourlies. The vertical bars are observed visibilities. The small squares represent observations when no fog was present. The bars extending downward represent fog of the type to which the bars extend. The cases are described in the text.

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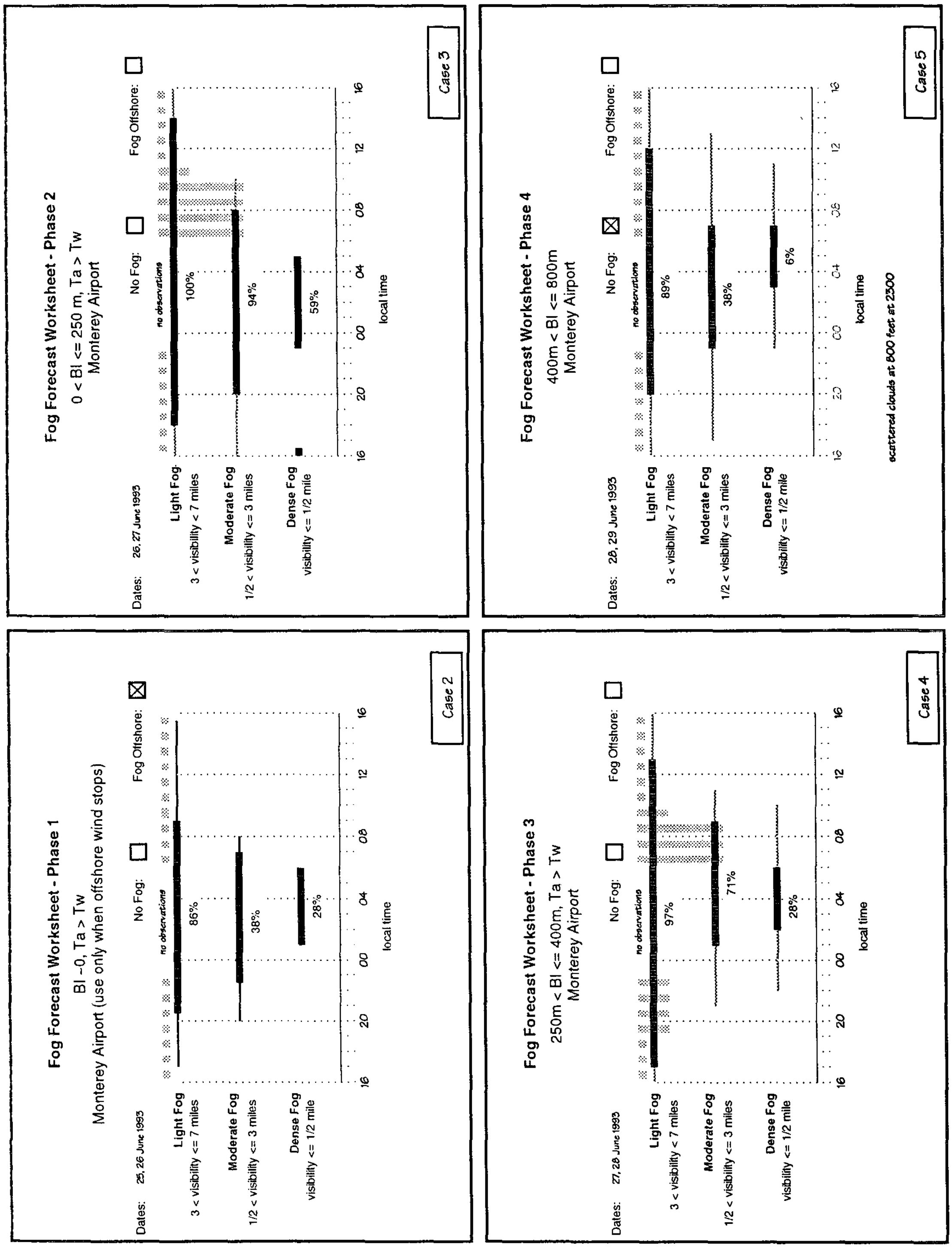

FIG. 9. Similar to Fig. 8 except for 1993 case studies.

