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INSTRUMENTS AND METHODS

A merchant ship thermo-salinograph network in the Pacific Ocean

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Abstract—The need for better knowledge of sea surface salinity (SSS) and sea surface temperature (SST) distribution in the tropical oceans was brought to light during the 10 years of the TOGA programme (1985–1994). In order to improve on the original "meteorological bucket" method of sampling, we developed a network of merchant ships among those operating regular routes through the tropical Pacific, and equipped them with thermo-salinographs.

Accurate positioning of the ships was obtained using a satellite positioning system. High frequency sampling (every 15 s) and recording of the median values for every 5 min resulted in quite precise monitoring of the SST and SSS, and in a description of the salinity fronts along the routes followed by the ships. Using this equipment, we were able to detect the influence of local rainfall on salinity and temperature and the diurnal cycle of sea surface temperature.

The accuracy of salinity measurements (0.02) was better than that of the old sampling technique by one order of magnitude. Temperature measurement by the thermo-salinograph was very stable but yielded results that are 0.2–0.3°C higher than sea surface temperature. To ensure reliability of data, the equipment was carefully checked every time the ships called at Noumea (i.e. every 2–3 months), and re-calibration every year or two is essential. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Temperature and salinity play a critical role in ocean water circulation and, therefore, in the distribution of water masses. For this reason, the description and analysis of sea surface salinity (SSS) and sea surface temperature (SST) and of their seasonal and inter-annual variations are essential for understanding the influence of oceans on global climate. The inter-tropical western Pacific happens to be the oceanic area of the planet where rainfall is most abundant, which results in a marked lowering of surface salinity; it is also the place where the warmest waters in the upper layers are found, acting as the planet's heat source, and usually referred to as the "Warm Pool" (Wyrtki, 1989).

This area is characterized by weak winds and intense rainfall. The freshwater flow reduces surface salinity, stabilizes the Warm Pool surface, and makes it very sensitive to heat transfers and water movement. In this area, the effect of salinity makes the interaction between ocean and atmosphere more complex, and there are significant feed-back mechanisms between surface temperature, rainfall, surface salinity and the mixing action of the wind. In the western tropical Pacific one of the results of the TOGA program (Tropical Ocean and Global Atmosphere) was the discovery of the barrier layer (Godfrey and Lindstrom, 1989; Lukas and Lindstrom, 1991). This "barrier layer" is the layer between the halocline and the pycnocline, which quite often are not at the same depth. One of its

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effects is to reduce vertical mixing (Lukas, 1991). This barrier layer is a climatological feature that can be seen in the historical data (Sprintall and Tomczak, 1992). Shinoda and Lukas (1995), using a Lagrangian mixed layer model, have shown that horizontal advection of salty waters from the central Pacific strongly affects the upper ocean salinity variation in the western Pacific. Zonal SSS gradients may also generate "fresh equatorial jets" (Roemmich *et al.*, 1994). In order to successfully simulate El Niño events, it is essential that feed-back relationships be taken into account when designing coupled ocean–atmosphere numerical models. Several papers have stressed the influence of salinity on models of tropical oceans (Cooper, 1988) and the influence of rainfall anomalies linked to the ENSO phenomenon on models of global oceanic water circulation (Reason, 1992).

Therefore, one of the main objectives of COARE (Coupled Ocean–Atmosphere Response Experiment), part of the international TOGA program, is the assessment of the space–time distribution of surface salinity in the Warm Pool, and of the processes controlling its variations over time scales ranging from a few days to several years.

While global surface ocean temperatures have been fairly well documented through satellite remote measurements, available data on salinity are scarce. However, some studies (Hires and Montgomery, 1972; Rochford, 1977; Donguy and Hénin, 1978; Kessler and Taft, 1987; Donguy, 1994) have shown the importance of surface salinity and temperature in the characterization of ocean structures and in the study of the whole tropical Pacific.

CURRENT STATE OF SSS AND SST OBSERVATIONS FROM MERCHANT SHIPS

In 1969, J. R. Donguy and C. Hénin developed a network of commercial vessels operating between New Caledonia and Japan. By regrouping meteorological and surface temperature and salinity measurements taken along their routes by these vessels, the authors were able to correlate salinity distribution, rainfall and the movements of the South Pacific Convergence Zone (SPCZ) in this region (Donguy and Hénin, 1976, 1978). In the southwestern Pacific a study by Delcroix and Hénin (1989) spanned the 1979–1985 period and focused especially on the 1982–1983 El Niño phenomenon, which was particularly well developed. This phenomenon resulted in the formation of a number of tropical cyclones that devastated French Polynesia, causing widespread damage. In this region the interannual salinity changes were very significant, having an amplitude more than five times greater than the seasonal changes.

Since 1969, from its centers in Noumea (New Caledonia), Papeete (French Polynesia) and Le Havre (France), *ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération*) has been carrying out systematic observations of surface temperature and salinity in the Pacific, Atlantic and Indian Oceans, using surface water samples taken by merchant ships. The technique consists of having the watch officer take water samples four to six times a day, using an insulated bucket equipped with a thermometer. This bucket, known as a "meteorological bucket", is hoisted up to the bridge—which can be as high as 25–30 m above sea level—where the temperature is measured and salinity samples collected. Measurements taken in these conditions can easily be inaccurate due to several hard-to-assess parameters, such as loss of heat through evaporation, heat gain through solar radiation, influence of ambient air temperature, amount of cloud cover, or effect of apparent wind (ships are often steaming at 18–20 knots). The accuracy of the measurement of temperature is questionable, the thermometer being supplied with a calibration correction that is, unfortunately, often ignored by the person doing the measurement. The uncertainty thus introduced is usually considered to be of the order of 0.2–0.3°C. The water sampled is then placed in an airtight container, to be analyzed later. On certain routes, a ship may call only once every four months, and the preservation of the samples in good condition becomes questionable. There again, evaporation may become a problem, depending on the quality and condition of the sample bottles, and current estimates indicate that accuracy in salinity is of the order of 0.2.

Furthermore, this old technique is becoming harder and harder to put into practice, due to the physical difficulties involved: retrieving sample buckets from the bridge of ships cruising at 15–20 knots can be an arduous and acrobatic process. So, when one considers that modern vessels operate with reduced crews and increasingly make use of automated equipment for their other data-gathering needs, it becomes evident that our original and often imprecise sampling techniques need to be upgraded.

In spite of the current lack of accuracy of the measurements, the ORSTOM Pacific surface temperature and salinity database, gathered over the last 24 years, is particularly useful. The ORSTOM bucket merchant ship network is the only one to have monitored both parameters over such a long time span. As an example the distribution of salinity observations by bucket for the year 1990 is presented in Fig. 1.

The annual number of measurements (Fig. 2) taken by the ships taking part in the ORSTOM Pacific network has varied, reaching as many as 10,000 observations/year between 1977 and 1983. Unfortunately, this number has gradually decreased, due to difficulties encountered. For example, in June 1992, the Papeete ORSTOM Centre, which provided a large amount of data, stopped collecting measurements of surface temperature and salinity from merchant ships in the central Pacific.

While a large number of oceanographic measurements—such as sea level by tide gauges, currents by satellite-tracked drifting buoys, vertical temperature distribution from ships (XBT probes) or from fixed platforms (ATLAS buoys with thermistances chains of the TAO

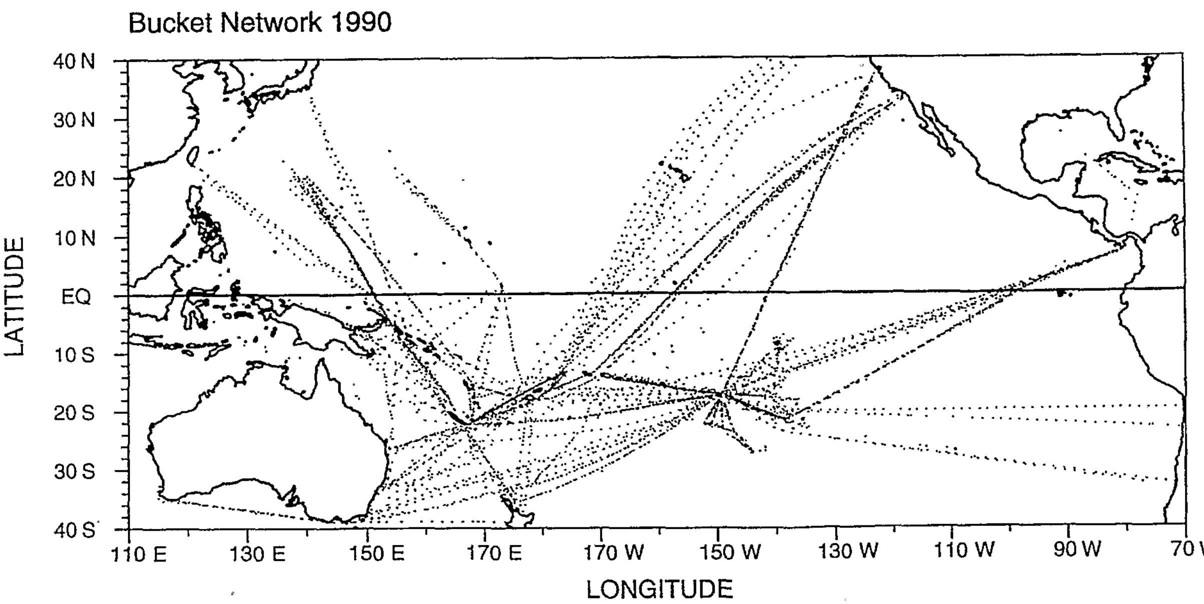


Fig. 1. Distribution of sea surface salinity observations made by the ORSTOM merchant ship network during 1990.

