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Surface and subsurface salinity in the tropical Pacific Ocean.

Relations with climate

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Abstract – Sea Surface Salinity (SSS) data have been collected in the tropical Pacific Ocean since 1969. From this data set, relationships of SSS with ENSO have been found in both the western and the eastern Pacific. These have mainly been associated with the presence of the ITCZ and equatorial upwelling. In the Central South Tropical Pacific a surface salinity maximum is formed by a positive Evaporation-Precipitation balance which undergoes seasonal and interannual variations. It is prolonged in the west by a subsurface salinity maximum. During ENSO events, the surface and subsurface salinity maxima expand westward. Initially, the subsurface salinity maximum is strengthened and shoals, but eventually it is driven back eastward by the equatorial jet. Such changes in surface and subsurface salinity need to be included in the scenario of an El Niño event.

CONTENTS

1. INTRODUCTION

The long-term mean field of Sea Surface Salinity (SSS) has been shown in various atlases (LEVITUS, 1982), but at the oceanic scale the variability of SSS is poorly known. Routine sea surface salinity measurements are not easy because of the difficulty of sampling over the sides of modern ships because of their high speeds and freeboard. In addition, not only is storage in heavy and cumbersome bottles inconvenient, but also accurate determination requires evaporation proof bottles, a costly salinometer and a trained technician. Moreover, unlike sea surface temperature (SST) used in fisheries, there is at present no commercial application of this parameter; so surface salinity data are seldom routinely gathered and never in real time. However, the routine use of a thermosalinograph aboard merchant ships was initiated in 1991 and this recorder is currently being operated in the tropical Pacific.

A renewed interest in SSS has developed during recent years for the following scientific reasons:

1. SSS varies as a result of exchanges of water across the atmosphere-ocean interface and riverine inflows at the coast which result in spreading tongues of low salinity water which can be used as tracers of oceanic circulation.
2. The accuracy of the dynamic calculation of geostrophic currents with XBT profiles is greatly improved by incorporating SSS information (KESSLER and TAFT, 1987).
3. Three-dimensional ocean models must be initialised by incorporating salinity (COOPER, 1988).
4. SSS is important in the western pacific, not only for its implications for heat content storage but also for its association with the propagation of Rossby and Kelvin waves and the genesis of Equatorial Monsoon Jet (LUKAS, 1989).
5. According to historical data there is a horizontal salinity boundary layer in the tropical regions of the three oceans (SPRINTALL and TOMCZAK, 1992).

With the assistance of officers and crew of ships of opportunity, ORSTOM has collected the first routine surface data set that includes SST and SSS over the three oceans:

- from 1969 to present, in the tropical Pacific Ocean (Fig.1);
- from 1977 to present, in the tropical Atlantic Ocean;
- from 1977 to present, in the tropical Indian Ocean.

The purpose of this paper is to summarise the principal scientific results of the salinity monitoring program in the Pacific.

Section 2 of this paper refers to the SSS description in the tropical Pacific by various text-books or atlases. Section 3 reviews SSS in the western tropical Pacific and Section 4 examines SSS in the eastern Pacific. Sections 5, 6 and 7 present new interpretations from several reports or unpublished data. Section 5 presents a description of the tropical surface salinity maximum in the south Pacific, including its annual and interannual variations. In Section 6, the extension of the subsurface salinity maximum into the southwestern Pacific is described. Section 7 points out the eventual influence of the salinity in the ENSO scenario.

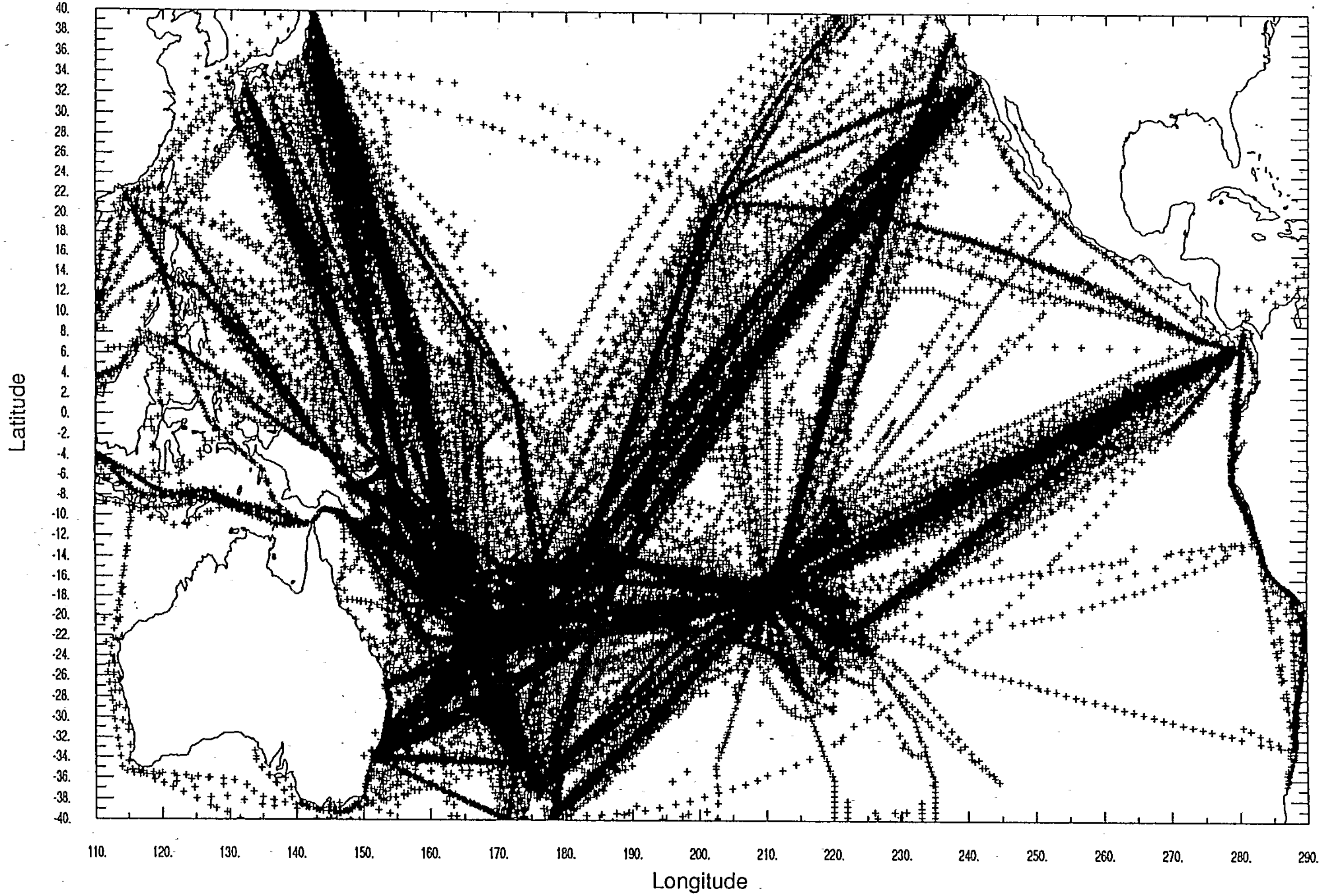

FIG.1. Distribution of SSS collected from 1969 to 1988 along shipping tracks in the Pacific Ocean.

2. SEA SURFACE SALINITY IN THE TROPICAL PACIFIC OCEAN

The general descriptions of SSS in the tropical Pacific Ocean in text books and atlases are rarer and less accurate than those of SST. SVERDRUP, JOHNSON and FLEMING (1942) only gave a map of SSS of the oceans during the northern summer. BARKLEY (1968) present seasonal maps of SSS in the Pacific Ocean but some of them were based on very sparse data. GORSHKOV (1976) illustrated maps of SSS in the Pacific Ocean for February and August. ROBINSON (1976) showed monthly SSS maps for the North Pacific which only extended southward to 5°S. LEVITUS (1982) presented monthly SSS maps for the world ocean based mostly on hydrographic data retrieved from data banks. At a smaller space-scale, DONGUY and HENIN (1978b) compiled two SSS maps per year from 1956 to 1973 for the southwestern tropical Pacific Ocean, in order to illustrate seasonal and interannual variability.

Later, with the same data and the help of computers, MONTEL, MASIA and WAIGNA (1990) produced bimonthly SST and SSS maps in the south west and south central Pacific. DELCROIX and MASIA (1989) analysed the SST and SST variations along the tracks of the ships of opportunity.

In the south western tropical Pacific (Fig.2) the main features are a SSS maximum between 12 and 25°S latitude and between 100 and 150°W longitude, and a minimum from 5 to 20°S latitude and west of 160°S. East of 170°E when easterlies are blowing, a high salinity tongue appears along the equator because of the combined influence of the equatorial upwelling, westward advection and Evaporation-Precipitation (E-P) balance. This tongue seems to connect with the surface salinity maximum.

In the western tropical Pacific, DONGUY (1987) computed the height of freshwater inferred from SSS relative to a constant salinity at depth d. The distribution of the resulting freshwater is not in agreement quantitatively with the E-P balance from WEARE, STRUB and SAMUEL (1981), but along the equator the E-P maximum coincides with freshwater minimum and the E-P minimum with a freshwater maximum at 10°S. The discrepancy observed north of New Guinea was possibly the result of river runoff. SSS depends upon three factors: E-P balance, horizontal and vertical advection, and river runoff. Neglecting this last factor and diffusion, one may write the following equation for a stationary regime:

$$U \frac{\delta s}{\delta x} + V \frac{\delta s}{\delta y} + W \frac{\delta s}{\delta z} = \frac{P\text{-}E}{d} (x,y)$$

which means that advection is compensated by the E-P balance.

3. SEA SURFACE SALINITY IN THE WESTERN PACIFIC

In 1969, with the help of the officers and crew of numerous ships of opportunity (or Voluntary Observing Ships, VOS) a program sampling SST and SSS in the tropical Pacific Ocean was initiated from Noumea (New Caledonia). Taking advantage of the trade in nickel, the shipping route New Caledonia-Japan was first sampled in 1969 as far north as 10°N. In 1974, sampling along two other shipping route Fiji-Hawaii and Tahiti-Panama was initiated, and later in 1976 sampling a fourth route Tahiti-California was initiated as a part of the SURTROPAC program.

In the 'seventies, the first results of the salinity monitoring between New Caledonia and 10°N became available. The seasonal cycle of SSS was described and the main characteristics were related to climatic features. The equatorial salinity maximum was found to be connected with the occurrence of upwelling and the minimum at 7°N with the presence of the Intertropical

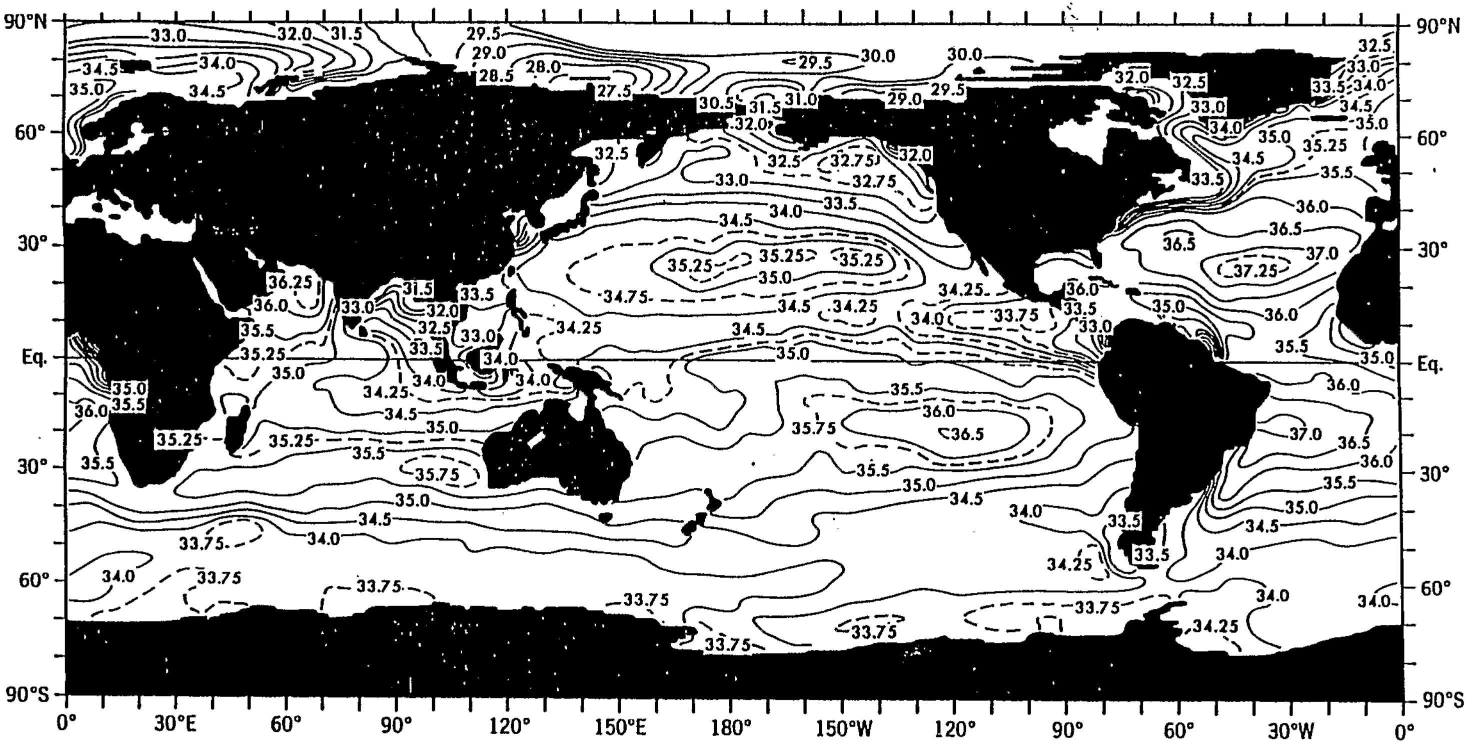

FIG.2. Annual mean salinity at the sea surface (from LEVITUS, 1982).

