The Association of Low-Level Inversions with Surface Wind and Temperature at Point Arguello

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ABSTRACT

Inversions at Point Arguello, California, as detected in 4½ years by rawinsondes at 0400 and 1600 PST, are related to surface wind direction and speed and surface temperatures. Nocturnal inversions based below 1000 ft msl have their maximum frequency in winter and their minimum in summer. Most of them occur with downslope surface winds. Afternoon inversions are most frequent in July and least frequent in January. Nocturnal surface inversions appear to develop when the downslope drainage air from the interior is cool enough to undercut the marine layer. There is evidence that the critical surface temperature for this to take place is 9C.

1. Introduction

A rawinsonde program at Point Arguello was initiated in July 1959 as part of the weather-observing program on the Western Test Range. Fig. 1 shows the location of the rawinsonde station and other facilities on, and adjacent to, the range. The ground at the rawinsonde station is about 370 ft above mean sea level.

A useful report (Holzworth *et al.*, 1963) on the climatology of low-level inversions at Point Arguello, based on 33 months of rawinsonde data, indicated that nocturnal inversions occurred almost daily in winter but only on roughly one-third of summer nights. Daytime inversions were most frequent in late summer and fall, and least frequent in winter. Although surface winds were included in the special records that had formed the basis of the analysis, no use had been made of these in developing the inversion statistics. Arrangements were made with the State of California Bureau of Air Sanitation to obtain these inversion records on punched cards for 1 July 1959 thru 31 December 1963. The data consisted of twice-daily (0400 and 1600 PST) records of inversions and surface winds[1] that specify among other things the base and top of the lowest inversion below 10,000 ft and the temperature at the base and top of the inversion. Thus, for surface-based inversions, but not for inversions aloft, surface temperatures were also available. There were observations at both hours for just under 1600 days or 54 months.

The analysis described herein was performed on these data. Although the original intent was simply to investigate the association between wind direction and inversions, the available information made it possible to include the association of inversions with wind speed and with surface temperature.

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[1] Beginning 1 January 1963, surface winds are replaced by 1000-mb winds.

2. Main features of inversion climatology at Point Arguello

Average frequencies of inversions at Point Arguello are presented in Table 1. No attempt at stratification according to wind direction or surface temperature is included, since the intent is simply to indicate seasonal trends. A seasonal trend is evident for the nocturnal (0400), surface-based inversions with a winter maximum and a summer minimum. The other important inversion type in this region, namely the subsidence inversion aloft, which is identified more readily during the day (1600), exhibits a maximum in July and a minimum in January.

In most regions, the surface-based inversion results from substantial surface cooling of an air mass exhibiting a neutral or unstable lapse rate by day to a few thousand feet. However, in regions where subsidence inversions are frequently based within a few hundred feet of the ground by day, very little cooling is required to convert an inversion aloft to a surface-based inversion. It is interesting to examine the monthly frequency of those surface-based inversions that cannot be attributed to a carryover of a daytime surface inversion or downward extension of a daytime inversion aloft. These may be inversions caused exclusively by surface cooling. An approximation to this frequency is obtainable from Table 1, if we assume that surface inversions at 1600 are still present at 0400 and that one-fourth of the inversions aloft at 1600 PST have risen about 1500 ft at 0400 and that three-fourths of them

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TABLE 1. Percentage frequencies of low-level inversions at Point Arguello 1 July 1959 to 31 December 1963, by month, time of day, and inversion base.

			Frequency (%)											
Time	Base	Symbol	J	F	M	A	M	J	J	A	S	O	N	D
0400	Surface	f_1	86	78	63	56	28	21	25	31	46	67	81	86
	Surface to 1000 ft above msl	f_2	0	0	0	7	5	4	11	10	5	1	3	0
	1000 to 1500 ft above msl	f_3	0	0	5	7	14	25	38	25	23	6	3	1
1600	Surface	f_4	18	7	3	10	0	6	5	3	5	9	20	21
	Surface to 1000 ft above msl	f_5	12	19	24	20	15	13	25	33	26	32	22	21
	1000 to 1500 ft above msl	f_6	12	11	20	23	26	31	51	37	36	25	14	12

are still below 1500 ft. Since we know the frequency based above the surface but below 1500 ft at 0400, we can compute the frequency of daytime inversions aloft that appear as surface inversions and, thus, separate those attributable to surface cooling. If we denote the frequencies in the lines of Table 1 as $f_1, f_2, f_3, f_4, f_5, f_6$, then the frequency, F, of inversions caused exclusively by surface cooling is given by

$$F=f_1+f_2+f_3-f_4-3/4f_5-3/4f_6.$$

These frequencies appear in Table 2.

