SEA SURFACE SALINITY
A REGIONAL CASE STUDY FOR THE TROPICAL PACIFIC

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ABSTRACT *- The tropical Pacific warm pool region is offered as a case study which might guide the design of regional surface salinity observing networks. The present scientific understanding is reviewed and requirements for surface salinity measurements in the warm pool are examined. This includes evidence that salinity anomalies affected the surface dynamic height by up to 5-10 cm in recent years. An analysis of spatial and temporal decorrelation scales indicates that 100 km and monthly resolution and 0.1 psu error is sufficient to resolve the climatologically important seasonal to interannual signals. It is evident that sample error from sparse in situ measurements will be on the order of 0.1-0.2 psu given the observed space-time variability. These errors are consistent with projected measurement errors from future satellite sensors. Satellites offer more systematic and higher space-time resolution sampling than can be achieved readily with in situ systems. We conclude that a robust surface salinity observing system within the next five years can be achieved with a modest investment to enhance the existing in situ network of ships, moorings and drifters in tandem with experimental satellites.*

1 - INTRODUCTION

It has been noted that sea surface salinity (SSS) and the vertical profile of salinity (S(z)) are among the fundamental variables for which global sustained observations are needed in CLIVAR (WCRP-IIP, 1998). In this report, we examine the need for SSS in more detail, which is found to an important variable in many parts of the ocean. Documentation about SSS changes in the tropical Atlantic ocean can be found in Dessier and Donguy (1994); in the tropical Indian Ocean in Donguy and Meyers (1996). In the subpolar North Atlantic, low frequency SSS events such as the Great Salinity Anomaly (Dickson et al, 1988) are believed to influence the large scale thermohaline convection. The emphasis in this report will be on the Tropical Pacific Ocean (TPO). This is because the SSS data set is most extensive there, and because recent discoveries reveal the dynamic and thermodynamic importance of upper layer salinity variations to ENSO. These are reported in several poster abstracts presented in this conference (Delcroix et al, 1999; Vossepoel et al, 1999; Maes et al, 1999). The deliberate neglect of other ocean regions, particularly in higher latitudes, is not a sign of lesser importance, but rather of the authors' more intimate knowledge and understanding of the TPO and the activity of present-day research there. We will present a rationale for a TPO SSS observing system, with attention paid to lessons learned from existing data, the important physical processes, and the space-time scales and amplitudes of the signals that must be observed. The intent is that this will serve as a prototype for designing an SSS observing network in other climatically important areas.

Another consideration for focusing on the tropics is the future availability of satellite SSS observations. It will be shown below that signals will be more easily detected by satellite sensors over warmer oceans than over colder oceans, resulting in a more favorable measurement signal to noise ratio in the tropics. High latitude oceans may need to rely more heavily on *in situ* SSS observations, and satellite observations there will require more extensive space-time averaging to reduce noise (Lagerloef, 1998). Likewise, careful calibration of a satellite system from a robust tropical *in situ* network will improve the satellite performance as it passes over the higher latitudes.

Webster (1994) has shown that the buoyancy flux contributions from the net surface heat flux and freshwater flux are about equal magnitude in the Indo-Pacific warm pool. This is in contrast to much of the remainder of the tropics where the relative heat flux contribution is considerably larger. The warm pool is also the region where surface freshwater flux induces a shallow salt stratification and a "barrier layer" that isolates the surface from the main thermocline with important consequences for surface layer heating (Lukas and Lindstrom, 1991; Anderson et al, 1996). The dynamical importance is evident in Fig. 1 (from Maes and Behringer, 1999), which shows the influence of neglecting upper layer salinity anomalies in estimating dynamic height from temperature profiles. Comparison with TOPEX/Poseidon sea level shows that errors of 5-10 cm are possible in the warm pool when only the historical T-S relationship is applied. During the period 1995-1997, a negative salinity anomaly caused the true dynamic height to be less than would be found with the mean T-S relation, and the actual heat storage was greater than would be indicated in the observed sea level change from thermosteric effects. A developing capability to estimate S(z) in the warm pool using SSS with vertical EOFs and surface height (Maes and Behringer, 1999) suggests that SSS offers an important piece of information to describe the warm pool dynamics.

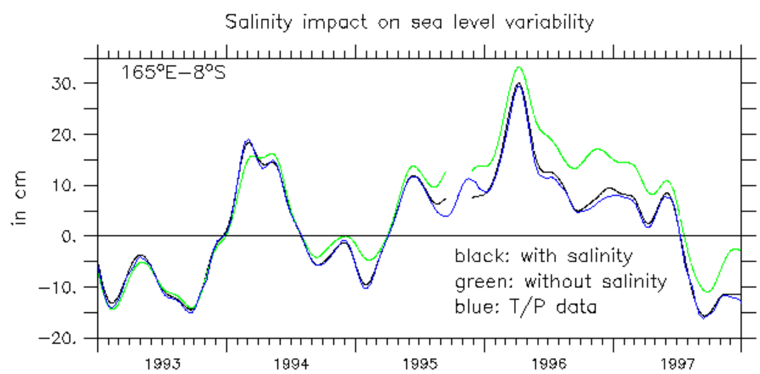


Fig. 1: Time series of dynamic height with (dark curve) and without (upper light curve) salinity variability, compared with TOPEX/Poseidon (lower light curve) (from Maes and Behringer, 1999).

2 - OVERVIEW AND IMPLICATIONS OF SSS CHANGES IN THE TROPICAL PACIFIC

2.1 - High-frequency and small-scale SSS variability

The highly zonally, meridionally (both 0.02 deg. resolution) and temporally (1 hour resolution) resolved TSG measurements from Volunteer Observing Ships (VOS) and Tropical Atmosphere Ocean (TAO) moorings can be used to evaluate the scales of SSS variability. The autocorrelation functions of unfiltered data collected in the western tropical Pacific are shown in Fig. 2 for: (a) a zonal section along the equator in October 1994 (Henin et al., 1998), (b) a meridional section from Fiji to Japan in August 1996 (Delcroix et al., 1998), and (c) a time series at 0°-156°E in 1993-94 (Cronin and McPhaden, 1998). These functions, which are representative of frequently encountered situations in the warm pool, indicate that the decorrelation scales for SSS are of the order of 4 deg. longitude, 3° deg. latitude, and 2-3 months. A closer look at Fig. 2 also reveals the existence of sharp meridional, zonal and temporal fronts of the order of 2 psu per degree longitude, 1 psu per degree latitude and 1 psu per 15 days.

