Proceedings of the Workshop on the Phenomenon known as 'El Niño'

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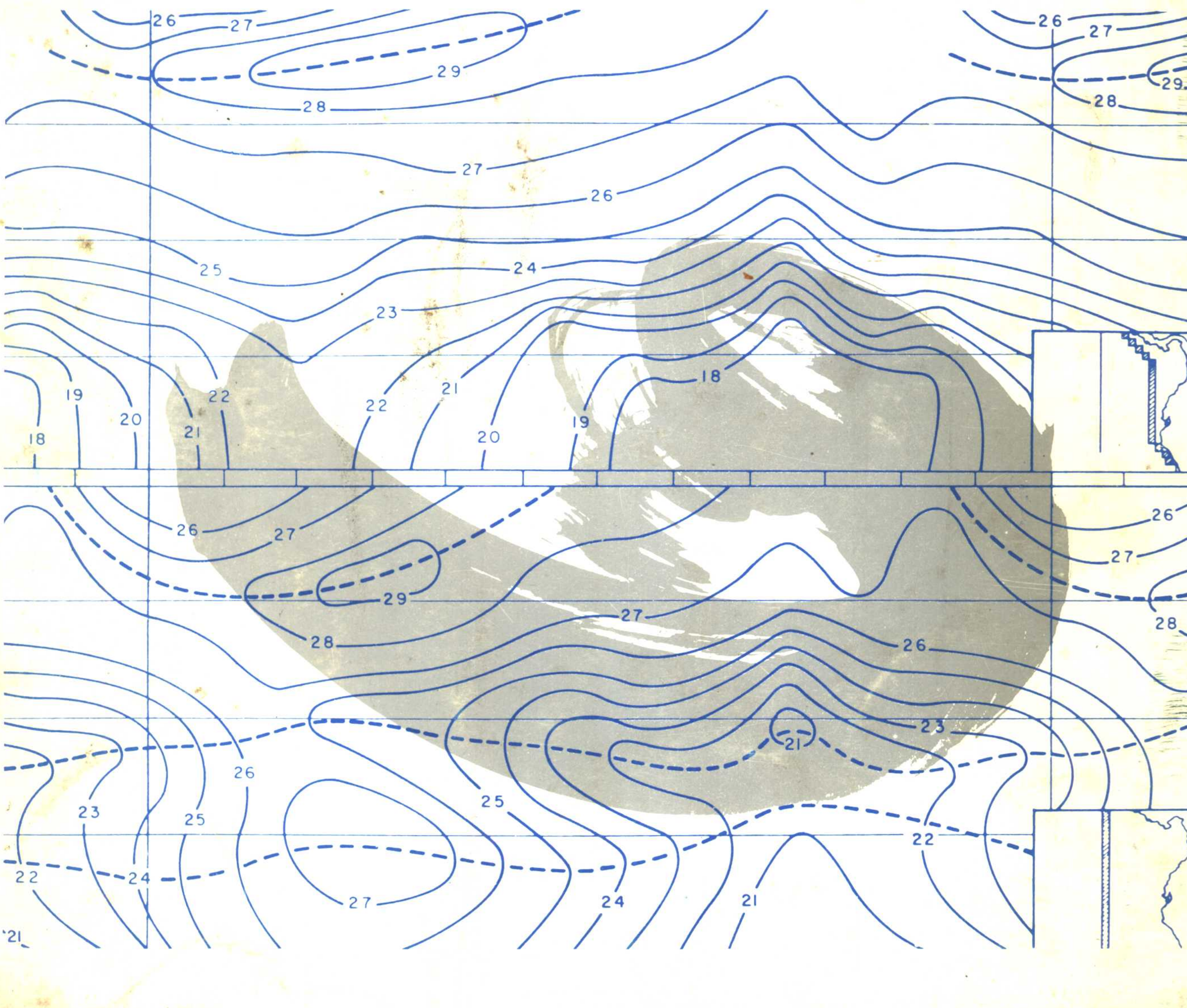

Proceedings of the Workshop on the Phenomenon known as 'El Niño'

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Guayaquil, Ecuador
4-12 December 1974
Organized within the
International Decade of Ocean Exploration (IDOE)

by
the Intergovernmental Oceanographic Commission (IOC)
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Preface

This publication forms part of the Proceedings of the Workshop on the Phenomenon known as 'El Niño', organized jointly by the Intergovernmental Oceanographic Commission, the United Nations Educational, Scientific and Cultural Organization, the Food and Agricultural Organization, and the World Meteorological Organization, within the framework of the International Decade of Ocean Exploration. The workshop was held at Guayaquil, Ecuador, from 4 to 12 December 1974, under the patronage of the Instituto Oceanográfico de la Armada Nacional del Ecuador.

