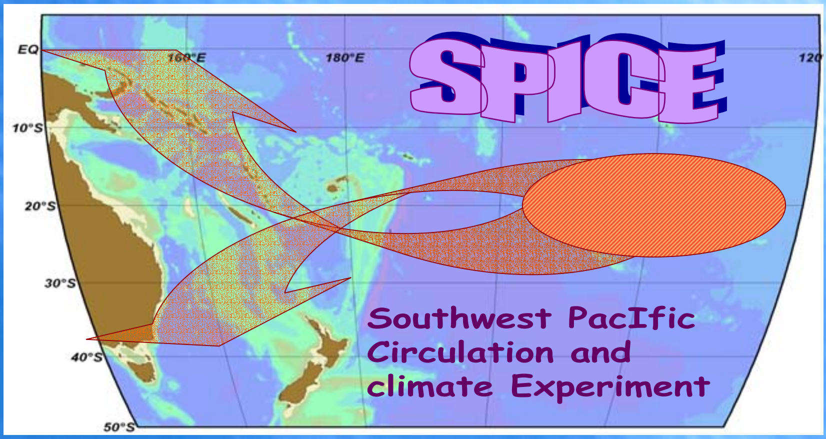

Southwest PacIfic ocean Circulation and climate Experiment

"Workshop on the Southwest Pacific Ocean Circulation
and its relation with climate"

Cairns, Australia
Friday 19 August 2005~Sunday 21 August 2005

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1. Introduction

Attention has focused on circulation in the southwestern Pacific because of its position athwart a major pathway from the subtropics to the equator. These pathways are of great interest because changes in either the temperature or the amount of water arriving at the equator have the potential to modulate the ENSO cycle and thereby produce basin-scale climate feedbacks (Gu and Philander 1997; Kleeman et al. 1999; Schneider et al.1999). Both observational (Tsuchiya 1981; Tsuchiya et al. 1989) and model tracer studies (Blanke and Raynaud 1997; Izumo et al. 2002; Fukumori et al. 2004) suggest that a substantial fraction of the water arriving at the equatorial cold tongue has passed through the western boundary current system of the South Pacific. Other model tracer experiments suggest that the bulk of the transport feeding the Indonesian Throughflow also passes through this region (Inoue and Welsh 1993; Blanke et al. 2002), and observational evidence confirms that at least the lower thermocline to deep water masses of the Throughflow originate in the South Pacific (Talley and Sprintall, 2005). Thus an overriding physical oceanographic issue in the southwest Pacific is how the inflow from the subtropical gyre is redistributed meridionally to the equator and beyond as it arrives at the western boundary.

A substantial literature exists in the North Pacific, where equatorwards oceanic currents are limited by the dynamical barrier imposed by the Inter-Tropical Convergence Zone (ITCZ). No such barrier exists in the less documented South Pacific, from which up to 70% of the Equatorial UnderCurrent (EUC) waters are believed to originate (e.g. Blanke and Raynaud, 1997; Johnson and McPhaden, 1999). Recent numerical analyses, forced and data-assimilated, suggest that ENSO decadal modulation mainly originates from the South Pacific. Geise et al. (2002) found, for instance, that thermocline waters formed near the centre of the South Pacific subtropical gyre propagated spiciness anomalies (temperature anomalies along isopycnals) to the equator via complex pathways through the Southwest Pacific Ocean. Anomalies of 0.5°C affected the equatorial sea surface temperature (SST) in about 10 years (see also Yeager et al. (2004) and Luo et al. (2005)). As shown by Schneider (2004), decadal spiciness anomalies in EUC waters on the equator in a coupled ocean-atmosphere model have a significant influence on the amplitudes of El Niño and La Niña.

Despite its apparent importance to the climate system, few observations are available to diagnose the processes and pathways of transport through the complicated geography of the southwest Pacific. The region is remote and difficult to work in, and the large temporal variability and strong narrow currents in a very complex bathymetry pose serious challenges to an observing system. Numerical model results are sensitive to the parameters and forcing, and the results are highly impaired by the lack of validation against in situ data. For instance there is a dilemma between a direct (through the ocean interior) link and an indirect (through western boundary currents) link to the equatorial region, each having a very different impact on equatorial SST (Fukomori et al., 2004; Lee and Fukomori, 2003; McCreary and Lu, 1994). Furthermore, observations have shown that the equatorward thermocline transports in the ocean interior have changed in the past decades (McPhaden and Zhang, 2004), but no one knows how western boundary currents affect this change.

To the south, the western boundary current is the East Australia Current (EAC) and forms the predominant dynamical feature in the region. Its circulation is complicated by the numerous islands, deep basins and ridges that form a complex topography at the southwest Pacific Ocean boundary. The long-term average picture of the EAC develops following the South Equatorial Current (SEC) bifurcation and is observed along the eastern coast of Australia from 18º to 35ºS. The main portion of the EAC separates from the coast at ~32ºS, and either recirculates northwards or flows eastward across the Tasman Sea (as the Tasman Front). Further components of the northward retroflection form a broad, shallow northeastward flow, the Subtropical Counter-Current (STCC). A portion of the Tasman Front reattaches to the northern coast of New Zealand, forming the East Auckland Current and a sequence of permanent eddies. The residual of the EAC transport continues southward along the Australian coast as far as Tasmania and then turns westward into the eastern Indian Ocean

The existing observational network (ARGO, VOS XBT sampling, and satellite winds and altimetry) is beginning to provide a large-scale picture, but the complex circulation and western boundary currents require further dedicated study. This document is a first step in planning such an effort (the Southwest PacIfic ocean Circulation and climate Experiment, or SPICE), and synthesizes discussions of a workshop that was held in Malanda, Australia, August 19-21, 2005 (http://www.ird.nc/UR65/SPICE). The main aim of SPICE is to integrate both observational and modelling analysis in order to provide a more complete description of the mean and variable circulation in the Southwest Pacific Ocean and its importance to the climate system. The document is organized in six parts. Firstly, a background section presents current knowledge on the mechanism, origins and variability of the circulation; it is followed by four sections corresponding to specific research foci (Bifurcation and jets; East Australian Current; North Coral Sea and Impacts and Outreach); and the last section "integration" gives the baseline for a coordinated oceanographic program in the Southwest Pacific.

2. Objectives

The main objective of SPICE is to *understand the role of the Southwest Pacific in the transmission of decadal climate signal to the equatorial and Tasman region*. To achieve this objective we will focus on four goals:

1. Understanding the inflow to the Coral Sea and the bifurcation dynamics
2. Understanding the dynamics of the EAC, Tasman Front and the STCC
3. Understanding the circulation in the North Coral Sea
4. Understanding the feedback between coastal island dynamics and the large scale flow

3. Ocean Circulation and variability

The SEC inflow to the Coral Sea occurs in three jets determined principally by the location of the islands of Fiji, New Caledonia and Vanuatu (Figure 1); these are the South Caledonian Jet (SCJ, 24°S), the North Caledonian Jet (NCJ, 18°S) and the North Vanuatu Jet (NVJ) at 13°S. The NCJ bifurcates on the east coast of Australia, feeding both the EAC and the New Guinea Coastal Current (NGCC) system. The NGCC supplies the Equatorial Undercurrent and emerges as the east Pacific cold tongue (Butt and Lindstrom, 1994).

