Qatar Univ. Sci J. (1999), 19:

CORAL BLEACHING AND ENSO ANOMALY : WAS THE PAST SIMILAR TO THE PRESENT ?

By

Francis Rougerie

Observatoire Océanologique Européen. Centre scientifique de Monaco. Avenue St-Martin, MC 98000 MONACO

Key words : *Coral bleaching. ENSO anomaly. Oxygen and carbon isotopic composition. Paleothermometer.*

ABSTRACT

Bleaching of reef corals is due to partial or total loss of symbiotic micro-algae as a consequence of environmental stress such as an oceanic warming linked to the ocean-scale hydroclimatic anomaly termed ENSO (El Nino Southern Oscillation). In the Indian ocean, ENSO episodes modify the monsoon regime and are accompanied by large changes in rainfall, wind oceanic current and heat distribution.

As growth and calcification in corals are controlled by light and temperature, their skeletal record can be used to reconstruct past hydroclimatic regimes, such as ENSO. Long term (i.e., 100s of years) skeletal records can be obtained by removing drill core samples form massive reef corals such as Porites, which can live for many centuries and attain sizes of several meters in diameter. The oxygen and carbon isotopic composition of cores taken form corals correlates well with sea surface temperature and salinity. Changes in isotopic composition can reveal growth hiatus due to bleaching events Indian reef corals also show sensitivity to hydroclimatic fluctuations : depletion in 18-O and 13-C reflect high oceanic temperature combined with enhanced precipitation and cloud cover. Other paleoclimatic records can be extracted from the aragonite skeletons of corals, such as the ratios of sr/Ca, U/Ca and Mg/Ca. These ratios are also temperature-dependent and can be used to construct a paleothermometer with an accuracy of ± 0.5 °C.

Reef corals in the Arabian Gulf can be used in the same way to compare present and past patterns of growth in relation to global climate change.

INTRODUCTION

Although the tropical ocean-atmosphere is a key component of the Earth's climate system, its past behavior remains poorly characterized. Over interannual to decadal periods, tropical climate variability has global consequences, as seen in extra tropical manifestations of ENSO (El Nino Southern Oscillation) and the Asian monsoon. Over longer time-scales, the available marine and terrestrial paleoclimatic reconstructions provide contradictory evidence regrading the sensitivity of the tropics to high-latitude changes. Low latitude instrumental records are generally limited to the past several decades and to isolated sites, leaving proxy climate archives as the principal source of information about natural variability in tropical climate. Corals are uniquely capable of extending the observational record, continuously over the past several centuries and via isolated (but well-dated) windows throughout the Holocene and late Pleistocene.

Because corals grow close to the sea surface, they can provide excellent records of tropical air and sea conditions. Such data is of extreme importance to climatologist because the tropical oceans play a central role in the global machine as regulators of heat and moisture exchange between large area of the sea surface and atmosphere. This interaction creates and fuels great ocean circulations and wind patterns that generate and push weather systems around the world.

As corals are widely distributed throughout the low latitude ocean, they are considered as organisms able to tolerate elevated sea surface temperature. Data and field observations taken during the last decade have shown that corals are sensitive to extreme oceanic temperature and that they bleached and died above a thermal threshold generally near 30°C. That means that vital metabolitic functions as growth and skeletal calcification can be hampered when coral colonies are closed to their thermal limits : the use of corals as paleo indicators is then constrain by biological limits.

In a situation of stress or of environmental shift, a coral colony can react in three different ways :

- the metabolism is affected, without hampering the process of growth-calcification; the paleorecord is continue and easy to read.
- the stress is severe, triggering a partial or total bleaching, follows by a recovering; the paleorecord is at its best.
- the stress is letal, giving bleaching ant mortality; the paleorecord is killed, but gives important clues on limits of natural variability.

Possible environmental factors responsible for coral stress are varied (1); however evidence form both observations and field/laboratory experiments indicates that mass coral bleaching in both oceans could be explained by either the negative effects of elevated sea surface temperature (SST), or increased levels of ultraviolet light which accompany warm, nutrient-depleted waters, or a combination of both. While episodes of mass coral mortality have been reported throughout the world since the late 1800s(2), the magnitude, frequency and scale of these events over the past 20 years is unprecedented. Stress events resulting form high sea surface temperature, high or abnormal nutrient availability, low salinity and high rainfall can potentially be recorded in the coral skeleton either as a disruption in growth or as a distinct geochemical signal (e.g., trace metals and isotopes) both of which can be used to assess the frequency and magnitude of environmental perturbations.

Corals records can however offer unique opportunities to reconstruct the history of ocean-atmosphere variability, particularly in time of large scale hydroclimatic anomalies. For now, the predominant world-wide source of intrannual climate variability is the El Nino southern Oscillation (ENSO). The period of which being between 3 to 6 years. Recent climate information derived from century-long isotopic records in reef corals indicate that the ENSO system may also display decadal and centennial scales of variability (3;4). The prolonged ENSO conditions that persisted between 1990-95 have been suggested as being so anomalous that it is highly unlikely to be due to natural decadal-timescale variation. Wether we are already witnessing signs of an anthropogenic effect on ENSO is currently being debated.

Other statical analysis argue that conditions like those of 1990-95 may be expected as often as every 200 years at the 95% confidence level. This debate highlights the importance of developing a longer term understanding of ENSO through the development of annually resolved paleoclimatic records from key regions chosen in the main coral provinces. These paleo-records need to extend back before the late 1700's. In fact, this objective is one of the main goals of both PAGES (Past global Changes) and international CLIVAR (Climate Variability and Predictability) programs.

Paleoclimatic archives.

Paleoclimatic archives capable of recording interannual hydroclimatic variations must offer both absolute dating at seasonal through interannual tim scales, adn accurate preservation of variations in surface ocean and/or atmospheric conditions. In many studies, large massive corals such as Porites which grow in shallow water and live for centuries, are proving to be uniquely suited to this task. They gorow continuously at rate of one centimeter/year and produce annual growth bands. These bends are expressed as couplets of low and high density portions of the coral skeleton that can serve as time markers in the development of long chronologies. Accurate chronologies spannig many hundred of years can be assigned using annual density banding, annual geochemical signals, and radiometric dating. The high growth rate of hermatypic corals enables subannual sampling of skeletal aragonite, with a demonstrated resolution on the order of weeks to months.

Recent studies have shown that chemical tracers within coral skeletal aragonite can accurately record seasonal and interannual changes in environmetnal parameters such as sea surface temperature (SST), salinity, rainfall, nutrients availability and river input (5;6;7 and many others). Coral records can thus be used to assess long-term climate trends as well as the range of natural variability in many tropical environments. Corals also act as useful monitors of man's impact on reef environments worldwide (8).

These paleoclimatic records suggest that while much progress has been made in describing the proximate mechanisms responsible for ENSO's, we lack a complete picture of the pre-and post-historical patterns of these events. Currently, the best coral-based paleoclimate records for evaluating the frequency and amplitude of ENSO events have been derived from the equatorial reefs in the western and eastern Pacific. However, these sites are not always reliable records either because atmospheric convection cells overshoot key sites (where precipitation anomalies define the ENSO signal), or because corals have been stressed by extremely high sea temperature anomalies and stop growing. To fully reconstrcut the surface ocean response to past ENSO events, more records from both inside and outside the equatorial centers of action are needed, in particular in the Indian ocean.

Among the key questions in balance, several must be seriously addressed (9) :

- Has the pacing of the ENSO system changed over the last 300 years, after the onset of cold period named "the little ice age" ? How is the record of ENSO different in the zones of wind convergences compared to other coral-climate record of anomalies and particularly in the South Pacific Converagence Zone, whom the position and seasonal shift control the intensity of the rainy season.?
- Has the occurrence of extremely large ENSO evetns (such as 1982-83 and 1997-98) or long duration events (such as 1991-95) increased in the 20th century relative to the last several centuries ?
- Are long term and decadal trends in coral isotopic records consistent within an area and are they regional ? If regional, are they related to long term climatic cahange.
- What are optimal sampling techniques for recovering a paleoclimatic signal in corals ?

METHODS AND RESULTS

One of the main question to be addressed is the suitability of the sites where data are taken. Coral paleoclimate records are often developed as proxies for variability in large-scale systems such as upwelling regimes, a subtropical gyre, or ENSO. The best results are achieved when corals are recovered from a region with a strong, direct sensitivity to the system or process under investigation. We can identify sites sensitive to large-scale climate variability via several means. Among them, maps giving the Southern Oscillation index in regions of high variations in SST. Also, satellite imagery is a powerfull tool for identification of the spatial extent of surface water thermal and chemiacl signals tied to specific climate phenomena. for example, Coastal Zone Color Scanner (CZCS) images can e used to assess the variability of current or wind-driven upwelling. Figure 1 shows the seasonal contrast in an upwelling system off the coast of Oman. The annual upwelling cycle is driven by large-scale changes in the regional wind field associated with the Asian monsoon. Long lived coral heads have been identified in this region and provide the menas ot examine upwelling variability on short (annual to century) time scales, thus bridging the available instrumental and geological records.

