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PROHASKA

CHAPTER 11

NEW EVIDENCE ON THE CLIMATIC CONTROLS ALONG THE PERUVIAN COAST

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The subtropical-tropical west coast deserts have always drawn a great deal of attention because of their apparently anomalous characteristics. Among such coasts, the coast of Peru attracted the most attention due to its population concentration and unique bioclimate (Knoch, 1930; Meigs, 1966; Rudloff, 1959; Schweigger, 1964; Unanue, 1940). The Peruvian coast is noteworthy also for other climatic peculiarities such as anomalous equatorward extension of desertic conditions, great uniformity and stability in the weather, high degree of atmospheric humidity during the entire year, and, last but not least, a nearly uninterrupted stratus layer that hovers over a great part of the coast during the winter all the way from northern Chile northward to about 8°S. Other striking features are the large number of hours with precipitation that totals only a negligible amount, the large annual and small daily ranges of temperature (unusual for a tropical latitude), the increase of thermal oceanity inland (decrease of annual temperature range), and the high persistency and shallowness of the trade winds.

One wonders why it was just in this atypical tropical coastal climate that the most important place of worship in pre-Columbian time (Pachacamac) developed, a worship of the God of Sun in a place where the sun is not visible nearly half of the year, while only a few miles inland it is shining practically all the time. By the same token, one wonders why Pizarro founded Lima just in this spot, to the surprise of the Incas, rather than on the coast or farther inland, for certainly he was aware of its rather dreary climatic characteristics. However, as it has turned out, the presence of the cloud cover and continuous advection of marine air, which regulate the temperature, probably have been the most important factors conducive to the fast growth of the Peruvian capital. Metropolitan Lima, with far more than two million inhabitants, has become the largest city of the Pacific coast of South America and is outstanding among tropical coastal cities for its high concentration of non-native population.

Discussions of the Peruvian coastal climate in geographical literature have always mentioned the obvious controls, such as cool ocean temperatures and temperature inversion; but such discussions were limited by lack of aerological information and had to be based on what few surface data were available and what comparisons could be made with similar coastal deserts in other parts of the world (Lydolph, 1957; Trewartha, 1961). Such studies could pretty well explain temperature and humidity conditions at the coast but could not explain fully the almost complete lack of precipitation, which is the most outstanding climatic feature of the area. Such explanations can be adequately based only on upper air data, which indicates the degree of stability in combination with the available water vapor.

In tropical coastal regions no lack of precipitable water ever exists (Tuller, 1968). Therefore, the key to aridity lies in stability considerations, which at best can be deduced only in general terms from surface pressure fields. Even these are not well known in this area. Radiosonde data, however, are available from over Lima for the decade of the 1960s at least, and much more is known about the circulation and thermal structure of the eastern Pacific Ocean (Wyrtki, K., 1964; Wyrtki, L., 1967). This new information allows a more genetic approach to understanding the special features of the Peruvian coastal climate. This chapter will concentrate on an analysis of the more recent data of the central Peruvian coast. Only the pertinent facts will be treated, and no climatography of the general area will be attempted.

Sources of Data†

For Lima about 2,750 radiosonde records have been summarized for the period 1957–65 in the form of averages of height, temperature, and relative humidity for the different pressure levels at 50-millibar intervals. Wind statistics exist only for the mandatory isobaric levels (surface, 850 mb, 700 mb, and 500 mb) over the period 1957–1962.‡ In addition, the author made use of daily radiosonde observations of the entire year 1967.

* Deceased.

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‡These data are available from Environmental Science Services Administration (ESSA), Weather Bureau, Washington, D.C., in microfilm or print-out form.

The launching hours were at 0700 Lima time (1200 GMT) from October 1957 through June 1961, and 1900 Lima time from October 1957 through September 1960 and since July 1961.

The mean monthly surface pressure values of the American west coast between 30°N and 30°S were taken from World Weather Records, 1951–1960, and from unpublished records of the Peruvian coastal stations at Talara, Chiclayo, Lima, and Tacna. Moreover, for the year 1967 the following data have been analyzed: Hourly surface observations at Lima Airport, 12°01′S, 77°07′W, 13 meters elevation, 3 kilometers inland in a straight line or 6 kilometers in an upwind direction from the coast; climatic statistics of the meteorological observatory "Alexander von Humboldt," La Molina, 12°05′S, 76°57′W, 238 meters elevation, 11 kilometers from the coast; three daily observations at Matucana, 11°50′S, 76°24′W, 2,374 meters elevation, 80 kilometers inland from the coast. Personal observations of cloudiness and other phenomena during the year 1967 added insight to these data. A tropical location such as this has the distinct advantage of consistent weather patterns so that the results of a thorough study of even a short period of time, such as one complete annual cycle, can be instructive and quite significant.

Southeast Pacific Trade-Wind Circulation

The trade winds have a manifold effect on the coastal climate. They cause cool ocean currents and upwelling, especially at the coast, and hence keep the marine layer cool and moist. By contrast the air above the marine layer is dynamically heated by subsidence. The result is a well-expressed *trade-wind inversion* and with it a high degree of stability that counteracts any development of convective air currents (which might bring on precipitation) and thereby produces "dry" oceans and arid or desert coasts.

The average pressure distribution exhibits in winter a high-pressure ridge over South America connecting the South Pacific and South Atlantic anticyclones; in summer a low-pressure trough extends from the equator south over the tropical west coast. Over the southeast Pacific at 90°W the pressure difference between the subtropical high and the equatorial trough, which activates the trades, is approximately 10 millibars. During the year this difference is nearly constant but shows a latitudinal displacement. During January it extends between 25°S and 5°N, while in July it shifts to a position between 20°S and 10°N. As a consequence of this latitudinal shifting by seasons, the atmospheric pressure along the Peruvian coast during the southern hemispheric winter is 3 to 4 millibars higher than during the summer. This range decreases toward the equator to around one millibar. This seasonal variation in pressure pattern is only another expression of a more intense subsidence in winter than in summer that is also evidenced by the higher temperatures above the trade-wind inversion in winter than in summer.

The marine layer below the inversion has just the inverse annual temperature variation. As a consequence, the thermal differences between the two layers, separated by the inversion, is greatest in winter; therefore the stability is at its maximum. Such a seasonal variation of the intensity of the inversion is observed along the coastal area from Ecuador to northern Chile. The main purpose of this chapter is an analysis of the structure of the inversion at the central Peruvian coast and its climatic implications.

Figure 11-1 exhibits the annual variation of the atmospheric pressure field along the tropical Pacific coast in detail. It shows that (1) in no season does the meteorological equator coincide with the geographical equator but lies between 10°N and 15°N latitude; (2) the intertropical trough varies only slightly in position and intensity during the year; (3) the pressure gradient continues across the geographical equator during the entire year along the South American coast and is stronger in winter than in summer because the high-pressure influence extends nearly to the equator during the winter season; (4) a distribution of absolute values and annual variations of pressure along the Pacific coasts of South and North America that is different and asymmetric with not only the geographical equator but also the intertropical convergence zone (ITC), or however this region may be defined.

Figure 11-1 also shows the known inverse relationship between atmospheric surface pressure and oceanic surface temperature. Furthermore, it reveals that genuine tropical temperatures (above 26°C) are found only in the Northern Hemisphere. The transition to cooler subtropical waters is concentrated in each hemisphere in a relatively small area (between 20°N and 25°N and between 0° and 5°S), and so are the pressure gradients. Even though the pressure data for figure 11-1 are based on only five stations in the Southern Hemisphere and seven in the Northern Hemisphere, the pressure pattern derived can be considered reliable since it is confirmed by the independently observed ocean temperatures.

The climatic effects of the trade winds and the concomitant phenomena along the coast are determined to a great degree by the orientation of the coastline in relation to the direction of the trade-wind flow and by the topography of the hinterland and its influence on the circulation pattern (Lettau, 1967; Lydolph, herein). Such features are different from continent to continent which exhibit low-latitude dry coasts. The Pacific coast, except for the area between 30°S and 40°S, has a NNW-SSE direction to about 14°S and then changes to a NW-SE direction southward to the Chilean border. Such an orientation coincides closely with the prevalent trade-wind direction. In addition, the Andes rise almost immediately from the coast to a mean crest height of 4,000 to 5,000 meters poleward of 8°S. The coast, therefore, is well protected from tropical air masses in the Amazon basin, and the orientation of the mountains parallel to the coast must have a channeling effect on the trade winds.