The present volume contains translations of ten papers contributed in Spanish by marine scientists from the region, and which were presented or distributed at the workshop in their original version. These papers are published here in English in order to make the work of Spanish-speaking scientists more familiar to their English-speaking colleagues. Two papers presented to the workshop in English by scientists from the region have been published separately and they are therefore not reproduced here.

The FAO publication, *Reunion de Trabajo sobre el Fenómeno Conocido como 'El Niño'* (FAO Informes de Pesca, No. 185) contains the Spanish texts of all twelve papers from the region.

A complementary list of the papers presented or distributed at the workshop which are not included in the present volume is appended to the Introduction; bibliographical references are given for those which have been published.

The opinions expressed in this publication are those of the authors, and do not necessarily coincide with those of the sponsoring organizations.

Contents

Introduction

At the eighth session of its assembly, the Intergovernmental Oceanographic Commission (IOC) adopted resolution VIII-17 in which it instructed the Secretary to organize jointly with the Food and Agricultural Organization of the United Nations (FAO) and the World Meteorological Organization (WMO) a workshop on the phenomenon known as 'El Niño' to: (a) analyse the present state of knowledge concerning the phenomenon; (b) identify the key questions that must be answered to allow understanding and prediction of the phenomenon; (c) devise a co-operative scientific research programme, with priorities, with the direct participation of the coastal countries affected by this phenomenon and with the collaboration and co-ordination of the IOC and other Specialized Agencies of the United Nations; and (d) formulate proposals for a study of the interaction between this phenomenon and the biological resources of the region.

The Steering Committee which was formed to plan this workshop held its first meeting in Callao, Peru, 17–18 January 1974. The members of this committee, under the chairmanship of Dr Warren Wooster, reached the following conclusions: (a) although the resolution stresses the set of anomalous conditions known as 'El Niño', the workshop should also be concerned with variations in the total coupled systems of atmosphere-ocean-biosphere in the eastern South Pacific Ocean; (b) the goal of the investigations to be considered by the workshop should be to predict variations in the ocean environment of the region and the consequences of such variations, and in particular to predict the development of 'El Niño' conditions and their consequences.

Dr Rómulo Jordán (Peru) was invited to serve as Chairman of the workshop.

Twenty-four scientific papers were presented and discussed by sixty scientists from fifteen countries participating in theworkshop. The report of the workshop together with the recommendations has been issued in English (*FAO Fish. Rep.*, No. 163, 24 p.) and Spanish (*FAO Inf. Pesca*, No. 163, 26 p.).

In addition to the studies by Spanish-speaking scientists from the region, which have been translated for this publication, the following participants also contributed papers:

Dr David Cushing, Fisheries Laboratory, Lowestoft, Suffolk, United Kingdom: 'Models in Marine Ecology'.

David B. Enfield, INOCAR Guayaquil, Ecuador. 'The Oceanography of the Region North of the Equatorial Front: Physical Aspects'.

Dr Reuben Lasker and Dr Paul E. Smith, National Marine Fisheries Service, Southwest Fisheries Center, La Jolla, California, United States of America: 'Estimation of the Effects of Environmental Variations on the Eggs and Larvae of the Northern Anchovy'.

Dr Jerome Namias, Scripps Institution of Oceanography, La Jolla, California, United States of America: 'Ocean-Atmosphere Interaction of Large Time and Space Scales', *Collective Works of J. Namias, 1934 through 1974,* Vols. 1 and 2, San Diego, University of California, 1975.

Dr Colin Ramage, Department of Meteorology, University of Hawaii, Honolulu, Hawaii, United States of America: Meteorological Aspects of the 1972–73 'El Niño' Phenomenon', *Bull. Amer. Meteorol. Soc.*, Vol. 56, No. 2, 1975, p. 234–42.

