The Southwest Pacific Ocean Circulation and Climate Experiment (SPICE)
Report to CLIVAR SSG

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1 Highlights

The Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) is a CLIVAR international research program and was endorsed in 2008. The key objectives are to understand the Southwest Pacific Ocean circulation and the South Pacific Convergence Zone (SPCZ) dynamics, as well as their influence on regional and basin-scale climate patterns. South Pacific thermocline waters are transported in the westward flowing South Equatorial Current (SEC) toward Australia and Papua-New Guinea (Figure 1). On its way, the SEC encounters the numerous islands and straits of the Southwest Pacific and forms boundary currents and jets that eventually redistribute

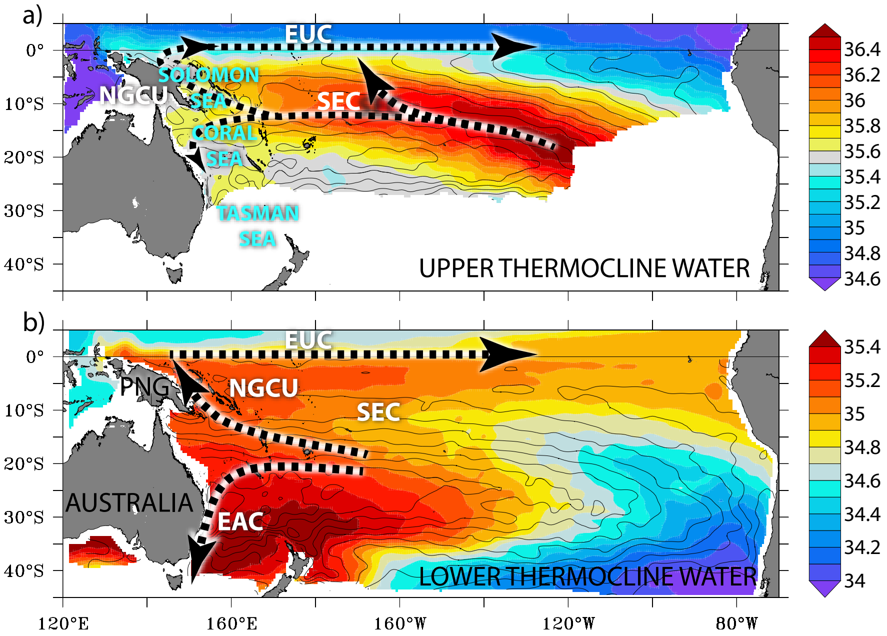

Figure 1: Salinity on isopycnal a) $\sigma_\theta = 24.5$ kg.m^{-3} (color) and geostrophic streamlines (contours) from the CARS climatology (*Ridgway et al.*, 2002). The (dashed) arrows represent the approximate pathways of the Upper Thermocline Waters (UTW) b) on $\sigma_\theta = 26.2$ kg.m^{-3}; Lower Thermocline Waters (LTW). The two isopycnals correspond respectively to the upper and lower part of the Equatorial Undercurrent (EUC). Main currents are indicated: the South Equatorial Current (SEC); New Guinea Coastal Undercurrent (NGCU) as well as the East Australian Current (EAC). Adapted from *Grenier et al.* (2014)

water to the equator and high latitudes. The transit in the Coral, Solomon and Tasman Seas is of great importance to the climate system because changes in either the temperature or the amount of water arriving at the equator have the capability to modulate the El Niño-Southern Oscillation, while the southward transports influence the climate and biodiversity in the Tasman Sea. After seven years of substantial in situ oceanic observational and modeling efforts, our understanding of the region has much improved. We have a refined description of the SPCZ behavior, boundary currents, pathways and water mass transformation, including the previously undocumented Solomon Sea. The transports are large and vary substantially in a counter-intuitive way, with asymmetries and gating effects that depend on time scales. The SPICE authors of this report submitted a review article to JGR-Special issue on western Pacific Ocean and Climate recent advancements discussing current knowledge gaps and important emerging research directions (*Ganachaud et al.*, 2013, 2014). We provide here the main points of this review.

1.1 Motivations

The Southwest Pacific Ocean region contains the major oceanic circulation pathway that redistributes waters from the South Pacific subtropical gyre to the equator and high latitudes. The South Equatorial Current (SEC) flows into the Coral Sea, transporting distinct water masses: the salty Upper Thermocline Waters (UTW, $\sigma_\theta \sim 24.5$ kg.m^{-3}) subducted in the dry and windy center of the southeast Pacific gyre (high salinity patch Figure 1a; see also *Qu et al.*, 2008; *Hasson et al.*, 2013); the Lower Thermocline Waters (LTW, $\sigma_\theta \sim 26.2$ kg.m^{-3}), in part subducted north east of New Zealand (high salinity patch Figure 1b; *Tsubouchi et al.*, 2007; *Qu et al.*, 2009), and the low-salinity Antarctic Intermediate Waters (AAIW, $\sigma_\theta \sim 27.2$ kg.m^{-3}) formed around 50°S (*Qu and Lindstrom*, 2004) and subducted between 170°W and Drake Passage (*Sallee et al.*, 2010;