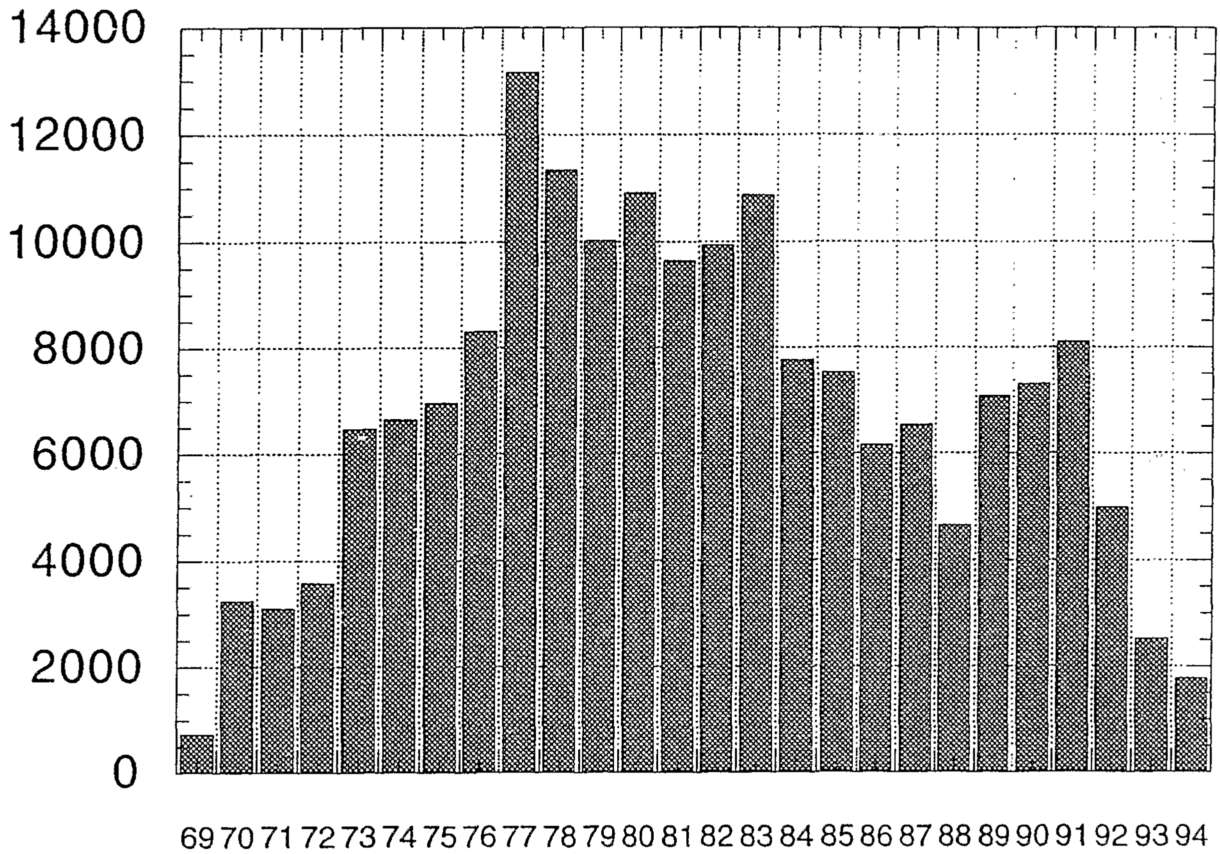


Fig. 2. Number of sea surface salinity samples from the ORSTOM merchant ship network for the 1969–1994 period.

network)—have been automated for a number of years, the monitoring of surface temperature and salinity by commercial vessels has remained a manual process, with low accuracy and too few measurements taken.

DEVELOPMENT OF THE AUTOMATED THERMO-SALINOGRAPH

We have just pointed out the need to introduce automation in the measurement of surface temperature and salinity, i.e. the need for better accuracy, for simplicity of method and for a much greater number of observations. This goal of automating SSS and SST measurements from commercial vessels has now been reached. Having studied the various types of equipment available, we finally selected the SBE21 thermo-salinograph manufactured by SeaBird Electronics Inc. (Bellevue, Washington, U.S.A.). The conductivity cells incorporate tributyl tin coatings to reduce biological fouling. For thermo-salinographs installed on commercial ships at sea and in harbors in the tropical regions tested, the biological fouling process may be critical. We therefore carefully change the coatings when the ships call at Noumea (every 2–3 months) and test the equipment. A thermistor is used to measure water temperature. The two sensors give frequency data, which are converted to conductivity and temperature, then to salinity, by appropriate algorithms using calibration coefficients.

The thermo-salinograph has to be installed as close as possible to the engine water-intake, mainly to minimize increase of temperature. Depending on the ship, this was generally possible. A correct circulation of water in the thermo-salinograph is obtained when the pressure of seawater at the exit of the ship's pumps is 2 bar. The seawater is generally discharged at atmospheric pressure. When necessary an auxiliary pump is installed after the thermo-salinograph in the water circuit in order to reduce air bubbles which may occasionally appear and distort conductivity measurements. Bubble traps were not used on our commercial ship network due to the very rare occurrence of bubbles during the first three years of development of our network. This situation would appear to be in contradiction with the air bubble occurrences observed by Bitterman and Millard (1994) during shipboard TSG intercomparison tests (spikes of −0.5 in salinity) onboard a research vessel during the course of a single cruise.

The software provided at the beginning of the project by the manufacturer (SeaBird) gave only temperature and salinity. For the geographical positioning of the observations, having the officer on watch enter the ship's position and time on the computer keyboard proved too much of a nuisance, and we were able to interface our equipment with a reasonably inexpensive separate satellite positioning system. A useful complete data acquisition program was written in C language in order to record thermo-salinograph and GPS (Global Positioning System) data on a laptop PC installed on the ship's bridge. A complete description of the system used can be found in Grelet *et al.* (1992). The installation, in schematic form, can be seen in Fig. 3. When the ship calls in Noumea the data are

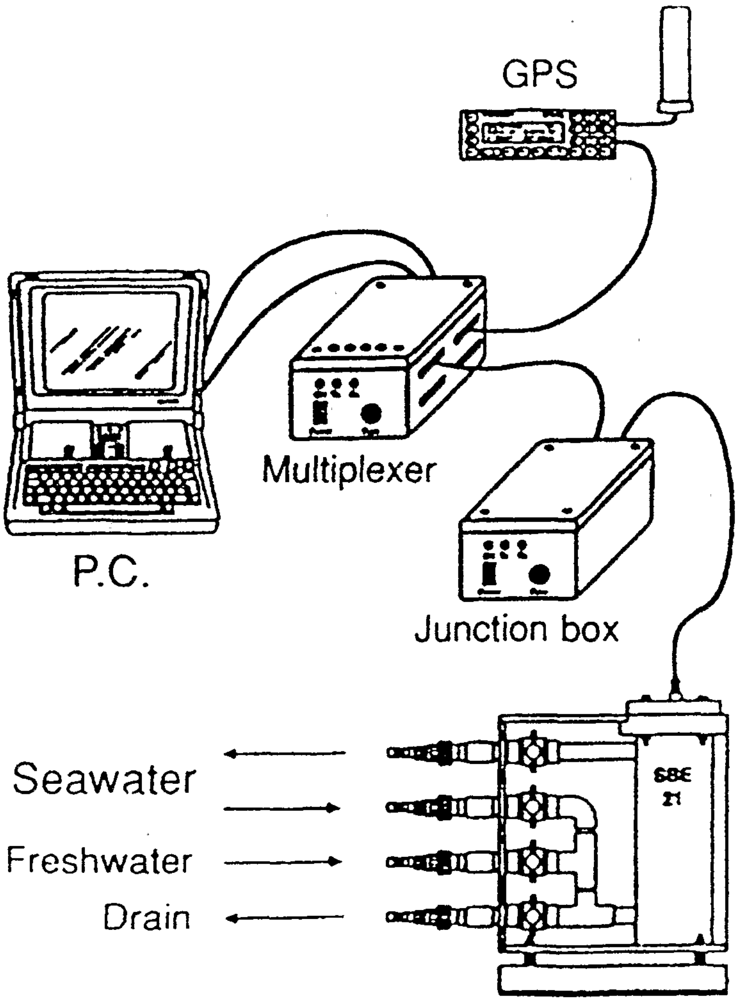


Fig. 3. Thermosalinograph installation on board a commercial vessel: SBE21 + PC + GPS.

Table 1. *Total number of observations*

Cruise	Date	SST		SSS	
		Bucket	SBE21	Bucket	SBE21
SURTROPAC 14	11 March–6 April 1991	16	61	13	64
SURTROPAC 15	18 July–14 August 1991	64	61	64	64
COARE 01	20 August–15 September 1991	—	33	—	33
COARE 02	21 February–17March 1992	72	72	72	72

transferred to a SUN workstation, where they are validated and entered into a data base (Hénin *et al.*, 1994).

The final setting up and tuning of the system was done during several oceanographic cruises aboard the ORSTOM and GENAVIR research vessels *L'Alis*, *Le Suroît*, *Le Noroît* and *l'Atalante*. During the course of four different oceanographic cruises in 1991 and 1992 in the western equatorial Pacific we were able to test the accuracy of the thermo-salinograph by comparisons with measurements taken from bucket sampling and CTD casts. The precision of the measurements given by both thermo-salinograph and bucket sampling techniques were compared and assessed along cruise tracks following the 156°E and 165°E meridians in the inter-tropical Pacific (Table 1).

For each hydrographic station, reference measurements were taken at the surface using a calibrated CTD system (SeaBird SBE-9). At the same time, a sample was taken with the bucket and measurements made with the operating thermo-salinograph. Note that the bucket was sampling water from less than half a meter below the surface, while the CTD probe operated at a depth of 1–2 m. The water going through the thermo-salinograph came from the water intake of the ship's cooling system, located 4 m below the surface. This water was led to the main deck level, resulting in a warming of the water of a few tenths of a °C. Thus, at this stage of the process, the methodology introduces some significant variations.

It can be seen from Table 2 that the new automated technique constitutes a notable improvement in the accuracy of both surface temperature and salinity over the old bucket sampling technique.

One must also consider that the bucket sampling technique as used aboard a commercial vessel underway is likely to be far less accurate than that practiced aboard a research vessel, if only because of the latter's smaller physical size and slower speed.