A. Hellmut and C. Sievers, Instituto Hidrográfico de la Armada, Valparaiso, Chile, and Nelson Silva

Sandoval, Centro Investigaciones del Mar Valparaiso, Chile: 'Water Masses and Circulation in the Southeast Pacific Ocean' Latitudes 18° S.–33° S. (Operation Marchille VIII)'. Published in English and Spanish by the Comité Oceanográfico Nacional de Chile en Cienci y Tecnología del Mar as Contribución CONA No. 1. Valparaiso, Chile, 1975, 45 p.

Dr Robert Smith, School of Oceanography, Oregon State University, Corvallis, Oregon, United States of America: 'Investigations of Coastal Upwelling Processes'.

Dr Martha Vannucci, Unesco Regional Office for Science and Technology in Asia, New Delhi, India: 'Effects of Environmental Variations on the Distribution of Marine Fauna'.

Dr Klaus Wyrtki, Department of Oceanography, University of Hawaii, Honolulu, Hawaii, United States of America: 'A Review of Recent Research on the Circulation of the Equatorial and Eastern South Pacific Ocean'.

Papers distributed at the workshop:

CPCP Carlós Blandin, Meteorological Service, Quito, Ecuador: 'Caracteristicas del Fenómeno de "El Niño" y la Influencia de la Corriente de Humboldt en las Costas del Ecuador' [Characteristics of the 'El Niño' Phenomenon and Influence of Humboldt's Current on the Ecuadorian Coasts], National Institute of Meteorology and Hydrology, Climatology Section, 1974. (Publication No. 17–1).

Dr Eric D. Forsbergh, Inter-American Tropical Tuna Commission, La Jolla, California, United States of America: 'The Fishery of Skipjack in the Eastern Pacific Ocean'.

Dr Forrest R. Miller, Department of Mathematics, Kansas State University, Manhattan, Kansas, United States of America: 'The "El Niño" of 1972 in the Eastern Tropical Pacific Ocean'. (See also F. R. Miller and R. M. Laws, *Inter-Amer. Trop. Tuna Comm., Bull.,* Vol. 16, No. 5 1975, p. 403–48.

Dr Merritt R. Stevenson and Helen R. Wicks, Scripps Institution of Oceanography, La Jolla, California, United States of America: 'Bibliography of "El Niño" and Associated Publications (in English and Spanish)', *Inter-Amer. Trop. Tuna Comm. Bull.,* Vol. 16, No. 6, 1975, p. 451–501. (This bibliography has now also been made available on microfiche.)

Physical aspects of the 1972–73 'El Niño' phenomenon

Salvador Zuta
David Enfield
Jorge Valdivia
Pablo Lagos
Carlos Blandin[1]

Introduction

The 'El Niño' phenomenon is a spectacular oceanographic-meteorological anomaly that develops in the Pacific off Peru. The event causes enormously widespread effects on marine production, fisheries, northern coastal agriculture, and the life of the Peruvian coastal population, all of which finally result in a reduction of the national economy; the economic effects of the 1972–73 even were felt world-wide.

BRIEF HISTORY OF THE PHENOMENON

'El Niño' is a phenomenon that manifested itself off Peru at Christmas. Thus the fishermen of the port of Paita gave it the name of 'Corriente del Niño', in English 'Current of the (Christ) Child' (Carrillo, 1892). This designation was used by many past authors, although today it is a tacit convention to use the term 'phenomenon' instead of 'current', since it involves a transitory irregularity in the ocean-atmosphere system.

Wooster (1960) proposed a definition that tended to generalize the characteristics of 'El Niño' to processes that occur off the coasts of California, South-west Africa, West Australia and Viet Nam.

The first documents referring to 'El Niño' go back to the observations of Captains Colnet in 1795, Lartigue in 1822–23 and Carranza in 1891. According to existing sources, the most notable occurrences were those of 1891 (Schott, 1931), 1925 (Murphy, 1926; Schott, 1931), 1934–41 (Lobell, 1942; Bjerknes, 1961, 1966), 1965 (Guillén and Flores, 1965; Guillén, 1967; Zuta and Guillén, 1970) and 1972–73 (Zuta, 1972, 1973; Zuta *et al.*, 1973; Zuta and Yoza, 1974; Wooster and Guillén, 1974).

