Review Paper

The Indian Ocean dipole – the unsung driver of climatic variability in East Africa

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Abstract

A growing body of evidence suggests that an independent ocean circulation system in the Indian Ocean, the Indian Ocean dipole (IOD), is partly responsible for driving climate variability of the surrounding landmasses. The IOD had traditionally been viewed as an artefact of the El Niño–Southern Oscillation (ENSO) system although increasingly the evidence is amassing that it is separate and distinct phenomenon. We review the causes of the IOD, how it develops within the Indian Ocean, the relationships with ENSO, and the consequences for East African climate dynamics and associated impacts on ecosystems, in particular along the Eastern Arc Mountains of Kenya and Tanzania. We evaluate current research initiatives focussed on characterizing and constraining the IOD and examine how effective these will be in determining climate change impacts on East African ecosystems and how such predictive capacity can be used in developing policy.

Key words: Eastern Arc Mountains, Indian Ocean Dipole, Biodiversity Pollen

Résumé

Un nombre croissant de preuves suggère qu'un système indépendant de circulation des eaux de l'océan Indien, le Dipôle de l'océan Indien (IOD), est partiellement responsable de la variabilité du climat des terres environnantes. L'IOD est habituellement considéré comme un artéfact de l'Oscillation Méridionale El Niño (ENSO) bien que les preuves s'accumulent pour montrer que c'est un phénomène séparé et distinct. Nous revoyons les causes de l'IOD, comment il se développe au sein de l'océan Indien, ses liens avec l'ENSO et ses conséquences pour la dynamique du climat de l'Afrique de l'Est, ainsi que son impact sur les écosystèmes, particulièrement sur la chaîne des montagnes orientales au Kenya et en Tanzanie. Nous évaluons les initiatives de recherches actuelles qui visent à caractériser et à circonscrire l'impact de l'IOD et nous examinons dans quelle mesure elles seront efficaces pour déterminer les impacts du changement climatique sur les écosystèmes est-africains et comment on pourra se servir d'un tel moyen de prévision pour mettre au point des politiques.

Introduction to East African climatology

The tendency of tropical climates to change relatively suddenly, even over the past millennia, has been one of the most surprising outcomes of the study of earth history (Adams *et al.*, 1999; Allen *et al.*, 1999; Marchant & Hooghiemstra, 2004). The tropics, rather than following climate change events recorded at temperate latitudes are increasingly shown to record changes first, often through ecosystem response such as species range shifts resulting in changed ecosystem composition, form and functioning. To interpret proxy evidence for such changes, including changed ice accumulation rates (Thompson *et al.*, 2002), changes in lake level (Stager, Mayewski & Meeker, 2002) or ecosystem composition (Leiju, Taylor & Robertshaw, 2006) a range of forcing mechanisms are invoked: these

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include change in climatic systems, solar forcing and, more recently, anthropogenic impacts. Before being able to assess the impacts of climate variability on ecosystem form and function it is necessary to understand first the present climatology of the region. The responsive nature of tropical ecosystems means that they may provide an early warning system to climate change, particularly within the present interglacial period when climatic ties to high latitudes have weakened considerably with the contraction of polar ice sheets (Johnson *et al.*, 2002), a situation that one would expect to continue in the future as ice sheets undergo accelerated contraction. Hence the tropics have hitherto been underestimated in understanding ecosystem response to global climate change (Dunbar, 2003; Kerr, 2003; Turney *et al.*, 2004).

