Advances from the Southwest Pacific Ocean circulation and climate experiment (SPICE)

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Endorsed by CLIVAR in 2008, the Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) is an international research project which aims to understand the southwest Pacific Ocean circulation, as well as its direct and indirect influence on both regional and basin-scale climate, and the South Pacific Convergence Zone (SPCZ). SPICE was designed to measure and monitor the ocean circulation, and to validate and improve numerical models.

South Pacific thermocline waters are transported in the westward flowing South Equatorial Current (SEC), from the subtropical gyre centre toward the southwest Pacific Ocean - creating a major circulation pathway that redistributes water from the subtropics to the equator and to the southern ocean (Figure 1). The transit in the Coral, Solomon and Tasman Seas is potentially of great importance to the climate system. Changes in either the temperature or the amount of water arriving at the equator have the capability to modulate the El Niño Southern Oscillation (ENSO) and produce basin-scale climate feedbacks. The southward thermocline pathways are, comparably, of major influence on Australia and New Zealand areas, affecting climate and biodiversity.

At the outset of SPICE in 2005, few observations were available to diagnose the processes and pathways through the complicated geography of the southwest Pacific. The region is remote, and the large temporal variability and strong narrow currents in a complex bathymetry posed serious challenges to both observation and numerical modelling. This led scientists from France, Australia, USA, New Zealand, Japan and several Pacific Island countries to develop a coordinated program, including intensive observations and focussed modelling experiments (Ganachaud et al. 2007, 2008a). Since its inception, the SPICE modelling and regional field studies have addressed many aspects of the Southwest Pacific: heat and mass transports; properties and dynamics of the strong boundary currents and jets; and water mass transformations.

SPICE provides a platform to stimulate international collaboration and funding from national programs (http://www.obs-mip.fr/spice). Data collected during SPICE are shared following the CLIVAR data policy, and distributed through existing national facilities.

While SPICE is regionally focused, it integrates basin-scale studies of the ocean-atmosphere system. Those, including the South Pacific circulation and its connection with equatorial processes and climate variability, are more broadly addressed within CLIVAR.

We summarize here the recent progress, following two major meetings: a SPICE special session at the 10th International Conference on Southern Hemisphere Meteorology and Oceanography, Nouméa, April 2012; and the Western Pacific Ocean Circulation and Climate, Qingdao, October 2012 which allied SPICE and the Northwestern Pacific Ocean Circulation and Climate Experiment (NPOCE) scopes.