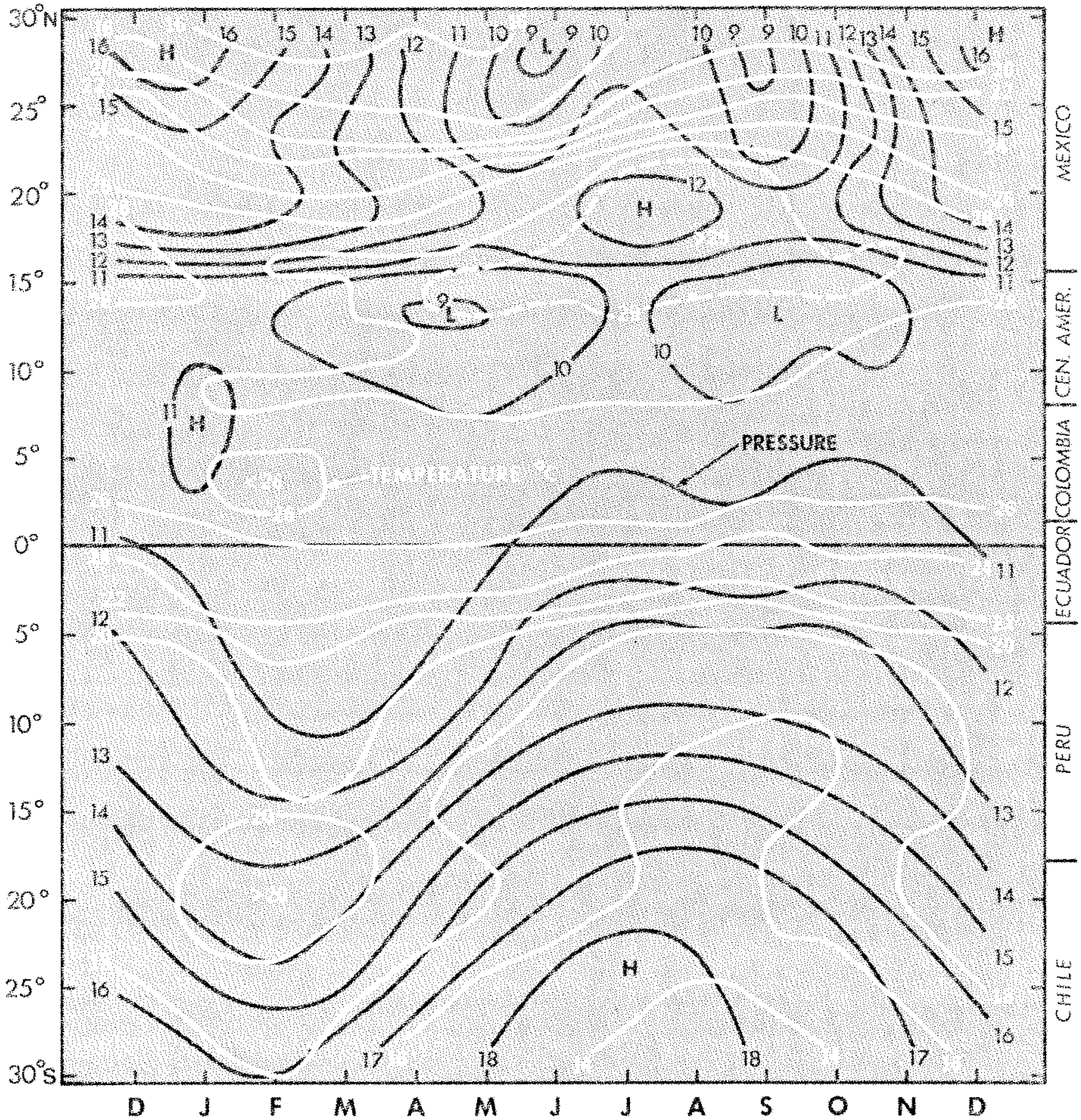

Fig. 11-1. Annual variations of atmospheric pressure (1,000+ mb) and ocean surface temperature (°C) along the west coast of the Americas between 30°N and 30°S.

All these facts taken into consideration, there is no reason to expect any similitudes of climates at corresponding latitudes in the two hemispheres along the tropical west coast of the Americas. Thus, the equatorward extension of the Peruvian coastal desert may be considered a climatic abnormality only as long as it is referred to the planetary setting, that is, the geographical equator. If one realizes that the low-latitude coastal deserts are not functions of astronomical parameters but are dependent on the trade-wind circulation and its intensity to determine their geographic location, then the Peruvian coastal desert starts at a similar latitudinal distance from the intertropical trough as the coastal desert in Baja California does, and the Baja California desert extends even further toward the intertropical convergence zone than the Peruvian desert does.

Winds Along the Peruvian Coast

Throughout the year the trade winds blow along the Peruvian coast and extend northward to and even across the geographical equator. The nearly constant direction of the pressure gradient implies an extraordinary persistency of the winds, which is corroborated by figure 11-2 and table 11-1. At Lima at 7 AM and 7 PM (launching hours of the radiosondes) 74 percent of all *observed* surface winds (excluding calms) are from the south (62 percent) and south-southeast (12 percent) and have, therefore, a small onshore component. The 24-hour frequency distribution is similar. The only difference is a higher frequency of the direction parallel to the coast (SSE), which is observed above all during the night and in winter, and from the west, which is characteristic of the morning hours in summer. It is noteworthy that no offshore component is manifest at all.

Similar conditions are found in Puerto Chicama at 7°42′S, where at 7 AM wind directions are from SE (37 percent), SSE (43 percent), and S (15 percent), accounting for 95 percent of all winds. The change of the prevalent wind direction from S in Lima to SSE in Puerto Chicama is due to change in direction of the pressure gradient. The afternoon winds (4 PM) at Puerto Chicama are similar to those in the morning and show the same total of 95 percent of the winds from a southerly direction if SSW winds are included. Thus, the trades here also show a slight onshore component, which is enhanced in the afternoon when the SSW direction increases from 2 percent at 7 AM to 20 percent at 4 PM. The small offshore component (SE) decreases during the same time interval from 37 percent to 26 percent. Neither at Puerto Chicama nor at Lima is it possible to speak of a land-sea breeze circulation, since the ocean-coast temperature contrast, even though rather large in some months, is able to shift the trade-wind direction just a few degrees. Rather incomplete wind statistics for Tacna at 18°S (Peru, Dirección General Meteorológica, 1956 & 1957) and nine guano islands (Valdivia Ponce, 1957) that lie between 7°S and 18°S latitude show

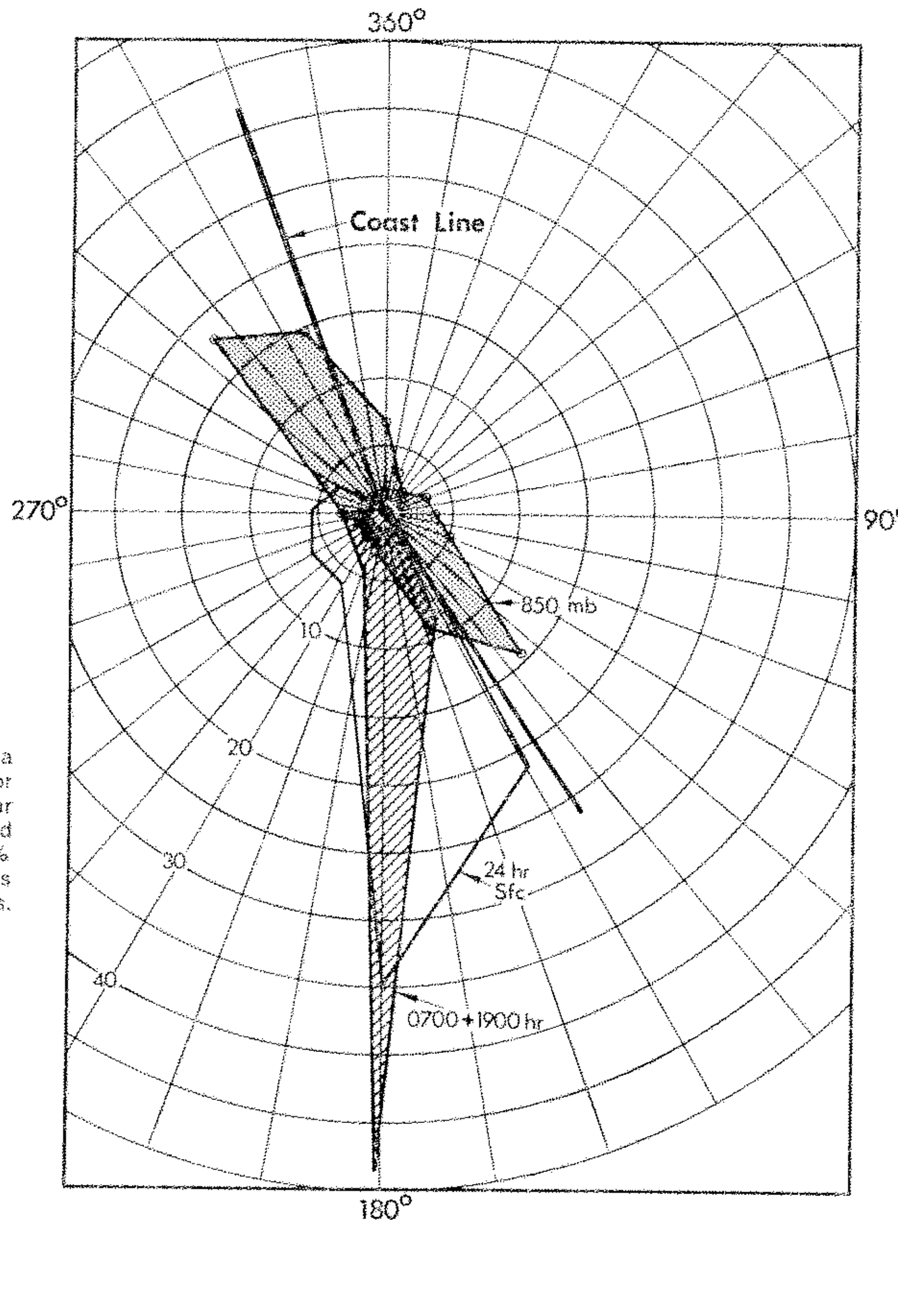

Fig. 11-2. Annual wind roses at Lima (airport) in percent of all observations for surface in 8 directions for 24-hour observations (1967) with 20% calms, and 0700 + 1900 hours (1957–1962) with 24% calms, and 850 millibars in 16 directions (1957–1962) with 1% calms.