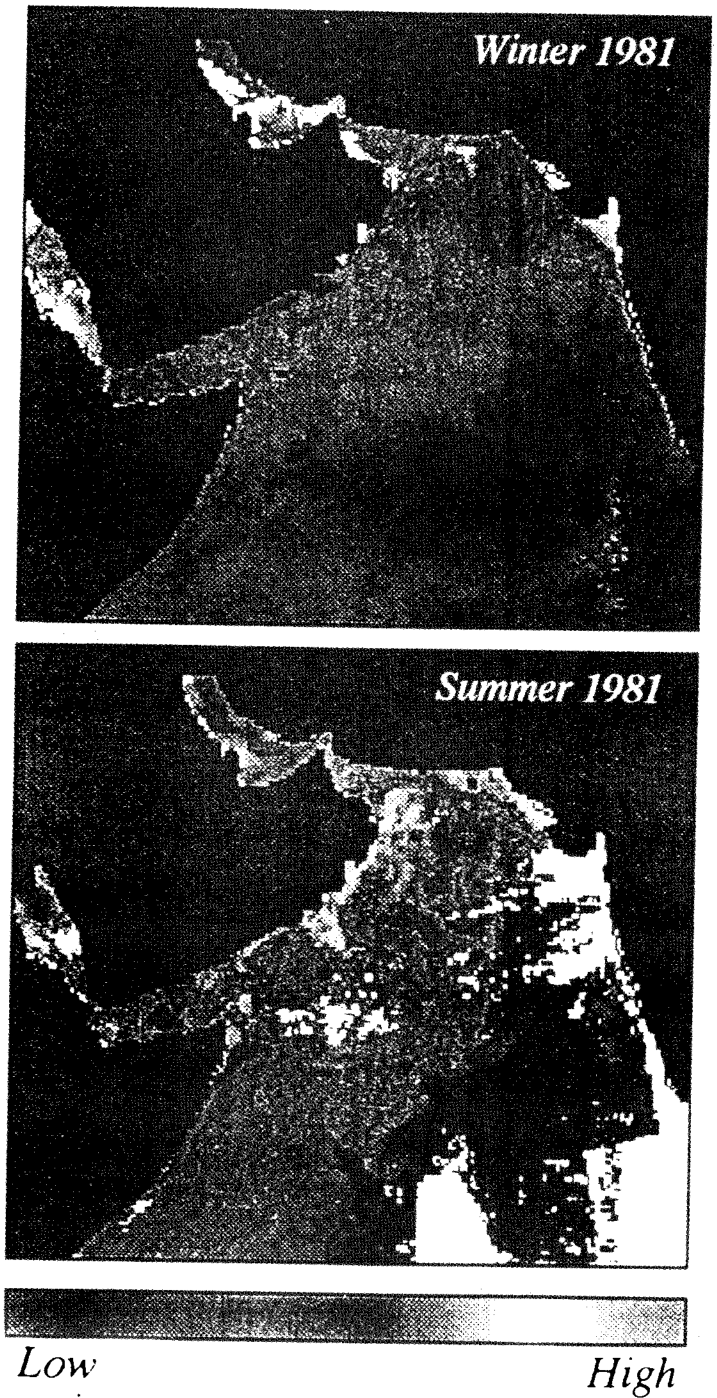


Fig. 1, Pigment concentration

Paleoclimate tracers in corals.
Among the present array of available tracers, oxygen isotopes and Sr/Ca ratio have become mainstays in coral-based climate reconstructians. First works in the equatorial western Pacific clearly show good correlations between the ENSO index (SOI), the δ18-O coral, sea surface temperature (SST), rainfall and salinity (Figures 2 and 3).

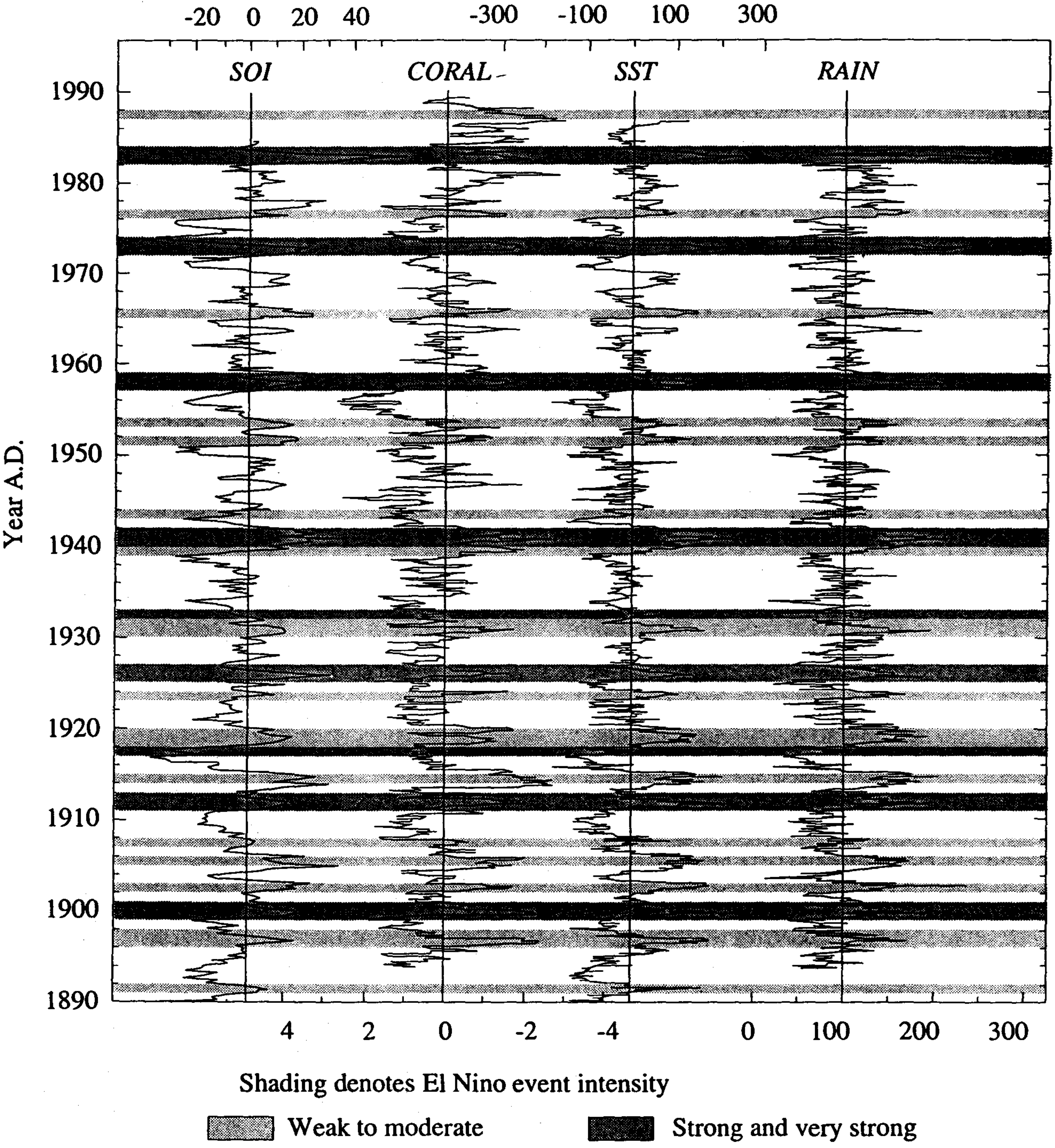
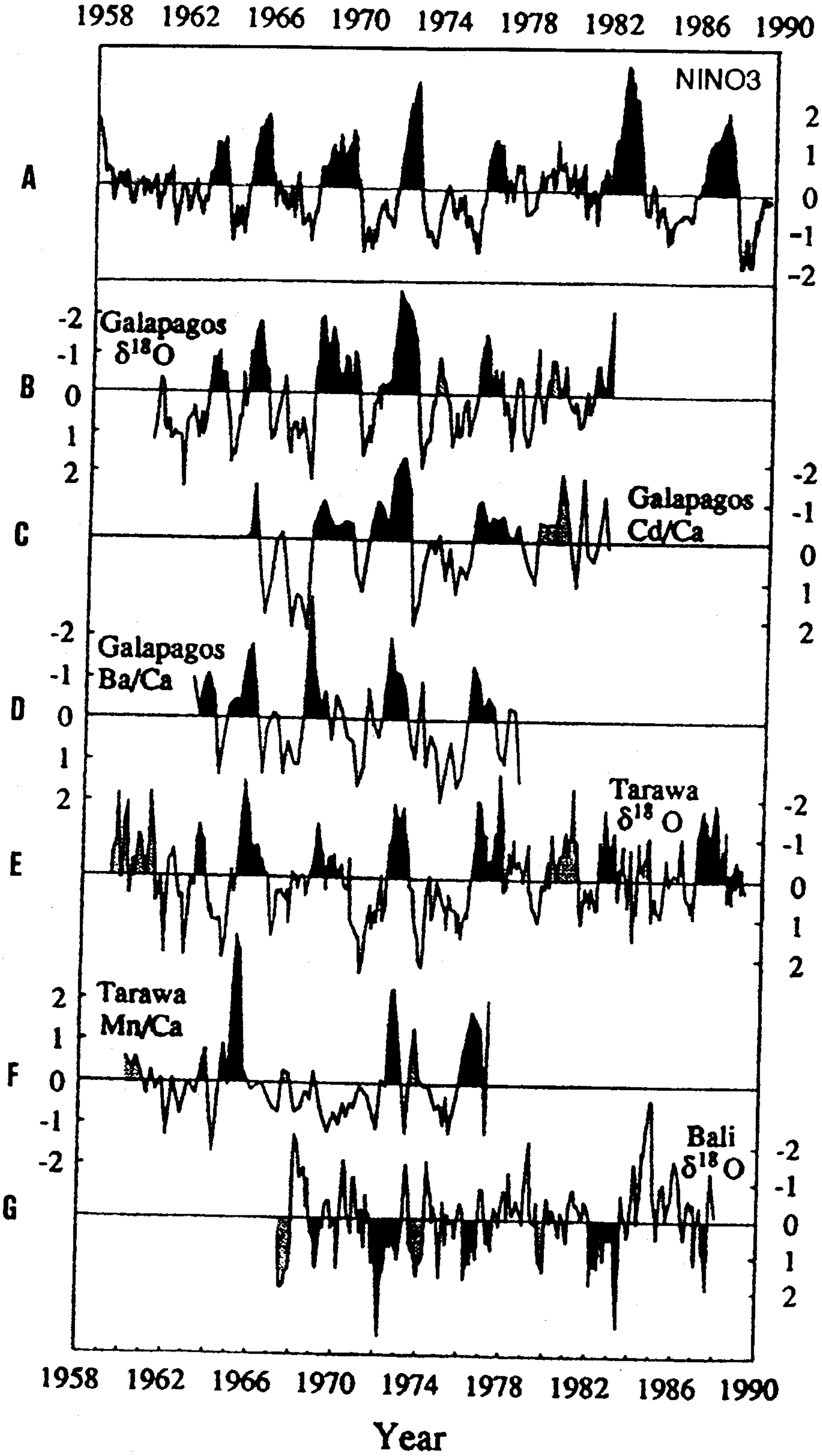