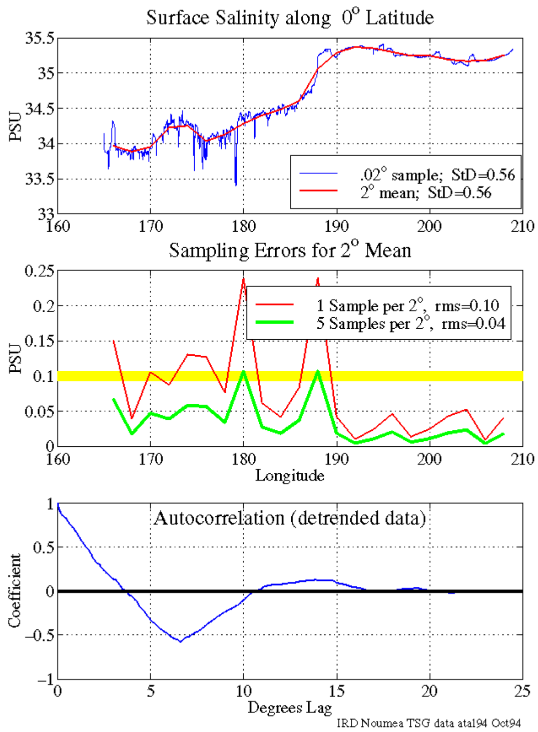


Fig. 2a: Top: zonal SSS section along equator; middle: sample errors; bottom: auto-correlation function.

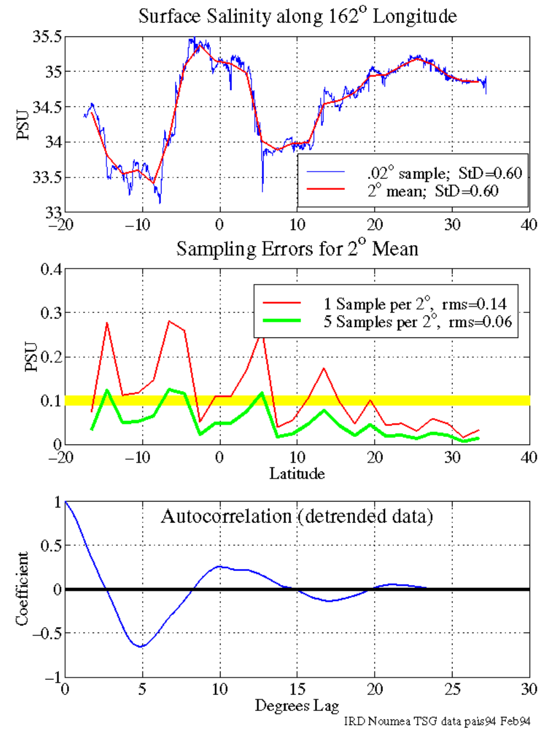


Fig. 2b: Same as Fig. 2a for a meridional section.

2.2 - Low-frequency and large-scale SSS variability

A monthly gridded SSS field was assembled using a combination of bucket, TSG and CTD data (Delcroix, 1998). The 1979-92 mean and standard deviations of SSS are shown in Fig. 3. Low-salinity waters are observed near the Inter Tropical Convergence Zone (ITCZ), near the South Pacific Convergence Zone (SPCZ), and in the western Pacific warm pool. The maximum variability is located in both convergence zones, and near the eastern edge of the warm pool at the equator (between 150°E-160°W). An EOF analysis (not shown here) reveals that the variability in the convergence zones occurs chiefly at seasonal time scale, in relation to seasonal changes in precipitation and zonal advection of the North and South Equatorial Counter Currents, and to a lesser extent at the ENSO time scale, in relation with the equatorward (poleward) shift of the ITCZ and SPCZ during El Niño (La Niña). An EOF analysis was performed on low-passed data (1 cycle per year and higher frequencies removed) to focus on the interannual variability. The temporal function (not shown) is in phase with the Southern Oscillation Index (SOI). The spatial pattern (Fig. 4) clearly reveals a sharp decrease (increase) of SSS in the equatorial band

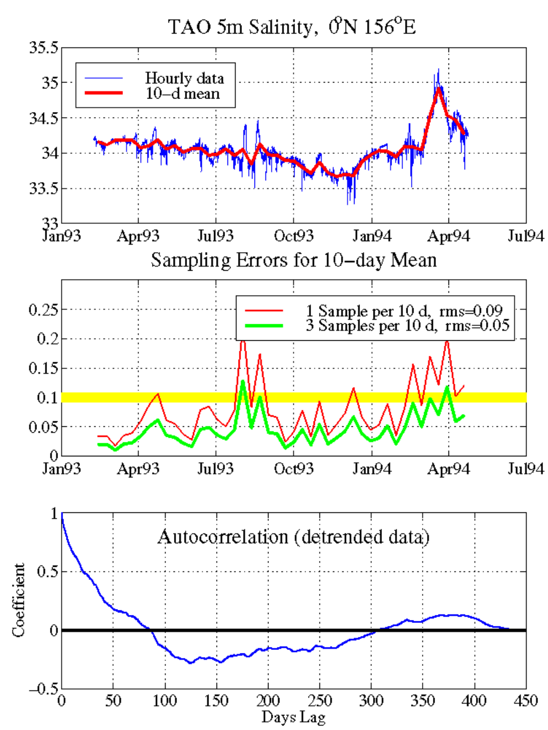
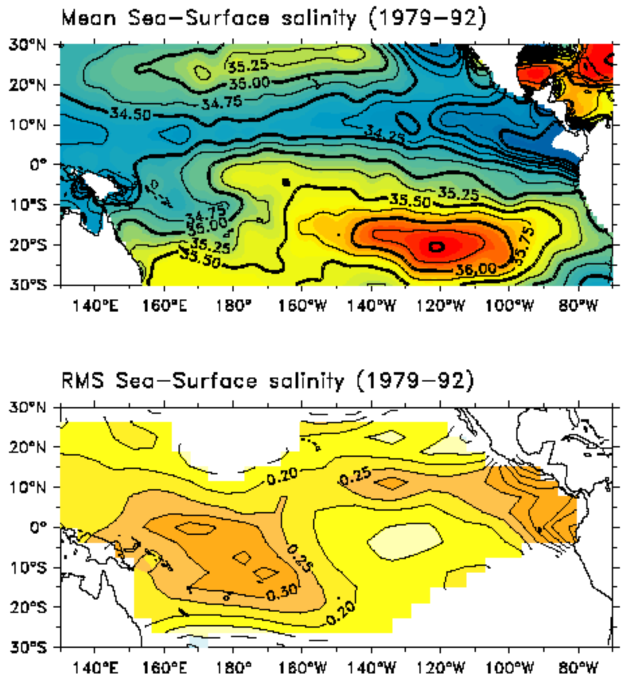


Fig. 2c: Same as Fig. 2a except for a time series at 0, 156E.

near the dateline during El Niño (La Niña) events. Similar features were observed as well during the recent years, as exemplified from the TSG data collected along the Fiji-Japan shipping track across the warm pool (Delcroix et al., *this issue*).



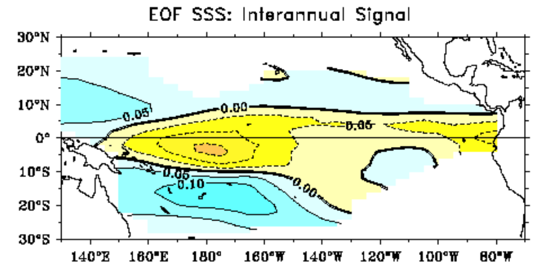


Fig. 4: Spatial pattern of the interannual EOF in SSS. The time function (not shown) is in phase with the SOI. (Adapted from Delcroix, 1998).