PREVIOUS KNOWLEDGE OF 'EL NIÑO'

The present understanding of the principal characteristics is fairly general and cannot clearly explain the generating mechanism of the phenomenon, a fundamental necessity for its prediction.

It is known that 'El Niño' occurs at irregular intervals in time, with variable intensity and peculiarities in the formation process, as for example in 1891 and 1925. Its most apparent physical manifestations off the Peruvian coast are: (a) the abnormal displacement of the tropical surface water layer to 10°–14° S. with temperature of 23°–29° C and salinities of 34.5–32.4 per mille; and (b) heavy rains typical of the intertropical convergence to about 7° S., e.g. rainfalls cited for the port of Zorritos by Peterson in the years 1914 (860 mm), 1925–26 (1,395 mm), 1939 (656 mm), 1953 (632 mm) were approximately three to six times the normal. These abnormalities produce temporary (four- to fourteen-month) modification in the ocean and atmosphere with consequent effects on marine fauna and fishing.

We can summarize current accepted ideas and theories as follows:

The north-east and south-east trade winds, the (north) Equatorial countercurrent, the Peru

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current, Equatorial front, and the Cromwell current (Equatorial undercurrent) all play important roles during the appearance of 'El Niño'.

In the months preceding 'El Niño', there occurred an abnormal dropping of the north-east trades, an intensification of the Equatorial counter-current and an accumulation of warm water off the coast of Central America (Bjerknes, 1961; Namias, 1973; Wyrtki, 1973).

Using the term of Mujica (1972), the 'firing' of 'El Niño' is produced by the abnormal weakening of the south-east trades, enormously reducing the upwelling along the Equator and off Peru.

In some cases, as in 1925 (Bjerknes, 1961, 1966), there occurred no previous weakening of the north-east trades, rather a predominance of north-west winds at Balboa.

A trans-Equatorial circulation, favoured by the weakening of the south-east trades displaced the Equatorial front southwards, resulting in the 'El Niño' phenomenon (Bjerknes, 1961).

The 'El Niño' waters proceed from the Equatorial region, at times advancing from the sector south-west of the Galapagos Islands; this seems to have been the case in 1891, and at other times from the east side of those islands, as seems to have been the case in 1925.

One can establish or talk of various levels of 'El Niño', according to intensity, duration and consequences by taking the area off Peru as a reference.

Materials

All existing information from different sources was gathered for the purpose of describing the physical panorama of the 1972–73 occurrence and of increasing the knowledge of 'El Niño'.

The oceanographic cruises of the Instituto Oceanográfico de la Armada del Ecuador (INOCAR) and the Instituto del Mar del Perú (IMARPE) were fortunately carried out almost simultaneously and permitted data 'splicing'. In both cases there were limitations in data on depth and offshore distance at which readings were taken. The cruises off Ecuador extended to no further than 86° W. and those off Peru to a maximum distance of 300 nautical miles from the coast. These limitations do not necessarily permit the optimum assessment of the advance of the 'El Niño' phenomenon, as will be apparent in the following sections.

ORIGIN AND NATURE OF THE DATA

The oceanographic and meteorological data gathered and presented here were obtained from oceanographic cruises, fishery explorations and shore stations.

The oceanographic cruises[1] yielded sea temperature and salinity from the surface to depths of 500 m, isothermal topographics for 15° to 20° C, wind, air temperature and surface atmospheric pressure.

The fisheries explorations of IMARPE, listed in Table 1, provided sea-surface temperature and degree of salinity up to about 120 miles offshore between the latitudes indicated in the right-hand column of the table.

The shore stations, listed in Table 2, provided data on sea temperature, air temperature, wind and precipitation (to the right of the table are indicated the position and period of each series of observations).

PROCESSING AND ANALYSIS OF THE DATA

Oceanographic and meteorological data from cruises were processed by INOCAR (Ecuador) for the area north of 3° S., and by IMARPE (Peru) for the area between 4° and 19° S. Data from fixed stations were processed by SENAMHI and IGP (Peru) and INAMHI (Ecuador). It is worth noting that salinity data was processed by INOCAR using a Beckman salinometer and by IMARPE using an Australian salinometer. Data from the cruises of the r/v *Mesyatsev* were processed by silver nitrate titration.