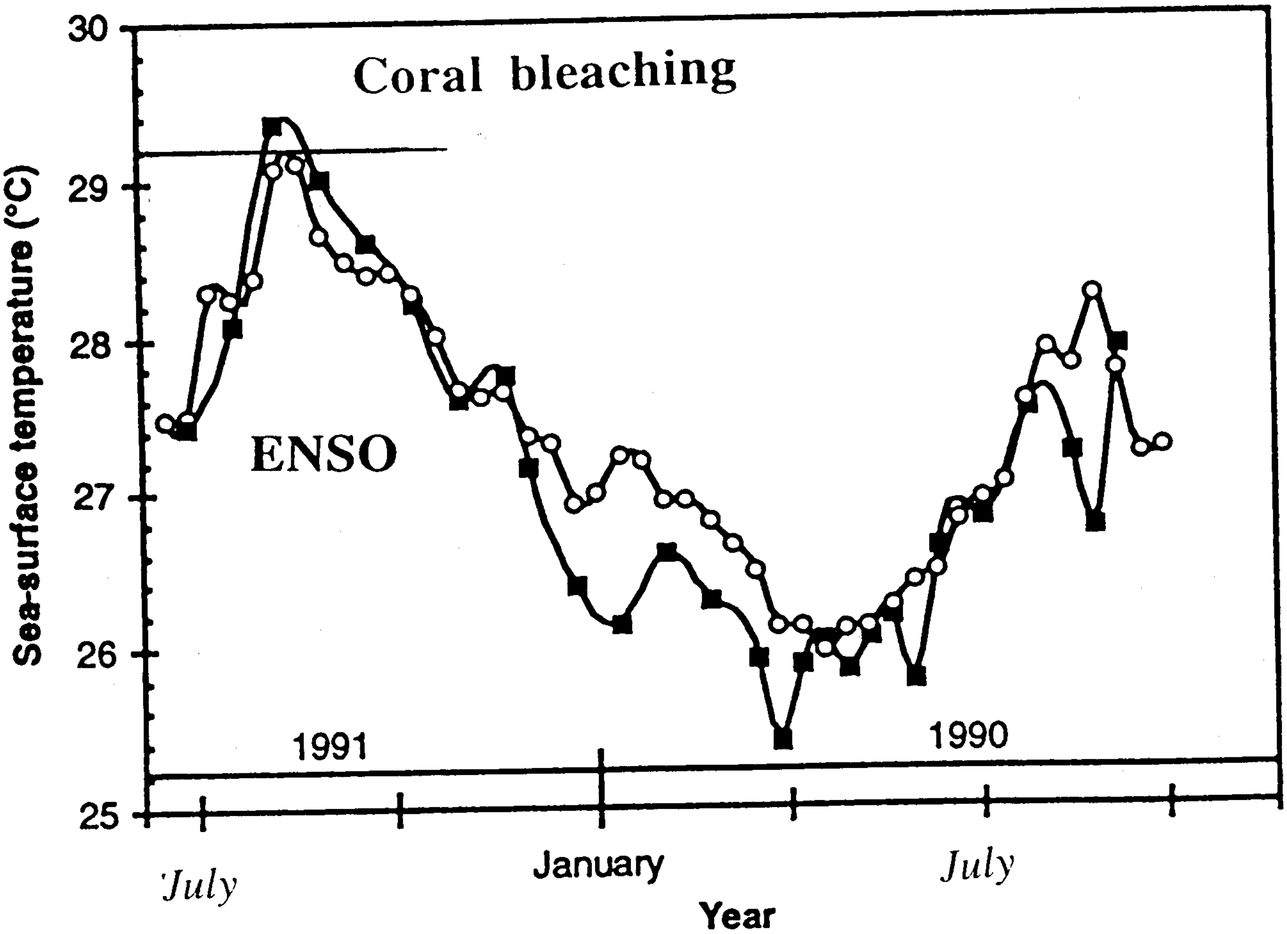
Fig. 2, Shading denotes El Nino event intensity


1958
1962
1966
1970
1974
1978
1982
1986
1990
A
NINO3
2
1
0
-1
-2
B
Galapagos
δ18O
-2
-1
0
1
2
C
Galapagos
Cd/Ca
D
Galapagos
Ba/Ca
E
Tarawa
δ18 O
F
Tarawa
Mn/Ca
G
Bali
δ18O
Year

(Fig. 3)