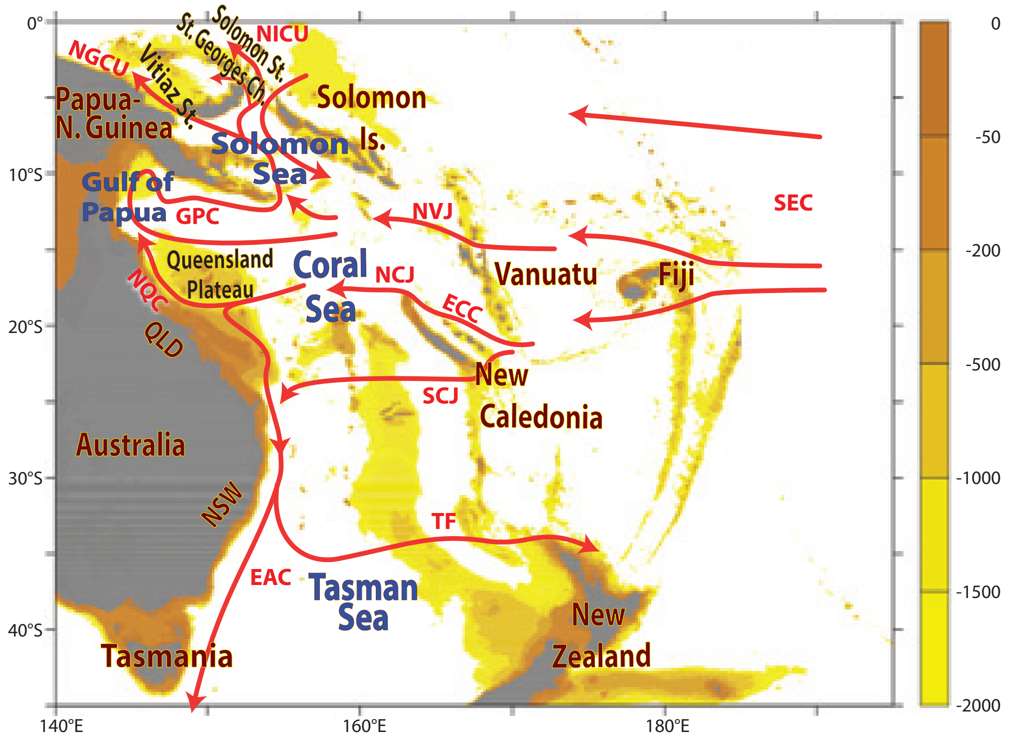

Figure 1. Topography of the southwest Pacific, where only depths shallower than 2000 meters are shaded (QLD=Queensland; NSW=New South Wales). Red arrows denote the main thermocline currents (SEC=South Equatorial Current; NVJ=North Vanuatu Jet; ECC= East Caledonian Current; NCJ=North Caledonian Jet; SCJ=South 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). Surface counter currents are not represented for clarity.

Modelling groups and efforts

To unravel the dynamics of basin-scale climate variability in this ecologically sensitive region, SPICE researchers use global and regional models, at eddy-resolving spatial scales (10km and less), to explore mesoscale activity, multi-decadal climate trends and link coastal impacts to regional and global phenomena such as ENSO, the South Annular Mode (SAM) and Pacific Decadal Oscillation (PDO). Furthermore, there is an increasing synergy between climate modelling and operational oceanography efforts such as those pursued by MERCATOR Ocean and BLUElink. Combining observations and models enables the exploration and analysis of;

- The jet-like structures in the SPICE area;
- The eddy dynamics in boundary currents such as the East Australian and the Gulf of Papua Currents;
- The shelf-scale upwelling processes
- The dynamical drivers of sea surface temperature (SST) anomalies in the Coral Sea and associated coral bleaching events.

Despite successful simulations and model-based analyses of ocean dynamics in the SPICE region, many model-related challenges remain. Eddy-resolving models covering the whole SPICE domain still do not have the spatial and vertical resolution necessary to fully resolve all key features such as narrow jets between islands, sub-mesoscale phenomena of the western boundary currents (WBC), reefs and straits which dominate large parts of the region, e.g., the Great Barrier Reef. High resolution (1/36°) nested regional simulations are presently analyzed, but the computational burden to run these at basin-scale over multiple decades is still prohibitive and –if pursued- would require a truly major international effort. Other related issues include inaccurate or missing topography at high spatial resolution, and lack of accurate multi-scale coast-to-shelf-to-open ocean sub grid-scale parameterisations, for both vertical and horizontal mixing, (including effects by tides). Algorithms capable of fully parameterising such modelling challenges are under active development but it will take some time before they become available to the broader scientific community.

In situ observations

The SPICE field program (Figure 2) aimed to:

- Complete large-scale surveys of the Coral, Solomon, and Tasman Sea inflows and outflows with special attention to the WBC;
- Test large scale monitoring of key climate quantities such as the thermocline inflows and outflows and air-sea fluxes;
- Observe simultaneously in different parts of the basin to accomplish regional mass, heat, and freshwater budgets;
- Achieve island-scale process studies to address local specificities.

High-resolution hydrographic surveys of the water column provide temperature, salinity and dissolved oxygen down to at least 2000 m. When possible, nutrient and geochemical data were collected, in collaboration with the GEOTRACES programme. Glider measurements first served to demonstrate the application of recent technology with lines in the Solomon Sea; across the western boundary currents off Queensland and New South Wales; and two coastal jets near New Caledonia. Since 2007 gliders have monitored the transport across the Solomon Sea, with four to eight crossings annually . Moorings and Pressure Inverted EchoSounders (PIES) deployed across the entrance of the Solomon Sea have provided horizontal integrals of mass transport, with high temporal resolution. EXpandable bathyThermograph (XBT) probes were deployed at high resolution across key sections, providing a temperature survey of the upper water column and associated oceanic transports. Sections, initiated in 1991 across the “Tasman box” were continued, in conjunction with the onset new sections. Argo floats seeded in southwest Pacific during SPICE increased the number of temperature and salinity profiles from 50 per year in 2005 to 1700 per year in 2011. Surface drifters were released on cruise or XBT lines with an enhanced focus on the Eastern Australian Current (EAC).

