Large-scale ocean-atmosphere dynamics of the Indian Ocean and coral bleaching

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ABSTRACT

Sea surface temperature anomalies and associated onset, duration and severity of coral bleaching episodes in the Indian Ocean are not simply controlled by basin-wide warming during El Nino events but appear mediated by complex internal basin dynamics in which regionally variable sea surface temperature variations are accompanied by changes in sea surface height and cloud cover statistics and rainfall patterns. This has implications for the understanding of past Indian Ocean bleaching events and the prediction of future bleaching patterns in the Indian Ocean and the need to link explanations of bleaching more closely to oceanographic dynamics than has been the case hitherto.

Keywords ENSO, El Niño, Sea surface temperature, Ocean warming, Global environmental change, Indian Ocean

Introduction

Coral bleaching and bleaching-related coral mortality across the major coral reef regions in 1997-98 was the most extensive since 1982-83 (Goreau et al. 2000). Following the pioneering model of Williams and Bunkley-Williams (1990), these episodes have been linked, in a general sense, to elevated sea surface temperatures (SSTs) associated with the warm, or El Niño, phase of El Niño Southern Oscillation (ENSO) ocean-atmosphere perturbations. The 1982-83 and 1997-98 El Niño events were probably the strongest such events since 1877/78 (Kiladis and Diaz 1986) with, on some indices, the 1997-98 event being the strongest episode this century (Slingo 1998, McPhaden 1999).

Several authors (e.g. Wilkinson 1998, Linden and Sporrong 1999, Wilkinson et al. 1999, Spencer et al. 2000) have remarked upon the appearance of high levels of bleaching in the western Indian Ocean in 1998, previously a region not known for such large scale impacts. And whilst ENSO events have been traditionally defined by reference to a series of linked ocean-atmosphere processes in the equatorial regions of the Pacific Ocean, it has been suggested, from studies of the inter-annual variability of SSTs, that there is a periodic ENSO signal in the Indian Ocean also, with the dominant mode of variability in phase with the peak El Niño warm phase off the west coast of South America or lagged some six to nine months behind it (Tourre and White 1995, 1997, Nicholson 1997).

This paper looks further at ENSO - coral bleaching linkages in the Indian Ocean.

Methods

Monthly mean SST anomalies (1961 - 1990 baseline) were extracted from the MOHSST6D database held by the Hadley Centre for Climate Prediction and Research, UK Meteorological Office. Statistics were calculated from amalgamated data collected on a 1° x 1° grid for areas surrounding selected individual sites in the western Indian Ocean (see Fig. 3 for details of areas sampled). The base year for analyses was taken as 1961; SST data are available for earlier periods but the record contains missing values.

Water levels (mm) were obtained from the monthly and annual mean sea level station files of the Permanent Service for Mean Sea Level (PSMSL) (Proudman Oceanographic Laboratory 2000), and from the ‘research quality’ and the World Ocean Circulation Experiment ‘fast delivery’ databases of the University of Hawaii Sea Level Center (2000). Available sea level data were extracted for Diego Garcia, Chagos (07° 17’S 072° 24’E - March 1988- July 2000), Port Victoria, Hodoul Is., Seychelles (04° 40’S 055° 28’E - Feb 1993 – June 2000) and Zanzibar (06° 09’S 039° 11’E - Jan 1988 – July 2000), the latter being the most complete over the time period examined. Additional data points for the Seychelles database were obtained from the Directorate of Civil Aviation (Pers Comm 2000) the responsible authority for tide gauges in the Seychelles. The mean sea level for each month in the period January 1988 - July 2000 was calculated and used as a baseline from which monthly anomalies were calculated.

Results

A 40-year record of monthly mean SST anomalies for the southern Seychelles (6-10°S 45-54°E) makes clear the magnitude of the 1997-98 warming (Fig. 1).

The Pacific-based multivariate ENSO index (CDC 1998) recognises 13 El Nino warmings for the period 1950-98; overlaying the 6 ‘strongest’ of these events since 1961 shows a good, but not perfect, association between these episodes and the pattern of elevated SSTs in the Indian Ocean. The further linkage to coral bleaching events is difficult because the historical reporting of bleaching has been poor in the Indian Ocean. Even allowing for these difficulties, however, the fit is not particularly good (Fig. 1).