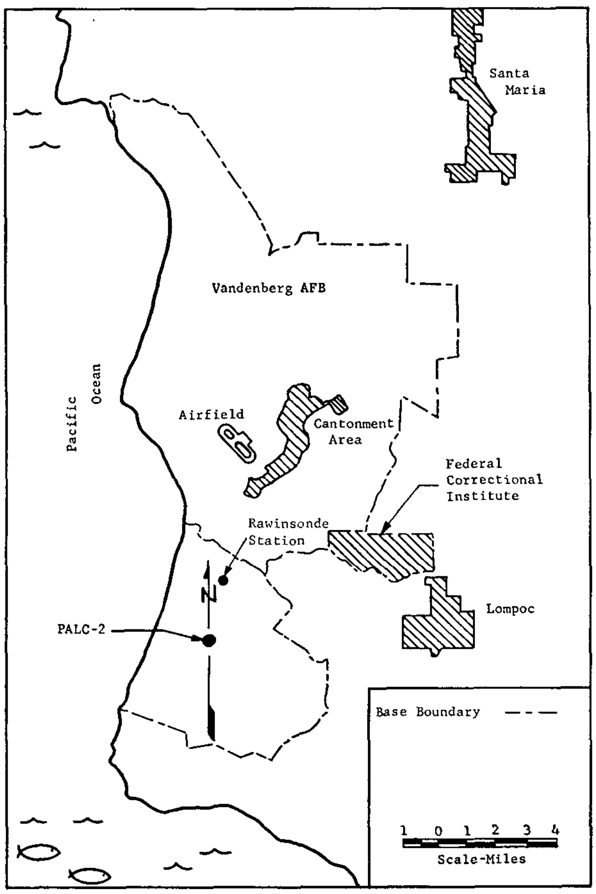

FIG. 1. Map of the Western Test Range showing the location of Point Arguello Rawinsonde Station.

Table 2 indicates that the typical nocturnal inversion that results from strong surface cooling is most frequent in winter and least frequent in summer. The anomalous nature of this seasonal pattern becomes evident by a comparison with other regions.

Munn, Emslie, and Wilson (1963) studied inversions at Detroit, Ottawa, and Montreal. For these cities with continental climates, radiation-type inversions occurred on an average of 91% of the summer nights and only 63% of the winter nights. At Brookhaven, Singer and Smith (1953) found that stable stratifications associated with their type D wind trace occur 76% of the time during summer nights and 62% of the time during winter nights. Some maritime influence is no doubt present in the Brookhaven climate. From the comprehensive report on the meteorology of Oak Ridge, (U. S. Weather Bureau, 1963) one can estimate the frequencies of nocturnal inversions between 5 and 183 ft for each of the seasons to be:

Winter	Spring	Summer	Fall
72	88	90	94

The good agreement among these five stations suggests that the norm is a summer frequency maximum for nocturnal inversions rather than the winter maximum observed at Point Arguello.

3. The association of inversion with wind direction

Two temperature-profile categories and two wind-direction categories were used for analysis. Temperature-profile categories were:

1) Inversion based below 1000 ft msl;
2) No inversion based below 1000 ft msl.

For brevity these will be referred to as "inversion" and "no inversion." A natural choice of wind-direction categories is suggested by the land and sea breeze effect.

TABLE 2. Relative frequency of nocturnal surface-based inversions that are attributable to surface cooling at Point Arguello, 1 July 1959 to 31 December 1963.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Frequency	50	49	32	28	16	11	12	11	13	22	40	41

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Winds from north–northwest clockwise through to southeast have their maximum frequency at night, whereas winds from south–southeast through to northwest have their maximum frequency by day. The former group represents essentially offshore winds, with the latter group being mainly onshore winds.

This section considers the evidence that the frequency of inversions with offshore winds differs significantly from the frequency with onshore winds. The method is to compare, by means of a χ^2 test and a contingency table (Panofsky and Brier, 1958), the observed frequencies with the frequencies expected under the null hypothesis, "no significant difference." The statistical model on which the test is based requires that the separate members of the sample be independent, whereas persistence is certainly present in the inversion data. Moreover, it is known that the χ^2 test does not give reliable results if the expected number of occurrences in any cell of the table is less than five. In a chapter devoted to the subject of persistence and its effect on statistics, Brooks and Carruthers (1953), while offering no specific comments on the χ^2 test, make two helpful observations:

1) Such phenomena as gales, rain, clouds, fog, and frost (which are loosely associated with inversions) have a persistence factor of about 2:
2) Phenomena have a tendency to occur in groups of average size equal to their persistence factor.

