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Large-scale

Climatic and Oceanic Conditions around Santo

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The Pacific Ocean is the largest of the oceans. It is divided by an inter-oceanic ridge system close to its eastern boundary, producing sub-basins in the central and western Pacific Ocean similar in size to the Atlantic and Indian Oceans. In the southwest Pacific, New Zealand and the various Melanesian Islands and Archipelagos provide natural boundaries for the adjacent Tasman and Coral Seas. The Vanuatu archipelago, including Santo, marks the main entrance of the Coral Sea that is bounded, respectively, northward and southward by the Solomon Sea and the New Caledonia basin. Over such a vast area, the climate of the region is mainly controlled by its oceanic context and by large-scale atmospheric circulation features. The latter include the trade winds, the Hadley and the Walker circulations, the tropical convergence zones, the subtropical high-pressure belt and the zonal westerlies to the south. The InterTropical Convergence Zone (ITCZ) lies just north of the Equator and the South Pacific Convergence Zone (SPCZ), extends from near the Solomon Islands to Samoa and beyond. Convergence zones are regions of lower pressure where converging, rising air produces clouds and rainfall. The southeastern Trades associated with the SPCZ are weaker than their northeastern counterparts, but they are extremely steady such that completely calm conditions under the SPCZ are encountered not more than 30% of the time over the course of a year and the region is one of the most persistently cloudy regions on earth. At seasonal and biannual timescales the southwest Pacific region is also under the influence of the Australian summer low pressure that produces a monsoonal wind pattern in the northern Coral Sea and across the Vanuatu archipelago. The Australian monsoon circulation results mainly from feedbacks in the seasonal cycle of the atmosphere-ocean interaction in the warm water pool region (a vast area of the western tropical Pacific with surface water warmer than 28°C). The warm pool and its local variability also influence the generation and propagation of tropical cyclones, which occur in the region during the October-May period. Because of the significance of these major circulation features, long-term climate trends are largely determined by corresponding long-term trends in the strength and position of the SPCZ, the Australian summer monsoon and the trade winds.

From an oceanographic point of view, the geographical position of Santo places it within a very interesting transition zone between the largely zonal equatorial circulation and the subtropical gyre circulation to the south. In the gyre, the circulation of the upper ocean layers, typically throughout the upper one or two kilometres of the water column, results directly from the wind-driven transports in the Ekman layer and from the geostrophic flow produced by the pressure gradient forces down to bottom. Under the trade winds the major westward components of the Pacific equatorial current system are the North Equatorial Current and the South Equatorial Current (SEC). These currents respond quickly to variations in the wind fields and they are therefore strongest during the winter of their respective hemispheres when the trades reach their greatest strength. The subtropical part of the SEC (near 15° S) blends with the northern limb of the subtropical gyre circulation of the South Pacific that transports water toward the equator at the depth of the main thermocline. The mass temperature and salinity characteristics of that water were formed far away to the southeast when that water was at the surface and interacted with the atmosphere. By transporting water masses over such long distances toward key regions such as the equatorial band where climate events as El Niño occur, the various pathways of this ocean circulation are of primary importance for understanding the role of the ocean in the global climate system. A more precise understanding of the role of the global thermohaline circulation and of the confluence of many different water masses appears crucial nowadays. Consequently, the western equatorial Pacific Ocean, as a crossroads for thermocline and intermediate waters formed at higher latitude, has gained renewed attention in recent years. However, the region presents a serious challenge to our descriptive abilities because of strong temporal variability, complicated topography and non-linear dynamics. Direct observations at sea remain relatively sparse and are often confined near the main routes of commercial vessels. In addition, it had been generally assumed that the circulation in the subtropics of the southern hemisphere was weaker than in its northern counterpart. This perception was in part confirmed by large-scale analyses of hydrographic measurements that indicated a broad westward flow at a depth of a few hundred meters. This point of view began to break down only in early 2000 when several studies reported the existence of a series of zonal jets resulting from the splitting of the SEC flow by the topography associated with the main reefs and archipelagos of the southwest Pacific Ocean. Recently, direct observations from an underwater autonomous glider have offered the first description of the zonal jets entering the Coral Sea through the gap between New Caledonia and the Solomon Islands. The main patterns of the circulation across the Vanuatu archipelago thus rely on the characteristics of the so-called North Vanuatu Jet (NVJ), a 300 km wide westward current that is associated with the slope of the main thermocline between 12° S and 16° S. When entering into the Coral Sea the NVJ is choked by the topography between the Banks Islands and the northern tip of Santo resulting in a separation of the water originating from the Fiji archipelago. The relatively deep extension of the NVJ along the water column, as revealed by autonomous deep floats (at ~1 000 m depth), also represents a surprising result that is not completely understood. All these recent results need further study to understand the relationship of the jets with smaller scales and coastal dynamics. However, to our knowledge, no existing investigations have focused on the circulation patterns in the immediate vicinity around Santo.