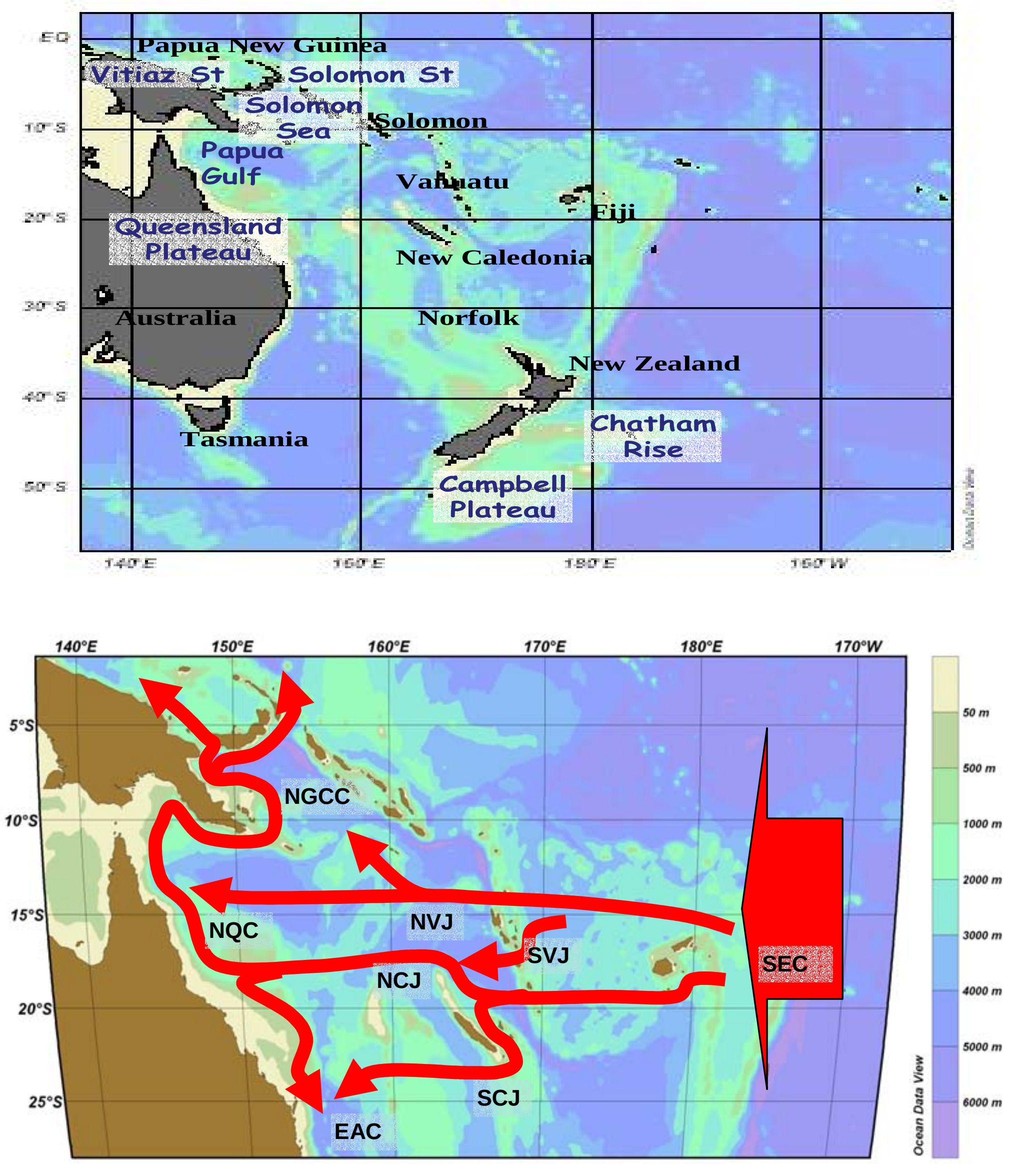

Figure 1 : (upper): Topography of the South West Pacific Circulation (lower) Sketch of the thermocline water current system. Complex pathways divide the southern part of the South Equatorial Current (SEC) into jets : North/South Vanuatu Jet (NVJ/SVJ), and South/North Caledonian Jet (NCJ/SCJ). Those jets feed the western boundary current system: the East Australian Current (EAC), North Queensland Current (NQC) and New Guinea Coastal Current (NGCC) before feeding the Equatorial Undercurrent to the North, through the Solomon Straits.

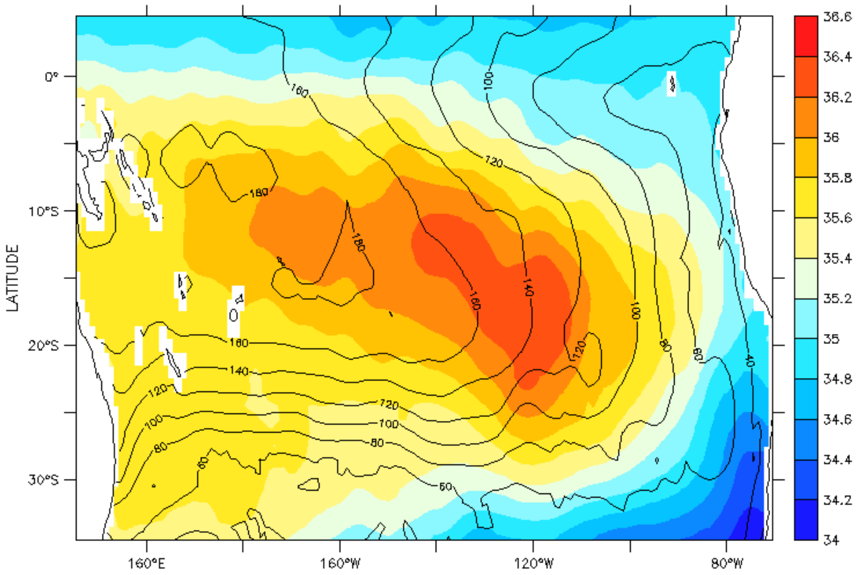

Figure 2 : Salinity on isopycnal σ=25.5 (color) and isopycnal depth (contours). σ=25.5 corresponds to the core of the EUC.

In the CARS climatology, the geostrophic transport relative to 2000m of the jets feeding the Coral Sea total about 35 Sv, roughly equally distributed (Figure 1, upper). The jets have subsurface maxima (from 100m in the north to 250m in the south), with eastward shear above, due to the downward tilt to the south of the entire gyre. The eastward surface flow extends to about 15°S, broken into filaments by the islands and jets. This eastward tendency is the STCC, due to the peeling off of isotherms above the main thermocline, and consequent shallow eastward shear (Reid 1986; Qu and Lindstrom 2002). This reflects the general tilt of the subtropical gyre, with the deepest point of 20°C near 14°S, of 15°C near 22°S, of 10°C near 27°S, and of 5°C near 32°S at 1100m depth. Above these centers of the gyre bowl, eastward shear weakens or reverses the westward SEC. In the vertical integral, the gyre center in the western Pacific is near 30°S, but the tilt means that some of the eastward limb of the gyre occurs as shallow flows north of 30°S. A first approach to understand thermocline water circulation is to integrate the flow below the Ekman layer. In the Southwest Pacific, the flow is driven by both Sverdrup dynamics, and interaction with islands. The wind stress pattern in the South Pacific is comparable to that of other subtropical gyres with a complication due to the presence of the South Pacific Convergence Zone (SPCZ). Kessler and Gourdeau (2006) showed that jets dynamically appeared even without islands. The, meridional variation of the large scale wind curl solely triggers the jet formation (Figure 3), and flow interaction with islands (Fiji, Vanuatu, New Caledonia) is assumed to stabilize and enhance those jets (Nakano and Hasumi, 2005) through the island rule (Godfrey, 1989).

The thermocline water originates from "South Pacific Eastern Subtropical Mode Water" (SPESMW, Hanawa and Talley, 2001) that forms in the middle of the Southeast Pacific gyre (south half of the high salinity patch on Figure 2). In this region, water acquires its high salinity essentially through diapycnal mixing due to winter erosion of a strong vertical salinity gradient, rather than subduction (Johnson, Generation and initial evolution of a mode water ∇-S anomaly, submitted manuscript, 2005; Yeager and Large (2004)). SPESMW then propagates to the west, forming the core of the SEC with salinities in excess of 36PSU.

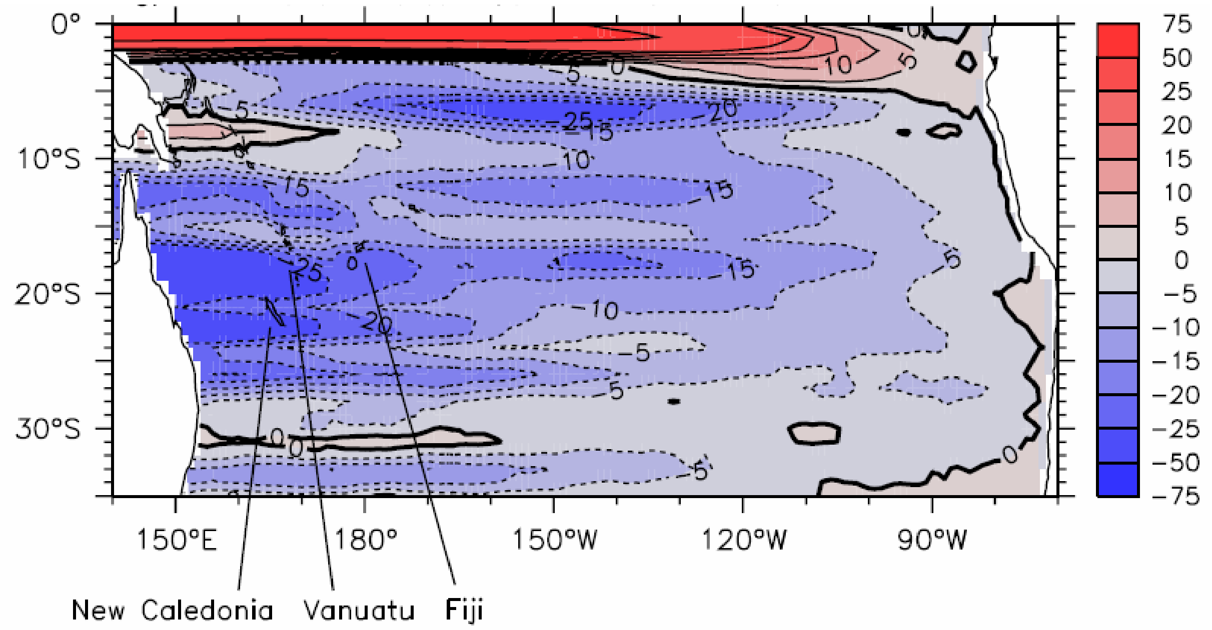

Figure 3 : Zonal Sverdrup transport (m^2/s^2) calculated from ERS satellite winds over 1991-2002 (From Kesser and Gourdeau, 2006). The three island groups are indicated, nevertheless the Sverdrup transport calculation assumed they were absent.