Therefore, one might assume that the number of independent members in the contingency table is about one-half the sample size. Two adjustments compensate for this. First computed values of χ^2 are halved; secondly a minimum of 10 rather than 5 is required in each cell of the expected occurrences.

In the present study, this requirement was met by combining the months in pairs beginning with January and February. Calms were included with the less frequent onshore winds at 0400 and with the less frequent offshore winds at 1600 PST. Table 3 contains the observed and expected frequencies in January and February at 0400 PST. The observed frequencies produce an observation of $\chi^2=10.24$ after adjustment, a value exceeded about once in a thousand by chance under the null hypothesis. It is inferred that the 89% frequency of inversions with offshore winds is significantly greater than the 64% frequency observed with onshore winds.

TABLE 3. Observed and expected occurrences of low-level inversions by wind direction categories at Point Arguello, 0400 PST, January and February, 1960 to 1963.

	Observed occurrences		
	NNW-SE	SSE-NW and Calm	Total
Inversion	149	43	192
No inversion	18	24	42
Total	167	67	234
	Expected occurrences		
	NNW-SE	SSE-NW and Calm	
Inversion	137	55	
No inversion	30	12	

The χ^2 test was performed for the other pairs of months and for 1600 PST as well as 0400. At 1600 there is no significant association of inversion frequency with wind direction.

A definite pattern emerges at 0400 with the frequency of inversions significantly greater (at the 5% level) with offshore winds than with onshore winds from September through April. For the two midyear pairs (May and June, and July and August), the observed inversion frequencies were less with offshore winds than with onshore winds although not significantly so. However, since the May-through-August period is clearly unlike the balance of the year, it is tentatively inferred that during these 4 months inversions are less frequent with offshore winds than with onshore winds. The results of this analysis are summarized in Fig. 2, where the overall inversion frequencies at 0400 PST are compared to the conditional frequencies given offshore winds and onshore winds.

4. The association of inversions with wind speed

The association of light winds with inversions is well documented. There is the familiar comparison, reproduced by Sutton (1953) as his Fig. 25, of wind-speed profiles for inversion, neutral, and superadiabatic conditions showing the lightest winds with inversions. Geiger (1957) discussed the change in temperature gradients with increasing wind speed as reported by researchers in a number of countries. He noted that, in general, the surface temperature at night rises as the wind speed increases. Jenne and Hilst (1950) investigated the association of inversions with wind speed at the Hanford Works area. The following broad trends were evident. During the day, as the wind speed increased from calm to 20 mph, the lapse rate increased but beyond 20 mph no further increase in lapse rate occurred. Moreover, all the lapse rates were positive, and nearly all were super-adiabatic. During the night, almost all lapse rates were less than dry adiabatic. For wind speeds less than 11 mi per hr, inversions were the rule, and for wind speeds greater than 11 mi per hr, the average profile was isothermal. Between calm and 11 mi per hr there was a definite trend of decreasing stability with increasing wind speed.

A necessary, though not sufficient, condition for a similar association of lapse rate with wind speed at Point Arguello would be for the diurnal variations of wind speed and temperature to be in phase. Fig. 3, a comparison of the diurnal variations of wind speed and temperature at Point Arguello based on a recent sum-

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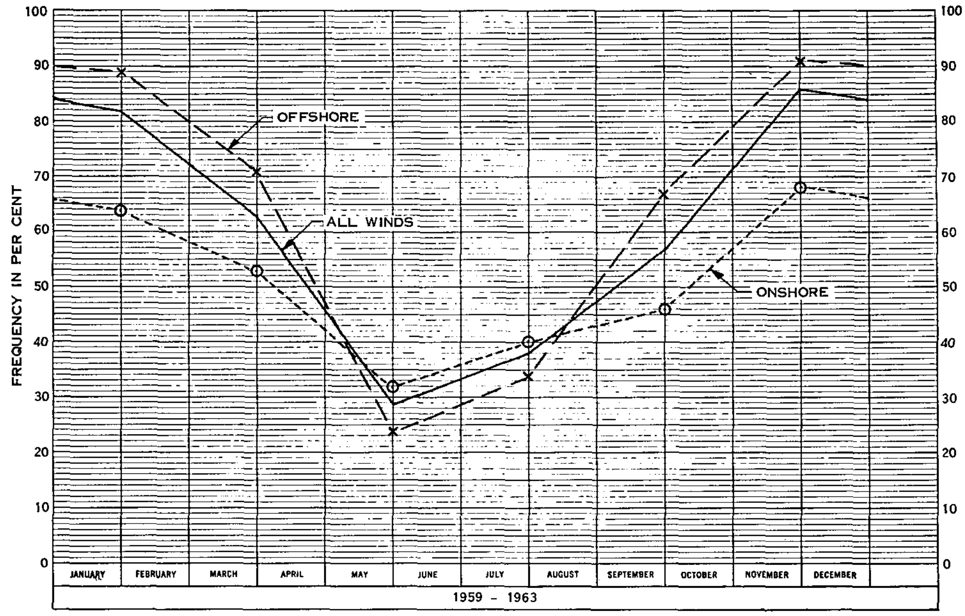