Convergence Zone (ITCZ) of the winds (DONGUY and HENIN, 1977). In the southern hemisphere, the occurrence of low salinity water north of the Coral Sea is associated with the prevalence of west wind and the local presence of the South Pacific Convergence Zone (SPCZ) bringing rainfall. From 1973, the monitoring was extended to the North pacific and then to the whole Pacific Ocean. In the north west Pacific from 5°N to Japan, the seasonal cycle of the surface salinity is also related to climatic features: the high rainfall associated with ITCZ is connected with low salinities at 7°N; the anticyclone inducing weak wind from the Asiatic continent is linked with the surface salinity maximum at 25°W, and the kuroshio advects low salinity water in the vicinity of Japan.

An attempt was made (HENIN and DONGUY, 1979) to characterise the tropical currents by their surface salinity. Low SSS is characteristic of the Kuroshio. The North Equatorial Current is located in a meridional gradient of salinity between the surface maximum at 25°N and the low salinity of the North Equatorial Counter Current. The North Equatorial Counter Current carries relatively fresher water. The South Equatorial Current is characterised by high SSS as a result of upwelling, evaporation and westward advection, whereas the South Equatorial Countercurrent carries low salinity water from the western Pacific.

HIRES and MONTGOMERY (1972) used SSS data obtained from voluntary observing ships in the Central Pacific in making an attempt to quantify the relationship between SSS and rainfall. They found a three month lag between rainfall maximum and SSS minimum formation.

For the southwest Pacific Ocean, two data sets are available; a compilation of SSS for 1956-1974, and the rainfall from the numerous meteorological stations located on islands in the western Pacific. The comparison of these two data sets (DONGUY and HENIN, 1978b) confirmed the conclusion of HIRES and MONTGOMERY (1972). Moreover, by comparing the rainfall on islands along 180° with SSS in the same vicinity, DONGUY and HENIN (1978a) were able to show that SSS is predominantly determined by rainfall, evaporation or upwelling, and that the influence of advection, at least in the western tropical Pacific, had been overestimated.

The general conclusion was that in the western tropical Pacific, the SSS may be considered to mirror the prevailing climatic conditions. This has been confirmed by PORTE (1992) who, however, found a poleward displacement of the region of low SSS relative to the rainfall distribution, which may result from meridional advection.

3.1 Normal and El Niño years

A change in surface salinity related to El Niño in the Western Pacific was first observed by DONGUY and HENIN (1976b). In a normal year, the main features are, as already described above (Fig.3, top panel): to the south of 10°S and of 160°W there is a tropical SSS maximum which extends westward along the equator, and from 5°S to 20°S, west of 170°W there is a SSS minimum. In general, a tropical salinity maximum results, either from positive Evaporation-Precipitation balance, or along the equator to the occurrence of equatorial upwelling, which is generated by the easterly winds and westward advection (WYRTKI, 1981). The SSS minimum results from the rainfall which occurs at the South Pacific Convergence Zone (SPCZ). During El Niño, climatic conditions change dramatically (Fig.3, bottom panel): westerly winds prevail along the equator bringing rainfall and a collapse of the upwelling. The SPCZ moves close to the equator, bringing drought conditions to the region south of 10°S (DONGUY and HENIN, 1980a). Consequently, the minimum of salinity is replaced by an equatorial salinity maximum, whereas to the south of 10°S in the western Pacific a maximum replaces the minimum (DELCROIX and HENIN, 1989, 1991).

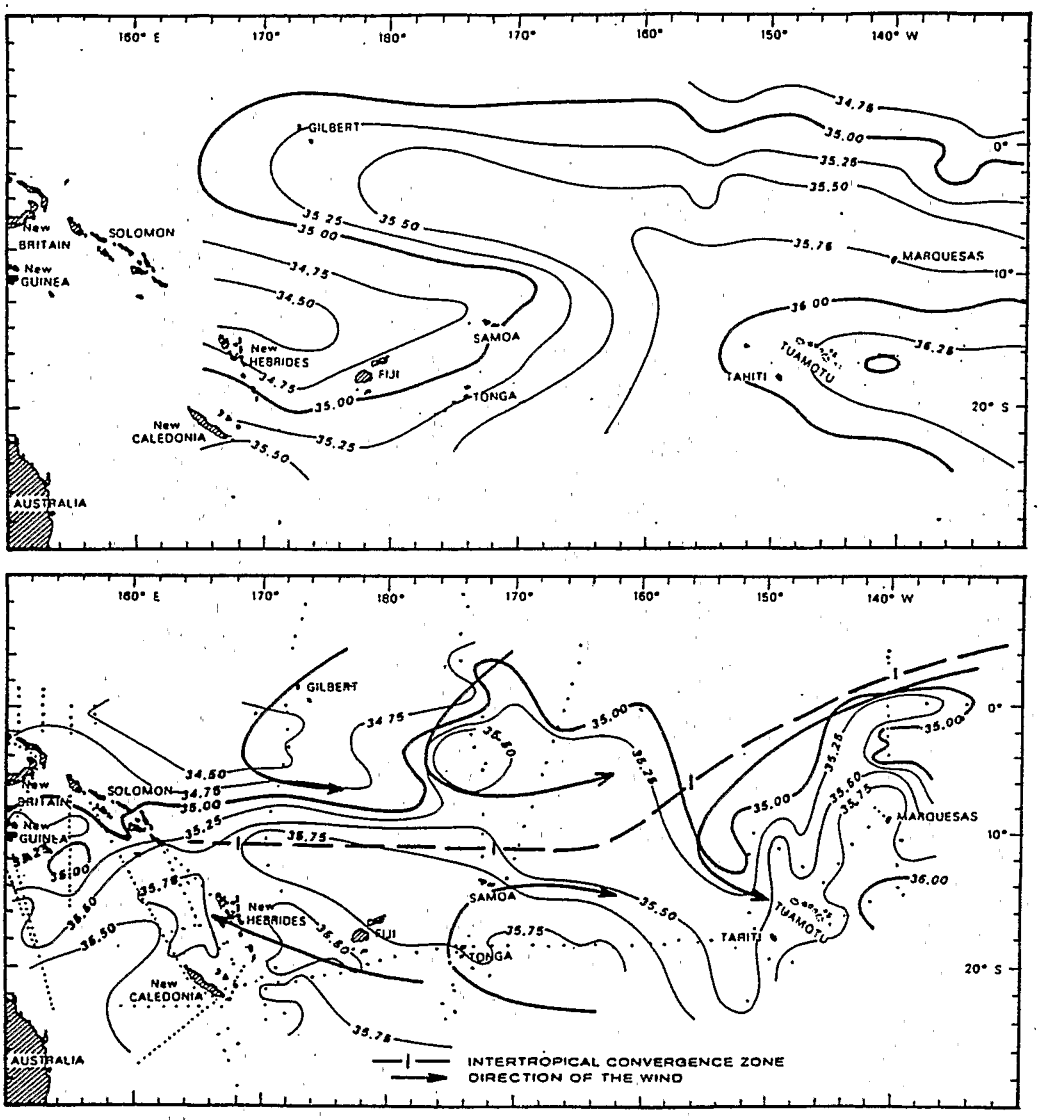

FIG.3. Mean surface salinity, 1956-1974 (top panel). Surface salinity January-June 1958 (bottom panel).

3.2 *Two different sea surface salinity states*

It is possible to separate the years between 1969 and 1982 into pre-El Niño years (1970, 1971, 1974, 1975, 1978, 1980, 1981) and post-El Niño years (1972, 1976, 1977, 1979, 1982). The post El Niño years correspond to the major El Niños and to the El Niño-like event observed in 1979 by DONGUY, HENIN, MORLIERE, REBERT and MEYERS, (1982). In the western Pacific the SSS change is significant (DONGUY and MORLIERE, 1983). During the first half of the year there are few differences in surface salinity between the pre-El Niño and post-El Niño conditions. In February (Fig.4) for example, the distribution of the water of salinity >35.0 was almost the same in both cases reaching 170°E, but in the southern part of the equatorial region (0-5°S), SSS was higher during the pre-El Niño period than during post-El Niño. In contrast, during the second part of the year strong salinity changes occur. During August (Fig.4) equatorial upwelling is intense during the pre-El Niño period with SSS >35.0 occurring in the equatorial region as far west as 150°E, whereas during the post-El Niño period, SSS <34.75 occur along the equator. In October, again during pre-El Niño period, high salinities are located between the equator and 5°S to as far westward as 150°E, whereas during the post-El Niño period, SSS >35.0 reached only as far as 170°E.

Consequently, as with several other phenomena connected to El Niño, there are two surface salinity states in the western tropical Pacific Ocean. The evolution of the SSS in the pre- and post-El Niño periods may be linked to the location of dramatic changes in the E-P balance, associated with the SPCZ. Consequently SSS properties play a role in the climatic scenario associated with El Niño in the western Pacific (DONGUY, 1982): for example, high salinity (>35.0) is both an index of upwelling on the equator and an index of drought in the tropical region, whereas low salinity is an index of precipitation.

4. SEA SURFACE IN THE EASTERN PACIFIC

Similar changes of SSS associated with El Niño can be identified in the eastern Pacific but with a smaller spatial coverage (DONGUY and HENIN, 1980b). Before the salinity monitoring program began, the only maps of seasonal salinity in the eastern tropical Pacific were those resulting from Eastropac cruises in February-March 1967 and August-September 1967 (LOVE, 1972), both observed during normal climatic conditions. In February-March 1967, a tongue of SSS <33.0 extended westward along 5°N. The 35.0 isohaline followed 5°S latitude. SSS <34.0 occurred east of 85°W, whereas very low SSS (<30.0) was found in the Gulf of Panama. In August-September 1967, there was a region of SSS <33.0 north of the equator and east of 85°W, which extend along the coast. The 35.0 isohaline followed the equator and between 5-10°N SSS was <33.5.

In 1975 El Niño watch cruises provided more information about salinity in the eastern tropical Pacific (PATZERT, 1978). There were two El Niño events between 1970-1977 which had significant economic consequences, a major event in 1972 and a weaker one in 1976. For both events, surface salinity charts are available for the area bounded by 10°N-10°S, and 75°W-105°W, during the onset (November-December), during the peak phase (February-March) and before the transition phase (April-May) (Figs 5-7) (RASMUSSON and CARPENTER, 1982). The wind data were obtained either from ship observations or from the National Climate Center (USA).

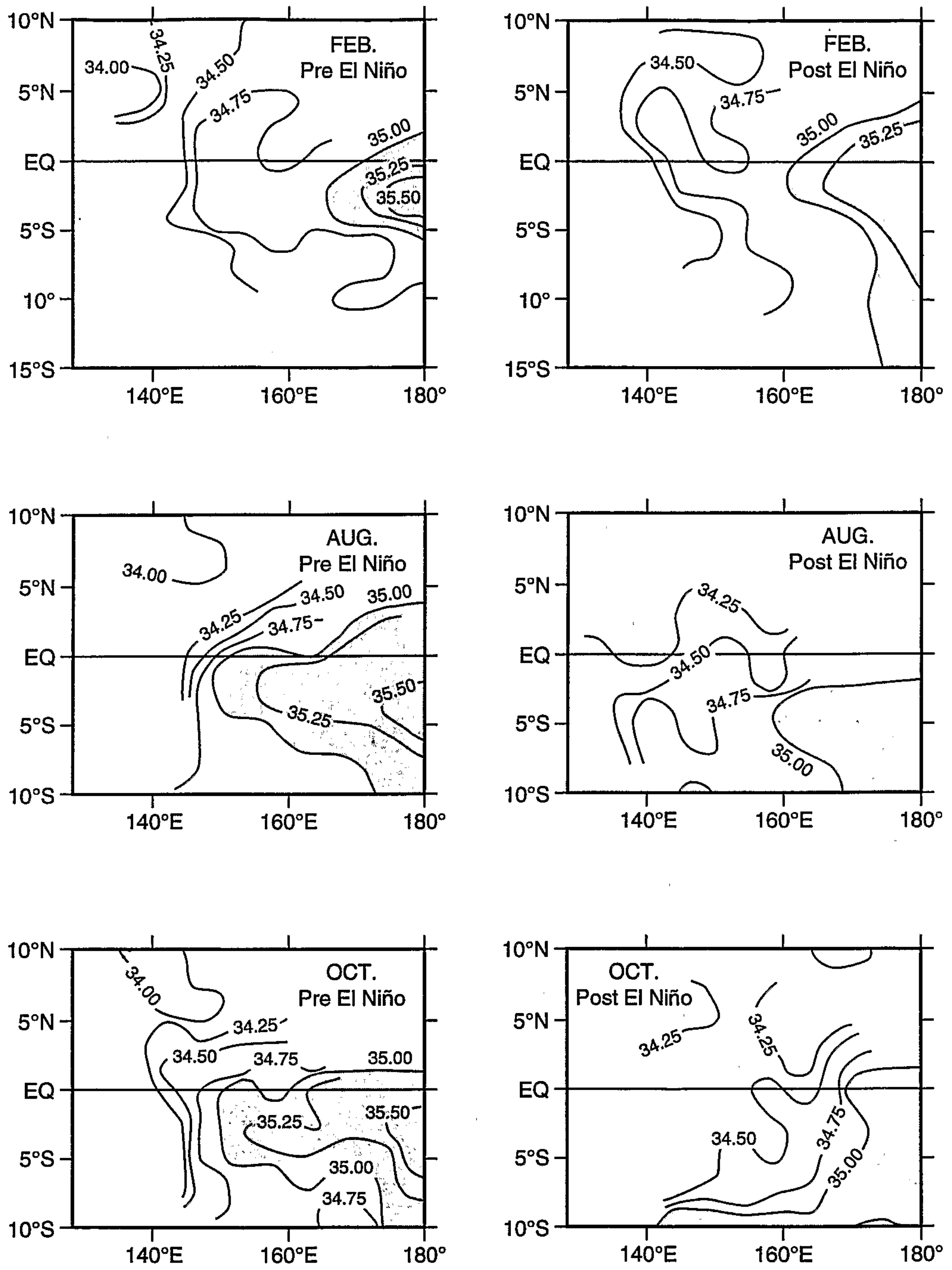

FIG.4. SSS in the western Pacific during February, August and October with pre-El Niño conditions (left panel) and post-El Niño conditions (right panel).