TABLE 11-1

Monthly Averages of Pressure Differences and Winds Along the Peruvian Coast

	J	F	M	A	M	J	J	A	S	O	N	D
Pressure Differences in millibars between Tacna, 18°14'S and Talara, 4°04'S (1957–1966)												
	2.3	2.1	2.2	2.8	3.4	4.0	4.0	4.0	4.3	3.7	2.9	2.7
Prevailing wind direction (D), frequency (%), and speed (Sp) in knots												
Puerto Chicama, 7°42'S, 4 PM (1941–1953)												
D	SE	SE	S	S	S	S	S	S	SE	SE	S	SE
%	43	40	42	45	43	40	45	48	45	48	43	46
Sp	8.2	7.8	8.2	9.4	9.0	8.2	7.8	8.2	9.4	9.4	9.0	8.6
Lima, 12°01'S, 7 PM (1957–1962)												
D	S	S	S	S	S	S	S	S	S	S	S	S
%	53	61	65	66	53	53	69	56	65	72	69	66
	6.4	4.8	4.7	5.3	3.5	4.3	4.6	6.5	4.8	6.0	5.3	6.2
Resultant wind direction (azimuths)												
	175	184	181	178	183	186	177	184	182	181	183	177
Resultant wind speed (knots)												
	5.7	3.9	4.1	4.7	2.2	2.8	3.9	5.4	4.1	5.4	4.7	5.6
Steadiness of resultant wind vector (%)												
	89	81	88	88	63	64	84	84	87	89	89	89
Tacna, 18°14'S, 3 daily observations (1956)												
D	S	S	S	S	S	S	S	S	S	SW	S	S
Sp	3	5	2	4	3	3	–	6	6	6	5	5

exactly the same predominance of S and SE directions during the entire year.

Similarly uniform is the wind speed along the coast and across the islands offshore, where it is generally stronger (table 11-1). The average velocities are limited to between four and nine knots, with a tendency toward the lower limit during the first half of the year and toward the higher limit in the second half. In Lima, the resultant daily wind direction is from the south during the entire year with a persistency in its vector between 60 percent and 90 percent. Therefore, the resultant wind speed is only a little less than the actual speeds.

The trade winds have a vertical extent of no more than 1,000 to 1,500 meters at the central Peruvian coast, as can be judged from radiosonde data taken at Lima, the only aerological station along the Pacific coast between Panama (9°N) and Antofagasta (23°S). Figure 11-2 and table 11-2 reveal that at 850 millibars, or about 1,500 meters above sea level, NW is the most frequent wind direction and is the direction of the resultant wind. This direction is most predominant during December through April. Also during the period of the strongest development of the trades, June through September, the NW winds are still more frequent than the SE winds. The steadiness of the resultant wind vectors at this altitude is very low, particularly in winter (around 10 percent), and the resultant wind velocity is only a fraction of the actual wind speed. Further aloft, between 850 and 500 millibars, the wind speed is stronger in winter than in summer. Thus, in winter there is a rapid decrease in wind speeds downward toward and within the friction (marine) layer. This change is no doubt enhanced by the strong temperature inversion that exists during this time of year. The result is a nearly opposite annual variation of wind speed in the marine layer below the inversion where a summer maximum prevails and in the subsiding air above the inversion where the winter maximum prevails. These aerological conditions over Lima will be treated in more detail elsewhere in connection with the comparison with the climate of the Peruvian highlands.

TABLE 11-2

Resultant Wind Direction (D) in Azimuths, and Average Wind Speed(Sp) in Knots, Over Lima in 1957–1962

	J	F	M	A	M	J	J	A	S	O	N	D
850 mb (1500 m approx.)												
D	357	328	342	325	360	13	307	331	301	244	334	332
Sp	5.0	5.4	5.3	5.4	6.6	7.7	7.2	7.2	7.1	6.4	5.9	5.9
Resultant Speed												
	1.3	1.3	1.6	1.4	0.6	0.9	0.9	1.1	1.9	0.4	0.8	1.3
Steadiness of resultant wind vector (%)												
	26	25	31	21	10	12	12	15	3	7	13	22
700 mb (3140 m approx.)												
D	300	327	342	113	148	137	148	131	140	120	18	337
Sp	7.4	7.0	5.9	6.8	8.8	8.5	7.9	7.7	7.6	7.3	7.3	6.3
500 mb (5860 m approx.)												
D	130	109	99	13	341	10	356	10	16	63	64	147
Sp	9.1	8.4	8.3	9.2	12.3	12.7	13.6	13.0	10.8	10.1	9.8	10.3

Temperature Inversion

The equatorward extension of the trade winds is accompanied by a continuance of the trade-wind inversion. Salinas, at 2°S (U.S. Navy, 1959), shows inversion conditions similar to those at Lima 12°S. The inversion is a function of both subsidence-induced adiabatic heating from above and cooling from below, and hence its day-to-day and season-to-season variations depend upon surface and upper air conditions, both of which are a direct consequence of trade-wind intensities and pressure fields. To obtain an insight into frequencies of occurrence and annual variations of height, intensity, and thickness of the inversion, it was necessary to evaluate daily radiosonde data according to the significant levels for one entire year at least, since ESSA data averaged for each 50-millibar level smoothed out the characteristic inversion features. The following discussion is based on the daily 7 PM radiosonde observations for the year 1967 at Lima, a year which experienced no major climatic abnormality on the coast.

During 1967, of all soundings (320 total), 95 percent showed a surface inversion, 2 percent showed isothermal structures, and 3 percent, normal lapse rate conditions, up to 850 millibars at least. The seven days with isothermal structures were scattered between December and April, and the ten days with average lapse conditions were scattered between January and March. Hence, from May through November, the inversion was present without interruption. Even though radiosonde observations were skipped a few times within this period, it seems safe to assume that the inversion was present throughout the period.

Since an inversion constitutes a convectional "lid" between the marine layer and the layers above; it becomes a controlling factor on the coastal climate throughout the year. Such a persistent inversion is extraordinary anywhere on earth, let alone in tropical latitudes. The comparisons of 10-year averages for Lima with the U.S. Standard Atmosphere at 15°N (U.S. Standard Atmosphere, Supplements, 1966) demonstrates that up to 800 millibars (2 kilometers) the troposphere over Lima is markedly cooler than the Standard Atmosphere, which reveals the strong oceanic influences, but between 700 and 270 millibars (10 kilometers) it becomes as much as 4°C warmer than the corresponding averages for 15°N, which indicates the great importance of subsidence over Lima. The two effects together are responsible for the extraordinary stability at the Peruvian coast.

In spite of the persistency of the inversion, its structure and variability differ markedly from summer to winter in conjunction with the change from low-pressure to high-pressure influence along the Peruvian coast. As an example, the mean monthly structures of the vertical temperature distribution for the two seasons are represented in juxtaposition in figure 11-3. It becomes immediately evident that the winter type represents the typical trade-wind (subsidence) inversion, and the summer type represents the combined effects of heating by subsidence from above and cooling by oceanic influences from below. The change of the structure of the inversion is in relation to and only a symptom of the change in stability that takes place not only at the coast and along the west side of the Andes but over the entire western part of tropical-subtropical South America south of the equator. The trade-wind inversion type, which is manifest June through September or October, coincides with the dry season in the Andes and the upper Amazonian watershed and signifies the high-pressure influence over this entire region at this time of the year, while the summer-type inversion coincides with the rainy season, December through March or April, and signifies the influence of low pressure.

The different controls and structures of the inversion in different seasons have different influences on the marine layer and hence on the coastal climate. Therefore, the analysis of the local climate will be broken down by seasons.

Winter or Trade-Wind Inversion and Climatic Consequences (May 16 through September 30, 1967)

Along the coast of central Peru, winter conditions prevail as long as the primary cause of the inversion is heating by subsidence, normally from June through September or October. It is apparent that winter in 1967 started on May 16 when this type of inversion was first observed. The end of the winter was arbitrarily taken as September 30 in order to have climatic statistics averaged over a period approximately equal in length to that considered to be the summer season, as discussed later. This