1. The cruises were as follows: INOCAR (Ecuador) 7111 (23 November–21 December 1971), 7202 (23 February–8 March 1972), 7205 (4–9 May 1972), 7209 (14 August–2 September 1972), 7211 (20 November–10 December 1972), 7302 (23 February–10 March 1973), 7305 (17–30 May 1973); IMARPE (Peru) U7108 (16 August–2 September 1971), U7111 (12–27 November 1971), U7202 (26 February–10 March 1972), U7204 (26 April–24 May 1972), SNP7204 (27 April–16 May 1972), U7206/7 (22 June–20 July 1972), M7208/9 (4 August–24 September 1972), U7210 (24 October–2 December 1972), U7212 (4–13 December 1972), U7302 (23 February–16 March 1973). M7305 (6 May–27 June 1973). Data from the South Tow expedition (Scripps Institution of Oceanography, 3–13 May 1972) and the YALOC-71 cruise (Oregon State University, 13 November–3 December 1971) were included.

OCEANOGRAPHIC OBSERVATIONS

The basic data used were temperature and salinity. Oxygen measurements, which would have helped in identifying the Cromwell current, were not included since they were not sampled by the INOCAR cruises. It was not possible to perform dynamic (geostrophic) calculations because the appropriate section lacked sufficient depth data to establish a reference level. Instead, we present the 15° and 20° C isothermal topographies; the 20° C topographies are given only for cruises from November to March during which the water off Peru was warm. Only sea surface temperature data were obtained from shore stations, and past measurements permitted the calculation of long-term monthly means (see Figs. 1–5).

The shore temperature and salinity sections of Figures 6, 7 and 8, corresponding to the November/December (1971), February/March (1972) and August/September (1972) cruises respectively, were prepared from cruise stations along or near 82°30′ W., north of 6° S., and about eighty miles offshore further south.

For average seasonal variations of surface temperature and salinity off the coasts of Ecuador and Peru, data from 1° Mardsen subsquares between 82° and 83°W., north of 7° S. and from the subsquares, shown in Table 3, further south were used.

In order to examine the seasonal fluctuations up to 400 m in depth, four areas off Peru were selected (see Table 4) (circular areas of twenty-seven-mile radius), the centres of which are indicated in the right-hand column.

METEOROLOGICAL OBSERVATIONS

The basic data treated are air temperatures, wind and precipitation at selected fixed stations. In addition, we present some of the monthly synoptic atmospheric pressure charts for mid-February 1971-73 (Figs. 9(a),(b),(c)). Distributions of air temperature with altitude and time were prepared by the radiosond stations of Guayaquil and Callao (Figs. 10(a),(b),(c)) and the long-term operation at Callao permitted the calculation of 1961–73 monthly means and monthly deviations for the period 1971–73 (Fig. 11(b)).

For the computation of mean values of winds at fixed stations (Fig. 12), the predominant direction at 13.00 local time (21.00 GMT) was used.

Description of meteorological conditions

In terms of latitude, northern Peru should have a tropical climate. In reality, most of its coast is eminently arid and, north of 7°S., semi-arid. This seems to be the result of several interacting geographic circumstances such as the predominance of oceanic areas in the southern hemisphere; the north-west to south-east trend of the Peru coast; and the high Andean barrier between Atlantic (moist) and Pacific (dry) air masses. The result is a strong and positionally almost invariable anticyclone, strong and persistent south-east trade winds, the north-flowing Peru current made abnormally cold by coastal upwelling and a strong diurnal land–sea circulation. These factors in turn produce powerful atmospheric subsidence, a marked thermal inversion and maximum aridity.

Prohaska (1968*a*) considered that the subsidence-induced inversions play a decisive role in the coastal climate. According to him (as cited by Mujica, 1972), these inversions at Lima had two types of structures—one in winter from 200 to 1,500 m and one in summer below 700 m. Near the surface, temperature follows a quasi-harmonic cycle ranging from approximately 16° C in August (winter) to 23°C in February (summer). Surface conditions are similar at other coastal stations though with some latitudinal variation.