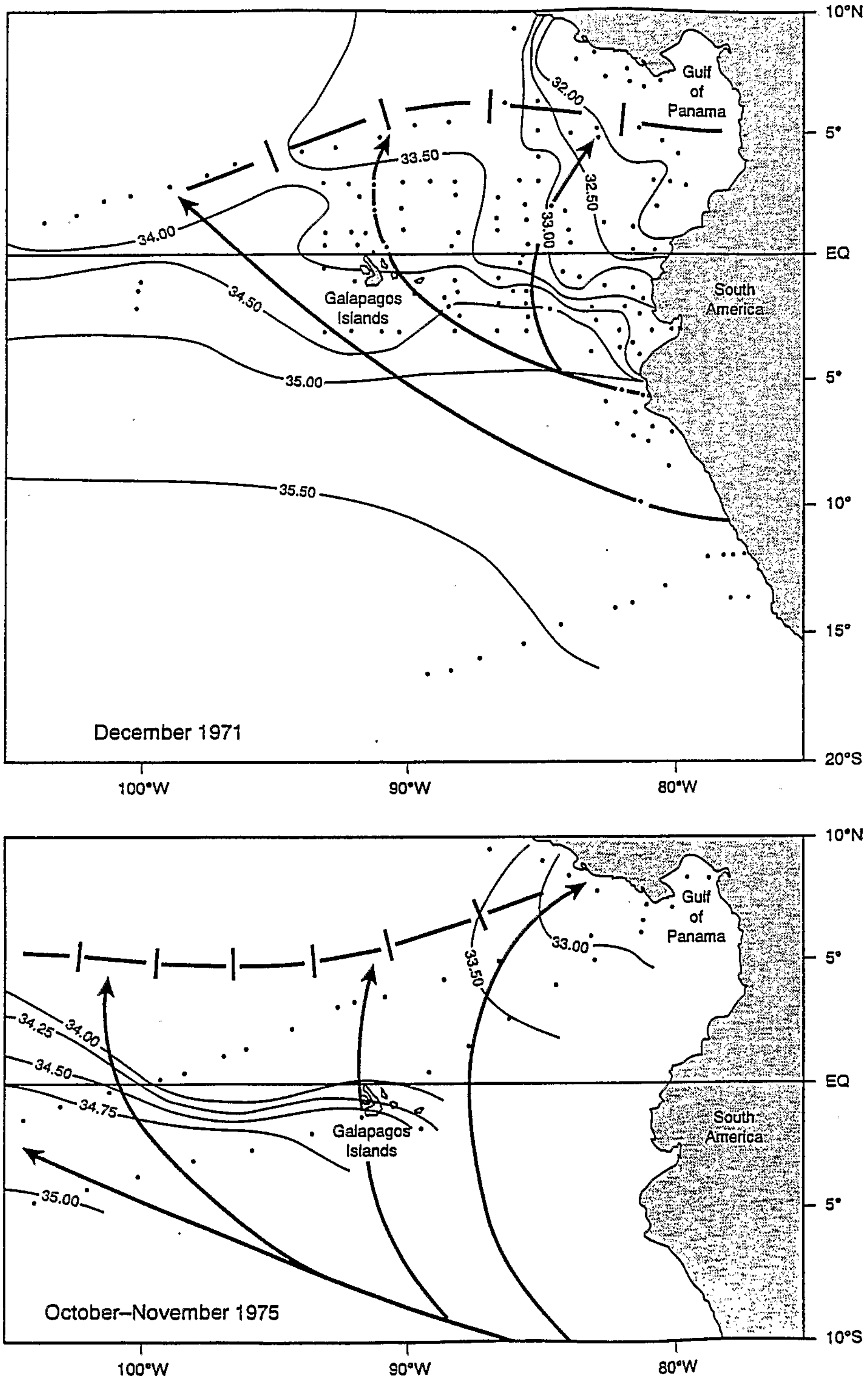

FIG.5. SSS in December 1971 and in October-November 1975 in the eastern equatorial Pacific (before El Niño).

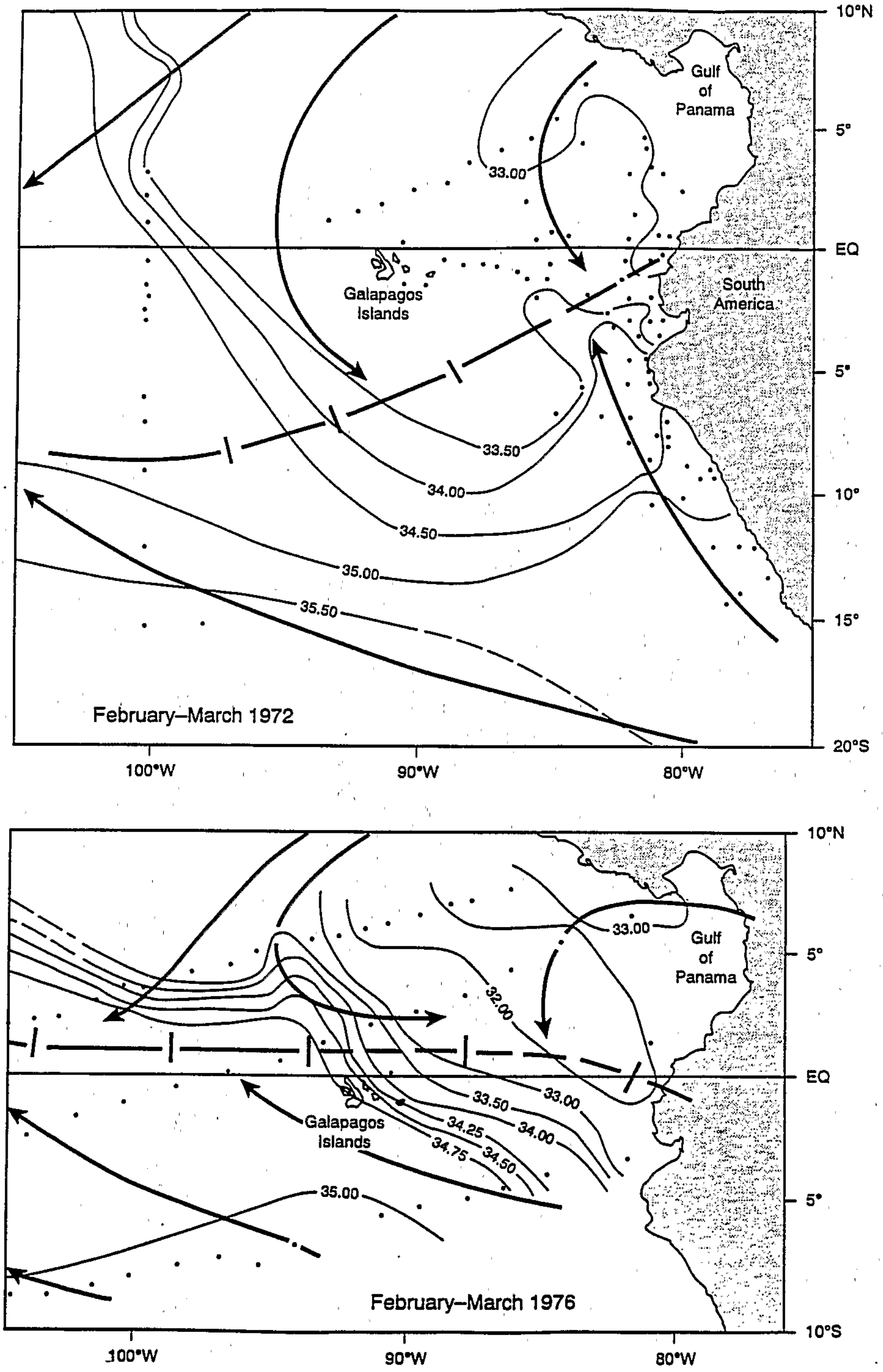

FIG.6. SSS in February-March 1972 and in February-March 1976 in the eastern equatorial Pacific (during El Niño).

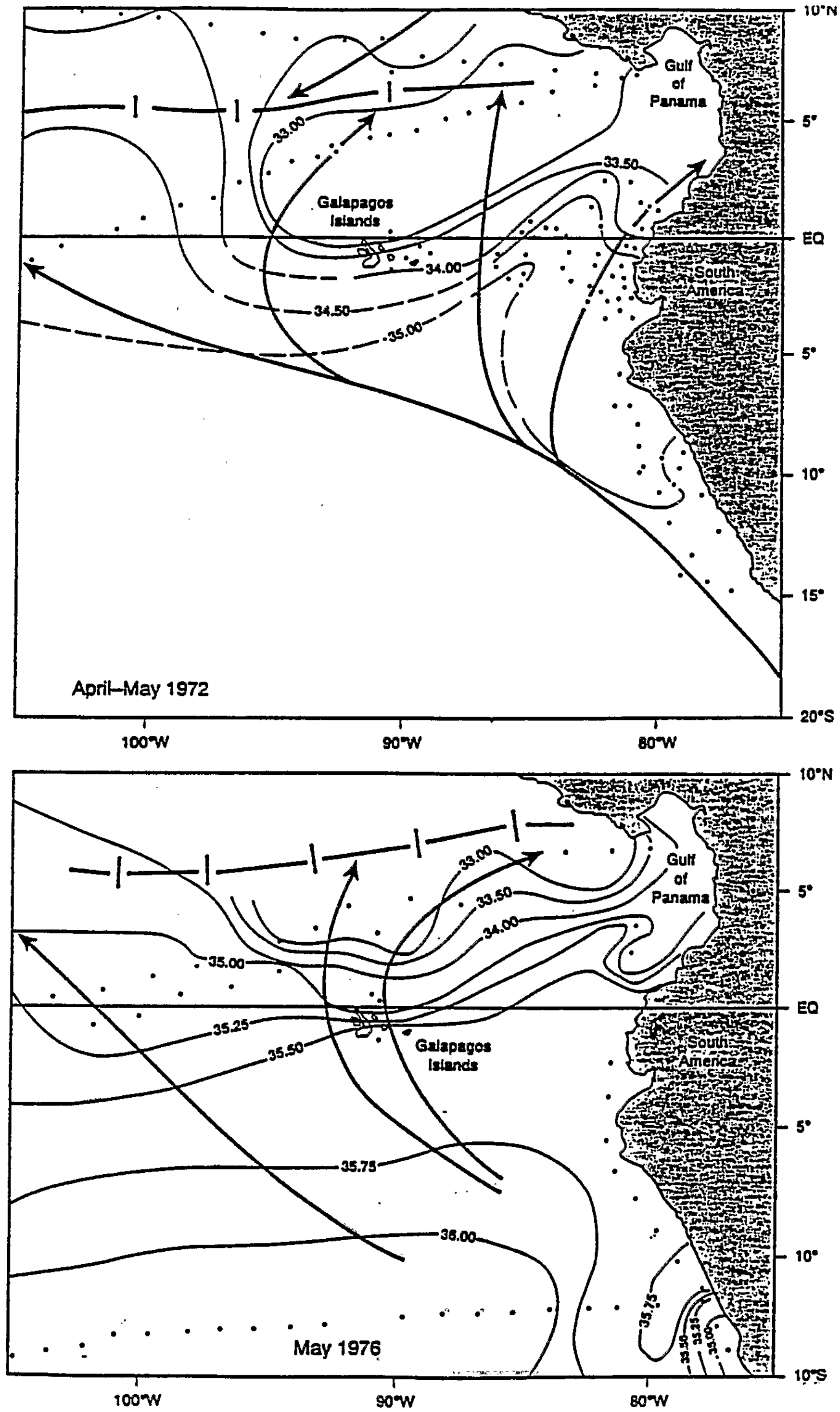

FIG.7. SSS in April-May 1972 and May 1976 in the eastern equatorial Pacific (after El Niño).

4.1 Sea surface salinity during the onset phase

Figure 5 shows the surface salinities during the latter part of 1971 (mainly December) and just prior to the El Niño event at the end of 1975 (October-November). On both these occasions the wind fields were similar, with the Intertropical Convergence Zone (ITCZ) at 5°N close to its usual position (7-10°N) (SADLER, LANDER, HURI and ODA, 1987). South of the Intertropical Convergence Zone, and east of 90°W, the southeasterly winds were being deflected to the southwest. An equatorial salinity front, which was particularly conspicuous in 1975, separated high-salinity waters in the south from low salinity waters to the north.

