Past and present coral growth variability on Moorea Island (French Polynesia): A perspective for the future?

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Introduction

Because they are restricted to shallow waters, coral reefs can experience the effects of climatic change acting through the atmosphere or the marine environments. For this reason, many scientists have considered the reef ecosystem particularly vulnerable to climate change. Furthermore, direct effects of changes in atmospheric CO_2 on coral communities may be as great as greater than the effects on climate change. These atmospheric change will cause significant changes in the carbon chemistry of surface ocean water, especially decreases in pH and carbonate ion concentration, which will reduce the calcium carbonate saturation state. J. Kleypas *et al.*, (1999), outlined a range of geological and chemical evidence to suggest that coral reefs will not form and grow in a greenhouse-affected world because the coral's ability to form skeletons will be degraded by carbonate changes in the ocean. That change may come about within 100 years and coral reefs may change dramatically. By the middle of the next century, an increased concentration of carbon dioxide will decrease the aragonite saturation state in the tropics by 30 percent and biogenic aragonite precipitation by 14 to 30 percent. These authors indicates that aragonite and high-magnesium calcite precipitation in the tropics has already decreased an average of 6 to 11 % and will be another 8 to 17 % lower under doubled CO_2 conditions.

However, the scientific debate has been widened by Barnes and Lough (2000) who suggest that the ocean chemistry is more complex than portrayed above. They argue that the ocean buffer the changes in acidity, and any changes in coral growth will be positive and driven more by temperature changes than by carbonate changes.

In the paper, we have generated a two centuries-long time series (1800 to 1990) of change in coral growth of a *Porites* coral head in order to investigate how sensitivity to calcium carbonate saturation state, in conjunction with other influences operating over various scales, means that global-climate related change will apply significant stresses to coral head in the tropical South Central Pacific region. Firstly, measurements of coral growth has led to a refined annual records of skeletal extension, density and calcification rates. Secondly, data series has compared with instrumental environmental data.

Materials and method

Location

The islands of French Polynesia (134° to 158° W, 8° to 28° S) which lie in the heart of the Pacific ocean, make up a total land area of 4 millions of km^2 (Figure 1). Moorea island (Society archipelago) is a high island (total areas of 135 km^2) with a central volcano and a barrier-reef protecting a lagoon. This island has an oceanic climate with relatively dry and cold season (May to October) and a wet and warm season (November to April). Monthly air temperature range 27.5°C, in March, to 24.4°C in August.