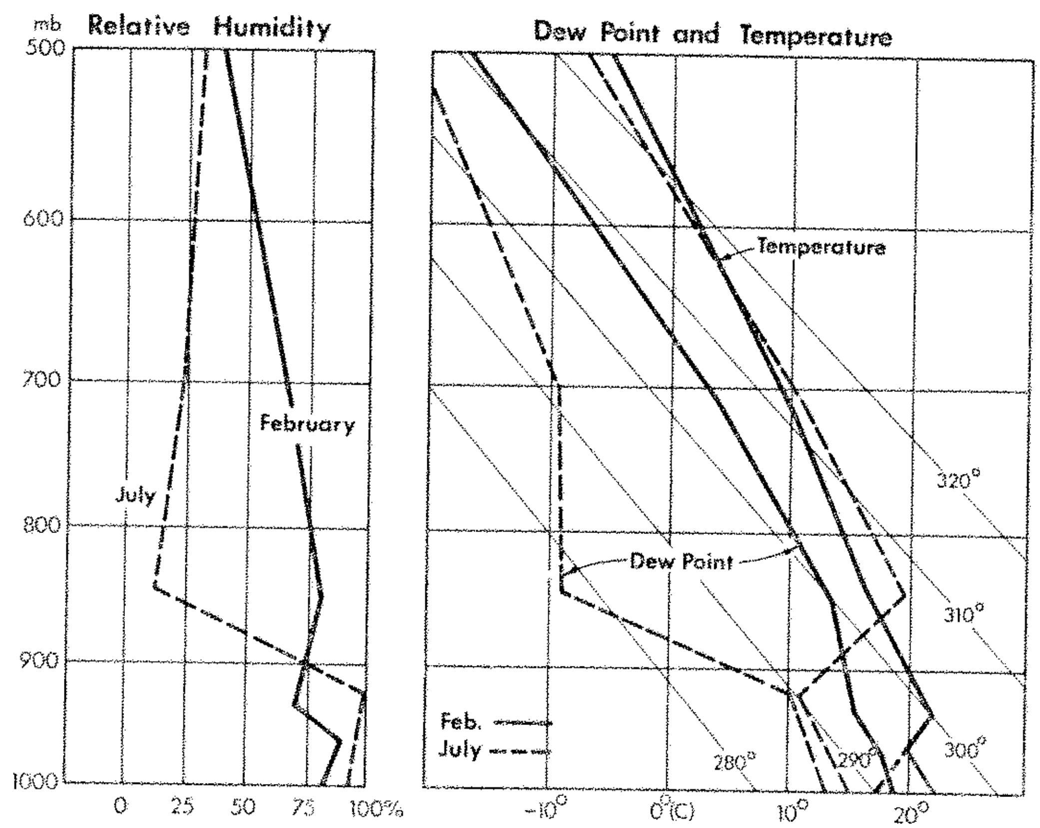

Fig. 11-3. Average vertical cross-sections of temperature, dew point, and relative humidity for February and July 1967 over Lima.

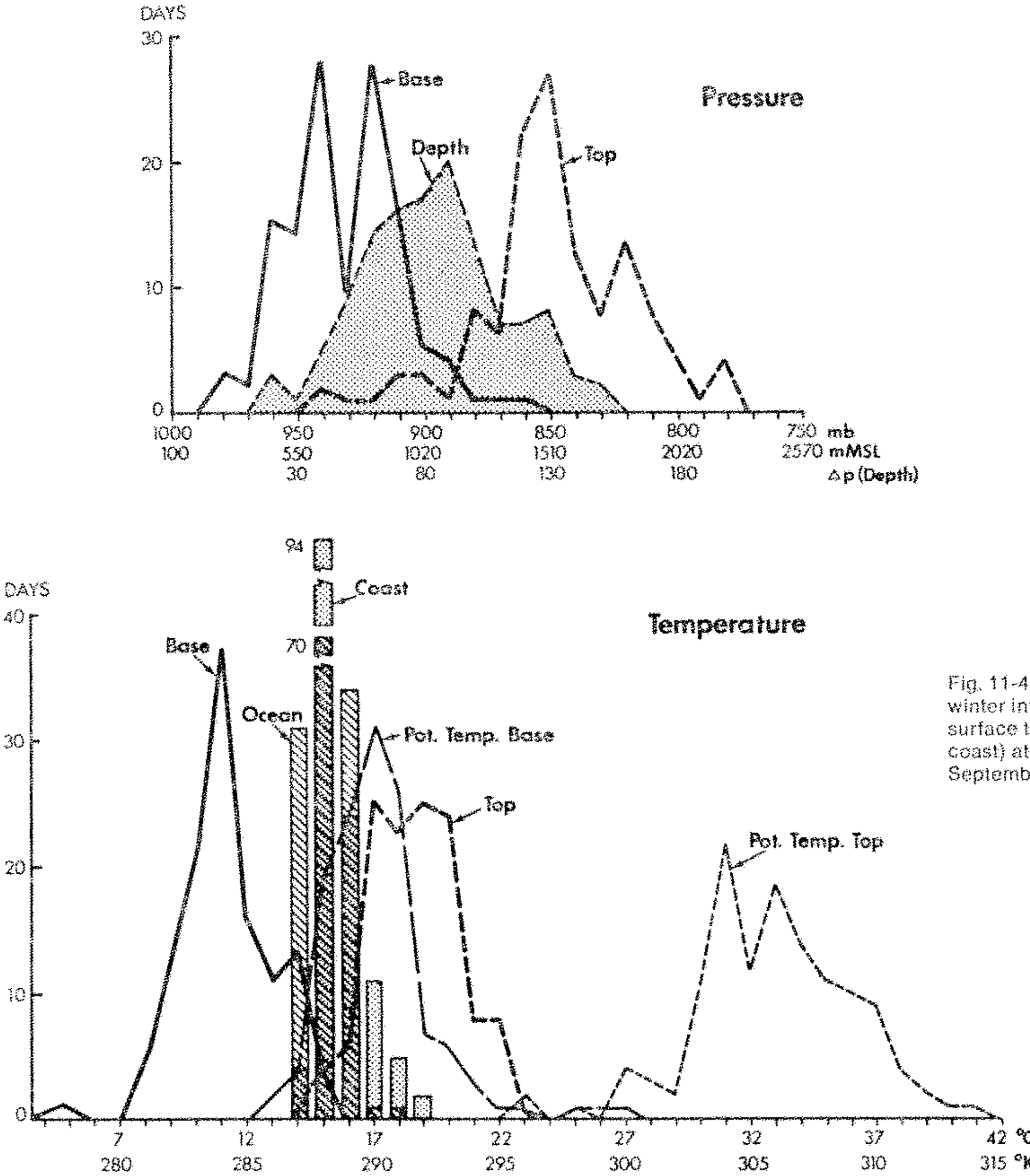

Fig. 11-4. Frequency distributions of winter inversion characteristics and surface temperatures (ocean and coast) at Lima, May 16 through September 30, 1967.

was justified somewhat by the fact that other parameters such as day length, solar radiation, and surface temperatures started to show seasonal changes around the end of September in spite of the fact that the trade-wind inversion type, and with it the stratus layer, persisted into October.

Characteristics of the Inversion

The main characteristics of the inversion during the winter season are illustrated in figure 11-4. The inversion base fluctuated between 300 and 1,400 meters above sea level, with most frequent occurrences between 600 and 800 meters. The temperatures of the inversion base were most frequently between 10° and 11°C. The inversion top fluctuated between 650 and 2,250 meters, with the mode at 1,500. The temperature at the inversion top had a mode between 17° and 20°C. The inversion depth averaged about 830 meters, had its mode at 870, and varied from 200 to 1,500. The temperature increase through the inversion was generally between 6° and 10°C but amounted to as much as 15°C. The corresponding increase of potential temperature varied generally between 14° and 18°K but reached a maximum of 23°K. The average lapse rate through the inversion, thus, amounted to approximately −11°C per kilometer and showed a frequency mode of −15°C per kilometer.

The increase of the variability upward was common to all elements represented in figure 11-4. The interdiurnal variability increased also for both pressure and temperature from the surface up to the top of the inversion. At the top of the inversion, 35 percent of the interdiurnal variabilities fluctuated within the limits of ±10 millibars (90 m), while at the inversion base 43 percent of the interdiurnal variabilities lay within these limits. The maximum interdiurnal variability at the top was 100 millibars or 900 meters, while at the base it was only 60 millibars or 540 meters. Therefore, the interdiurnal variability of the depth of the inversion resulted primarily from fluctuations in the height of the inversion top. Such a condition is an obvious consequence of subsidence as the primary cause of the trade-wind inversion. Associated temperature values exhibited interdiurnal variabilities within the limits of ±1°C in 66 percent of the cases at the base of the inversion and in 56 percent of the cases at the top. At the inversion top, day-to-day changes of as much as 4° to 6°C were not infrequent. The normally inverse relationship between depth and intensity of the inversion was only weakly expressed in 1967. During the same year the data indicated no relationship between the height of the base of the inversion and the height of the top of the inversion, between temperatures at the base and the top, or between the inversion structure and vertical changes in wind direction and/or speed.

Atmospheric Humidity

The steady onshore trade winds, together with the inversion, have a strong influence on the humidity content of the marine layer. The winds increase the evaporation, but the inversion inhibits the transport of water vapor upward, and the coastal mountains intercept its lateral diffusion inland. Therefore, the humidity content in the marine layer is very high and contrasts sharply with drier layers above the inversion, a contrast that increases with the strength of the inversion. The result is a marine layer saturated nearly throughout its depth, with a low and stable stratus cover produced by continuous mixing below the inversion. At Lima Airport the 24-hour average of the relative humidity was 88 percent during the four winter months of 1967, and the hourly values never fell below 60 percent. Even at 2 PM, when the daily temperature is usually at a maximum, the mean value of the relative humidity was above 80 percent. The strong contrast between the humid marine layer below the inversion and the dry air above the inversion can best be illustrated by the mixing ratio. The uniform values of 9 grams per kilogram in the marine layer decrease to 3 grams per kilogram at the top of the inversion, which corresponds to a decrease in relative humidity across the inversion from 100 percent at the base to 20 percent at the top.

Clouds

The stratus in the marine layer is extraordinary in its persistency. During the winter of 1967, 90 percent of all days were overcast (cloud cover of more than 95 percent of each hourly observation). Only five days had less than six oktas (eighths of sky cover), and the clearest day during the entire period had an average of 3.4 oktas. The longest consecutive overcast period was 44 days, during which just 10 hours, recorded during six different days, had a cloudiness of only 5 to 7 oktas. During the entire winter period only 53 hours or 1.6 percent of the time had clear sky, generally around sunset. Previous years had shown short sunny periods but with an irregular frequency.