CLIMATIC VARIABILITY

Seasonal and interannual variations

The most important seasonal variability in the dynamics of the southwest Pacific Ocean is linked to the displacement of the SPCZ which shows more movement in austral summer than at other times of the year. Such variability is strongly coupled to the very warm sea surface temperatures (SSTs) above 28 °C of the tropical warm pool. The variations observed at Santo reflect primarily its position on the southwest fringe of the warm pool as shown in figure 48. Because of the ongoing MOTEVAS program which is dedicated to geodesic studies, observations of in situ temperature and salinity at two sites on the western side of Santo, namely the Sabine and Wusi banks (near 16° S-166° 20' E and 15° 20' S-166° 30' E, respectively), are available since the end of 1999 (Fig. 49). Thermal and conductivity sensors are installed there with a tidegauge anchored at a depth of 15 m and so, these measurements could be thus viewed as representative of the surface. These timeseries illustrate the dominance of seasonal to interannual variations in the climatic conditions near Santo. Whereas the temperature varies seasonally with a typical range of 4-5 °C the salinity appears more representative of the interannual conditions. Using a 25-year timeseries of SST near the Sabine bank a spectral analysis reveals an interannual band between two and seven years with a maximum peak around 5.5 years. In addition, the variations in salinity measured from thermosalinographs installed on commercial vessels also confirm that a difference larger than 0.2 exists between periods of La Niña (positive SOI) and El Niño (negative SOI) conditions. Even if local rainfall plays an unquestionable role in the salinity variations, these differences indicate different origins of the water masses around Santo depending on the interannual state of the equatorial Pacific Ocean. Another interesting point regards the quite permanent difference in temperature as large as 2 °C between Sabine and Wusi banks during the austral winter season. The difference may result from the effect of wind-driven coastal upwelling that