Fig. 3: (a) Mean and (b) standard deviation of SSS, calculated from monthly values for the 1979-92 period

Observational and modeling results (Delcroix and Picaut, 1998; Hénin et al., 1998; Picaut et al., 1996, 1999) indicate that the equatorially-trapped interannual variability owes its existence to the zonal displacements of the eastern edge of the warm pool in response to zonal current anomalies. Moreover, the eastern edge of the warm pool is characterized by strong zonal salinity fronts (e.g., Fig. 2) resulting from the zonal convergence of relatively cold and high-salinity waters from the east towards warm and low-salinity waters from the west (Picaut et al., 1996). Such a convergence results in the subduction of the eastern surface waters below the western surface waters (Kuroda and McPhaden, 1993), and it is one of the main mechanisms responsible for the formation of the "barrier layer" which could play a role in ENSO (Lukas and Lindstrom, 1991; Vialard and Delecluse, 1998). Interestingly, the zonal salinity front on the eastern edge of the warm pool is associated with a sharp increase in pCO_2 (Inoue et al., 1996), and its zonal displacement at the ENSO time scale is connected with the zonal displacement of the world's most important tuna fishery (Lehodey et al., 1997). The multiple consequences of the zonal front for ENSO and biogeochemical phenomena are discussed in Picaut et al. (1999).

2.3 - Using SSS to estimate variability in salinity profiles

An ideal observing system should provide information on salinity profiles S(z) as well as SSS because notable salinity changes occur in the upper 300 m (Fig. 5). Mean T-S curves have been used to infer knowledge of S(z) from more numerous temperature profiles (Helland-Hansen, 1918; Stommel, 1947). This classical method assumes T-S curves to be stable, which is generally not often the case in the warm pool, as exemplified in Fig. 6. Various methods were developed to make use of mean T-S curves and

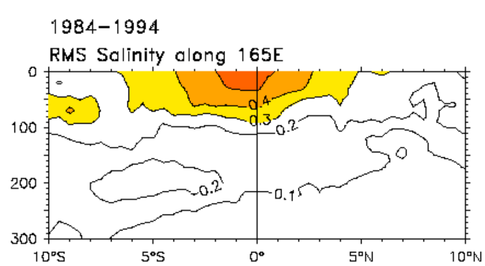


Fig. 5: Salinity standard deviation along the 165°E longitude from 42 sections during 1984-1992. (Adapted from Delcroix and Picaut, 1998).

SSS to improve estimates of salinity profiles (Kessler and Taft, 1987; Hansen and Tackler, 1998). A more recent method makes use of EOFs to reconstruct temperature and salinity profiles from their signature in the surface dynamic height anomaly (Maes, 1999). In all these methods, the inclusion of SSS has a marked improvement on the reconstruction of salinity profiles, particularly in the upper 100 m, with RMS error of the order of 0.1-0.2 psu (compare Figures 7a-7b in Maes, 1999).

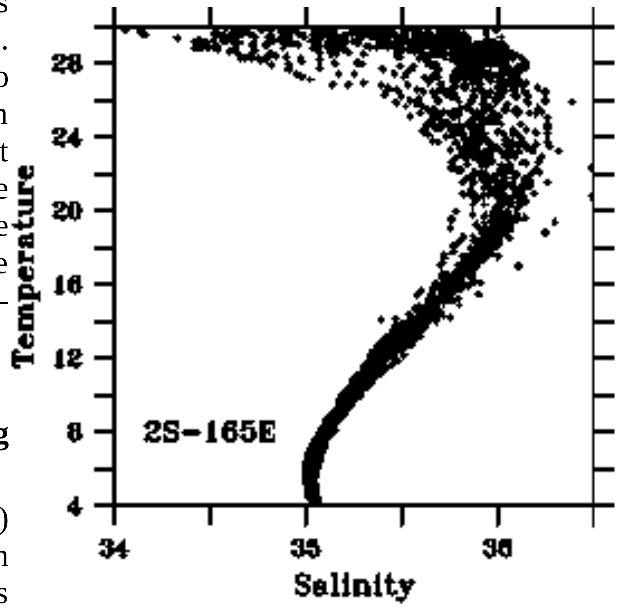


Fig. 6: Variations of T-S curves at 2°S-165°E.

2.4 - Using salinity to improve ocean modeling and ENSO prediction

To our knowledge, the variability of SSS and S(z) is presently not adequately reproduced in ocean models, especially in regions of sharp spatial fronts such as the eastern edge of the warm pool. Salinity however plays an important role in model dynamics and thermodynamics. In a recent paper, Murtugudde and Busalacchi (1998) demonstrated that including salinity effects in the tropical Pacific results in an improved cold tongue simulation which reduced the zonal SST gradient along the equator and thus will have significant influence in a coupled ocean-atmosphere system. Also, Acero-Schertzer et al. (1997) demonstrated that the lack of salinity control in the NCEP model results in major discrepancies between near-surface modeled and observed currents, a defect which is particularly relevant in the warm pool where zonal advection is a major mechanism of ENSO (Picaut and Delcroix, 1995).

Efforts to exploit altimeter-derived sea level anomalies for improving ENSO prediction have been underway for few years (Chen et al., 1998; Ji et al., 1999). Assimilation of TOPEX/Poseidon data is done by correcting the temperature field in contemporary assimilating prediction models because subsurface temperature is a key factor which contributes to the ENSO prediction skill. Sea level anomalies however reflect the combined role of temperature and salinity, especially in the warm pool where salinity changes alone can induce sea level changes of the order of 5-10 cm (Fig. 1). As discussed by Ji et al. (1999), the strong salinity signal occurring during the onset phase of ENSO in 1996-97 (Delcroix et al., 1998) could markedly impact the accuracy of ENSO prediction in their model. As noted above, the actual heat storage differs from what would be indicated in the observed sea level change from thermosteric effects alone. Methods to optimally combine sea level anomalies, temperature profiles from VOS and TAO, T-S relationship and SSS are currently underway to assess their usefulness to data assimilation and ENSO prediction (Maes et al., 1999; Maes and Behringer, 1999; Troccoli and Haines, 1999).