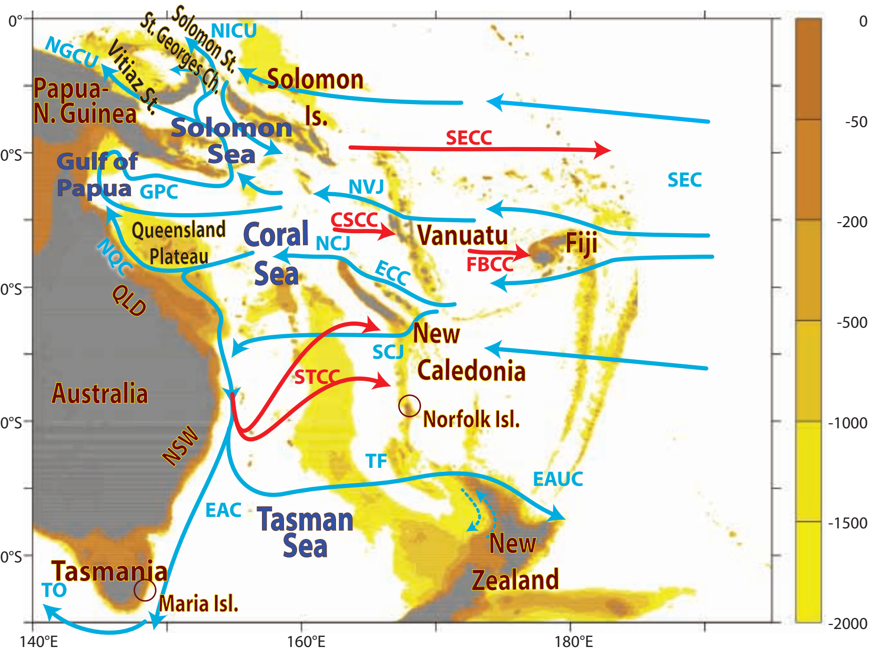

Figure 2: Southwest Pacific topography: only depths shallower than 2000 meters are shaded (color scale in meters). The Queensland (QLD) and New South Wales (NSW) coasts are indicated. Blue arrows denote the main currents, integrated 0 − 1000 m (SEC=South Equatorial Current; NVJ=North Vanuatu Jet; ECC= East Caledonian Current; NCJ=North Caledonian Jet; SCJ=South Caledonian Jet; NQC=North Queensland Current; GPC=Gulf of Papua Current; NGCU=New Guinea Coastal Undercurrent; NICU=New Ireland Coastal Undercurrent; EAC=East Australia Current; TF=Tasman Front; EAUC=East Auckland Current; TO= Tasman Outflow). The red arrows indicate the main surface-trapped counter-currents (STCC=South Pacific Subtropical Counter Current; CSSC=Coral Sea Counter Current; FBCC=Fiji Basin Counter Current; and SECC=South Equatorial Counter Current).

Hartin et al., 2011).

On the poleward pathway, large quantities of heat energy are transported in the East Australian Current (EAC). The main core of the EAC separates from Australia and flows eastward into the Tasman Sea, giving rise to a region of intense eddy activity and air-sea exchanges, with marked influence on climate over Australia and New Zealand (*Sprintall et al.*, 1995). The remaining EAC continues to flow southward as the *EAC Extension*; where some eventually forms the Tasman Outflow (TO) that connects the South Pacific subtropical gyre with the Indian Ocean, forming a *supergyre* that redistributes water amongst the basins (*Speich et al.*, 2002; *Cai*, 2006; *Ridgway and Dunn*, 2007).

On the equatorward pathway, the Low Latitude Western Boundary Currents (LLWBC) flowing through the Solomon Sea constitute an essential part of the *subtropical cell* circulation (*McCreary and Lu*, 1994). They contribute to the recharge of the equatorial Warm Pool, and supply the Indonesian Throughflow and the Equatorial Undercurrent (EUC), thereby feeding the downstream surface waters of the cold tongue in the eastern Pacific (*Fine et al.*, 1994). Documenting the LLWBC transports and properties is important in many ways. On interannual timescales, it has been shown that the LLWBC transport variations partially compensate the interior transport variations (e.g., *Lee and Fukumori*, 2003; *Qu et al.*, 2013). On decadal timescales, it has been suggested that changes in either the temperature (*Gu and Philander*, 1997) or the amount of water (*Kleeman et al.*, 1999; *McPhaden and Zhang*, 2002) arriving at the equator modify the equatorial thermocline and surface equatorial properties, thus having the capability to modulate the El Niño-

Southern Oscillation (ENSO). Temperature and salinity anomalies of O(0.5°C / 0.2 psu) can indeed be traced from the southeastern Pacific as they advect toward the west, both in models (*Luo et al.*, 2005; *Nonaka and Sasaki*, 2007; *Qu et al.*, 2013) and Argo float observations (*Kolodziejczyk and Gaillard*, 2012; *Zhang and Qu*, 2014). Tracking them until they reach the equatorial band is much more difficult, due to the complex LLWBC system and mixing in the Southwest Pacific.

Quantifying the EAC and LLWBC transports and variability in the Coral, Tasman and Solomon Seas is thus of great importance to climate prediction; documenting hydrological properties and water mass mixing along their pathways is also crucial to understand if (and how) anomalies in hydrological properties are transmitted from the subtropical/tropical South Pacific to the equatorial band and to southern Australia. But the oceanic circulation in this region is complex. The bulk of the South Pacific subtropical gyre waters entering the Coral Sea in the broad westward flowing SEC encounter islands, resulting in boundary currents that divide into westward jets at their northern and southern tips, according to the *island rule* dynamics (*Godfrey*, 1989). These jets include the South Caledonian Jet (SCJ), the North Caledonian Jet (NCJ), and the North Vanuatu Jet (NVJ) (Figure 2). Upon reaching the Australian coast, the NCJ bifurcates and supplies both the EAC and the Gulf of Papua Current (GPC). The GPC enters into the Solomon Sea, becoming the New Guinea Coastal Undercurrent (NGCU) that flows around intricate topography before exiting northward through three narrow passages: the Vitiaz Strait, Solomon Strait and St. George's channel. To the south, the EAC strengthens as it flows along the coast of Australia. Southward of $\sim 33°$S, it starts to separate into filaments, forming the northwestward South Pacific Subtropical Counter Current (STCC), the eastward Tasman Front (TF, Figure 2), and the EAC extension.

This circulation and its dynamics have been previously identified in numerical simulations (*Webb*, 2000) and low resolution climatologies (*Qu and Lindstrom*, 2002; *Ridgway*, 2003), which motivated enhanced observations to improve their description and understand the connections between currents at different depths, along with the variability. Concurrently, the increased model resolution and bathymetry greatly improved the quality of numerical simulations of the Coral Sea. The structure and strength of the Southwest Pacific circulation are related to the southeasterly trade wind structure. Their structure depends on the presence and intensity of the South Pacific Convergence Zone (SPCZ), a region that extends on average from the Solomon Islands to Fiji and southward (see Figure 2) with strong precipitation, wind convergence, and diabatic heating (*Zhang*, 2001). Modeling the Southwest Pacific circulation is further challenged because our understanding of the SPCZ dynamics is limited, with coupled climate models exhibiting strong biases with the modeled SPCZ extending zonally which is in contrast to the observed SPCZ which slants eastward and turns poleward around the dateline (*Brown et al.*, 2011, 2012a).

1.2 SPICE objectives and organization

At the outset of SPICE in 2005, relatively few observations were available to diagnose the processes and pathways through the complicated geography of the Southwest Pacific. With most of the region difficult to access, a large temporal variability and strong narrow currents, observations and numerical modeling faced serious challenges. This led scientists from France, Australia, USA, New Zealand, Japan and Pacific Island countries to develop a coordinated program, including intensive observations and focussed modeling experiments (*Ganachaud et al.*, 2007, 2008), endorsed by CLIVAR since 2008. SPICE has since been providing a platform to stimulate international collaboration and funding from national programs (*http://clivarspice.org*).