Temperature

We note that temperature measurements with the bucket technique depend to some extent on the type of bucket and of thermometer used. The same equipment will not necessarily be used from one voyage to the next, and even if it was, its characteristics are liable to change over time. The thermometer comes with a correction and calibration certificate from its manufacturer, but this is all too often ignored by the person responsible for the observations. Given that the CTD probe was correctly calibrated before and after each mission, and can thus serve as a reliable reference, we note that the discrepancy for the bucket technique can vary from +0.60°C (SURTROPAC 15) to −0.16°C (SURTROPAC

Table 2. Statistics of the differences in temperature and salinity between the CTD system and the bucket technique, and between the CTD system and the thermosalinograph

	CTD-bucket		CTD-thermosalinograph	
	Average	Standard deviation	Average	Standard deviation
Temperature				
SURTROPAC-14	−0.16	0.22	−0.17	0.12
SURTROPAC-15	0.60	0.48	−0.20	0.10
COARE-1	—	—	−0.19	0.05
COARE-2	−0.13	0.34	−0.30	0.08
Salinity				
SURTROPAC-14	−0.13	0.19	0.02	0.02
SURTROPAC-15	0.07	0.10	0.00	0.02
COARE-1	—	—	0.03	0.02
COARE-2	−0.10	0.09	0.02	0.01

14), while the error in the measurements yielded by the thermo-salinograph apparatus stays within −0.17°C (SURTROPAC 14) and −0.30°C (COARE 02). Also, the dispersion of the measurements differs, the standard deviation being almost an order of magnitude smaller for the thermo-salinograph (0.05–0.12°C) than for the bucket data (0.22–0.48°C).

The temperature of the water measured in the thermo-salinograph is indeed different from that of the sea surface. First, the water intake on commercial vessels is located at a depth of 4–6 m; second, the water is mixed by the passage of the ship. Then between the hull intake and the thermo-salinograph system the water temperature changes within the pipes. During the comparisons made onboard R.V. "*Le Noroit*", the measured temperature was approximately 0.1–0.3°C greater than the CTD temperature. On the commercial vessels the difference is certainly smaller, because the thermo-salinograph system is closer to the water intake than on R.V. *Le Noroit*. At the Noumea ORSTOM Centre we are testing a Seabird hull temperature sensor, but the significance of hull temperature in regards to SST is yet to be investigated.

Salinity

For salinity, the bucket sampling technique again proved less accurate than the automated thermo-salinograph.

The salinity mean difference between thermo-salinograph and CTD are a good order of magnitude smaller (0.00–0.03) than between bucket and CTD (−0.13 to +0.07). The dispersion of the measurements is also much better with the thermo-salinograph (standard deviation of 0.01–0.02 vs 0.09–0.19 for the bucket technique).

Here again, we must point out that the comparisons were made during the course of oceanographic research missions, where salinity of surface sea water was measured onboard within 24–48 h of sampling, using high precision equipment. Typically, the salinity of the samples brought back by commercial vessels would be analyzed 2–4 months later at the Noumea ORSTOM Centre, and the results obtained would be considerably less reliable.

DAILY COMPARISONS

The ships' officers provided us with daily samples from their ship's cooling circuit near the thermo-salinograph. This represented generally between 25 and 40 observations per voyage. Salinity analysis of the samples brought back was performed at the Noumea ORSTOM Centre. Table 3 shows, in summary form for some voyages, the mean and standard deviation of the difference between the salinity of the samples analyzed 2–5 months later and that recorded *in situ* by the thermo-salinograph (Table 3).

Table 3 shows that the mean difference between sample analysis and the salinity level recorded by the thermo-salinograph is usually less than +0.1, but at times reaches 0.2. As the salinity measured by salinometer analysis is always greater than the thermo-salinograph reading, we may suspect that this is due to evaporation of the samples, which undergo analysis in Noumea 2–5 months after collection, depending on the duration of the voyage between two calls at Noumea. Stored bottle salinity drift was estimated by P. Rual (personal communication) to be 0.05 month^{-1}, which corresponds well to the 0.10–0.25 stated in Table 3 for an analysis of samples 2–5 months after sampling.

The standard deviation of the difference is usually of the same order as the average value. At this stage, we have no rational explanation for this except to note that the technique of discrete bucket sampling, or even of sampling from the ship's cooling circuit, followed by laboratory analysis 2–5 months later obviously has its limitations. Table 2 had shown that the standard deviation of the difference between salinity values as measured by CTD probe and salinity measured onboard from bucket sampling during the course of oceanographic missions was also relatively high (between 0.1 and 0.2). It would be surprizing indeed if samples collected from commercial vessels and analyzed some months later were to prove more reliable than observations made from smaller and slower research vessels, and analyzed onboard within a few days.

This study shows that discrete seawater sampling does not lead to improvement in the accuracy of the TSG salinity measurements. However, it allows one to spot malfunctions in

Table 3. *Statistics (number of comparisons, average and standard deviation) of the difference between samples salinity (measured 2–5 months later) and thermosalinograph recorded salinity*

Voyage	Date voyage	*N*	Mean	Standard deviation
paci9201	10 May–6 July 1992	34	0.24	0.19
paci9202	7 July–3 September 1992	37	0.12	0.06
paci9203	10 September–28 October 1992	35	0.08	0.07
paci9204	19 November 1992–8 January 1993	33	0.02	0.01
paci9301	12 January–10 March 1993	37	0.01	0.12
paci9302	12 March–6 May 1993	32	0.03	0.20
voya9102	13 December 1991–27 January 1992	24	0.02	0.18
voya9202	12 June–10 August 1992	26	0.15	0.16
voya9203	11 August–13 November 1992	26	0.19	0.10
paci9304	9 July–2 September 1993	39	0.11	0.10
paci9303	10 May–8 July 1993	37	0.10	0.06
alis9302	1 June–1 September 1993	94	0.12	0.07
expl9301	27 June–22 August 1993	16	0.19	0.08
expl9302	23 August–23 October 1993	14	0.10	0.09

the equipment (such as poor water flow in the circuit, air bubbles, failure or dysfunction of the sensing units).

CALIBRATION

The TSGs were regularly calibrated at the SeaBird factory, because the drifts in temperature and salinity are fundamental parameters that have to be appreciated. In Table 4 we have gathered drifts measured from basic data (frequencies) and pre- and post-calibration coefficients for four different thermo-salinograph systems during the 1993–1995 period from voyages of commercial vessels TAS Explorer and Pacific Islander between Japan, New Zealand and Tahiti.

Bitterman and Millard (1994), during an intercomparison test, estimated the salinity drift of their SBE21 system to be 0.018 per month during 4 months. It is clear from Table 4 that the observed salinity drift for our systems, which was never more than 0.001 per month, is comparatively very small. This may be due to the careful use of an anti-fouling protection as suggested by the SeaBird manufacturer. The anti-foulant is changed at every call of the ships at Noumea, that is, every 2–3 months. A calibration every year or every two years may ensure that the change in salinity remains of the order of 0.01. However, conductivity cells were occasionally damaged. The salinity measurements of the samples taken every day (previous chapter) allowed us to determine, approximately, the period of misfunction, to eliminate the erroneous data and to change the equipment.

The temperature is also quite stable, the observed temperature drift for the four systems being $0.3–2 \times 10^{-4}$°C/month. Note that after 26 months of use the temperature drift of the N°805 equipment was less than 4×10^{-3}°C. With a calibration of the thermo-salinograph every year or every two years, we may estimate that the temperature change is less than 5×10^{-3}°C.

Thus, it would seem essential to calibrate the thermo-salinographs every year or two. This can be rather inconvenient, particularly as it requires the sensing units to be shipped back to their manufacturer in the United States, creating the need for additional spare units, but the accuracy of the measurements demands it.

Automated salinity and temperature measurements made with equipment for which careful calibration before and after the mission evidenced only minimal variations are bound to be far superior to those obtained by the current technique of sending a bucket over

Table 4. Calibration statistics. Mean, drift/month and standard deviation of salinity and temperature differences using post- and pre-calibration coefficients

Identification number	Dates of calibration		Spost–Spre ($\times 10^{-3}$)			Tpost–Tpre ($\times 10^{-3}$°C)		
	Pre-	Post-	Mean	Drift/mo	St. dev.	Mean	Drift/mo	St. dev.
805	7 April 1993	9 June 1995	−26.5	1.0	0.0	3.5	0.1	0.5
603	14 July 1993	27 January 1995	−12.5	−0.7	1.8	2.9	0.2	0.4
462	23 July 1993	5 October 1995	−4.1	−0.2	0.6	4.8	0.2	0.6
1324	17 March 1993	31 March 1994	9.1	0.8	0.5	−0.4	−0.03	0.7

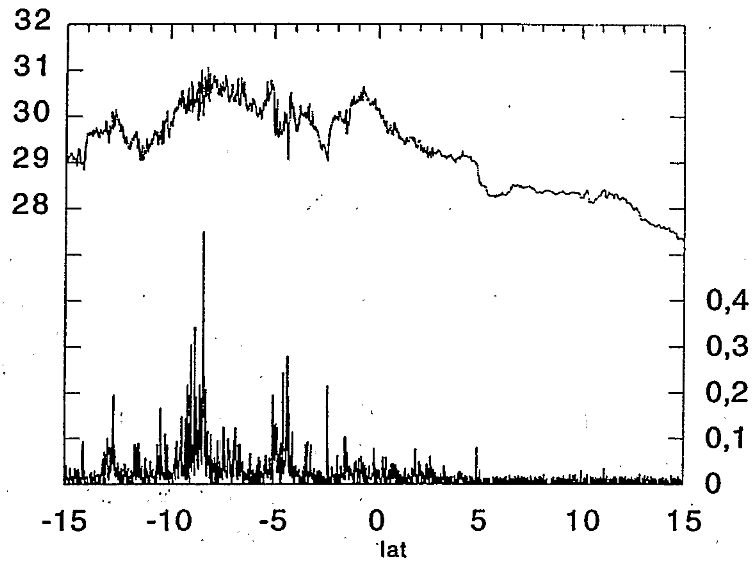


Fig. 4. Latitude distribution of surface temperature and standard deviation of T over 5 min between 15°S and 15°N on the New Caledonia/Philippines track (4–14 March 1994).

the side every 6 h. This was indeed the conclusion arrived at in the preceding chapter after comparing the results obtained during oceanographic missions.