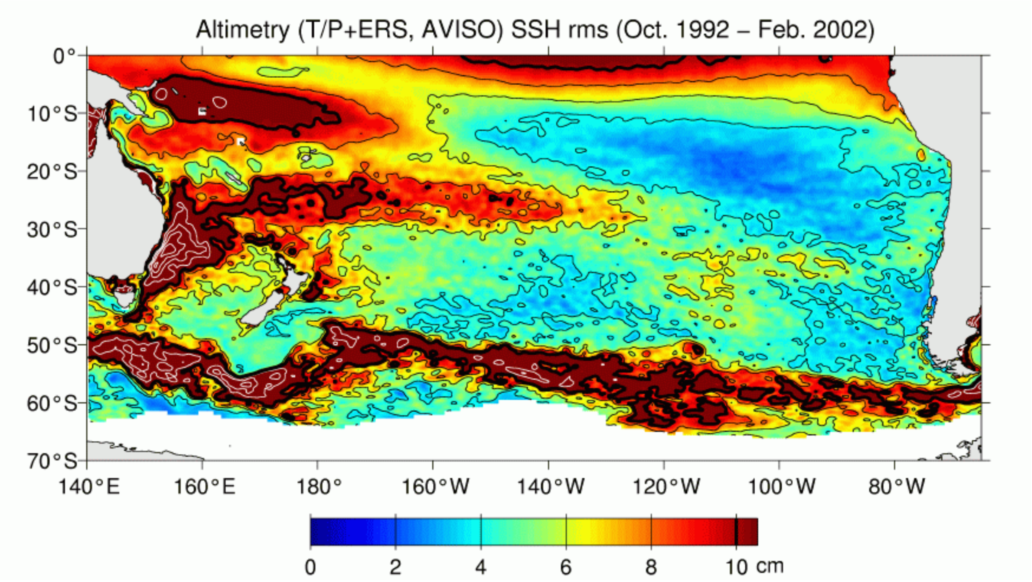

Figure 4 : (Reproduced from Qiu and Chen, 2004) Map of the rms sea surface height variability in the South Pacific Ocean. Base don the combined T/P and ERS ½ altimetric data from Oct 1992 to Feb 2002. Thick solid lines denote the 0.1-m contour. In regions above 0.1 m, thin white lines denote contours at a 0.05 m interval.

The ocean circulation in the Southwest Pacific is highly variable on a large range of time scales. On decadal time scales, important changes are underway in the South Pacific: Roemmich et al. (2005) found a strengthening of the Southwest Pacific subtropical gyre over the last decade, related to an upward trend of the Southern Annular Mode (SAM) (Cai et al. 2003). Over the past 50 years, trends in the SAM have been related to Antarctic Ozone depletion and global warming (Cai, 2006 and Cai et al., 2005). Numerical models also suggest variability in the thermocline circulation of the Southwest Pacific. Decadal variations that modulate equatorial waters may be due to either changes in the mean advection towards the equator (Kleeman et al., 1999) or changes in spiciness anomalies (Gu and Philander, 1997). The partition between those is not clear in the aforementioned numerical model studies, all impaired by the lack of in situ data and a coarse resolution within key Straits. At higher frequencies, satellite measurements reveal a very inhomogeneous surface variability. Qiu and Chen, 2004 identify four regions of high variability (Figure 4): (1) the South Equatorial CounterCurrent, SECC; (2) the EAC; (3) the STCC; and (4) the Antarctic Circumpolar Current (ACC). The observed eddy signals tend to migrate westward, accumulating ultimately along the western boundary of the basin. Questions remain to be addressed as to what extent these signals impact the regional circulation changes in the west on the intraseasonal timescales, as well as on longer timescales through eddy-mean flow interaction.

4. Bifurcation

Investigation of the extra-equatorial part of the circulation is motivated by the fact that the bifurcation of the South Equatorial Current (SEC), roughly at 18°S along the coast of Australia, separates water that flows into the equatorial current system from that which recirculates in the subtropical gyre (Godfrey 1989; Qu and Lindstrom 2002; Blanke et al. 2002). Thus, it has been thought that migration of the bifurcation point could be a key variable in the modulation of the equatorial climate system. The South Pacific bifurcation is little documented compared with its North Pacific equivalent, and relies essentially upon climatological description (Figure 5; Qu and Lindstrom, 2002). According to Sverdrup theory, the bifurcation latitude is determined by the zero zonally-integrated wind stress curl line as modified by the Godfrey (1989) "Island Rule" that shifts its latitude 1°-2° to the south. However, this simple steady-state, depth averaged theory is not sufficient to describe the strong spatial and temporal variations in the location of the bifurcation, as well as its dependence on topography. Just as the subtropical gyre circulation varies substantially with depth, so does the latitude of the bifurcation. The bifurcation is found at 15°S near the surface, and 22°S at 800m (Figure 5), a structure that may also be modified by the complex reef structure of the Queensland plateau at 17°S, 150°E on Figure 5 (Ridgway and Dunn, 2003). The mean position of the bifurcation latitude is often wrong in numerical experiments (Luo et al. 2005) because of its high sensitivity to a several parameters, including the Indonesian Throughflow.

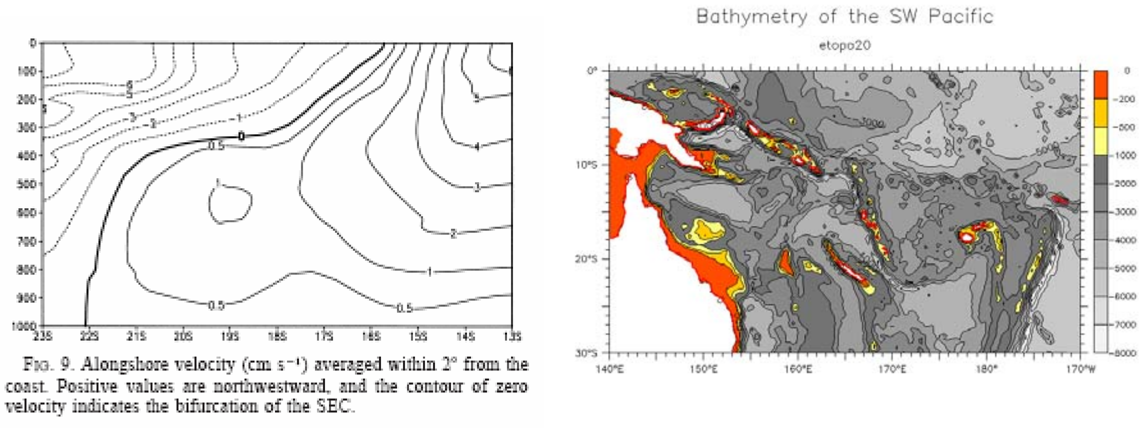

FIG. 9. Alongshore velocity (cm s⁻¹) averaged within 2° from the coast. Positive values are northwestward, and the contour of zero velocity indicates the bifurcation of the SEC.

Bathymetry of the SW Pacific

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Figure 5 : (Reproduced from Qu and Lindstom, 2002): Alongshore velocity (cm/s) averaged within 2° from the coast. Positive values are nortwestward, and the contour of zero velocity indicates the bifurcation of the SEC.

On seasonal to interannual time scales, the dynamics and the variability of the bifurcation latitude is poorly understood. The different sources of variability for the bifurcation latitude need to be identified: ENSO teleconnections, Rossby waves, local wind forcing, or circulation around Australia? A theory needs to be proposed and tested to explain the bifurcation latitude: is it a “dynamical variable” that is controlled by the zero wind stress curl that determines the splitting of the flow, or is the location just a consequence of the strength of western boundary currents (WBC), itself controlled by the wind curl over the Coral Sea? One also needs to understand what causes the jets. The NCJ is located at the mean bifurcation latitude, which raises the question of its role in the variability of the WBCs, versus the role of the complex bathymetry in the vicinity of the Queensland plateau. There is a need to understand at what depth the bifurcation latitude conditions the WBCs. The partitioning of mass, heat and salt transports needs to be understood, as well as the way the tilt in the bifurcation and its variability affects this partition. Finally, the relationship of the bifurcation latitude with the inflow and the outflow streams of the Coral Sea needs to be explained. The variability and partitioning of the Great Barrier Reef UnderCurrent (GBRUC), the North Queensland Current (NQC), and the New Guinea Coastal Current (NGCC) needs to be understood in the models, and if necessary monitored.

Satellite data and simultaneous moorings that close a box around the bifurcation region will allow analysis of the phase relationship of the variability of the currents and their relationship with the bifurcation latitude. Specific repeat-transect cruises will be necessary to determine the bifurcation latitude, its variation and the relation with the NCJ. Gliders released in the NCJ (for instance between Noumea and Guadalcanal) may in addition permit investigations of the relation between the inflow and the WBCs. Simultaneously, a glider line between New Caledonia and Brisbane would allow monitoring of the southern outflow, and therefore the partitioning of the EAC and the NQC.

5. East Australian Current

The EAC provides both the western boundary of the South Pacific Gyre and the linking element between the Pacific and Indian Ocean gyres (Speich et al, 2002). Climatology shows that the current is accelerated, southward along the coastal boundary and then separates into northeastward (STCC), eastward (Tasman Front) and residual southward (Tasman Outflow) components (Figure 6a, Ridgway and Dunn, 2003). Between 18º to 35ºS the southward transport ranges from 25 to 37 Sv, the latter value includes a significant recirculation feature. A portion of the Tasman Front reattaches to the northern coast of New Zealand, forming the East Auckland Current and a sequence of semi-permanent eddies. An alternative pathway for the EAC water is westward, via the subtropical front south of the South Island, and northward along the eastern coast of the South Island (Chiswell, 1996; Tilburg et al., 2003), suggesting a modification to the south par of filament A on Figure 6a. The residue of the EAC transport continues southward along the Australian coast as far as Tasmania and then turns westward into the eastern Indian Ocean (Tasman Outflow) with an important impact on the global ocean circulation (Speich et al., 2002).