FIG. 2. 0400 PST frequency of low level inversions at Point Arguello, by months, compared to conditional frequencies given offshore (north-northwest—southeast) and onshore (south-southeast—northwest) or calm winds.

mary, (Naval Weather Service Division, 1963) shows that they are indeed in phase.

Evidence was, therefore, sought that surface-based inversions at Point Arguello were more frequent with below-average than with above-average winds. Two-by-two contingency tables were prepared for 0400 and 1600 PST for each month. Wind speed categories were "less than monthly average" and "greater than or equal to monthly average"; temperature profile categories (for the surface layer) were "lapse" and "inversion," which included isothermals. Dependence of inversion on wind speed can be investigated using the χ^2 test in the manner described in Section 3. Month-by month application of the test is not possible, however, because

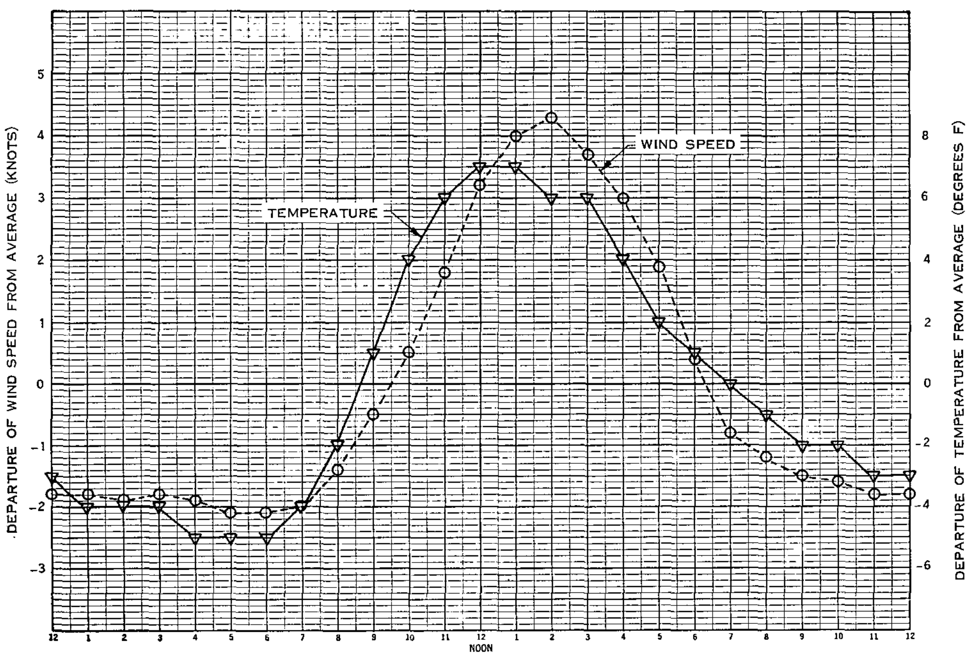

FIG. 3. Diurnal variation of wind speed and temperature at Point Arguello, annual average, July 1959–June 1963.

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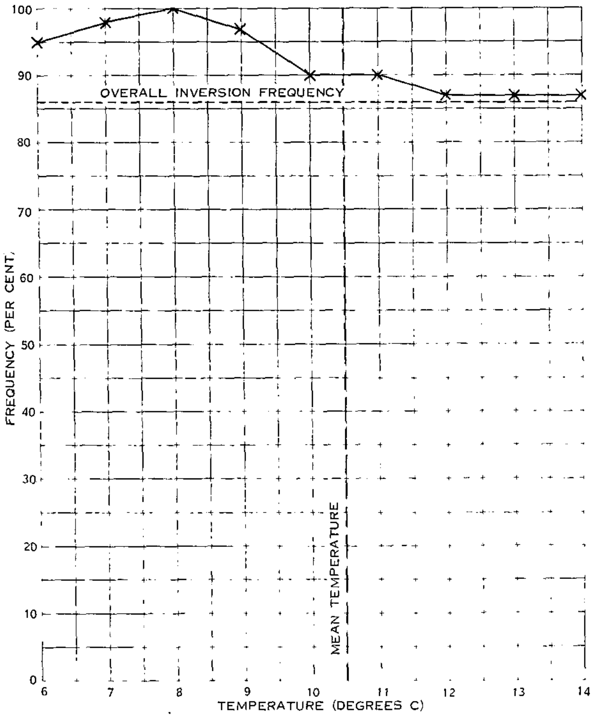