4.2 Sea surface salinity during the peak phase

Figure 6 shows the surface salinities observed in February-March 1972 and in February-March 1976, both El Niño years. The wind field was similar in both cases, but in 1972 the ITCZ was between the equator and 10°S, whereas in 1976 it was at 1°N. In 1972 the presence of a convergence zone at 10°S is consistent with the hypothesis that it was a double feature; to the south of the convergence zone, southeasterly winds persisted, and to the north of it and to east of 95°W, the winds became northwesterly. Westerly winds are unfavourable for the development of upwelling, and in the absence of upwelling low salinity water spread into the southern hemisphere, so that the equatorial front shifted southwards. The surface salinity conditions in February-March 1972 were very similar to those in February-March 1975 (PATZERT, 1978) when a small El Niño aborted.

4.3 Sea surface salinity during the transition phase

Figure 7 shows the surface salinity observed in April-May 1972 and in May 1976, after the El Niño event. Once again the wind fields were similar: the ITCZ lay at 7°N close to its usual position at about 10°N. West of 95°W, the wind was once again from a direction which favoured equatorial upwelling, so the equatorial front had developed. In April-May 1972 the surface salinity conditions had reverted to become similar to those seen in normal conditions in April-May 1975 (PATZERT, 1978). However, in May 1976 the conditions were again rather similar to those in August-September 1967 (LOVE, 1972) except for the unusual presence of SSS >36.0 which extended as far east as 85°W at 12°S. For both the 1972 and 1976 El Niño, the spreading of the low-salinity water is related to the position of the ITCZ, through the presence or absence of the equatorial front, and the formation of low-salinity water masses by local precipitation. During El Niño events, the convergence zone lies to the south of its normal location, and in many cases a second convergence zone developes to the south. PATZERT (1978) showed the same meteorological feature occurred in February-March 1975.

4.4 Sea surface salinity during 1982-83 El Niño

The 1982-83 El Niño also affected SSS along the Tahiti-Panama route (DESSIER and DONGUY, 1987) (Fig.8). An SSS anomaly occurred during the first half of 1983 when a region of low salinity (SSS <34.0) extended to the south of the equator to 5°S and was associated with a patch of SST anomaly. This SSS anomaly may have either had a zonal origin, induced by rainfall, or a meridional origin resulting from a southward propagation of low SSS from the Gulf of Panama to the southern hemisphere. During the 1972 and 1976 El Niños a meridional origin was the most likely, whereas in 1983, there was propagation eastwards at a phase speed of $0.3 ms^{-1}$ of a low SSS anomaly along the equator which was associated with wind, sea level, SST and rainfall anomalies which implied a zonal origin (Fig.9) (DONGUY and ELDIN, 1985). However, HARRISON, KESSLER and GIESE (1989) failed to hindcast SSS variations for the 1982-83 El Niño, probably because of a lack of parameterization of the E-P balance in the model physics. (The authors noted the need to improve this parameterization.) During the 1991-92 El Niño, no such kind of eastward fresh jet reached 160°W (ROEMMICH, MORRIS, YOUNG and DONGUY, 1994).

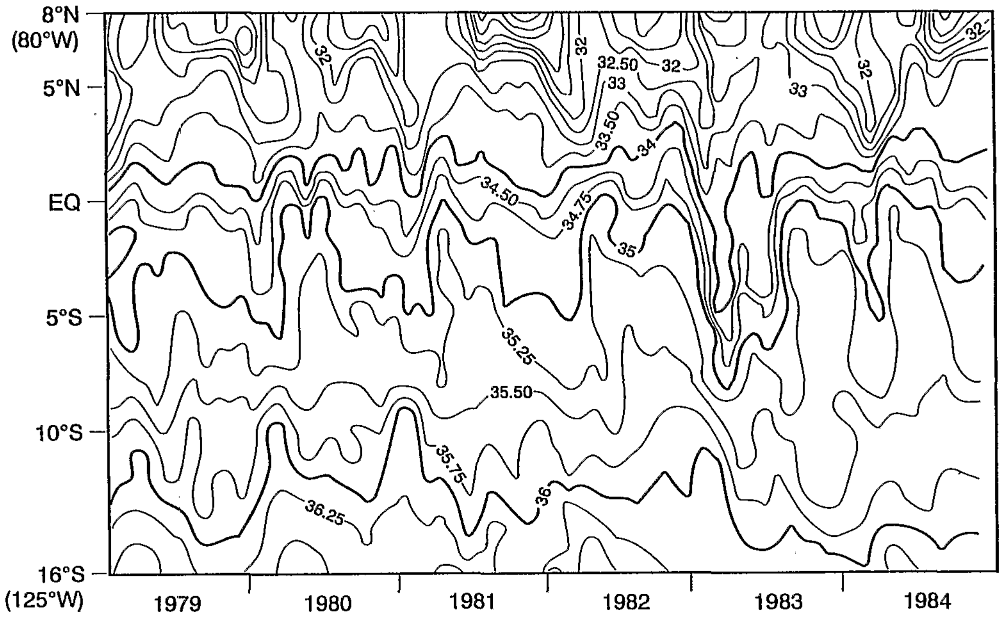

FIG.8. Latitude-time diagram of SSS along the shipping route Tahiti-Panama.

4.5 Connections between eastern and western Pacific

Looking at the connections between anomalous conditions in the western tropical Pacific and those in the eastern tropical Pacific (DONGUY and DESSIER, 1983) it appears that during El Niño events there is a lag of approximately six months between the eastern event (described mainly by either a positive equatorial anomaly of temperature or an unusually long warm season), and the western event (described mainly by a negative equatorial anomaly of salinity).

In 1976-77 (Fig.10) the 0-1°S sea surface temperature exceeded 26°C for four months compared to an average duration of two months during normal years. At the end of the 1976 negative anomaly of salinity was -0.20 in the western equatorial area. As low SSS on the equator is also connected with high salinity in the tropical area and as, in turn, high salinity is an index of drought, the possibility of forecasting this western climatic feature as soon as the eastern positive anomaly is observed, has arisen. However, according to MORLIERE and REBERT (1986), in New Caledonia, the correlation of the rainfall anomaly with ENSO is poor and 'only a small part of the rainfall variance could be predictable through ENSO'. Moreover, in 1979, negative anomalies of SSS in the western Pacific were not connected with positive anomalies of SST characteristics of El Niño in the eastern Pacific (DONGUY, HENIN, MORLIERE, REBERT and MEYERS, 1982). It seems that this feature was not an isolated event and that there is some decorrelation of the intensity of such episodes in the western and eastern pacific (REBERT and DONGUY, 1988).

Connections between eastern and western Pacific are illustrated in Fig.11 (DONGUY, 1987). Along the equator, the pre-El Niño period is characterised by a well developed Walker cell in the atmosphere. In the westernmost Pacific, at the location of the ascending branch, the thermocline is deep and the SSS is <35.0. During post-El Niño periods, the Walker cell shifts eastward so that its ascending branch is now situated in the central Pacific where the thermocline is deep and the SSS is low.

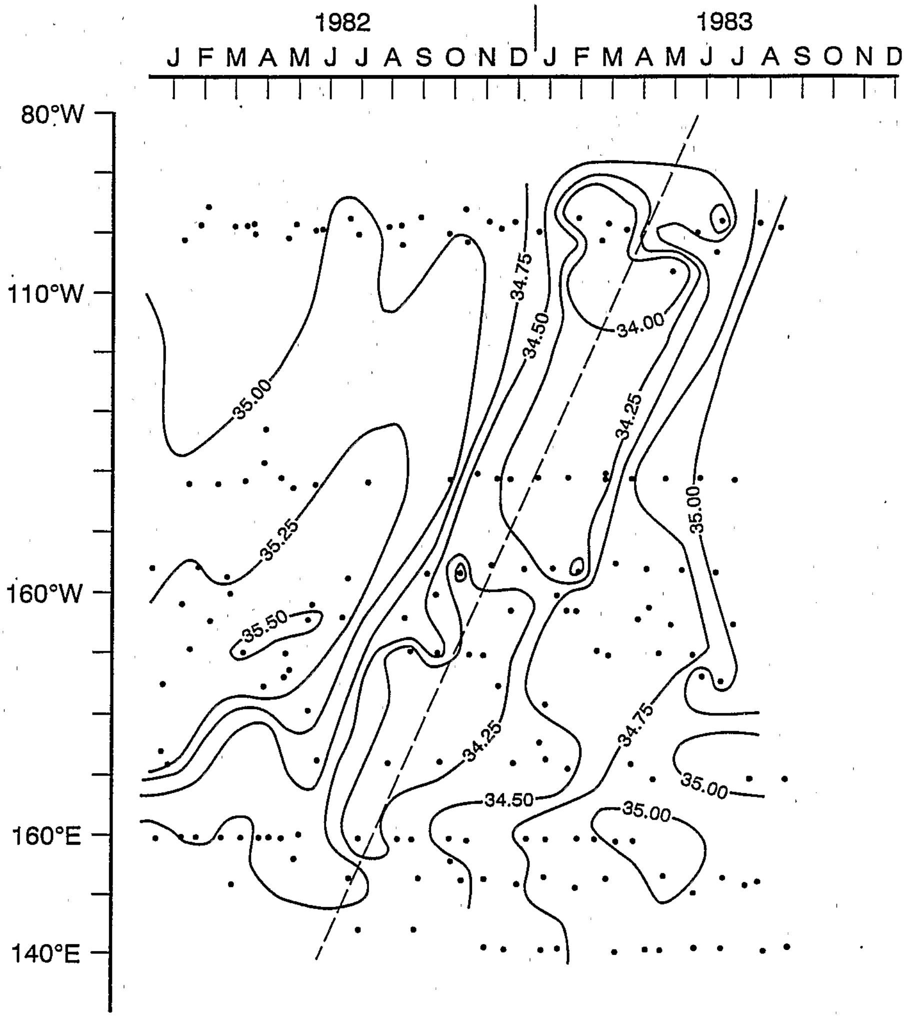

FIG.9. SSS along the equator during 1982-83 (1°N - 1°S, 130°E - 80°W).

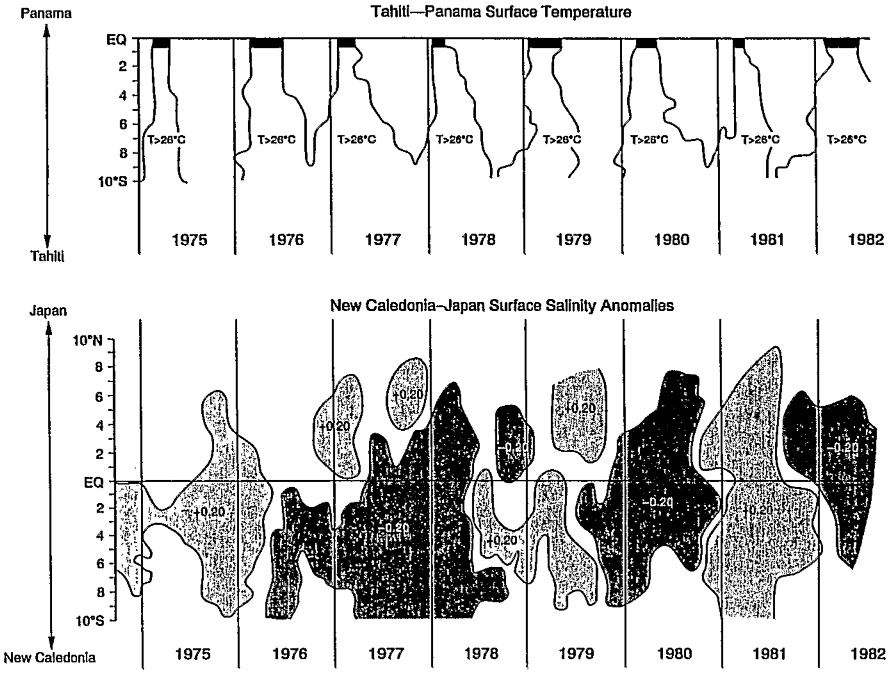

FIG. 10. Warm season at 1°S with SST more than 26°C along the shipping route Tahiti-Panama (top panel). Equatorial anomalies of the SSS 1975-82 along the shipping route New Caledonia-Japan (bottom panel).

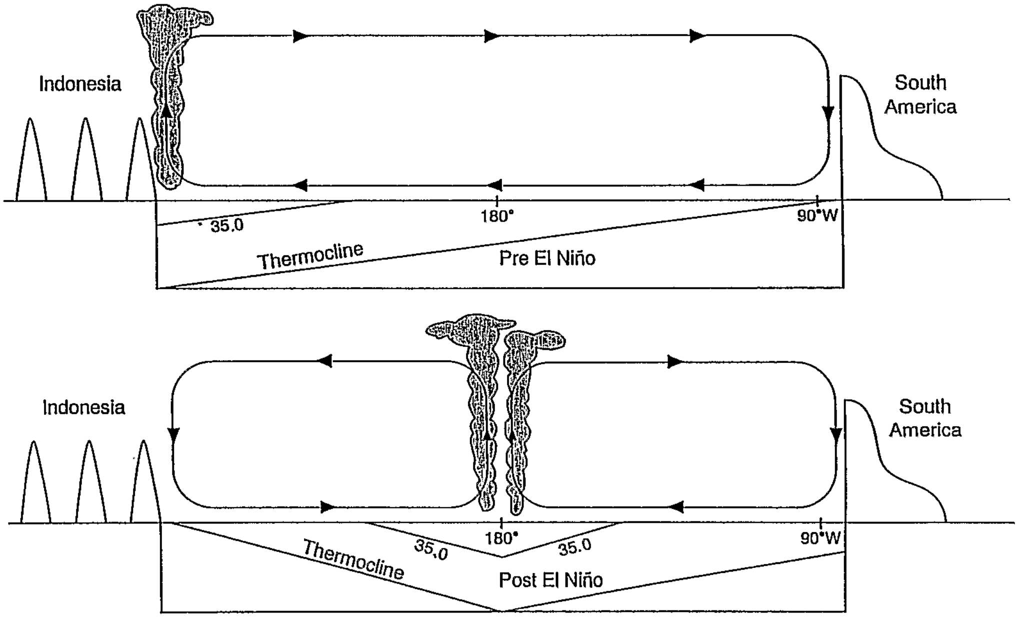

FIG. 11. Schematic representation of atmospheric and oceanic conditions including the salinity for pre- and post-El Niño.

