Hydroclimatic conditions in the southwest Pacific Ocean

Christophe MAES [1], Andres VEGA [1], and Joël SUDRE [2]
[1] Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS), Institut de Recherche pour le Développement (IRD), Centre IRD de Nouméa, BP A5, 98848 Nouméa cedex, New Caledonia
[2] LEGOS/CTOH, Centre National de la Recherche Scientifique, Toulouse
Christophe.Maes@ird.fr

Abstract

The southwest Pacific Ocean represents a unique region in the world due to the presence of the only intertropical atmospheric convergence zone in the southern hemisphere. Near the northwest boundary of Australia the effect of the monsoon regime is also felt and both the Coral and Solomon Seas are under its influence. Despite such a strong seasonal forcing the main signals at seasonal to interannual timescales are linked to the variability of the ENSO phenomenon. Since the time of the TOGA program, an observing system in the equatorial band of the Pacific Ocean has provided sufficient observations to allow models to predict ENSO events with certain accuracy and useful lead times. At longer time-scales the influence of the subtropical regions must be also considered because of their potential modulation of the equatorial mean state. Whatever their origin, extra-tropical events in the Southern Hemisphere must transit the southwest Pacific region to reach the equatorial belt. However the circulation of this region is less well understood than its northern counterpart due to its high variability in time and its strong interaction with the complex bathymetry of the region. The presence of several archipelagos represents indeed a specific feature of the southwest Pacific region. More precisely, the processes influencing the general conditions around New Caledonia, including meteorological forcing and regional ocean dynamics, are shortly presented and discussed. Finally, it is argued that ongoing efforts to enlarge the present observing strategy in the region will result in a better understanding of the variability of the southwest Pacific from large-scale ocean dynamics to small–scale near-island dynamics.

Introduction

Tropical Oceans strongly influence the Earth's climate due to their capacity to store locally and to export poleward the heat provided by the sun. Studies of several El Niño-Southern Oscillation events in the 1970s pointed out the great influence of the equatorial Pacific Ocean. It became evident that it would be necessary to monitor continuously the thermal state of the equatorial band in order to benefit from forecasts at seasonal time scales. This objective was almost achieved during the 1984-1994 decade by the international program Tropical Ocean-Global Atmosphere (TOGA). Understanding the importance of the ocean-atmosphere coupling over the Pacific in the context of short-term climate predictions enlarges our view not only toward the Atlantic and Indian tropical sectors but also toward the extratropical oceans.

This review deals with the southwest Pacific, a vast, largely oceanic, area extending from 150°E to the dateline and from 5°S to 30°S (~10 millions of km^2). Other authors have described other parts of the tropical Pacific. The hydroclimatic environment of the Tuamotu Archipelago of French Polynesia in the central Pacific has been reviewed by Rougerie & Rancher (1994). A more recent review, focusing on the eastern tropical Pacific, has been published in a special volume of Progress in Oceanography by Lavin *et al.* (2006). Here, with a much more modest ambition in mind, we propose a brief review of the hydroclimatic conditions that characterized the southwest Pacific. In the following, we do not intend to provide a full description of the whole oceanographic state; such a view is already available in general surveys published in books such as the ones by Pickard & Emery (1990) or by Tomczak & Godfrey (1994). Building on these descriptions of the mean ocean circulation the principal focus of this review is on the seasonal, interannual and longer time-scale variability of the main parameters involved in air-sea exchanges. This does not mean that we are concerned only with the ocean surface. For example, atmospheric winds drive the ocean circulation of the upper layers, typically down to depths of about 1000 m. Although there is a growing recognition of the importance of interconnections between climate variations in the southwest Pacific and parts of the globe well outside that region, we are adopting a more closely focused point of view in order to underline the major impacts, at the different scales of variability, of the atmospheric and oceanic circulations around the reef of New Caledonia.

The climate of the southwest Pacific region is controlled by its oceanic nature and large-scale extra-tropical atmospheric circulation features as shown in figure 1. These features include the trade wind regimes, the Hadley and Walker circulations, the seasonally varying tropical convergence zones, the semi-permanent subtropical high-pressure belt and the zonal westerly winds to the south. In January, the prominent feature is the trough of low pressure that extends eastward from the monsoonal low centred over northern Australia across the Pacific Ocean to a location near the equator and 170°W. In July, in contrast to January, there is a high pressure dome located over southern Australia. Following the strict definition of a monsoon regime (i.e., a 180° reversal in the wind direction), only the northern part of the present region of interest is under the influence of such a regime. However, the effect of the Australian summer low is felt west of 170°W throughout the Vanuatu archipelago and the northern part of New Caledonia. Another very important feature of the atmospheric circulation in this region is the South Pacific Convergence Zone (SPCZ) that extends from east of Papua New Guinea southeastward toward 120°W, 30°S. The SPCZ maintains one of the most expansive and persistent cloud bands on earth and plays a major role in the crossequatorial flow. Interactions between the SPCZ and the other locations occur on a variety of timescales from synoptic to interannual as reviewed by Vincent (1994). In the annual mean, the signature of the SPCZ must be seen not as a wind speed minimum but more as a convergence in wind direction. Completely calm conditions are encountered during not more than 30% of the time during the course of the year (Tomczak & Godfrey, 1994). South of 30°S the atmospheric circulation is characterized by the presence of an anticyclonic belt associated with the high pressure of the Kermadec islands.

The present paper is organized as follows. Section 2 reviews the climate conditions of the southwest Pacific region at timescales ranging from seasonal to long-term variations and trends. A brief summary of the meteorological impacts around New Caledonia is also included. Section 3 addresses more specifically the ocean circulation at both large and regional scales and concludes with a closer look at the circulation around New Caledonia. Some points on the ongoing activities from a physical oceanographic point of view within the southwest Pacific region are discussed in the last section.

Climate variability

Seasonal and interannual variations

Within the equatorial region, seasonal and interannual variations of the fundamental parameters involved in climate (including the surface wind stress, the sea surface temperature, rainfalls, solar radiation and turbulent heat fluxes) have been studied with the focus of understanding and forecasting the ENSO phenomenon (e.g., Delcroix, 1998). The southwest Pacific Ocean lies, however, in a transition zone between the equatorial band and the extra-tropical region. Using repeated tracks between New Zealand and Hawaii, Morris *et al.* (1996) documented the variability of the subtropical gyre in the southwest Pacific Ocean. Proceeding southward from 10°S the most important feature is the spreading and outcropping of the thermocline around the mean position of the 20°C isotherm that is located around 200 m near 18°S. At these extratropical latitudes, the thermocline exhibits some seasonal variations that are mainly confined to the upper 100 m column (Delcroix & Hénin, 1989). The most important seasonal variability in the regional ocean dynamics is linked to the displacement of the SPCZ which is more active in southern summer than at other periods of the year. The amplitude of the interannual signal is an order of magnitude less than the amplitude of the seasonal signal for SST and precipitation, whereas it is twice the amplitude of the seasonal signal for sea surface salinity (Gouriou & Delcroix, 2002).