Surface winds at coastal stations are persistently from the south-east sector throughout the year, south of 14° S. From that point northward to the Equator they are progressively more from the south and south-west, becoming somewhat more variable during the southern summer. Monthly mean wind speeds along the Peruvian coast vary from a summer (S.H.) low of 1.1 m/s to a winter (S.H.) high of 8.8 m/s (Zuta and Guillén, 1970). At a representative coastal station in Ecuador (Salinas) speeds range from 3.6 m/s to 4.6 m/s respectively.

Certain modifications in the atmospheric circulation result in spells of relatively cold or warm weather; in particularly anomalous cases the latter culminate in 'El Niño'. During 'El Niño', wind slackens and may become variable, upwelling is greatly decreased, and the Peru current becomes warmer or is overrun by warm water from the north. Surface air temperatures increase and the inversion is greatly weakened, while subsidence in the air mass probably decreases. The greatly decreased stability then results in torrential rains over much of northern Peru.

The monthly averages during 1971–73 of surface wind at fixed stations in Ecuador and Peru are shown in Figure 12. Data on wind collected during oceanographic cruises are also shown for that period (7111, 7202, 7208, 7212 and 7305). The monthly averages at coastal stations did not generally display well-defined trends of reduced speeds or variable or reversed directions for a single extended period. Some were generally variable in direction (such as Esmeraldas and Pto Pizarro) but with no clear preponderance in a given year. More southern stations (Callao and San Juan) showed only a slight weakening in 1972 but no clear change in direction. Salinas showed a marked decrease in intensity and change from southerly to westerly direction in 1972. Only the wind at Talara showed a clear reduction from February through September 1972, but with no distinct changes in direction.

The cruises (Figs. 13–18) took measurements over shorter periods (one to two weeks) than the fixed stations; their data therefore displays greater extremes of wind conditions.

To give an overall idea of conditions during the quarterly cruises from November 1971 to June 1973, speed ranges and principal direction quadrants can be summarized for the two crucial zones (see Table 5, also Fig. 13).

There were only three periods of significantly abnormal winds. In November–December 1971 (Fig. 14), winds south of 6° S. were weak (2–4 m/s), and were strong to the north. In February–March 1972 (Fig. 15), winds north of 6° S. were very weak and variable in direction. In August–September 1972 (Fig. 16), winds were strong north of 4° S. and from the northern quadrants (data missing south of 4° S.). In the first instance a trans-Equatorial flow would not be favoured due to strong southerly winds in the north; such flow presumably would be possible in the second and third cases. These abnormal wind periods were poorly reflected, if at all, by the monthly averages at coastal stations, suggesting that they occurred over much shorter time scales–possibly days. While the cruises detected extreme conditions, these were at best fortuitous and other interesting wind episodes were probably missed. This suggests that even intermittent, short-lived periods of abnormal wind conditions will allow the development and persistence of 'El Niño' conditions.

There is not enough information to confirm that abnormal wind episodes were as limited as these data seem to suggest. Another view, that abnormal conditions actually predominated over the ocean but were poorly represented by the data at fixed stations is possible.

Lettau and Lettau (1972) theoretically argued that, along the Peruvian coast, land–sea effects produce a thermotidal diurnal oscillation (not strictly a sea-breeze) in the coastal wind. In their model, a marked daytime pressure decrease from sea to land produced a quasi-geostrophic, equatorwards wind that was normally superimposed on the mean wind. Limited observations tend to support their model (Burt *et al.*, 1973). Warmer sea-surface temperatures and reduced upwelling during an 'El Niño' would decrease the intensity of this residual wind but not eliminate it, while offshore its effects would not be felt.

SURFACE PRESSURE DISTRIBUTION

Wooster and Guillén (1974) pointed out the abnormally low atmospheric pressure which occurred along the Peruvian coast during 'El Niño' periods, especially during the 1972 'El Niño'. To see how this might be related to the wind regime off Peru, charts of monthly mean pressure were prepared for February 1971, 1972 and 1973 over the eastern South Pacific (Fig. 9). The lack of data makes pressure analysis over oceanic areas somewhat debatable, though the Easter Island station data helped to position the South Pacific high.

The low pressure referred to by Wooster and Guillén (1974) appears as a pressure trough over the South American Pacific coast. In February 1972, the low pressure was more intense than in either 1971 or 1973. Mostly because the central high pressure east of Easter Island was 3 millibars higher in 1972, the analysis for that month showed a somewhat larger pressure gradient over the Peruvian current. If we accept this analysis, it would suggest that the average south-east trades were not significantly weaker off most of Peru. It would be more plausible, rather, that abnormally weak winds may have occurred in intermittent, short-lived episodes. In view of the mean pressure distribution, the reasons for such behaviour are not clear.