Tropical climate prediction continues to be a great challenge with the rains of East Africa a particularly intriguing target (Hastenrath, 2001; Hastenrath, Polzin & Camberlin, 2004). Rainfall distribution and quantity are highly variable both over space and through time as witnessed by the recent (2005–2006) drought recorded throughout the Horn of Africa, and the subsequent localized floods following the onset of rains. Rainfall sea-sonality is primarily driven by the bi-annual north–south migration of the position where the trade winds converge resulting in cooling warm air and bi-modal rainfall distribution. The inter-tropical convergence zone (ITCZ), otherwise called the meteorological or caloric equator (Fig. 1), is largely manifested by the migration of the equatorial rainfall belt that corresponds to the belt of maximum solar isolation. Although it is useful to refer to the passage and strength of the ITCZ when considering inter-annual rainfall variability of two wet and two dry seasons in East Africa, it should be emphasized that the ITCZ represents the sum of many smaller scale systems that are important in understanding local climate variability. The ITCZ is predominately an oceanic feature, where its position changes to lie over the warmest surface waters (Barry & Chorley, 1997), this zonal character breaking down over land. For example, over Africa, differential heating of the landmass is strongly influenced by topography, and in East Africa the presence of large freshwater lakes with a resulting sinusoidal profile of the ITCZ (Fig. 1). The ITCZ, in addition to acting as a climatic metronome in its own right, will interact with numerous other climate systems. For example, rainfall distribution is particularly responsive
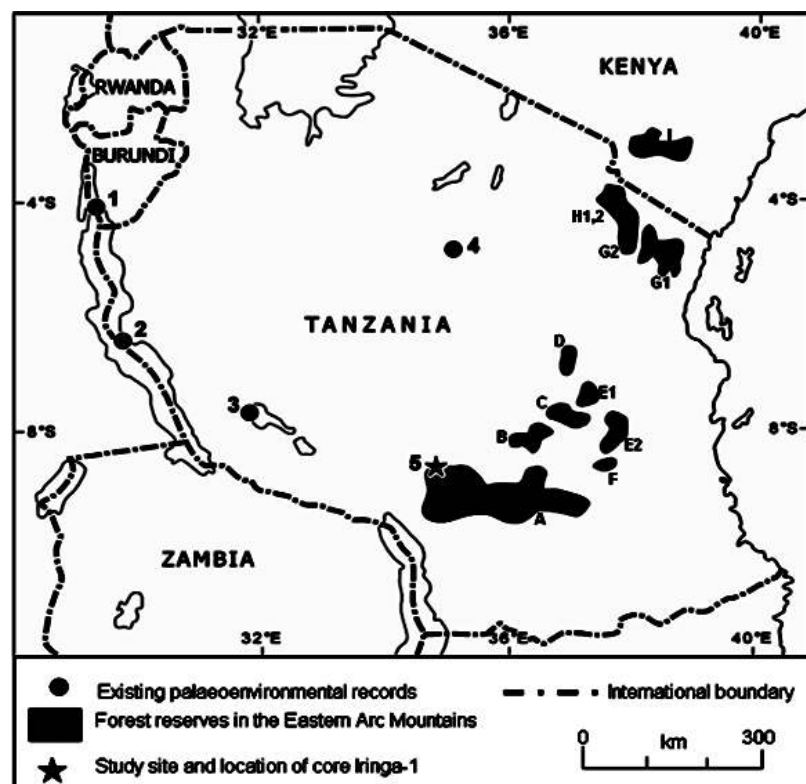

Fig 1 Climate schematic representation of the East African region indicating position of the inter-tropical convergence zone and major climate systems

to shifts in the strength and direction of zonal trade wind systems, these undergoing latitudinal shifts with seasonal displacement of the ITCZ (Nyberg *et al.*, 2002). Trade wind character also responds to the steepness of the longitudinal pressure gradients between the low- and high-pressure cells near the cooler equator (Rossignal-Strick, 1983; Wirrmann, Bertaux & Kossoni, 2001). Also important are sea surface temperature (SST) variations and changes in the land surface boundary conditions such as albedo, soil moisture and surface roughness. SST variations have a clear impact on the production of stratiform clouds; these deliver orographic moisture to highland areas, either directly as rainfall or as occult precipitation, the latter largely being dependent on the presence of vegetation to strip moisture from the air (Maley & Elenga, 1993; Servant *et al.*, 1993; Hemp, 2006). Precipitation patterns can be driven by topography: highland areas forcing moisture-laden air to rise, cool and condense, in essence acting as water towers for the surrounding lowlands (Gasse, 2002). This review focusses on the role of SST variation around the Indian Ocean and associated impacts and feedback on East African climates, particularly in montane areas of Kenya and Tanzania. The region encompasses one of the world's top biodiversity hotspots at a range of taxonomic measures (Burgess *et al.*, 1996; Myers *et al.*, 2000) and is characterized by steep gradients of natural climatic variability associated with tropical mountains.

Background to Indian Ocean dipole (IOD)

For decades, climate researchers have regarded the Indian Ocean as an unexciting basin, lacking the dynamic climates that El Niño–Southern Oscillation (ENSO) and La Niña engender where warm SSTs migrate across the Pacific Ocean and abut South America. In the context of the present interest in African climatic variability, and impacts on ecosystems and their associated functioning and services offered to resident populations, ENSO and Tropical Atlantic Variability (TAV) are recognized as cyclical oceanographic phenomena with strong influence on the regional climate (Koutavas *et al.*, 2002; Moy *et al.*, 2002; Tudhope & Collins, 2003). While understanding the mechanisms and processes that determine ENSO-related variability and its impact on the African climate are important, this should not detract from understanding the Indian Ocean SST variations and ensuing ramifications for regional climate, components of which are increasingly shown to be separate from ENSO. Until recently it was