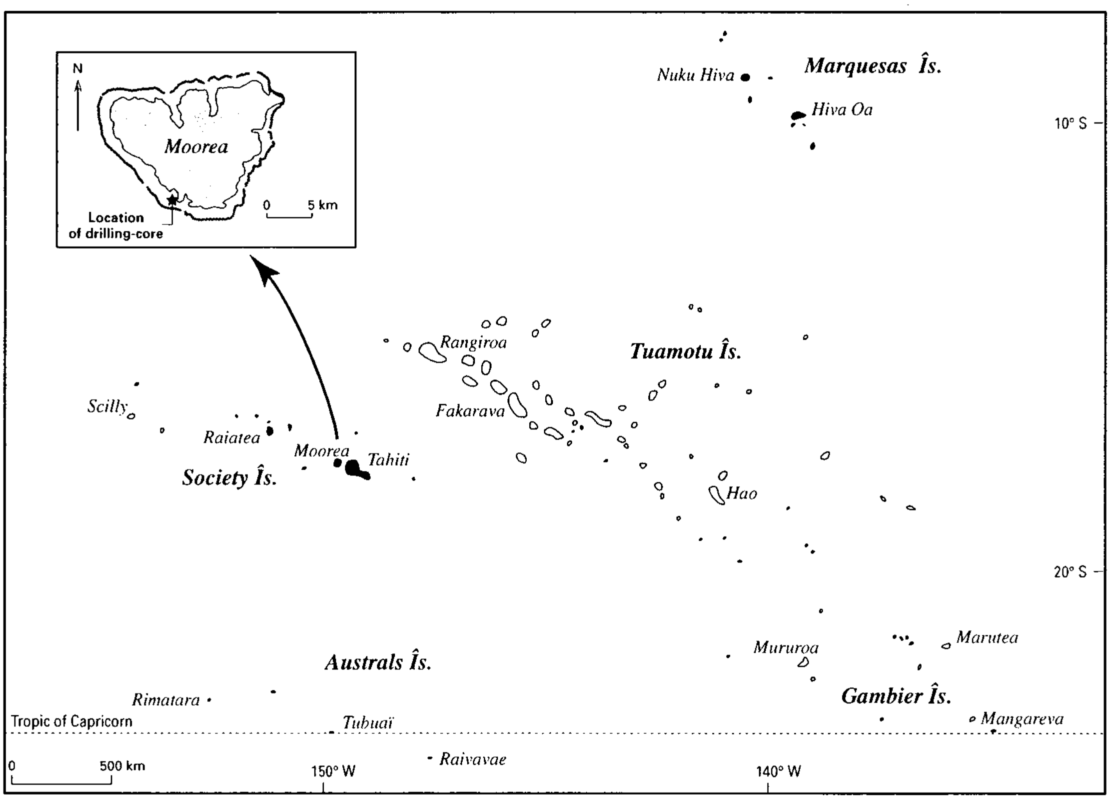

Figure 1
Coral study area in the central Pacific ocean and sampling locality at Moorea island.

Material

In October 1990, a colony of *P. lutea* located on the edge of the lagoon in front of the district of Haapiti was drilled at the depth of 5 m (Figure 1). The core was cut into 8 mm thick slabs oriented parallel to the growth axis and perpendicular to the density bands.

To better understand long-term coral growth variability on the coral reef, we used and developed Computerized Tomography (CT) analysis (Bessat, 1995, 1997). Unlike conventional X-ray radiography, tomography creates a two dimensional matrix of absorption values of the scanned slice (1.5 mm in this study). The resulting density image allows a quantitative interpretation of the X-ray absorbing structures in the sample and the construction of precise density curve along the growth axis. A data series of absolute density vs. distance was generated. Successive density peaks were then dated backwards from the date of collection of the colony.

Times series of the skeletal density parameters were then obtained for each slice ; linear extension measured between high density peaks ($cm.yr^{-1}$), annual density ($g.CaCO_3.cm^{-3}$) and annual calcification ($g.CaCO_3.cm^{-2}.yr^{-1}$). The calcification rate is the product of the linear extension rate (measured directly from banding seen in tomography picture) and the average density at which skeleton was deposited in making that extension.

Results

Temporal variability of coral growth characteristics

Since 1801, mean annual extension rate over the entire series is 10.86±2.31 $mm.yr^{-1}$. It varies from 6.1 $mm.yr^{-1}$ to 16.8 $mm.yr^{-1}$. Annual density of the core have varied from 0.97 $g.cm^{-3}.yr^{-1}$ to 1.33 $g.cm^{-3}.yr^{-1}$ with average of 1.15 $g.cm^{-3}.yr^{-1}$. The time series for annual calcification varied from a maximum of 1.96 $g.cm^{-2}.yr^{-1}$ to a minimum of 0.66 $g.cm^{-2}.yr^{-1}$ with annual calcification average of 1.26 $g.cm^{-2}.yr^{-1}$ (Table 1).

	$\bar{x}$	σ	min	max	n
Extension ($mm.yr^{-1}$)	10,86	2,31	6,14	16,88	190
Density (g.cm-3.yr^{-1})	1,15	0,07	0,97	1,33	190
Calcification g.cm-2.yr^{-1}	1,25	0,27	0,66	1,96	190

Table 1
Mean and s.d., over the period 1801-1990, of coral growth variables from *P. lutea* at Moorea.

After discussing the entirely records, we compared coral growth measurements which occurred between 1801-1905, 1905-1990 and 1940-1990 (Table 2). Some features are noticed. Average linear extension present a tendency to increase; it varies from 10.7 $mm.yr^{-1}$ (1801-1905) to 11.44 $mm.yr^{-1}$ (1940-1990). Consequently, calcification tempts to increase, from 1.23 $g.cm^{-2}.yr^{-1}$ to 1.33 $g.cm^{-2}.yr^{-1}$, over the common periods. The decrease values of the minimum data of calcification measurements was significant (Figure 2). The standard deviation (s.d) expressed as a percentage of the mean, was lowest for annual calcification during the last period, from 1940 to 1990 (Table 2).