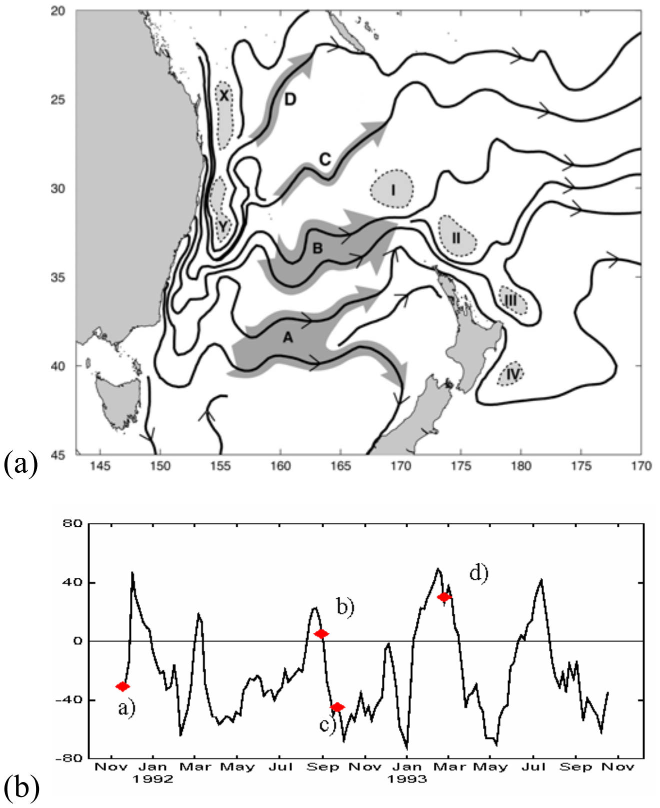

Figure 6: (a) A schematic summary of the EAC and its outflows in the Tasman Sea (Ridgway and Dunn, 2003). (b) The time series of EAC volume transport from a mooring at 30ºS (Mata et al, 2000).

The variability of the EAC is as large as the mean flow. At 30ºS a WOCE mooring found a mean transport of 22Sv with an rms variability of 30 Sv (Figure 6b, Mata et al, 2000). The peak variability is enclosed within an abyssal cul-de-sac basin adjacent to the western boundary. Much of this variability arises from the production and propagation of mesoscale eddies (rings). In addition to the strong local instability, the timing and frequency of the eddies may be partially controlled by remotely forced Rossby waves from the eastern Pacific (Bowen et al, 2005; Ridgway, 2006). The eddy trajectories follow complex patterns which resonate within the deep basin at periods of 100 and 150 days. The EAC also demonstrates a strong seasonal cycle with maximum alongshore flow in summer (Ridgway and Godfrey, 1997), although the origin of this seasonality is not well understood.

The variability of the East Auckland Current (EAuck) is spread over a wide range of frequencies (Stanton and Sutton, 2003). Annual excursions of the surface waters of the EAuck onto the shelf are observed and implicated in triggering harmful algal blooms (Sharples, 1997). Fluctuations of the EAuck may also induce localised upwelling along the coast (Sharples and Greig, 1998). The western boundary current continues along the NZ coast as the East Cape Current, the Wairarapa Eddy north of the Chatham Rise on Figure 1 (Chiswell, 2005), and turns eastward along the Chatham Rise where it meets with the subtropical front from the south (Sutton, 2001).

Surprisingly, few modelling studies have focussed on the dynamics of the EAC (Tilburg et al, 2001; 2002). Tilburg et al. (2002) suggested that gradients in wind stress curl control the current separation locations; while non-linear dynamics induce the southward loop of the EAC as it separates from the coast and that the eastward meandering flow and quasi-permanent eddies are associated with upper ocean-topographic coupling. However in the model, the EAC variability and the southward outflows were simulated very poorly.

The circulation and water mass penetration through the South Pacific western boundary region need to be established by determining robust estimates of the mean and seasonal cycle of each inflow and outflow component and identifying the source, strength, property variability, and pathways of the major water masses (SLW, STMW, SAMW, AAIW). The mechanisms associated with features such as current separation and reattachment, location of semi-permanent eddies, retroflection, and the partitioning of the flow needs a comprehensive, quantitative description. The EAC is highly variable and dominated by eddies, but the formation mechanism of the eddies is poorly understood. Are the eddies generated by local forcing or are they remotely forced from the east? How does the mean EAC flow interact with the eddies, and how are they attenuated or enhanced by topography? An appropriate theory for the mechanism of eddy generation needs to be developed. Western boundary currents are known to play an important role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Kelly, 2004). While recent studies in the Tasman Sea have indicated that ocean advection processes are important for the region (Roemmich et al., 2005), the relative contributions of advection and heat storage compared to the surface heat flux are poorly understood, especially on interannual to decadal time scales. We seek an improved understanding of the heat flux components within the EAC, particularly their variability, and how heat is partitioned between the atmospheric fluxes and recirculated within the gyre. On a larger-scale, we need to define how the western boundary flow is partitioned between the Pacific and Indian Ocean gyres. The region is a source of South Pacific Mode Water (SPMW) and provides a pathway for intermediate water into the Indian Ocean (Ridgway and Dunn, 2006). This means determining the mean and time-varying components of the EAC, the Tasman Front, STCC and the Tasman Outflow. How do these components vary over interannual to decadal time scales? Are we able to observe the effects of anthropogenic change? How are decadal and longer time scale changes in gyre transport and density structure communicated through the western boundary via the EAC?

For example models suggest that a southward shift of the EAC can occur from a spin-up of the gyre, resulting in turn from a poleward displacement of the southern hemisphere circumpolar westerly winds (Cai et al., 2005). The consequence of this shift is an increase in the EAC flow into the Tasman Sea (Cai, 2006). Although a spin-up of the gyre has been observed south of 32S (Roemmich et al., 2006), Bowen et al. (2006) note that available observations do not indicate a stronger EAC between 1993 and 1996 and dynamic height constructed from Argo data also show no increase of gyre strength north of 32S. Clearly, a longer term monitoring program is required.

A research plan to address these questions will involve both observational and model studies. Determining mechanisms for the current features will require process and high-resolution regional modeling studies as well as the analysis of hindcast runs of GCMs. An understanding of the air-sea interaction processes at interannnual and decadal timescales will require the diagnosis of the output from coupled models along with high-quality long-term observations.

High-density VOS-XBT transects that enclose the Tasman Sea region (the "Tasman Box") form the basis for the proposed observation network and should be upgraded. Over 10 years of XBT measurements are now available along each transect, and sampling typically occurs ~ 4 times each year (Roemmich et al., 2005). To determine air/sea fluxes at the highest possible resolution IMET sensors need to be installed on the vessels. Deployment of a buoy to measure meteorological quantities in the western central Tasman Sea is being considered by NIWA. The addition of deep XBTs (2000-m) would remove uncertainties in the mass and heat transport through the transects. Finally the frequency of Tasman Box sections should be increased to 6 per year to reduce temporal aliasing in the EAC mean and seasonal flow estimates.

Supplementary information of the temporal and spatial variability in the subsurface structure can be obtained from the existing ARGO float deployments, although the gaps in ARGO coverage in the Eastern Tasman Sea need to be filled. Strategically placed mooring arrays are needed to characterize the system at a full range of timescales in a few key locations:- South of Tasmania for the Tasman Outflow, at the Brisbane end of Tasman Box section (EAC), the Norfolk Ridge (Tasman Front) and in the EAuck. Regular shipboard surveys will be needed across key currents, including lowered ADCP. Some of those already exist, and would benefit from being integrated in a large-scale strategy. Glider transects across the EAC should be established too, in a monitoring perspective. The long-term hydrological stations at Maria Island and Port Hacking (Sydney) should be maintained and upgraded where required.

6. North Coral Sea (8°S-18°S, Australia to 170°E)

The pioneering WEPOCS cruises of 1985-86 (Lindstrom et al. 1987) provided important snapshots of the tropical end of this system, but observations in the Coral Sea consist of scattered surveys that only sketch the large-scale mean flows. Climatology (Figure 7; Ridgway and Dunn (2003)) suggests that SEC waters use two pathways to reach the Solomon and Vitiaz Straits: one coming from the NCJ, bifurcating against the Australian coast near 18°S and circulating around the northwest corner of the Coral Sea (Gulf of Papua), with another more direct pathway between the northern Vanuatu region (10°S-15°S) and the centre of the Solomon Sea. The only existing full-depth, synoptic meridional section across the Coral and Tasman Seas was the WOCE P11 line along 154°E-156°E from the tip of New Guinea, south to 43°S during June-July 1993 (Sokolov and Rintoul 2000). Taking geostrophic velocities relative to the bottom, they estimated the transport of the SEC across this section to be 55 Sv, balanced almost equally by flow northward into the Solomon Sea via the NGCC (26 Sv) and southward into the EAC (28 Sv). These single-realization transports are about 30% larger than those indicated by climatology.

There is a need to better understand the relation between the inflow and the outflow and its variability. Within the North Coral Sea, local versus remote influences on the circulation need to be better understood. Water mass transformations and the role of incoming eddies require attention. Long-term observations in the region are sparse, and the ARGO float do not sample this enclosed area well as the fast flow around the numerous small islands and passages are hazardous when the float surfaces to transmit. There is a need measure the characteristics and transports of waters transiting through the Solomon Sea. Specifically, the partitioning between the Vitiaz and Solomon Strait transport over seasonal to interannual time scales along with measurements of the direct flow from the SEC to the Solomon Sea needs to be understood. A theory needs to be established to understand what governs the dynamics of the boundary current (e.g. Firing-type island rule on density levels).

Regional modelling experiments with high resolution should be designed to simulate the flow along the boundary and across the straits. Given the lack of historical data, a pilot survey and modelling study of two to three years needs to be designed as a first step towards establishing a sustained observational program in selected regions. The survey should include:

- CTD survey (T,S,O, properties including tracers such as Neodynium); ADCP survey over the Solomon Sea and the Gulf of Papua
- Moorings (Triton-type with ADCP) in the Vitiaz and Solomon Straits.
- A Glider line was initiated between Solomon and New Caledonia (Figure 8), and this type of observation needs to be continued and expanded.
- Mooring lines may be considered to properly measure the NGCUC.