IMPROVEMENT OF THE QUALITY OF THE MEASUREMENTS

Since 1992 we have improved substantially the quality of the thermo-salinograph measurements by increasing the frequency of sampling (every 15 s instead of every 5 min). We then recorded the median values for every 5 min interval.

Figures 4 and 5 present the data obtained during the voyage of the commercial vessel Pacific Islander between New Caledonia and the Philippines (4–14 March 1994). The temperature and salinity are presented as a function of latitude between 15°N and 15°S, as well as the standard deviation every 5 min over the 15 s measurements. Figures 4 and 5 show that the measurements are generally stable with low values of standard deviation (0.01–

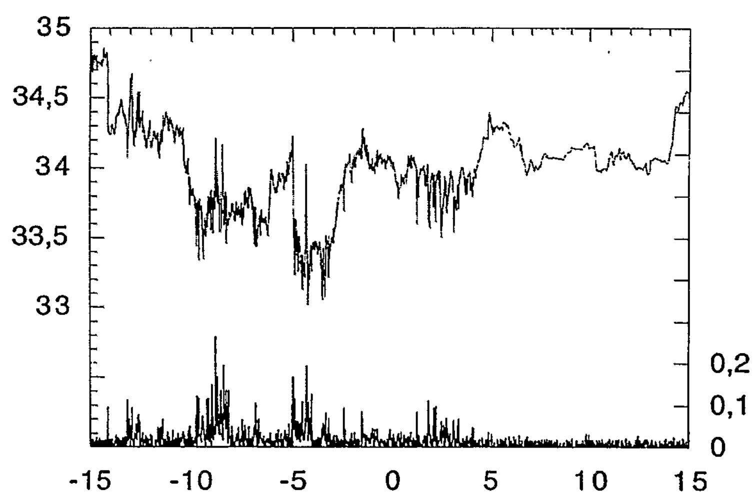


Fig. 5. Latitude distribution of surface salinity and standard deviation of S over 5 min between 15°S and 15°N on the New Caledonia/Philippines track (4–14 March 1994).

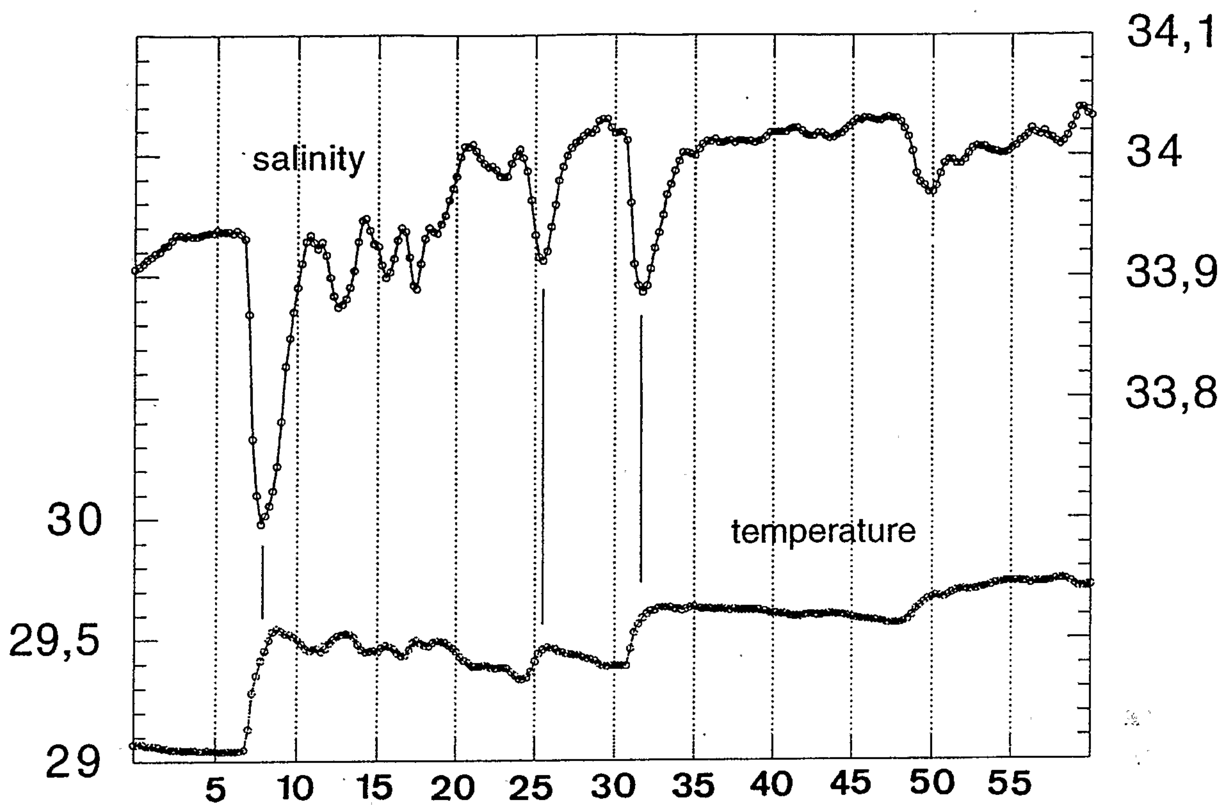


Fig. 6. Example of 15 s sampling in temperature and salinity during a 1-h period near 3°S–150°E. Vertical marks correspond to 5 min time intervals.

0.02°C in temperature and 0.01–0.02 in salinity), but they can also be scattered (standard deviation of higher values reaching 0.3°C and 0.2°C, respectively) in the 13°S–3°N latitude band. This may be explained by the presence under the South Pacific Convergence Zone (SPCZ) and Inter Tropical Convergence Zone (ITCZ) of surface freshwater lenses due to heavy rainfall, inducing abrupt changes in T and S as the ship passed through.

Temperature and conductivity were measured every 15 s, salinity being calculated from these two values. The geometry of the two sensors, their different positions in the water circuit and their different time responses may give erratic values for salinity because temperature and conductivity sensors do not measure exactly the same water mass. This feature is well shown in Fig. 6, presenting the record of a 1 h period in the vicinity of 3°S–150°E, with artificial salinity peaks corresponding to temperature gradients.

Therefore, storing instantaneous values every 5 min may give erroneous data, and we decided to store a more representative value of the signal by using the median figure over 5 min. We have chosen to store the median value instead of the mean value to reduce the effect of outliers caused by artificial peaks, which generally are less than 2.5 min long. Unfortunately, if air bubbles occur occasionally, low salinity peaks are observed (Bitterman and Millard, 1994). If they are longer than 2.5 min, a simple visual inspection of data during the validation phase will suffice to eliminate the spurious data. Fortunately, at this point, we have had few occurrences of air bubbles.

The difference between mean and median values over 5 min is generally very small but increases when the standard deviation is larger. For salinity, this difference is between -0.02 and $+0.02$ when standard deviation is smaller than 0.05 but may extend to between -0.05 and $+0.05$ when standard deviation reaches 0.1. Fortunately, large variability of T