Fig. 4. December conditional frequency of surface inversions at 0400 PST given temperature less than the indicated temperature, Point Arguello, 1959–63.

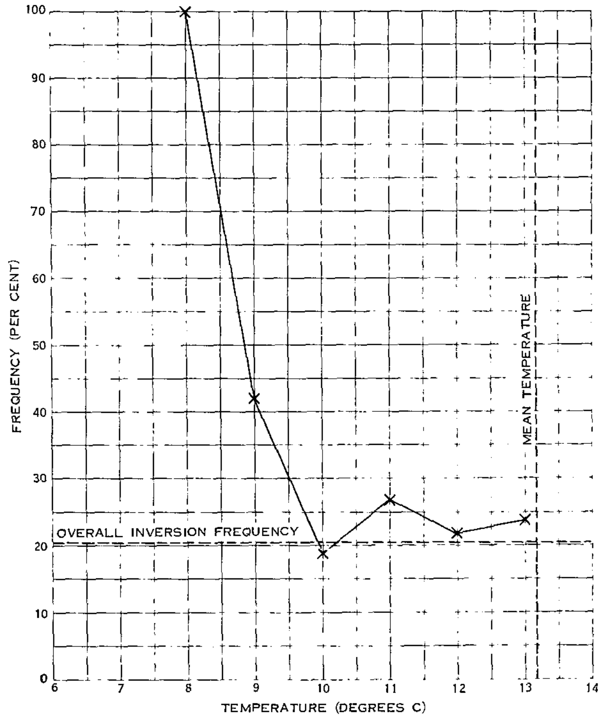

Fig. 5. June conditional frequency of surface inversions at 0400 PST given temperature less than the indicated temperature, Point Arguello 1960–63.

the expected number of occurrences in each cell of the table does not always exceed the required minimum of ten. Accordingly, all months were combined to yield one contingency table for 0400 PST and another for 1600 PST, as shown in Table 4.

When applied to the data in Table 4, the χ^2 test suggests that surface inversions are independent of wind speed at 0400 PST but are more frequent with below-average wind speed at 1600. From the entries in Table 4, the frequency of inversions with below-average and above-average winds at 1600 PST are 22 and 7%, respectively

Intuitively, one is inclined to be skeptical of the statistical findings for 0400, which are in conflict with

Table 4. Contingency tables displaying observed association of lapse rate with wind speed at Point Arguello, 1 July 1959 to 31 December 1963 by time of day.

	0400 PST $V<\bar{V}$	$V\geqq\bar{V}$	Total
Lapse	494	219	713
Inversion	629	240	869
Total	1123	459	1582

	1600 PST $V<\bar{V}$	$V\geqq\bar{V}$	Total
Lapse	204	1204	1408
Inversion	58	90	148
Total	262	1294	1556

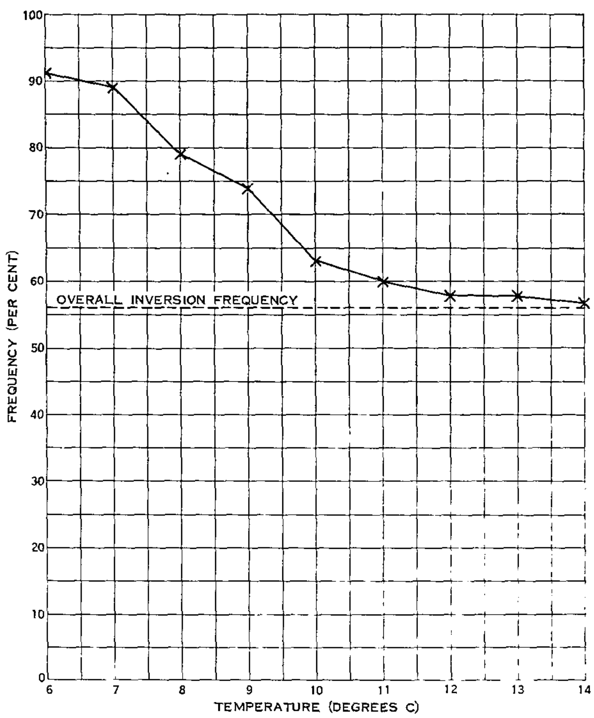

Fig. 6. Annual conditional frequency of surface inversions at 0400 PST given temperature less than the indicated temperature, Point Arguello, 1 July 1959–31 December 1963.