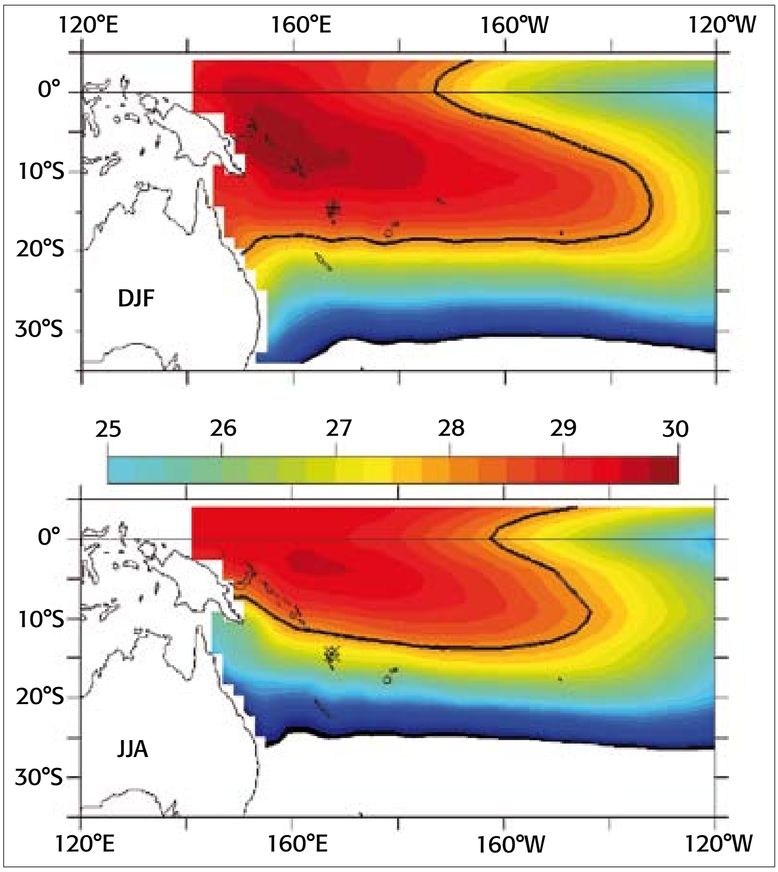

Figure 48: Mean Sea Surface Temperature (in °C) of the southwest Pacific at the seasonal timescales (**DJF** indicates December-January-February and **JJA** indicates June-July-August). The dark line represents the 28 °C isotherm and subtropical values below 22 °C are not represented. The black star recalls the position of Santo.

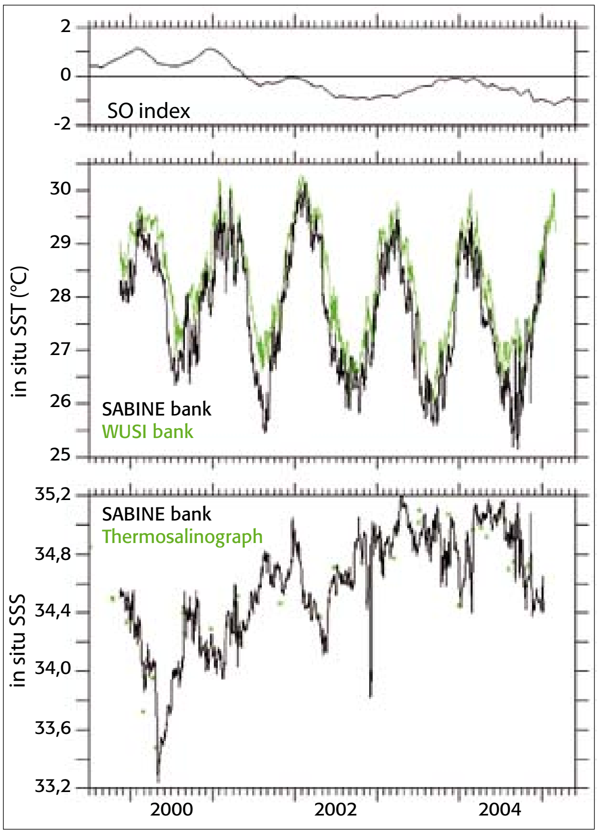

Figure 49: Timeseries of the Southern Oscillation Index, of in situ **SST** at Sabine and Wusi banks and of the sea surface salinity (**SSS**) at Sabine bank for the period 2000-2004. The thermal and conductivity sensors are located at 15 m depth. On the lower panel the star symbol represents the salinity measurements collected on commercial vessels in the context of the ORE-SSS (www.legos.obs-mip.fr/observations/sss).

appears during the strongest season for the trades. These upwelling events may share some similar origins and dynamical processes with the variability observed during strong cooling events off the western barrier reef of New Caledonia.

Longer term changes and trends

Connections between the tropical and subtropical oceans through the wind-driven meridional overturning ocean circulation are believed to be of primary importance for decadal and longer temperature fluctuations. This phenomenon is referred as the Pacific Decadal Oscillation in the North Pacific whereas, in the South Pacific, it is also known as the Interdecadal Pacific Oscillation (IPO). This variability is characterized by low frequency fluctuations with ~15 to ~30-year time-scales. During the 20th century three phases of the IPO have been identified:

- A positive phase (1922-1944);
- A negative phase (1946-1977);
- Another positive phase (1978-1998).

Spatial patterns in these decadal trends are strongly affected by the SPCZ, especially for the changes during the mid-70s. The shifts in the position of the SPCZ are apparently related to El Niño Southern Oscillation variability on interannual time-scales and to the IPO variability on decadal time-scales. The variations at the two time-scales appear to be of similar magnitude and they are independent. However, the physical processes involved in these different fluctuations are still the topic of an open debate that depends in part on the tropical or extratropical origin of the particular phenomenon. Among the different theories, a particular emphasis has been placed on the importance of the South Pacific in sustaining tropical decadal variability through remote influence of the atmospheric circulation.