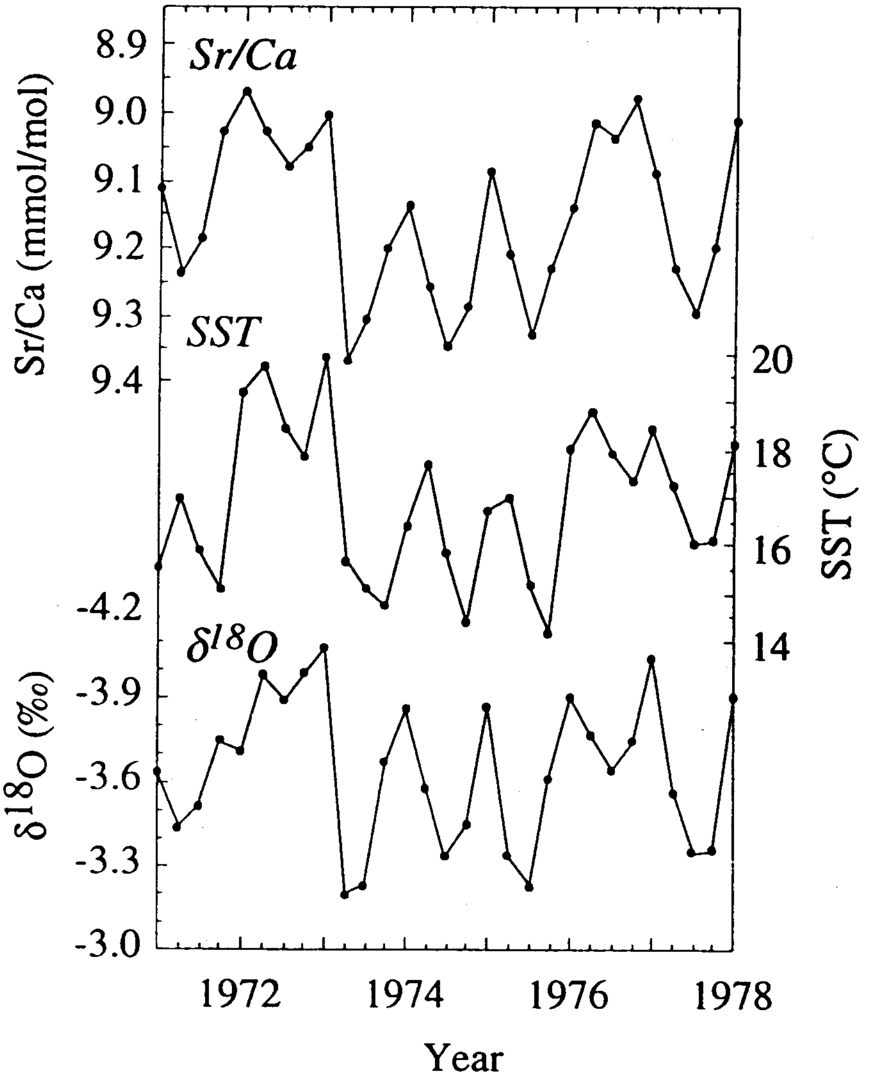
- Oxygen isotopes.

They are currently the "workhosre" tracer for coral paleoceanography; these measurements of δ18-O in coral skeletal reflects a combination of local SST an the δ18-O of ambient seawater. The δ18-O of biogenic calcium carbonate decrease by about 0.22%0 for every 1°C rise in water temperature. In corals, this effect is biologically mediated such that the δ18-O of the coral skeleton is offset belwo seawater δ18-O. This offset is constant with a coral genus for the rapidly growing central axis of the skeleton. Coral δ18-O records taken alog the axis of maximum growth rate thus track ambient temperatures at subseasonal resolution (10). A calibration study on Galàpagos and Indonesian corals (11) have shown that the quaterly measurements of δ18-O and other tracers closely parallel regional SST anomalies associated with ENSO events (Figure 4).



(**Fig. 4**)

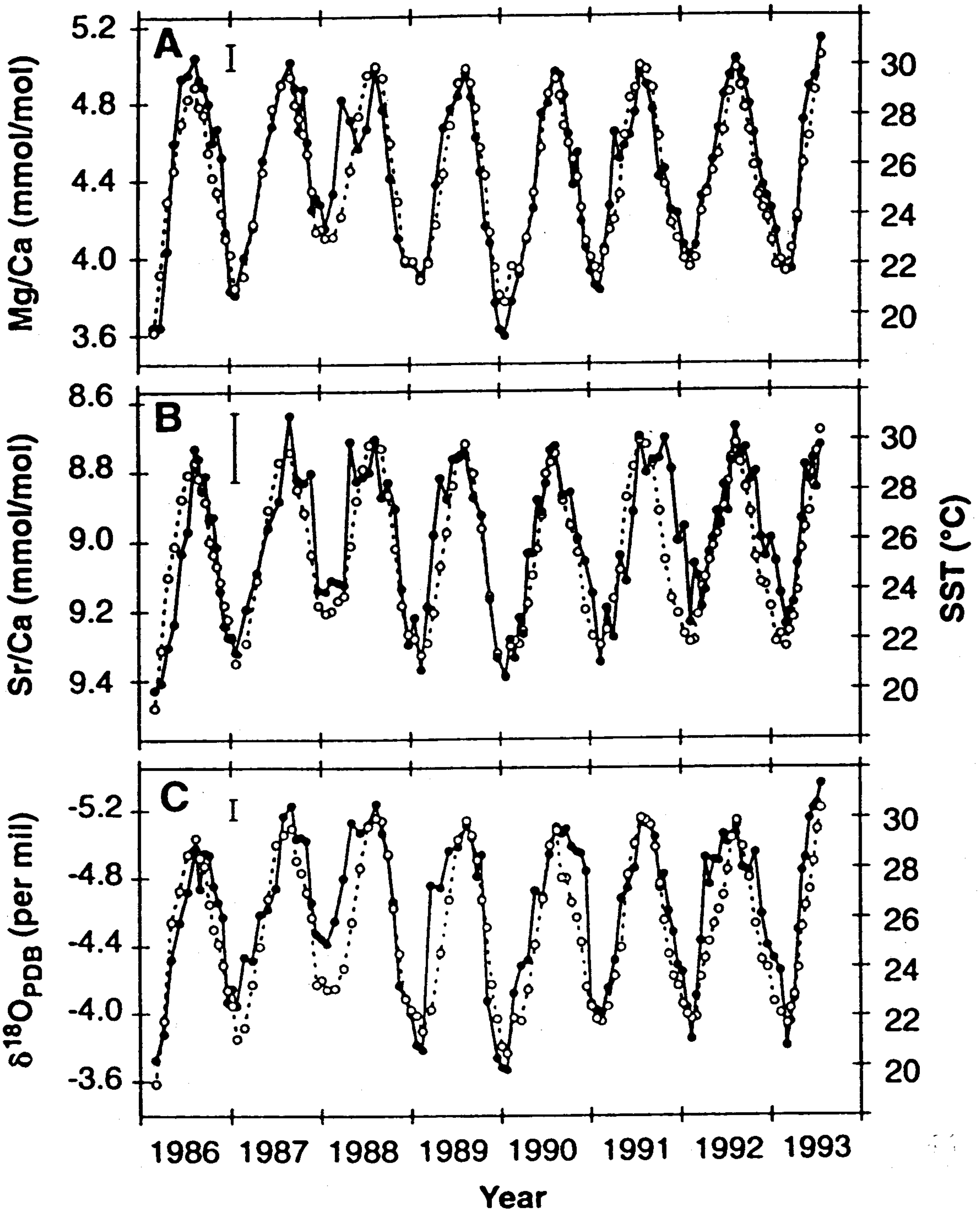
Coral skeleton δ18-O also records variations in the δ18-O of seawater. Such variations are small in most regions of the tropical ocean, but in some locations, changes in evaporation, rainfall, or runoff may cause profound variability. In regions with fairly constant or well known temperatures history, coral δ18-O monitors variations in the hydrologic balance. In many cases, coral skeletal δ18-O reflects a combination of themral and hydrologic factors, Moreover, growth rates may be significantly reduced in both winter (lack of solar radiation) and in summer (thermal stress leading towards bleaching and possible mortality; Figure 5).



(Fig. 5)

- *Srtontium/calcium.*

This ratio is now recognised as one of the best paleothermometer (12). The recent advance has been driven, as in the case of 230-Th/234-U dating, by conversion of the analytical methodology to the highly accurate thermal ionization mass spectrometry (TIMS), Thus, where as the temperature dependace of coral skeletal srontium was demonstrated 15 years ago with a measurement precision of ±2°C, the current reproductibility of ±0.03°%. High resolution calibraion show remarquable agreement between Sr./Ca in reef corals and coral δ18-O or instrumental SST at several sites Figure 6 shows stron covarinace between coral Sr/Ca and measured SST over a 6-year period in the Galàpagos Islands. The large thermal variability of this siet is due to alternance between normal upwelling (cold phase) and aperiodic ENSO events (warm phase).