3 - ELEMENTS OF THE PRESENT AND FUTURE *IN SITU* SSS OBSERVING SYSTEM

The seasonal distribution of all SSS measurements obtained from station measurements and S/CTD sensors (see Levitus et al., 1994; their Figures F1, F7, F13, F19) clearly evidences the poor time/space resolution of this type of data, even though they have been collected since the beginning of the century. Such a resolution enables one to compute only climatological mean values, and at best a monthly mean climatology in specific and limited regions (e.g., Levitus, 1986). In the early years of the TOGA program, most of our knowledge about seasonal and interannual SSS changes in the tropical Pacific originated from water samples collected in buckets along merchant ship tracks (Donguy and Hénin, 1976; Delcroix and Hénin, 1991; Donguy, 1994). The space-time distribution of the resulting data set is shown in Delcroix et al. (this issue). The bucket network was gradually abandoned in the middle of TOGA years, and it was progressively replaced by a merchant ship thermosalinograph (TSG) network (Hénin and Grelet, 1996), which improved the accuracy (0.02 instead of 0.2 psu), the along-track resolution (every 5 minutes instead of 6 hours), and the availability of SSS data (real time transmission since mid-98 instead of 2-3 months delay with the bucket sampling). Together with the TSG measurements collected from the research vessel maintaining the TAO/TRITON moorings, the merchant ship TSG network now provides routine SSS measurements for the tropical Pacific. The distribution of the measurements for 1997 is shown in Fig. 7 (similar in 1998-1999), and details about the TSG network and data are given in Delcroix et al. (this issue; see also http://noumea.ird.nc/ECOP). The continuing cost for maintaining the present TSG network is ~$30K per year in equipment and about 3.5 man years in salary.

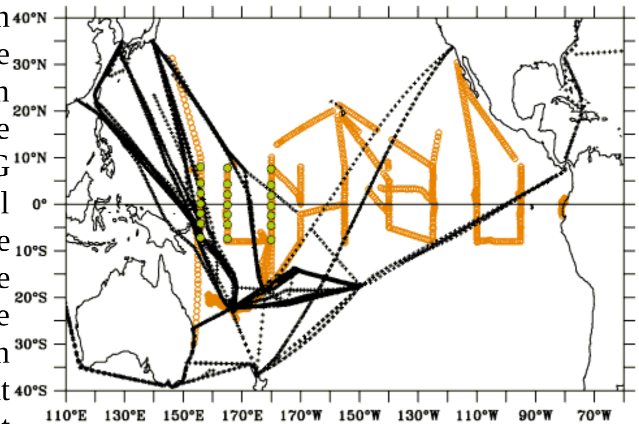


Fig. 7: Typical yearly distribution of shipborne thermosalinograph lines and TAO moorings with SSS during 1997-1999.

The figure also indicates the ~20 TAO/TRITON mooring locations (between 156°E and 180°E) with SSS sensors maintained presently by France (IRD/Noumea), Japan (JAMSTEC) and USA(NOAA/PMEL). Some of these records have been in place since 1992 and used to study the temporal evolution of warm pool SSS on various time scales (Cronin and McPhaden, 1998). JAMSTEC will be deploying additional TRITON moorings with salinity sensors to the west of these within the next few years. Several additional moorings along the equator and in the eastern Pacific (not shown) temporarily carry salinity sensors sponsored by the NASA TRMM program. An extensive description of the TAO observing system, including recommendations for salinity observations, is given by McPhaden (*this issue*).

Autonomous drifting buoys represent another possible platform for SSS measurements. The proposed ARGO system (Roemmich et al, *this issue*) will transmit an S(z) profile about once every 10 days with a mean spacing of about 300 km once the network is fully deployed. The surface velocity program (SVP) deploys ~150 surface drifters in the tropical Pacific every year (Niiler, *this issue*). No salinity data are recorded from these at present. However, experimental salinity sensors were successfully deployed on some buoys in 1992-1993. It is feasible to include specially designed salinity sensors on surface drifters in the future at a unit cost of about $2K. Thus, the ~150 or so drifters deployed in the tropical Pacific each year can be enhanced for a incremental hardware cost of $300K/year. The major technical issue to be addressed is maintaining calibration stability over ~1 year life of the drifter.

4 - FUTURE CONTRIBUTION OF SATELLITE SSS REMOTE SENSING

4.1 - Relative merits

Satellite SSS remote sensing technology is advancing rapidly and has potential to be a major asset to the Tropical Pacific SSS Observing System in the middle of the next decade. The obvious advantages offered by a satellite system are the spatial and temporal resolution with systematic global repeat sampling. In the case of SSS, the optimal resolution will be ~40 km and 3 days, but 100-300 km and 10-30 day averaging will be required because of the expected large measurement noise. Other advantages of satellite measurements are near-real time data distribution and understandable error covariance properties which will facilitate operational ocean model assimilation efforts. It is important to recognize that a satellite system will not work optimally as a stand-alone, but rather in tandem with a robust *in situ* network where the satellite provides high resolution sampling and the *in situ* system offers, among other unique advantages, a resource for routine stability monitoring and bias correction of the satellite data. Such a combination has a very successful heritage today for objectively analyzed SST fields using *in situ* data and satellite infrared sensors (Reynolds and Smith, 1994).

4.2 - Space and time scales and sampling

The necessary time and space resolution scales will vary depending on the scientific questions and the relevant physical processes as discussed above. Nevertheless, some indicators to guide the choice of resolution scales are the natural decorrelation scales of SSS variability in the tropics. Using an SSS time series for the TAO mooring at 0°-156°E, and several VOS transects in the Pacific warm pool, decorrelation scales are estimated to be ~70-90 days temporal and 3-4° spatial (Fig. 2), based on the zero crossing of the autocorrelation function. Signal strengths as indicated by the standard deviations range from 0.4 to 0.6 psu. Presently, the proposed GODAE accuracy requirement for satellite SSS is specified for a 10 day and 2°x2° resolution requirement. This represents 7-9 samples within the decorrelation time scale and 1-2 in the spatial scale, giving relatively much higher temporal than spatial resolution with respect to these estimated scales of variability. Similar retrieval error can be obtained with either 10 day and 2°x2° averages or with ~30 days and 1°x1° averages from a generic satellite sensor whose footprint is ~40 km and revisit time is 3 days. The advantage with the latter may be to provide more balanced spatial-temporal resolution in the western pacific warm pool; about 3 samples within the respective decorrelation scales. A different balance of spatial and temporal filtering may be more suitable in other regions. It appears that 1°x1° or finer spatial resolution is an important scientific requirement for the warm pool SSS, and accordingly, satellite observations represent a potentially fundamental contribution to the observing system.

The remaining issue concerns observational error at the specified resolution. A relative assessment of errors associated with *in situ* versus satellite is made considering both measurement and sampling error. Measurement error is defined here as the difference between a value measured from a sensor and the true value. For *in situ* observations, measurement errors are small (~.01 psu or less) as long as calibration procedures are adopted. On the other hand, measurement error with satellite SSS sensors may range from ~0.1->1 psu, depending on averaging scales and other factors. Sampling error is defined here as the uncertainty of a single measurement within a particular space-time interval as representing the mean over that interval, given the space-time variability. This is estimated here for the GODAE resolution requirement by calculating the standard deviation over 10 day blocks in the TAO time series and 2 degree blocks in the ship transects described above (Fig. 2). The sampling errors sometimes approach .3 psu, while the root sum square (rss) of all the blocks within the respective time or space dimensions are consistently about 0.1 psu. An rss of all three dimensions (time, lat and lon) combined implies a sampling error of sqrt(3*.1^2), or about .17 psu for one observation in a 2°x2° square every 10 days. This potential sampling error is much larger than the *in situ* measurement error and can be considered as the only important *in situ* error source in designing the observing system.