Superimposed on the decadal variability that may be inferred from modern observations is an acceleration of the warming trend over the last 50 years that is due to the increase of anthropogenic gases in Earth's atmosphere. An increase is observed not only in the ocean heat content of the upper layers but also in the deeper layers of the oceans. These climatic changes and their future projections over the next 50 years are very important consequences for coral reefs. Although it may be tempting to link this warming to the enhanced greenhouse effect, the response of the entire Pacific to El Niño- or La Niña-like conditions remains still uncertain. Coupled numerical models as well as historical reconstructions based on sparse observations such as those most often used for the SST field have their own flaws and caution is required in using them as evidence of the present climate variability. Similar conclusions have been drawn from the various paleoclimate proxies that describe the variability during the last millennia. A great advantage of these last data is that they facilitate separating the natural from the anthropogenic effects. Coral proxies in the South Pacific indicate however that expansion of the SPCZ would imply a gradual change in the South Pacific to more La Niña-like conditions in the long term mean. Such variations in the position/displacement on decadal time scales of the SPCZ influence not only mean precipitation, but also daily rainfall and temperature extremes as observed on islands.

Another very important climate change for island communities of the South Pacific concerns the rise of the mean sea level. Sea level tendencies suffer however from the same uncertainties as the surface temperature variations with regard to the possible influence of decadal fluctuations. The large variability in climatic signals and the shortness of many of the individual records contribute to uncertainty of historical rates of sea-level rise. For 1993-2001, all the data available exhibit large rates of sea-level rise, approaching 30 mm/yr, over the western Pacific Ocean. If there is some evidence that the sea level rise observed over the last decade is largely due to thermal expansion, present estimates are still sufficiently uncertain to exclude other contributions. For instance, a clear freshening trend of the order of 0.1-0.3 per 30-yr, together with an extension of the low-salinity water at the surface, has been reported from a recent analysis of sea surface salinity measurements in the SPCZ region.

REGIONAL OCEANIC CIRCULATION

• • • Water masses

The SST and SSS features result principally from direct air-sea interactions and the action of the winds driving the ocean circulation of the upper layers. Heat and freshwater transfer between the atmosphere and the ocean penetrates into deeper layers through the surface mixed layer. In the tropics, winter cooling is not strong enough to destroy the seasonal stratification, and a permanent thermocline is maintained throughout the year. It is a transition zone from the warm waters of the surface layer to the cold waters of great oceanic depths. The processes that formed the permanent thermocline and fixed its properties are governed by a combination of water mass formation and vertical pumping in response to the wind. The water masses of the thermocline are injected in the subtropical convergence zone at intermediate depths through a subduction mechanism. Because their properties are fixed at the surface these water masses keep characteristics that can be traced in temperature-salinity relationships along isopycnal surfaces. Six thermocline water masses can be distinguished in the Pacific Ocean, and the most saline of them is observed in the western and southern region. Below the thermocline depth the water column is mainly filled with intermediate water characterized by a minimum in salinity near the 800-1 000 m depth. All the above features are illustrated by the vertical profiles of temperature and salinity (Fig. 50), observed on the western side of Santo and recorded by autonomous floats of the international ARGO program. The bottom of the mixed layer deepens to 120 m depth during the boreal summer (linked to the colder temperature as shown in Fig. 49) and is shallower than 20-40 m during boreal winter. The permanent thermocline corresponds to waters with temperature between 10 and 20 °C associated with the maximum salinity near 200 m depth. The intermediate waters fill the lower part of the column, down to 2 000 m depth and deeper, and they could be identified by a minimum in salinity. The rest of the ocean depths is filled with abyssal water masses those the origins are linked to the Antarctic bottom water. Such waters are renewed very slowly and their westward spreading is strongly influenced by the bottom topography.

• • • Currents around Santo

The most prominent feature of the ocean circulation in the South Pacific is the subtropical gyre, consisting of the South Equatorial Current (SEC) at around 15°S, the East Australian Current, and the eastward return current and the Peru/Chile current in the eastern Pacific Ocean (Fig. 51A). However, the traditional and climatological view of the SEC as a broad and weak westward flow is misleading. Because of the presence of shallow and complex topography associated with islands and reefs the SEC, the inflow toward the southwest Pacific is broken into several narrow zonal jets at the southern and northern tips of the larger islands such as Fiji, New Caledonia and Vanuatu. A more careful consideration of the influence of the topography in updated analyses based on historical hydrographic data sets has led to the recognition of these zonal structures in the ocean circulation of the southwest Pacific. However the amplitude and the properties of these different pathways for the SEC inflow remains poorly documented. These jets have been directly observed with recently developed observational tools such as sea gliders and their dynamics