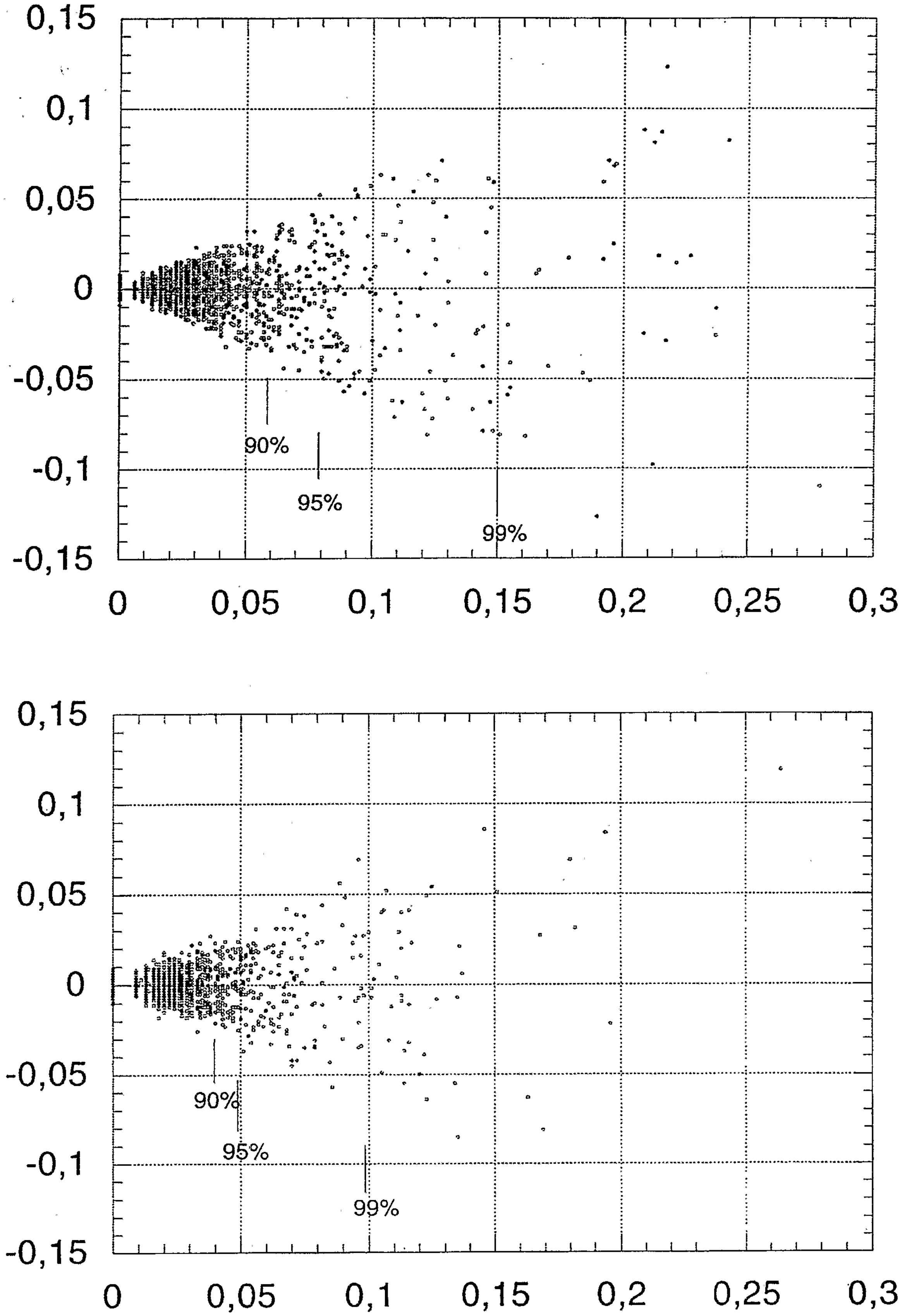


Fig. 7. Difference between median and mean value relative to standard deviation over 5 min of temperature (top) and salinity (bottom) on the New Caledonia to Philippines track (4–14 March 1994). Cumulative occurrence of standard deviation of 90, 95 and 99% are also shown.

and S over 5 min is relatively rare: more than 99% of standard deviations of T and S over 5 min remain under 0.15°C and 0.1, respectively, and more than 95% are under 0.08°C and 0.05°C, respectively (Fig. 7). Initially, the median value technique was chosen for our thermo-salinograph network to suppress erroneous values due to artificial salinity peaks, but other methods that identify and remove data outliers might be tested.

In order to develop our studies of seasonal and interannual variability of SSS in the tropical oceans, the primary objectives of our TSG network were

— to improve accuracy in salinity measurement,
— to increase the number of observations and
— to make them easier to perform

For our thermo-salinograph network the choice of a 5 min time interval to record data was guided by the processes studied, the technological limitations, and the speed of the observation platforms. In addition, the description of very sharp horizontal gradients in SSS was made possible by the high frequency of sampling (one value recorded every 1.7 nautical miles (3.2 km) at a speed of 20 knots with a 5 min sampling).

DEVELOPMENT OF THE THERMO-SALINOGRAPH NETWORK

Since the beginning of the project, we have been able with this system to obtain records covering several shipping routes in the Pacific, Indian and Atlantic Oceans and some other tracks corresponding to oceanographic cruises. Since late 1990, six commercial vessels and four research vessels have been used to refine and perfect the automated surface-water measurement system.

The number of cruises and observations recorded per year by our commercial ship network is as follows:

Year	Number of voyages	Number of observations
1990	2	8500
1991	12	60 000
1992	17	117 000
1993	18	177 000
1994	27	184 000
1995	30	134 000

The monitoring effort was focused on the western and central Pacific, where the salinity distribution is well contrasted, with high salinity waters of more than 36.2 near French Polynesia and low salinity waters (less than 34.8) under the convergence zones (Intertropical Convergence Zone, ITCZ, and South Pacific Convergence Zone, SPCZ) (Delcroix *et al.*, 1996). The area of observation extends from Japan to New Zealand and from southeast Asia and Australia to French Polynesia, crossing the COARE domain (10°N–10°S/140°E, 180°) (Fig. 8).

Thus, during this experimental period, and using a limited number of ships, we were able to demonstrate that intensive automated surface-water monitoring was indeed possible, and that it improved the accuracy of the data and the density of coverage along the tracks followed.

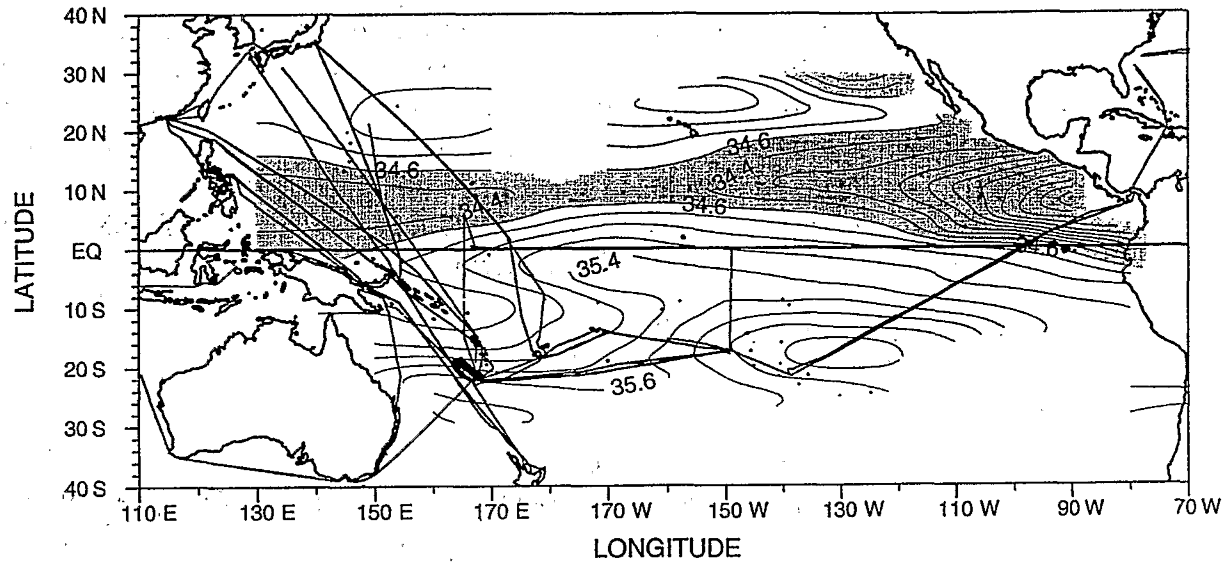


Fig. 8. Thermosalinograph network observations in the Pacific Ocean during 1994 and mean sea surface salinity for the 1974–1989 period.

VARIABILITY OF SSS AND SST OBSERVED WITH TSG NETWORK

For illustration we will present some results obtainable only from an intensive and more accurate SST and SSS network.

The diurnal temperature cycle

During the course of the WEPOCS III (*Western Equatorial Pacific Ocean Circulation Study*) mission (16 June–31 July 1988), and making use of observations obtained by bucket sampling of the upper half-meter layer, Lukas (1991) was able to observe diurnal temperature cycles with an amplitude of as much as 2°C. This amplitude of the diurnal cycle of surface temperature is highly variable and depends, among other parameters, on cloud cover, sea state and wind strength.

According to Taft and McPhaden (1989), lower amplitudes (1°C) were observed around 165°E with wind speeds in excess of 6 m/s. Generally speaking, amplitudes are smaller (0.4–0.6°C) in the mid-latitudes (Ostapoff and Worthen, 1974; Price *et al.*, 1986).

In the western equatorial Pacific, during the intensive observation period (IOP) of the COARE programm (Coupled Ocean Atmosphere Response Experiment), we had the opportunity to observe the diurnal cycle with our thermo-salinograph system. The measurements were at depths of 4–6 m, depending on the location of the ship's cooling water intake. Thus, strictly speaking, we are not dealing with true surface water, but with water from the near surface layer. A diurnal temperature cycle with an amplitude varying from 0.4°C to 2.0°C was observed while R.V. *L'Alis* was keeping station in the equatorial zone (2°S/156°E) in November 1992, with temperatures reaching a maximum around 14:00 h local time (Radenac *et al.*, 1993).

During a three month period (December 1992–February 1993), R.V. *Le Noroit* cruised along 18 trans-equatorial tracks, experiencing varying cloud cover and wind strength conditions (Delcroix *et al.*, 1993). These conditions affected the amplitude of the diurnal