assumed that the Indian Ocean did not have an inter-annual ocean–atmosphere coupling cycle, or it being forced primarily by the annual monsoon cycle and connection with global scale oceanic circulations systems such as ENSO and TAV. However this is not the case; recent studies have identified a unique ocean–atmosphere mode characterized by anomalously warm SSTs over the western Indian Ocean and anomalously cold SSTs in the eastern Indian Ocean (Saji *et al.*, 1999) (Fig. 2). The evidence indicates Indian Ocean SST anomalies have a significant impact on regional atmospheric circulation and rainfall anomalies that extend into East and southern Africa. For example, Indian Ocean SST anomalies are thought to have caused the widespread weather problems in 1997 characterized by localized droughts and floods (Reverdin, Cadet & Gutzler, 1986; Ogallo, Janiowiak & Halpert, 1988; Jury, 1996; Goddard & Graham, 1999). The sum of Indian Ocean SST variations is termed the Indian Ocean dipole (IOD), a coupled ocean–atmosphere phenomenon that occurs inter-annually in the tropical parts of the Indian Ocean (Figs 2 and 3). The IOD was identified only recently (1999) by a group of scientists working within the Climate Variations Program of Frontier Research System for Global Change of the Japan Marine Science and Technology Centre. Typical of ocean-driven climate oscillations, the IOD experiences a 'positive' phase and a 'negative' phase (Fig. 2). During a positive IOD event the SST drops in the south-eastern part of the Indian Ocean: off the northern coast of Australia, the eastern coast of Japan and Indonesia, counteracted by SST rises in the western equatorial Indian Ocean, off the eastern coast of Africa, from the northern half of Madagascar to the northern edge of Somalia. Inverse conditions exist during a negative IOD event (Fig. 2b). The name IOD represents the zonal dipole structure of the various coupled ocean–atmosphere parameters such as SST, surface pressure, outgoing long-wave radiation and sea surface height anomalies (Yamagata *et al.*, 2003, 2004).

As a considerable amount of East African rainfall originates from the Indian Ocean, it would be reasonable to assume that IOD SST anomalies would have a marked influence on the moisture supply to the adjacent landmasses (Reason, 2001). There is evidence for decadal variations in the background state that can influence the Indian Ocean (Janicot, Moron & Fontaine, 1996; Kleeman, McCreary & Klinger, 1999). Associated with these IOD changes in ocean SST character, there are changes in the normal convection patterns situated over the

Positive Dipole Mode
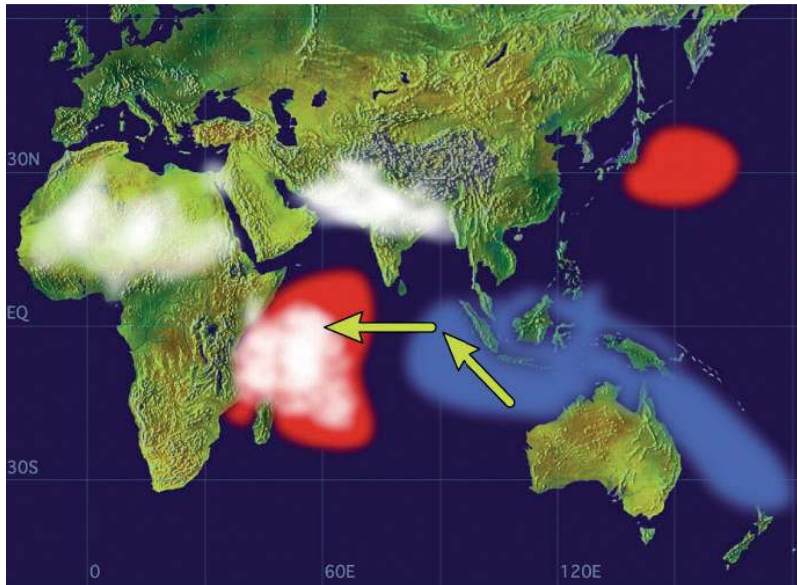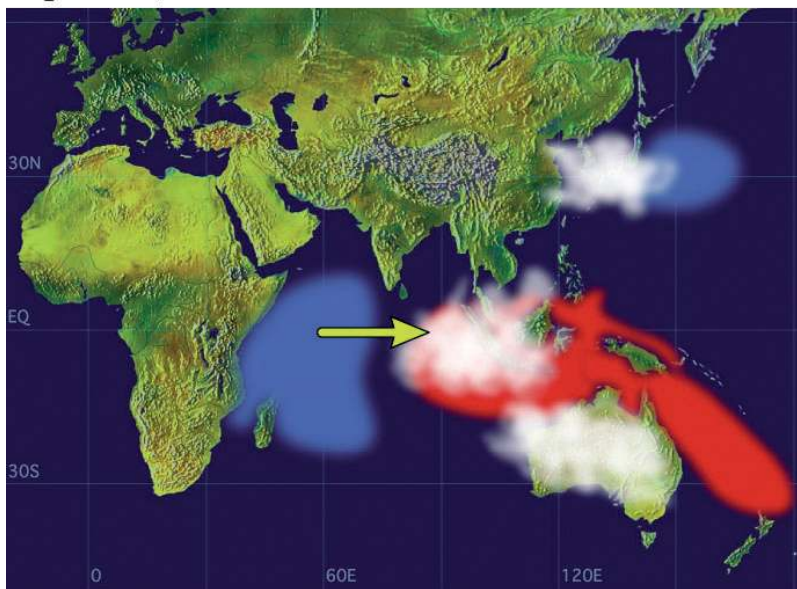