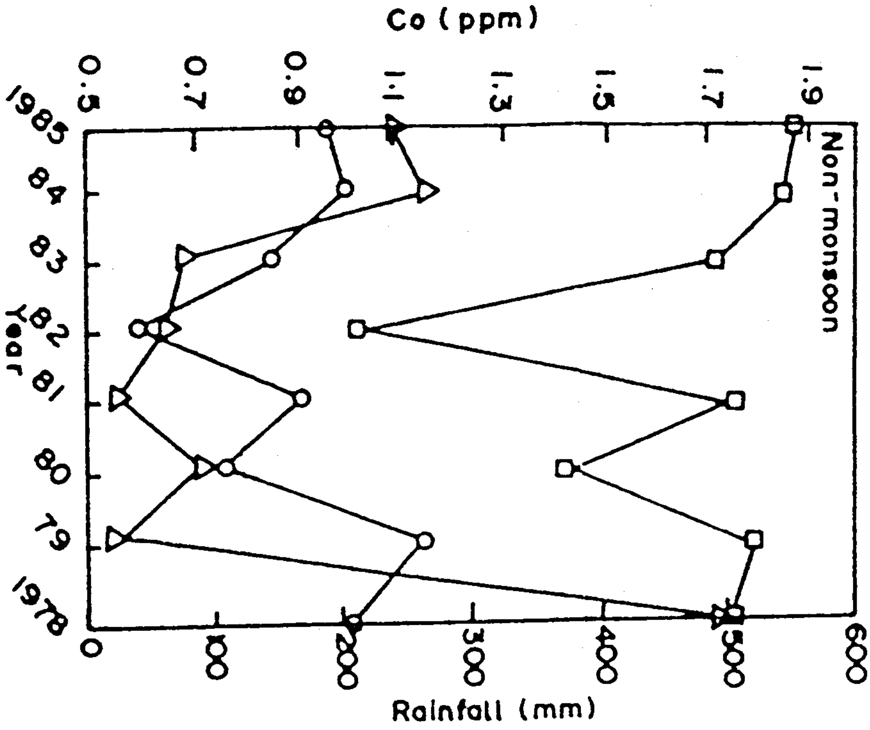
(Fig. 6)

The same kind of High resolution coral studies can generated hundreds to thousands of smaples. The normal output for Sr/Ca analyses in TIMS no more than 20 samples per day. Even if low resolution sampling protocols are used, the development of century-scale Sr/Ca time series is difficult to reach, Refinement is obtained thanks to ICP-TIMS (inductively coupled plasma mass spectrometer). U/Ca and Mg/Ca are complementary tools that can be used in the same way to confirm the coral records, or cross-check the sensitivity-accuracy of this approach.

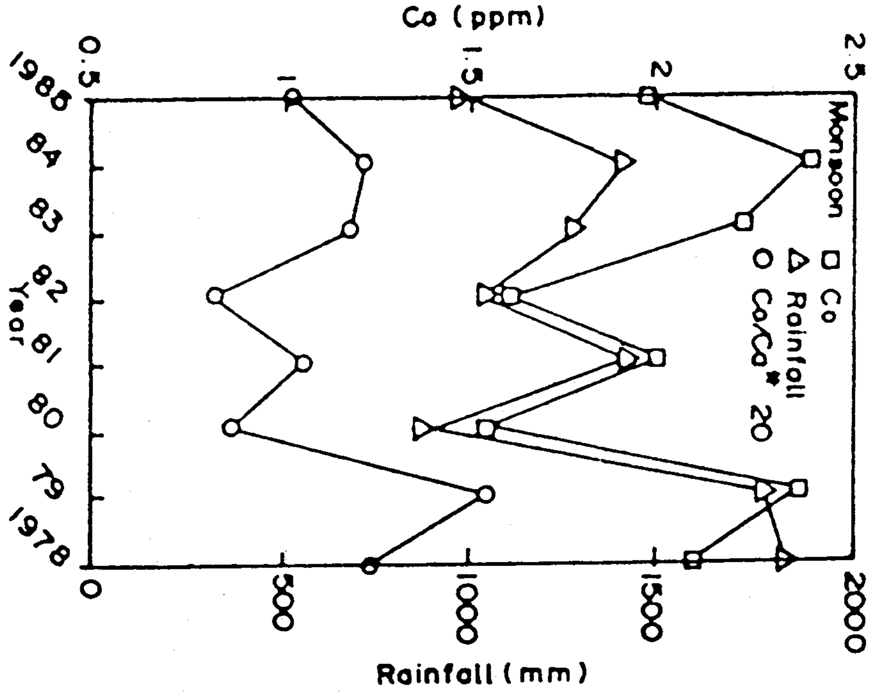
- *Trace elements.*

The oceanic distribution of certain trcac elements reflects processes of climatic interest, and many of these elements substitute readily for Ca in coral skeleton. The first trace element shown to have paleoclimatic significance in corals wers cadmium and barium. These applications were demonstrated in the eastern equatorial pacific, where by virtue of their nutrient-like distribution, Ba and Cd are sensitive indicators of vertical mixing. Their skeletal abundance can the be correlated to temperature changes associated wiht upwelling and linked to the Pacific-wide ENSO phenomenon.

In a reciprocal sense, Mn/Ca ratios can also be used to infer changes in upper ocean dynamics. Manganese display a surface ocean maximum in the eastern Pacific and others regions with strong coastal upwellings. In western Pacific atolls, Mn/Ca traces a specific climatological manifestation of ENSO : skeletal concentrations of Mn in corals record the occurrence of reversals in the normal trade wind regime. Used in concert with δ18-O, this tracer povides a mean to document historical episodes of ENSO related changes in both precipitation and winds. Mg/Ca is also a sensitive parameter, and high latitudes corals as in Japan can reveal strong seasonal and interannual variations, both in Sr/Ca and in Mg/Ca (Figure 7).

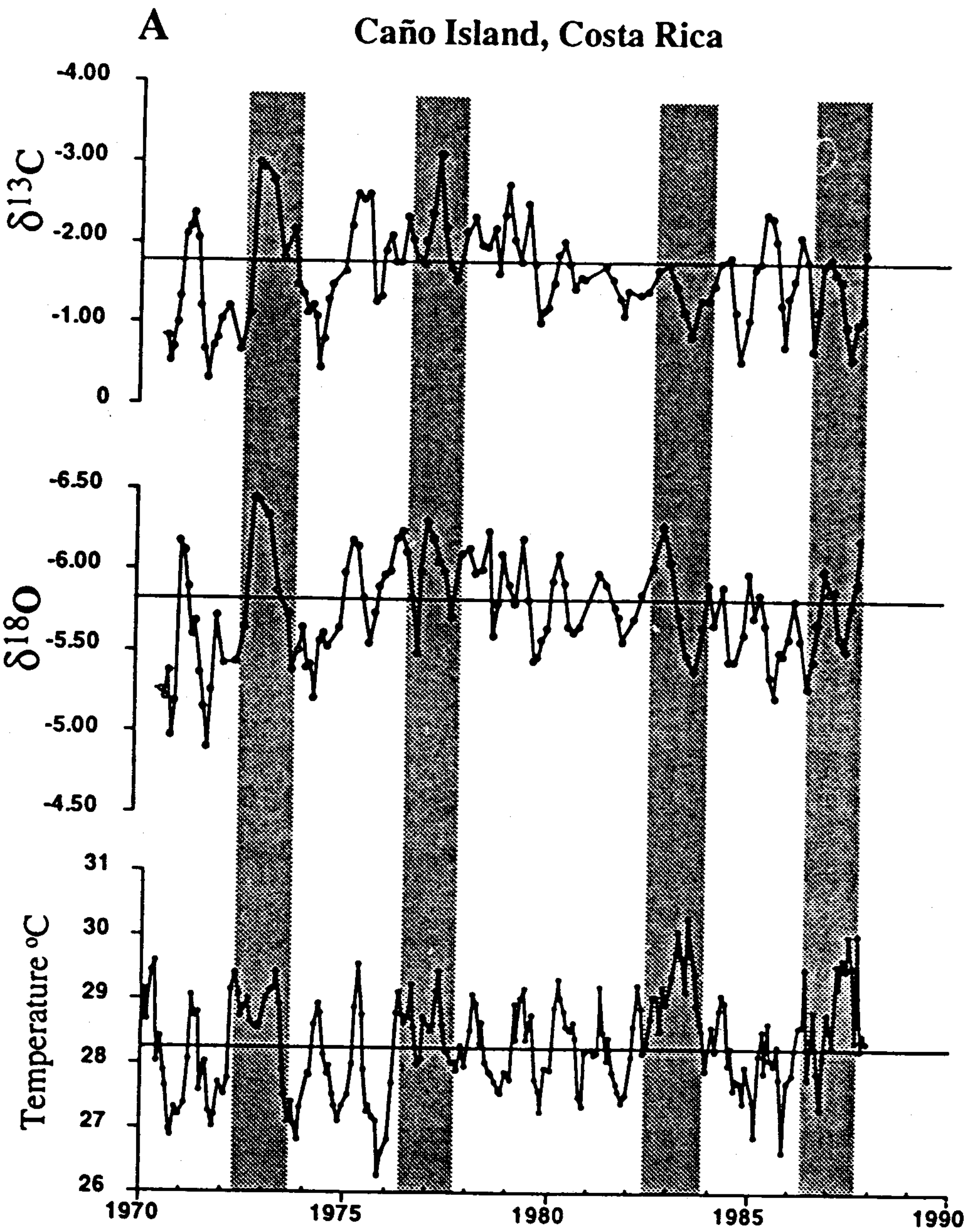

Co (ppm)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Non-monsoon
1985
84
83
82
81
80
79
1978
Year
0
100
200
300
400
500
600
Rainfall (mm)

(**Fig. 7**)


Co (ppm)
0.5
1
1.5
2
2.5
Monsoon
□ Co
△ Rainfall
○ Co/Ca* 20
1985
84
83
82
81
80
79
1978
Year
0
500
1000
1500
2000
Rainfall (mm)

(**Fig. 8**)

A final process potentially recorded by trace elemets in corals is fluvial discharge. Owing to its enrichment by weathering and estuarine desorption, barium (Ba) may provide a useful lfingerprint of discharge fluctuation. Cobalt concentration in growth bands of massive Porites from Kalpeni atoll of the Lakshadweep Islands (Arabian Sea) revealed that cobalt and Co/Ca exhibit similar trends (13). Cobalt concentration are in tune with the internsity of land run-off which is the main source of cobalt to surface seawater, Results suggest that cobalt could be a potential proxy for paleomonsoons (Figure 8).