The main aim of SPICE has been to understand the role of the Southwest Pacific Ocean circulation and its influence on climate, from the Tasman Sea to the equator. This has involved complementary challenges to understand:

1. The circulation, boundary currents and jets for the different water masses;
2. Transformation and mixing of these waters during their transit;
3. The circulation variability in conjunction with SPCZ dynamics;
4. The impact on equatorial and Tasman Sea water properties; and
5. The key observation metrics whose monitoring is of importance to climate prediction.

These objectives have been addressed through a combination of analysis of historical observations, new observations and focused modeling efforts. The field programs have measured and monitored the ocean circulation, which have helped validate and improve numerical simulations. In turn, simulations have been used to improve understanding of the dynamics, put observations in context, and provide basic knowledge in unexplored areas.

We have reached a mid-point in SPICE. Some work is ongoing and some questions remained unresolved. As research has progressed, new science perspectives have come into view. SPICE included strong in situ and modeling aspects. The research concentrated on three locations (Coral Sea; Tasman Sea; Solomon Sea); the SPCZ and the oceanic link from the subtropical latitudes to the equator and to the Tasman Sea.

1.3 Major achievements

The *Ganachaud et al.* (2014) review details all operations and recent progresses, and references to a number of articles to be published in that same issue. We now have a much improved understanding of the region. We summarize here the major achievements.

The field program was designed to survey the Southwest Pacific inflows, outflows and Western Boundary Currents (WBCs) quasi simultaneously in a concerted attempt to close the regional mass, heat, and freshwater budgets. An important purpose was also to test ocean transport monitoring technologies (Figure 3).

Specifically, SPICE has lead to

- A refined description of the oceanic pathways to the equator: Jets, WBCs, *direct* NVJ path to the Solomon Sea and EUC water origins; as well as their seasonal and interannual variations;
- The observation that equatorward spiciness anomalies are strongly damped in the LLWBC system, with the transport anomalies dominating the signals;
- Discovery of the deep extension of the NCJ and GPC, versus the broad and shallow NVJ;
- Unprecedented description on the Solomon Sea circulation, its inflows, outflows, and their partitions;
- Discovery of the TF/EAC interplay and opposite variations on decadal timescales;
- A much improved description of the TF outflow and circulation around northern New Zealand;
- A much improved description of the EAC Extension, variability and impact on ocean conditions;
- An improved understanding of the southeastward tilt of the SPCZ in relation with SST, wind and rainfall.

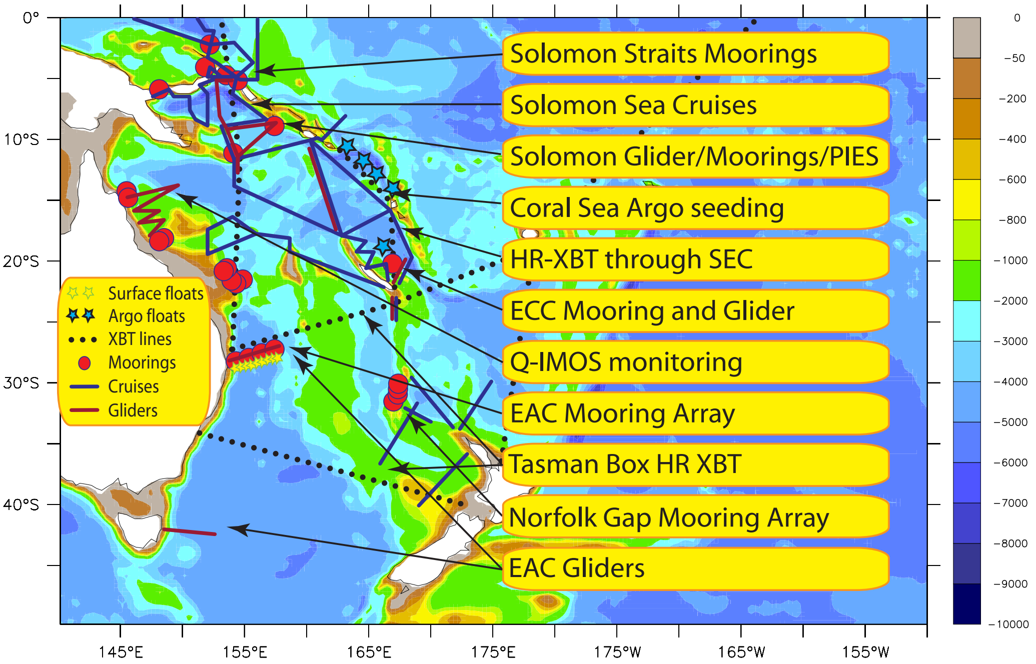

Figure 3: Main elements and regional structure of the SPICE field program, as indicated by the legend. (PIES=Pressure Inverted EchoSounder; HR-XBT=High resolution XBTs; Q-IMOS=Integrated Marine Observing System (Queensland node). The background map and color-bar indicates ocean depth.

2 Future plans and issues

2.1 Ongoing operations

Despite successful simulations and model-based analyses of ocean dynamics in the SPICE region, many numerical modeling challenges remain. Very high resolution (order 1/36°) nested regional simulations are presently analyzed, but the computational burden to run these at basin-scale and over multiple decades is still prohibitive. Other challenges include inaccurate or missing topography at high spatial resolution and lack of accurate multi-scale coast-to-shelf to open-ocean subgrid-scale parameterization, for both vertical and horizontal mixing, including effects by tides and internal waves. Algorithms capable of such full parameterization are under active development.

The high variability seen in both the circulation and water properties (see *Kessler and Cravatte*, 2013, Table 1) produces aliasing in point-wise measurements from cruises and gliders, suggesting that repeat measurements are needed. Monitoring of key currents and transports is ongoing: into the Coral Sea (HR-XBT, mooring and glider measurements across the ECC and SEC (*Maes et al.*, 2011)); Tasman Sea transports through the HR-XBT “Tasman Box” (*Roemmich et al.*, 2005), as well as the Brisbane−Yokohama line that crosses the Coral and Solomon Seas. In the Solomon Sea, two hydrographic surveys were completed and moorings have been deployed since 2012 in the Solomon Straits to provide direct observation of the outflows (*Eldin et al.*, 2013).