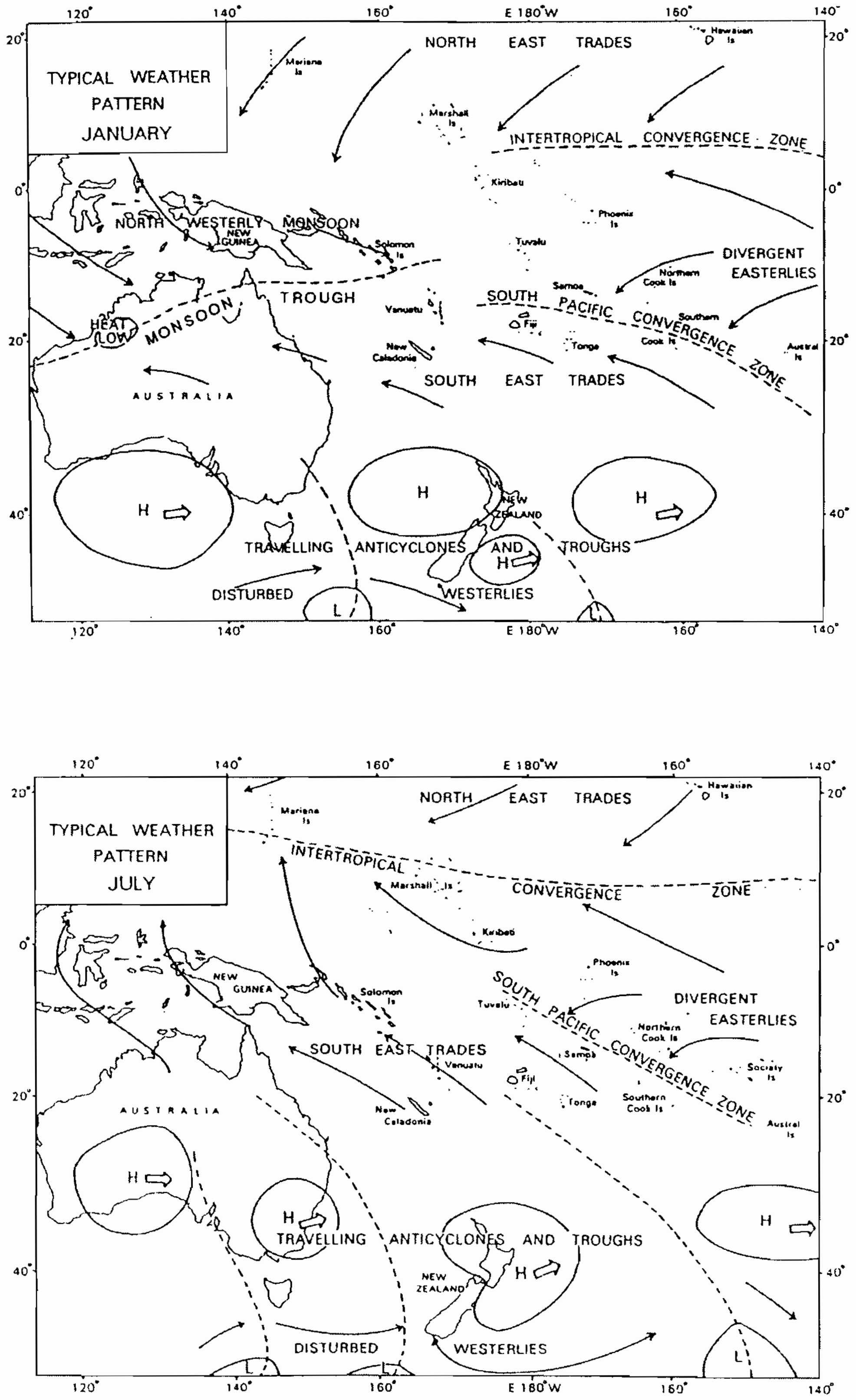


Figure 1. The southwest Pacific hydroclimatic conditions showing the main features of the seasonal atmospheric circulation in the region (extracted from Salinger *et al.*, 1995). In addition of the main pressure highs, the seasonal positions of the atmospheric convergence zones are represented by dashed lines. The figures are representatives for mean conditions in January (top) and in July (bottom).

In the western Pacific Ocean, the interannual variations are usually connected to the appearance of the El Niño phenomenon and, consequently, to the Southern Oscillation. Both processes are closely linked and could be indexed by the SST anomaly in the eastern equatorial Pacific and/or the atmospheric pressure difference between Tahiti and Darwin. There have been many attempts to list El Niño and La Niña years going back to the seminal papers by Quinn *et al.* (1987). The most recognized version using modern observations is described by Trenberth (1997). Classifying the years in terms of ENSO conditions is not a simple problem (Hanley *et al.*, 2003). In the last decade, several processes have been proposed to explain the observed variability in ENSO, ranging from the importance of high frequency disturbances to decadal variations and global warming (Federov & Philander, 2000). Another example of such difficulties, as applied to the southwest Pacific, is illustrated by the conjoint influence of the Indian Ocean Dipole (Saji *et al.*, 1999), IOD hereafter, with ENSO. Using a statistical approach Meyers *et al.* (2006) have recently shown that most of the El Niño years could be associated with a positive Indian dipole, and conversely, most of the La Niña years with a negative dipole (Table 1). Nevertheless, caution is required when multiyear data sets collected in a regional context are to be analyzed in terms of climate variability. For instance, composite maps of SST around New Caledonia averaged for June to November and calculated for the categories of pure IOD (no event in the Pacific Ocean) and of pure ENSO events (no event in the Indian Ocean) are shown in figure 2 (plate 4/1). Despite lower amplitude for the first category, the region is characterized by negative anomalies in SST that have resulted from two distinct type of remote variability. If the climatic consequences over New Caledonia during El Niño years are relatively well known (see below) the specific impacts of the pure IOD variability on global rainfall patterns and local climate remain to be explored.

Table 1. Classification of years when El Niño or La Niña and/or positive or negative Indian Ocean Dipole occurred. Bold print (normal print) indicates a higher (lower) level of certainty in the classification as discussed by Meyers *et al.* (2006). The top three boxes show all the El Niño years and when they occur with negative, positive, or no IOD-event. And so forth for the other rows. This classification shows that an approximately equal number of positive IOD events occurred during an El Niño event as without. Note also that a positive dipole with La Niña event never occurred, and a negative dipole with El Niño occurred only once.

	NEGATIVE IOD	NO EVENT	POSITIVE IOD
EL NINO	**1930** **1914** 1918 1925 **1940** 1941 **1965** **1986** **1987**	**1877** **1888** **1899** **1911** 1957 **1963** **1972** **1982** **1991** **1997**	**1896** **1902** **1905** **1923**
NO EVENT	**1880** 1956 **1958** **1968** **1974** **1980** **1985** **1989** **1992**	1881 **1882** **1883** **1884** **1890** **1895** **1898** 1900 **1901** **1904** **1907** **1908** **1912** 1913 1915 1920 **1921** **1927** **1929** 1931 **1932** **1934** **1936** **1937** **1939** **1943** **1947** **1948** 1951 1952 **1953** 1959 1960 **1962** **1966** **1969** 1971 **1976** **1979** **1990** 1993 **1995**	**1885** **1887** **1891** **1894** **1919** **1926** **1935** **1944** **1945** **1946** **1961** **1967** 1977 **1983** 1994
LA NINA	**1906** **1909** **1910** 1916 **1917** **1928** **1933** **1942** **1950** **1975** 1981	**1878** 1879 1886 1889 **1892** **1893** **1897** **1903** 1922 1924 **1938** **1949** 1954 1955 **1964** 1970 **1973** 1978 1984 **1988** 1996 1998	

Long term changes and global warming 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 in the Pacific Ocean (McPhaden & Zhang, 2002). Due to the north-south asymmetry in the amount of available data, most of the analyses of historical observations have focused on the North Pacific where this variability is called the Pacific Decadal Oscillation (Mantua *et al.*, 1997). In the South Pacific, this variability is known as the Interdecadal Pacific Oscillation (IPO) and 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) and another positive phase (1978-1998). Spatial patterns of these decadal trends are strongly affected by the SPCZ, especially the changes in the mid 1970s (Salinger *et al.*, 1995, 2001). According to Folland *et al.* (2002), the shifts in the position of the SPCZ are related to ENSO 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 are linearly independent. However, the physical processes implied in these different fluctuations are still the objects of an open debate as reviewed by Wang & Picaut (2002) that depends in part on the tropical or extratropical origin of the particular phenomenon. Among the different theories, the importance of the South Pacific in sustaining tropical decadal variability through the atmospheric circulation has been especially emphasised by Luo & Yamagata (2001). More recently, an increase at decadal time-scales in the circulation of the subtropical gyre, extending from the sea surface to mid-depth, has been described through direct observations by Roemmich *et al.* (2006).

Superimposed on the decadal variability that may be inferred from modern observations there is an acceleration of the warming trend over the last 50 years as illustrated for the ocean surface in figure 3; in the deep ocean such a warming tendency is also described by Bindoff & Church (1992). These climatic changes and their future projections over the next 50 years are very important to consider for coral reefs (Hughes *et al.*, 2003). Although it may be tempting to link this warming to the enhanced greenhouse effect (Barnett *et al.*, 2005), the response of the entire Pacific to El Niño - or La Nina-like conditions remains uncertain (Collins, 2005). Coupled models as well as historical reconstructions based on sparse observations such as those most often used for the SST field (e.g., Kaplan *et al.*, 1998) 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 different 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 (Cobb *et al.*, 2003; Corrège *et al.*, 2004). Recently, Linsley *et al.* (2006) reported that expansion of the SPCZ implies a gradual change in the South Pacific to more La Niña-like conditions in the long term mean.