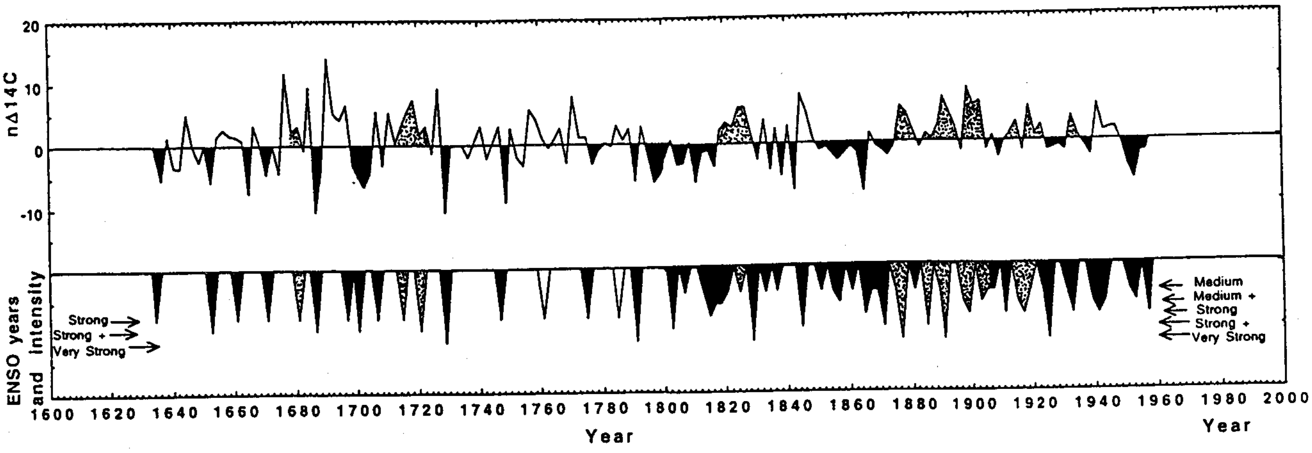


(Fig. 9)

- Stable carbon isotopes.

The δ13-C signal in coral skeleton is often difficult to decipher in environmental terms because of complicated interactions with physiological processes that involve strong isotopic fractionation. Controls on skeletal δ13-C include the isotopic signature of seawater ΣCO2, the geometry and growth rate of the coral head and endosymbiotic photosynthesis (8).

Seawater δ13-C is controlled by a balance between primary production and respiration as well as by air-sea exchange and varying contributions of surface and upwelled waters (14). Figure 9 shows that in coral from Costa Rica, δ13-C signal closely matches δ18-O and instrumental SST.



(Fig. 10)

A decrease in skeletal δ13C in coral Montasrea has been observed with depth, which is related to decreased light intensity. At certain sites, coral δ13-C corelates strongly wiht changes in cloudiness. Much of the variations in corla skeletal δ13-C may be explained by site-specific differences in insolation and water column transparency. Corals growing in the same reef may show little similarity in their δ13-C signatures. Clearly, development of robust paleoclimatic interpretations from coral δ13-C records requires improved understanding of both endogeous and exogenous factors that control carbon isotonci fractionation in coral skeleton.

- *Radiocarbon.*

The rediocarbon concentration of the surface ocean reflects diverse processes, including atmospheric input, advection, upwelling, and aging. Corals preserve records of the Δ14-C content of the overlying surface ocean in their skeletal aragonite. Coral records have documented anthropogenic effects on oceanic radiocarbon (Δ14-C), including the input of dead carbon from fossil fuel burning and he addition of radiocarbon from atmospheric testing of nuclear bombs (15) Coral Δ14-C records show secular changes associated with the Little ice age and the Maundr sunspot minimum. A 323-year history of Δ14-C form a Gret Barrier Reef coral indicates significant decadal changes in the relative contributions of water masses to the Coral Sea, and a variable teleconnection between this region and ENSO extremes in the tropical Pacific (16); figure 10.

- Growth banding.

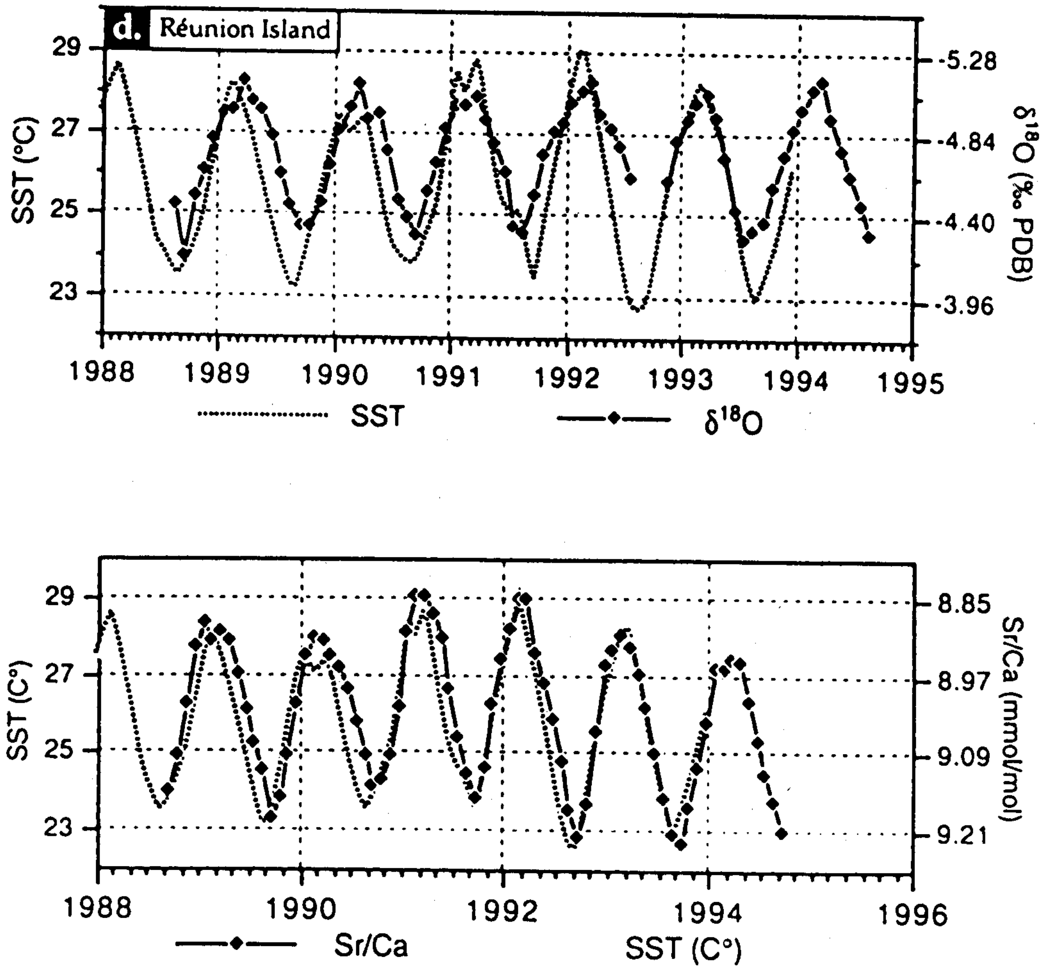
The thickness and density of annual growth banding in corals is related to nutrient and food supply, light internsity and environmental stressors that may include turbidity, temperature and salinity extremes, and disease. Stress events related to ENSO, cyclones and cold water intrusions are known to produce unusually thin, dense growth bands and/or hiatuses. A good correlation has been established (17) between density and band width in Porites from the great Barrier Reef and cloud cover temperaure and the Southern oscillation index. However, growth rates show only weak covariance with the oxygen isotopic record of SST and the growth ban/climate link stays an open question.

- Fluorescence.

In corals, this phenomena is produced by the incorporation of marine fulvic acids (which show a blue color undr UV light) and terrestrial fulvic and humic acids (yellow-green in color). Fluorescent bands in corals were first described by Isdalt (6), who found good corespondence between these bands in Great barrier Reef corals and the discharge of a near large river. Fluorescene can persist over thousands of years, and large discharge events and changes withen drainage basin often produce unique and recognizabel patterns of fluorescent bands in coral cores.