Annual calcification was significantly correlated with annual linear extension ($r=0.95$, $p<0.000$, $n=192$) and (though not statistically significant) with annual density ($r=0.20$, $p=0.0045$, $n=192$). Annual density was not related to annual extension ($r=0.07$, $p=0.309$, $n=192$) (Fig 3). Lough and Barnes (2000) found also a strong relationship between annual calcification and extension, but average annual density was significant and inversely related to average annual extension. Thus, variations in calcification rate were mostly caused by variations in extension rate, but density could sometimes modulated calcification rate.

	$\bar{x}$	σ	min	max	n
			period 1800-1905		
Linear extension (mm.yr⁻¹)	10,70	2,54	6,14	16,88	104
Density (g.cm-3.yr⁻¹)	1,152	0,069	1,010	1,339	104
Calcification (g.cm-2.yr⁻¹)	1,233	0,301	0,663	1,939	104
			period 1905-1990		
Linear extension (mm.yr⁻¹)	11,07	2,00	7,67	16,88	85
Density (g.cm-3.yr⁻¹)	1,159	0,068	0,976	1,329	85
Calcification (g.cm-2.yr⁻¹)	1,293	0,216	0,840	1,962	85
			period 1940-1990		
Linear extension (mm.yr⁻¹)	11,445	2,103	7,676	16,887	45
Density (g.cm-3.an⁻¹)	1,156	0,077	0,976	1,329	45
Calcification (g.cm-2.yr⁻¹)	1,337	0,201	0,988	1,962	45

Table 2
Mean and s.d., over the period 1801-1905, 1905 and 1940-1990, of coral growth variables from *P. lutea* at Moorea.

The Moorea coral growth results suggest several different kinds of coral annual linear extension, density and calcification variability over the past two centuries (Figure 2) : coral growth records include, firstly, inter-annual environmental pulses events, secondly, decade-scale variability. The results present here highlights that *P. lutea* growth characteristics are highly variable and the data show frequent extended periods during which coral growth characteristics were above or below the long-term mean. There is no long-term trend versus annual extension and calcification rates ; however, several "minimum" and "maximum" intervals are evident. Maximum calcification rate includes the years 1801-1820, 1866-1880, 1940-1952 and 1960-1976. Annual density of the core was characterized by long-term variations while annual extension and annual calcification were characterized by higher frequency variations. These results reinforce data found by Lough and Barnes (1997, 2000).

To estimate time-series stability, the coral growth data sets were analyzed with Petitt and Mann-Kendal tests (Vandiepenbeck, 1995 for descriptions of the method). The test on annual linear extension and annual calcification rate data reveals two significant changes around 1960 and 1939. It means that annual coral growth is faster from 1939 to 1960 and from 1960 to 1990 while annual calcification rate is more important since 1939. Test on annual density series shows more complex results; three significant times, in 1930, 1960 and 1976, are found.

Coral growth and their relationship with temperature

Annual calcification shows a relationship with records of air temperature available for the period 1958-1990 (Table 3). Linear regressions of air temperature against density data shows a highly significant ($r=0.61$, $p<0.00$, $n=34$) trend in which a rise in temperature from 1°C would increase the density rate by about 10.5% (Figure 4). Furthermore, linear regression of air temperature against