At the eastern edge of the North Coral Sea along 165°E, CTD surveys from New Caledonia to the Equator have been repeated annually and sometimes semi-annually for the past 22 years. To understand the SEC inflow this transect needs to be continued, with an additional short zonal leg along 9°S between 165°E and the Solomon Islands to enclose the northern outflow of the SEC, and also extended to reach the southern tip of Northern New Caledonia and thus capturing all the SEC inflow. The benefits of extending the TAO mooring array southwards to 10°S at 165°E with one more mooring to capture the SEC flow should be assessed through preliminary modelling and observational work; more ARGO floats need to be released in the Coral Sea (see section "integration" below). The supplementation of additional XBT lines should be examined, with the possibility of strengthening existing lines (higher resolution, deeper probes and IMET station installation). Tide gauges may not be directly usable because of the depth dependence of the flow but a strategy should be considered to supplement in situ measurements.

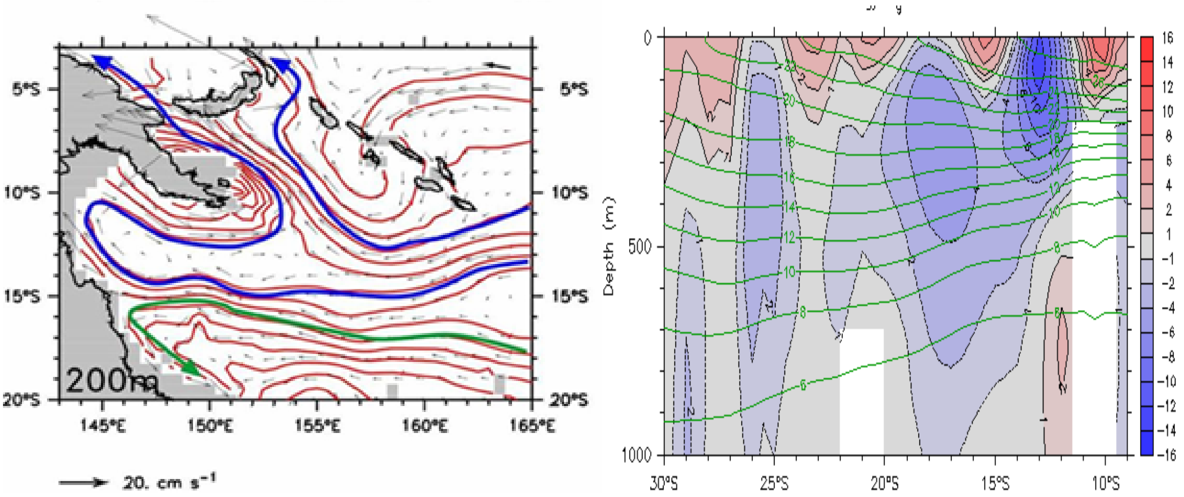

Figure 7: Climatological circulation at 200m depth (left; CARS climatology) and mean zonal current relative to 2000m and temperature along 162°E (right).

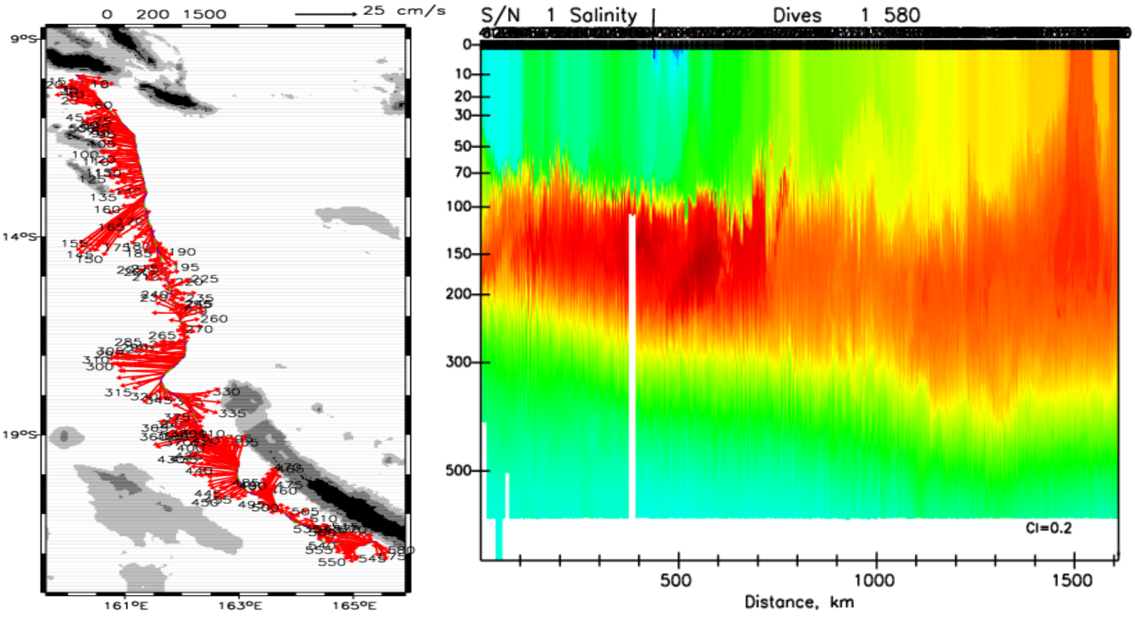

Figure 8 : ***Glider velocity measurements and salinity profiles***

7. Impacts and outreach

On the regional scale, climate in the South-West Pacific is dominated by the position of the SPCZ, which is modulated by ENSO and decadal variability (Salinger et al., 2001). Long time series and model predictions reveal changes in the ocean circulation in relation with atmospheric patterns (Cai et al., 2005) with consequences to local climate and ecosystems. Changes in ocean heat transports in the Tasman Sea, for instance, dramatically impacted local air temperatures in New Zealand with the 1992 coldest winter on record being related to a decreasing in the northern Tasman Sea heat content (Sprintall et al., 1995). Heat content in the Tasman rose markedly in 1998, leading to an increase in New Zealand's land temperatures (Sutton et al., 2005) and a reduction of food for juvenile fish (Bradford-Grieve et al, 2005).

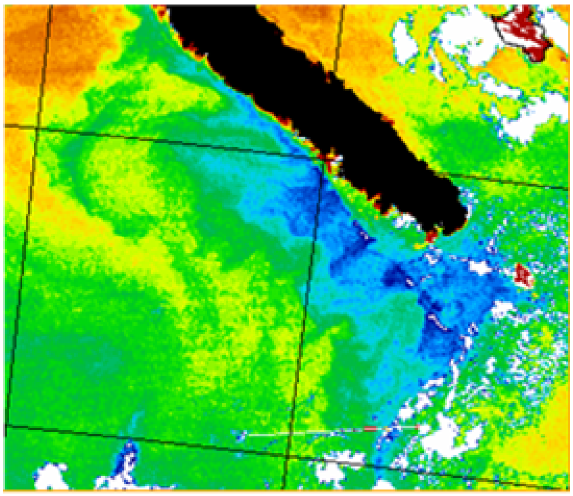

Figure 9 : SST image of the southern part of New Caledonia during an upwelling event (Courtesy A. Vega, LEGOS/IRD-Noumea)

Southwest Pacific countries are particularly sensitive to climate variability and the oceanic environment: droughts in Australia are related with ENSO and decadal variability (Powers et al., 1999); and small Pacific Islands Nations (PINs) are isolated, low-lying and densely populated, and thus may suffer from dramatic consequences of sea level rise, with their coral reefs and fragile ecosystems threatened by temperature elevation. The Pacific Islands Global Ocean Observing System (PI-GOOS, www.sopac.org/tiki/tiki-index.php?page=PIGOOS) program has been created to establish useful links between large-scale oceanography programs and their environmental and societal applications.

The ocean circulation close to islands is complex. The large scale flow with its inherent mesoscale variability is disturbed by bathymetry; the atmospheric circulation is influence by islands. In turn, changes in wind patterns close to the island affect the oceanic circulation and biochemistry through a complex ocean-atmosphere interaction (e.g. Martinez and Maamaatuaiahutapu, 2004). How does the large scale ocean circulation interact with regional climate and circulation near the Pacific Islands? How does the ocean circulation and its variations affect ecosystems and populations? How will climate change influence these systems? These three questions are of a major concern to all Southwest Pacific nations.

Analysis of societal and environmental impacts of ocean and climate changes in the South-West Pacific belongs to specific programs (PI-GOOS, BOM, START-Oceania, PRIDE) and is outside the scientific area addressed within SPICE. Nevertheless, coastal oceanography should be investigated along with the large scales in a coherent way. As described above, the circulation in this region results from a complex interaction between large scale circulation and the numerous topographic features. Types of island effects vary considerably with location. In New Caledonia, a regular occurrence of a cold water tongue on the west coast (Alory et al., 2006; Figure 9) associated with wind-driven upwelling is suspected to play an important role on the lagoon ecosystem, the local climate and hurricane trajectories. In other islands, upwelling can be caused by internal wave activity (Wolanski et al., 2004). The ocean circulation near most small islands is poorly known, as is the associated biogeochemistry, and the interactions with lagoon ecosystems, and this type of investigation needs to be continued and extended to other places. The development of operational oceanography will also be of great interest to PINs, whose economic exclusive zones are the largest in the world, with applications ranging from monitoring of sea level change and coral reef health to hurricane prediction. Also, internal wave energy is little documented in the area. Internal wave models suggest that the Southwest Pacific is a region of very high energy (Nash, 2005) with impacts on both the local circulation and large scale ocean mixing.