In spite of this stable cloudiness with ceilings generally between 150 and 300 meters, fog is rather infrequent at the coast at levels below 100 meters (airport and downtown Lima). An earlier study had shown that during the period 1943–1950, low-ceiling frequencies below 120 meters had an inverse relationship to wind speed (Graves, 1944). Therefore, it appears that nightly calms might produce fog, but the data for 1967 indicate that usually calms do not last long enough to allow the ceiling to descend to the surface.

The stratus is only a few hundred meters thick and extends upward approximately to the inversion base. Its thickness is a function of the strength of the mixing process in the marine layer (mixing condensation level) and the height of the inversion base, which depends on the simultaneous intensity of subsidence from aloft among other factors. This can be deduced from daytime cloud observations at La Molina, at 235 meters elevation, 22 kilometers east of the airport. During periods when both stations had overcast sky, the marine layer was deeper and inversion stronger than normal. That is, the inversion base was higher with a correspondingly lower temperature, and the inversion top had a higher temperature but only a slightly higher altitude. Hence, the temperature gradient across the inversion was nearly twice as great as it was when the stratus was rather thin and the sun or sky was partially visible at La Molina. Above the inversion, the western slopes and the highlands have very small amounts of cloud, 2 to 4 oktas during winter, which consist primarily of cirrus, the typical dry season cloud type.

Precipitation

The continuous advection of marine air inland and the resultant concentration of water vapor below the inversion cause frequent saturation in the surface layer during nighttime. This factor, together with strong nocturnal cooling as a result of intense net long wave radiation from the cloud top into the extremely dry atmosphere above, increases the instability in the marine layer and leads to frequent drizzlers, called *garúa*. This is a typical night and early morning phenomenon all along the Peruvian coast from about 8°S latitude southwards.

During the 1967 winter, *garúa* was recorded 877 hours at Lima Airport, which produced a total amount of precipitation of only 6.1 millimeters. It occurred most frequently between 11 PM and 9 AM, during which slightly more than half of all days recorded garúa. It was least evident in the afternoons between 12 PM and 5 PM. This pronounced daily variation applies only to the coastal strip itself. On the slopes and hills (lomas) between 100 and 200 meters and about 700 to 800 meters, where the inland advance of the marine air is lifted orographically, almost continuous drizzle is experienced in the contact zone of the stratus with the ground (fog precipitation). Here the total amount increases to between 100 and 200 millimeters during the winter, which, with the very reduced evaporation loss, is enough to produce the so-called lomas vegetation (Roessl, 1967).

As vegetation itself is a fog catcher, once its growth is started, the soil beneath the vegetation receives amounts of water several times greater than would have been produced on a barren slope by *garúa* processes alone. This in turn fosters further vegetational development. Here then is a case of vegetation acting not primarily as a water-consuming factor but as a water-producing factor in a self-increasing process. All this is plainly visible in the landscape as a zone of intensively green pasture with grazing cattle between completely desertic landscapes both below and above, which indicate respectively the lower and upper limits of the stratus. The botanical aspect of this singular and seasonal phenomenon has been widely investigated (Weberbauer, 1945), and it is not necessary to enlarge upon it here, even though it is a direct consequence of the trade winds and their intrinsic inversion. From October through December as the stratus cover and its *garúa* precipitation fades away, the vegetation slowly disappears, and the landscape changes back once more to the uniform, almost complete desert so characteristic of the lower part of the western slope of the Andes.

Temperature

Another direct effect of the stratus cloud cover, or indirect effect of the inversion, is the influence on the insolation and ultimately on the temperature in the marine layer. Since during the winter about 80 percent of the incoming solar and sky radiation is reflected or absorbed by the clouds, it has little effect on temperatures. Thus, surface temperatures along the coast depend almost entirely on the temperature of the marine air that is being advected inland by the onshore component of the trade winds.

During the winter of 1967, the daily water temperatures at La Punta (Callao) were between 14°C and 16°C except on two days (fig. 11-4). Equally consistent were the air temperatures at Lima Airport. The 7 PM values, which practically coincide with the daily averages, remained almost the same from day to day (a true tropical behavior), despite the low absolute values. On 84 percent of all days the temperatures stood at 15° or 16°C, and the extremes during the entire winter were 14° and 19°C (fig. 11-4).

The cloud cover also strongly reduces the effective outgoing surface radiation. The result is a very small diurnal range of temperature at the coast (3°C), which is completely atypical of a tropical station (table 11-3). Table 11-3 shows also the very insignificant temperature variations experienced from one ten-day period to another during the winter of 1967. As a matter of fact, during the months July through September, the interdiurnal variability never exceeded ±0.9°C, and 70 percent of the time it was 0.0°C; only in June was it once as much as −2.0°C.

By comparing sea and air temperatures in table 11-3, it becomes evident that in winter the air temperature is merely a function of the sea temperature. This continues to hold even as late as the spring equinox when the noon solar zenith distance is only 15°. Obviously, as long as the trade winds and, hence, the cloud cover persist, the direct influence of incoming and outgoing radiation on surface temperatures is practically nil. This strong control by the cloud cover can be exemplified by its absence during the only clear night, 11/12 of June, when the minimum temperature dropped 4.5°C lower than it was either the day before or the day after.

During the winter, temperatures at the base of the inversion are 4°C to 5°C lower than at the surface, which results in an average lapse rate of 6.7°C per kilometer through the marine layer, if one defines the upper limit of the marine layer as the base of the inversion. The inversion top has temperatures 2° to 5°C higher than those at the surface. The mode of the potential temperature at the inversion top is about 16°K warmer than that at the surface (304°K = 31°C, a temperature which is seldom observed at the coast even in midsummer). During the entire winter the free atmosphere at an altitude of 1,500

TABLE 11-3

Ten-Day Average Air and Sea Temperatures at Lima (Callao) During Winter 1967

	June			July			August			September			Winter
	1–10	11–20	21–30	1–10	11–20	21–31	1–10	11–20	21–31	1–10	11–20	21–30	June 1 to Sept. 30
Lima Airport (Callao), Air Temperature (°C)													
Mean maxima	18.0	17.5	16.9	16.6	17.1	16.4	16.3	17.2	16.7	17.0	16.8	17.4	17.0
Mean minima	15.1	14.3	14.6	14.6	14.5	14.1	13.6	14.3	13.2	13.8	13.8	14.0	14.2
Range	2.9	3.2	2.3	2.0	2.6	2.3	2.7	2.9	3.5	3.2	3.0	3.4	2.8
Average	16.6	15.9	15.7	15.6	15.8	15.3	14.9	15.7	15.0	15.4	15.3	15.7	15.6
Callao (La Punta), Ocean Surface Temperature (°C)													
Average	16	16	15	15	15	15	15	15	14	14	14	14	15

meters was 3.1°C warmer than Lima Airport. At this elevation the western Andean slopes experience, too, the highest monthly temperature averages. One has to go to an elevation of 2,300 meters to find daily mean temperatures as low as those at sea level, and to find diurnal maximum temperatures as low as those observed along the coast one has to ascend to 3,500 to 4,000 meters. Such high daily maximum temperatures are the consequence not only of subsidence but also of intense solar radiation and dry soils. In combination with intense heat loss during nighttime, the daily ranges of temperature increase with elevation even at steep slope exposures and show the typical behavior of tropical arid zones.

At the climatic station at Matucana, 2,374 meters, 90 kilometers east of Lima Airport, the average diurnal range of temperature is more than 10°C in winter. On less-inclined slopes, valleys, or rolling plains above the inversion, as in southern Peru and northern Chile, daily ranges of more than 20°C are regionally observed even at elevations above 3,000 meters, and certain places may have the highest daily ranges of temperatures anywhere at the earth surface (Weischet, 1966). Hence, in regard to temperature, the inversion produces a stronger contrast over a smaller distance than the Andes do, and most of the atypical climatic features in this oft-mentioned area are products of the extremely narrow coastal zone below the inversion layer.

Fig. 11-5. West coast of South America as seen by Satellite ESSA 5, PASS 1381–1393, August 7, 1967.

In Lima the winter temperature is 9°C below the latitudinal average, a temperature observed in Salvador (Bahia) at the Atlantic coast of South America at the same latitude. In the northern hemisphere the same latitude and exposure (west coast of Nicaragua) has 10° higher temperatures than Lima. To find temperatures similar to those in Lima, one has to go to 24°S along the west coast of Africa and to 28°S along the west coast of Australia. The Australian coast best represents the latitudinal mean (cf. Chapt. 24).

The Peruvian coastal weather in winter, and its stability in space and time, is, thus, the consequence of the persistence of the inversion together with the onshore component of the equally persistent trade winds. The mixing processes in the marine layer produce the quasi-permanent stratus cover belt below the inversion, which largely inhibits water-vapor diffusion into the higher atmospheric layers.

It should be pointed out, however, that the inversion and the associated stratus are not produced by or limited to the area of the Peruvian coastal current, or to the coast itself and its hinterland, as a result of friction and onshore-upslope movements, since both the inversion and the stratus extend far into the Pacific, well beyond the western fringes of the Peruvian current. This can be documented by occasional radiosonde observations taken by oceanographic vessels and can be seen very clearly on ESSA 3, ESSA 5, and ATS 3 satellite pictures, which show an immense and uniform cloud shield over the subtropical southeast Pacific that starts at the South American coast and extends west-northwestward to be dissolved eventually in the typical trade wind cumuli (fig. 11-5).