Negative Dipole Mode

Fig 2 Schematic diagram of sea surface temperature anomalies (red shading denoting warming; blue cooling) during a positive Indian Ocean dipole (IOD) event (top). White patches indicate increased convective activity with arrows indicating wind direction. The negative IOD (bottom) which is, in effect, the reversal of the positive IOD – complete with increased convective activity over Australia, Indonesia and Japan. Image courtesy: A. Suryachandra Rao, Institute for Global Change Research, Yokohama City, Japan

eastern Indian Ocean warm pool – this shifting to the west and bringing heavy rainfall over the East Africa and severe droughts/forest fires over the Indonesian region. Indeed some 70% of the inter-annual variability is accounted for by the concurrent intensity of the equatorial Indian Ocean, but this lacks obvious strong long-lead precursors (Hastenrath *et al.*, 2004) making prediction and clarification difficult. As more research is conducted into IOD, it is becoming more apparent that there is a widespread footprint of IOD activity, both spatially and temporally.

Relationship of IOD to ENSO

Like all tropical oceans, the Indian Ocean is not characterized by a single mode of variability but has several
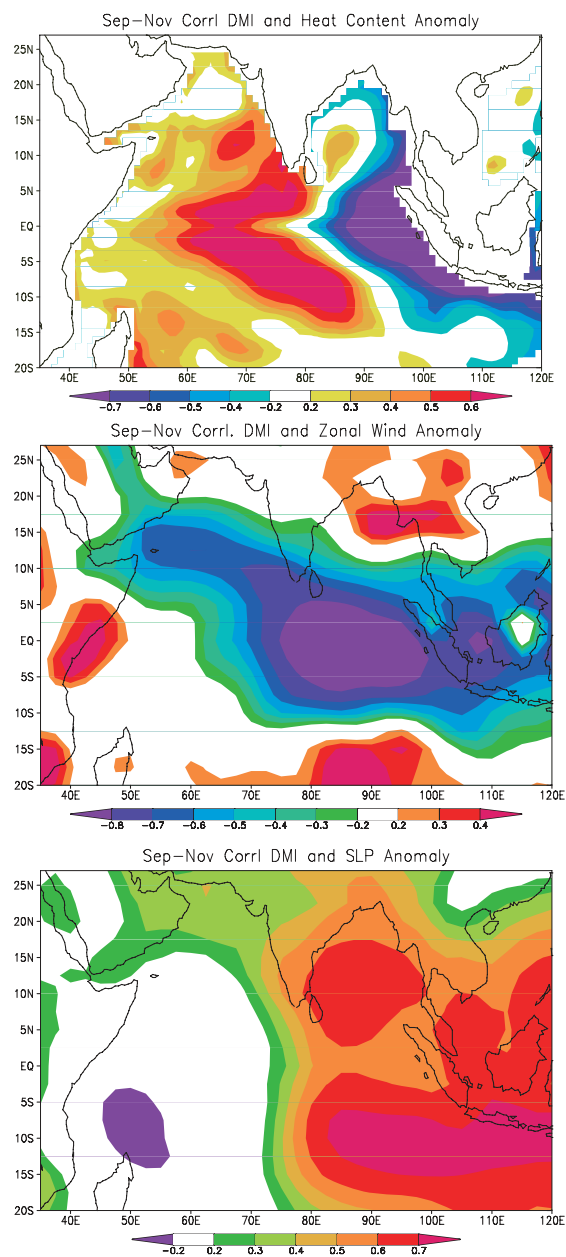
Fig 3 September–November correlation of dipole mode index (as defined in Saji *et al.*, 1999 but derived from HadISST) with the anomalies of heat content (upper panel), zonal wind (middle panel) and sea level pressure (lower panel)

interacting processes. One key process, demonstrated by the long history of research into the relationship, is linked with ENSO. Tropical climates oscillate at irregular time intervals (3–7 years) between an El Niño phase, when warm tropical waters up well off Pacific coastal South America, and a La Niña phase when cold tropical waters up-well. Although some studies indicate a single, region-wide impact of ENSO, the direction, magnitude and timing of this impact are ultimately controlled by the regional climate system and more local influences. This relationship with ENSO activity has led to uncertainty about the origin and sphere of influence of the IOD with the controversy continuing. Black, Slingo & Sperber (2003) advocate that Indian Ocean zonal mode, a synonym for IOD, should not be viewed as being independent of ENSO. Pfeier & Dullo (2006), following the high resolution analysis of coral cores, indicate that the El Niño index is strongly correlated with Indian Ocean SSTs over the past 150 years; supporting the notion that the ENSO strongly influences the Indian Ocean. Others suggest that IOD must be considered as independent of ENSO (Saji & Yamagata, 2003), where Behera *et al.* (2006), based on state of the art coupled GCM experiments, recently demonstrated that the IOD could evolve independently of ENSO. This controversial relationship between ENSO and IOD will be explored within this review. The ENSO is the largest coupled ocean–atmosphere phenomenon resulting in climatic variability on inter-annual time scales (Godínez-Dominquez *et al.*, 2000). This wide-ranging influence of ENSO has attracted the attention of the global change community, particularly due to the well-documented economic and cultural impacts, both today and throughout historical times, recorded locally and globally, within a wide latitudinal band about the equator. As climates, particularly rainfall patterns are driven by temperature differences between land and ocean, changed character of the tropical Pacific Ocean can represent a dominant mode of modern climate variability with the effects recorded across the globe (Clark *et al.*, 2002). During the warm phase of ENSO, the central Indian Ocean is usually warmer than average (Tourre & White, 1997) resulting in more benign land–ocean contrasts manifested as reduced East African rainfall – not surprisingly rains in East Africa being less under weaker westerly winds (Bergonzini, 1998).