The EAC has a major impact on the shelf circulation and ecosystem south of 20ºS. The seasonal cycle of the EAC penetrates onto the shelf, producing the strong currents (Ridgway and Godfrey, 1997; Huyer et al., 1988). Interaction of the EAC and its eddies with local topography and wind forcing are involved upwelling processes (Gibbs et al, 1998; Oke and Middleton, 2001) observed there (Rochford, 1975). On the coast of New Zealand, ocean circulation ecological impacts have been identified, with excursions of the EAuck triggering harmful algal blooms; inducing also coastal upwelling; and the semi-permanent eddies along the east coast of the North Island retaining lobster larvae near the New Zealand coast during their planktonic stage (Chiswell and Booth, 1999).

While the aforementioned research topics are too specific to be united within single plan, a general strategy can be built on experience from the few existing studies. Understanding of flow around islands requires specific programs. A great amount of knowledge has been gained from interactions of the Australian Great Barrier Reef (GBR) with the ocean interior and from projects that are island specific. Such studies and associated modeling and observing methods and infrastructure may be applied to other sites. For instance, existing nested numerical ocean and atmosphere models used to zoom on complex topographic regions can be easily adapted. Reciprocally those regional ocean models will help to better take into account island effects in the large scale flow. Similarly, observation infrastructures may be optimally used between coastal and seafaring programs (e.g. a project on the bifurcation may be coordinated with studies on the GBR).

8. Integration

a. Objectives

A coordinated study of the circulation of the SW Pacific fits in a larger scale context of the whole South Pacific circulation and its connexion with equatorial processes and climate variability. The large scale context is already addressed within CLIVAR and associated national programs, and what is proposed here is a focus on the SW Pacific, designing a feasible experiment based on existing resources. In other words, “Think globally, act locally” is the basis of SPICE conception. Objectives that are regionally specific are summarized on Figure 10.

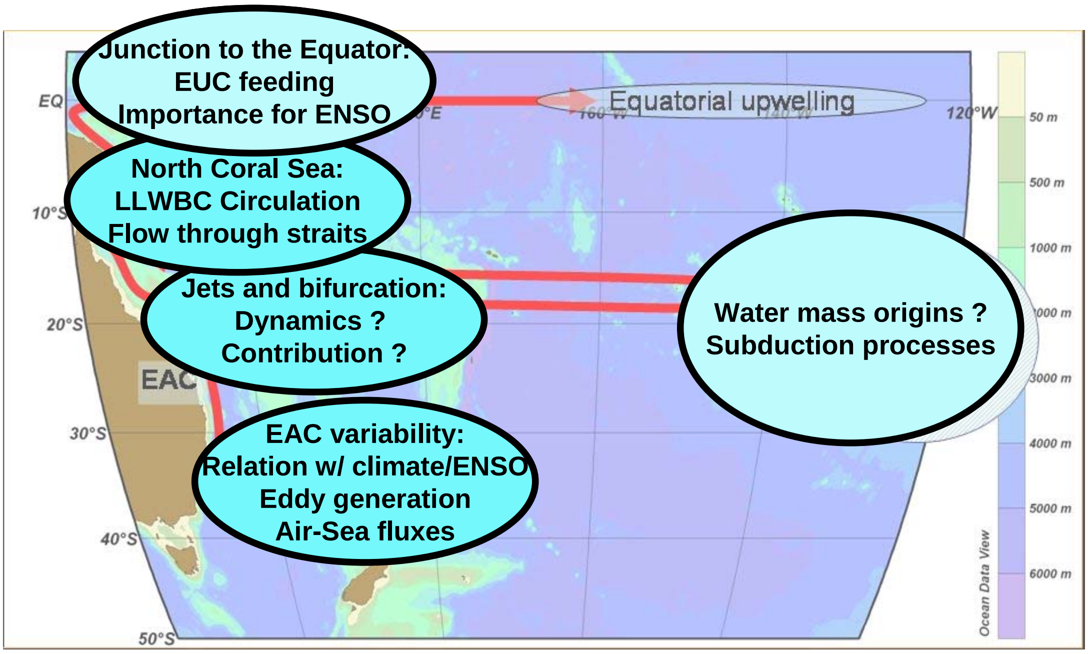

Figure 10 : Geographical research topics addressed by SPICE (Cyan). The clear bubbles refer to adjacent topics that are addressed in a context wider than SPICE.

The following provides the basic elements of a feasible experiment based on the actual human and material potential.

Modelling Strategy

Model experiments will provide the needed linkage between the large scale questions (e.g. how the subtropical gyre waters get to the Equator) and the regional issues (e.g. what are the detailed pathways in the SW Pacific). Using nested models should be encouraged for this purpose (e.g. ROMs), with possible coupling to evaluate island effects. There is a clear need to use models to understand dynamical aspects that cannot be adequately observed such as bifurcation. Those experiments would help with identifying the observable aspects. More generally, models should be used to guide and optimise in situ measurements, e.g. simulating a glider trajectory or a CTD section.

Model experiments may be divided into 6 types: basin-scale GCM, coupled GCM, operational GCM, adjoint GCM, regional (nested) models and process (or simplified) models. Based on the scientific objectives, metrics specific to each experiment need to be identified to evaluate the model skills (e.g. getting the patches of high SSH variability observed in the satellites in Figure 4). Because models cannot get every aspect correctly, the implications of having some aspects erroneous should be examined. For instance the occurrence of the double ITCZ (versus SPCZ) is a major model bias that needs to be better understood in terms of cause and implications.

Flux products are of major importance to forced (and indirectly to coupled) models. Ways to improve SW Pacific fluxes should be considered (see below). Some formats/aspects of the products could be generalized, such as averages on density surfaces.

Important operational oceanography projects concern the Southwest Pacific (e.g., Bluelink, Mercator and SODA). Those assimilated models may be used to provide realistic boundary conditions to regional models, regional groups adding regional knowledge.

Observations:

Figure 11 provides background guidelines for the design of a coordinated observational program. For convenience, observations are split into three categories: (1) regional adaptation of large scale programs; (2) pilot studies and (3) sustained observations, with a focus on the thermocline water circulation.

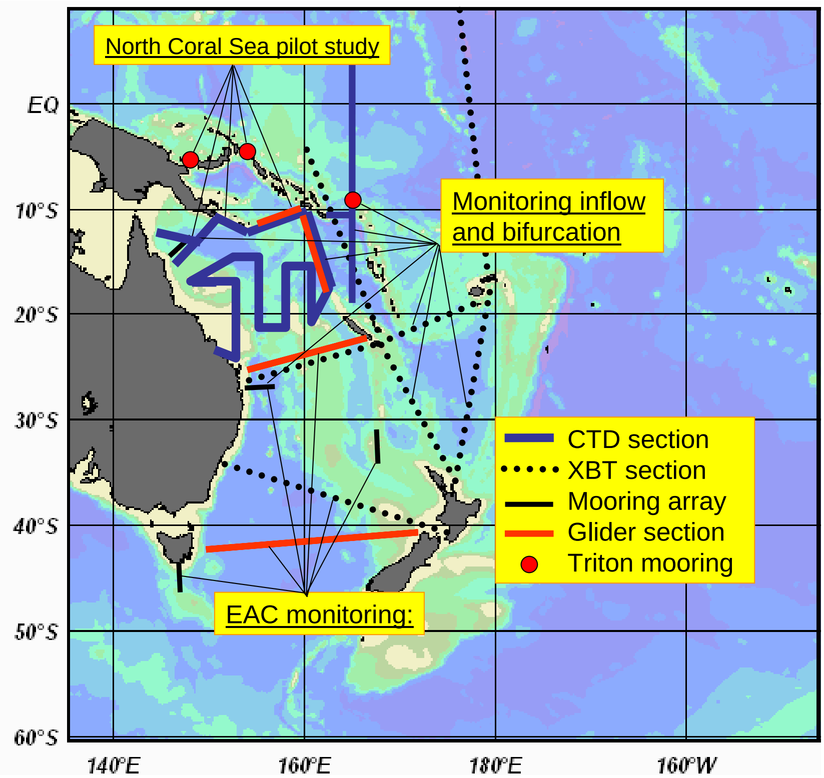

Figure 11 : Tentative outline for a Southwest Pacific observation program. This diagram is based on the working group conclusions, and each component is subject to further investigation.

Pilot studies

Pilot studies will be necessary to understand basic processes in regions that are very poorly sampled. The North Coral Sea (Papua Gulf and Solomon Sea) is one of these, and a preliminary investigation is needed to provide basic knowledge for further, and possibly sustained, observations, including monitoring the Vitiaz and Solomon straits. There is a need for CTD surveys (hydrology and water mass tracers) and also to test glider technology (Figure 8). The fate of the North Caledonian Jet and the Bifurcation zone are two other areas where pilot experiments are needed.

Sustained observations

Some features of the circulation will need to be observed repeatedly, specifically:

1. Along 165°E, and between 20°S and 0°, a CTD section has been repeated for 22 years, and provides an invaluable data set to study the SEC inflow and variability. Such observations should be continued, and possibly adapted - to include the eastern edge of the Solomon so as to enclose the northern Coral Sea (Figure 11).
2. The emerging glider technology can be adapted for repeat measurements at a low cost compared with use of research vessels. The possibility of using gliders to monitor boundary currents should be examined using data from gliders that operate

simultaneously with mooring lines. Such a test could be carried out between Noumea and Brisbane (red lines on Figure 11)

3. Monitoring of strong currents may include all the WBC along the Australian Coast and the flow through Vitiaz and Solomon Straits.
4. XBT lines (dotted lines on Figure 11) have been providing repeat observations for 35 years. Adapting those lines to SPICE objective is considered below.
5. The benefit of creating of a Southwest Pacific HOT-type observatory could be considered. The observatory could be beneficial to IRD infrastructure in New Caledonia.