Summer Inversion (January 1 through May 15, 1967)

Typical summer conditions prevail from January through April. In this period, too, an inversion is almost continuously manifest, the trade winds blow with the same persistency as in winter, and occasional rains give only scarcely measurable amounts. But with the exception of the unidirectional steadiness of the wind, these similarities are only apparent; subsidence is restricted to higher levels (Foehn effect), and precipitation falls not in the form of drizzle but as big rain drops. Other climatic parameters, such as cloud cover, radiation, and temperature, are also quite different from what they are

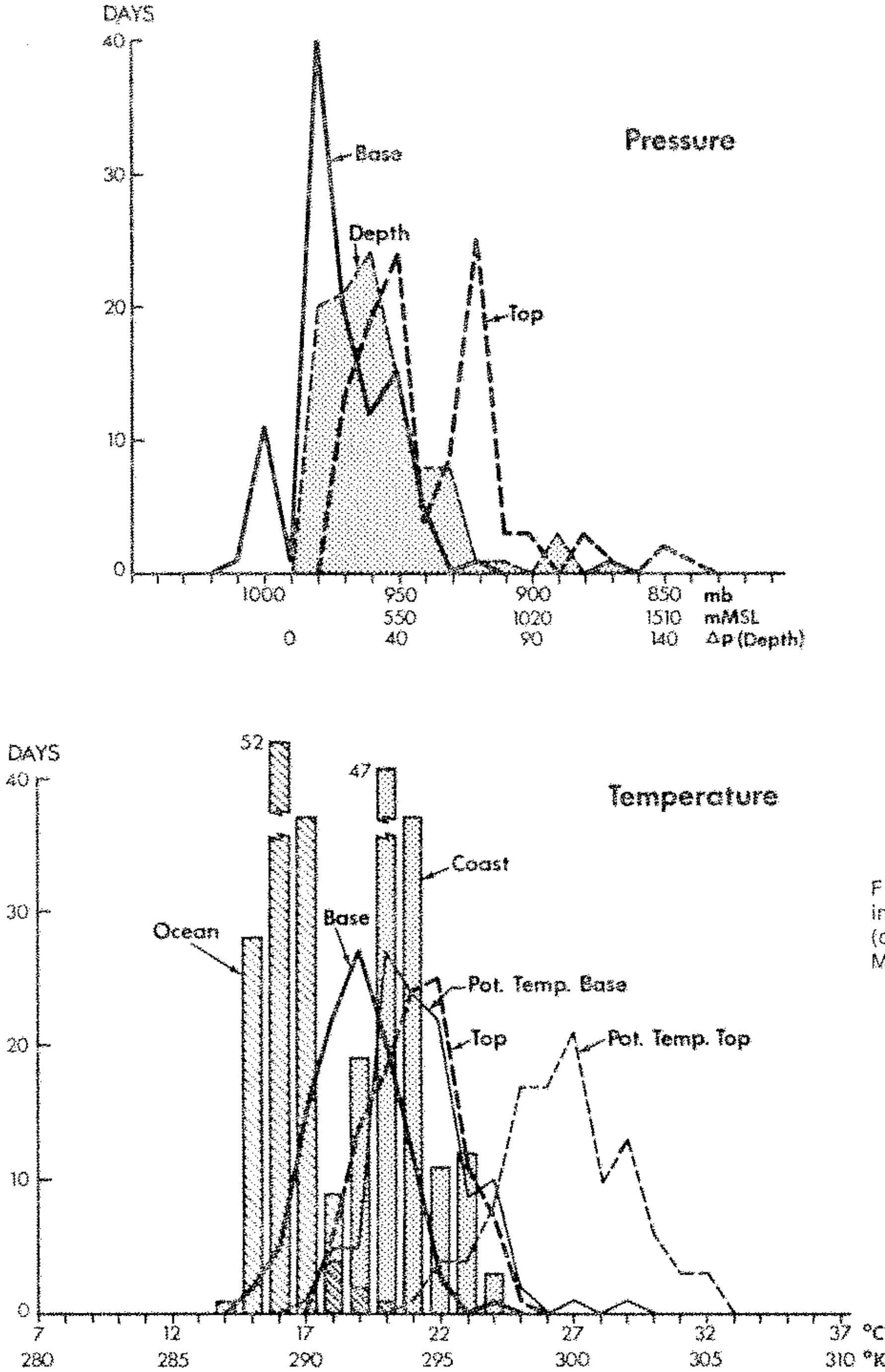

Fig. 11-6. Frequency distributions of summer inversion characteristics and surface temperatures (ocean and coast) at Lima, January 1 through May 15, 1967.

in winter. Consequently, a much greater seasonal contrast is observed at the coastal area than farther inland where the cloud and rain regimes are the primary climatic determinant. This relatively large contrast adds another atypical aspect to the Peruvian coastal climate.

Characteristics of the Inversion

During summer, the surface inversion is primarily the consequence of the cool ocean. In contrast to the winter inversion, it starts nearer to the surface, is less pronounced, and shows a greater day-to-day change in intensity, depth, and altitude. In fact, during summer the inversion top is normally at or below the altitude of the inversion base in winter. With a few exceptions the top lies between 400 and 900 meters (fig. 11-6). The inversion base most frequently lies between 200 and 500 meters, and the inversion depth is generally only 100 to 300 meters (dp 10 mb to 35 mb), in contrast to the winter inversion when the thickness is around 800 meters.

During summer the temperature increases through the inversion normally by only 1° to 4°C. The mode of the lapse rate through the inversion is the same as in winter, −15°C per kilometer. These inversion characteristics are representative only for the coastal strip itself, where a marine layer exists. Inland, the fast-rising slopes soon penetrate the inversion, and over the ocean the inversion probably starts nearly at sea level. This can be assumed because the temperature of the inversion base over Lima is higher than the ocean temperature just offshore, which ipso facto excludes a genuine marine layer. Furthermore, the extrapolation of the inversion slope downward to sea level gives approximately the actual ocean temperatures (fig. 11-3). The thickness of the inversion over the sea is, thus, between 600 and 800 meters, a depth similar to that found in winter. The mode of the temperature increase through the inversion over the sea has to be between 5° and 6°C, or an increase in potential temperature of about 10°K.

Atmospheric Humidity

The mixing ratio decreases slowly from 13 grams per kilogram at sea level to 12 at the inversion base and to 11 at the inversion top. The relative humidity decreases accordingly from 80 percent to 90 percent in the marine layer to a little less than 70 percent at the inversion top. Saturation is generally not observed at or below the inversion base. These are typical features of a "cold water type" inversion. Subsidence becomes increasingly important only at higher altitudes. A vertical cross-section of relative humidity makes this evident in spite of the fact that the isohumes are based on the average values for 50-millibar surfaces (fig. 11-7). Figure 11-7 also demonstrates the great seasonal contrast in the vertical distribution of humidity over the dry coastal areas as high as data are available (up to 10 km).

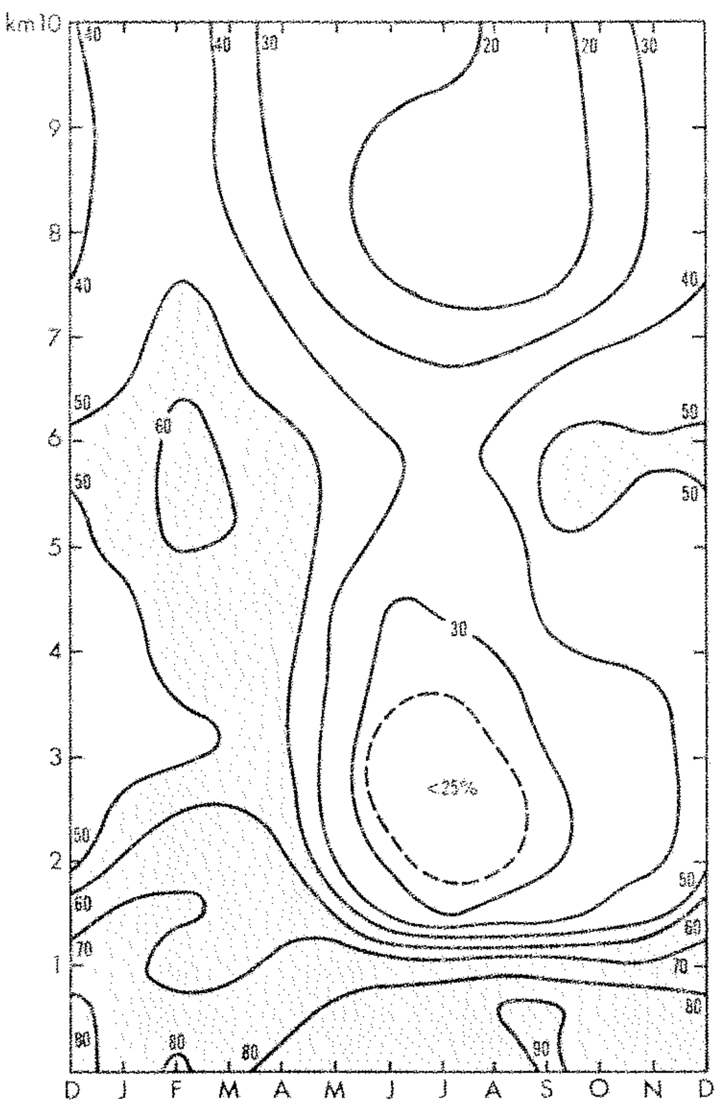

Fig. 11-7. Vertical cross-section of relative humidity over Lima, 1957–1965.