5. SURFACE SALINITY MAXIMUM

Most publications resulting from the SURTROPAC programme have been devoted to the study of SSS in the western pacific. Few have been devoted to the eastern Pacific (DONGUY and HENIN, 1980b; DESSIER and DONGUY, 1985; DESSIER and DONGUY, 1987) but almost none to the southern central Pacific features. These features have received comment in several reports from a variety of institutions and there is a need for a synthesis which will lead to new considerations.

The main feature is a cell of high surface salinity water, the maximum for the Pacific, located in the south-eastern Pacific (Fig.2). This cell of maximum surface salinity has a subsurface westward extension. Similar features also occur in the subtropical southwestern Atlantic and Indian Oceans.

5.1 Definition of the surface salinity maximum

The surface salinity maximum in the south-eastern pacific may be defined by values >36.0 and it can reach 36.5 in some locations. According to LEVITUS (1982) the mean position of the cell with SSS >36.0 is between 12° and 25°S latitude and its western limit lies between 160° and 150°W longitude (Fig.2). The area occupied by this feature is approximately $7.10^6 km^2$. The western part of this zone is occupied by islands of Polynesia such as Society Islands and Tuamoto Archipelago.

5.2 Formation of the surface salinity maximum

This surface salinity maximum must result from a positive balance of E-P, and indeed all the atlases of precipitation show a minimum of rainfall in this area (TAYLOR, 1973; ELIOT and REED, 1984). Recent charts using Outgoing Longwave Radiations (OLR) are more reliable in oceanic areas where few islands exist. According to the annual charts of 1974-1989 rainfall from OLR (PORTE, 1992), the eastern part of the surface salinity maximum has a precipitation minimum of 50mm y^{-1}, but in the western part of the zone, precipitation reaches 1000mm y^{-1}.

According to ESBENSEN and KUSHNIR (1981), the surface salinity maximum is mostly occupied by a maximum of downward radiative flux (160W m^{-2}) and hence a maximum in evaporation. The Meteorological Station network of the Service de la Meteorologie de Polynésie Française takes advantage of the locations close to the sea level on most of the Polynesian islands to provide a reliable chart of the oceanic balance of E-P[1]. According to ROUGERIE, MAREC and GOURIOU (1980, 1981), there is a good correlation between high E-P values and the location of the surface salinity maximum. Moreover, the line of E=P lies close to and parallel with the 36.0 isohaline (Fig.12); the region with SSS >36.5 approximately coincides with the E-P maximum. The highest recorded SSS value in the study zone from 1975 to 1989 was 36.7. However, SSS does not increase indefinitely, so the persistently high E-P balance is compensated by advection (see paragraph 2).

5.3 Seasonal variations of the surface salinity maximum

As the surface salinity maximum is related to the E-P balance, which in turn is subject to seasonal variations, the surface salinity maximum can be expected to vary seasonally. The maximum salinity values attained do not change, but their regional coverage does with the maximum expansion of the cell in which SSS >36.0 occurs during the southern winter; for example in 1981 the 36.0

[1]Potential Evapotranspiration was used rather than the measured Evaporation. However, in Polynesia, Potential Evapotranspiration is not directly measured but calculated by the PENMAN method, using air temperature, humidity, wind velocity, insolation, albedo and some other parameters.

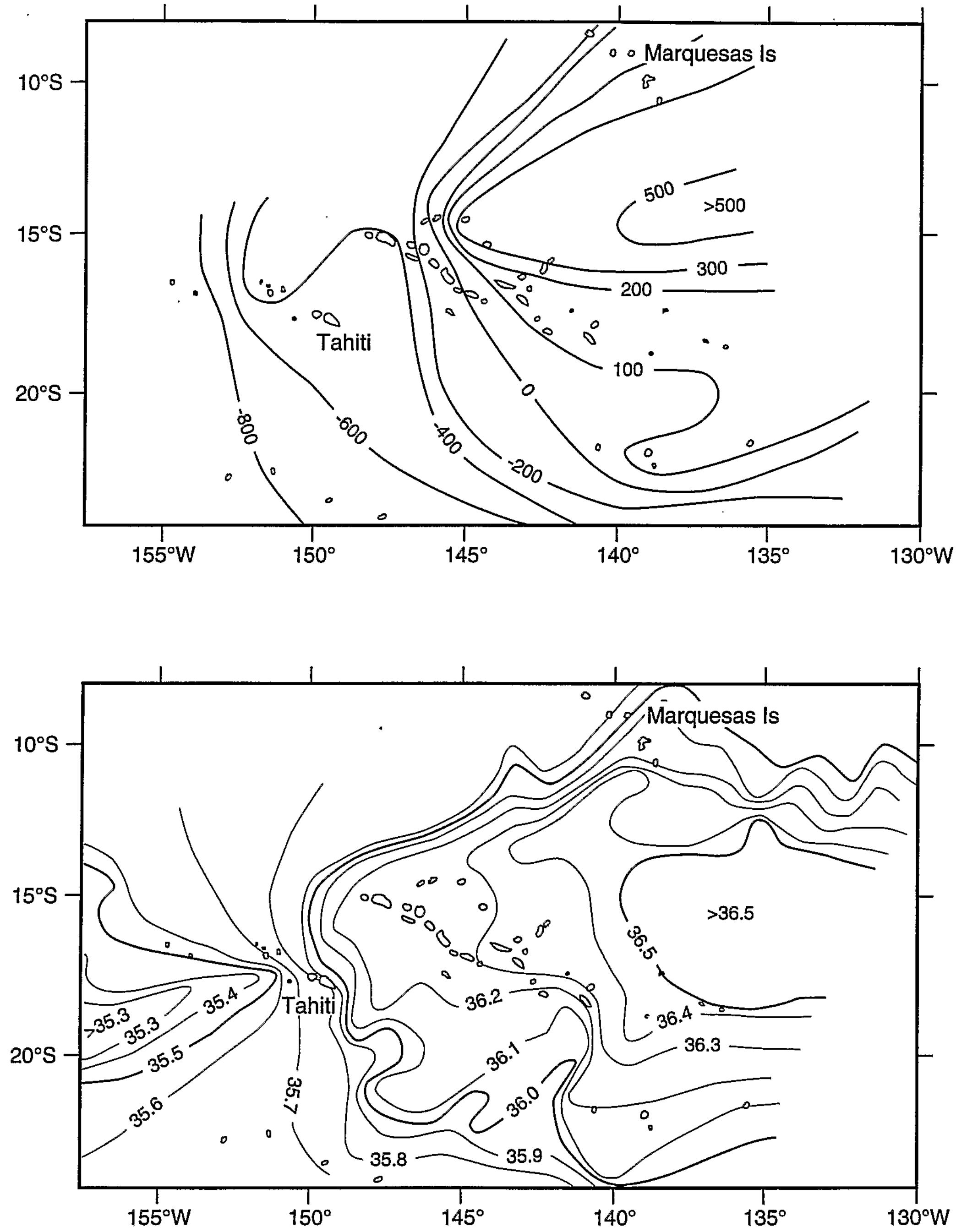

Fig.12. Evapotranspiration - Precipitation balance averaged for 1979 in mm (top). Sea surface salinity average for 1979 (bottom) from ROUGERIE *et al* (1980).

isohaline reached 10°S in the north, and 153°W in the west (ROUGERIE, MAREC and PICARD, 1982). This expansion of high salinity water resulted from the strong south-easterly winds pushing the saltier water mass northwestward during the southern winter (SADLER *et al*, 1987). Such seasonal variations were also detected along the shipping tracks Tahiti-California and Tahiti-Panama (DELCROIX and HENIN, 1991), along which the greatest extension of the surface salinity maximum occurs in September.

5.4 Sea surface salinity maximum and ENSO

Climatic disturbances induced by ENSO have some important effects on the surface salinity maximum. According to DONGUY and HENIN (1980a) in the western Pacific, there are two areas where there is good correlation between the rainfall and the intensity of ENSO; close to the equator there is a positive correlation and a negative one occurs between 10° and 25°S, extending from Polynesia to Australia. During El Niño events, the pattern of precipitation changes (PORTE, 1992) from the normal pattern observed by DONGUY and HENIN (1976b). The dry zone normally occurring in the Polynesian area, instead of extending along the Equator, is southwards where it extends uninterrupted along as far west as Australia with precipitation falling to <1000mm y^{-1} (Fig.13). According to ROUGERIE *et al*, (1981), during a normal year, the line E=P surrounds Polynesia, whereas in 1983 (ROUGERIE, MAREC and WAUTHY, 1985), there were two lines E=P at 15°S and 25°S which extended further west. So, at the beginning of 1983, it can be inferred that the surface salinity maximum extended as far west as 175°W at 15°S, instead of just to 150°W (MONTEL, MASIA, GERARD and WAIGNA, 1990). The mean position of the 36.0 isohaline was persistently located west of 160°W during 1983 (Fig.14) (ROUGERIE *et al*, 1985). This is not an isolated case (DONGUY and HENIN, 1978a); for example, during the 1957-58 El Niño, the surface salinity maximum reached 170°W. In 1972-73, it reached 160°W, with an isolated patch of high salinity being observed at 180°. In 1976, it reached 170°W (DONGUY and HENIN, 1978c). The shape of the area of surface salinity maximum also changes; it not only extends westward but also becomes meridionally restricted to the south, reaching only 20°S instead of 25°S. There are almost no data to document a possible eastward extension of the surface salinity maximum except in May 1976 (Fig.7) when the 36.0 isohaline reached 85°W. DELCROIX and HENIN (1991), who used an EOF analysis, also mentioned that during El Niño there is an SSS increase south of 10°S along the shipping lines Tahiti-California and Tahiti-Noumea. Moreover, DELCROIX and HENIN (1989) in analysing the causes of such changes, concluded that they result from a combination of three processes: southward displacement of the SEC, Ekman pumping and northward displacement of the SPCZ.

6. SUBSURFACE SALINITY MAXIMUM

6.1 Formation of the subsurface salinity maximum

Between 10° and 20°S, in normal conditions (.i.e. non-El Niño periods), SSS decreases from 36.0 at 150°W to 35.0 at 170°W. To the west of 170°W this high salinity water sinks under a lighter water mass (Fig.2) with low SSS (<35.0) which originates from a negative E-P balance resulting from the high precipitation associated with the SPCZ (DONGUY, 1987; DELCROIX and HENIN, 1989). Consequently, the surface salinity maximum becomes a subsurface salinity maximum, which continues to move westward. An example of this westward progression comes from the *Atoll* cruise

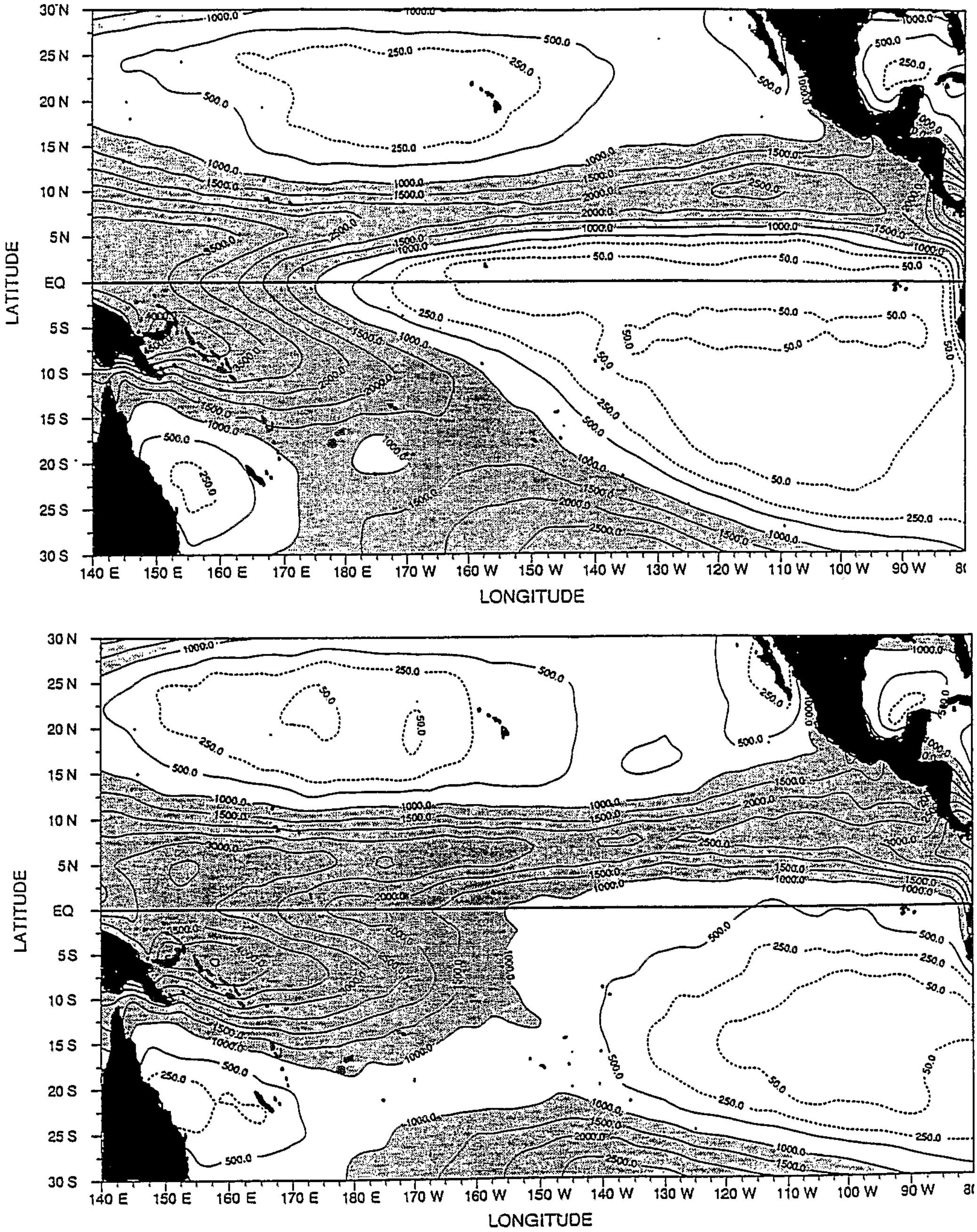

FIG. 13. Distribution of mean 1974-89 precipitation in mm m^{-1} without ENSO years (1976, 1982-83, 1987) (top). Distribution of mean precipitations in mm y^{-1} for ENSO years (1976, 1982-83 and 1987) (bottom). From PORTE (1992).