Regional adaptation of large-scale programs

1. Floats from the ARGO program (www.argo.ucsd.edu) will help answer the large scale questions. Nevertheless, the ARGO coverage in the Coral Sea is very low. On reason is that long surface transmission times cause floats to be pushed ashore by winds. New floats using faster transmission (Iridium) should be tested and used there.
2. The same is true for surface drifters from the Global Drifter Program (www.aoml.noaa.gov/phod/dac/gdp_drifter.html), the coverage of which may be usefully increased in the Coral Sea.
3. Australia, the United States and France have been developing and maintaining a voluntary observing ship program since the 70’s in the Western Pacific (www.brest.ird.fr/soopip). A strong infrastructure is operational in New Caledonia and Tasmania, and XBT lines are currently crossing the Coral Sea. Those lines may be adapted to the SPICE objectives, with for instance an increase in frequency, deeper (2000m) probes and new line creation. The possibility of equipping the same ships with IMET stations should be considered, given the very high need of accurate air-sea fluxes.
4. The TAO array ends at 8°S at 165°E. A southward extension to about 10°S to monitor the SEC inflow is a possibility that should be assessed by preliminary modelling and observational work (red circle on Figure 11).

Infrastructure

Locally, five large oceanographic centres will be able to contribute to SPICE:

1. IRD (www.ird.nc, Noumea; 12 scientists and technicians in physical oceanography; numerical modelling and seagoing facilities; 28-m Research Vessel (RV) and possibilities for using French National Fleet RVs (www.ifremer.fr/flotte/navires); XBT and thermosalinograph network management)
2. CSIRO (www.cmar.csiro.au, Hobart: some two dozens of physically oceanographers and technicians, some 100 marine biological scientists , 66m RV Southern Surveyor, state-of-the-art ocean reanalysis system with a domain that includes the whole of the Indo-Pacific, ROM, XBT , and Argo data analysis center.)
3. CSIRO (www.cmar.csiro.au, Melbourne; some half of dozen of global climate modellers, state-of-the-art global climate model, RAM).

4. NIWA (http://www.niwascience.co.nz/ncco, Wellington, New Zealand, 10 scientists and technicians in physical oceanography; numerical modelling and sea going facilities; 70m RV Tangaroa, 28m RV Kaharoa; XBT and Argo support; regional modelling using ROMS, MOMA, Gerris, RiCom; met buoy)

SPICE will also benefit from infrastructures of

5. NOAA (PMEL); possibility of TRITON mooring additions maintenance)
6. University of Hawaii (http://www.soest.hawaii.edu/oceanography/), Honolulu, Analysis and interpretations of satellite altimetrically-derived sea surface height data in conjuction with in-situ observational data and numerical model output.

9. Conclusion

In conclusion, the emergence of a new, coordinated program in the Southwest Pacific has started. Oceanographers from the aforementioned countries are wishing to contribute to this program. SPICE will contribute substantially to the CLIVAR area of interest D4 (Pacific and Indian oceans decadal variability), and serve to some extent G1 (Extending and improving ENSO prediction). Because small scales are necessarily involved, SPICE will establish a link between deep ocean currents and coastal/island circulation. Preliminary studies should be encouraged by national programs in the coming years (2006-2007) to allow the establishment of a complete SPICE science plan.

10. Programmatic Context

SPICE would serve of larger-scale CLIVAR Pacific areas of interest: subduction, ENSO modulation, supergyre dynamics.

SPICE will build on collaboration with programs that work on application of oceanic data to Pacific Island Countries: PRIDE/PI-GOOS.

11. References

Alory, G., A. Vega, A. Ganachaud and M. Despinoy, 2006. A simple upwelling index to monitor coastal SST off New Caledonia, submitted.

Blanke, B., and S. Raynaud, 1997. Kinematics of the Pacific equatorial undercurrent: an Eulerian and Lagrangian approach from GCM results, J. Phys. Oceanogr., 15, 650-669.

Bowen M, J, Wilkin, W. Emery, 2005. Variability and forcing of the East Australian Current, *J. Geophys. Res.*, 110, C) 3019, doi:10.1029/2004JC002533, 2005

Bradford-Grieve, J, M Livingston, P Sutton, M Hadfield, 2004: Fisheries Oceanography: Ocean variability and hoki decline, Water and Atmosphere 12(4).

Butt, J. and E. Lindstrom, 1994. Currents off the east coast of New Ireland, Papua New Guinea, and their relevance to regional undercurrents in the western equatorial pacific ocean, J. Geophys. Res., 99, 12503-12514.

Cai, W. J., 2006. Antarctic ozone depletion causes an intensification of the southern ocean supergyre circulation, Geophys. Res. Lett., in press. .

Cai, W. J., P.H. Whetton, and D.J. Karoly, 2003. The response of the Antarctic oscillation to increasing and stabilized atmospheric CO2, J. Climate, 16, 1525-1538, 2003.

Cai, W. J., G. Shi, T. Cowan, D. Bi, and J. Ribbe, 2005. The response of southern annular mode, the East Asutralian Current, and the southern midlatitude ocean circulation to global warming. Geophys. Res. Lett., 32, doi:10.1029/2005 GL024701.

Chiswell, S. M. (1996), Variability in the Southland Current, New Zealand, N. Z. J. Mar. Freshwater Res., 30, 1--17.

Chiswell, S. M. (2005), Mean and variability in the Wairarapa and Hikurangi Eddies, New Zealand, N. Z. J. Mar. Freshwater Res., 39, 121--134.

Chiswell, S. M. and J. D. Booth (1999), Rock lobster Jasus edwardsii larval retention by the Wairarapa Eddy off New Zealand, Mar. Ecol. Prog. Ser., 183, 227--240.

Delcroix, T., and C. Hénin, 1989. Mechanisms of subsurface thermal structure and sea surface thermohaline variabilities in the southwestern tropical Pacific during 1975-85, J. Mar. Res., 47, 777-812.

Davis, R. 2005. Intermediate-depth circulation of the Indian and South Pacific Oceans measured by autonomous floats. Journal of Physical Oceanography, 35, 683 - 707.

Donguy, J.-R., and G. Meyers, 1996. Mean annual variation of transport of major currents in the tropical Pacific Ocean, Deep Sea Res. I, 43, 1105-1122.

Fukumori, I., T. Lee, B. Cheng, and D. Menemenlis, 2004. The origin, pathway and destination of the Niño-3 region waters, J. Phys. Oceanogr. 34, 582-604,

Fyfe, J. C., G. J. Boer, and G. M. Flato, 1999. The Arctic and Antarctic oscillations and their projected changes under global warming, Geophys. Res. Lett., 26, 1601-1604, 1999.

Freeland H. J., F. M. Boland, J. A. Church, A. J. Clarke, A. M. G. Forbes, A. Huyer, R. L. Smith, R. Thompson, and N. J. White, The Australian Coastal Experiment: The search for coastal trapped waves, *J. Phys. Oceanogr.*, 16, 1230-1240, 1986.

Gibb, M. T., J. H. Middleton and P. Marchesiello, Baroclinic response of Sydney shelf waters to local wind forcing and deep ocean forcing, J. Phys. Oceanogr., 28, 178-190, 1998.

Giese, B., C. Uzinar, and N. Fučkar, 2002. Southern hemisphere origins of the 1976 climate shift, Geophys. Res. Lett., 29 (2), doi: 10.1029/2001GL013268.

Godfrey, J. S., 1989. A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulations, Geophys. Astrophy. Fluid Dyn. it 45, 89-112.

Gouriou, Y. and J. Toole, 1993. Mean circulation of the upper layers of the western equatorial Pacific Ocean, J. Geophys. Res., 98, 22495-22520.

Gu D. and S. G. H. Philander, 1997: Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275**, 805-807.

Hanawa, K., and L. Talley, 2001. Mode waters. In Ocean circulation and climate-observing and modelling the global ocean, G. Siedler, J. Church, and J. Gould, eds., Academic Press, 373-368.

Huyer, A., R. L. Smith, P. J. Stabeno, J. A. Church, and N. J. White, Currents off southeastern Australia: results from the Australian Coastal Experiment, *Aust. J. Mar. Freshw. Res.*, 39, 245-288, 1988.

Izumo, T., J. Picaut and B. Blanke, 2002: Tropical pathways, equatorial undercurrent variability and the 1998 La Niña. *Geophys.Res.Lett.*, **29**, doi:10.1029/2002GL015073.

Johnson, G., and M. McPhaden, 1999. Interior pycnocline flow from the subtropical to the equatorial pacific ocean, J. Phys. Oceanogr., 29, 3073-3089.

Johnson, G. and A. Orsi, 1997. Southwest Pacific Ocean water-mass changes between 1968/69 and 1990/91. Journal of Climate, 10, 306-316.

Kelly K, The relationship between oceanic heat transport and surface fluxes in the western North Pacific, 1970-2000, *J. Clim.*, 17, 573-588, 2004.

Kessler, W., and L. Gourdeau, 2006. Wind driven zonal jets in the South Pacific Ocean, Geophys. Res. Lett., ms 2005GL025084, in press.

Kleeman, J.P. McCreary, and B.A. Klinger, 1999. A mechanism for the decadal variation of ENSO. Geophys. Res. Lett*.*, 26,1743 -1746.

Kushner, P. J., I. M. Held, and T. L. Delworth, Southern Hemisphere atmospheric circulation response to global warming, 2001. J. Climate, 14, 2238-2249.

Lee, T., and I. Fukumori, 2003. Interannual to decadal variations of tropical-subtropical exchanges in the Pacific Ocean: Boundary versus interior transports, J. Climate, 16, 4022-4042.

Lindstrom, E., R. Lukas, R. Fine, E.firing, J. S. Godfrey, G. Meyers and M. Tsuchiya, 1987: The western equatorial Pacific Ocean circulation study. *Nature*, **330**, 533-537.