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Fig 1. Long-term monthly SSTs anomalies (MOHSST6D) for the area 6-10°S 45-54°E, 1961-1998, using 1961-1990 as a baseline. Regression line indicates warming trend of 0.108°C per decade. Lightly shaded areas correspond to occurrences of ENSO events. During this period coral bleaching reports in the Western Indian Ocean are limited to the post-1983 period (indicated by dark boxes).

Fig 2. The Dipole Mode Index (DMI) as compared to the ENSO index from the ‘Niño 3’ area. Note the coincidences of these anomalies in the two indices in 1972 and 1997 and those years where there is no coincidence yet strong DMI anomalies - 1961, 1967 and 1994 (after Saji et al. 1999).

The strength of these correlations suggests that ENSO may not be the only explanatory variable for Indian Ocean coral bleaching. Recently it has been argued that climatic and oceanographic variability within the Indian Ocean may be a response to internal ocean basin dynamics rather than being necessarily externally forced by ENSO controls (Anderson 1999, Webster et al. 1999). A 'dipole structure' has been identified, characterised at one extreme by positive SST anomalies and increased rainfall over the western Indian Ocean and East Africa and negative SST anomalies off Sumatra and drought over Indonesia. Saji et al.’s (1999) ‘Dipole Mode Index’, constructed from differences in SST between the eastern and western Indian Ocean, can be compared with a classic ENSO index, the record of temperature anomalies from the ‘Nino 3’ area in the central and eastern equatorial Pacific for the period 1958-1998 (Fig. 2). In some years the two indices coincide - as in 1972 and 1997 but in many years do not - as in 1961, 1967 and notably in 1994 when a significant dipole mode event corresponded to a weak El Nino.

During a dipole maximum, cooling in the eastern Indian Ocean weakens convective rise and causes the development of significant easterly wind anomalies replacing the usually weak westerlies, with the SE Trades extending further west and north than is usual. With less latent heat release with lower windspeeds, the Indian Ocean outside the equatorial zone warms considerably; this in turn triggers persistent convection which in turn maintains the easterly winds and reinforces the SST anomaly. Furthermore, the pattern of anomalies in outgoing longwave radiation, a surrogate for the presence of deep, convective clouds and hence rainfall, shows greater than average precipitation in the northwestern and southern Indian Ocean and relative drought in the east, at times of dipole maxima (Webster et al. 1999). These internal dynamics thus result in strongly differentiated regional climatologies and oceanographies and can help explain the site-by-site variability of SST records, and the onset and severity (or not) of coral bleaching on reefs, in the western Indian Ocean in 1998 (Fig. 3). In the northwest Indian Ocean, at Socotra, positive temperature
anomalies were of relatively low magnitude but sustained: an anomaly of +1°C was reached in September 1997 and thereafter fluctuated between +0.5°C and +1.5°C until July 1998. In the southern Seychelles, an anomaly >+1°C was maintained between November 1997 and March 1998, with a maximum excursion of +1.84°C in February 1998. On the Kenyan coast and the Seychelles Bank, excursions were much greater, reaching +2.5°C, but of shorter continuous duration above the +1°C anomaly level. At Mayotte, and particularly in the Chagos Archipelago, anomalies built over time to exceed the +1°C level. Finally, to the south, anomalies of over +1°C were only briefly maintained (and see also Turner 1999). Thus whilst coral bleaching, and bleaching-related coral mortality, typically ranged from 50 to 90%, or more, on the reefs of the Maldives, Seychelles, Chagos and Kenyan coast, bleaching levels of 1 - 15% only were reported from Mauritius, with only 'slight' subsequent coral mortality (Wilkinson 1998, Wilkinson et al. 1999).