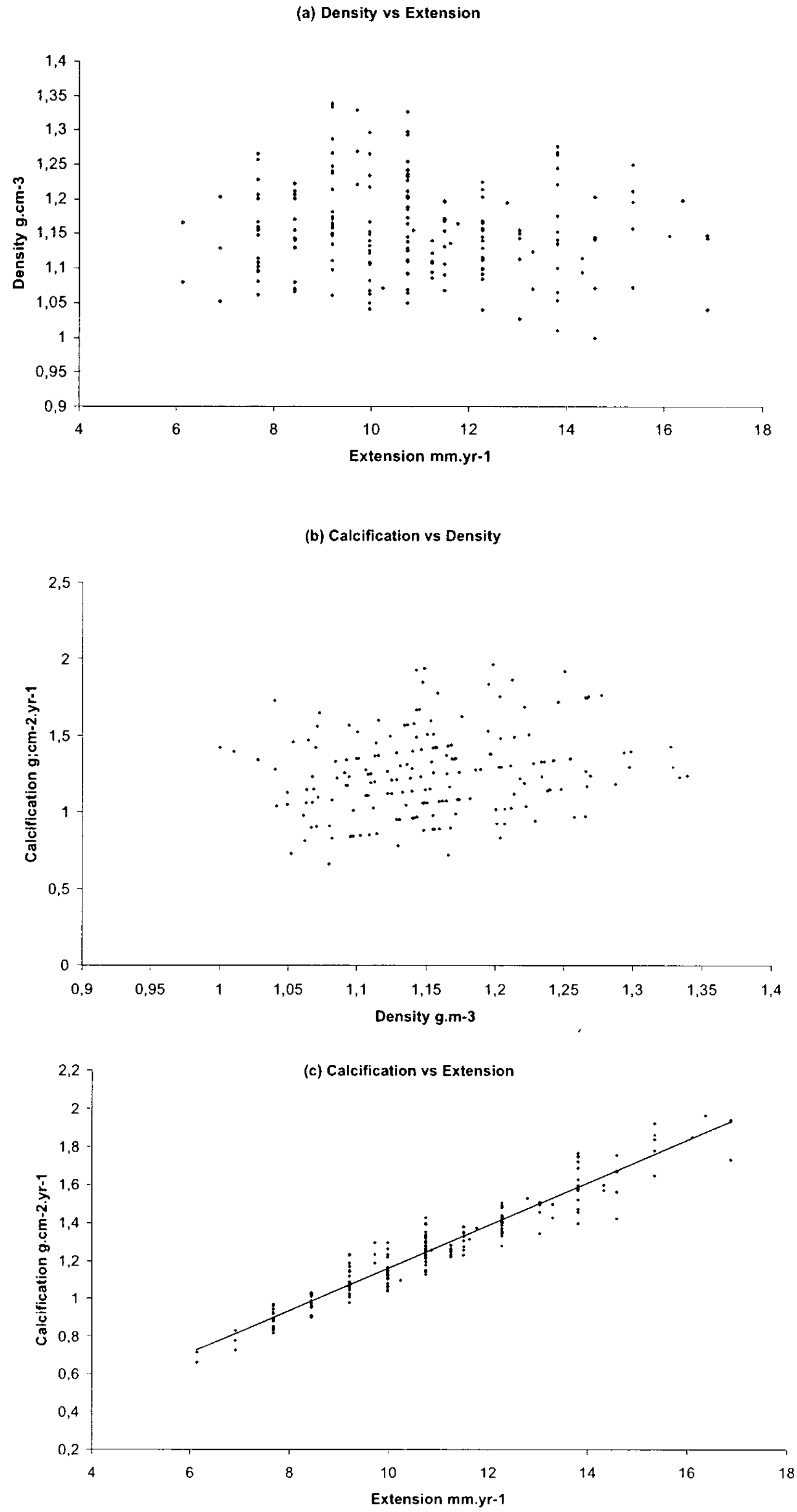

Figure 2
Time series from a coral core at Moorea covering the period 1801-1990 for extension, density and calcification. Thin line is data smoothed with a 10-year filter.