Luo, Y., L. Rosthstein, R.-H. Zhang and A. Bussalacchi, 2005. On the connection between South Pacific subtropical spiciness anomalies and decadal equatorial variability in an ocean general circulation model, J. Geophys. Res., 110, C10002, doi: 10.1029/2004JC002655.

Martinez, E. and K. Maamaatuaiahutapu, 2005. Island mass effects in the Marquesas Islands: time variations, Geophys. Res. Lett., 31, doi: 10.1029/2004GL020682.

Mata, M. M., Tomczak, M., Wijffels, S., Church, J. A., 2000. East Australian Current volume transports at 30°S: Estimates from the World Ocean Circulation Experiment hydrographic sections PR11/P6 and the PCM3 current meter array, *J. Geophys. Res*., 105, 28,509-28,526.

McCreary, J. and P. Lu, 1994. Interaction between the subtropical and equatorial ocean circulations: the subtropical cell, J. Phys. Oceanogr., 24, 466-497.

McPhaden, M. and D. Zhang, 2002. Slowdown in the meridional overturning circulation in the upper Pacific Ocean. Nature, 415, 603 - 608.

McPhaden, M. and D. Zhang, 2004. Pacific Ocean circulation rebounds. Geophysical Research Letters, 31, L18301, doi:10.1029/2004GL020727

Nakano, H. and H. Hasumi, 2005. A series of zonal jets embedded in the broad zonal flows in the Pacific obtained in eddy-permitting ocean general circulation models, J. Phys. Oceanogr., 35, 474-488.

Nash, J. D., M. H. Alford, and E. Kunze, 2005. Estimating internal wave energy fluxes in the ocean, J. Atmos. Ocean. Tech., 22, 1551-1570.

Oke, P. R., and J. H. Middleton, Nutrient enrichment off Port Stephens: the role of the East

Australian Current, *Cont. Shelf Res*., 21, 587-606, 2001.

Powers, S., T. Casey, S. Folland, A. Colman, and V. Mehta, 1999. Inter-decadal modulation of the impact of ENSO on Australia, Climate Dynamics, 15, 319-324.

Qu, T. and E. Lindstrom, 2002. A climatological interpretation of the circulation in the western south Pacific, J. Phys. Oceanogr., 32, 2492-2508.

Qiu, B.and S. Chen, 2004. Seasonal modulations in the eddy field of the South Pacific Ocean, J. Phys. Oceanogr., 34, 1515-1526.

Qiu, B. and S. Chen, 2006. Decadal variability in the large-scale sea surface height field of the South Pacific Ocean: Observations and causes, Journal of Physical Oceanography, in press.

Reid, J. 1997. On the total geostrophic circulation of the Pacific Ocean: flow patterns, tracers and transports. Progress in Oceanography, 39, 263 - 352.

Ridgway, K. R., Godfrey, J. S., 1997. Seasonal cycle of the East Australian Current, *J. Geophys. Res*, 102, 22,921-22,936.

Ridgway, K. and J. Dunn, 2003. Mesoscale structure of the East Australian Current System and its relationship with topography. Progress in Oceanography, 56, 189 - 222.

Ridgway, K. R., East Australian Current eddies: A response to remotely forced Rossby waves and local topography, submitted to *Deep-Sea Res*., 2006.

Rochford D. J., Nutrient enrichment of Australian coastal waters II Laurieton upwelling, *Aust. J. Mar. Freshw. Res*., 26, 233-243, 1975.

Roemmich, D. and P. Sutton, 1998. The mean and variability of ocean circulation past northern New Zealand: Determining the representativeness of hydrographic climatologies. Journal of Geophysical Research, 103, 13041 - 13054.

Roemmich, D., J. Gilson, J. Willis, P. Sutton and K. Ridgway, 2005. Closing the time-varying mass and heat budgets for large ocean areas: The Tasman Box. Journal of Climate, 18, 2330 - 2343.

Roemmich, D., J. Gilson, R. Davis, P. Sutton, S. Wijffels, and S. Riser, 2006. Decadal spin-up of the South Pacific subtropical gyre. Journal of Physical Oceanography, In press.

Salinger, J., J. Renwick and A. Mullan, 2001. Interdecadal pacific oscillation and South Pacific climate, Intern. J. Climato., 21, 1705-1721.

Schneider, N., 2004. The response of tropical climate to the equatorial emergence of spiciness anomalies, J. Climate, 17, 1083-1095.

Sokolov, S. and S. Rintoul, 2000: Circulation and water masses of the southwest Pacific: WOCE section P11, Papua New Guinea to Tasmania. *J.Mar.Res*., **58**, 223-268.

Sokolov, S and SR Rintoul, 2002: Structure of Southern Ocean fronts at 140E, J. Mar. Sys., 37, 151--184.

Speich S., B. Blanke, P. de Vries, S. Drijfhout, K. Doos, A. Ganachaud, and R. Marsh, Tasman leakage: A new route in the global conveyor belt, *Geophys. Res. Let*., **29**, 10,416, 10.1029/2001GL014586, 2002.

Sprintall, J., D. Roemmich, B. Stanton, and R. Bailey, 1995. Regional climate variability and ocean heat transport in the Southwest Pacific Ocean, J. Geophys. Res., 100, 15,865-15,871.

Stanton, B., D. Roemmich and M. Kosro, 2001. A shallow zonal jet south of Fiji. Journal of Physical Oceanography, 31, 3127 - 3130.

Sharples, J., 1997, Cross-shelf intrusion of subtropical water into the coastal zone of northeast New Zealand, Cont. Shelf. Res., 17, 835--857.

Sharples, J. and M. J. N. Greig, 1998, Tidal currents, mean flows, and upwelling on the north-east shelf of New Zealand, N. Z. J. Mar. Freshwater Res., 32, 215--231.

Stanton, B. and P. Sutton, 2003, Velocity measurements in the East Auckland Current north-east of North Cape, New Zealand, N. Z. J. Mar. Freshwater Res., 37, 195--204.

Sutton, P., 2001, Detailed structure of the Subtropical Front over the Chatham Rise, east of New Zealand, J. Geophys. Res., 106, 31,045--31,056.

Sutton, P., 2003, The Southland Current: a subantarctic current, N. Z. J. Mar. Freshwater Res., 37, 645-652.

Sutton, P., M. Bowen and D. Roemmich, 2005. Decadal temperature changes in the Tasman Sea. New Zealand Journal of Marine and Freshwater Research, 39, 1321-1329.

Talley, L. and J. Sprintall, 2005. Deep expression of the Indonesian Throughflow: Indonesian intermediate water in the South Ewuatorial Current, G. Geophys. Res., 110, C10009.

Tilburg, C. E., H. E. Hurlburt, J. J. O'Brien, J. F. Shriver, 2002, Remote topographic forcing of a baroclinic western boundary current: an explanation for the Southland Current and the pathway of the Subtropical Front east of New Zealand, J. Phys. Oceanogr., 32, 3216--3232.

Tilburg C. E., H. E. Hurlburt, J. J. O’Brien, and J. F. Shriver, 2001, The dynamics of the East Australian Current system: the Tasman Front, the East Auckland Current, and the East Cape Current, *J. Phys. Oceanogr*., **31**, 2917- 2943.

Tsuchiya, M., 1981: The origin of the Pacific Equatorial 13°C water. *J.Phys.Oceanogr*., **11**(6) 794-812.

Tsuchiya, M., R. Lukas, R. A. Fine, E. Firing and E. Lindstrom, 1989: Source waters of the Pacific Equatorial Undercurrent. *Prog.Oceanogr*., **23**(2) 101-147.

Webb, D. 2000. Evidence for shallow zonal jets in the South Equatorial Current region of the southwest Pacific. Journal of Physical Oceanography, 30, 706 - 720.

Willis, J., D. Roemmich and B. Cornuelle, 2004. Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, Journal of Geophysical Research, 109, C12036, doi:10.1029/2003JC002260.

Wolanski, E., P. Colin, J. Naithani, E. Deleersnijder, and Y. Golbuu. 2004. Large amplitude, leaky, island-generated, internal waves around Palau, Micronesia. Estuar. Coast. Shelf Sci. 60:705-716.

Wong, A., N. Bindoff, J. Church, 1999: "Large-scale freshening of intermediate waters in the Pacific and Indian oceans", Nature, 400, 440-443.

Yeager, S. and W. Large, 2004. Late winter generation of spiciness on subducted isopycnals, J. Phys. Oceanogr., 34, 1528-1547.

12. Glossary of Technical Terms

AAIW : Antarctic Intermediate Water

ACC : Antarctic Circumpolar Current

EAC : East Australia Current

EAuck : East Auckland Current

EUC : Equatorial UnderCurrent

GBRUC : Great Barrier Reef UnderCurrent

IMET : Improved Meteorology (IMET) system for marine meteorological observations

ITCZ : Intertropical Convergence Zone

NCJ : North Caledonian Jet

NGCC : New Guinea Coastal Current

NQC : North Queensland Current

NVJ : North Vanuatu Jet

SAM : South Annular Mode

SAMW : SubAntarctic Mode Water

SCJ : South Caledonian Jet

SEC : South Equatorial Current

SECC : South Equatorial Counter Current

SLW : Subtropical Lower Water

SPCZ : South Pacific Convergence Zone

SPESMW : South Pacific Eastern Subtropical Mode Water

SPMW : South Pacific Mode Water

SST : Sea Surface Temperature

STCC : SubTropical Counter Current

STMW : Subtropical Mode Water

VOS : Voluntary Observing Ship

WBC : Western Boundary Current

XBT : eXpandable Bathy Thermograph