The coupled ocean-atmosphere dynamics described above are accompanied by changes in sea surface height. Wind stress from strengthened easterlies results in a sea surface slope rising from east to west along the equator (Chambers et al. 1999). Anomalously low sea levels associated with dipole maxima have been described from western Sumatra (Potemra and Lukas 1999, Chambers et al. 1999) and Thailand (Dunne and Brown, in press). Surface current flows generated by easterly winds near the equator and westerlies south of 10°S produce a sea surface high - or 'Ekman bump' - of ca. +30 cm elevation in the region of 4 - 8°S which develops initially in the east and then propagates and intensifies to the west. At the end of a dipole maximum, this sea surface slope is reversed (Webster et al. 1999). At 4-8°S, and although the tide gauge record is very incomplete, sea surface highs can be seen to have propagated from the Chagos Archipelago (71-73°E), through the Seychelles Bank (55-57°E) to the East African coast (39-41°E) between October 1997 and April 1998 (Fig. 4). These patterns are repetitive over time, being linked to dipole maxima, as can be seen from the peaks in SSH in 1992, 1995 as well as 1998 which follow a dipole maxima (Fig. 4).

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**Fig. 3** Monthly SST anomalies (MOHSST6D), July 1997-July 1998 for selected 1°x1° grid cells at eight sites in the central and western Indian Ocean. The arrows indicate, where available, the first reports of bleaching (Adapted from Spencer et al. 2000).

**Fig. 4** Anomalies from monthly sea level means 1988-2000 along an Indian Ocean transect (Chagos-Seychelles-Zanzibar). Peak positive anomalies follow times of dipole maxima (see Fig. 2). Note the suggestion of migration of sea level high from Chagos to Seychelles and then to Zanzibar in 1998.
Discussion

Explanations of bleaching events require an understanding of the interaction of the space-time dynamics of environmental controls with coral responses. It is now becoming clear that coral bleaching is due to the combined effect of elevated sea surface temperature and solar irradiance (Brown 1997, Jones et al. 1998). This adds complexity because the space-time dynamics of the two controls are quite different, with solar radiation showing much greater inherent variability, short-term modification by other environmental controls (such as water depth) and much more localised impacts on individual coral heads (Dunne and Brown in press). Furthermore, the time course of such temperature changes and solar radiation receipts is also important (Podesta and Glynn 1997, Winter et al. 1998, Brown et al. 2000).

At the Indian Ocean basin scale, coupled atmosphere-ocean dynamics can explain both the broad scale distribution of warm and cool water masses and their migration, typically at weekly/fortnightly timesteps from satellite-derived mapping (Strong et al. 2000). These shifting water masses are accompanied by regional-scale patterns of high cloud cover and heavy rainfall on the one hand and clear skies on the other, which through determining solar radiation receipts, may offset or enhance respectively the sea surface temperature control. These linked processes may thus help explain low levels of coral bleaching in overcast and windy Mauritius in March-April 1998 (Turner 1999) and the reduction of live coral cover on seaward reefs from 75% in 1996 to ca. 12% in 1999 under clear skies in the Chagos Archipelago (Sheppard 1999). Furthermore, the low wind speeds which enabled the Indian Ocean outside the equatorial zone to warm considerably in 1998 (Yu and Reinecker 1999) may have produced calm sea surface conditions and thus a reduction in the seawater attenuation coefficient for U/V penetration, as has been argued elsewhere (e.g. Caribbean: Goreau and Macfarlane 1990; Papua New Guinea: Davies et al. 1997). At the same time, however, these ocean-atmosphere dynamics in the Indian Ocean basin, as in 1998, lead to positive sea surface height anomalies in the western basin, thus potentially offsetting enhanced solar radiation. This is in contrast to the eastern Indian Ocean where sea level anomalies act to further reinforce solar radiation receipts (Potemra and Lukas 1999, Dunne and Brown in press).

Although beyond the scope of this paper, it should be remembered that these regional scale effects are in turn modified by both spatial and vertical changes in water movements at the reef scale, changes which are themselves reef-type specific, and by environmental impacts down to the scale of the individual coral head. It is not surprising, therefore, that bleaching events show considerable spatial and temporal variation. These patterns then have implications for the pattern and time course of reef recovery and rejuvenation. It is important, therefore, that explanations of bleaching episodes are tied much more closely to oceanographic dynamics than has previously been the case.

In this regard it is important to recognise that ocean warming events in the Indian Ocean - and there have been six extreme events (Fig. 2: normalised anomaly >1.5) since the event of 1961 - do not necessarily coincide with ENSO events. Caution is therefore required in a) establishing a probable record of Indian Ocean bleaching events in the past on the basis of Pacific-based ENSO chronologies and b) predicting Indian Ocean reef futures from the expected frequency of ENSO events in the twenty first century.

References

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