Sea level tendencies suffer from the same uncertainties as the surface temperature variations with regard to the possible influence of decadal fluctuations (e.g., Cazenave & Nerem, 2004). A recent detailed analysis of the sea-level rise at tropical Pacific and Indian Ocean islands may be found in Church *et al.* (2006). If there is some evidence that the sea level rise observed over the last decade is largely due to thermal expansion (Lombard *et al.*, 2005; Ishii *et al.*, 2006), present estimates are still sufficiently uncertain to exclude some contributions from other sources.

Meteorological impacts around New Caledonia

The manifestations of ENSO changes in the atmospheric circulation are felt throughout the tropics and the global atmosphere via the so-called teleconnections. The links between ENSO and large scale precipitation patterns have been thoroughly explored beginning with the pioneering work by Sir Gilbert Walker in the 1920s. In more recent studies, these relationships have been studied using data from meteorological stations (Ropelewski & Halpert, 1987) or a combination of *in situ* observations and satellite products (Dai & Wigley, 2000). A schematic diagram illustrating the underlying processes associated with the atmospheric bridge linking tropical SST anomalies to changes in the extra-

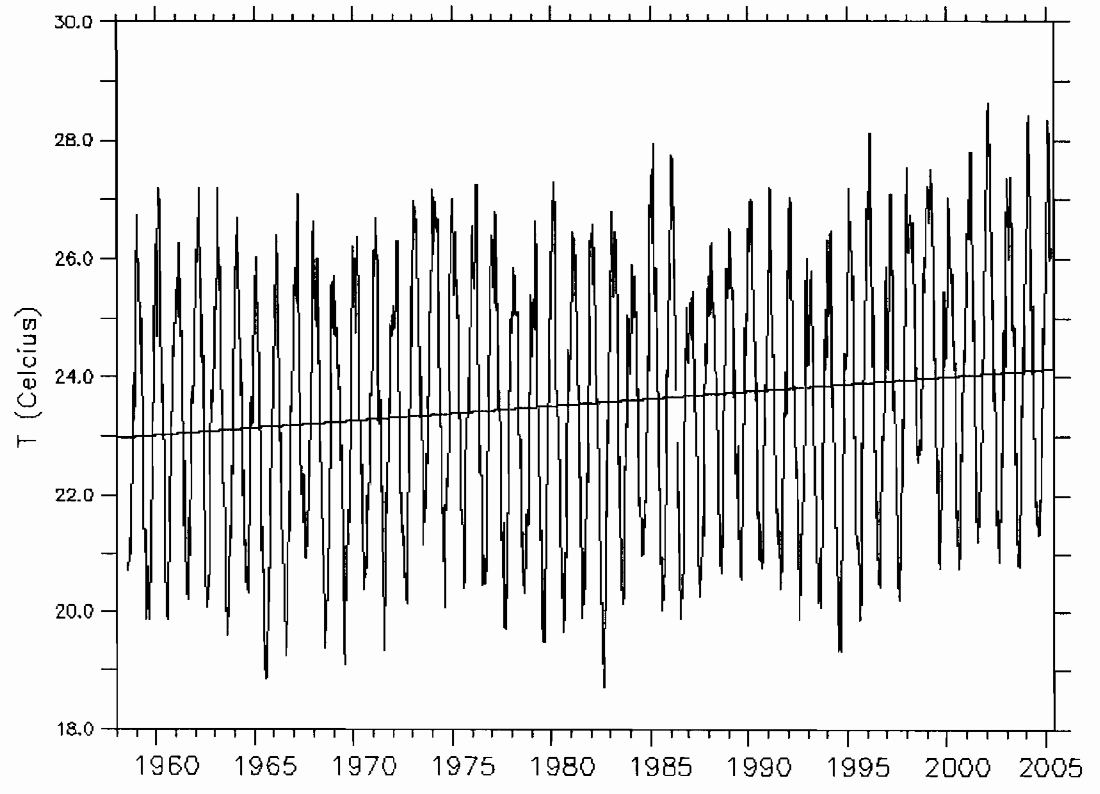


Figure 3. Timeseries of the sea surface temperature observed at the Anse Vata Bay in Nouméa, New Caledonia (IRD data source). A linear trend has been superimposed that roughly correspond to a warming of 2°C per century.

tropical oceans is discussed with some details by Trenberth *et al.* (1998). More specifically, the signature of El Niño events in the oceanic region around New Caledonia is characterized by cold temperature anomalies over the top 50 m (Delcroix & Lenormand, 1997), by a 20-50% decrease in precipitation (Nicet & Delcroix, 2000) associated with saltier-than-averaged anomalies in sea surface salinity. The latter effects result mainly from the equatorward displacement of the SPCZ in response to ENSO anomalies in the eastern Pacific. This relationship suggests that there is a potential for useful rainfall predictions over New Caledonia (Fischer *et al.*, 2004). Conversely, the signature of La Niña events is characterised by anomalies of same amplitude but of opposite sign. Some other examples of the ENSO signature within the Caledonian lagoon are analyzed by Ouillon *et al.* (2005). These different studies appear to be consistent with the robust relationship between El Niño strength and the spatial extent of droughts established by Lyon (2004).

Atmospheric and oceanic conditions in the southwest Pacific are nearly always favourable for intense tropical cyclone activity. Consequently, the relationship between ENSO and enhanced cyclone activity is weak, although the primary influence on tropical cyclone incidence has been associated with local SST conditions (Basher & Zheng, 1995). This point is also illustrated by the 2002-03 cyclone season that had a below average number of tropical cyclones just below the average and a shift toward the east of the activity, both points that are consistent and an eastward shift in the center of the cyclone activity, both points that are consistent with the prevailing moderate warm ENSO conditions (Courtney, 2005).

A summary of each cyclonic season as well as climatic surveys of the South-west Pacific islands are available from the Island Climatic Update (www.niwascience.co.nz/ncc/icu/).

Regional ocean circulation

The equatorial band received most of the attention during the TOGA program, but more recently, attention has shifted to the southwest Pacific where the circulation represents a major pathway for water masses arriving in the equatorial band from the subtropics (Tsuchiya *et al.*, 1989; Fine *et al.*, 1994). The properties of these water masses have the potential to modulate the ENSO variability at decadal time scales (Gu & Philander, 1997). In addition to these climatic objectives there is an increasing interest in regional and coastal ocean circulation studies in response to societal demands.

Open ocean circulation of the southwest Pacific

An overview of the total geostrophic circulation of the Pacific Ocean from the surface to abyssal depths is reported by Reid (1997). A closer examination of geostrophic circulation patterns near the western boundary of the South Pacific is presented by Sokolov & Rintoul (2000). Only the upper part of the ocean under the influence of the wind and the subtropical southwest part of the basin will be considered here. 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. Gouriou & Toole (1993) estimate the total transport of the SEC at 165°E as 25 to 41 Sv (1 Sv= 10^6 m^3/s) between 15°S and 3°N. Using indirect computations based on the thermal structure observed by XBT casts, Donguy & Meyers (1996) find a similar transport of 20 Sv that is confined to the top 400 db layer and is characterized by a weak seasonal variability. However, the traditional view of the SEC as a broad westward flow begins to break down with the advent of high resolution modelling studies (Webb, 2000). The presence of a shallow and complex topography associated with islands and reefs is conducive to the formation of narrow zonal jets at the southern and northern tips of the larger islands such as Fiji, Vanuatu and New Caledonia. Recent direct observations of these jets using an autonomous buoyancy-driven underwater glider reveal a narrower and more vigorous North Caledonian Jet (Fig. 4, plate 4/2) than was previously imagined, but whose characteristics are otherwise poorly understood. 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 (Qu & Lindstrom, 2002; Ridgway & Dunn, 2003). The extension of such studies with numerical models has allowed a more complete explanation of dynamical processes such as the bifurcation of the SEC near the Great Barrier Reef (Kessler & Gourdeau, 2006b) and the nature of the zonal jets (Richards *et al.*, 2006; Kessler and Gourdeau, 2006a). Complementary studies on the variability of the surface circulation that may be deduced through satellite products such as sea level anomalies investigate the physical mechanisms at work at the scale of the entire Pacific basin (Qiu & Chen, 2004; Maharaj *et al.*, 2005). At depth, preliminary results from direct observations based on autonomous floats reveal a higher level of energy in the mean currents as compared to currents deduced from hydrological climatologies (Davis, 1998).