The temperature inversion is strong enough to restrict the diffusion of water vapor upwards. Along the coast the result is a high atmospheric humidity, notwithstanding desert soils. At Lima Airport the average dewpoint is 2° to 4°C higher than the ocean temperature offshore and coincides with the mean minimum temperature at the airport, which signifies frequent dew formation during the early morning hours. By noon, the time of strongest advection and insolation, the dewpoint has generally increased slightly by about ½°C. The similar daily variation of air and dewpoint temperatures yields a continuously high relative humidity throughout the day, which even at noon is seldom below 65 percent.

If one accepts Scharlau's limit of sultriness of 18.8 millibars vapor pressure (Scharlau, 1952), or 16.6°C dewpoint, one can see that from a bioclimatic standpoint the Lima area is a continuously sultry region, since the hourly values of humidity are above the limit of sultriness throughout the entire summer and they are considerably above this limit during midsummer. Some days the dewpoint is more than 21°C during the early afternoon, which is equivalent to a vapor pressure of more than 25 millibars. In comparison, the vapor pressure of the upper Amazonian basin gives values of 30 millibars if extrapolated to sea level.

Clouds

The inversion controls the upper limit of the maritime summer fog. The fog is formed far offshore near the western border of upwelling and is driven onshore by west winds. This kind of sea breeze is observed only in the morning and only on those days when the preceding night has experienced a lull in the winds. It lasts only until the south winds take over again, generally around noon. The fast advance of a fog or cloud bank toward the coast is a typical sight in the first hours after sunrise. At the coast the fog is quickly transformed into low fracto-stratus or fracto-cumulus clouds, which are dissolved inland. The inversion prevents the upward diffusion of water vapor and causes the high atmospheric humidity in the thin marine layer. Moreover, the inversion, together with the increasing subsidence aloft, inhibits the formation of the typical tropical cumulus clouds.

The small amount of low clouds is more than balanced by the sharply increasing amount of middle and high clouds towards the Andes. During summer the Peruvian part of this mountain massif is embedded in the deep tropical easterlies, which is evidenced by the wind distribution over Lima from the 500-millibar level upward. These moist easterlies, rising to great heights, wrap the Andean peaks in towering clouds which are visible from the Pacific side sometimes even as an impressive foehn-

Fig. 11-8. West coast of South America as seen by Satellite ESSA 3, PASS 1531–1543, February 1, 1967.

wall or "Föhnmauer." Descending the westward, leeward slope, the foehnwall dissolves into alto-cumulus lenticularis, the most frequently observed cloud form at the coast. These ground observations are corroborated by satellite pictures which consistently show, at this time of year, extensive cloudiness over the upper Amazon basin which extends across the Andes westward to the Pacific coast where generally it cuts off rather sharply, indicating the stabilizing influence by subsiding movements together with the cool ocean (fig. 11-8). Clouds in so many different forms and levels in toto produce a rather high amount of total sky cover in summer as well as in winter. Although a completely overcast sky seldom occurs in summer, neither does a cloudless sky throughout a full 24-hour period. During the summer of 1967, the monthly means varied around 6 to 7 oktas. The lowest daily mean was 0.5 okta, and the most frequent value observed was 7.5 oktas.

Precipitation

The characteristic abnormality of the summer climate along the Peruvian coast is the almost complete lack of precipitation. It is obvious that the main obstacle to the extension to the Pacific coast of the rainy season, which is so well expressed throughout tropical South America, is the high rising Andes which cause a great loss of water vapor through intensive orographic precipitation on the windward, east side of the mountains and a great drying of this same air by forced downward movement (Foehn effect) on the leeward, west side. In addition, even the weakened trade-wind circulation is strong enough to enhance the forced subsidence and, together with the cool-water inversion, inhibits the normally local precipitation processes in Pacific air masses. The overall stability is far less strong and uniform than it was in winter, but instead of the one intensive trade-wind inversion that is experienced in winter, multiple smaller inversions typically occur one above another during the summer. Unfortunately, the monthly mean data averaged for each 50-millibar surface smooth out these multiple inversions and produce a lapse rate which shows an overall absolute stability.

The occasional light rainfalls that do occur in summer, consisting of large raindrops and lasting a maximum of only a few hours during nighttime, are mostly not of Pacific origin but are a spillover of the intensive precipitation in the Andes and the Amazonian watershed. This is logically deduced from the observations of cumulonimbus clouds advancing westward over the Andes and is corroborated by the humidity cross-section shown in figure 11-7, which clearly indicates a continuous moist layer between 6,000 and 4,000 meters, which is the altitude of the base of the summer clouds. On days with light coastal rains, the surface inversion may disappear and nearly moist adiabatic conditions characterize the vertical atmospheric structure. The rapid decrease of precipitation down the western slope is well illustrated by data from February 1967 (table 11-4). During this month the exceptionally heavy precipitation in the Andes produced flooding and avalanches in the valleys of the Pacific watershed, yet the coast had only three days with measurable rain that totaled just 2.4 millimeters. The sharp decrease in precipitation as the western Andes slope downward is depicted clearly by the changes in vegetation. This becomes more and more xerophytic at the lower elevations and finally disappears completely at around 2,000 to 1,500 meters above sea level.

Temperature

Coastal temperatures during the summer are the result of the interaction of radiative and oceanic influences, as well as the inversion. The inversion has to be taken into consideration as a third factor because it is responsible for the moist marine layer which inhibits normal nighttime cooling that is generally intense in desert regions. The resulting relatively high minimum temperatures in this area are not, therefore, the consequence of direct oceanic influences, as they generally are in other coastal climates, but rather as mentioned above they are caused by the higher humidity so that they are on the average 3°C higher than the water temperatures offshore. The daily range of temperature along the Peruvian coast is twice as large in summer as in winter, but even so it is only 6° to 7°C. Mean maximum temperatures during the summer along the central Peruvian coast are high and rise to as much as 10°C above the ocean surface temperature and even higher where the coastal plains are wider. They are only 3° to 4°C lower than in "normal" tropical coastal situations at similar latitudes as, for instance, at Salvador (Bahia). A few miles inland, in downtown Lima, the mean maxima are similar to those experienced at Salvador (28° to 29°C in Lima-Campo Marte; 30°C in Salvador). Since the atmospheric humidity is quite similar to that in Salvador, at Lima the

TABLE 11-4

Precipitation Profile of the Western Andean Slope During Summer 1967

Station	Latitude	Longitude	Elevation (meters)	Precipitation (millimeters) February	Precipitation (millimeters) January–April
Cerro de Pasco	10°40'S	76°20'W	4360	220	530
Jauja	11°47'S	75°30'W	3387	191	473
Matucana	11°50'S	76°24'W	2374	148	334
La Molina	12°05'S	76°57'W	238	5	9
Lima Airport	12°01'S	77°07'W	13	2	6

"effect" of the summer temperature is just as tropical as at the same latitude on the Brazilian coast where Salvador shows almost exactly the same effective temperatures as Lima.

Seasonal Changes (Transition From Winter to Summer-type Inversion) and the Inversion as Climatic Divide

The transition from the trade-wind to the cold-water inversion type and vice versa occurs in a different pattern during the astronomical spring than during the autumn. In spring, periods of winter and summer type alternate until the latter become more frequent and extended and eventually prevail at about the end of the year or the beginning of January. In autumn, on the other hand, the transition is a matter of only a few days, or at the most a few weeks. As a matter of fact, in 1967 the trade-wind inversion was established between one day and the next, and, taking cloudiness as the criterion, the winter stratus layer appeared between one hour and the next. The sunny warm summer weather changed to the cool damp winter conditions on May 16 between 3 AM and 4 AM. This change of inversion type and concomitant weather conditions is represented in figure 11-9. During the first half of May the most frequent hourly cloud observation was 0 oktas, while during the second half of May it was 8 oktas. The mode of the maximum temperature dropped from 23° to 20°C, and the average relative humidity rose from 85 to 89 percent. At the same time the summer inversion characteristics changed to the trade-wind type.

The sudden start of winter conditions was conspicuous in previous years as well, as can be documented by aerological data. In other years the change was not as dramatic as it was in 1967, but it never extended over a period of many weeks or even several months, as is regularly the case of the transition in the opposite direction. This fact is expressed in the rapid decrease in the mean temperature from the summer to the winter level (by 8°C) and the slow increase during the reverse process at the opposite season. Neither transition in temperature is due to oceanic influences alone, since the sea temperature has an annual range of less than 3°C. Actually, the sudden establishment of the trade-wind inversion at the beginning of winter is an expression of a change in the general circulation pattern which brings on both the beginning of a wet season onto the Pacific coast and the dry season to the tropical Andes and the Amazonian basin.

Consequently, the seasonal change in the intensity of the trade-wind circulation and, thus, of the inversion type is the main control of the Peruvian coastal climate and of the atypical features which it possesses in a tropical location: large annual and small daily ranges of temperature, higher relative humidity, more extensive cloudiness, and more frequent precipitation during the dry season (hemispheric winter) than during the tropical rainy season. These abnormal conditions are restricted to the narrow coastal area. A few miles inland, along the Andean slopes, the climate becomes nearly "normal." Humidity, cloudiness, and precipitation are higher during the rainy season (hemispheric summer) than during the dry season, although not very high owing to the lee effect of the Andes; the daily range of temperature increases while the annual range decreases. In fact, the annual range of temperature decreases from the coast inland at the same rate as the mean annual temperature rises and becomes nil at an elevation of about 1,500 meters, the same altitude at which the highest mean annual temperature is observed. Above this elevation the annual variation even becomes inverted (the monthly averages become slightly higher during the dry season than during the rainy season). This is due to the fact that the monthly mean temperature at the west-facing slopes below the mean elevations of the highlands depends more on the annual variation of the maxima than of the minima (as it does in the highlands) because of good air drainage. Furthermore, the maxima are primarily a function of insolation, and along the desertic western slopes this is more effective at raising sensible temperatures in the winter months when there is less cloudiness and a drier atmosphere than in the summer. For instance, in Matucana, the mean daily maxima during the period January through March 1967, were 17.3°C and during July through September, 20.8°C. During the same periods the minima were 11.1°C and 9.5°C respectively. Hence, the minimum temperatures varied in the opposite direction from the maximum temperatures, as is normally the case, but to a lesser degree. As a result, the mean temperatures were 14.3°C for the astronomical summer and 15.3°C for the astronomical winter.