Several studies have documented a link, or teleconnection, between ENSO events and precipitation amounts and distribution over the Great Lakes region of East Africa: regional precipitation excess corresponding to ENSO events (Ogallo, 1988; Nicholson, 1996). The connection between ENSO and African precipitation is recorded as reduced rainfall during the wet season north of the equator (Cole *et al.*, 2000; Diaz, Hoerling & Eischeid, 2001). However, other studies (Hastenrath, 1991; Richard, 1994;
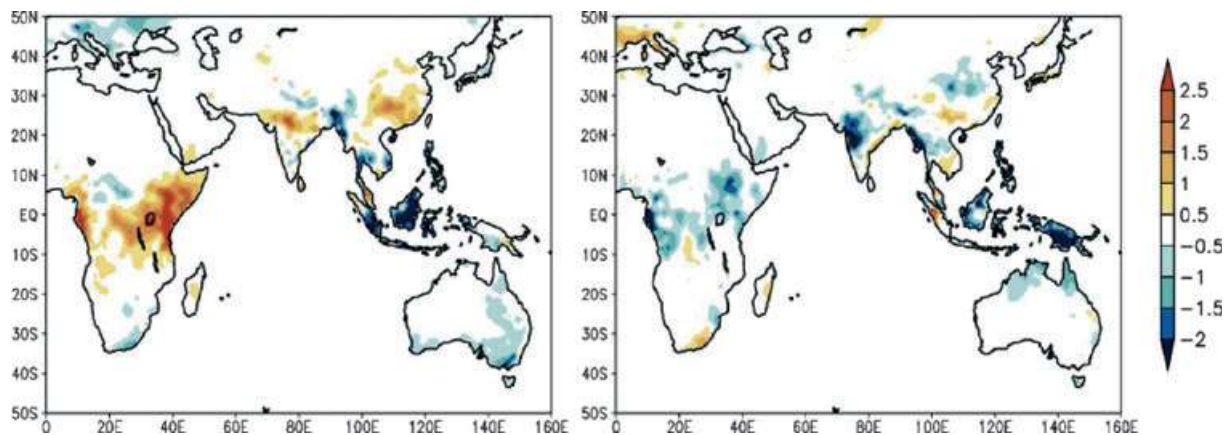
Fig 4 Composite rainfall anomalies (mm day^{-1}) for September–November during (left) pure Indian Ocean dipole (IOD) and (right) pure El Niño Southern Oscillation (ENSO) events. The rainfall anomalies for the period 1958–1999 are derived from University of Delaware gridded precipitation analysis. The independent years used in the composites of pure IOD and pure ENSO are taken from Yamagata *et al.* (2004) (from Behera *et al.*, 2006)

Bergonzini *et al.*, 2004) have shown that this link is not direct or systematic (Fig. 4), in particular that excess rains during the October–December rainy season are preferentially linked to zonal circulation over the Indian Ocean. Indeed, it seems that the spatial patterns of this are complex: during warm ENSO phases the Lake Victoria region records warmer and more humid conditions, while in neighbouring central Tanzania warmer and drier conditions are recorded (Plisner, Serneels & Lambin, 2000). Over the recent instrumental record in the Sahel, summer rainfall deficiencies have tended to follow ENSO events in the eastern equatorial Pacific; even to the extent that Sahelian rainfall, a boreal summer feature, fails dramatically during an El Niño year (Hastenrath, 1991). Although it is possible to account for annual variation, it is not possible to account for the long-term trend of rainfall change such as the drought of the 1970s and 1980s and recent more stable moisture supply. The longer-term picture shows that the dominant factor driving Sahelian rainfall can only be explained in terms of disruption of Atlantic atmospheric circulation resulting in a decrease in western African rainfall (Bigg, 1996) combined with warmer Indian Ocean SST (Kerr, 2003).