Upwelling and ocean dynamics around New Caledonia

In the ocean, upwelling represents a very important process that plays a major role in oceanic productivity. The equatorial upwelling represents the largest contribution by volume to the total global upwelled waters (Reverdin, 1995) but regions of coastal upwellings are also very important to consider. Near the main island of New Caledonia, trade winds are persistently favorable to upwelling because of their alignment with the coastline of the western barrier reef. It is quite surprising, however, that this process had not received much attention until only recently, in particular by Henin & Cresswell (2005). These authors describe strong seasonal wind-driven upwelling events that appear in SST and ocean colour satellite images. From a dynamical point of view, upwelling processes observed off New Caledonia are as intense as the events observed on the eastern boundary of ocean basins. The events are mostly located along the southern half of the western barrier reef, although they can occasionally extend to the north of the island. The strong seasonality of the upwelling has been related to the seasonal variability of the mixed layer depth and thermocline by Alory *et al.* (2006). The biological consequences of upwelling remains uncertain and to address further the upwelling-driven nutrient enrichment more observations and studies of the vertical reach of the upwelling cell and the vertical structure of the temperature and nutrient fields are required. An important aspect of the upwelling along New Caledonia is the strong interaction with the surrounding circulation related to the island wake effect. However, careful consideration must also be given to the processes that interfere in such relationships (Le Borgne *et al.*, 1985; Martinez & Maamaatuaiahutapu, 2004). Numerical simulations based on regional models show that the island effect controls the offshore extension of filaments and limits the spatial extention of the events to the southwest coast (Fig. 5, plate 4/1).

These recent studies emphasize the importance of satellite observations for investigating the variability at the ocean surface. In addition to upwelling, satellite-derived SST could be used to study variations in diurnal warming. For example, Stuart-Menteth *et al.* (2003) show that large regions in the tropics and midlatitudes are frequently characterized by a diurnal warming that is dictated by a combination of the wind and the solar insolation. The largest diurnal amplitude in SST is observed all around New Caledonia in December of each year, but a contrast between the eastern and western coasts exists in the duration of such warming as shown in figure 6 (plate 4/2). Such diurnal effects are important to consider, for example, in the computation of air-sea heat exchanges and air-sea gas fluxes. Another important variable that may be deduced from several satellite-derived observations are the surface currents following an approach similar to Lagerloef *et al.* (1999). An example of the surface ocean circulation that may be derived from wind stress and sea surface height observed from space is given in figure 7 (plate 4/3). Snapshots such as these mainly reveal cyclonic and anticyclonic eddies that are in quasi geostrophic equilibrium with the mass field. Across the domain, the mesoscale eddy activity appears stronger and more persistent south of 20°S. More detailed studies based on combined altimetry and currents are required to identify the north-south heat transport of such eddies activity following the methodology proposed by Morrow *et al.* (2004). Another application of such products for biological studies is illustrated by Girard *et al.* (2006). Finally, it should be noted that the spatial extension of these currents from the open ocean toward the coast is currently under investigation.

Perspectives and ongoing activities

A growing interest in the western tropical Pacific as a focal point for understanding the dynamics of low frequency modulation of the equatorial band and of the associated ENSO phenomena, has spurred research into the ocean circulation in the southwest Pacific as part of the subtropical-tropical interaction. A careful consideration of the complex topography of the region leads to a description of a more complex relationship between the subtropical gyre of the South Pacific and its exchanges with the equatorial and high-latitude oceans. However, there are many issues that are still under debate regarding, for example, long term changes and these need to be further investigated. In order to increase our knowledge, and potentially to improve our ability to predict such changes, an international research program called South PacIfic ocean Circulation Experiment, SPICE, at the horizon of the 2008-2010 time period is presently underway (www.ird.nc/UR65/SPICE/). The ambition of this project is to encompass all the components from the large-scale of the southwest Pacific down to the island coastal dynamics.

To understand the ocean dynamics and its role in climate, weather and ocean atmosphere interactions, observations on a basin-wide scale with adequate time and space resolution are required. The combined use of satellite-derived and *in situ* observations will provide some answers and will allow, in addition, a focus on more regional and coastal scales. The ongoing studies devoted to the upwelling and the island wake effect along the coasts of New Caledonia represent two good examples. Two other areas of high potential are observations of large scale ocean circulation and water masses from autonomous floats deployed in the context of the Argo program (www.argo.ucsd.edu) and ocean state estimates based on numerical models devoted to operational applications. Both programs are part of the French national effort in the context of the Coriolis and Mercator projects (www.coriolis.eu.org/; www.mercator-ocean.fr/), respectively. A similar synergy occurs in the operational ocean prediction systems that have been developed in Australia around the Bluelink project (www.marine.csiro.au/bluelink/). The synergy that will arise from these different but complementary efforts will certainly result in the progress of our understanding of the southwest Pacific Ocean.

Acknowledgements. Figures 2 and 6 have been gracefully provided by Gary Meyers and Alice Stuart-Menteth, respectively. The representation of the data shown in the figure 3 has been done with the help of Jérôme Lefèvre. Comments by D. Ponton, V. Garçon, D. Behringer, R. Le Borgne, G. Alory, L. Gourdeau and A. Ganachaud helped improve the manuscript.

REFERENCES

ALORY G., A.VEGA, A. GANACHAUD & M. DESPINOY, Influence of upwelling, subsurface stratification and heat fluxes on coastal SST off south-western New Caledonia, *J. Geophys. Res.*, in press, 2006.

BARNETT T. P., D. W. PIERCE, K. M. ACHUTARAO, P. J. GLECKLER, B. D. SANTER, J. M. GREGORY & W. WASHINGTON, Penetration of human-induced warming into the world's oceans, Science, 309, 284-287, 2005.

BASHER R. E. & X. ZHENG, Tropical cyclones in the Southwest Pacific: spatial patterns and relationships to Southern Oscillation and sea surface temperature, *J. Clim.*, 8, 1249-1260, 1995.

BINDOFF, N. L. & J. A. CHURCH, Warming of the water column in the southwest Pacific Ocean, *Nature*, 357, 5962, 1992.

CAZENAVE A. & R. S. NEREM, Present-day sea level change: Observations and causes, *Rev. Geophys.*, 42, RG3001, doi:10.1029/2003RG000139, 2004.

CHURCH J. A., N. J. WHITE & J. R. HUNTER, Sea-level rise at tropical Pacific and Indian Ocean islands, *Global and Planetary Change*, in press, 2006.

COBB K. M., C. D. CHARLES, H. CHENG & R. L. EDWARDS, El Niño/Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, 424, 271-276, 2003.

COLLINS M. & the CMIP groups, El Niño- or La Niña-like climate change?, *Clim. Dyn.*, 24, 89-104, 2005.

CORRÈGE T., M. K. GAGAN, J. W. BECK, G. S. BURR, G. CABIOCH & F. LE CORNEC, Interdecadal variation in the extent of South Pacific tropical waters during the Younger Dryas event, *Nature*, 428, 927-929, 2004.

COURTNEY J. B., The South Pacific and southeast Indian Ocean tropical cyclone season 2002-03, *Australian Meteo. Mag.*, 54, 137-150, 2005.

DAI A. & T. M. L. WIGLEY, Global patterns of ENSO-induced precipitation, *Geophys. Res. Lett.*, 27, 12831286, 2000.

DAVIS R. E., Preliminary results from directly measuring middepth circulation in the tropical and South Pacific. *J. Geophys. Res.*, 103, 24 619-24 639, 1998.

DELCROIX T., Observed surface oceanic and atmospheric variability in the tropical Pacific at seasonal and ENSO timescales: a tentative review. *J. Geophys. Res.*, 103, 18 611-18 633, 1998.

DELCROIX T. & C. HÉNIN, Mechanisms of subsurface thermal structure and sea surface thermohaline variabilities in the southwestern tropical Pacific during 1975-85, *J. Mar. Res.*, 47, 777-712, 1989.