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the findings of Geiger and others. Careful examination of the records, however, shows that out of the 1582 soundings at 0400 there were 177 positive lapse rates with calm winds and 21 inversions with winds equal to or greater than 15 knots.

5. The association of inversions with surface temperatures

At the outset, this phase of the investigation was expected to be routine. It was anticipated that surface-based inversions at 0400 would become more probable in any month if the surface temperature dropped a few degrees below normal. The technique used to confirm the presence of this influence was to compute the conditional frequency of inversions where the surface temperature was less than T_i, and T_i was allowed to vary. The conditional frequency is evaluated by the expression

$$F\left\{\begin{matrix}\text{Inversion given}\\ \text{sfc temp} < T_i\end{matrix}\right\} = \frac{F\,(\text{Inversion and temp} < T_i)}{F\,(\text{Temp} < T_i)}.$$

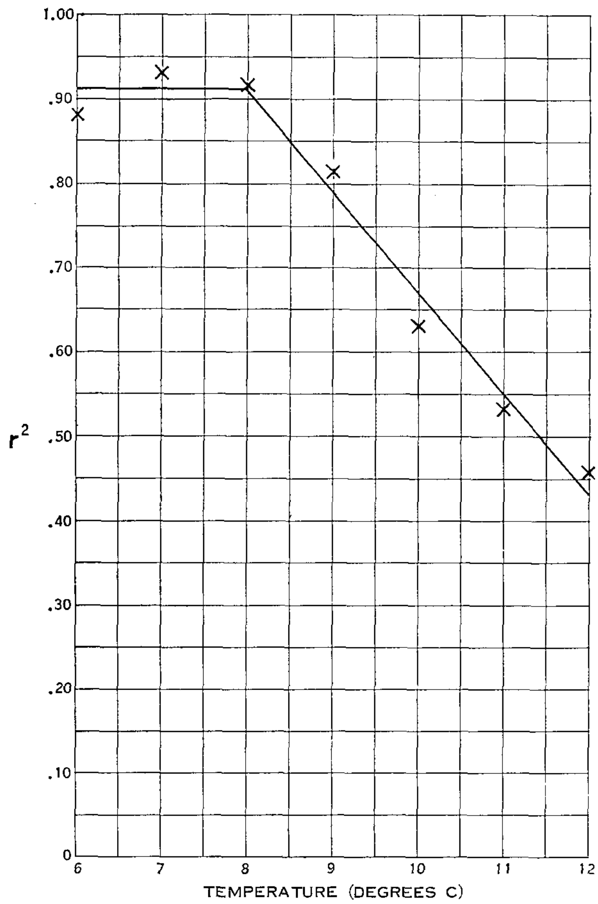

FIG. 7. Temperature versus square of the correlation coefficient between monthly frequencies of nocturnal inversions at Point Arguello and monthly frequencies of 0300–0500 temperatures less than a given value at Vandenberg Air Force Base. (Inversion frequencies from Table 2.)

The inversion data yielded values of the numerator but, because surface temperatures were not given in the absence of a surface inversion, the denominator was obtained from a temperature summary for Vandenberg Air Force Base (AFB) (Climatic Center, 1962). Cumulative temperature distributions were plotted for the period 0300 to 0500. Since temperatures at Vandenberg appear to be slightly higher than those at Point Arguello, cumulative distributions for Point Arguello were obtained from the Vandenberg curve by a simple adjustment based on the difference between the 0300 to 0500 mean at Vandenberg and the 0400 mean at Point Arguello. By varying T_i, the manner in which inversion frequency was influenced by temperature could be studied.

The anticipated pattern of a different critical temperature for each month did not emerge, but there was a suggestion of a single critical temperature near 9C for all months. The variation of the conditional frequency with temperature is shown for December in Fig. 4, for June in Fig. 5, and for the whole year in Fig. 6. The conditional frequency shows a tendency to approach the overall frequency at temperatures above 9C.