El Niño–Southern Oscillation, and therefore the degree to which there was interaction with the Indian Ocean, adjacent climate systems and resultant rainfall patterns, is known to be dynamic over the recent period (Fig. 4) and more broadly over the Holocene (Sandweiss *et al.*, 1996, 2001; Marchant, Hebblen & Wefer, 1999). This variation would be even greater when extending to glacial inter-glacial cycles when global sea level fluctuated by some 100 m. Such a fluctuation should not be considered as something confined to geological history, as such cycles characterize the world we live in. Indeed our world has spent some of the last 80–90% of the past 2 million years under low sea levels, reduced atmospheric CO_2 concentration, lower lake levels, more extensive montane forests and Afroalpine vegetation and a generally cooler drier climate. Climate is strongly influenced by the presence of large lakes, local topography or proximity to the coast, additionally geology, soils and vegetation might also influence the magnitude and time lag of any ENSO impact (Plisner *et al.*, 2000). For example, the recent (1997–1998) rise in the level of Lake Victoria correlates with SST anomalies in the western equatorial Indian Ocean following a strong El Niño event (Webster *et al.*, 1999). Thus, our understanding of long-term ENSO dynamics is still poorly resolved, the reason behind these deficiencies lies in the complexity of the system and interplay with atmospheric and oceanic circulation and the relatively sparse nature of high-resolution palaeo-archives required to register such changes. One way to enhance our understanding is by constructing models of the climate to investigate how this interacts with terrestrial ecosystems and ocean circulation.

Using an ocean general circulation model forced with inter-annual winds, Vinayachandran, Saji & Yamagata (1999) investigated the role of equatorial jets on IOD evolution; results showed that wind anomalies played a role in

generating the SST anomalies during 1994 IOD event and enhanced the large-scale air–sea interaction, independent of ENSO. In an attempt to find the subsurface role of the Indian Ocean on the evolution of IOD, Rao *et al.* (2001) carried out an empirical and numerical modelling study showing that significant subsurface changes in the Indian Ocean occur only during the IOD events and not during the El Niño years – contradicting several previous studies. Rao *et al.* (2001) further showed that the Indian Ocean sub-surface helps in driving the reversal of polarity of the IOD through propagation of Rossby waves in the off-equatorial regions; such influence stresses the need to investigate broader connections. There is an established climatic tele-connection between ENSO and Indian summer monsoon rainfall (ISMR) during June–September: whenever the ENSO–ISMR correlation is low (high), the IOD–ISMR cor-relation is high (low) (Ashok, Guan & Yamagata, 2001). It is shown that the Indian monthly rainfall can be modelled in a better way using these two climatic variables concurrently, especially in those years when negative correlation between ENSO and ISMR is not well reflected (e.g., 1997, 2002). Thus monthly variation of ISMR is influenced by the con-current effects of ENSO and IOD; as the relationship between ENSO and Indian rainfall variability becomes increasingly weak (Kumar, Rajagopalan & Cane, 1999), IOD will become increasingly important (Kripalani & Kumar, 2004).

Climatic and ecosystem impacts of IOD

Understanding the ocean–atmospheric interactions, such as IOD, that result in different climate modes for East Africa will not only increase climate forecasting capabilities for the region, but it is also crucial for understanding the global climate dynamics and issues surrounding environ-mental change throughout Africa. The importance of the oceans as a 'climate forcer' of terrestrially recorded envi-ronmental change has recently been demonstrated for equatorial Africa (Broecker, 2000). For example, Indian Ocean warming has been linked to drying of the Sahel, the latest ocean-drought connection to be made – this further demonstrates the importance of atmospheric bridges link-ing biosphere, atmosphere and ocean (Kerr, 2003). Understanding how this has operated in the past and what the important underlying processes are, such as the influence of changed land surface conditions, will allow for an enhanced predictive capability of future climatic vari-ability. For example, the 1950–1969 droughts in southern Africa were associated with regional ocean–atmosphere

anomalies over the south-west Indian Ocean (Richard *et al.*, 2001). The climate evolution from about September 1997 to March 1998 was extreme with high rainfall and associated floods experienced throughout Eastern Africa; this was associated with significant SST warming of the western equatorial Indian Ocean and has been suggested to be primarily an expression of internal Indian Ocean dynamics (Webster *et al.*, 1999). It is believed that the resulting strong SST gradient was a strong factor in the extreme rainfall in East Africa, but this is yet to be quan-tified. The warming in the western Indian Ocean also extended beyond equatorial latitudes into the subtropics, and may have been a factor in inhibiting the impact of the 1997/98 ENSO on southern Africa. Historical data show extreme IOD events have happened six times in the past 40 years (Fig. 3); the associated climate can bring devas-tating rains to Kenya and neighbouring countries, which in turn can spawn epidemics such as Rinderpest (Tury-anhikayo-Rugyem, 1942) and the incidence of Malarial outbreaks (Patz & Olson, 2006). Using SSTs to predict when East Africa might be vulnerable, and the greenness index (a remotely sensed measure of recent plant growth) to provide information on spatial character of precipita-tion, it might be possible to pinpoint where potential danger from infectious diseases exacerbated by climate change will occur (Planton, 1999), determine appropriate remedial action, target resources and provide insight for appropriate policy formulation. Unfortunately, too little is known about the mechanisms of atmosphere–ocean coupling in the central and western Indian Ocean that gives rise to the observed SST anomalies and subsequent climate anomalies in the African–Indian Ocean sector and should be a target for future research.