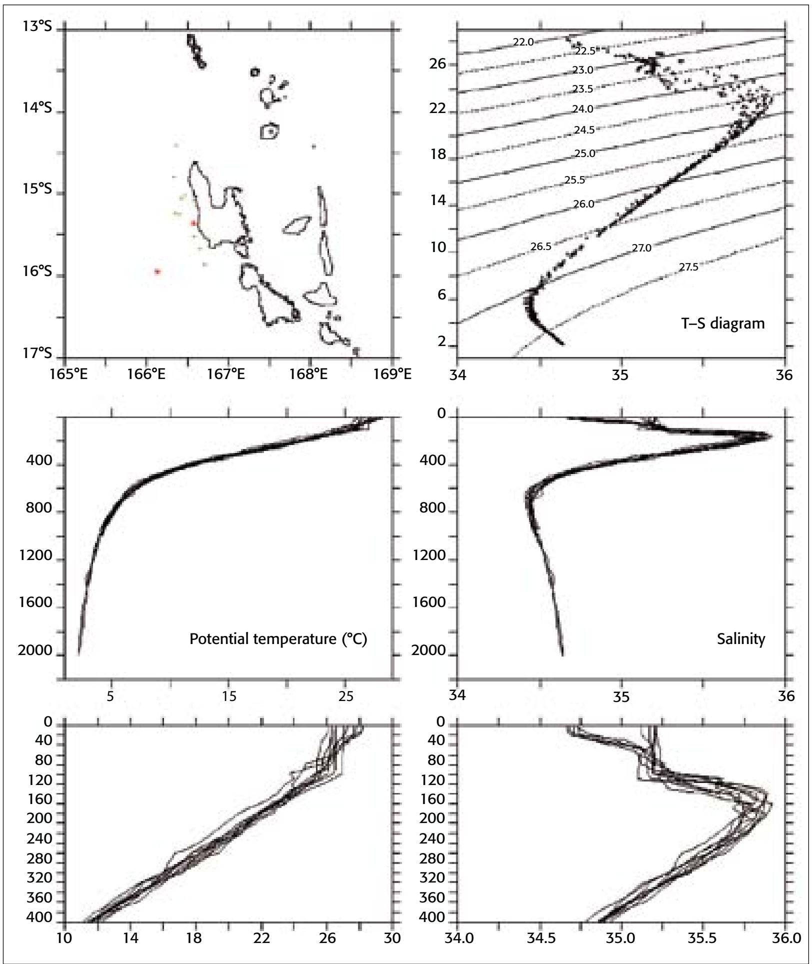

Figure 50: Distribution and profiles of temperature (in °C) and salinity observed in the southwest region of Santo (green symbols). On the geographical map the red stars indicate the position of the sensors at Sabine and Wusi banks (see figure 49). On the T-S diagram the continuous and dashed lines indicate the corresponding isopycnal values (kg/m³). The lower figures zoom on the upper layers as shown in the middle.