Main scientific advancements

With a partition of each group's efforts into geographic or topical sector (Figure 1), numerous observations were collected, greatly improving numerical simulations.

Coral Sea

The bulk of the South subtropical gyre water enters the Coral Sea in the broad South Equatorial Current (SEC; Figure 1). It then divides into jets that were pointed out in early numerical simulations and data-deficient climatologies. In situ SPICE observations confirmed the circulation schematics and revealed its vertical structure, with a broad and shallow North Vanuatu Jet (NVJ) and a narrow and deep North Caledonian Jet (NCJ) (Gourdeau et al. 2008, Ganachaud et al. 2008b), which both have a strong surface signature as shown by drifter observations (Choukroun et al 2010). The NCJ sources from East Caledonia Current (ECC) waters (Maes et al. 2007, Gasparin et al. 2011). Limited observations suggest the presence of a South Caledonian Jet (SCJ), and further characterization will come from new glider data. Against the coast of Australia, the NCJ bifurcates feeding the boundary currents; the East Australian Current (EAC) to the south and North Queensland Current (NQC) to the north, (Choukroun et al. 2010).

The NQC waters flow clockwise against the Gulf of Papua coast, leading the community to name it the Gulf of Papua Current (SPICE community, 2012), and eventually feed into the Solomon Sea. In the lee of Vanuatu Islands, and just south of the NVJ, a counter current was discovered, the Coral Sea Counter Current (Qiu et al. 2009). Similarly, a Fiji Basin Counter Current was found to the west of Fiji. More accurate bathymetry has greatly improved currents in numerical simulations in the Coral Sea (Schiller et al. 2008). Previously these dynamically important straits between islands were not well represented in simulations, resulting in spurious jets to the north of south of the islands.

The Coral Sea jets and counter currents result in dynamical instabilities and high variability, generating westward-moving Rossby waves (Maharaj et al. 2007, 2009, Qiu et al. 2009). At seasonal to decadal timescales, the SEC, the jets and WBCs respond to large scale forcing, either locally or remotely depending upon latitude and timescale (Qiu and Chen 2006, Kessler and Gourdeau 2006, 2007, Roemmich et al. 2007). An El Niño event generally enhances the SEC transport and the transport entering into the Solomon Sea (Kessler and Cravatte 2013; Davis et al., 2012; Melet et al., 2010b, 2013), particularly in the NVJ.

Tasman Sea

The EAC provides both the western boundary of the South Pacific Gyre and the linking element between the Pacific and Indian Ocean gyres. Climatology shows that the EAC strengthens southward along the coast and then separates into filaments that are northeastward (STCC), eastward Tasman Front (TF, Figure 1), and a residual "Tasman Outflow" to the south. This circulation was identified as part of a supergyre that flows westward around Tasmania and connects the south Pacific subtropical gyre with the Indian Ocean, thereby redistributing waters amongst the major oceanic basins (Ridgway and Dunn 2007).

In situ measurements were intensified with the start of the Australian Integrated Marine Observing System (IMOS) programme in 2007 (Figure 2) and the deployment of hydrography and mooring arrays in the Tasman Front and subtropical boundary current around New Zealand (Sutton and Bowen 2011). Along with new ocean simulations and ocean state estimates (Schiller et al 2008, Brassington et al. 2007), they permitted major new documentation of the average circulation, its variability and corresponding mechanisms in the region. Combined satellite and in situ data showed that net poleward flow across the Tasman Sea has a strong variability on eddy scale; seasonal and interannual to decadal scales that affect seawater properties (Ridgway 2007a, Ridgway et al. 2008,