DISCUSSION

The major variability on human time scale is due to ENSO events. These phenomena concern principally the intertropical zones of the Pacific and Indian oceans, but have an important impact on worlwide climate. It is now admitted that monsoon variability is interconnected with ENSO, possibly playing a role in the onset of this aperiodic event. For example recent studies made in Seychelles Islands (18) allow to better understand the monsoon interannual fluctuation. That study was based on the oxygen and carbon analysis (δ18-O and δ13-C) of a massive Porites drilled on the external slope of Mahe Island. The depletion observed in δ18-O and δ13-C reflects respectively high SST combined with enhanced precipitations and increased cloudiness, in relation with ENSO events. During those events, the south-west monsoon precipitations are often abnormally reduced, the intertropical convergence zone (where winds converge) remaining near the equatorial area. The same kind of fluctuations is observed in corals from the Réunion Island, on the south tropical line (Figure 11). Those climate perturbations appear alomst simultaneously with Eastern Pacific ENSO occurences.



(Fig. 11)

Similar works have been made on a 4 meters long coral core in the south-west of madagascar, showing a warming of SST by 2°C from the late 17th century to the end of the 19th one. The last cool phase within the Little ice age, recognised between 1675 and 1850 in southern Africa (19), is seen in this δ18-O coral. The following sea surface warming at Madagascar lasted until 1890. A new cooling occured until 1930, when a general warming is observed. Spectral density in growth rate data is generally low, however signs of periodicities around 11 to 14,22 and 90 years are visible. In the south west Pacific, measurements on a fossil coral indicate that 10.000 years ago, mean annual SST near Vanuatu Islands were about 5°C colder than today and that seasonal variations in SST were larger. These data suggest that tropical climate zones were compressed toward the equator during deglaciation (12).

Coral cores drilled in the Island of Moorea (French Polynesia, central Pacific) have given informations on the atmospheric and oceanic evidences of past ENSO events (20). Analysis of the annual δ13-C and δ18-O time series from 1853 to 1989, has allow to detect a significant variability in the 2.5 and 5.2 year periodicity bands. The two annual records clearly contain a signature of a quasi-biennal component, which has previously been detected in the Southern Oscillation Index series and in monthly averages data covering the equatorial Pacific. In addition, they show different lower frequencies which have also been documented and attributed to ENSO behavior, from 4 to 7 years (21). The two low-frequency spectral peaks in coral isotopic records at Moorea arei similar to the other coral isotonic studies from the entire Pacific ocean.

On the basis of a high 13-C/12-C ratio followed by a low 18-O/16-O ratio from the four siptopic climatic series, Boiseau *et al.* (20) recognized 36 ENSO events which have affected the climatology of this zone over the last 137 years. Moreover, seven events were revealed by that study, which are not referenced by the classical ground-based ENSO reconstruction (22). So, althogh Moorea is not located in a region where ENSO associated anomalies are strong, the climatic variations in the south central Pacific ocean reflect the variability of the regional hydroclimatic regime. That study confirms that used in cunjonction with δ18-O, δ13-C is a powerful tracer.

The efficiency and the accuracy of that double tracer approach allows to reconstruct a double proxy, in term of meteorological and ocenic changes and to understand the real significance of ENSO anomalies.

The corals of the Islands of Galapàgos, which are on the equatorial line in the eastern Pacific, have given a great lot of informations on the changes induced by brutal ENSO events, when SST is warmed by 4 to 8 °C (14). As δ13-C is influenced by cloud cover, corals growing in sites near the intertropical convergence zone, characterized by high rainfall, must show a depletion in 13-C. The autospectra for δ13-C and δ18-O at these equatorial sites show increased variance at period between 2 to 4 years, within the high frequency portion of the ENSO band. A comparaison of δ13-C versus δ18-O indicates a significant positive correlation between high light (low cloud cover) and cooler water and supports the hypothesis that insolationcontrols skeletal δ13-C. But due to intra seasonal variations in water clairty, cloud cover and intensity of cold phases (upwellings), ENSO events have no predictable effect on coral δ13-C.

Windows of large time-scale.

Inasmuch the limitaions to its use and some questioning on the validity of the conclusions drawn, δ13-C has the advantage of a large potential for past studies. In the Caribbean Sea, high resolution δ18-O and δ13-C records of benthic foraminifera from a 150,000-year along ocre indicate that there was generally high δ13-C during glaciation and low δ13-C during deglaciation. These variations are clearly corelated with pathway and regime of the deep oceanic waters and principally with their nutrient load. That parameter applies a strong control to the dynamic of the fixation of CO2 in surface waters. So, since glacial-interglacial atmospheric CO2 variability is a consequence of oceanic nutrient distribution, studies of ocean circulation changes may enhance our understanding of the cause of the atmospheric CO2 changes over the past 150,000 years.

Skeletal Sr/Ca an 18-O/16-O ratios in corals from the Great Barrier Reef (Australia) indicate that the tropical ocean surface 5350 years ago was 1°C warmer and enriched in 18-O by 0.5 per mil relative to modern seawater. The results suggest that the temperature increase enhanced the evaporative enrichment of 18OO in seawater. Transport of part of the additional atmospheric water vapor to extratropical latitudes may have sustained the 18-O/16-O anomaly. The reduced glacial-Holocene shift in seawater oxygen ratio produced by the mid-holocene 18-O enrichment may help to reconcile the different temperature histories for the last deglaciation given by coral Sr/Ca thermometry and foraminiferal oxygen-isotope records (23).

The recent history of the central Pacific can be summarized thanks to the data given by isotopic and trace elements analysis. ENSO events between 1929 and 1976 are detected using these methods but there are discrepancies between the records of El Ninos from corals and those determind using historical hydrographic and meteorological data. The average annual depletion of δ18-O during El Nino events is greater in the east (Galapàgos) than at the atolls more in the west (Canton). Of price importance is evidence of decade time scale variability of SST in the tropical pacific. In particular, anually averaged SST appears to have been 1°C higher in the eastern tropical pacific during the 1930's than during subsequent years. A significant net flux of CO2 from the surface ocean to the atmosphere is envisioned during these peridos of higher SST.

Compilations of SST anomalies have demonstrate that the ENSO phenomenon is equaly important in both the Indian and Pacific oceans, which implies a climate connection over much of Earth. However, the different basinal geometry and the seasonally reversing monsoon currents demand a separate set of physical processes governing internnual temperature vriability in the Indian ocean, and therefore the degree of coupling between the ocean basins is not necessarily fixed. In fact, the tendency for this coupling to evolve may explain why the relation between the ENSO and the Asian monsoon has been the subject of one of the longest standign debates in climatology (24).

Previous analyses have variously concluded either that the Asian monsoon affects the ENSO, or that the converse is true. Each of these conclusions allows the possibility for different large-scale feedbacks. The interannual surface termperature changes in the western tropical Indian ocean reflect a response (through upwelling and evaportation) to the organised atmospheric convection to the east, composed seasonally of the Asian monsoon, the Indonesian Low and the Australian monsoon, Therfore given the potential for both the zonal and monsoonal influences, the western trpical Indian ocean SST represents an efective gauge of fundamental interactions in the global climate sysem.

In summary, the coral record shows that the interannual vairability in the western equatorial Indain ocean has been related to that of the equatorial pacific for over a century. This teleconnection simplifies modeling of the global ENSO phenomenon and any climate change associated with the redistribution of SST, for example, rainfall in South Africa, By preserving a long index record of both Asian monsoon and ENSO intensity at seasonal resolution, the coral provides a unique perspective on the interaction between these processes and their characteristic time scales.

Limits of these methods.

Observations of a living tissue layer that penetrates several millimiters below the coral surface has raised questions about the depth range over which calcification-skeletogenesis occurs. Calcification that occurs over the entire depth of the tissue would smooth the incorporate paleoclimatic signal. However, high variability in coral skeletal chemistry over short depth scales suggests that the skeleton is deposited primarly over a submillimeter-scale surface. Interpreting density banding in climatic terms requires understanding the relationship between seasonal coral growth and climate, Observations of corlas that accrete several bands per year have yet to be explained by environmental parameters, especially as such corals may grow in the same region as annually banded colonies (25).