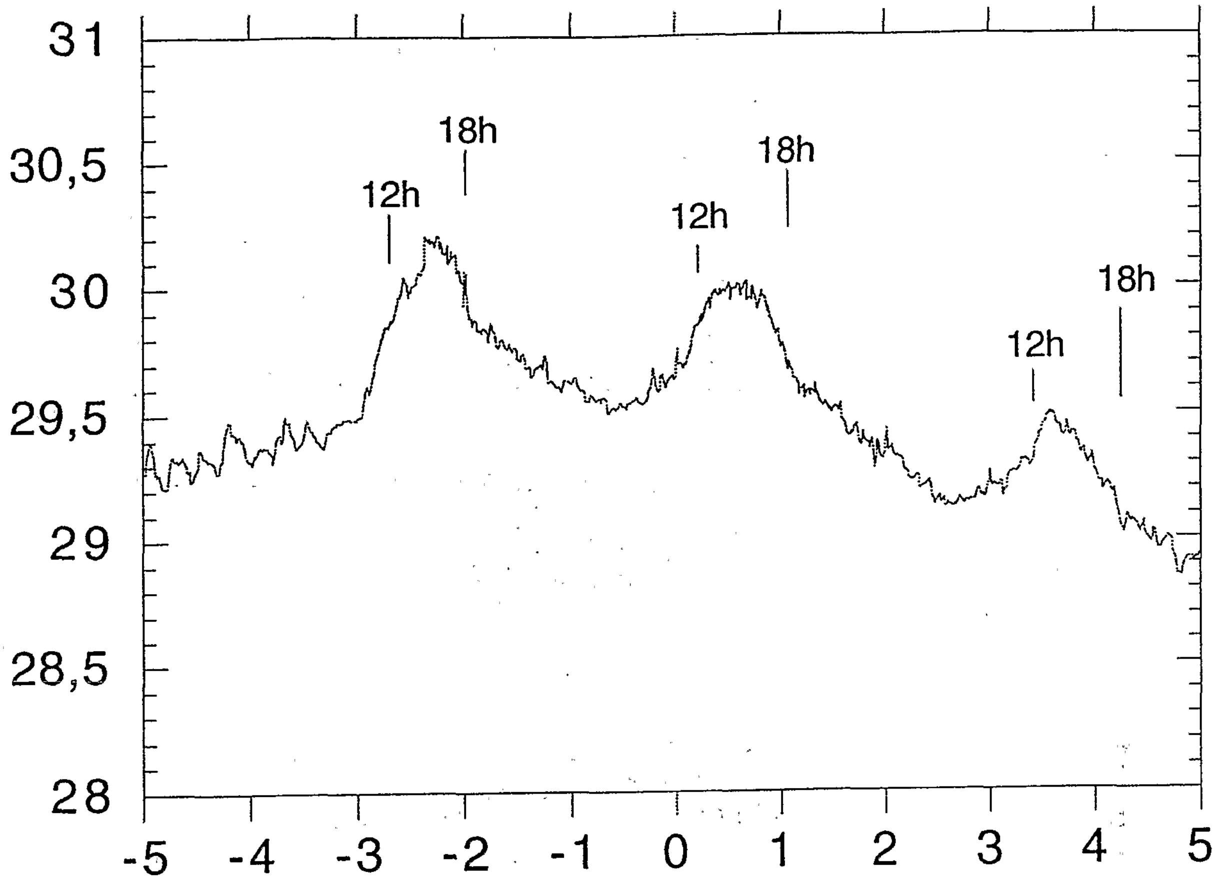


Fig. 9. Sea surface temperature distribution (°C) along the 156°E meridian between 5°N and 5°S during a light wind period (20–23 January 1993).

temperature cycle and disturbed the description of temperature distribution along the 5°S–5°N runs (each leg lasting approximately three days). During the 20–23 January 1993 section (Fig. 9), over a 3 day period of weak winds, the diurnal heating was well observed on the SST records with an amplitude of about 0.7°C and a maximum occurring at approximately 14:00–15:00 h local time.

Effect of rainfall

Local rainfall affects both temperature and salinity. The effect on temperature is small (a 0.1–0.3°C temperature drop has been frequently observed during a rain squall), but much greater on surface salinity. Depending on the intensity and duration of rainfall, this latter may vary by as much as 0.5 (observed onboard R.V. *L'Alis* while on station), or even 1.0 (observed from R.V. *Le Noroit* between 3°N and 4°N during the 30 December 1992–3 January 1993 leg) (Fig. 10). The effect is nearly immediate locally and can last up to 3–6 h after the end of rainfall (Radenac *et al.*, 1993). The rainfall lowers the sea surface salinity and the sea surface temperature. This effect is well evidenced on the surface *T–S* diagram of another transect of R.V. *Le Noroit* (Fig. 11).

This temperature diurnal variability, coupled with the effect of localized rainfall in tropical areas, could lead one to question the validity of surface temperature and salinity measurements taken by the traditional network of commercial vessels, and even those gathered by research vessels. Studies are being carried out on the diurnal temperature cycle

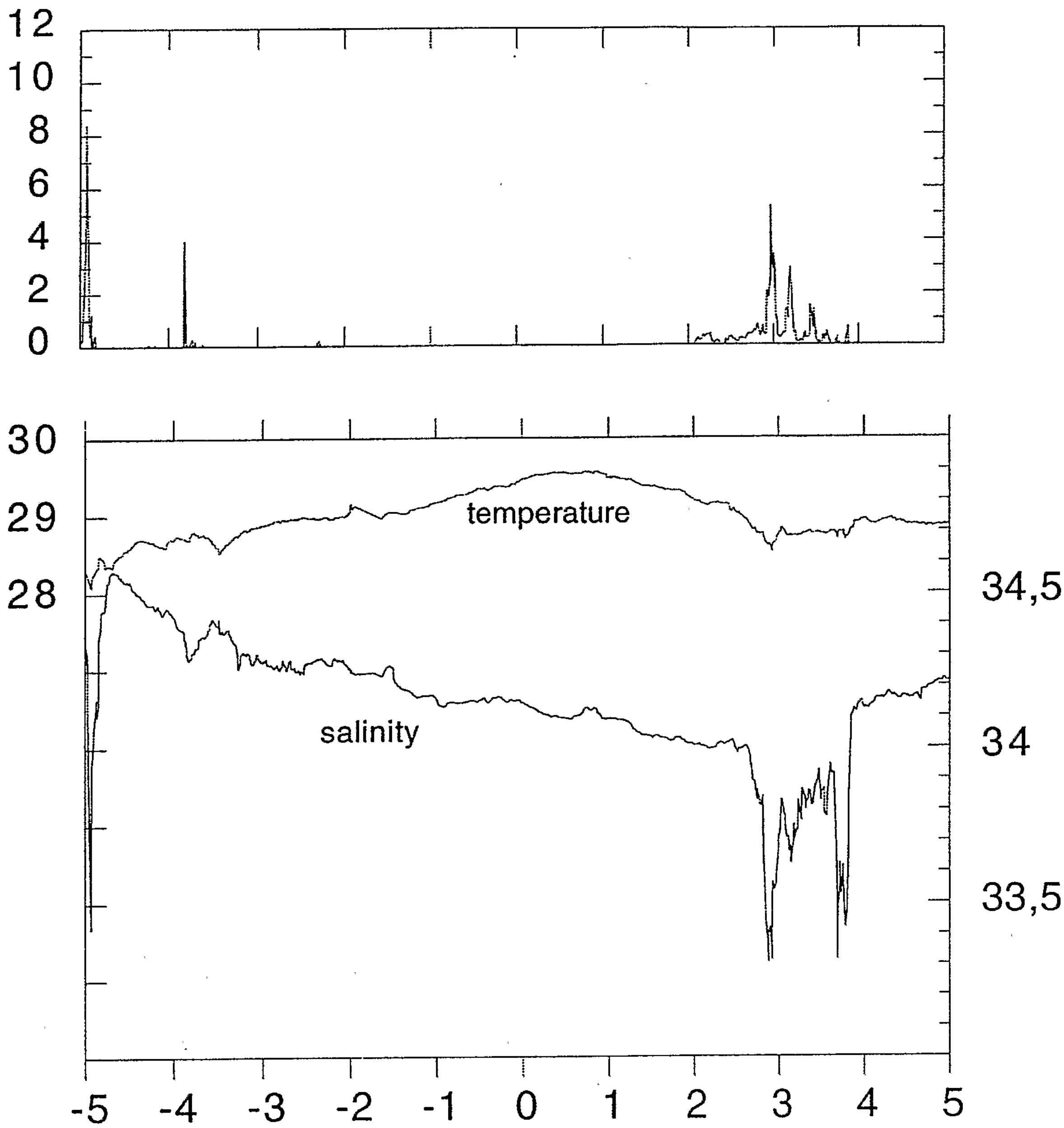


Fig. 10. Sea surface salinity and temperature (bottom) and rainfall (top, in mm/5 min) distribution along the 156°E meridian between 5°N and 5°S (30 December 1992–3 January 1993).

and on the effect of freshwater on the surface layer of oceans. They will enable us to better take into account the diurnal cycle, particularly in modeling. Furthermore, the understanding and quantification of the factors affecting the diurnal surface temperature cycle and salinity (wind, cloud cover, rainfall...) may enable us to correct individual observations of SSS and SST and fit them within the general distribution field of these parameters.

Surface salinity fronts

As hydrological structures generally have different zonal and meridional distribution characteristics, we will make a distinction between observations taken along zonal routes and those taken along meridional routes.