The resolution of a generic satellite system allows 3 samples per 10 days and 5 samples per 2° transect, with respective temporal and spatial sample errors of ~.05 psu respectively. The rss combined 3-dimensional error plus a 0.1 psu measurement error is about 0.13 psu. This is comparable to, and perhaps slightly better than, the uncertainty of a single *in situ* observation, given the observations and assumptions presented here. This conclusion, however, assumes satellite sensors will deliver 0.1 psu accuracy on the indicated space-time scales.

4.3 - Principles of SSS remote sensing

The physical basis for SSS remote sensing is that microwave brightness temperature (Tb) is proportional to salinity, among several other factors that require correction. A complete discussion is found in Klein and Swift (1977), Swift and McIntosh (1981) and Lagerloef et al. (1995). A recent example of a successful survey of the lower Chesapeake Bay with an aircraft system is given by Miller et al (1998). The salinity effect increases as the microwave frequency decreases, and the practical threshold is at about 1-3 Ghz. A band centered at 1.413 GHz is chosen because it is protected from radio interference for astrophysical research. The SSS model function, shown in Fig. 8, illustrates a near linear Tb/SSS relationship for a given SST. The largest Tb signal per SSS will be found in the warmest latitudes, making the SSS retrieval accuracies highest in the tropics. Note that the Tb range is only about 4 K over the range of open ocean conditions and radiometers will need unprecedented accuracy to resolve oceanic signals. Present-day satellite microwave radiometers do not have the required low frequency channels, and it is necessary to build a specialized satellite radiometer for this purpose. The major engineering constraint is that the antenna aperture must be made larger as the measurement frequency is made lower in order to maintain a specified surface footprint size.

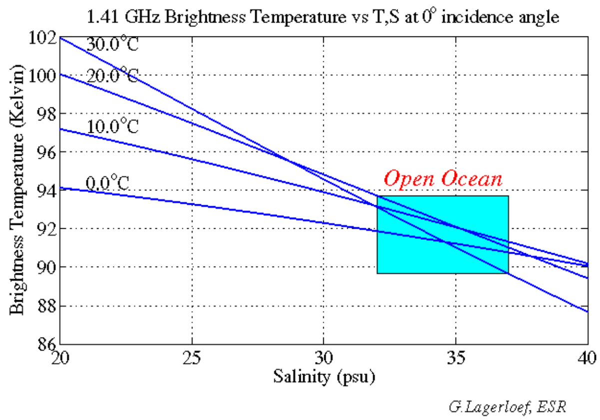


Fig. 8: The model of Tb and SSS at nadir view for different surface temperatures. Shaded area indicates the range of open ocean conditions.

4.4 - Candidate satellite systems

4.41 - SMOS (Soil Moisture Ocean Salinity): This satellite mission proposal was approval by the European Space Agency (ESA) in June 1999 (see http://www-sv.cict.fr/cesbio/smos) and a collection of posters is presented at this conference (Font et al., 1999 and Boutin et al., 1999). The sensor is a Y-shaped array, 2-D interferometric, 1.4 GHz, dual polarization radiometer (Fig. 9). The orbit will be 6am/pm helio-synchronous at an altitude of 757 km, and the mission is planned for 3-5 year duration. SMOS is designed to address terrestrial hydrology and ocean science, as the name implies. The flexible interferometric imaging geometry allows for higher spatial resolution imaging over land and larger scale multi-beam averaging over the ocean to reduce measurement noise. The ground resolutions will vary from about 30 to 90 km. Ocean retrieval and image reconstruction algorithms will be quite complicated and some technical obstacles must be overcome. The ultimate SSS accuracy requires further simulation studies to be resolved, and the work is in progress. The anticipated launch year is 2004 or 2005.

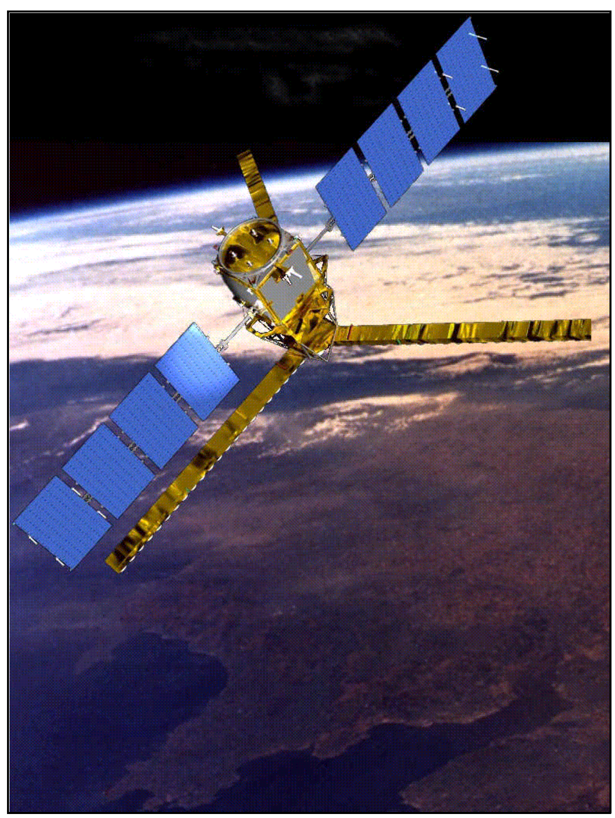


Fig 9: Soil Moisture Ocean Salinity (SMOS) satellite concept (ESA).

4.42 - OSIRIS (Ocean salinity Soil moisture Integrated Radiometric Imaging System) is a large mesh antenna design under development at NASA/JPL and described in the conference poster (Njoku et al. 1999a). OSIRIS is designed with the primary objective of obtaining ocean salinity retrievals, as well as soil moisture, with the highest possible measurement accuracy using current technology. The philosophy is to use a high gain, real aperture antenna to attain a low noise, well calibrated, multi-channel radiometer system with the necessary ancillary measurements to correct important sources of geophysical error such as SST, surface roughness and ionosphere (Njoku et al, 1999b). Large aperture mesh antenna designs have been developed by aerospace companies for microwave telecommunications, are light weight, and can be adapted to passive microwave radiometry. OSIRIS includes a conical scanning ~6 m antenna and constant incidence angle viewing geometry that will allow forward and backward beams to be averaged with a spot resolution of ~40 km (Fig. 10). The baseline radiometer will measure both 1.4 and 2.7 GHz (L&S-band) with H&V and HV (Stokes-3) polarization using a flexible design that makes it relatively inexpensive to add channels. An optional L-band radar for wind and sea state correction is also being evaluated. Antenna beam efficiency is expected to exceed 95%. The flexible bandwidth over the ocean can be employed to reduce the rms noise per pixel to~0.1 K (about 0.2-.3 psu salinity error).