The WBC transports through the Solomon Sea are monitored through moorings and repeat gliders, as well as the NQC/GPC off the GBR, whereas the EAC current-meter array measurements are still being pursued (Section 2.4). In addition, Argo floats are released on a regular basis in the SPICE region.

Information about operations is available from the SPICE web site *http://spiceclivar.org*. These new measurements, along with the aforementioned very high resolution simulations, will help better resolve the regional oceanic circulation and atmospheric affects, in the coming $2-3$ years.

2.2 Mixing

Temperature anomalies undergo significant damping along their pathways to the equator and high latitudes. Two model studies identify the Solomon Sea and downstream as areas of strong mixing (*Melet et al.*, 2011; *Grenier et al.*, 2011), as do global simulations of internal wave activity (*Simmons et al.*, 2004), however, in situ measurements are unavailable to verify these simulations. The potentially large mixing contribution from intense mesoscale and sub-mesoscale activity in the Solomon Sea, as well as tidal forcing in the straits also needs to be quantified (Section 2.8 *Gourdeau et al.*, 2014; *Jackson et al.*, 2012). Mixing occurring on the edge of EAC eddies and at the Australian continental shelf due to internal wave energy dissipation is also under investigation (B. Sloyan, personal communication).

2.3 Coral Sea

The deep extent of the NCJ and GPC still needs to be better measured and understood. While the SEC and jets have been thoroughly documented at the entrance of the Coral Sea, three regions lack basic descriptions. The SCJ was not properly documented due to its subsurface nature, high level of eddy activity (*Qiu et al.*, 2009) and priorities given to other currents. The NCJ bifurcation region against Australia, as well as the GPC variability still lack documentation.

2.4 Tasman Sea

Understanding of the full-depth EAC property transport and its time variations is far from complete. We still lack a sustained time series of full-depth property observations of the boundary flow of the EAC across its entire offshore extent that are of sufficient duration to resolve seasonal, interannnual and decadal signals.

The complicated dynamics at the EAC separation point and the high eddy variability makes it challenging to design an appropriate monitoring array. A 2-year mooring array was maintained at 30°S (*Mata et al.*, 2000), but its limited width did not fully resolve the offshore edge of the EAC. Furthermore, its location within the most energetic portion of the EAC eddy field weakened the signal-to-noise ratio. A mooring array was deployed in 2012 in a more suitable location, 26°S, where the EAC is still coherent and its flow is relatively uniform with minimum variability and coincident with an HR-XBTs *Tasman Box* line (Figure 3). Initial analysis of the EAC mooring array indicates large transport variability (K. Ridgway and B. Sloyan, personal communications) and emphasizes the need for the long-term monitoring of the EAC. To fulfill this key observational requirement, redeployment of the IMOS EAC mooring array is planned for mid-2015.

2.5 Solomon Sea

The Solomon Sea circulation, water mass transformation and strait transport partition are presently being measured (Section 2.1). In spite of new observations, three questions remain in the Solomon Sea: 1) Is there a WBC east of the Solomon Islands such as the SICU? 2) How much water is transported in the Indispensable Strait? 3) Is the interannual variability of the flow partition through the different straits similar to what models suggest? These questions will need to be addressed through further in situ measurements.

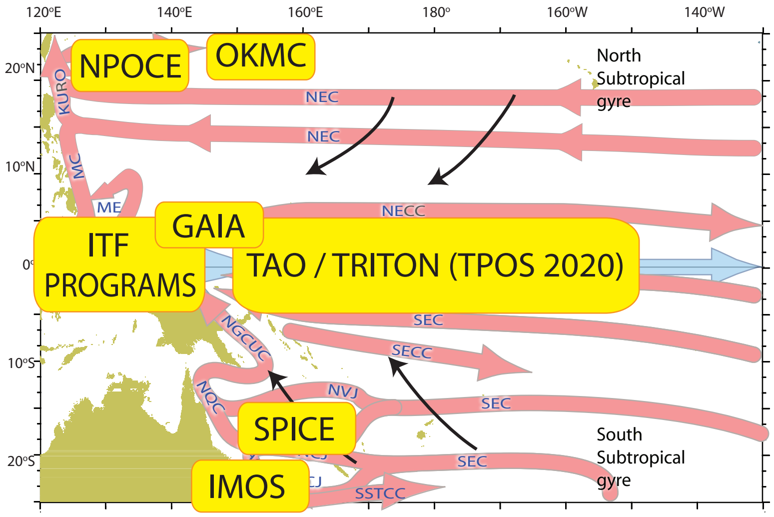

Figure 4: Concurrent CLIVAR programs in the western Pacific. With the equatorial TAO/TRITON array (*http://pmel.noaa.gov/tao*), the Indonesian Throughflow (ITF Gateway; *http://www.ldeo.columbia.edu/res/div/ocp/projects/SE_Asian_Archipelago*), the Northwestern Pacific Ocean Circulation and Climate Experiment (*NPOCE, http://npoce.qdio.ac.cn*), Origins of the Kuroshio and Mindanao Currents (OKMC), Korea Institute of Ocean Science & Technology GAIA observations (*http://eng.kiost.ac*) and SPICE (*http://spiceclivar.org*), all oceanic pathways to the equator are being measured simultaneously.

2.6 Link to the Equator and ENSO

Further investigation is needed to fully identify the main regions and mechanisms responsible for the damping of the subtropical anomalies along different water pathways and how much is ultimately transmitted to the EUC. But the EUC is not the sole destination of the waters exiting the Solomon Sea, and the fate of the anomalies is unclear. For instance, some of the excess waters during an El Niño that may feed the NECC, the EUC (which increases in the far west, but weakens over the central Pacific in the course of El Niño), or the Indonesian Throughflow. We know that the NGCU system contributes to the deep Indonesian Throughflow, but it remains unknown how much is contributed in the surface layer and how the pathways vary with ENSO. LLWBCs of the Northwest Pacific have also been the focus of CLIVAR programs, so that measurements are made north and south of the equator and through the Indonesian Throughflow quasi-simultaneously (Figure 4). Analysis of these adjacent observations will provide a more balanced budget of the equatorial waters supplies.

With these new advances, it will be timely to re-assess the questions of the impact of the Southwest Pacific waters on ENSO, decadal variability and longer climate signals. Such questions include 1) Does refined modeling of the southern thermocline water inflow improve ENSO or decadal prediction? 2) Is monitoring important to ENSO prediction? These issues will need to be addressed using the newly available and developing observational platforms and high-resolution regional models combined with global coupled models.