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Visibilities during the time when observations were made stayed above 30 miles, that is, the site remained in the offshore flow of warm, dry air. The fog was nearby, offshore. There is usually a sharp boundary between this warm, dry air and the first shallow, dense, cold fog.

3) CASE 3, 26–27 JUNE 1993

This is the third period in the sequence. The objective forecast, as in Table 2, would use the phase 2 (0 < BI to 250 m) worksheet. The satellite image for 1601 LT 26 June showed that the southern branch of offshore fog had broadened and was close to shore as would be expected in the late portion of phase 2, entering phase 3. The forecast for 26–27 June was that fog would occur. The probabilities were 100% for haze, 94% for moderate fog, and 59% for dense fog, according to the worksheet. The worksheet also shows the most probable times.

It turned out that moderate fog did occur (see Fig. 9), and possibly dense fog occurred as well. The BI at Oakland had risen to 133 m on 26 June, fitting phase 2. Fog offshore had extended as the forecast period began. On the hourlies for Monterey Airport, visibilities stayed above 15 miles until 2246 LT and then there were no observations until 0547 LT. Dense fog had been predicted in this unobserved period of time. At 0547 LT, visibility was 1.5 miles in fog (see Fig. 9). This improved to 2.5 miles by 0748 LT, to 5 miles at 0750 LT, and to 15 miles by 1046 LT.

4) CASE 4, 27–28 JUNE 1993

This is the fourth 24-h period of the objective prediction of the sequence. The phase 3 worksheet would apply (BI > 250–400 m) according to the typical sequence progression of Table 2. The observed BI was 337 m on 27 June (see Table 4). The forecast was that fog would occur. The probabilities were for light fog 97%, moderate fog 71%, and dense fog 34%.

It turned out that moderate fog, less dense than in the previous period, did occur (see Fig. 9c). From the hourlies, starting at 1746 LT, visibility was 20 miles but a fog bank was reported W–N an hour later. There were no hourlies from 2245 to 0557 LT, an interval when dense fog might have occurred, but at 0557 LT visibility was 3 miles in fog. It varied from 2 to 5 miles until 1002 LT when it became 10 miles and continued to improve. A fog bank was reported W–N at 1046 LT.

5) CASE 5, 28–29 JUNE 1993

This was the fifth 24-h period of the sequence. Following Table 2, the worksheet for phase 4 (BI > 400–800 m) was used to make the forecast. Since the BI was expected to be over 400 m, no dense fog would be forecast. Light fog, probability 89%, and moderate fog, probability 40%, were predicted. There was a slight chance of dense fog, probability 6%.

It turned out that there was no fog in this period while hourly observations were being made. However, there were scattered clouds at 800 feet (see Fig. 9d), and visibility did drop to 10 miles before observations ceased at 2300 LT. The next six hours were the most probable times for dense fog to occur at Monterey, but any occurrence will not be known since there was no record. Beginning at 0550 next morning, visibility was 10 miles, and it remained that until 1146 LT when it improved. At 0550 LT there were broken clouds at 1100 feet, becoming scattered at 1500 feet at 0845 LT and remaining most of the period.

Thus, the forecasts of Fig. 9 were prepared on the appropriate worksheets from Fig. 4 for individual 24-h periods. After each forecast period, or a portion of it, has passed, the observed visibilities are entered upon these forecast worksheets for verification.

7. General comments

Since MOS forecasts, including visibilities, were issued by the NWS for Monterey during the time of these 1993 case studies, Dr. J. Paul Dallavalle, NWS Techniques Development Laboratory, arranged to send copies. None of the MOS forecasts issued during the June case study period predicted a reduction below 5 miles in visibility at Monterey, with one exception. On 27 June, the 42-h forecast made at 1200 UTC dropped visibility to the range of 1 to 2.75 miles. This drop was predicted to occur after the observed fog sequence had ended. It should be noted that a somewhat improved version of MOS became operational in July 1993.