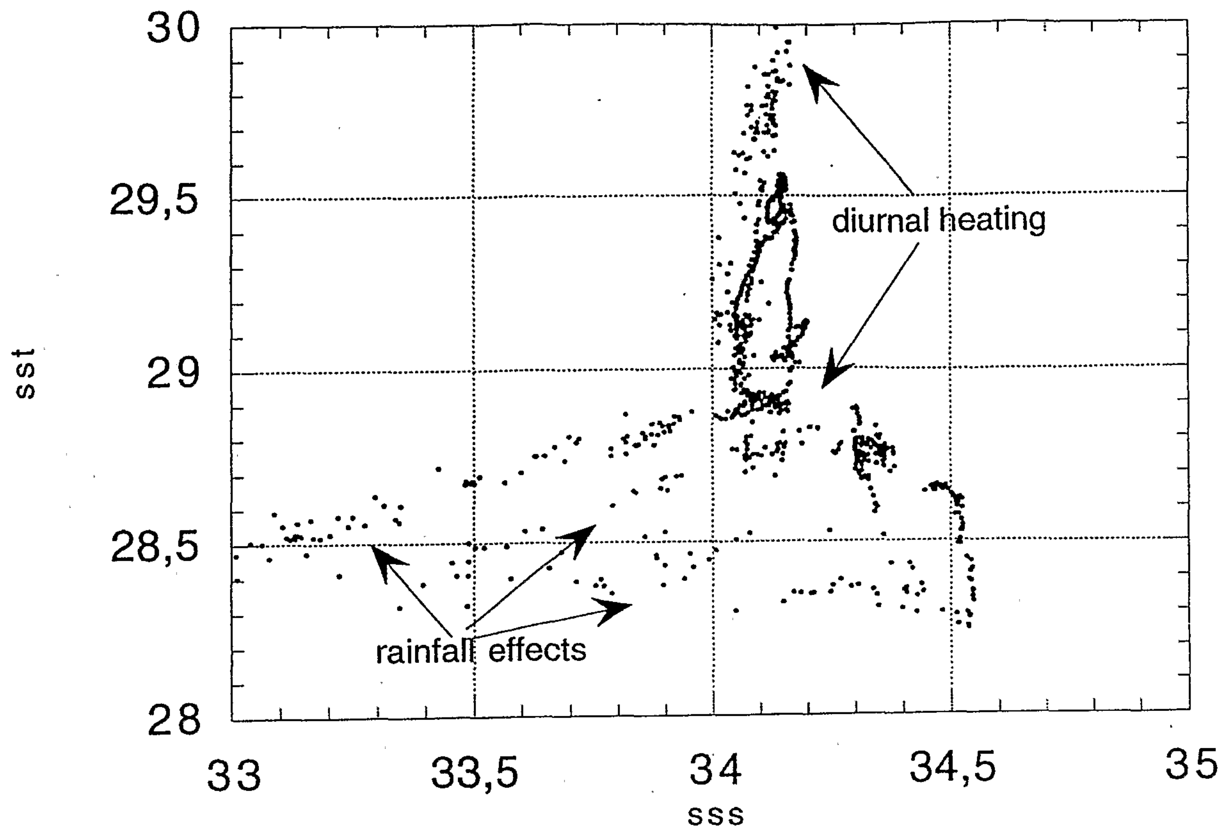
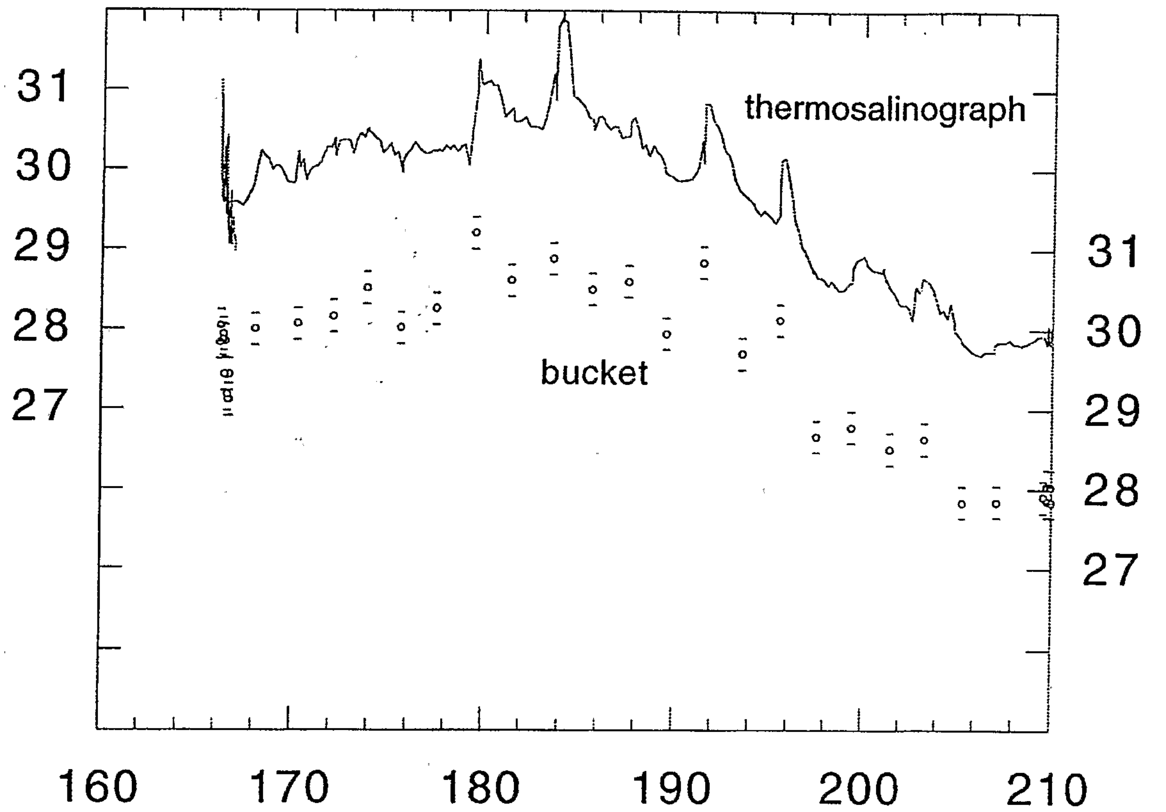


Fig. 11. Temperature/salinity diagram observed along 156°E on the 5°S–5°N section showing rainfall and diurnal heating effects (3–6 January 1993).

Zonal routes. We have available, in the region under study (the inter-tropical zone), two series of data derived from automated observations, one along the Equator between 170°E and 150°W during the Flupac cruise of R.V. *L'Atalante* in September–October 1994, and the other collected between Papeete (French Polynesia) and Noumea (New Caledonia), at tropical latitudes (17°S–22°S), by R.V. *L'Alis* in May 1995.

Along the Equator, a very large zonal surface salinity front was observed in October 1994 during the Flupac cruise (Fig. 12), with a sharp gradient near 172°W (33.8–34.5 west of 175°W and 35.2–35.3 east of 170°W), while during the Alizé-2 cruise in February 1991 the sea surface salinity was nearly constant (35.2–35.3) between 170°E and 150°W. The October 1994 observations reflect the El Niño event, with a large eastward displacement of the Warm Pool (SST maximum of more than 30°C near 175°W) but also an eastward extension of low salinity waters reaching 172°W. Local rainfall effects were also observed with low salinity peaks occurring mainly in the western part of the route. These new observations bring to light the eastward displacement of the Warm (but also Fresh) Pool during an El Niño event and the strong zonal salinity gradient on its eastern edge.

On the Papeete–Noumea tropical route, temperature variations of 1.2°C–1.8°C and salinity variations of 0.5 over a few nautical miles had been observed in 1981 with intensive bucket observations (Hénin *et al.*, 1981). During a recent cruise of R.V. *L'Alis* in May 1995 (Fig. 13), we observed a similar distribution with the thermo-salinograph. A decrease in temperature corresponded with an increase in salinity, which may have been due to northward intrusion of cold high salinity surface waters associated with the mesoscale eddy



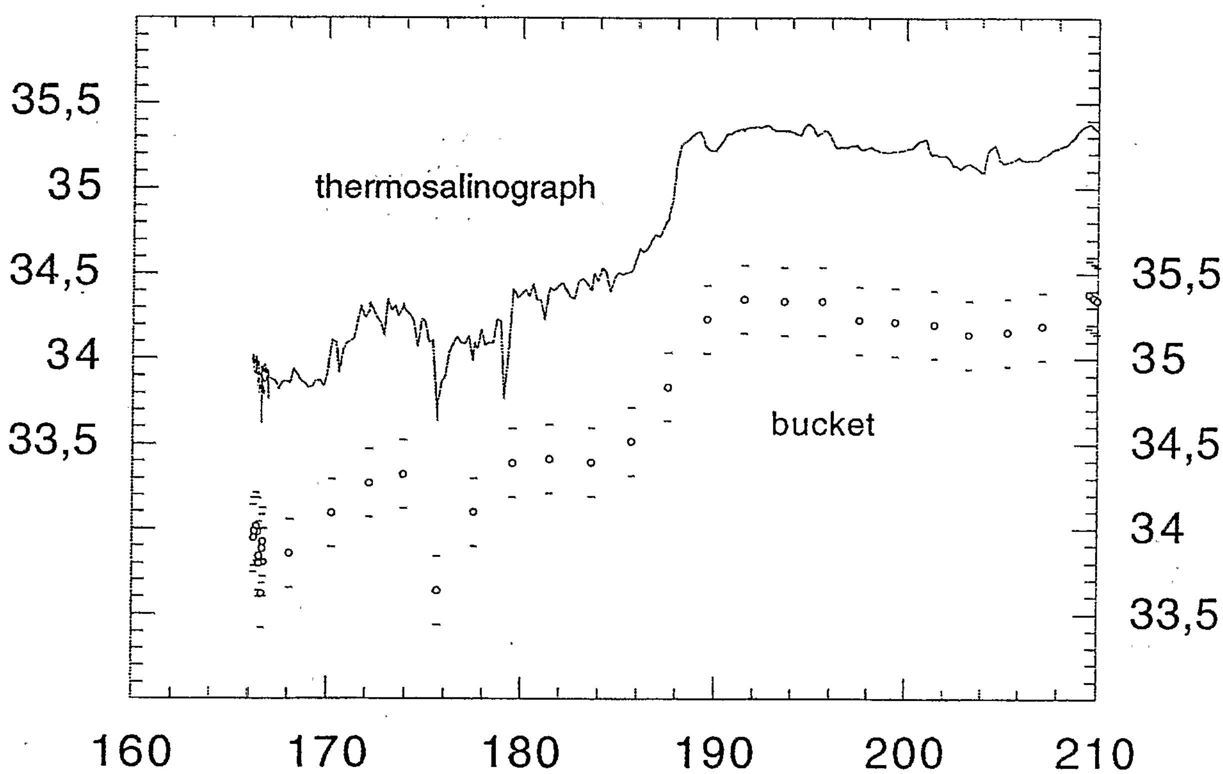


Fig. 12. Sea surface temperature (top) and sea surface salinity (bottom) distribution along the equator during the Flupac cruise (October 1994). Equivalent bucket sampling (every 6 h at a speed of 15–20 knots) with a ±0.2°C and ±0.2 envelope is also presented.