2.7 Link to high latitudes

The connection between the South Pacific and Indian oceans via the TO varies due to different factors and an improved understanding of its variability and trend is important as it is a component of the global overturning circulation, modulating the global ocean heat and carbon budgets. Whereas the relationship with the TF has been established on decadal timescales, no link between the two systems has been determined at longer timescales. There is abundant evidence to show that the EAC Extension off Tasmania has increased over the past 60 years but the mechanism underlying this trend remains uncertain. For example, *Wu et al.* (2012) suggest that the EAC warming is due to an intensification of the current, whereas previous results indicate that there has been a poleward shift of the South Pacific winds and EAC system within a related poleward displacement of the gyre core (*Cai et al.*, 2005). In contrast, the WBCs and their confluence east of New Zealand (which is the gyre western boundary at these latitudes) show higher temperatures and increased eddy activities, but no southward displacement (*Fernandez et al.*, 2014).

2.8 Future developments and new questions

2.8.1 Submesoscale processes

The present high-resolution numerical simulations point to exceptionally large variability in the Solomon Sea related to mesoscale eddies (*Gourdeau et al.*, 2014; *Hristova et al.*, 2014). The Solomon Sea was used as a regional "modeling laboratory", because of its specific configuration with tides, islands and WBCs. The sub-mesoscale permitting resolution is now providing access to new and rich information, with possible consequences on horizontal and vertical mixing. The discovery of this part of the energy spectrum lead to exploring new approaches of image data assimilation, strongly motivated by the prospects of the SWOT satellite (a NASA/CNES project that will provide map of the sea surface topography at sub-mesoscale resolution over the satellite swath extension *Gaultier et al.*, 2014). The sub-mesoscale features were also observed in surface salinity observations in the Coral Sea (*Maes et al.*, 2013), leading hopefully to new research foci.

2.8.2 Southwest Pacific and climate change

Whereas large uncertainties remain among climate models regarding the ENSO and the SPCZ responses to climate change (*Collins et al.*, 2010; *Brown et al.*, 2012b), the majority of future projections suggest faster warming along the equator compared to the SPCZ region. The changing SST pattern is likely to enhance equatorial convection (*Ma et al.*, 2012), strengthen southeasterly trade winds and weaken meridional SST gradients (*Xie et al.*, 2010), potentially leading to moisture divergence and future drying in parts of the SPCZ (*Widlansky et al.*, 2012). The uneven future warming of the tropical Pacific may almost double the frequency of 'zonal-SPCZ' events, possibly shifting the mean rainfall pattern equatorward (*Cai et al.*, 2012; *Widlansky et al.*, 2012), with direct consequences on freshwater resources in the Pacific islands.

Projected changes to the wind strength and direction in the South Pacific will affect Southwest Pacific currents. To the south, high-resolution regional models embedded in global climate simulations project increased transport in the EAC Extension during the 21^{st} century (*Sun et al.*, 2012; *Oliver and Holbrook*, 2014a). Similarly, direct examination of CMIP projections suggests future increase in the NGCU transport towards the equator (*Sen Gupta et al.*, 2012), with foreseeable changes in the thermocline structure and water properties. Together, these simulations suggest likely future impacts on ENSO dynamics and equatorial ecosystems.

2.8.3 Towards coastal and island scales

Islands in the Southwest Pacific region are particularly sensitive to climate variability and the oceanic environment. Over the past 20 years, sea level around the SPICE region has risen at over three times the global average rate (*Meyssignac et al.*, 2012) and the ocean acidification combined with ocean warming could jeopardize coral growth towards the middle of this century or even before

(*Veron et al.*, 2009). Clearly, sustainable development in the region must incorporate adaptation to climate variability and change.

Island sea level, SST and climate is controlled by the ocean via both basin scale conditions and local processes. Drought and flooding events are often related to ENSO conditions and the associated location and intensity of the SPCZ (e.g., *Murphy et al.*, 2014), which also influences sea level variability (*Widlansky et al.*, 2014). Furthermore, the ocean conditions control local temperature and air-sea fluxes, tropical cyclone intensity and trajectories, transports of fish larvae as well as steric sea level.

SPICE has led to new measurements and modeling of the Southwest Pacific. Numerical simulations and ocean assimilation products are more accurate, providing improved boundary conditions to high-resolution models on island scales. Coastal and island processes alter the large scale conditions in various ways, specific to each place and therefore requiring focussed studies (see, e.g., *Schiller et al.* (2009) regarding the GBR; *Ganachaud et al.* (2010); *Lefevre et al.* (2010); *Marchesiello et al.* (2010); *Fuchs et al.* (2012); Cravatte, S., E. Kestenare, J. Lefevre, and G. Eldin, Circulation around New Caledonia from SADCP data, altimetry, and numerical simulations (in preparation), regarding the island of New Caledonia).

3 Relevance to CLIVAR

SPICE has been built to contribute to the CLIVAR objectives, with a large-scale approach targeted toward decadal climate prediction through a better understanding and modeling of the equatorial and southwest Pacific Ocean circulation, and an embedded smaller-scale objective targeted toward coastal and island climate processes and prediction. There is a particular focus here on western boundary currents, which are recognized as a key issue by CLIVAR because they accomplish a large and rapid meridional transport of mass and heat. Though the Southwest Pacific boundary currents are less studied than in other parts of the world, they are of special interest for climate because they provide an efficient communication from the subtropical gyre to the equator. In SPICE we take the first steps toward implementing the observations necessary to interpret the southwest Pacific circulation and its effects on local and remote climate, and to build a regional observing system that will allow on- going monitoring of its variability.

SPICE contributes to the new CLIVAR imperatives in the following ways:

- Imperative 1 (Improved atmosphere and ocean component models of Earth System Models. Reduce the negative impact of biases in model representations of atmospheric and oceanic processes): improvement of the knowledge of the circulation and its modeling, as major contributors to the Warm Pool, EUC, EAC and Tasman Outflow, which all are major components of the regional and basin-scale climate systems.
- Imperative 2: (Data synthesis, analysis, reanalysis and uncertainty. Provide credibility to climate projections by understanding the past and present state of the ocean): SPICE-stimulated in situ data, as well as high resolution regional numerical simulations, which all comply with the CLIVAR data policy.
- Imperative 3: (Ocean observing system. Maintain over many decades a sustained ocean observing system capable of detecting and documenting global climate change): SPICE identified key observation metrics whose monitoring is of importance to climate prediction and demonstrated the measurement feasibility, e.g. EAC, SEC and NGCU transports.
- Imperative 4 (Capacity building): SPICE involved early Pacific Island Countries through the Secretariat of the Pacific Community (SPC), Pacific Island-GOOS (South Pacific Regional

Environmental Programme, Samoa); University of the South Pacific (USP, Fiji) and University of Papua-New Guinea (UPNG). A second thesis is starting in collaboration with USP; and a SPICE training workshop took place at UPNG in 2013. UPNG students or faculty embarked regularly on SPICE cruises.