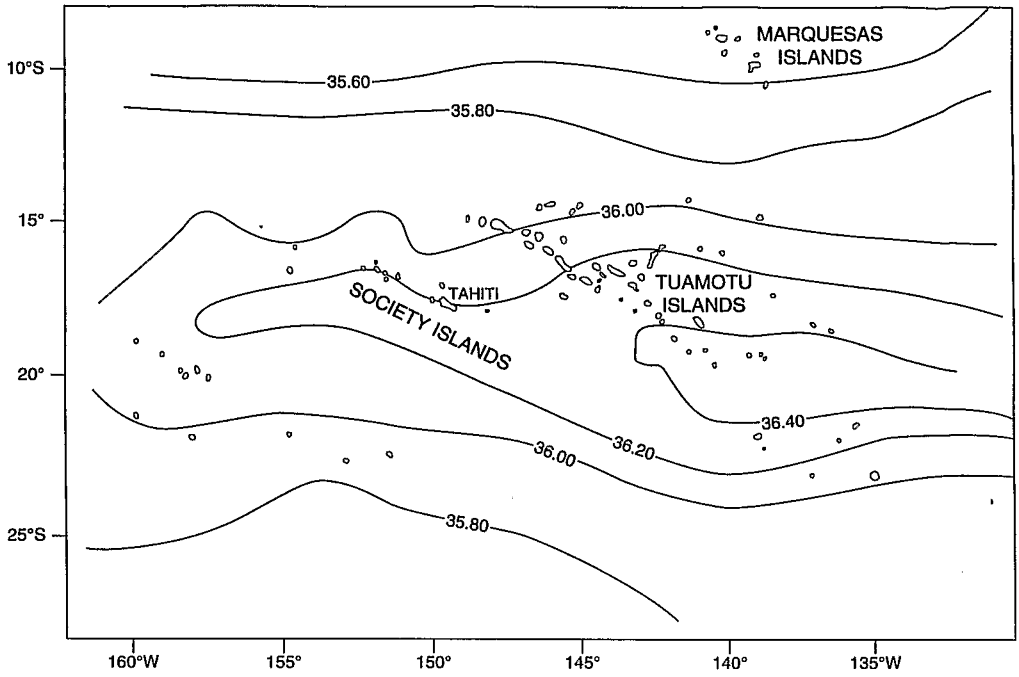

FIG.14. Sea surface salinity averaged for 1983 (from ROUGERIE *et al*, 1985).

(December 1964 - January 1965) (ANON, 1981) (Fig.15). At the surface, the western boundary of high salinity water (S>36.0) was close to 138°W, but at approximately 50m depth a tongue of high salinity water extended westward, with water of salinity >36.0 reaching 140°W meridian, and in the westernmost part of the region studied salinity at 50m depth was still >35.8 compared with surface values of only 35.6. Another cruise (*Thon-Australes*, February 1978) also documented the westward extension of the subsurface salinity maximum (HENIN, CALVEZ, CONAND, HOFFSCHIR, JOSSE and WAIGNA, 1980). The subsurface salinity maximum also extends northward, at 154°W the 36.0 isohaline reached 5°S at 150m depth (cruise *Danaides 2*); at 140°W it reached 8°S (cruise *Diademe*) (CREMOUX, 1980a) and during the Hawaii-Tahiti Shuttle Experiment at 155°W, it reached 6°S (WYRTKI and KILONSKY, 1982). No extension of water with salinity >36.0 has been observed to the south of 20°S, but RANCHER and ROUGERIE (1992) reported a salinity maximum <36.0 at a depth of 100m. In the eastern Pacific no evidence of a subsurface extension of the surface salinity maximum is to be seen in a salinity section observed along 15°S in November 1986 (LYNCH, MANGUM and HAYES, 1988) (Fig.16) in which the eastern boundary of high salinity water (S>36.0) was at about 100°W, whereas to the west the subsurface salinity maximum of >36.0 plotted from numerous cruises carried out before 1976 (Fig.17) does not extend much beyond 160°E (DONGUY and HENIN, 1976a). According to TSUCHIYA, LUKAS, FINE, FIRING and LINDSTROM (1989), the tropical water including the subsurface salinity maximum 'does not extend west much beyond 150°E, but returns to the east to join the equatorial undercurrent'.

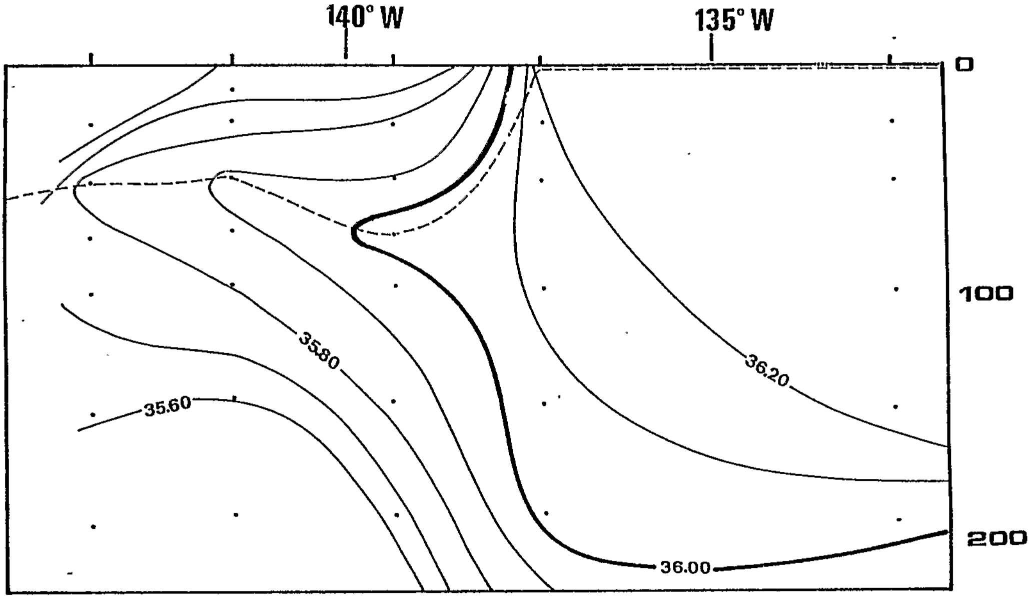

FIG. 15. Convergence of the salinity maximum in the Central Pacific during the ATOLL Cruise at approximately 20°S (January 1965).

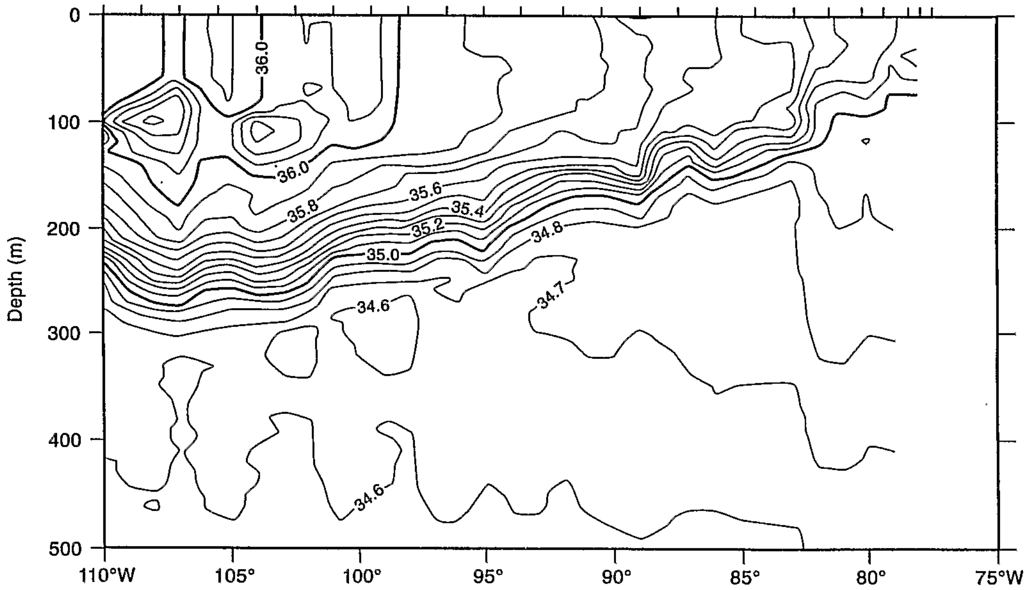

FIG. 16. Eastern boundary of the salinity maximum along 15°S in 1986 (from LYNCH *et al*, 1988).

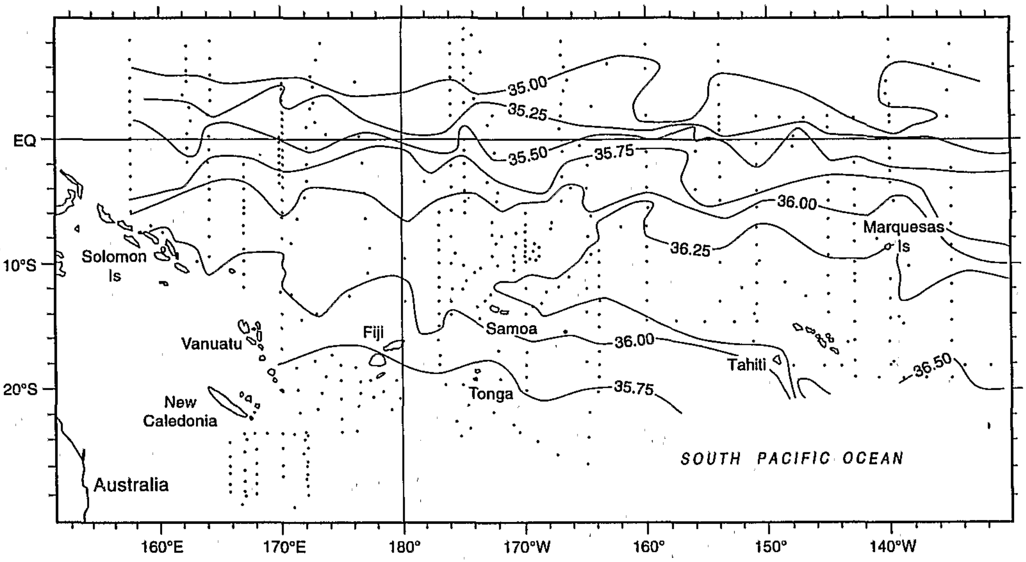

FIG.17. Subsurface salinity maximum in the SW Pacific (from DONGUY and HENIN, 1976a).

6.2 Subsurface salinity maximum and ENSO

During El Niño, the subsurface salinity maximum in the south tropical Pacific changes both in magnitude and depth. In the Polynesian area (30°S - 10°N, 135°-150°W) seasonal cruises carried out from 1986 to 1989 (RANCHER and ROUGERIE, 1992) encompassed the moderate 1986-87 El Niño event. In 1986-87, the subsurface salinity maximum decreased in the eastern part of the zone at 140°W, but increased in the western part at 145°W. At 20°S the subsurface salinity maximum was >36.0 in March 1987. These results for the 1986-87 ENSO indicate that during an El Niño event the subsurface salinity maximum only extends westward.

The *Bora* and *Cyclone* series of cruises were carried out at 170°E from 20°S to 5°N between 1965 and 1968 by the Centre ORSTOM de Noumea (ROTSCHI, HISARD and JARRIGE, 1972). The 1965-66 *Bora* cruises were conducted in post-El Niño conditions following the moderate 1965 event. They showed that a subsurface salinity maximum >36.0 was located at 10-15°S (Fig.18) whereas during the 1967-68 *Cyclone* cruises it was <36.0. In the same way, DONGUY and HENIN (1976b) observed a large cell of salinity >36.0 reaching the surface at 175°W in December 1957 (strong El Niño year), but in November 1961 the cell was small and limited to a depth of 150m.