The stronger increase of the maximum temperatures, in contrast to the lesser decrease of the minimum temperatures, from summer to winter results from the stronger heating by subsidence in winter, which acts in favor of high maxima and counteracts low minima. In fact, at similar elevations on the east side of the Andes the minima are significantly lower than they are on the west side at this time of the year, in spite of the higher atmospheric humidity in the east. The aerological data prove that subsidence plays a decisive role in this sense on the

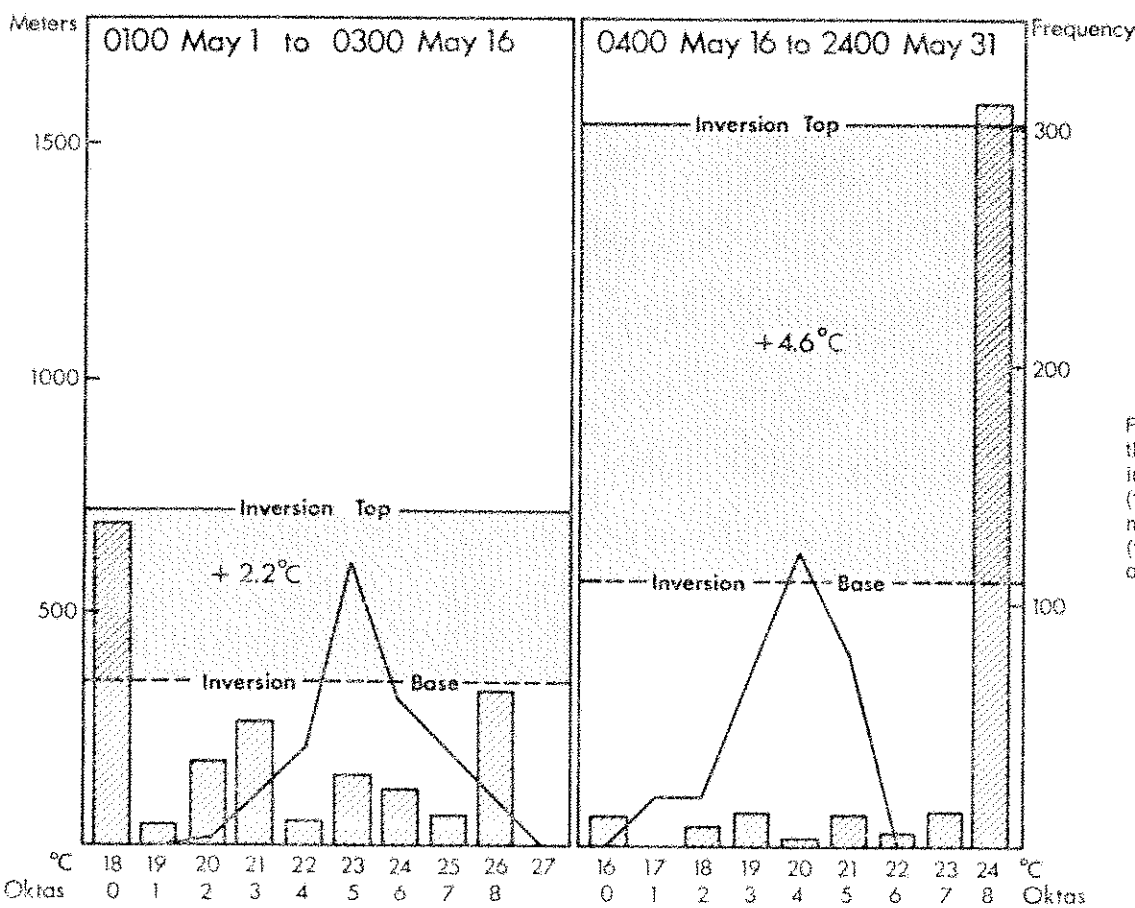

Fig. 11-9. Inversion (altitude, thickness, and temperature increase), surface temperature (frequency curve of daily maxima), and cloud cover (frequency histogram of 24 hours observations) at Lima in May 1967.

west side of the Andes, since temperatures are higher in winter than in summer between 1,500 and 4,500 meters altitude. Therefore the free atmosphere has the same seasonal temperature variation as the western slopes and hence a seasonal variation that is inverse to that experienced at the coast itself. In the free atmosphere above 4,500 meters, and in the highlands as well, the annual temperature varies in accordance with the corresponding change of seasons.

Remarks on the El Niño Phenomenon

No study on the Peruvian coastal climate seems to be complete without at least a mention of the El Niño problem. A large bibliography exists on this rather infrequent phenomenon (Schuette, 1968) in contrast to a few existing studies on the coastal climate in general. Nevertheless, the El Niño investigations have not produced a complete understanding of the phenomenon. There are obvious reasons for this. First of all, the occurrences are rare, supposedly only five times during the past century, and they have mostly happened at times of no systematic and regular meteorological and oceanographic observations. In addition, different criteria have been used to identify the phenomenon. For oceanographers, abnormally warm surface water is a sufficient criterion to speak of the Niño "current." Often the destruction of oceanic fauna or the variable salinity content is considered as additional criterion, since it may identify the origin of the water. Meteorologists, on the other hand, consider high coastal air temperatures and/or abnormal precipitation at the coast and/or in the hinterland to be essential features.

Nearly all of these phenomena may occur simultaneously and may have a common cause, but they may also be observed independently or in different combinations. Whatever the phenomena associated with the El Niño abnormality, threshold values of the meteorological and/or oceanological parameters and their extension in space and time have never been objectively defined. For all these reasons the results and conclusions depend on the criteria used and differ accordingly. In this dilemma, instead of seeking a generally acceptable definition, the best solution would be to rescind the El Niño concept completely in scholarly papers, as already suggested by Schweigger (1959). In addition, no "Niño-current" exists as such; at best it could be equated with the Peru Countercurrent, identified by Wyrtki (1963). The only disadvantage would be that a poetic and emotional term would disappear from the scientific literature, since El Niño means "the Christ child."

For a long time it has been known that an inverse relationship exists between pressure and temperature at the Peruvian coast. This relationship holds for the regular annual variation and for its irregular positive and negative deviations in winter and summer as well. The seasons are evident in view of the preceding discussion. A more intense or more equatorward position of the subtropical high causes a stronger than normal trade-wind circulation, since, in comparison, the changes of the pressure and location of the Inter-tropical Convergence zone (ITC) are relatively small. This, in turn, induces more intensive upwelling and cooler ocean surface temperatures, a stronger subsidence inversion with more cloudiness and less incoming radiation, and, as a result, a cooler marine layer and greater atmospheric stability. Years with extreme high pressure at the Peruvian coast are abnormally cold (Graves, Schweigger, and Valdivia, 1955). During the southern hemispheric winter when the subtropical high is in an equatorward position, the pressure gradient always seems strong enough to maintain a certain degree of the trade-wind circulation. But during the opposite season when the high shifts poleward, the pressure gradient may occasionally become so small that the predominance of the trades ceases, and other factors may become decisive, which leads eventually to the warming of the northern Peruvian coastal region and its consequences — El Niño.

Combining this deduction with the present knowledge on the complicated structure of the different currents off the Peruvian coast, J. Bjerknes (1966a) states that: "in weak trade-wind regimes the heat transfer to the atmosphere, both in sensible and latent form, is below normal, and more than normal amounts of heat remain stored in the ocean, thus raising its surface temperature. . . . Weakness of the trade winds has more sudden and spectacular ocean effects in terms of temperature induced by cessation of upwelling. . . ." In this context it is understood that by "cessation of upwelling" the Peru Countercurrent surfaces and/or extends toward the coast. Also in normal summers the side-by-side existing cold and warm waters are directly visible by their different albedo to observers flying at low altitudes over the coastal waters.

A decrease in the strength of the trades is also accompanied by a decrease in subsidence, and hence a decrease in stability or increase in instability, which is enhanced further by the increase of surface temperatures. The result can be intensive precipitation, sometimes even before the warming process at the ocean surface takes place. In general, it can be assumed that warm surface water is not a necessary or sufficient condition to produce coastal rains and that the El Niño phenomenon, whatever its definition may be, is neither produced by a shifting of the ITC to the south of the equator nor by an atmospheric circulation-induced reversal of the Peru Current as such. As Bjerknes (1966b and 1969) and Doberitz (1968) have shown, the El Niño phenomenon is just one of various side-effects of disturbances of the global tropical circulation. In this case, by and large, the normal "anomalies" of the equatorial eastern Pacific, that is, the coolness and dryness of the Ecuadorian and northern Peruvian coast, become anomalously "normal," and record temperatures and precipitation that are in conformity with tropical latitudes.

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