SPICE contributes to the new CLIVAR Research Foci, essentially:

- Decadal variability and predictability of ocean and climate variability
- Marine biophysical interactions and dynamics of upwelling systems (near Pacific Islands and in the PNG area)
- Dynamics of regional sea level variability
- ENSO in a changing climate

References

Brown, J. N., et al. (2012a), Implications of CMIP3 model biases and uncertainties for climate projections in the western tropical pacific, *Climatic Change*, doi: 10.1007/s10584-012-0603-5.

Brown, J. R., S. B. Power, F. P. Delage, R. A. Colman, A. F. Moise, and B. F. Murphy (2011), Evaluation of the south pacific convergence zone in IPCC AR4 climate model simulations of the twentieth century, *Journal of Climate*, *24*(6), 1565–1582, doi:10.1175/2010JCLI3942.1.

Brown, J. R., A. F. Moise, and R. A. Colman (2012b), The south pacific convergence zone in CMIP5 simulations of historical and future climate, *Climate Dynamics*, doi:10.1007/s00382-012-1591-x.

Cai, W. (2006), Antarctic ozone depletion causes an intensification of the southern ocean super-gyre circulation, *Geophysical Research Letters*, *33*(3), doi: 10.1029/2005GL024911.

Cai, W., G. Shi, T. Cowan, D. Bi, and J. Ribbe (2005), The response of the southern annular mode, the east australian current, and the southern mid-latitude ocean circulation to global warming, *Geophysical Research Letters*, *32*(23), L23,706.

Cai, W., et al. (2012), More extreme swings of the south pacific convergence zone due to greenhouse warming, *Nature*, *488*(7411), 365–369, doi:10.1038/nature11358.

Collins, M., et al. (2010), The impact of global warming on the tropical pacific ocean and el nino, *Nature Geoscience*, *3*(6), 391–397, doi:10.1038/ngeo868.

Eldin, G., A. Ganachaud, S. Cravatte, and C. Jeandel (2013), Pandora cruise provides an unprecedented description of the solomon sea, *CLIVAR Newsletter Exchanges*, *61*(18), 24–25.

Fernandez, D., M. Bowen, and Carter (2014), Intensification and variability of the confluence of subtropical and subantarctic boundary currents east of new zealand, *J. Geophys. Res. Special Issue on Western Pacific Ocean Circulation and Climate, SUBMITTED.*

Fine, R. A., R. Lukas, F. M. Bingham, M. J. Warner, and R. H. Gammon (1994), The western equatorial pacific: A water mass crossroads, *Journal of Geophysical Research*, *99*, 25,063–25,080, doi:10.1029/94JC02277.

Fuchs, R., C. Dupouy, P. Douillet, M. Caillaud, A. Mangin, and C. Pinazo (2012), Modelling the impact of a la nina event on a south west pacific lagoon, *Marine Pollution Bulletin*, (0), doi:10.1016/j.marpolbul.2012.05.016.

Ganachaud, A., et al. (2007), Southwest pacific ocean circulation and climate experiment (SPICE). part 1. scientific background, *Tech. rep.*, NOAA.

Ganachaud, A., et al. (2008), *Southwest Pacific ocean circulation and climate experiment (SPICE): part 2. Implementation plan*, no. 133 in CLIVAR Publication Series, NOAA.

Ganachaud, A., A. Vega, M. Rodier, C. Dupouy, C. Maes, P. Marchesiello, G. Eldin, K. Ridgway, and R. Le Borgne (2010), Observed impact of upwelling events on water properties and biological activity off the southwest coast of new caledonia, *Marine Pollution Bulletin*, *61*(7-12), 449–464.

Ganachaud, A., et al. (2013), Advances from the southwest pacific ocean circulation and climate experiment (SPICE), *CLIVAR Newsletter Exchanges*, *18*(61), 16–23.

Ganachaud, A., et al. (2014), Ocean circulation of the southwest pacific: new insights from the southwest pacific ocean and climate experiment (SPICE), *J. Geophys. Res.*, *SUBMITTED TO SPECIAL ISSUE on Western Pacific Ocean Circulation and Climate.*

Gaultier, L., B. Djath, J. Verron, A. Melet, J.-M. Brankart, and P. Brasseur (2014), Assessing the feasibility of the inversion of sub-mesoscales in a high-resolution solomon sea model, *J. Geophys. Res. Special Issue on Western Pacific Ocean Circulation and Climate, SUBMITTED.*

Godfrey, J. S. (1989), A sverdrup model of the depth-integrated flow for the world ocean allowing for island circulations, *Geophysical & Astrophysical Fluid Dynamics*, *45*(1-2), 89–112, doi:10.1080/03091928908208894.

Gourdeau, L., J. Verron, A. Melet, W. Kessler, F. Marin, and B. Djath (2014), Exploring the mesoscale activity in the solomon sea: A complementary approach with a numerical model and altimetric data, *Journal of Geophysical Research: Oceans*, *119*(4), 2290–2311, doi:10.1002/2013JC009614.

Grenier, M., S. Cravatte, B. Blanke, C. Menkes, A. Koch-Larrouy, F. Durand, A. Melet, and C. Jeandel (2011), From the western boundary currents to the pacific equatorial undercurrent: Modeled pathways and water mass evolutions, *Journal of Geophysical Research*, *116*(C12), C12,044.

Grenier, M., C. Jeandel, and S. Cravatte (2014), From the subtropicss to the equator in the southwest pacific: Continental material fluxes quantified using neodymium parameters along modeled thermocline water pathways, *J. Geophys. Res. Special Issue on Western Pacific Ocean Circulation and Climate, in press.*

Gu, D., and S. G. Philander (1997), Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, *Science*, *275*(5301), 805–807, doi:10.1126/science.275.5301.805.

Hartin, C. A., R. A. Fine, B. M. Sloyan, L. D. Talley, T. K. Chereskin, and J. Happell (2011), Formation rates of subantarctic mode water and antarctic intermediate water within the south pacific, *Deep Sea Research Part I: Oceanographic Research Papers*, *58*(5), 524–534, doi:10.1016/j.dsr.2011.02.010.