DELCROIX T. & O. LENORMAND, ENSO signals in the vicinity of New Caledonia, South Western Pacific, *Oceanologica Acta*, 20, 481-491, 1997.

DONGUY J.-R. & G. MEYERS, Mean annual variation of transport of major currents in the tropical Pacific Ocean. *Deep-Sea Res. I*, 43, 1105-1122, 1996.

FEDOROV A. V. & S. G. PHILANDER, Is El Niño changing?, *Science*, 288, 1997-2002, 2000.

FINE R. A., R. LUKAS, F. M. BINGHAM, M. J. WARNER & R. H. GAMMON, The western equatorial Pacific: a water mass crossroads. *J. Geophys. Res.*, 99, 25 06325 080, 1994.

FISCHER M., B. DEWITTE & L. MAÎTREPIERRE, A non-linear statistical downscaling model: El Niño/Southern Oscillation impact on precipitation over New Caledonia. *Geophys. Res. Lett.*, 31, L16204, doi:10.1029/2004GL020112, 2004.

FOLLAND C. K., J. A. RENWICK, M. J. SALINGER & A. B. MULLAN, Relative influences of the interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone, *Geophys. Res. Lett.*, 29, doi:10.1029/2001GL014201, 2002.

GIRARD C., J. SUDRE, S. BENHAMOU, D. ROOS & P. LUSCHI, Homing in green turtles (*Chelonia mydas*): do oceanic currents act as a constraint or as an information source?, *Marine Ecology Progress Series*, in press, 2006.

GOURIOU Y & J. TOOLE, Mean circulation of the upper layers of the western equatorial Pacific Ocean. *J. Geophys. Res.*, 98, 22 495-22 520, 1993.

GOURIOU Y. & T. DELCROIX, Seasonal and ENSO variations of sea surface salinity and temperature in the South Pacific Convergence Zone during 1976–2000, *J. Geophys. Res.*, 107(C12). 8011, doi:10.1029/2001JC000830, 2002.

GU D. & S.G. H. PHILANDER, Interdecadal climate fluctuations that depend on exchanges between the tropics and extra-tropics. *Science*, 275, 805-807, 1997.

HANLEY D. E., M. A. BOURASSA, J. J. O'BRIEN, S. R. SMITH & E. R. SPADE, A quantitative evaluation of ENSO indices. *J. Clim.*, 16, 1249-1258, 2003.

HÉNIN C. & G. R. CRESSWELL, Upwelling along the western barrier reef of New Caledonia, *Marine and Freshwater Res.*, 56, 1005-1010, 2005.

HUGHES T. P., A. H. BAIRD, D. R. BELLWOOD, M. CARD, S. R. CONOLLY, C. FOLKE, R. GROSBERG, O. HOEGH-GULDBERG, J. B. C. JACKSON, J. KLEYPAS, J. M. LOUGH, P. MARSHALL, M. NYSTRÖM, S. R. PALUMBI, J. M. PANDOLFI, B. ROSEN & J. ROUGHGARDEN, Climate change, human impacts, and the resilience of coral reefs, *Science*, 301, 929-933.

ISHII M., M. KIMOTO, K. SAKAMOTO & S.-I. IWASAKI, Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses, *J. Oceanogr.*, 62, 155-170, 2006.

KAPLAN A., M. A. CANE, Y. KUSHNIR, A. C. CLEMENT, M. B. BLUMENTHAL & B. RAJAGOPALAN, Analyses of global sea surface temperature 1856-1991, *J. Geophys. Res.*, 103, 18 567-18 589, 1998.

KESSLER W. S. & L. GOURDEAU, Wind-driven zonal jets in the South Pacific Ocean, *Geophys. Res. Lett.*, 33, L03608, doi:10.1029/2005GL025084, 2006a.

KESSLER W. S. & L. GOURDEAU, The annual cycle of circulation of the southwest subtropical Pacific, analyzed in an ocean GCM, *J. Phys. Oceanogr.*, in press, 2006b.

LAGERLOEF G. S. E., G. T. MITCHUM, R. B. LUKAS & P. P. NIILER, Tropical Pacific near-surface currents estimated from altimeter, wind, and drifter data. *J. Geophys. Res.*, 104, 23 313-23 326, 1999.

LAVIN M. F., P. C. FIEDLER, J. A. AMADOR, L. T. BALLANCE, J. FÄRDER-LORDA & A. M. MESTAS-NUÑEZ, A review of eastern tropical Pacific oceanography: Summary, *Prog. Oceanogr.*, 69, 391-398, 2006.

LE BORGNE R., Y. DANDONNEAU & L. LEMASSON, The problem of the island mass effect on chlorophyll and zooplankton standing crops around Mare (Loyalty Islands) and New Caledonia, *Bull. Mar. Science*, 37, 450459, 1985.

LINSLEY B.K., A. KAPLAN, Y. GOURIOU, J. SALINGER, P.B. DEMENOCAL, G.M. WELLINGTON & S.S. HOWE, Tracking the extent of the South Pacific Convergence Zone since the early 1600s, *Geochem. Geophys. Geosyst.*, 7, Q05003, doi:10.1029/2005GC001115, 2006.

LOMBARD A., A. CAZENAVE, P.-Y. LE TRAON & M. ISHII, Contribution of thermal expansion to present-day sealevel change revisited, *Global and Planetary Change*, 47, 1-16, 2005.

LUO J.-J. & T. YAMAGATA, Long-term El Niño-Southern Oscillation (ENSO)-like variation with special emphasis on the South Pacific, *J. Geophys. Res.*, 106, 22 211-22 227, 2001.

LYON B., The strength of El Ni–o and the spatial extent of tropical drought, *Geophys. Res. Lett.*, 31, L21204, doi:10.1029/2004GL020901, 2004.

MCPHADEN M. J. & D. ZHANG, Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, 415, 603-608, 2002.

MAHARAJ A. M., P. CIPOLLINI & N. J. HOLBROOK, Observed variability of the South Pacific westward sea level anomaly signal in the presence of bottom topography, *Geophys. Res. Lett.*, 32, L04611, doi:10.1029/2004GL020966, 2005.

MANTUA N. J., S. R. HARE, Y. ZHANG, J. M. WALLACE & R. C. FRANCIS, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Amer. Meteor. Soc.*, 78, 1069-1079, 1997.

MARTINEZ E. & K. MAAMAATUAIAHUTAPU, Island mass effect in the Marquesas Islands: time variation, *Geophys. Res. Lett.*, 31, L18307, doi:10.1029/2004GL020682, 2004.

MEYERS G., P. MCINTOSH, L. PIGOT & M. POOK, The years of El Niño, La Niña and interactions with the tropical Indian Ocean, *J. Clim.*, in press, 2006.

MORRIS M., D. ROEMMICH & B. CORNUELLE, Observations of variability in the South Pacific subtropical gyre, *J. Phys. Oceanogr.*, 26, 2359-2380, 1996.

MORROW R., F. BIROL, D. GRIFFIN & J. SUDRE, Divergent pathways of cyclonic and anti-cyclonic ocean eddies. *Geophys. Res. Lett.*, 31, L24311, doi:10.1029/2004GL020974, 2004.

NICET J. B., & T. DELCROIX, ENSO-related precipitation changes in New Caledonia, Southwestern tropical Pacific: 1969-98. *Mon. Wea. Rev.*, 128, 3001-3006, 2000.

OUILLON S., P. DOUILLET, R. FICHEZ & J.-Y. PANCHÉ, Enhancement of regional variations in salinity and temperature in a coral reef lagoon, New Caledonia, *C. R. Geoscience*, 337, 1509-1517, 2005.

PICKARD G. L. & W. J. EMERY, Descriptive physical oceanography, an introduction, 5th enlarged edition. *Butterworth-Heinemann publication*, 320 pp, 1990.

QIU B. & S. CHEN, Seasonal modulation in the eddy field of the South Pacific Ocean. *J. Phys. Oceanogr.*, 34, 1515-1527, 2004.

QU T. & E. J. LINDSTROM, A climatological interpretation of the circulation in the western South Pacific, *J. Phys. Oceanogr.*, 32, 2492-2508, 2002.

QUINN W. H., V. T. NEAL & S. E. ANTUNEZ DE MAYOLO, El Niño occurences over the past four and a half centuries. *J. Geophys. Res.*, 92, 14 449-14 461, 1987.