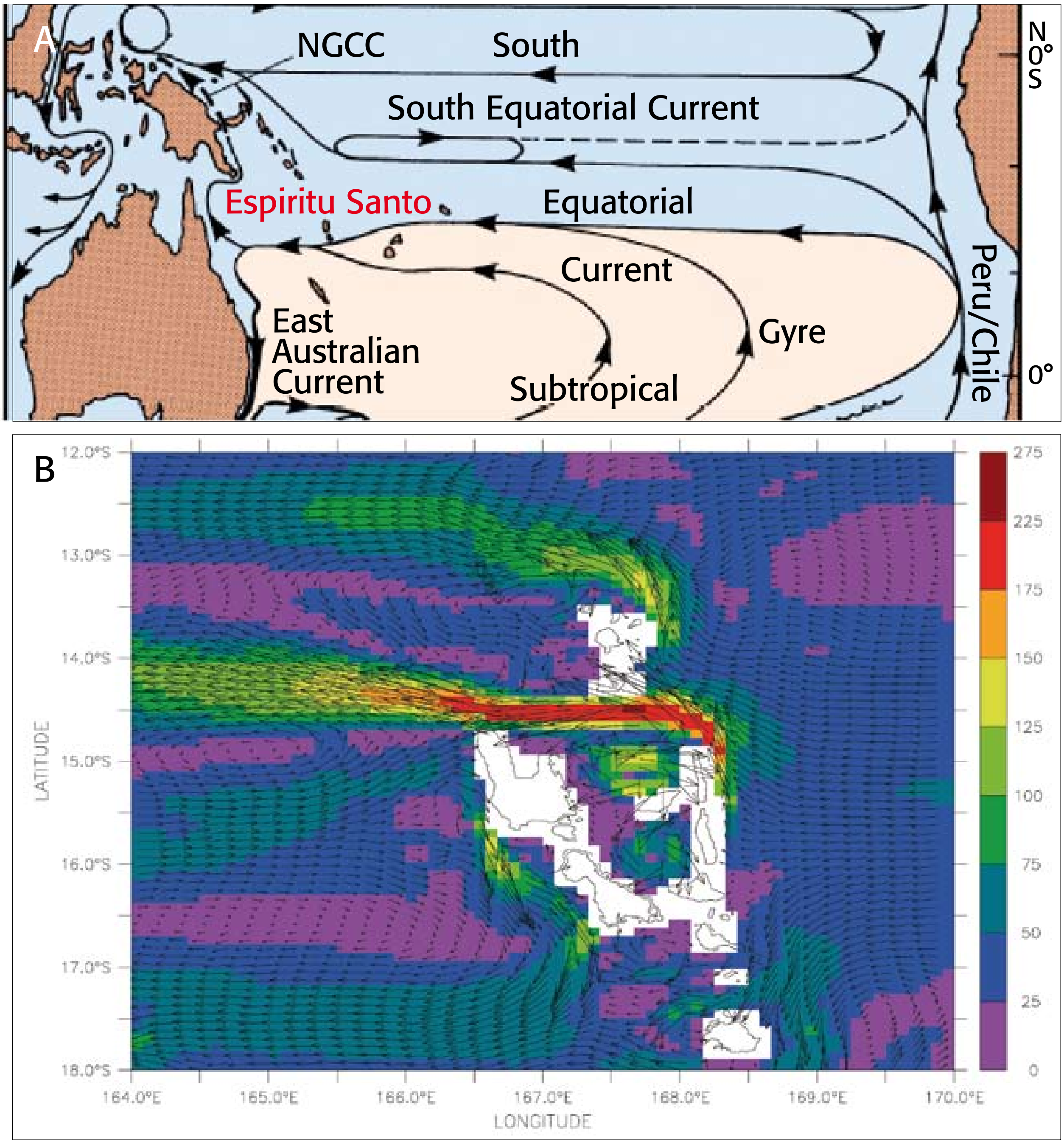

Figure 51: **A**: General sketch of the South Pacific Ocean circulation (from Tomczak & Godfrey, 1994). **B**: Integrated mean circulation (units in m^2/s) in the top 1 000 m depth.

have started to be properly simulated with high-resolution numerical models. The mean integrated circulation of the top 1 000 m around Santo from one of these models is displayed in figure 51B. On the eastward side of the Vanuatu archipelago the westward flow is associated with the subtropical limb of the SEC that has been deflected by the Fiji Islands. This flow is itself deflected by the presence of several islands before entering into the Coral Sea. The circulation on the westward side of the islands is also much more complicated with the presence of several counter-currents in the lee of the Banks Islands and Santo. Most of the flow that is choked off by these islands is observed at the northern tip of Santo and is slightly deflected equatorward in the Coral Sea. Northward of this position a second branch of the so-called North Vanuatu Jet is also deflected equatorward by the Banks Islands. These two components are nearly zonal and flow westward after the bifurcation toward the coast of Australia. On the westward side of Santo the eastward counter-current bifurcates near the coast and most of the flow is deflected toward the southeast before joining the westward flow between 17°S and 18°S that represents one of the sources of the North Caledonian Jet. The variability of these jets is still largely unknown but they must vary in phase with the interannual response of the trade winds and of ENSO. In the intermediate layers and deeper, the circulation is globally westward with typical speed amplitude of several mm/s. For such circulation the influence of the bottom topography is essential.