PRECIPITATION AND SURFACE AIR TEMPERATURE

Figure 20 shows the variations of monthly precipitation and surface air temperature from long-term means at coastal stations in Ecuador and Peru.

In 1971 anomalous precipitation occurred in Ecuador, especially in the period February to April. At Machala below-normal amounts were reported for that period, whereas rainfall in Peru was normal for the year. Temperatures were normal or subnormal in both countries in 1971. This would suggest that the rain in Ecuador in 1971 was perhaps associated with the abnormal activity or position of the Intertropical Convergence Zone (ITCZ) but not with large-scale warming of the sea surface.

A marked increase in surface temperature during the second half of 1971 was noted and most stations began to measure abnormally high temperatures at the start of 1972 with particularly large anomalies after May. These lasted until the end of that year and then returned to normal in March–April 1973. After this, most stations measured subnormal temperatures.

During this period of abnormal temperatures (February 1972 to March 1973), there were two periods of unusually heavy rain (in March 1972 and January 1973) at almost all stations as far south as 9° S. Other variations were reported at some stations but no geographical connection was evident for these secondary episodes. The two latitudinally coherent episodes coincided approximately with the two confirmed periods of trans-Equatorial invasions of warm tropical water associated with 'El Niño'.

It seems at first perplexing that during the winter (S.H.) of 1972, when the greatest increases in temperature were reported, there was little increase in precipitation. To understand this, we must first examine the behaviour of vertical temperature structure with time.

TEMPERATURE ALOFT

The vertical distribution of air temperature with time is shown for Callao in Figure 11 (a) and the deviation from the long-term mean in Figure 11 (b). There are two well-defined zones in the 0–3,000 m range—those above and those below 2,000 m. In the upper layer, the isotherms undergo undulatory vertical movements, They are higher (warmer) during the southern winter and lower (cooler) in the summer. In the lower layer, seasonal heating and cooling were much more apparent. During the winters of 1971 and 1972, a temperature maximum formed near 1,600 m (top of the inversion) and a minimum near 600– 700 m (inversion base). In 1972 both features were warmer than in 1971, the inversion base was slightly higher and the inversion layer slightly thinner. During the succeeding summers, the inversion disappeared entirely. A remarkable feature was the non-reappearance of the inversion in the winter of 1973.

The deviation (Fig. 11(b)) indicates abnormally cool air at all levels in 1971 and an early development of the inversion in May of that year. From February 1972 to March 1973, there was strong anomalous warming below the inversion base (800 m), reaching over 3° C in June and July (this was the period of unusually high sea-surface temperature off northern Peru). Beginning in April 1973, the first 100 m above the surface were exceptionally cold while above 1,600 m, temperatures were as much as 3° C above normal.

Positive variations in 1972 were transmitted to the inversion base with relative rapidity in contrast to subsequent cooling in 1973 which was limited to a thin surface layer. This suggests that convection is important below the inversion during 'El Niño'.

The mean monthly profiles of air temperature for February and August at Callao, and February in Guayaquil, are compared to mean profiles in Figure 10. February 1972 and 1973 were nearly normal at Guayaquil. In February 1972, conditions were already significantly abnormal at Callao. By August, the inversion was still marked but only between 1,000 and 1,500 m and the air below was considerably warmer. One year later (August 1973), the inversion had disappeared and the air was almost isothermal up to 1,400 m.

Contrary to what might have been expected, the inversion was not obliterated by convection mechanisms during the 'El Niño' period. This required a much longer time and was undoubtedly a large-scale process involving the entire South Pacific. The great extent of the air mass also explains why normal conditions were not re-established. In fact, since a return to normality requires surface cooling and renewed subsidence (both lower processes), an even longer time should be required for this to happen. Taken a step further, this suggests that the long periods required for the surface-temperature variations to eradicate or regenerate the inversion layer may in some way relate to the longer-term secular changes that occur over several years—that is, the multi-annual cycles of heating and cooling on a large scale, of which 'El Niño' is a manifestation.