Since the evidence of a critical temperature of 9C is more suggestive than conclusive, an attempt to confirm the existence of a critical temperature was made. Table 2 contains monthly frequencies of nocturnal inversions that were caused by strong surface cooling. For each month, the frequencies of temperatures below 6, 7, 8, 9, 10, 11 and 12C were computed for Vandenberg for 0300 to 0500 PST. The inversion frequencies were then correlated with the monthly temperature fre-

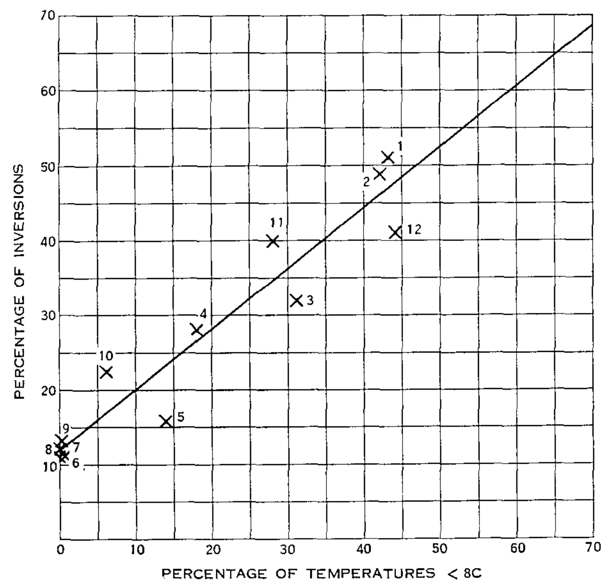

FIG. 8. Monthly frequencies at Point Arguello of nocturnal inversions caused by surface cooling versus monthly frequencies of 0300–0500 temperatures less than 8C at Vandenberg Air Force Base. (Numbers beside plotted points indicate month.)

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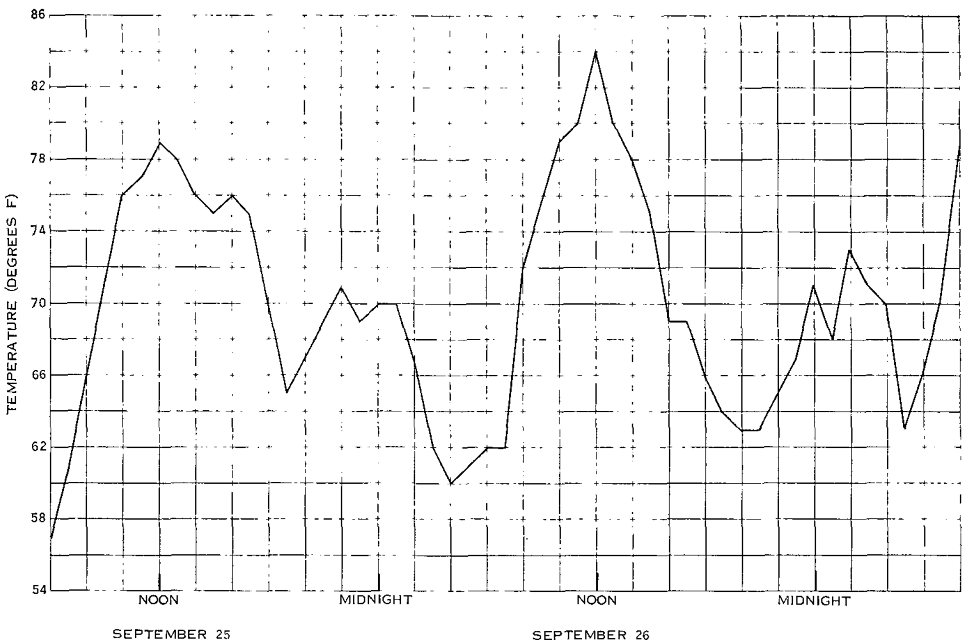

Fig. 9. Hourly temperatures at Point Arguello 25–27 September 1963, illustrating secondary maximum in nocturnal land breeze.

quencies for each of the above temperatures. The manner in which the correlation coefficient, r, varies with the choice of temperatures is shown in Fig. 7 by a plot of r^2 vs. T. Here, there is an indication of a critical temperature of 8C. Fig. 8 shows the strong association between the frequency of temperatures below 8C and the frequency of inversions. This approach lends support to the idea of a single critical minimum temperature of 8 or 9C required for the development of a surface inversion at Point Arguello.