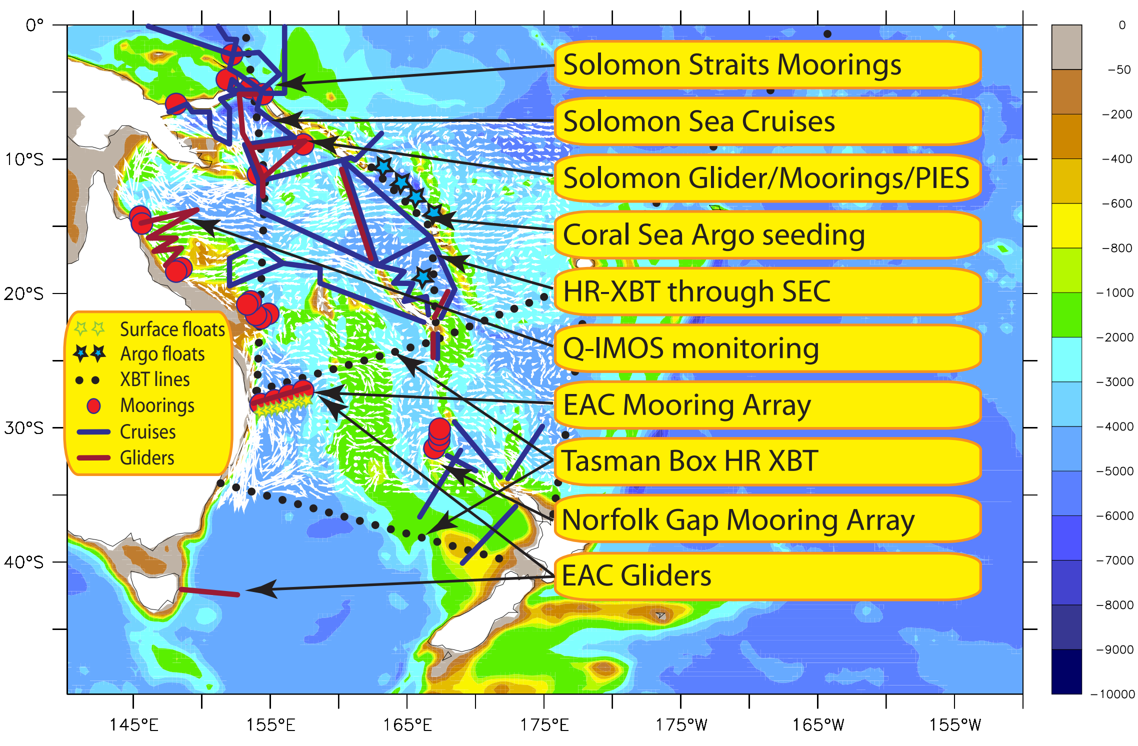

Figure 2. SPICE field program. White arrows indicate the 0-1000m integration of CARS geostrophic velocities referenced to velocities from Argo float trajectories (Kessler and Cravatte, 2013).

Holbrook and Maharaj 2008). The decadal variations were related to basin wide wind stress increases, consistent with linear dynamics, with increases in the EAC and decreases in the Tasman Front flow (Hill et al. 2008).

Over long time scales, the supergyre spin-up revealed by Argo data and altimetry (Roemmich et al 2007) implies an enhanced EAC, resulting in observed warmer, saltier waters near Tasmania (Ridgway 2007a,b, Hill et al. 2008) and higher sea level near Sydney (Holbrook et al 2010).

Solomon Sea

The Solomon Sea is a necessary transit for WBC waters on their way to the equator, where intense flows encounter complex and steep topography. This is by far the less documented sea of the southwest Pacific, and before 2007, there were very few in situ measurements besides scattered ADCP and XBT data collected during ship transits. Only very high-resolution numerical models (>1/12°) were able to simulate the flow through the narrow straits. Along with climatologies of shipboard-ADCP data and surface drifters, they revealed a first description of the inside circulation, pointing out the partition of the New Guinea Coastal Undercurrent (NGCU) into Vitiaz and Solomon straits (Melet et al. 2010a; Cravatte et al. 2011, Hristova and Kessler 2011). The inflow from the Coral Sea was estimated by a dedicated cruise, continuously repeated glider transects and Argo floats (Gasparin et al. 2012, Davis et al. 2012, Zilberman et al. in press).

The Solomon Sea was found to be the region of highest sea level variability of the subtropical South Pacific. From sea surface height satellite data, drifters and simulations, the seasonal variations of thermocline waters were described in relation with subtropical and equatorial dynamics, and the local wind influence (Melet et al. 2010a,b, Hristova and Kessler 2011, Zilberman et al. in press). Large interannual transport variations were observed by gliders (Davis et al. 2012) and in numerical simulations. El Niño events increase equatorward transport, and because the flow becomes saturated in Vitiaz Strait, more water is diverted through Solomon Strait (Melet et al. 2013).