It was mentioned that the Monterey Airport statistics (worksheets) might apply at other similar stations. The San Francisco Airport is not in a similar topographical situation but it is within the Oakland RAOB region. Thus, the hourlies for San Francisco were checked at the times that fog was forecast for Monterey Airport during this sequence. No fog was reported at the San Francisco Airport itself, but the observer did note a fog bank to the distant northwest at 2100 LT 25 June. It remained until 1200 LT 26 June. On 27 June patchy stratus was recorded in the morning. It would be interesting to prepare worksheets for San Francisco and see how they differed from Monterey.

Oakland hourlies were also checked. No fog occurred there.

Some strengths of LIBS are as follows: it meets the stated objective; it is simple to use; it facilitates monitoring of the synoptic situation; its physical mechanism has been demonstrated; it provides a basis for discussion among forecasters; and an original version has been in use 45 years at North Island in San Diego. It won in competition with nine other approaches; it utilizes recent gains in modeling, technology, and instrumentation.

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LIBS has some weaknesses. There are some fundamental concepts that are difficult to demonstrate sufficiently well but require first-hand experience, such as the 400-m mature fog thickness, the sequences of days, and the more specific nature of the fog phases. Also, the forecasts are probability forecasts only. Then, too, dense fog occurs only occasionally and requires constant alert. LIBS has data requirements that cannot be satisfied directly by the present weather reports (BI, heat index, sea temperature, quantities for synoptic climatology). Finally, the area to which a forecast for a particular site is applicable must be determined with care. It may extend several hundred kilometers offshore and 100 km along the coast.

8. Summary

Prior to LIBS, there has been little success in forecasting the probability of occurrence of West Coast fog, the intensity of the fog, or the time of its occurrence at given coastal sites and their immediate surroundings. LIBS offers a marked improvement in such forecasts. If fairly obvious initial conditions are recognized, LIBS offers an objective 5-day forecast. Hourly forecasts for any 24-h fog day within this sequence can also be objectively produced.

The LIBS approach to California coastal area fog forecasting, which probably could be utilized along the entire United States West Coast, is reviewed. The method can utilize the latest and best products of numerical methods and remote imagery. It employs synoptic climatology to incorporate diurnal and local influences. It can be carried out in an entirely objective manner but improved by subjective considerations based upon knowledge and experience. It provides five practical fog intensities (including no fog and stratus) with times of occurrence and probabilities. When the heat index is positive, LIBS utilizes a single variable, the early morning value of height of the inversion base, as the index of synoptic scale day to day weather affecting local visibility.

The physical sequence and its representation by the BI and the heat index provides a basis for profitable argument and discussion at forecast time. Forecasts of five days are possible. The physical nature of the LIBS method is such that it incorporates seasonal change as well as north–south geographical changes in location along the West Coast. The forecasting method is simple to use. The forecast may be updated as new information becomes available. Finally, the forecast may be verified readily by plotting the observed values, as they become available, against the forecast ones.

A number of other topics relevant to West Coast fog have been investigated but the results cannot be presented here because of lack of space.

Acknowledgments. I wish to acknowledge the assistance of my son, Bryan R. Leipper, a business consultant; all of the graduate students who have done fog theses with me; my research associates and assistants; and the sponsors of my research, especially the Office of Naval Research and the Naval Air Systems Command, the Scripps Institution of Oceanography of the University of California, and the Naval Postgraduate School, where most of the fog work was done. Also appreciated is the assistance received from the Western Regional Climate Center, especially Kelly Redmond, Dorothy Miller, and Jim Ashley; from Reno NWS personnel, especially Mary Cairns and John Corey; and from Dr. J. Paul Dallavalle of NWS Techniques Development Laboratory. I further thank the military service into which I was drafted in 1940 and the Air Force, through which I was educated in Meteorology and Oceanography and where I became interested in fog forecasting while stationed in the Aleutian Islands. Finally, thanks go to the reviewers for the AMS *Bulletin* and for *Weather and Forecasting* whose suggestions greatly improved this presentation.

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