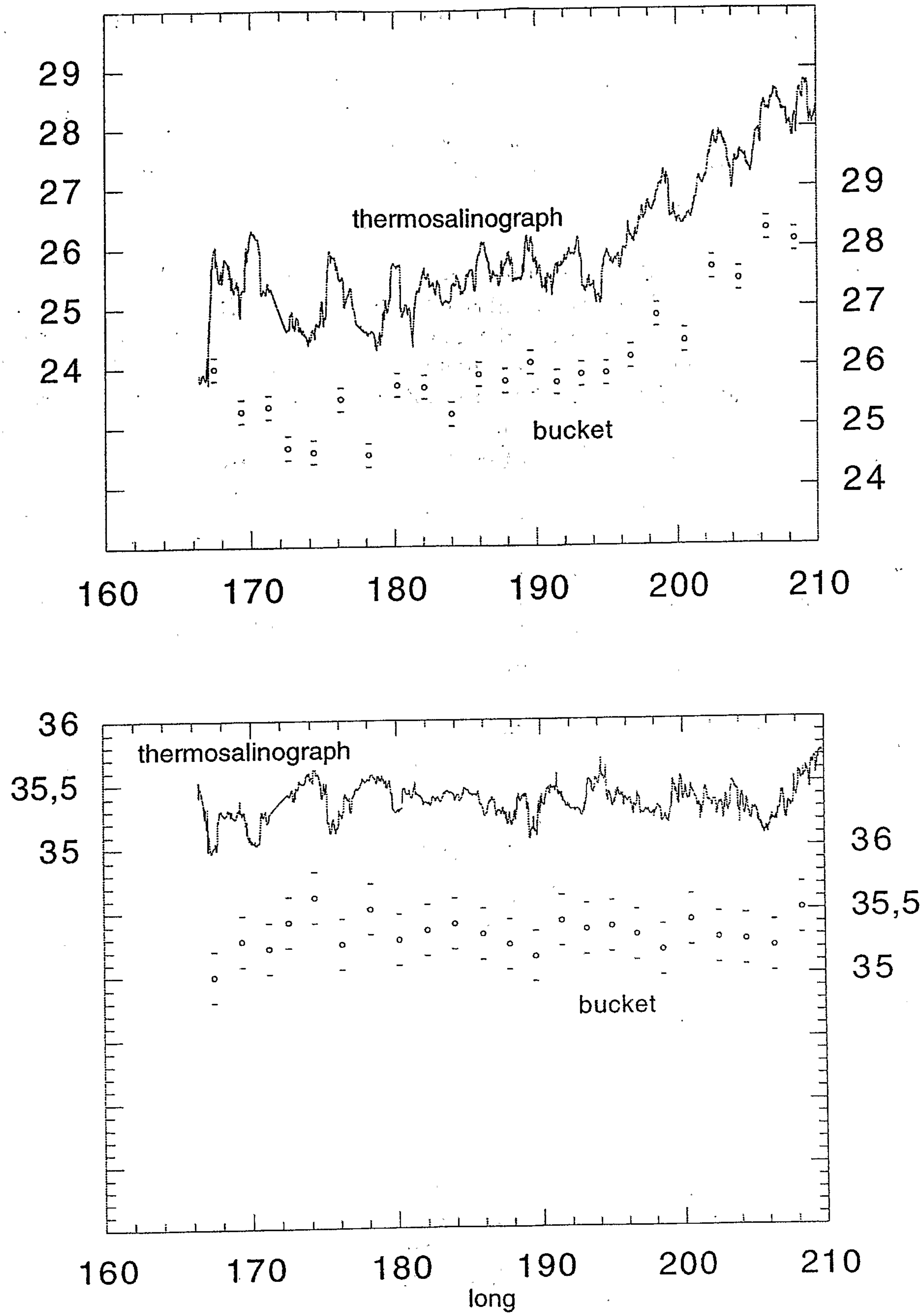


Fig. 13. Sea surface temperature (top) and sea surface salinity (bottom) distribution during R.V. *L'Alis* transit between New Caledonia and Tahiti (May 1995). Equivalent bucket sampling (every 6 h at a speed of 15–20 knots) with a ±0.2°C and ±0.2 envelope is also presented.

circulation. Variations in both SST and SSS were observed with a spatial decorrelation scale of a few hundred kilometers.

We simulate a traditional bucket sampling (every 6 h at a speed of 15–20 knots) in Figs 12 and 13. With the estimated bucket accuracy of 0.2 in salinity and 0.2°C in temperature, it is clear that the strong zonal salinity gradient along the equator and SST and SSS peaks associated with the tropical mesoscale circulation or diurnal heating are not so well observed with the bucket method.

Meridional routes. SST and SSS structures along nearly meridional merchant ship routes have already been described by Delcroix and Hénin (1991) and Porte (1992), respectively, on a 2° and 2.5° latitude grid and a time span of one month. They described the seasonal and the interannual variations, but the time and latitude grid was too large for the detection of detailed time and space variations. In the western Pacific, the influence of the convergence zones (ITCZ and SPCZ) on sea surface salinity through the rainfall they generate is manifest in the minima observed around 7°30′N (34.3) and 10°S (34.7), separated by a relative maximum around 2°30′S (34.8). The thermo-salinograph records now make it possible to observe fine sea surface structures along the shipping lines. As an example Fig. 14 presents the SST and SSS distribution (30 September–13 October 1993) along the Japan–Tarawa–Fiji line crossing the equator near 174°E. Low salinity was observed near 7°S (33.7) and 6°N (33.2). In addition to a few low salinity peaks caused by local rainfall over 10–30 nautical miles, we also observed some very pronounced sharp salinity fronts (for instance 0.6 and 1.1 over a few miles near 2°S and 4°N, respectively) which could not have been so well described with bucket sampling. Recent work using drifting buoys and SSS observations also suggests that zonal currents and equatorial upwelling may explain such SSS distribution (Hénin *et al.*, 1995).

CONCLUSION

The seasonal and interannual variability of SST and SSS are now established, and their consequences on mixing and oceanic circulation appear significant in the tropical oceans (Lukas *et al.*, 1991). Therefore an effort was made to get better *in situ* observations of these two parameters than those obtained from traditional bucket sampling with merchant ships. In spite of difficulties encountered during the experimental period, and using a limited number of ships, we were able to demonstrate that intensive automated sea surface monitoring with thermo-salinographs was indeed possible and that it improved substantially the accuracy of the data and the density of coverage along the tracks followed. Unfortunately, due to reduced financial support, the number of thermo-salinographs installed is still limited.

Some technical limitations exist (time responses and geometry of sensors) which prevent small scale observations. We have also shown that local rainfall may bring abrupt changes in the SSS and SST distribution. However, for our seasonal and interannual studies in the western Pacific this new thermo-salinograph network has revealed new structures, mainly on SSS distribution, related to current systems distribution.

We may hope that in the near future, real time transmission of the surface temperature and salinity data through satellite systems become operational and available for input into models.

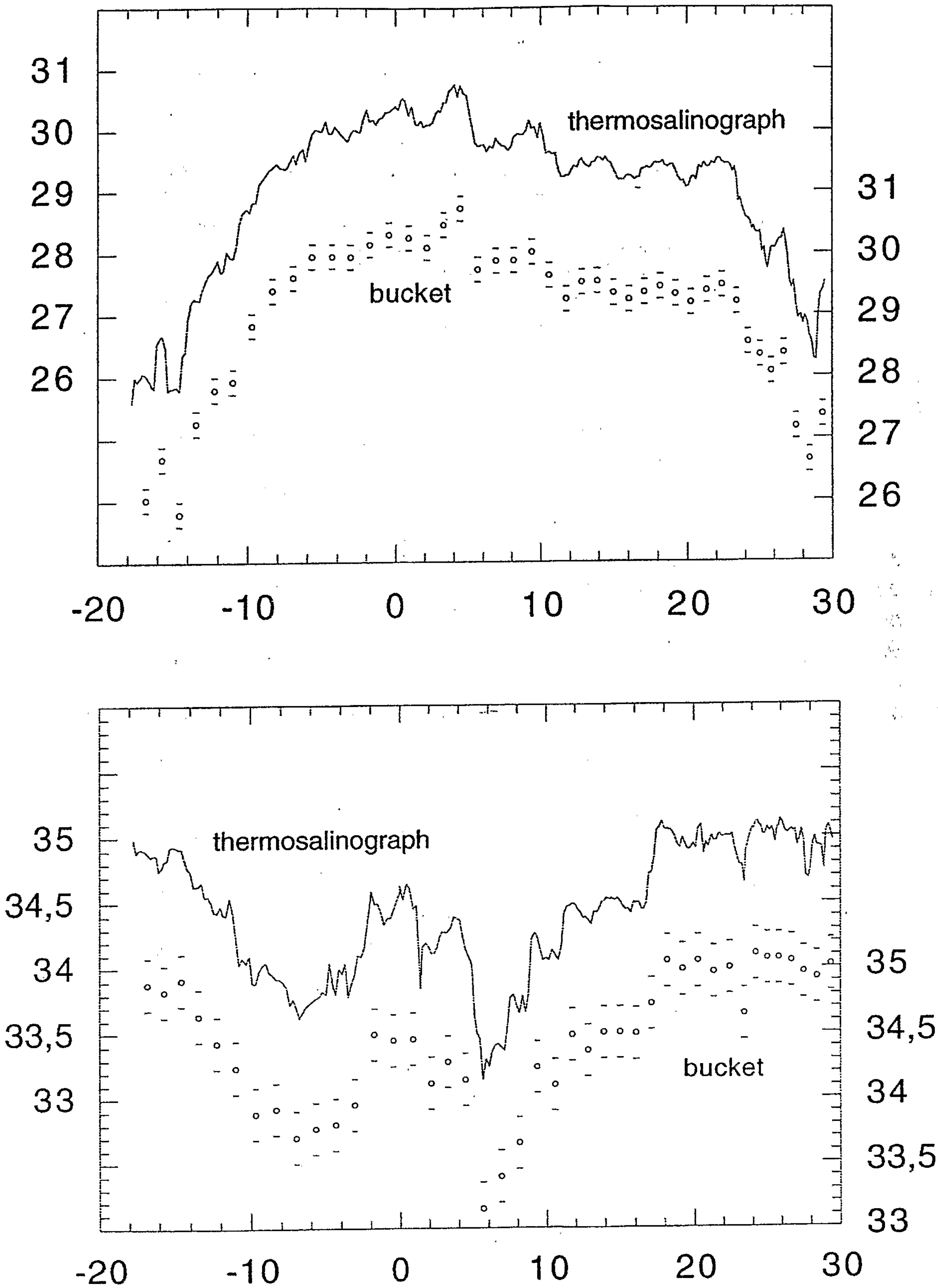


Fig. 14. Sea surface temperature (top) and sea surface salinity (bottom) distribution on the shipping route Japan–Tarawa–Fiji between 20°N and 20°S, measured by M.V. *Pacific Islander* (30 September–13 October 1993). Equivalent bucket sampling (every 6 h at a speed of 15–20 knots) with a ±0.2°C and ±0.2 envelope is also presented.

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