Link to the equator and high latitudes

Subtropical to Equator and high latitudes pathways:
North of the Solomon Sea, waters join the equatorial warm pool at the surface, and the equatorial undercurrent (EUC) just below. Numerical simulations, corroborated by existing observations, suggest that ~70% of EUC water comes from the combined Vitiaz and Solomon straits, the partition of which controls their route and fate (Grenier et al. 2011). In upper layers, the western boundary currents vary in opposition to the equatorial warm water volume (Melet et al., 2010b; Lengaigne et al. 2012), which is a predictor of ENSO characteristics (Bosc and Delcroix 2008, Singh et al. Eastern and central Pacific ENSO and their relationships to the recharge/discharge oscillator paradigm, submitted to Deep-Sea Research). Intermediate waters roughly follow the boundary currents of the southwest Pacific, with different geographic origins and partition among the straits (Qu et al. 2009; Gao et al. 2011, Grenier et al. 2011). These tropical-equatorial dynamics point to the importance of southwest Pacific transports to both climate predictability (e.g. Cheng et al. 2007, McGregor et al. 2007, 2008) and equatorial productivity (Slemons et al. 2010; Grenier et al., 2013).

Generation and motion of spiciness anomalies

The increasing coverage of Argo data allowed detection of large scale spiciness anomalies, formed during winter in the thermocline of the south subtropical gyre and subject to interannual ENSO variations (Qu et al. 2008, Sato and Suga 2009, Kolodziejczyk and Gaillard 2012). Numerical simulations suggest these anomalies advect westward, reaching the western boundary in about 5 years with greatly weakened amplitudes. In the Tasman Sea, strong interannual variability was observed in mode water formation (Tsubouchi et al. 2007, Holbrook and Maharaj 2008).

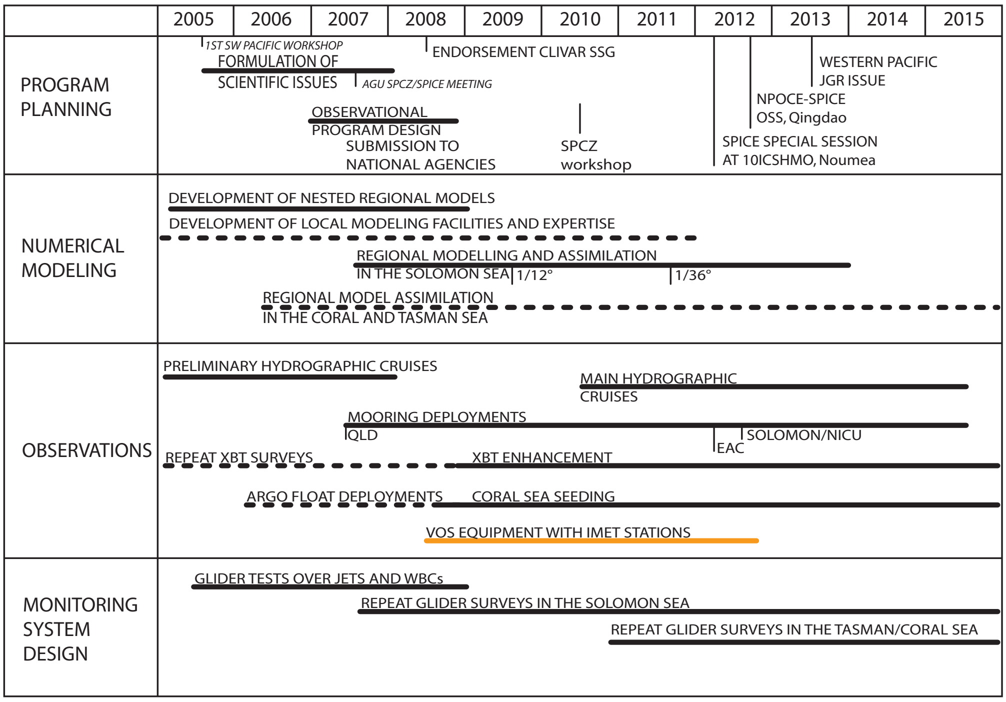

Figure 3. SPICE operation chronology since 2005.

Equatorward pathways

The fate and influence of equatorward anomalies is yet not clear. In the Solomon Sea historical data showed a strong erosion of the salinity maximum, which is reproduced in a model incorporating a specific tidal-mixing scheme (Melet et al. 2011); In addition, an alternative numerical simulation suggests that important diapycnal mixing also occurs downstream of the Solomon straits (Grenier et al. 2011). The recent new in situ data in the Solomon Sea will help understanding these different mechanisms.