But does the coral Sr/Ca thermometer really work at any short-medium time scales ? The long ocean residnce times of Sr and Ca would suggest that its Sr/Ca ratio should be relatively constnt on 100,000 years time scales. If not this poxy termometer should not suffer form the same defect as the oxygen-isotope thermomete, namely ocean water variability. There is also the issue of differing calibaraitons for the Sr/Ca thermometer among the various researchers in this fledgling field : these differences lead to discrepancies of up to 3°C. These discrepancies can be due to differences in the calcification rate (or growth rate) of the coral used in the different calibration studies, Alternatively, the calibration differences may be artifacts of local temperature variations, resulting form temperature differences between the sites at which the coral used for calibration grew, and the site at which the temperature records were taken form the calibration Recent works (25) have try to solve the poblem by deriving calibraion for Porites corals form three widely separated sites where the corals grew in suboptimal environmental conditions. These corals were exposed to wide seasonal extremes in SST, salinity, coastal upwilling and water color turbidity, but all yielded essentially the same calibration. Virtually no difference was found between these corals for either the Sr/Ca or the

18-O/16-O thermometer calibration.

The good correlation observed between coral Sr/Ca ratio and δ18-O has allow to construct and use a sensitive paleothermometer. That correlation makes possible to determine sea surface δ18-O on a large scale: maps generated in this way might be used to estimate the variations int the volume of the planetary ice caps or to generate maps of sea surface salinity. The latter might in principle be used to recover past patterns of rainfall and evaporation over the tropical oceanns. Heavy rainfall events can result in short term (week-long to month-long) depletions in surface waters δ18-O. Such events may cause deviations from the observed linear relation between Sr/Ca ratio and δ18-O. If so, it may be possible to assess the frequency of past tropical storms from time-series analysis of these isotopic ratios and trace elements records in coral, Possible nonequilibrium fractionation of the oxygen isotopes in corals, however, may limit recovery of information about such rainfall or ice volume variations.

Studies made on the seasonal variations of primary productivity and skeletal δ13-C and δ18-O in the zooxanthellate coral Acropora show that there was no clear evidence of any reltionship between isotopic ratio and productivity. The scattering of skeletal δ13-C observed particularly during summer demonstrates that the relationship between δ13-C and primary productivity is not very tight and that other internal and external parameters probably operate to explain the δ13-C variability (26). On the same genus Acropora, effects of calcification patterns on the oxygen isotope composition of the skeleton have revealed a large variability of the isotopic values recorded; as these values are taken from coral skeletons grown in identical physical and chemical coditions, the discrepancies cannot be ascribed to technical problems, but rather be induced by calcification nmechanisms. These studies stress that care must be taken when using the isotopic compositions of coral as a paleoenvironmental proxy.

Conclusion

Fossil coral heads provide high-resolution windows into tropical climate variability throughout the late Quaternary. More and more data show that this approach is useful for evaluating the long-term variability and sensitivity of tropical climate system. As the coral physiology palys an important role in detemining how the coral skeleton preserves environmental signals, cooperation between paleoclimatologists, geochemists and reef biologists can be a decisive step to improve the understanding of this linkage and the way it can give clues on the complex interactions and telecomnnectins that govern our climate.

REFERNCES

1) **Glynn, P.W. 1993.** Coral reef bleaching : ecological perspectives. Coral Reefs 12,1-18.

2) **Coffroth, M.A., H.R. Lasker, J.K. Oliver 1990.** Coral mortality outside of the eastern Pacific during 1982-1983 : relationship to El Nino, in: Glynn PW (ed). Global consequences of El Nino. Elservier Amsterdam, 141-182.

3) **Cole, J.E., R.G. Fairbanks and G.T. Shen 1993.** The spectrum of recent variability in the Southern Oscillation : results from a Tarawa Atoll coral. Science, 260, 1790-1793.

4) **Dunbar, R.B., G.M. Wellington, M.W. Colgan, and P.W. Glynn, 1994.** Eastern Pacific sea surface temperature since 1600 A.D. : the oxygen-18 record of climate variability in Galàpagos corals, Paleoceanography, 9,291-315.

5) **Swart, P.K. 1983.** Carbon and oxygen isotope fractionation in scleractinian corals : a review. Earth Sci.Rev., 19,51-80.

6) **Isdale, P. 1984.** Fluorescent bands in masive corals record centuries of coastal rainfall. Nature, 310,378-379.

7) **Cole, J.E. and R.G. Fairbanks 1990.** The Southern Oscillation recorded in the oxygen isotopes of corals from Tarawa Atoll. Paleoceanography, 5,669-683.

8) **Goreau, T.J. 1977.** Carbon metabolism in calcifying and photosynthetic organisms : theoritical model based on stable isotope data. Proc. 3rd Int. Coral Reef Symp., 2, 395-401.

9) **Dunbar, R.B, J.E. Cole 1993.** Coral records of ocean-atmosphere variability. Report from the workshop on coral paleoclimate reconstruction. NOAA. 38 p.

10) **McConnaughey, T.A. 1989.** C-13 and 0-18 isotopic disequilibria in biological carbonates : 1. Patterns, Geochim. Cosmochim. Acta, 53, 151-162.

11) **Shen, G.T., L.J. Linn, T.M. Campbell, J.E. Cole and R.G. Fairbanks 1992.** Surface ocean variabililty at Galàpagos from 1936-1982 : Calibration of geochemical tracers in corals. Paleoceanography, 7,563-583.

12) **Beck, J.W., R.L. Edwards, W. Ito, F.W. Tylor, J.Recy, F. Rougerie, P Joannot, and C. Henin 1992,** Sea-Surface temperature from coral skeletal strontium/calcuim ratios, Science, 257, 644-647

13) **Naqvi,S.A.S. and B. Nagendernath 1998.** Monsoon induced cobalt enrichmetn in Porites (coral) from the Arabian Sea. Indian Journal of Marine Sciences. 27 247-249.

14) **Wellington, G.M. and R.B. Dunbar 1995.** Stable isotopic signature of ENSO events in eastern tropical Pacific reets corals. Coral Reefs, 14, 5-25.

15) **Druffel, E.M. 1981.** Radiocarbon in annual coral rings from the eastern tropical Pacific Ocean, Geophysis. Res. Lett., 8, 59-62.

16) **Druffel, E.M., and S. Griffin 1993.** Large variations of surface ocean radioccrabon : evidence of circulation changes in the southwestern Pacific. J Geophys. Res. 98, C-11, 20,249 - 20,259.

17) **Lough, J. M., and D.J. Barnes 1990.** Possible relationships between environmental variables and skeletal density in a coral colony from the central Great barrier Reef. J. Exp. Mar. Biol. Ecol., 134, 221-241.

18) Le **Bec, N., and A. Juillet-Leclerc 1998.** Evaluating massive Porites corals from Mahe Islands (Seychelles) as proxy indicator of monsoon influences and ENSO events. European Meeting. ISRS. Perpignan.

19) **Tyson, P.D., and J.A. Lyndesay 1992.** The climate of the last 2000 years in southern Africa. The Holocene, 2,271-278.

20) **Boiseau, M. A. Juillet-Leclerc, P. Yiou B. Salvat, P. Isdale. and M. Guillaume 1998.** Atmospheric and oceanic evidences of ENSO events in the south central Pacific ocean from coral stable siotopic records over the last 137 year. paleoceanography. 13-6, 671-685.

21) **Jiang, N. J.D. Nellein and M. Ghil 1995.** Quasi-quadriennal and quasi-biennal variability in the equatorial Pacific. Clim. Dyn., 12,101-102.

22) **Quinn, W.H. 1992.** A study of Southern Oscillation related climatic activity for A.D. 622-1900 incorporating Nile river flood data; in El Nino : Historical and paleoclimatic aspects of the Southern Oscillation, ed. Diaz and Markgraph, Cambridge Univ. Press, New York, 119-149.

23) **Gagan, M.K, *et al.* 1998.** Temperature and surface-ocean water balance of the mid-Holocene tropical western pacific. Science, 279, 1014-1017.

24) **Charles, C.D., D.E. Hunter, R. Fairbanks 1997.** Interaction between the ENSO and the Asian monsoon in a coral record of tropical climate. Science. 277, 925-927.

25) **Druffel, E.M. 1987,** Bomb radiocarbon in the Pacific : annual and seasonal timescale variations. J. Mar. Res., 45,667-698.

26) **Juillet-Leclerc, A., J.P. Gattuso, L.F. Montaggioni, M. Pichon 1997.** Seasonal varitations of primary productivity and skeletal d13-C and d18-O in the zooxanthellate coral Acropora formosa. Mar. Ecol. Prog. Series. 157, 109-117.

27) **Huppert, A and L. Stone 1998.** Chaos in the Pcific's coral reef bleaching cycle. The American Naturalist, 152-3, 447-459.

28) **Mitsuguchi, T *et al.* 1996.** Mg/Ca Thermometry in coral skeletons. Science, 274, 961-962.

29) **Heiss, G.A., *et al.* . 1997.** Stable isotope and Sr/Ca-signals in corals from the Indian ocean. Proc. 8th Int. Coral Reef Symp. 2. Perpignan. 1713-1718.