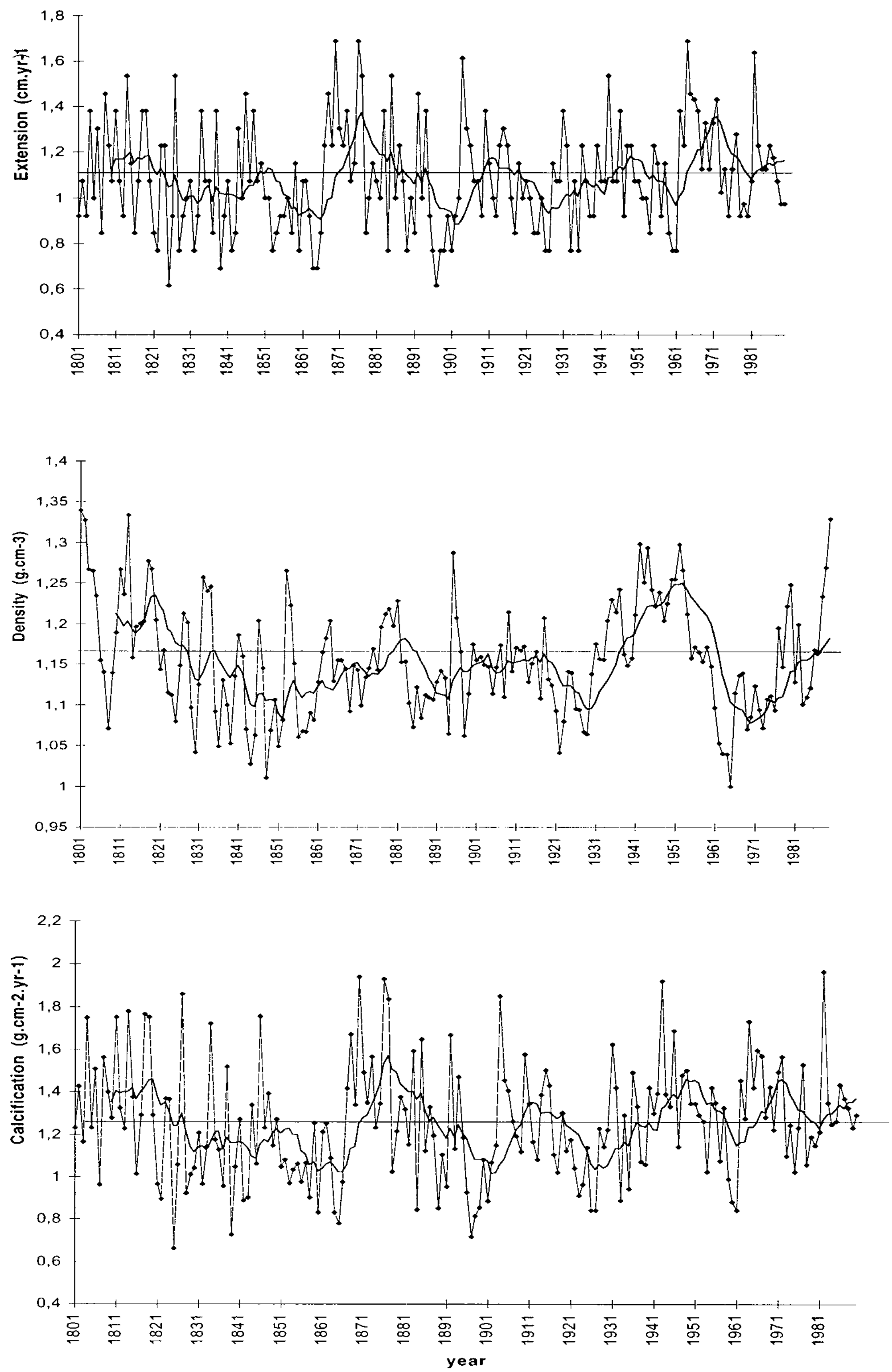

Figure 3
Scatter diagrams of average growth data for a *Porites* colony for the period 1801-1990. (a) Density vs. extension, (b) calcification vs. density, (c) calcification vs. extension.

	Temperature		Rainfall	
	Original	5-year filter	Original	5-year filter
Linear extension	0,121	0,149	0,110	0,040
Density	0,373	0,559	0,050	-0,197
Calcification	0,008	0,325	0,094	-0,147

Table 3
Correlation between annual climatic data and the coral growth time series for original and 5-year filtered series, 1958-1990. Bold italic indicates that the correlation is significant at the 5% level.