Likewise, large interannual and decadal variations are observed in measurements and models of the southwest Pacific transports and properties (Kessler and Cravatte 2013, Zilberman et al. in press, Gasparin 2013). Such variations are associated with substantial changes in the boundary current system, and temperature and salinity as they feed the warm pool and EUC (Melet et al. 2013).

Poleward pathways

Substantial variations are observed in the Tasman Sea, influencing local conditions from Sydney to Tasmania and New Zealand with measureable consequences on ecosystems (Roemmich et al. 2007, Ridgway 2007a, Hill et al. 2008, 2011, Holbrook et al. 2010). The repercussions on local climate, through the EAC/TF modulation (Sasaki et al. 2008, Hill et al. 2011), or on global climate via the supergyre acceleration are not yet clear.

South Pacific Convergence Zone

The South Pacific Convergence Zone (SPCZ) is the largest rainband in the Southern Hemisphere and this rainfall is oriented adjacent to SST gradients in the tropical (Lintner and Neelin 2008) and subtropical South Pacific (Widlansky et al. 2010). Regional SST gradients determine the basin-scale wind structure that supports SPCZ-related moisture convergence and was identified as a key driver of equatorial and boundary ocean currents (e.g. Melet et al. 2013). Hence, a SPICE objective is to better understand climate interaction with regional ocean circulations through study of the SPCZ formation, variability, and the southward tilt with longitude.

Progress towards understanding the SPCZ came from remote sensing data, climate model experiments, and oceanic in situ measurements such as sea surface salinity which is correlated with SPCZ associated rainfall (Delcroix et al. 2011). The tilted orientation of the SPCZ is explained by the blocking influence of the East Pacific subtropical high (Takahashi and Battisti 2007a,b) and associated accumulation of eastward-moving synoptic disturbances, which propagate from south of Australia into a jet-exit region over the central South Pacific where mean westerly winds are weaker (Widlansky et al. 2010; Matthews 2012).

On interannual timescales, four typical structures of the SPCZ position were identified, each influenced by the slowly varying SST pattern associated with ENSO (Vincent et al. 2009). During extreme El Niño events, the SPCZ collapses onto the equator as the meridional SST gradient vanishes between the equator and 15°S. Uneven future warming of the tropical Pacific may increase frequency of these 'zonal-SPCZ' events (Cai et al. 2012), possibly changing the mean rainfall pattern (Widlansky et al. 2012).

Further research and SPICE legacy

Although much recent scientific progress has been made understanding the circulation and dynamics of the SPICE region, numerous observational and modelling operations continue (Figure 3), and there are many remaining science questions.

Continuing SPICE operations

Mooring arrays are presently in the water; the Solomon Sea inflow and outflow will be monitored until 2014; the NQC array will continue although with less moorings; but budget restrictions will bring an early end to the EAC array. An experiment combining mooring, glider, XBT and along track altimetry is taking place in the ECC. Monitoring continues with gliders, moorings and Pressure Inverted EchoSounders (PIES) in the Solomon Sea, high-resolution XBT lines and Argo float deployments. Repeat glider transects are being conducted from the Central to the Northern Great Barrier Reef across the Queensland Trough. Modelling efforts are also taking a new step, with two very high-resolution simulations at 1/36° ongoing (NEMO/ROMS codes).

Outstanding science issues

The combined effect of spiciness and transport anomalies on equatorial and Tasman Sea conditions is confirmed to be potentially large; the potential effect of spiciness anomalies is questioned, given the strong salinity erosion into and downstream of the Solomon Sea; however, results need to be evaluated in light of the SPICE regional measurements combined with basin-scale data.

Despite great progress towards understanding the SPCZ shape and behaviour, the current generation of coupled climate models still poorly simulates the diagonal extension of the rain band towards southern latitudes. Model deficiencies limit the capacity to reproduce and predict rain, winds, and the ocean circulation in the South Pacific and—through teleconnections—over the whole basin.

The successful alliance of geochemistry and physics during SPICE operations suggests developing further multidisciplinary approaches to unravel the dominant impact of southwest Pacific waters on equatorial and high latitude geochemistry and ecosystems.