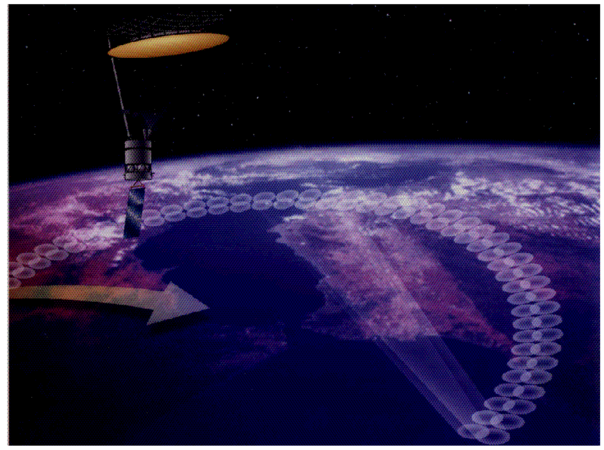


Fig 10: The Ocean Salinity Soil moisture Integrated Radiometric Imaging System (OSIRIS) satellite concept (NASA/JPL).

A satellite SSS mission will cost nominally about $100M, and the mission life will be about 5 years, giving an annual average cost of $20M/year. This does not take into account the 3-5 years needed to build and launch the satellite, when the actual funds would mostly be expended. Given that the data have strong scientific value for soil moisture and sea ice studies not discussed here, it can be assumed that the cost share for ocean climate is some fraction of these amounts; perhaps ~50%, or ~$10m/year. In assessing the relative merit of satellites in terms of cost for an observing system, it should be kept in mind that the space agency funds will go to other types of earth observing satellites if they are not secured for measurements relevant to ocean climate, and it is therefore important to advocate strongly where the needs are well established.

4.5 - Simulations of satellite SSS retrieval accuracy

Simulation studies of the OSIRIS system by S. Yueh (Njoku et al, 1999), including geophysical corrections, show accumulated measurement errors over 1°x1° scales for 30 day averages are ~0.1 psu in the tropics and 0.1 to 0.2 psu globally (Fig. 11). As noted above, measurement errors will be similar for 2°x2° and 10 day averages. Fig. 12 shows a tropical Pacific SSS anomaly in the Parallel Ocean Circulation Model (POCM) for a 10-day period, averaged by 2°x2°. Adjacent to that is an OSIRIS retrieval simulation by S.Yueh (unpublished) where the major large scale features of the anomaly remain quite evident embedded in the system noise. Retrieving the 0.1 psu accuracy level will be more challenging for SMOS than OSIRIS because of a variety of factors, including the complexity of the SMOS interferometric design, the required convolution algorithms, the range of viewing angles and the lack of S-band channels and L-band radar to correct for SST and wind effects. Similar simulations for SMOS are not yet available. In general, such studies help determine whether satellite SSS measurement accuracies of ~0.1-0.2 psu are feasible at the space-time scales needed to resolve scientifically important tropical Pacific SSS signals.

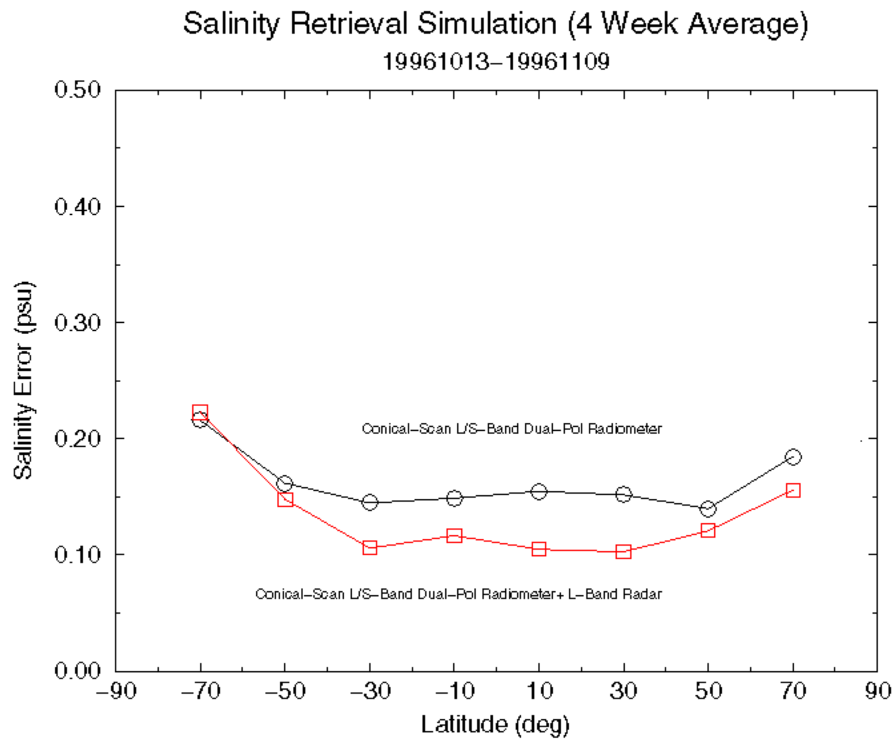


Fig. 11: Simulated global OSIRIS SSS measurement error versus latitude for 100 km and 30 day averages. Lower curve includes active radar for surface roughness corrections. (Courtesy S. Yueh, NASA/JPL).

5 - SUMMARY

The TPO, in particular the western warm pool, is a region where salinity variations have an important influence on upper layer dynamics and thermodynamics, with implications on ENSO modeling and prediction. It has been shown that upper layer salinity profiles can be estimated with SSS data combined with EOF basis functions and surface height (altimeter) data. Salinity corrections are critical to apply altimeter height data properly to initialize heat storage in an ocean model, considering that otherwise height errors can be as large as 5-10 cm.