RAYNER N. A., D. E. PARKER, E. B. HORTON, C. K. FOLLAND, L. V. ALEXANDER, D. P. ROWELL, E. C. KENT & A. KAPLAN, Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.* 108, 4407, doi:10.1029/2002JD002670, 2003.

REID J. L., On the total geostrophic circulation of the Pacific Ocean: flow patterns, tracers, and transports. *Prog. Oceanogr.*, 39, 263-352, 1997.

REVERDIN G., The physical processes of open ocean upwelling systems, published in "Upwelling in the Ocean: Modern processes and ancient records", edited by C. P. Summerhayes, K.-C. Emeis, M. V. Angel, R. L. Smith, and B. Zeitzschel, 1995.

RICHARDS K. J., N. A. MAXIMENKO, F. O. BRYAN & H. SASAKI, Zonal jets in the Pacific Ocean, *Geophys. Res. Lett.*, 33, L03605, doi:10.1029/2005GL024645, 2006.

RIDGWAY K. R. & J. R. DUNN, Mesoscale structure of the mean East Australian Current system and its relationship with topography, *Prog. Oceanogr.*, 56, 189-222, 2003.

ROEMMICH R., J. GILSON, R. DAVIS, P. SUTTON, S. WIJFFELS & S. RISER, Decadal spin-up of the South Pacific subtropical gyre. *J. Phys. Oceanogr.,* in press, 2006.

ROPELEWSKI C. F., & M. S. HALPERT, Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Wea. Rev.*, 115, 1606-1626, 1987.

ROUGERIE F. & J. RANCHER, The Polynesian south ocean: features and circulation, *Marine Pollution Bulletin*, 29, 14-25, 1994.

SAJI N. H., B. N. GOSWAMI, P. N. VINAYACHANDRAN & T. YAMAGATA, A dipole mode in the tropical Indian Ocean, *Nature*, 401, 360-363, 1999.

SALINGER M. J., R. E. BASHER, B. B. FITZHARRIS, J. E. HAY, P. D. JONES, J. P. MACVEIGH & I. SCHMIDELY-LELEU, Climate trends in the South-west Pacific, *Int. Journal Clim.*, 15, 285-302, 1995.

SALINGER M. J., J. A. RENWICK & A. B. MULLAN, Interdecadal Pacific oscillation and South Pacific climate, *Int. Journal Clim.*, 21, 1705-1721, 2001.

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

STUART-MENTETH A. C., I. S. ROBINSON & P. G. CHALLENOR, A global study of diurnal warming using satellite-derived sea surface temperature, *J. Geophys. Res.*, 108(C5), 3155, doi:10.1029/2002JC001534, 2003.

SUDRE J. & R. MORROW, Using satellite data to monitor global ocean surface currents, *Adv. Space Res.*, in press, 2006.

TOMCZAK M. & J. S. GODFREY, Regional Oceanography: an introduction. *Pergamon Press*, 422 pp, 1994.

TSUCHIYA M., R. LUKAS, R. A. FINE, E. FIRING & E. LINDSTROM, Source waters of the Pacific equatorial undercurrent. *Prog. Oceanogr.*, 23, 101-147, 1989.

TRENBERTH K. E., The definition of El Niño, *Bull. Amer. Meteor. Soc.*, 78, 2771-2778, 1997.

TRENBERTH K. E., G. W. BRANSTATOR, D. KAROLY, A. KUMAR, N.-C. LAU & C. ROPELEWSKI, Progress during TOGA in understanding and modelling global teleconnections associated with tropical sea surface temperatures, *J. Geophys. Res.*, 103, 14 291-14 324, 1998.

VINCENT D. G., The South Pacific Convergence Zone (SPCZ): A review, *Mon. Wea. Rev.*, 122, 1949-1970, 1994.

WANG C. & J. PICAUT, Understanding ENSO physics – A review, In: *Earth's Climate: The Ocean-Atmosphere Interaction*. C. Wang, S.-P. Xie, and J. A. Carton, Eds., AGU Geophysical Monograph Series, 147, 21-48, 2004.

WEBB D. J., Evidence for shallow zonal jets in the South equatorial current region of the southwest Pacific, *J. Phys. Oceanogr.*, 30, 706-720, 2000.

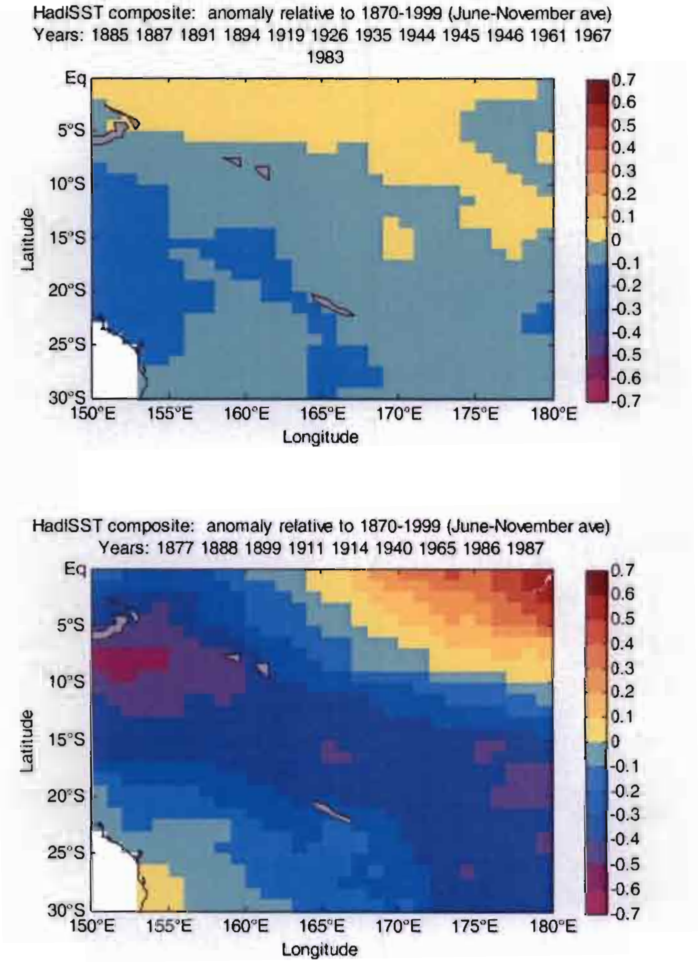


Figure 2. Composite averages of SST anomaly during June to November for the pure IOD mode (top) and pure ENSO mode (bottom) as classified in Table 1 (courtesy of Gary Meyers). These analyses were derived from the historical SST data compiled by the Hadley Centre for 1876 to 1999, the so called HadISST 1.0 data set (Rayner *et al.*, 2003).

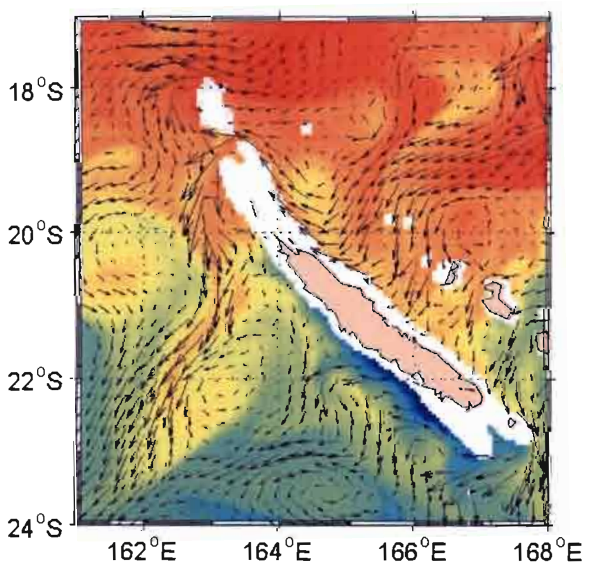


Figure 5. Snapshot of surface currents and SST simulated by ROMS in 29 April 2000 (after Vega, A., P. Marchesiello, J. Lefèvre and A. Ganachaud, Coastal upwelling modulated by island wake effect off New Caledonia, submitted *in Geophys. Res. Lett.*, 2006).