Basis for new developments

Pacific Island countries and territories are extremely sensitive to oceanic and atmospheric conditions. Sea level rise, rainfall variability, temperature changes greatly impact their resources and lifestyle (Bell et al. 2011, 2013, Australian Bureau of Meteorology 2011), thus regional evolution and projection of such variable is of great interest to policy makers. SPICE efforts, along with the Pacific-Australia Climate Change Science and Adaptation planning Program (PACCSAP) helped assess projections for oceanic conditions and the SPCZ (Brown JN et al. 2012, Brown JR et al. 2012, Widlansky et al. 2012; Ganachaud et al. 2012; Sen Gupta et al. 2012). Recent assessments suggest new and more integrated programs are needed in which training and capacity building can directly utilize scientific expertise and evolving predictive capabilities of the ocean and atmosphere in the region.

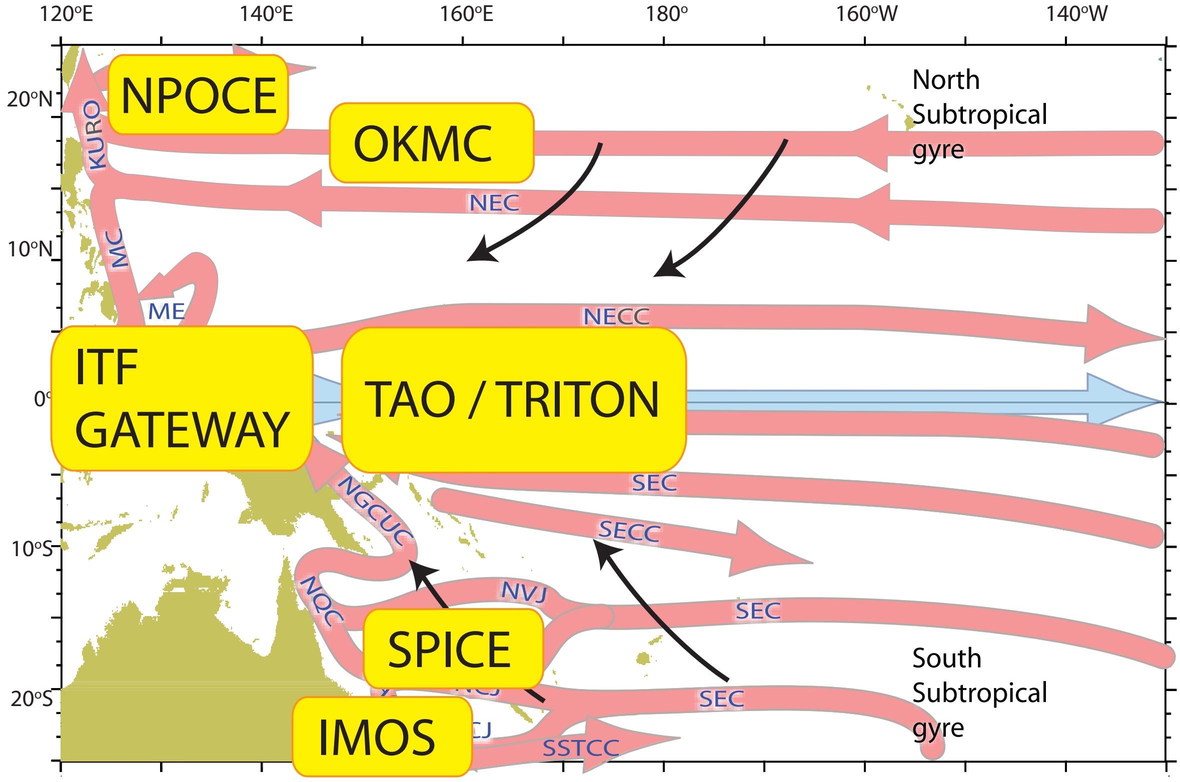

Figure 4. Concurrent CLIVAR programs in the western Pacific. With the equatorial TAO/TRITON array, the Indonesian Throughflow (ITF Gateway), the Northwestern Pacific Ocean Circulation and Climate Experiment (NPOCE), Origins of the Kuroshio and Mindanao Currents (OKMC) and SPICE, all oceanic pathways to the equator will be measured.

Western Pacific Coordination

The CLIVAR Pacific Panel provides a platform to coordinate international programs. This is illustrated in Figure 4, where the quasi-simultaneous occurrence of CLIVAR West Pacific programs is expected to provide an unprecedented understanding of the warm pool, along with EUC sources and dynamics. A special JGR issue on the Western Pacific Ocean Circulation and Climate, planned for 2014, will include many SPICE contributions.

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