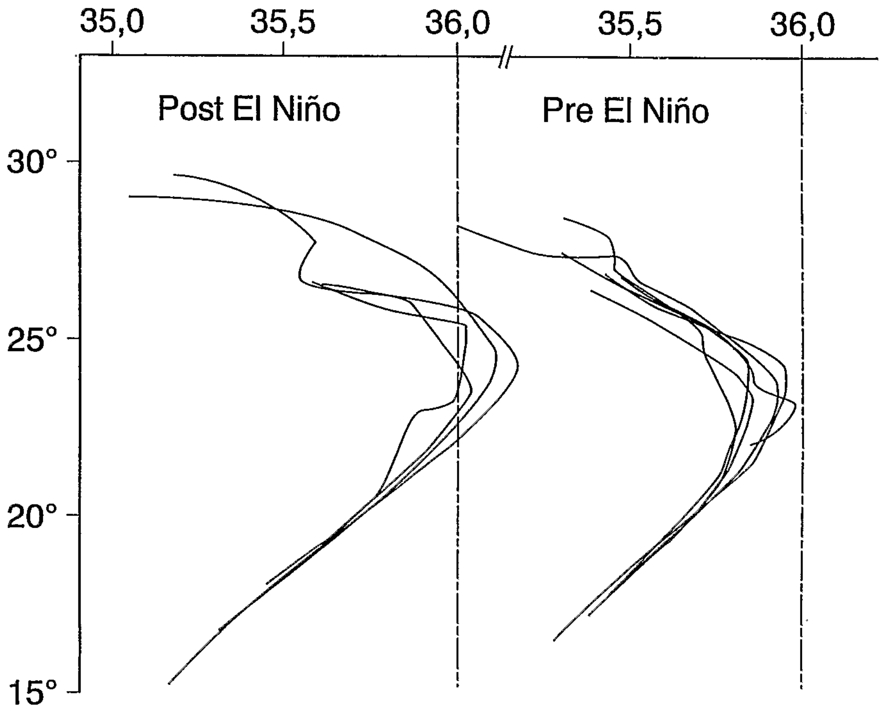

FIG.18. T-S diagrams at 10-15°S and 170°E during BORA Cruises (1965-66) (left panel) and CYCLONE Cruises (1967-68) (right panel).

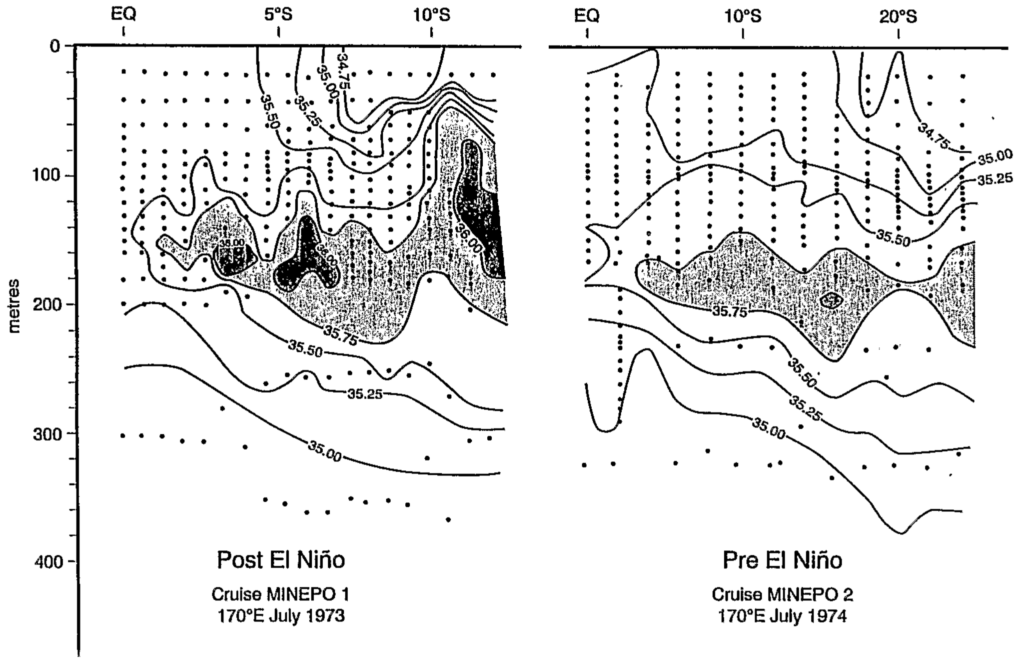

FIG.19. Meridional distribution of salinity at 170°E during the cruise MINEPO 1 in July 1973 (left panel) and during the Cruise MINEPO 2 in July 1974 (right panel).

In 1973 (post-El Niño 1972), the subsurface salinity maximum was greater and shallower at 170°E than in 1974 (Fig.19).

The *Surtropac* cruises were carried out at 165°E from 20°S to 10°N, twice a year between 1984 and 1989 (ELDIN, 1989). The data show two subsurface salinity maximum cores, one located between 10° and 15°S, and another between 2° and 7°S. The depth of both these cores have been plotted in Fig.20. During the 1986-87 El Niño, the depth of the southern core (10-15°S) decreased by 20m and the depth of the northern core (2-7°S) by 50m, but there was no change in the salinity values (HENIN, 1989). Moreover, in 1984, after the strong 1982-83 El Niño, the southern core had shoaled to lie very close to the surface and the northern core had shoalled by 50m. During the 1979-80 El Niño event, DONGUY, HENIN, MORLIERE and REBERT (1982) observed a similar behaviour of the isotherms at 170°E.

In summary, in the south-western Pacific, during post-El Niño conditions, the subsurface salinity maximum located in the vicinity of 15°S becomes stronger and shallower than during normal or pre-El Niño conditions. Such changes may have several causes:
- increase of the E-P balance inducing high SSS
- increase of the westward advection as pointed out by DELCROIX and HENIN, 1989)
- Ekman pumping as pointed out in the case of El Niño by DONGUY, HENIN, MORLIERE, REBERT, 1982)

It is difficult to determine the relative importance of each of these processes in the overall pattern of events. Only modellisation including surface and subsurface salinity can achieve this level of refinement.

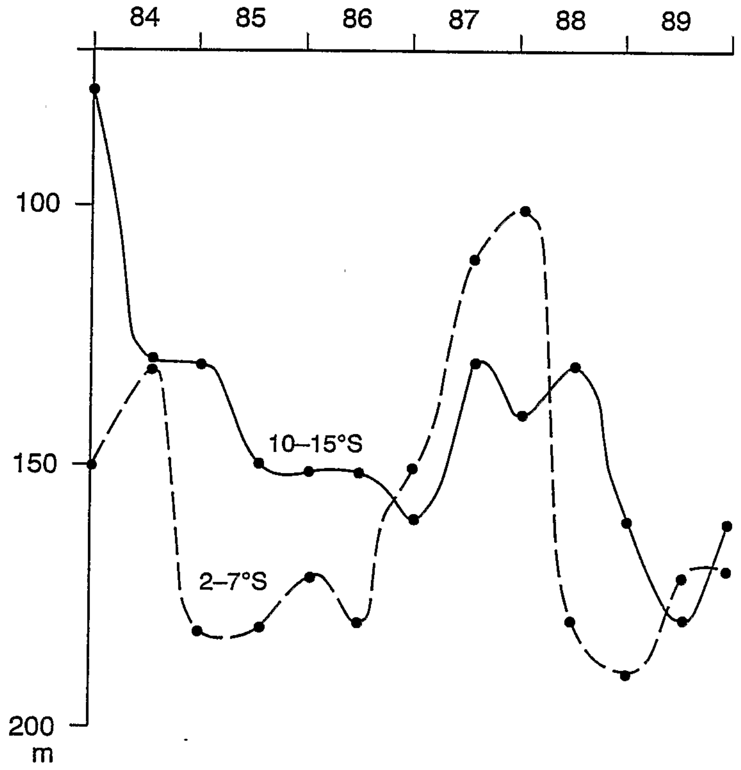

FIG.20. Depth in metres of the two cores of salinity maximum during SURTROPAC Cruises. Full line 10-15°S, dashed line 2-7°S.

6.3 Subsurface salinity maximum in the westernmost Pacific

Paucity of data prevents the clear delineation of the westernmost boundary of the subsurface salinity maximum. *Ryofu Maru* transects at 137°E and 155°E (JAPAN METEOROLOGICAL AGENCY) are available as well as data from *Coriolis* cruises in the same area (CREMOUX, 1980b,c).

At 137°E to the north of New Guinea at 1°S - 5°N vertical distributions of salinity were very different in July 1972 and January 1973 (Fig.21). In July 1972, water of a salinity <35.0 occurred between the surface and 100m depth, which was underlain by a subsurface salinity maximum (>35.5); this pattern may be considered to be the 'normal' case (MASUZAWA and NAGASAKA, 1975).

In January 1973, the intensity of the subsurface salinity maximum had not changed but it had shoaled and the water in the surface 100m had been replaced by water of salinity >35.0. Between January-February 1982 to January-February 1983, the same changes were repeated. So, in the post-El Niño conditions, both isohalines and water-masses shoal, as already pointed out for 165°E and 170°E region.

The 1967-85 data set at 137°E from *Ryofu Maru* cruises confirms that in the equatorial area (Equator - 2°N), SSS is maximum during El Niño events (1972-73, 1976, 1982-83) but no significant change occurs in the subsurface salinity maximum.

At 155°E, the 1971-79 data set from *Ryofu Maru* and *Coriolis* shows that subsurface salinity

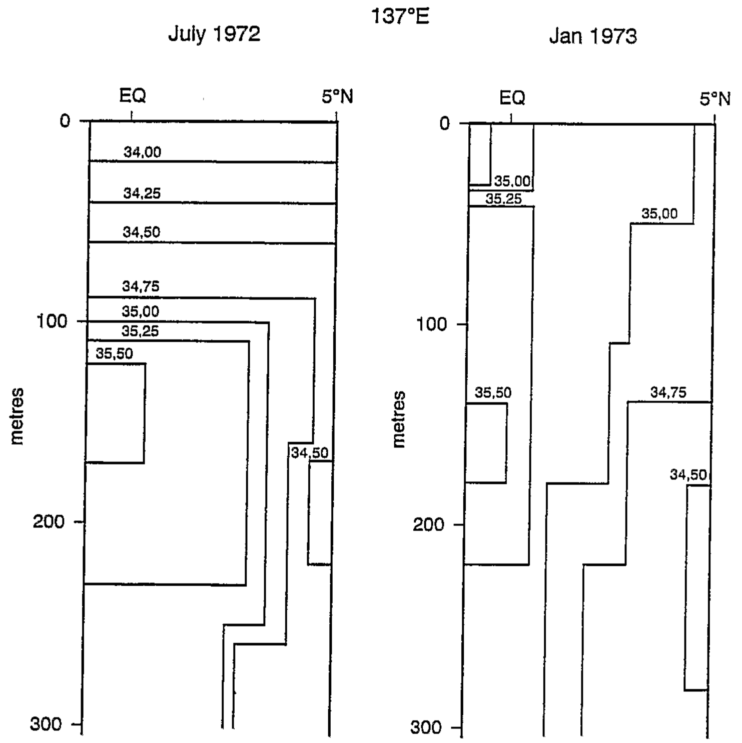

FIG.21. Schematic meridional distribution of salinity at 137°E during RYOFU MARU cruises in July 1972 (left panel) and January 1973 (right panel).

peaks were observed between 6°S and the Equator during the 1972 and 1976 ENSO, but only in 1977 did salinities reach 36.0.

Further east the 36.0 isohaline in the subsurface water reached 170°E, only in post-El Niño conditions during the 1965-68 cruises (Fig.18). During *Surtropac* cruises (1984-89) at 165°E, the subsurface salinity maximum was <36.0 except in 1989 (HENIN, 1989). However, during *Surtropac 15*, (July-August 1991), it exceeded 36.0 at 165°E (RUAL, GRELET, LANGLADE, WALICO and BONNET, 1991) which may have been connected with the 1991-92 El Niño.

During the post-El Niño period, as already mentioned, the shoaling of the isotherms and isohalines is mostly as a result of Ekman pumping in the tropical area (DONGUY, HENIN, MORLIERE and REBERT, 1982) and the prevalence of westerly winds in the equatorial area. Westerly winds neither induce equatorial upwelling nor pile up the water in the Western Pacific. The lowering sea level caused by baroclinic adjustment, elevates the isotherms and isohalines (WYRTKI, 1979). This has two consequences in the equatorial area: (1) in the western Pacific, west of 160°E, SSS is high (>35.0) but east of this longitude, in the central Pacific, SSS is low (<35.0) as a result of the rainfall (Fig.3); (2) in the subsurface, between 150° and 160°E, the salinity maximum core from the central Pacific is elevated and is driven back by the equatorial eastward flow; as was observed, for example, during *Surtropac 15* (RUAL *et al*, 1991) when from 3°S to 5°N circulation was eastward (Fig.22). ROEMMICH *et al* (1994) have provided a description and theory for this equatorial eastward flow.

7. SALINITY AND ENSO SCENARIO

The ENSO phenomenon is usually considered to involve changes in sea level and also surface and subsurface temperatures (WYRTKI, 1975; RASMUSSON and CARPENTER, 1982). However, little attention has been given to salinity, although changes in both surface and subsurface salinity during ENSO may well be important.

7.1 Influence of SSS changes on ENSO scenario

The thermodynamic consequences of the SSS changes in the western Pacific north of New Guinea and west of 160°E could be important. According to LUKAS and LINDSTROM (1991), two kinds of stratification of the near-surface water exist in this area: one which is almost isothermal from the surface to 70m depth but whose other properties are not homogeneous; the other is both isothermal and isohaline from the surface to 70m depth. The first case is characteristic of the pre-El Niño conditions found to the north of New Guinea, as in 1972 (Fig.21), the second case is characteristic of the post-El Niño conditions as in 1973.

According to LUKAS (1990), when low salinity occurs near surface but at a depth different from the isothermal layer, the net heat flux leads to an increase of SST, which may in turn feed back to the atmosphere, so any heat flux does not get transmitted to the isothermal layer: this is the pre-El Niño situation. However, during El Niño, the situation reverses such that homogeneous and shallow mixed layer become particularly favourable to the transmission and the storage of the heat flux.