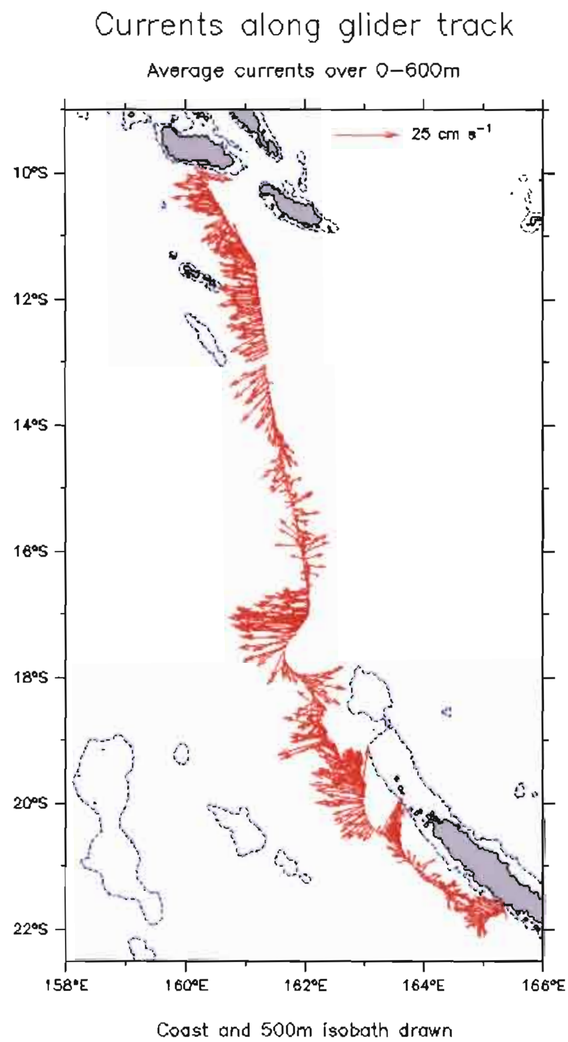


Figure 4. Vectors of the 0 to 600 m average velocity for each dive of the 4-month mission (July to October 2005) deduced from the position of an autonomous glider (after Gourdeau, L., W. S. Kessler, R. Davis, J. Sherman, and C. Maes, Zonal jets entering the Coral Sea, *submitted to Journal of Physical Oceanography*, 2006). Note the presence of the North Caledonian zonal jet around 17°S and the complex activity in eddies along the northwest coast of the Caledonian reef. The dashed line in blue represents the 500 m isobath.

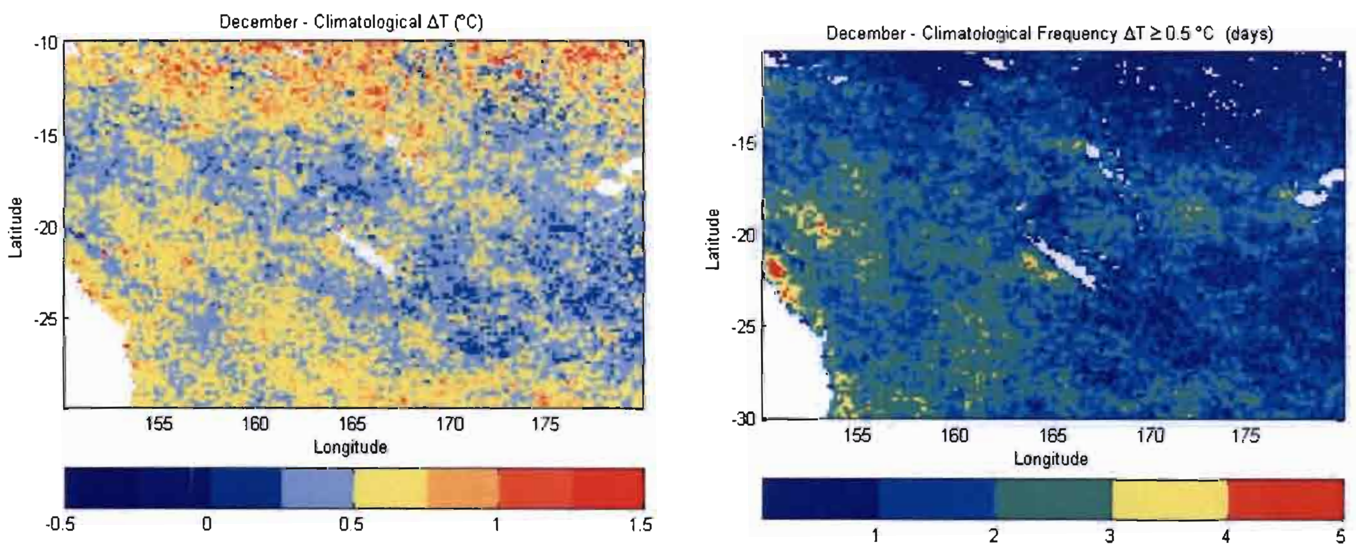
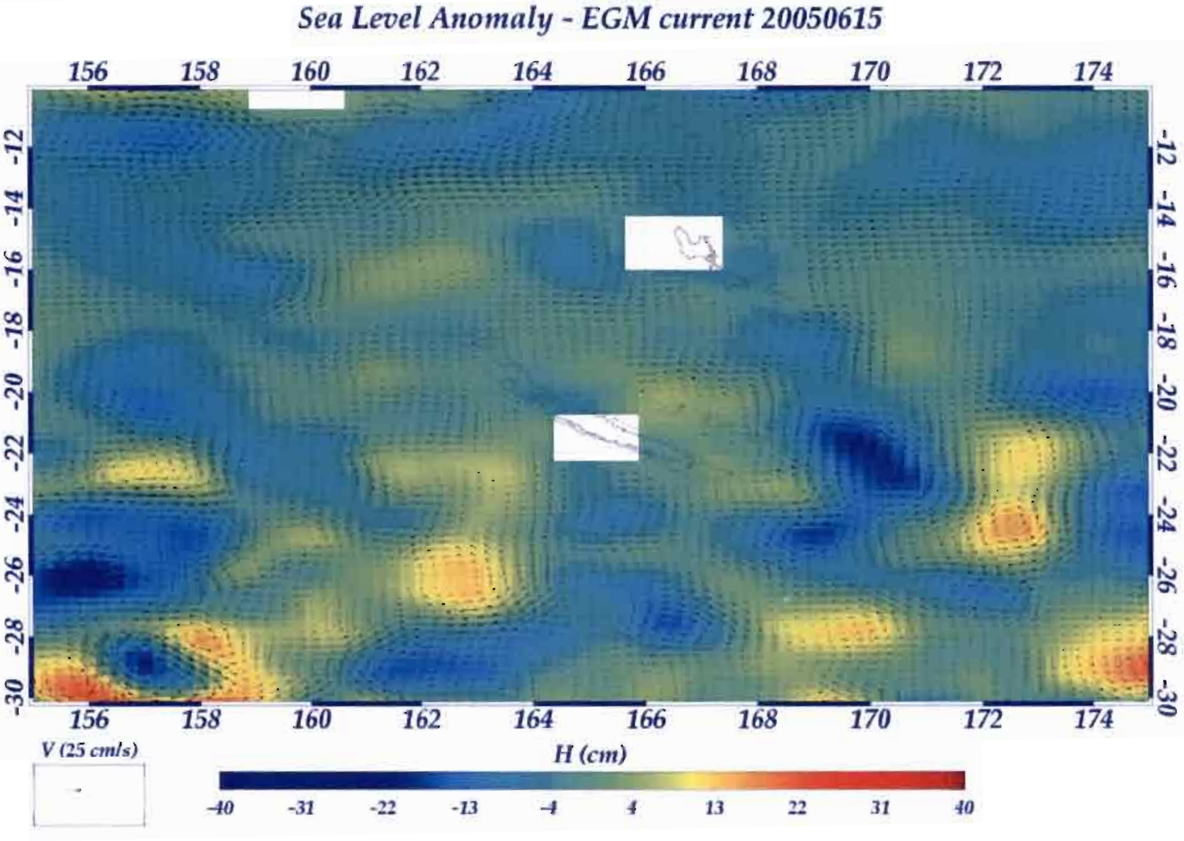


Figure 6. Monthly mean distribution in December of diurnal warming (left) and number of occurrences in days when $\Delta T > 0.5°C$ (right) based on satellite-derived SST (courtesy of Alice Stuart-Menteth).