6. Discussion of results

The existence of a critical temperature of 8 or 9C associated with the formation of nocturnal inversions is tenable provided a mechanism exists that would lead to this result. Such a mechanism must be compatible with the following features of the climatology of Point Arguello:

1) Nocturnal inversions are most frequent in the coldest months (see Tables 1 and 2);
2) Winds from the interior toward the ocean at 0400 PST are most frequent during November, December, and January and least frequent during May, June, and July;
3) Since the winds from the interior represent the land breeze, it is also relevant to compare mean sea surface temperatures near Point Arguello with mean air temperature at 0400. These are given in Table 5. A reasonable interpretation is that the temperature differential between sea and land is usually insufficient from May through September to induce the nocturnal land breeze;
4) From May to August, inversions are not strongly associated with winds from the interior. During the balance of the year, the probability of an inversion is high if the wind is from the interior (Fig. 2);
5) Only 15% of nocturnal inversions occur during calms. Less than half of the reported calms at 0400 occurred with inversions.

It is apparent that the nocturnal inversion at Point Arguello is a circulation phenomenon rather than one of stagnant air. Therefore, the following mechanism is proposed to account for a critical surface temperature

Table 5. Monthly mean air temperatures at 0400 PST and sea surface temperatures (U. S. Weather Bureau, 1961) Point Arguello (in deg F).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Sea temperature	57	56	56	55	55	56	57	58	59	59	58	57
0400 Air temperature	43	47	46	47	49	52	53	54	54	52	48	45
$T_s - T_{04}$	14	9	10	8	6	4	4	4	5	7	10	12

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of 8 or 9C associated with inversions. In all months the marine layer is normally present during the day. In view of the nearly constant sea surface temperature, averaging 57F (14C), it is suggested that the early evening temperature at heights of a few thousand feet will be nearly the same in all months, averaging about 9C at 2000 ft above msl. Under these circumstances, a surface temperature of 9C would be required to produce an inversion extending from the ground to 2000 ft. The choice of 2000 ft is arbitrary, and a lapse rate of 80% of the dry adiabatic is assumed over the water.

Only during the colder months is the wind from the interior usually cooler than 9C at night and able to displace the marine layer. During the warmer months, on rare occasions, a strong wind from the interior displaces the marine layer, creating a secondary temperature maximum during the night. Fig. 9 gives an example of this. However, the usual summer behavior is for the marine layer to persist with nocturnal cooling producing fog and stratus rather than an inversion.

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REFERENCES

Brooks, C. E. P., and N. Carruthers, 1953: *Handbook of Statistical Methods in Meteorology*. London, Her Majesty's Stationery Office, p. 412.

Geiger, Rudolf, 1957: *The Climate Near the Ground*. Cambridge, Harvard University Press, p. 113.

Climatic Center, 1962: Psychrometric summary, Vandenberg California AFB, June 1958–May 1962. Air Weather Service, Asheville, N. C. (Available from National Weather Records Center, Ashville, N. C.)

Holzworth, George C., Gordon B. Bell and Gerald A. DeMarrais, 1963: Temperature inversion summaries of U. S. Weather Bureau rawinsonde observations in California. Manuscript of the U. S. Weather Bureau and the State of California, Department of Public Health. (Available from U. S. Weather Bureau.)

Jenne, D. E., and G. R. Hilst, 1950: Meteorological and climatological investigations of the Hanford Works Area. General Electric, Hanford Works, Washington. (Available from the Hanford Laboratories, General Electric Company, Richland, Wash.)

Munn, R. E., J. H. Emslie and H. J. Wilson, 1963: A Preliminary analysis of the inversion climatology of Southern Ontario. CIR-3834 TEC-466, Meteorological Branch, Canada. (Available from Meteorological Branch, Dept of Transport, Toronto, Ontario.)

Naval Weather Service Division, 1963: Summary of monthly aerological records, Point Arguello, California, July 1959 to June 1963. Job No. 1189, National Weather Records Center, Asheville, N. C. (Available from NWRC.)

Panofsky, Hans A., and Glenn W. Brier, 1958: *Some applications of statistics to meteorology*. Pennsylvania State University, University Park, Pa., 224 pp.

Singer, Irving A., and Maynard E. Smith, 1953: Relation of gustiness to other meteorological parameters. *J. Meteor.*, **10**, 121–126.

U. S. Weather Bureau, 1953: A meteorological survey of the Oak Ridge Area. ORO-99, USAEC, Oak Ridge, Tenn. (Available from OTS, Washington, D. C., $3.15.)

——, 1961: *Climatological and Oceanographic Atlas for Mariners, Volume II, North Pacific Ocean*. Washington, D. C., Supt. of Documents.

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