As part of developing this understanding, a longer-term perspective that reaches beyond the information possible from historical records is required. For example, research investigating El Niño variability over the past 1000 years showed the Pacific climates were relatively cool and dry during the 10th century, in stark contrast to the wet and warm 20th century climate (Cobb *et al.*, 2003). In East Africa, there is a need to delve into the proxy record from sites that show the range of precipitation variability and changes in this (Gupta *et al.*, 2003). For example, unlike other studies which span the last glacial maximum (LGM) in East Africa (van Zinderen-Bakker & Coetzee, 1988; Street-Perrott & Perrot, 1990; Taylor, 1990; Marchant, Taylor & Hamilton, 1997; Vincens *et al.*, 2003), a palaeo-ecological record from Dama Swamp (Fig. 5), on the west-
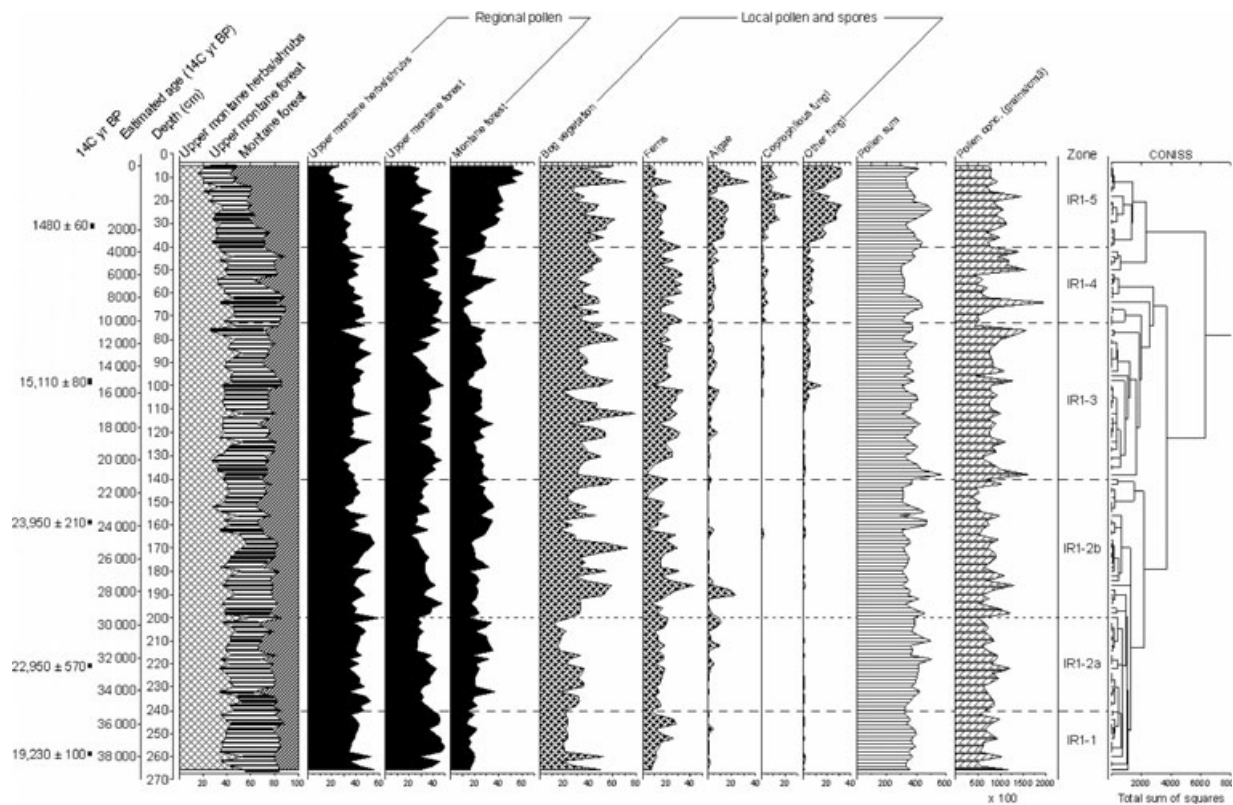
Fig 5 Summary pollen diagram from the core Iringa 1 taken from Dama Swamp on the western extent of the Eastern Arc Mountains. The pollen data show a remarkable lack of change given the record extends across the last glacial maximum

ern flanks of the Eastern Arc Mountains, shows relatively benign environmental change across the LGM (Mumbi et al., in press). Upper montane forest and montane forest taxa, although fluctuating, remain relatively constant percentages (Fig. 5). The stable isotope (δ^{13}C) record also shows that there is no marked shift in the composition of C_3 and C_4 plants within the catchment (Mumbi et al., in press), unlike that recorded on Mount Kenya (Ficken et al., 2002). Fjeldså & Lovett (1997) suggested that moist forests along the Eastern Arc Mountains were continually present throughout the LGM and by inference, may not show great changes in future (Lovett et al., 2006). These ideas are based on indirect evidence derived from ecological surveys and inferred biogeographic patterns (Lovett & Friis, 1996). The first proxy record of ecosystem composition dated about the LGM from the Eastern Arc Mountains does indeed show stable altitudinal forest distribution and composition through LGM supporting the hypothesis that the Eastern Arc Mountains are characterized by relatively stable environmental conditions through time. However, Dama