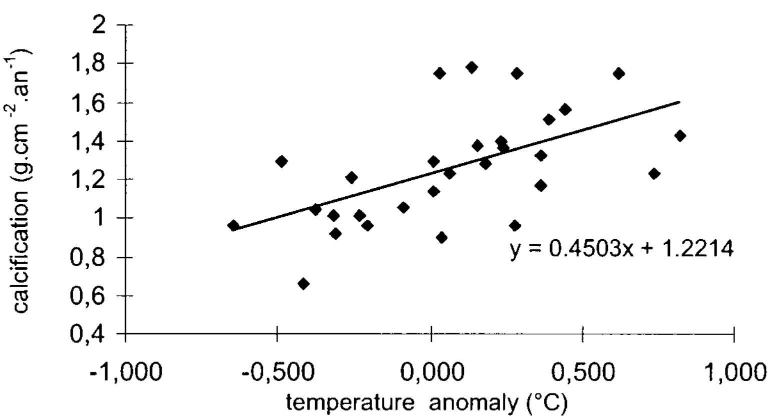

Figure 4
Linear regression between annual calcification and annual air temperature, 1958-1990.

calcification data shows a highly significant ($r=0.57$, $p<0.00$, $n=34$) trend in which a rise in temperature from 1°C would increase the calcification rate by about 4.5% (Figure 4).

Discussion

Our results suggest, like results found by Lough and Barnes (1997, 2000), that variations in *Porites* calcification on Moorea are driven by variations of temperature. Increase in calcification in *Porites* over the recent decades have been interpreted to be as a result of increase of air temperature trend, particularly the five last decade of the 20th century. These data differs notable from the 6-14% decline in calcification over the past 100 years predicted by certain researchers (Kleypas *et al.*, 1999).

The study of the stability of annual calcification rate over two centuries, on Moorea, has illustrated its singular character. An increase in the annual rate of calcification are perfectly identified, in particular at the beginning of this century and in a more marked way around 1940, 1960 and 1976. At the same periods, the decennal Oscillation of the Northern Pacific, from now known under the Anglo-Saxon acronym, PDO (« Pacific Decadal Oscillation « Mantua *et al.*, 1997) presents notable changes. The post 1976 trend corresponds to a decadal-scale climate transition that is a topic of much recent interest (Trenberth et Hurrell, 1994). The shift in 1960 found on Moorea coral may be related to a significant change in the structure of the oscillation of the northern Pacific. It will be noted that the diagram, observed since 1960 on the density bands data, present similarities with the results obtained, by the same statistical method, on the data of annual air temperature of Tahiti. For reference, a recent study (Quinn *et al.*, 1998) tends to show a significant relation between the isotopic recording of the oxygen of a coral colony from New-Caledonia and the PDO. Furthermore, they have also been identified several transitions on the century portions of the New Caledonia coral $d^{18}O$ record : an abrupt change in 1940-1941, after 1958 and after 1976.

Climate variability in the equatorial Pacific occurs over a variety diversity of timescales, ranging from the annual cycle to decadal shifts of unknown origin. The dominant mode is interannual climate variability in the Southern Oscillation (SO) which acts as the pacemaker of tropical Pacific sea surface temperature via a direct link with the El Niño phenomenon (Philander, 1990). Spectral analysis of instrumental records and ENSO indices reveals that the dominant variance in the SO and ENSO occurs over a broad range of periods from 3 to 10 years (Barnett, 1998). A near-biennal component of ENSO (2.2 to 2.8 years) has also been recognized (Ropelewski *et al.*, 1992). Periods of 2,4; 4,5 and 6,6 years observed on annual calcification rate data from Moorea between 1801 to 1990 (not shown here) suggest a relation with ENSO events. Same results are confirmed on several others *Porites* corals heads which have studied on Moorea and Mururoa (Bessat, 1997). In fact, ENSO events present a tendency to increase annual calcification rate.

Conclusion

Long-term changes in calcification of *Porites* at Moorea appear to be particularly sensitive to temperature variations with higher calcification associated with higher temperature.

Results presented here show that *Porites* growth characteristics are highly variable and the annual extension, density and calcification rates varied significantly about the mean, both from year to year and over decadal-scale periods. In this context, the real and perceptible degradation of the coral ecosystems in response to the human activities, particularly in the coastal zones (Wilkinson and Buddemeier, 1994), underlines the interest of recent work on the evolution of the current reefal communities and in particular of the massive coral colonies. The rebuilding of the history of the growth of the reefal communities, particularly of the massive coral colonies, over sufficiently long periods (> at 30 years) is a precondition to any definition of an average state (Lough and Barnes, 1997).