The abscence of excessive rain in Peru in the anomalously warm winter (S.H.) of 1972 coincided with the presence of the inversion at that time. Heavy rains only occurred during periods of convective warming in the absence of an inversion.

AIR/SEA TEMPERATURE DIFFERENCES

It is well established that a given excess of sea temperature over air temperature in the tropic results in a much greater transfer of heat to the atmosphere (mostly in the form of latent heat) than in temperate latitudes. This is due to the more rapid increase in vapour capacity of air per degree of temperature increase at higher temperatures. Thus, small increases in sea temperature during warm 'El Niño' conditions can be very effective in warming the atmosphere. Figures 20–22 show the distribution of air/sea temperature difference (*Ta–Tm*) in November–December 1971, February–March 1972 and December 1972 respectively. Analysis of these charts indicated that negative values (shaded) were usually associated with advection of air over relatively warm water (usually over 23°–25°C).

In November 1971 the air was generally cooled by the Peruvian current (2°–16° S.) and warming was found only off Ecuador, over the Equatorial front, and near 17°S. By February 1972 this situation was drastically changed when warm 'El Niño' waters and reduced upwelling caused large areas of sea-to-air heat transfer to appear more than 50 miles from the Peruvian coast. This condition persisted throughout the remainder of 1972.

Oceanographic aspects of the 1972–73 'El Niño'

THE PRE-'EL NIÑO' PERIOD

Zuta and Urquizo (1974) considered that the pronounced cooling in March 1971 in the Equatorial Pacific (2° N.–5°S., 110°–150° W.) was symptomatic of the phenomenon to come. At that time the Equatorial Pacific east of 110° W. was significantly warmer than in March of the previous year (Wooster and Guillén, 1974). In works published more recently, authors have felt that abnormally warm conditions may have been established south of 14° S. along the Peruvian coast as early as August 1971.

According to Zuta *et al.* (1973), the 1970–71 period was characterized by sea-surface temperatures off Peru from 2° to 6° C below normal; only in June 1971–south of 14° S.–and in November–over most of the Peruvian coast–did they find markedly higher-than-normal temperatures.

The surface distributions of temperature and salinity in November–December 1971 (Figs. 23(a), (b)) show the Equatorial front (21–24° C.; 33-35 per mille) at a more southern position than was normal for the season; it extended north-westwards from 5° S. near Paita) to about 2° S. west of 82° W. The north–south trend of the front immediately offshore of the Gulf of Guayaquil (3° S.) was due to the runoff of warm, fresh water from the Guayas River. To the north, the warm, low-salinity water had advanced southwards from the Panama Bight. Only two weeks previously, the YALOC-71 cruise detected water of over 26° C and under 28 per mille near 5°N., 80° W. (Enfield, 1974). It is noteworthy that strong S.S.W. winds were encountered over the frontal area in November–December (see Fig. 14). Thus it is possible that the front and the tropical waters were receding northwards at this time, having previously advanced further south.

South of 5° S., the colder coastal waters of the Peruvian current were characterized by temperatures of less than 19° C and salinities less than 35.1 per mille, with widening at the principal upwelling areas off Pimentel (7° S.), Chimbote (9° S.) and San Juan (16° S.). Temperatures at these areas ranged from 0.5° to 1° C below normal and alternated with above-normal values (1°–2° C) in the intervening areas, the latter being the more predominant (Zuta *et al.*, 1972). Subtropical surface water was found offshore as far north as 2°30′ S. (west of 83° W.).

The alongshore hydrographic sections of temperature and salinity with depth (November/December 1971) are shown in Figures 6(a),(b). They are composed of stations along or near 82° 39′ W., north of 6° S. and about eighty miles offshore further south. Based on IMARPE seasonal cruises over several years off Peru and 3½ years off Ecuador, the vertical temperature distribution of November–December 1971 was normal. The southern limit of the tropical permanent thermocline was found off Ecuador at depths of from 25 to 50 m. From 2° to 3° S. many of its isotherms surface in the Equatorial front, whereas the rest spread vertically to the south in a transition to the typical structure of the Peruvian current.

Off Ecuador, the 15° C isotherm is found at the base of the tropical thermocline and the 10° C isotherm is found near 400 m. There is a thermostad between 13° and 14° C from 60 m to 200 m. (The weaker