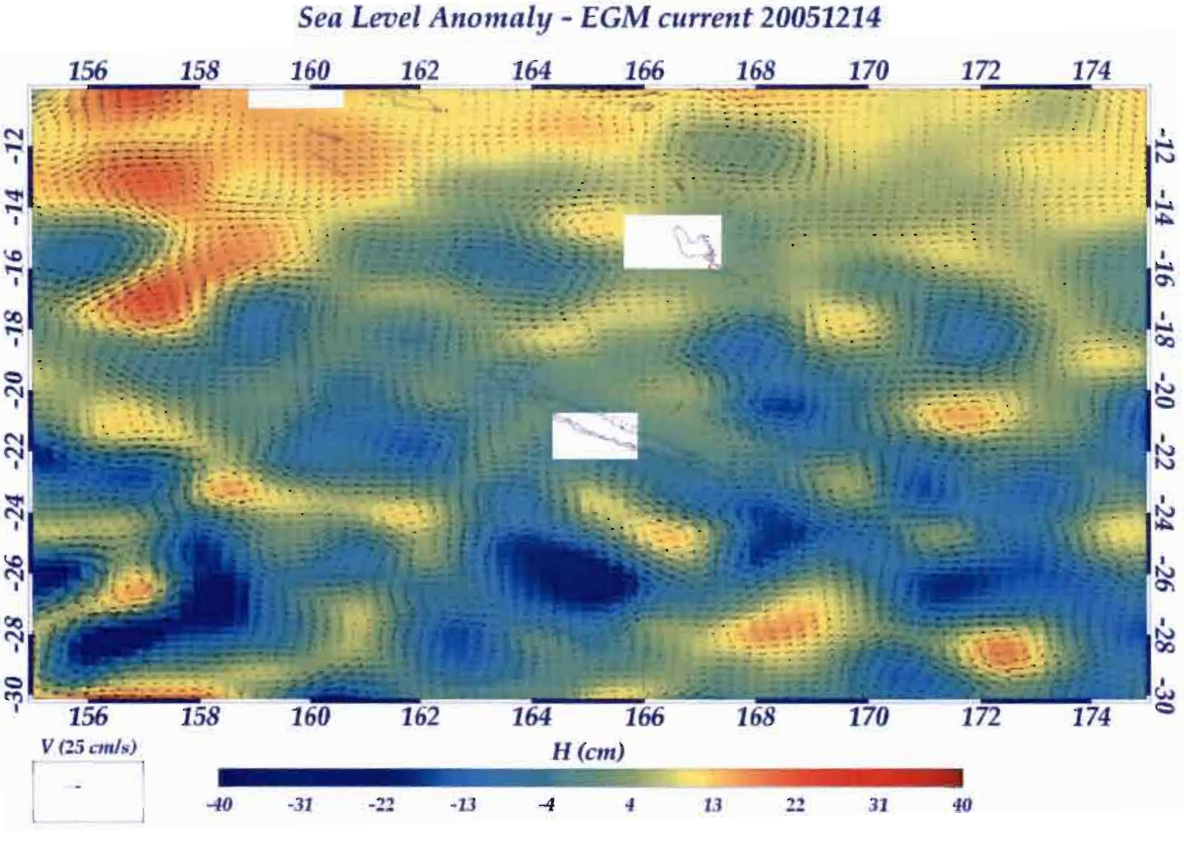


Figure 7. Sea surface currents derived from satellite data superimposed on sea level anomaly observed from altimetric satellites for the 15 June and 14 December 2005, respectively. Such analyses are based on the surface current products supplied by Sudre & Morrow (2006). These snapshots underline the strong activity in eddies superimposed on the general surface circulation, mainly zonal, from east to west.

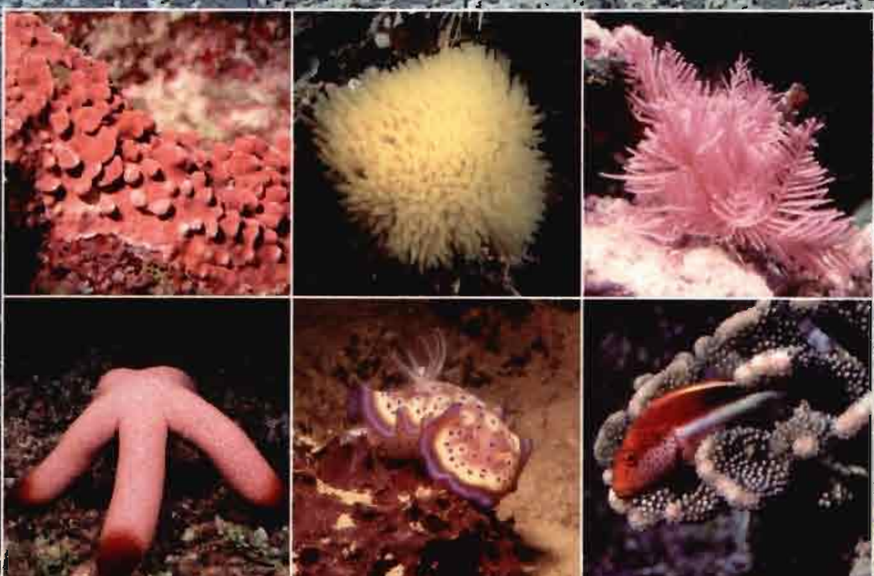
DOCUMENTS
SCIENTIFIQUES
et TECHNIQUES

II7

Volume spécial

Deuxième édition

COMPENDIUM of marine species from New Caledonia



Edited by
Claude E. PAYRI
Bertrand RICHER DE FORGES

IRD

Institut de recherche pour le développement

CENTRE DE NOUMÉA

DOCUMENTS
SCIENTIFIQUES
et TECHNIQUES

Institut de recherche pour le développement

Publication éditée par:
Centre IRD de Nouméa
BP A5, 98848 Nouméa CEDEX
Nouvelle-Calédonie
Téléphone: (687) 26 10 00
Fax: (687) 26 43 26

L'IRD propose des programmes regroupés en 5 départements pluridisciplinaires:

I DME Département milieux et environnement
II DRV Département ressources vivantes
III DSS Département sociétés et santé
IV DEV Département expertise et valorisation
V DSF Département du soutien et de la formation des communautés scientifiques du Sud

Modèle de référence bibliographique à cette revue:
Adjeroud M. *et al.*, 2000. Premiers résultats concernant le benthos et les poissons au cours des missions TYPATOLL. *Doc. Sci. Tech.* II 3, 125 p.

ISSN 1297-9635. Seconde édition
Numéro II7 - **Octobre** 2007

Distribué pour le Pacifique par le Centre de Nouméa.

Première de couverture : Récif corallien (Côte Ouest, NC) © IRD/C.Geoffray
Vignettes : voir les planches photographiques

Quatrième de couverture : *Platygyra sinensis* © IRD/C.Geoffray

Matériel de plongée sous-marine © IRD/C.Geoffray	L'Aldric, moyen naviguant de l'IRD © IRD/J.-M. Boré
Récoltes et photographies sous-marines en scaphandre autonome © IRD/J.-L. Menou	Traitement des récoltes en laboratoire © IRD/L. Mattio

CONCEPTION/MAQUETTE/MISE EN PAGE JEAN PIERRE MERMOUD/ISABELLE RITZENTHALER
MAQUETTE DE COUVERTURE CATHY GEOFFRAY/MINA VILAYLECK
PLANCHES PHOTOGRAPHIQUES CATHY GEOFFRAY/JEAN-LOUIS MENOU/GEORGES BARGIBANT
TRAITEMENT DES PHOTOGRAPHIES NOËL GALAUD

La traduction en anglais des textes d'introduction, des Ascidies et des Echinodermes a été assurée par EMMA ROCHELLE-NEWALL, la préface par MINA VILAYLECK.

Ce document est publié par le Service ISC du Centre IRD de Nouméa et financé par le Ministère de la Recherche et de la Technologie.

ISSN 1297-9635. Seconde édition
Numéro 117 - **Octobre 2007**

COMPENDIUM OF MARINE SPECIES FROM NEW CALEDONIA

SECOND EDITION

Edited by
CLAUDE E. PAYRI, BERTRAND RICHER DE FORGES