Hasson, A., T. Delcroix, and J. Boutin (2013), Formation and variability of the south pacific sea surface salinity maximum in recent decades, *Journal of Geophysical Research: Oceans*, doi:10.1002/jgrc.20367.

Hristova, H. G., W. Kessler, J. C. McWilliams, and M. J. Molemaker (2014), Mesoscale variability and its seasonal variability in the solomon and coral seas, *J. Geophys. Res. Special Issue on Western Pacific Ocean Circulation and Climate*, *SUBMITTED.*

Jackson, C., J. da Silva, and G. Jeans (2012), The generation of nonlinear internal waves, *Oceanography*, *25*(2), 108–123, doi:10.5670/oceanog.2012.46.

Kessler, W. S., and S. Cravatte (2013), ENSO and short-term variability of the south equatorial current entering the coral sea, *Journal of Physical Oceanography*, *e-view*, doi:10.1175/JPO-D-12-0113.1.

Kleeman, R., J. P. McCreary, and B. A. Klinger (1999), A mechanism for generating ENSO decadal variability, *Geophysical Research Letters*, *26*(12), 1743–1746, doi:10.1029/1999GL900352.

Kolodziejczyk, N., and F. Gaillard (2012), Observation of spiciness interannual variability in the pacific pycnocline, *Journal of Geophysical Research*, doi:10.1029/2012JC008365.

Lee, T., and I. Fukumori (2003), Interannual-to-decadal variations of TropicalSubtropical exchange in the pacific ocean: Boundary versus interior pycnocline transports, *Journal of Climate*, *16*(24), 4022–4042, doi:10.1175/1520-0442(2003)016⟨4022:IVOTEI⟩2.0.CO;2.

Lefevre, J., P. Marchesiello, N. C. Jourdain, C. Menkes, and A. Leroy (2010), Weather regimes and orographic circulation around new caledonia, *Marine Pollution Bulletin*, *61*(7-12), 413–431, doi:10.1016/j.marpolbul.2010.06.012.

Luo, Y., L. M. Rothstein, R.-H. Zhang, and A. Busalacchi (2005), On the connection between south pacific subtropical spiciness anomalies and decadal equatorial variability in an ocean general circulation model, *Journal of Geophysical Research*, *110*(C10), doi:10.1029/2004JC002655.

Ma, J., S.-P. Xie, and Y. Kosaka (2012), Mechanisms for tropical tropospheric circulation change in response to global warming, *Journal of Climate*, *25*(8), 2979–2994, doi:10.1175/JCLI-D-11-00048.1.

Maes, C., D. Varillon, A. Ganachaud, F. Gasparin, L. Gourdeau, and F. Durand (2011), Geostrophic component of oceanic jets entering in the eastern coral sea observed with high-resolution XBT surveys (2008-2010), *Coriolis Mercator Ocean Quaterly Newsletter*, (special 41), 25–32.

Maes, C., B. Dewitte, J. Sudre, V. Garcon, and D. Varillon (2013), Small-scale features of temperature and salinity surface fields in the coral sea, *Journal of Geophysical Research: Oceans*, doi:10.1002/jgrc.20344.

Marchesiello, P., J. Lefevre, A. Vega, X. Couvelard, and C. Menkes (2010), Coastal upwelling, circulation and heat balance around new caledonia's barrier reef, *Marine Pollution Bulletin*, *61*(7-12), 432–448, doi:10.1016/j.marpolbul.2010.06.043.

Mata, M. M., M. Tomczak, S. Wijffels, and J. A. Church (2000), East australian current volume transports at 30S: estimates from the world ocean circulation experiment hydrographic sections PR11/P6 and the PCM3 current meter array, *Journal of Geophysical Research*, *105*(C12), 28,509–28,526, doi:200010.1029/1999JC000121.

Matear, R. J., M. A. Chamberlain, C. Sun, and M. Feng (2013), Climate change projection of the tasman sea from an eddy-resolving ocean model, *Journal of Geophysical Research: Oceans*, *118*(6), 29612976, doi:10.1002/jgrc.20202.

McCreary, J. P., and P. Lu (1994), Interaction between the subtropical and equatorial ocean circulations: The subtropical cell, *Journal of Physical Oceanography*, *24*(2), 466–497, doi:10.1175/1520-0485(1994)024⟨0466:IBTSAE⟩2.0.CO;2.

McPhaden, M. J., and D. Zhang (2002), Slowdown of the meridional overturning circulation in the upper pacific ocean, *Nature*, *415*(6872), 603608.

Melet, A., J. Verron, L. Gourdeau, and A. Koch-Larrouy (2011), Equatorward pathways of solomon sea water masses and their modifications, *Journal of Physical Oceanography*, *41*, 810–826, doi:10.1175/2010JPO4559.1.

Meyssignac, B., D. Salas y Melia, M. Becker, W. Llovel, and A. Cazenave (2012), Tropical pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature?, *Climate of the Past*, *8*(2), 787–802, doi:10.5194/cp-8-787-2012.

Murphy, B. F., S. B. Power, and S. McGree (2014), The varied impacts of el NinoSouthern oscillation on pacific island climates, *Journal of Climate*, *27*(11), 4015–4036, doi:10.1175/JCLI-D-13-00130.1.

Nonaka, M., and H. Sasaki (2007), Formation mechanism for isopycnal TemperatureSalinity anomalies propagating from the eastern south pacific to the equatorial region, *Journal of Climate*, *20*(7), 1305–1315, doi:10.1175/JCLI4065.1.

Oliver, E. C. J., and N. J. Holbrook (2014a), Extending our understanding of south pacific gyre "spin-up": Modeling the east australian current in a future climate, *Journal of Geophysical Research: Oceans*, doi:10.1002/2013JC009591.

Oliver, E. C. J., and N. J. Holbrook (2014b), A statistical method for improving continental shelf and nearshore marine climate predictions, *Journal of Atmospheric and Oceanic Technology*, *31*(1), 216–232, doi:10.1175/JTECH-D-13-00052.1.

Oliver, E. C. J., S. J. Wotherspoon, M. A. Chamberlain, and N. J. Holbrook (2014), Projected tasman sea extremes in sea surface temperature through the twenty-first century, *Journal of Climate*, *27*(5), 1980–1998, doi:10.1175/JCLI-D-13-00259.1.

Qiu, B., S. Chen, and W. S. Kessler (2009), Source of the 70-day mesoscale eddy variability in the coral sea and the north fiji basin, *Journal of Physical Oceanography*, *39*(2), 404–420, doi:10.1175/2008JPO3988.1.