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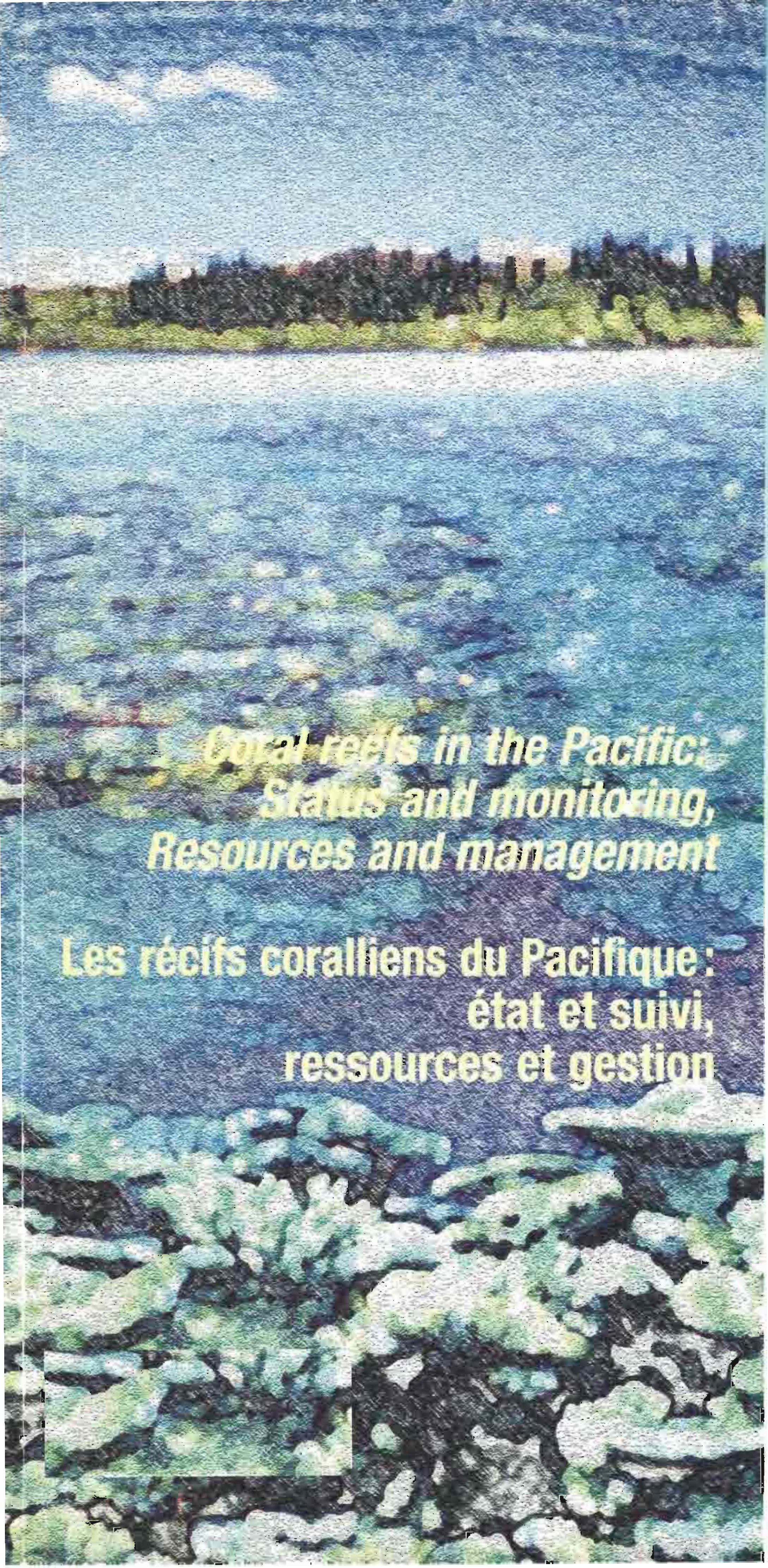

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