The existence of such patterns of vertical distributions of salinity and temperature should be included in the pre-El Niño scenario (Fig.11). The pre-El Niño period (DONGUY, 1987) is characterised along the equator by a well-developed Walker cell in the atmosphere. In the westernmost Pacific the thermohaline is deep. The salinity decreases from the thermohaline to the surface and the SSS is <35.0. A significant part of the net heat flux fails to reach the isothermal

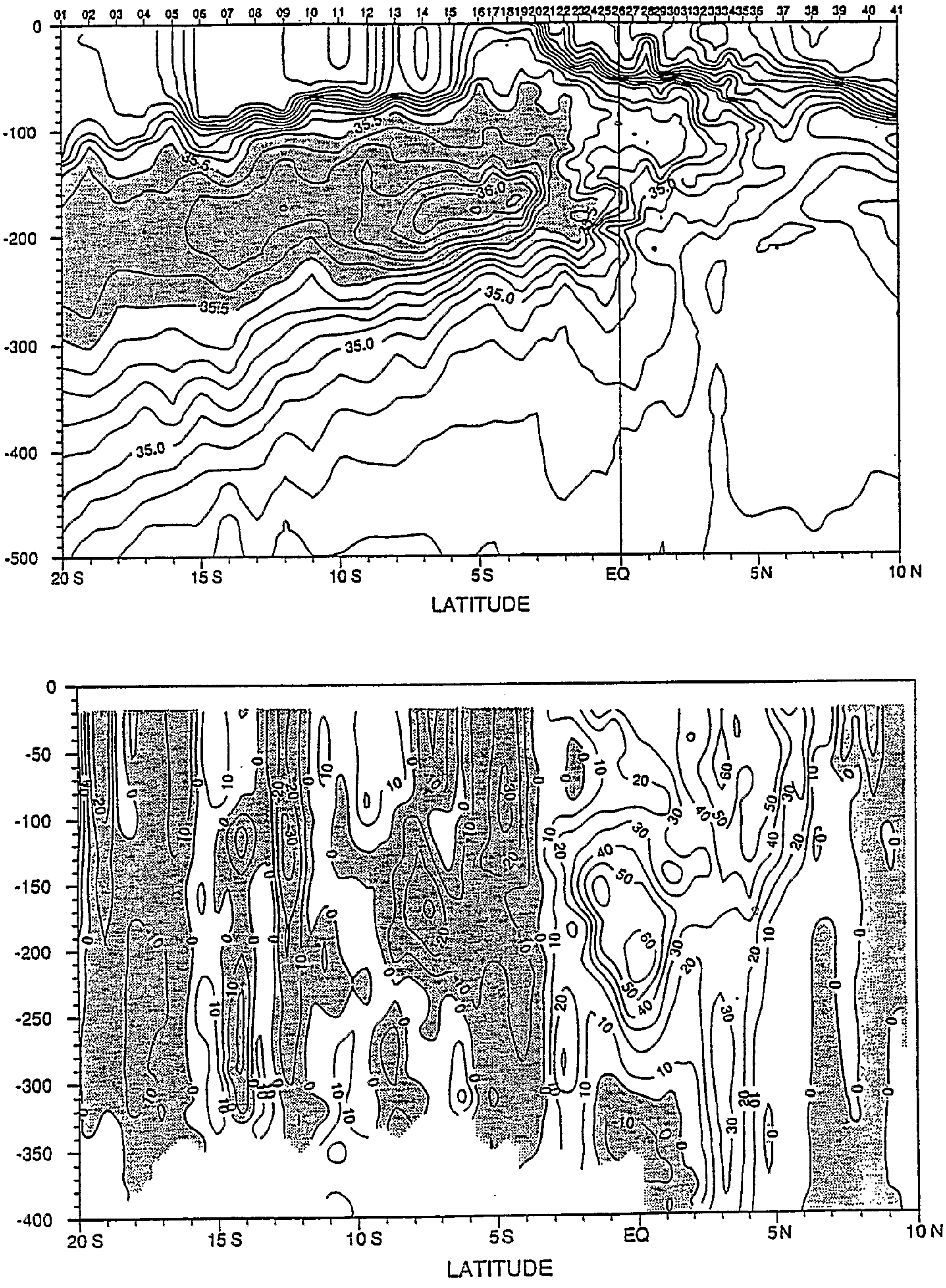

FIG.22. Distribution of salinity (upper panel) and E/W component from ADCP (lower panel) at 165°E during SURTROPAC 15 (July 1991) (from RUAL *et al*, 1991).

layer and is returned to the atmosphere, enhancing the convection. During post-El Niño period, when the Walker cell has shifted eastward, its descending branch is located in the western Pacific west of 160°E where temperature and salinity are homogeneous, conditions favourable to a net heating of the mixed layer.

In this way in the westernmost Pacific, during pre-El Niño conditions, the presence of low SSS results in heat being returned to the atmosphere, which slows the accumulation of heat in the ocean and delays the starting of El Niño. During post-El Niño conditions, the presence of high SSS enhances the acumulation of heat in the surface of the ocean favouring a rapid return to the normal conditions. In the central and eastern pacific, the pattern is reversed: during pre-El Niño period, high SSS enhances the accumulation of heat which is finally stored in the westernmost Pacific. During post-El Niño, the low SSS returns the heat upward and induces the dissipation of the heat back to the atmosphere. On the other hand, the shoaling and the return of the salinity maximum core along the equator to the central Pacific favours the formation of a new equatorial SSS maximum.

7.2 Changes in salinity in the southwestern Pacific

The westward extension of the surface and subsurface salinity maximum are concomitant in the tropical area, and so an EOF analysis of SSS east of 160°E gives an interesting time-series of the phenomenon (DELCROIX and HENIN, 1991; PORTE, 1992). The first EOF along the ship tracks Noumea-Japan and Fiji-Hawaii and a second EOF of SSS along the shipping tracks Tahiti-Los Angeles and Tahiti-Panama accounts respectively for 29, 25, 14 and 20% of the variance, and help to explain interannual variations. Figure 23 represents, in the upper panel, the time function (1974-88) and, in the lower panel, the space function along the different ship tracks. The space functions of the western tracks (Noumea-Japan, Fiji-Hawaii, Tahiti-California) are negative elsewhere in the tropical area but positive in the equatorial one (10°S-10°N). Along the easternmost track (Tahiti-Panama), the space function has shifted southward and is positive between 15°S and the equator, but negative elsewhere.

According to the time function, there is a simultaneous SSS increase in the equatorial area and decrease in the tropical area during several years before ENSO. For example, SSS increased in the equatorial area from 1976 to 1982, decreased abruptly in the 1982-83 and increased again until the 1986 El Niño. During the pre-El Niño period, a build up of the salinity is likely in the equatorial area of the western and central Pacific, as a result of a positive E-P balance, upwelling and westward advection. According to WYRTKI (1981), the typical equatorial upwelling is fed from the south from below 50m by an equatorward geostrophic convergence of 46 Sverdrups. When the equatorial flow reverses from westward to eastward, equatorial upwelling collapses and the geostrophic convergence becomes a southward geostrophic divergence which increases both surface and subsurface salinity. This change induces westward geostrophic flow south of 10°S which transfers salty water to the western Pacific. Eastward flows of fresher, warm water in the equatorial area and westward flows of salty, cool water in the tropical area constitutes a thermohaline gyre connecting the central Pacific to the western Pacific. In contrast to the warm, fresher pool in the western Pacific, the surface waters of the south tropical central Pacific may be considered to be the cool, salty pool needed for the climate regulation of the tropical Pacific. It is worth noting that during the pre-El Niño period, an anticyclonic gyre exists in the south tropical Pacific west of 160°W (WYRTKI, 1974; DONGUY, HENIN and ROUGERIE, 1976) and it is this gyre that advects the low salinity water. In the post-El Niño period, this circulation pattern

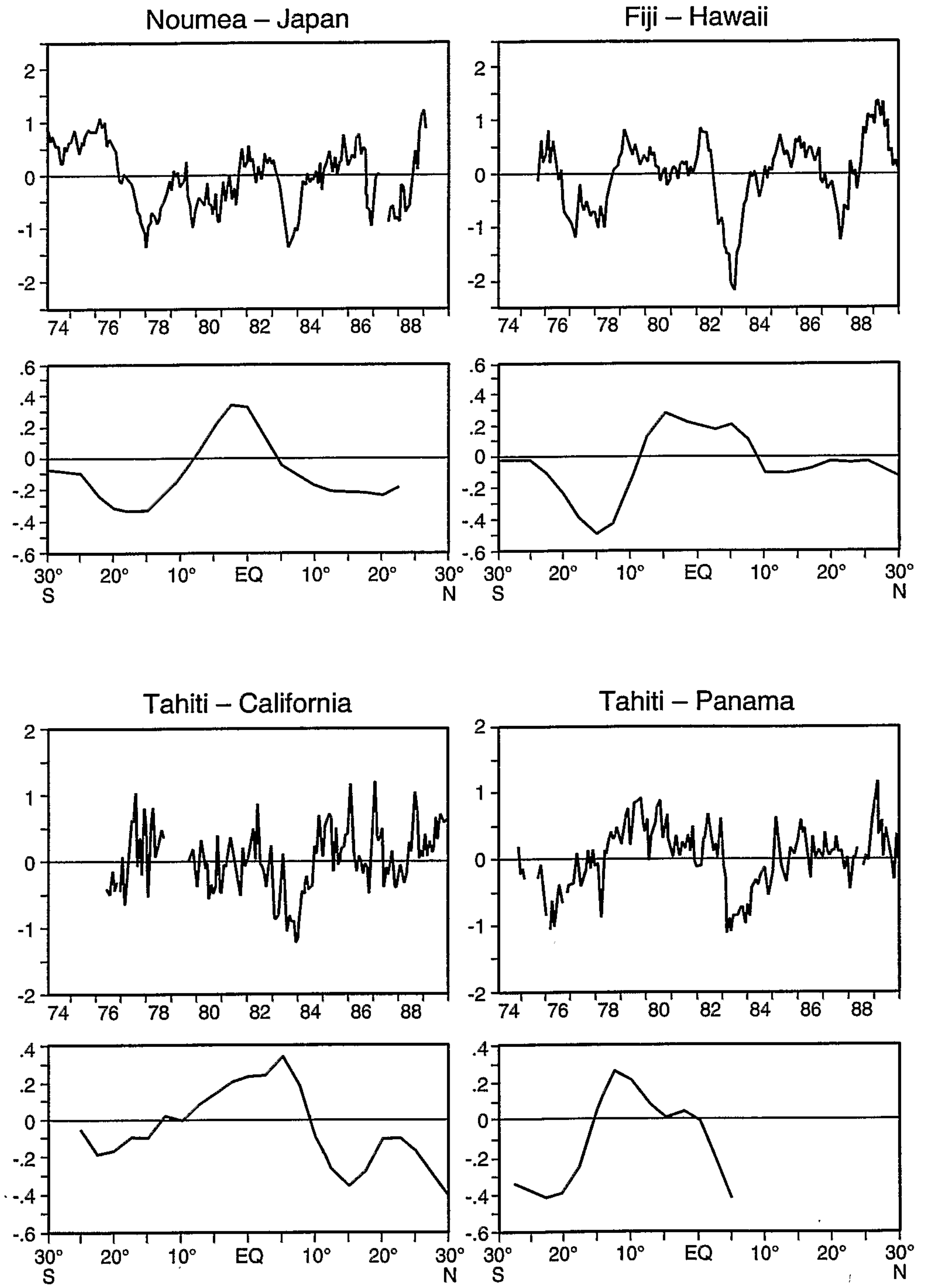

FIG.23. First empirical orthogonal function (EOF) for the track Noumea-Japan and Fiji-Hawaii, and second EOF of the SSS for the track Tahiti-Panama and for the track Tahiti-California (from PORTE, 1992).

is obviously replaced by a cyclonic gyre carrying high salinity water.

7.3 Thermohaline circulation in the southwestern Pacific during ENSO

The increase in the subsurface salinity maximum in the southwestern Pacific and its vertical extension creates a vertical barrier between the warm, fresher water along the equator and the cool, saltier water in the rest of the tropics. This barrier inhibits horizontal mixing of these two water masses. Moreover, according to DONGUY, ELDIN, MORLIERE and REBERT (1984) at 170°E, in the post-El Niño, there is a strong shear at approximately 10°S between a westward flow in the south and an eastward flow in the north. The eastward flow advects equatorial warm and fresher water from the western warm pool to the central or eastern Pacific, whereas westward flow advects cool, saltier water from the central to western Pacific. This latter flow at its western end, is reversed by the topography, so that it is returned to the east by the equatorial flow.

8. CONCLUSIONS

The oceanographic community has now begun to recognize the importance of the salinity on the climate in tropical areas. In the Pacific the time scale of the variation seems to be the same as ENSO, but it could be no longer in temperate and cold areas. For example, DICKSON, MEINCKE, MALMBERG and LEE (1988) tracked the displacement of a 'great salinity anomaly' in the north Atlantic between 1968 and 1982. Such low salinity may well inhibit the sinking of the cold surface water mass and reduce the ventilation of the subsurface. Consequently, warm water coming from the Gulf Stream which usually replaces the cold water could not reach the North Atlantic. The result would not only be poorly ventilated subsurface water, but also the persistence of cold surface water in the North Atlantic over several years, possibly inducing cooler climate for Europe.

The present work is an attempt to describe the salinity in the south tropical Pacific and its relationships with climate. During recent years, the oceanographic community has made intensive efforts to document the heat flow from the ocean to the atmosphere in the westernmost part of the Pacific with COARE (Coupled Ocean-Atmosphere Response Experiment). In the central tropical Pacific, the heat flux from the atmosphere to the ocean induces the surface salinity maximum. There is also little documentation about the convergence of the salinity maximum. A careful investigation of these important phenomena is suggested.

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