Salinity Retrieval Simulation (10 Day Average) – 19961105

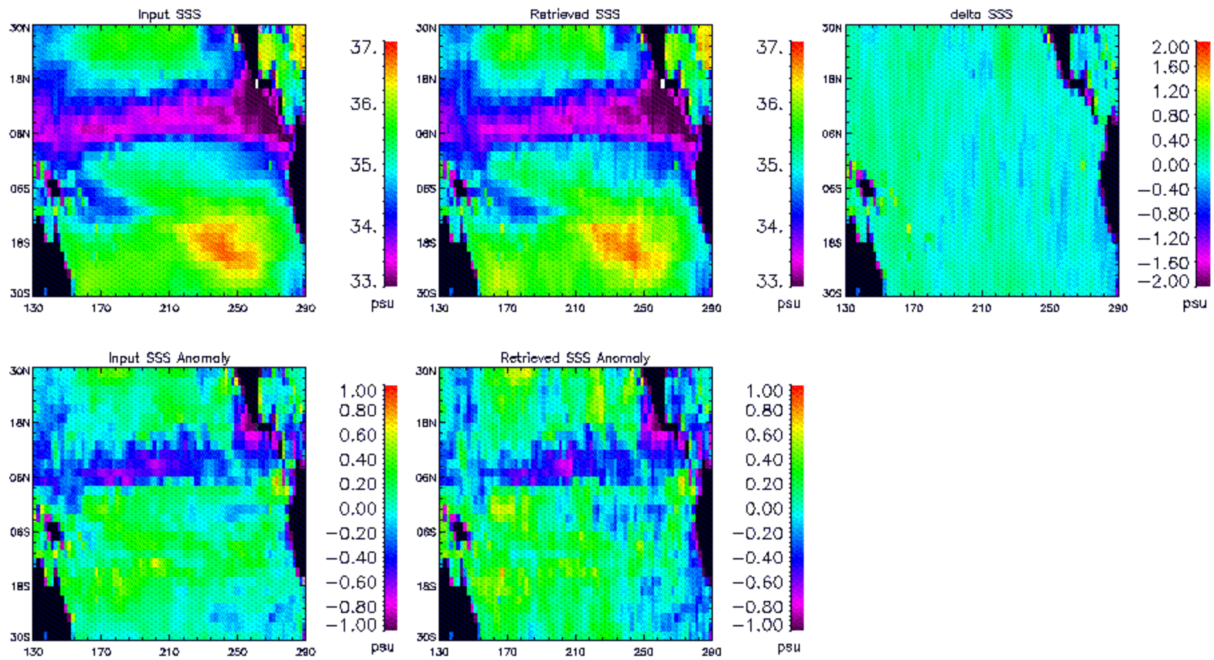


Fig. 12: SSS and SSS anomaly fields (left panels) for a 200 km 10 day average from the POCM4c ocean model (courtesy R. Tokmakian), the OSIRIS retrieval simulation (middle panels) and the difference (right panel). Courtesy S.Yueh (NASA/JPL).

Accordingly, considerations for a TPO SSS observing system are presented above with the intent that it may also serve as an example for other regions where SSS variability is important. In the warm pool, sampling is well balanced between space and time decorrelation scales (~300 km and 90 days, respectively) with approximately 100 km and 30 day resolution. The proposed GODAE resolution requirement of 200 km and 10 days represents relative undersampling in space and oversampling in time according to the observed scales. Errors on the order of 0.1 psu are adequate to resolve the important seasonal to interannual patterns. Sampling errors in a variable field from sparse measurements at the aforementioned scales are typically ~0.1 psu and may approach 0.3 psu. Measurement errors from satellite are projected to be ~0.1-0.2 psu. Satellites have the advantage of uniform, systematic sampling and high resolution, but space-time filtering will be required to reduce measurement error to these acceptable levels. *In situ* systems provide long time series monitoring, characterization of subgrid space and time scale variations along available ship tracks and at available moored time series respectively, and an essential resource for satellite calibration.

A multi-platform *in situ* system (ship tracks, moorings and drifters) is clearly preferable over a stand-alone platform. Ship tracks and moorings provide the essential information on space and time scales as shown above, as well as extended time series, while a drifting array (surface drifters and ARGO) will be needed to fill in the gaps between fixed ship tracks and mooring sites. The TPO SSS observing system presently has some essential *in situ* elements in place; namely the VOS TSG tracklines, and a number of TAO moorings with salinity sensors. However, the sampling remains very sparse and certainly inadequate to resolve the space-time decorrelation scales (Fig. 2 and 7). The advent of ARGO will improve the sampling rate considerably in both space and time. The component that has received less attention is the surface drifter program. It is recommended that stable calibrated autonomous salinity sensors be designed for the surface velocity drifters and implemented during the next few years.

Satellite SSS measurements will likely be available in the next half decade. Two satellite concepts, SMOS and OSIRIS, are relatively advanced in their design, and SMOS is an approved project in ESA. Other concepts exist that are not discussed here. SMOS has many technical challenges with its interferometric design. The ultimate SSS retrieval errors cannot be predicted reliably at present and need to be addressed. The relatively simple OSIRIS design allows retrieval simulation studies to predict that errors will be ~0.1 psu in the tropics when averaged to 100 km and 30 day scales. Satellites, in principle, will be able to resolve the important space and time scales with errors similar to or perhaps less than the sampling error of any foreseeable *in situ* network, but will not achieve this accuracy without perpetual calibration from *in situ* data. The satellite and *in situ* components together offer the optimal SSS observing system for climate studies in tropical Pacific, and this assessment is undoubtedly applicable to other regions as well.

REFERENCES:

[Acer 97] Acero-Schertzer C., D. Hansen, and M. Swenson: Evaluation and diagnosis of surface currents in the National Centers for Environmental Prediction's ocean analyses, *J. Geophys. Res., 102*, 21037-21048, 1997.

[Ande 96] Anderson, S.P., R.A. Weller and R. Lukas: Surface buoyancy forcing and the mixed layer of the Western Pacific warm pool: Observations and 1-D model results, *J. Climate*, 9, 3056-3085, 1996.

[Bout 99] Boutin, et al:Conference poster abstract, *this issue*, 1999.

[Chen 98] Chen D., M. Cane, S. Zebiak and A. Kaplan: The impact of sea level data assimilation on the Lamont model prediction of the 1997/98 El Nino, *Geophys. Res. Let*., 25, 2837-2840, 1998.

[Cron 99] Cronin M. and M. McPhaden: Upper ocean salinity balance in the western equatorial Pacific, *J. Geophys. Res.*, 103, 27,567-27587, 1999.

[Delc 91] Delcroix T. and C. Hénin: Seasonal and interannual variations of sea-surface salinity in the tropical Pacific ocean, *J. Geophys. Res*, 96, 22135-22150, 1991.

[Delc 98] Delcroix T.: Observed surface oceanic and atmospheric variability in the Tropical Pacific at seasonal and ENSO time scales: a tentative overview, *J. Geophys. Res*, 103, 18611-18633 , 1998.

[Delc 98b] Delcroix T., L. Gourdeau and C. Hénin: Sea surface salinity changes along the Fiji-Japan shipping track during the 1996 La Niña and 1997 El Niño period, *Geophys. Res. Letter*, 25, 3169-3172, 1998.

[Delc 98c] Delcroix and J. Picaut: Zonal displacement of western equatorial Pacific fresh pool, *J. Geophys. Res.,* 103, 1087-1098, 1998.

[Delc 99] Conference poster abstract, *this issue*, 1999.

[Dess 94] Dessier A. and J.R. Donguy: The sea-surafce salinity in the tropical Atlantic between 10°S and 30°N - seasonal and interannual variations (1977-1989). Deep Sea Res., 1, 81-100, 1994.

[Dick 88] Dickson, R.R., R. Meincke, S.-A. Malmberg and J.J. Lee: The 'Great Salinity Anomaly' in the Northern North Atlantic, 1968-1982, *Prog. Oceanogr.* 20, 103-151, 1988.

[Dong 76] Donguy, J. R., and C. Hénin: Relations entre les précipitations et la salinité de surface dans l'océan Pacifique tropical sud-ouest basées sur un échantillonnage de surface de 1956 à 1973, *Annales Hydrographiques*, *4*, 53-59, 1976.