Qu, T., and E. J. Lindstrom (2002), A climatological interpretation of the circulation in the western south pacific, *Journal of Physical Oceanography*, *32*(9), 2492–2508, doi:10.1175/1520-0485-32.9.2492.

Qu, T., and E. J. Lindstrom (2004), Northward intrusion of antarctic intermediate water in the western pacific, *Journal of Physical Oceanography*, *34*(9), 2104–2118, doi:10.1175/1520-0485(2004)034⟨2104:NIOAIW⟩2.0.CO;2.

Qu, T., S. Gao, I. Fukumori, R. A. Fine, and E. J. Lindstrom (2008), Subduction of south pacific waters, *Geophysical Research Letters*, *35*(2), doi:10.1029/2007GL032605.

Qu, T., S. Gao, I. Fukumori, R. A. Fine, and E. J. Lindstrom (2009), Origin and pathway of equatorial 13C water in the pacific identified by a simulated passive tracer and its adjoint, *Journal of Physical Oceanography*, *39*(8), 1836–1853, doi:10.1175/2009JPO4045.1.

Qu, T., S. Gao, and R. A. Fine (2013), Subduction of south pacific tropical water and its equatorward pathways as shown by a simulated passive tracer, *Journal of Physical Oceanography*, *43*(8), 1551–1565, doi:10.1175/JPO-D-12-0180.1.

Ridgway, K. (2003), Mesoscale structure of the mean east australian current system and its relationship with topography, *Progress In Oceanography*, *56*(2), 189–222, doi:10.1016/S0079-6611(03)00004-1.

Ridgway, K. R., and J. R. Dunn (2007), Observational evidence for a southern hemisphere oceanic supergyre, *Geophysical Research Letters*, *34*(13), doi:10.1029/2007GL030392.

Ridgway, K. R., J. R. Dunn, and J. L. Wilkin (2002), Ocean interpolation by four-dimensional weighted least squares–application to the waters around australasia, *Journal of Atmospheric and Oceanic Technology*, *19*(9), 1357–1375, doi:10.1175/1520-0426(2002)019⟨1357:OIBFDW⟩2.0.CO;2.

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*(13), 2330–2343, doi:10.1175/JCLI3409.1.

Sallee, J.-B., K. Speer, S. Rintoul, and S. Wijffels (2010), Southern ocean thermocline ventilation, *Journal of Physical Oceanography*, *40*(3), 509–529, doi:10.1175/2009JPO4291.1.

Schiller, A., K. R. Ridgway, C. R. Steinberg, and P. R. Oke (2009), Dynamics of three anomalous SST events in the coral sea, *Geophysical Research Letters*, *36*, doi:10.1029/2008GL036997.

Sen Gupta, A., A. Ganachaud, S. McGregor, J. N. Brown, and L. C. Muir (2012), Drivers of the projected changes to the pacific ocean equatorial circulation, *Geophys. Res. Lett*, *39*(9), doi:10.1029/2012GL051447.

Simmons, H. L., R. W. Hallberg, and B. K. Arbic (2004), Internal wave generation in a global baroclinic tide model, *Deep Sea Research Part II: Topical Studies in Oceanography*, *51*(25-26), 3043–3068, doi:10.1016/j.dsr2.2004.09.015.

Speich, S., B. Blanke, P. de Vries, S. Drijfhout, K. Doos, A. Ganachaud, and R. Marsh (2002), Tasman leakage: A new route in the global ocean conveyor belt, *Geophysical Research Letters*, *29*(10), doi:10.1029/2001GL014586.

Sprintall, J., D. Roemmich, B. Stanton, and R. Bailey (1995), Regional climate variability and ocean heat transport in the southwest pacific ocean, *Journal of Geophysical Research*, *100*(C8), 15,865, doi:10.1029/95JC01664.

Sun, C., M. Feng, R. J. Matear, M. A. Chamberlain, P. Craig, K. R. Ridgway, and A. Schiller (2012), Marine downscaling of a future climate scenario for australian boundary currents, *Journal of Climate*, *25*(8), 2947–2962, doi:10.1175/JCLI-D-11-00159.1.

Tsubouchi, T., T. Suga, and K. Hanawa (2007), Three types of south pacific subtropical mode waters: Their relation to the large-scale circulation of the south pacific subtropical gyre and their temporal variability, *Journal of Physical Oceanography*, *37*(10), 2478–2490, doi:10.1175/JPO3132.1.

Veron, J., et al. (2009), The coral reef crisis: The critical importance of <350 ppm CO2, *Marine Pollution Bulletin*, *58*(10), 1428–1436, doi:10.1016/j.marpolbul.2009.09.009.

Webb, D. J. (2000), Evidence for shallow zonal jets in the south equatorial current region of the southwest pacific, *Journal of Physical Oceanography*, *30*(4), 706720.

Widlansky, M. J., A. Timmermann, K. Stein, S. McGregor, N. Schneider, M. H. England, M. Lengaigne, and W. Cai (2012), Changes in south pacific rainfall bands in a warming climate, *Nature Climate Change*, doi:10.1038/nclimate1726.

Widlansky, M. J., A. Timmermann, S. McGregor, M. F. Stuecker, and W. Cai (2014), An interhemispheric tropical sea level seesaw due to el nino taimasa, *Journal of Climate*, *27*(3), 1070–1081, doi:10.1175/JCLI-D-13-00276.1.

Wu, L., et al. (2012), Enhanced warming over the global subtropical western boundary currents, *Nature Climate Change*, *2*(3), 161–166, doi:10.1038/nclimate1353.

Xie, S.-P., C. Deser, G. A. Vecchi, J. Ma, H. Teng, and A. T. Wittenberg (2010), Global warming pattern formation: Sea surface temperature and rainfall, *Journal of Climate*, *23*, 966–986, doi:10.1175/2009JCLI3329.1.

Zhang, C. (2001), Intraseasonal perturbations in sea surface temperatures of the equatorial eastern pacific and their association with the MaddenJulian oscillation, *Journal of Climate*, *14*(6), 1309–1322, doi:10.1175/1520-0442(2001)014⟨1309:IPISST⟩2.0.CO;2.

Zhang, L., and T. Qu (2014), Low-frequency variability of south pacific tropical water from argo: ZHANG ET. AL.; LOW FREQUENCY VARIABILITY OF SPTW, *Geophysical Research Letters*, *41*(7), 2441–2446, doi: 10.1002/2014GL059490.