[Dong 94] Donguy, J.R.: Surface and subsurface salinity in the tropical Pacific ocean. Relations with climate, *Progr. Oceanogr.*, *34*, 45-78, 1994.

[Dong 96] Donguy J.R. and G. Meyers: Seasonal variations of sea-surface salinity and temperature in the tropical Indian ocean, *Deep Sea Res.*, 43, 117-138, 1996.

[Font 99] Font et al: Conference poster abstract, *this issue*, 1999

[Heni 96] Hénin C. and J. Grelet: A merchant ship thermosalinograph network in the Pacific ocean, *Deep Sea Res.*, *11-12*, 1833-1856, 1996.

[Heni 98] Hénin C., Y. duPenhoat and M. Ioualalen: Observations of sea surface salinity in the western Pacific fresh pool: large scale changes in 1992-1995, *J. Geophys. Res.*, 103, 7523-7536, 1998.

[Inou 96] Inoue, H., M. Ishii, H. Matsueda, and M. Ahoyama: Changes in longitudinal distribution of the partial pressure of CO2 (pCO2) in the central and western equatorial Pacific, *Geophys. Res. Lett.*, 14, 1781-1784, 1996.

[Ji 99] Ji M., R.W. Reynolds, and D.W. Behringer: Use of TOPEX/POSEIDON sea level data of ocean analyses and ENSO prediction: some early results, *J. Climate*, in press, 1999.

[Hans 99] Hansen D. and W. Tackler: estimation of salinity profiles in the upper ocean. J. Geophys. Res., 104, 7921-7933, 1999.

[Hell 18] Hellan-Hansen B.: Nogen hydrografiske metoder. Foeh; Skand. Naturforskeres, 16, Kristiania , 1918.

[Kess 87] Kessler, W., and B. Taft: Dynamics heights and zonal geostrophic transports in the central tropical Pacific during 1979-1984, *J. Phys. Oceanogr.*, *17*, 97-122, 1987.

[Klei 77] Klein, L.A. and C.T. Swift: An improved model for the dielectric constant of sea Water at microwave frequencies, *IEEE Trans. Antennas and Prop.*, AP-25(#1), 104-111, 1977.

[Kuro 93] Kuroda, Y., and M. McPhaden: Variability in the western equatorial Pacific ocean during Japanese Pacific Climate Study cruises in 1989 and 1990. *J. Geophys. Res.*, *98*, 4747-4759, 1993.

[Lage 95] Lagerloef, G., C. Swift and D. LeVine: Sea surface salinity: The next remote sensing challenge. *Oceanography*, 8, 44-50, 1995.

[Lage 98] Lagerloef, G.: Final Report of the First Workshop Salinity Sea Ice Working Group (SSIWG) Preliminary Assessment of the Scientific and Technical Merits for Salinity Remote Sensing from Satellite, *Unpublished manuscript*, <http://www.esr.org/lagerloef/ssiwg/ssiwgrep1.v2.html>, 1998

[Leho 97] Lehodey, P., M. Bertignac, J. Hampton, A. Lewis and J. Picaut: El Niño Southern Oscillation and tuna in the western Pacific. *Nature,* 389, 715-718, 1997.

[Levi 86] Levitus S.: Annual cycle of salinity and salt strorage in the world ocean. J. *Phys. Oceanogr.*, 16, 322-343 , 1986.

[Levi 94] Levitus, S., R. Burgett, and T. P. Boyer: World Ocean Atlas 1994, Volume 3; Salinity. NOAA Atlas, NESDIS 3, U.S. Dept. of Commerce, Washington, D.C., 97 pages, 1994.

[Luka 91] Lukas, R., and E. Lindström: The mixed layer of the western equatorial Pacific ocean. *J. Geophys. Res.*, *96*, 3343-3358, 1991.

[Maes 99] Maes, C.: A note on the vertical scales of temperature and salinity and their signature in dynamic height in the western Pacific Ocean. Implications for data assimilation. *J. Geophys. Res*., 104, 11037-11048 , 1999.

[Maes 99b] Maes, C., D. Behringer, R. W. Reynolds, and M. Ji: Retrospective analysis of the salinity variability in the western tropical Pacific Ocean using an indirect minimization approach. *J. Atmos. Oceanic Technol.*, in press, 1999.

[Maes 99c] Maes C. and D. Behringer: Using satellite-derived sea level and temperature profiles for detremining the salinity variability: a new approach. Submitted to *J. Geophys. Res*, 1999.

[Maes 99d] Conference poster abstract, *this issue*, 1999.

[Mill 98] Miller, J., M. Goodberlet and J. Zaitzeff: Airborne salinity mapper makes debut in coastal zone, EOS Trans. Am. Geophys. Union, 79, 173 & 176-177, 1998.

[Murt 98] Murtugudde, R., and A. J. Busalacchi: Salinity effects in a tropical ocean model. J. Geophys. Res., 103, 3283-3300, 1998.

[Njok 99a] Njoku et al: Conference poster abstract, *this issue*, 1999.

[Njok 99b] Njoku, E. W. J. Wilson, S. H. Yueh, and Y. Rahmat-Samii: A Large Antenna Microwave Radiometer-Scatterometer Concept for High-Resolution Surface Sensing, Submitted to *IEEE Trans. Geosci. Remote Sensing*, 1999b.

[Pica 95] Picaut, J., and T. Delcroix: Equatorial wave sequence associated with the warm pool displacement during the 1986-1989 El Niño and La Niña. *J. Geophys. Res., 100*, 18,393-18,408, 1995.

[Pica 96] Picaut J., M. Ioualalen, C. Menkes, T. Delcroix and M.J. McPhaden: Mechanism of the zonal displacements of the Pacific Warm Pool, implications for ENSO, *Science*, 274, 1486-148, 1996 9.

[Pica 99] Picaut J., M. Ioualalen, T. Delcroix, F. Masia, R. Murtugudde, and J. Vialard: Displacements of an oceanic zone of convergence on the eastern edge of the Pacific Warm Pool: consequences for ENSO and bio-geochemical phenomena, *J. Geophys. Res*., submitted, 1999.

[Reyn 94] Reynolds, R.W. and T.M. Smith: Improved global sea surface temperature analysis using optimal interpolation. *J. Climate*, 7, 929-948, 1994.

[Stom 47] Stommel, H. M.: Note on the use of T-S correlation for dynamic height anomaly computations. *J. Mar. Res.*, 6, 85-92 , 1947.

[Troc 99] Troccoli, A., and K. Haines: Use of T-S relation in a data assimilation context. *J. Atmos. Oceanic Technol.*, in press, 1999.

[Vial 98] Vialard, J. and P. Delecluse: An OGCM study for the TOGA decade. Part I: Role of salinity in the physics of the western Pacific fresh pool, *J. Phys. Oceanogr*., 28, 1071-1088, 1998.

[Voss 99] Vossepoel et al: Conference poster abstract, *this issue*, 1999.

[Webs 94] Webster P.: The role of hydrological processes in ocean-atmosphere interactions, Rev. Geophys., 32-4, 427-476 , 1994.