Swamp is a single record from the Eastern Arc Mountain ecosystems and additional sites are presently being investigated to substantiate this. The main mechanism that would promote localized ecological stability is the continued supply of moisture derived from the Indian Ocean during periods of more arid climates. The important buffering force of cloud on maintaining low montane tropical ecosystem through a glacial climate has been demonstrated in Amazonian (Bush, Silman & Urrego, 2004). Exactly how local the impact of this 'localized' moisture is on the Eastern Arc montane ecosystems is unknown and needs to investigated, particularly how the character and extent of the cloud base could change under different climatic and oceanographic regimes. As with characterizing the range and extent of impact on IOD variability, the ecosystem impacts of changing moisture regime, and indeed how responsive these montane ecosystems are to change, are not yet quantified. Indeed, as Dama Swamp is the only site located some 400 km from the Indian Ocean, a number of such studies distributed across the range of environments are required

before suggestions on long-term ecosystem stability can be substantiated.

Future developments

The results from the first proxy record of past Eastern Arc Mountain ecosystem composition show evidence of environmental stability during some 10,000 years before and after the LGM (Fig. 5) whereas other more dryland systems are prone to large, infrequent disturbances (Vincens *et al.*, 2003; Gillson, 2006). Specific characteristics of some mountain areas, in combination with the stabilizing influence of continued moisture supply relatively constant temperature of the Indian Ocean and steep continental shelf may have allowed tropical moist forest to have persisted in parts of coastal East Africa throughout glacial periods. Such a stabilizing influence could have resulted in large numbers of endemic species in the Eastern Arc and Coastal forests (Burgess *et al.*, 1998; Burgess & Clarke, 2000). More records are required to substantiate the hypothesis that long-term ecological stability during the Pleistocene can explain why the Eastern Arc Mountains are so rich in species and, as a consequence, a biodiversity hotspot. By combining palaeoecology, biogeography, phylogeography and modelling approaches we will be able to determine if high levels of biodiversity depend on buffering from global climate changes, due to the close proximity of the Indian Ocean system, or if this is a response to high climatic and environmental variability. Unfortunately, comparable with the Eastern Arc Mountains, there is a lack of long-term records from the Indian Ocean with relatively few long-term observational data sets available. Information on longer-term climatic variability is very limited from marine sediments (Prell *et al.*, 1980) due to seabed topography where water flowing the Mozambique Channel prevents sediments accumulation. Records on Indian Ocean SST variation are crucial that need to be placed in context of other climatic forces of SST variation such as volcanic eruptions (Wilson, 1999).

Human activities are increasingly moderating climates by escalating atmospheric concentrations of greenhouse gases, aerosols and land surface changes that feedback to alter climate system. The impacts of such recent changes on climate variability are likely to remain controversial with little data to quantify the change in the land-surface forcing, feedbacks to the oceans and to the atmosphere. These changes are projected to lead to regional and global changes in climate and climate-related parameters such as temperature, precipitation, soil moisture, lake and sea level. Based on the range of sensitivities of climate reported by the Intergovernmental Panel on Climate Change (IPCC, 2001) and plausible ranges of emissions and aerosol concentrations, climate models project an increase in global mean surface temperature of about 1–3.5°C by 2100 and an associated increase in sea level of about 15–95 cm. For much of East Africa, a suite of Global Climate Models (GCMs) project an increase in moisture that, if true, would have significant impacts on ecosystems and associated services. However, such predictions must have a large number of caveats as while most climate models depict the East African region getting wetter (http://www.metoffice.com/research/hadleycentre/models/HadCM3.html), historical data from river gauging stations show the reverse situation to operate. Unfortunately, the reliability of regional-scale predictions is still low and the downscaling of GCMs is problematic and not appropriate for meso/micro-scale uses; hence the degree to which climates and variability in these may change in future remains uncertain and in urgent need for development. However, this uncertainty should not be taken for a nod for complacency, as potentially serious changes have been identified, including an increase in the incidence of extreme events, in particular floods and droughts, with resultant consequences of fires, pest outbreaks, disease, migration, and ecosystem composition, structure and functioning, including primary productivity, agriculture and HEP generation. Much of these changes will stem from hydrological change that, as we have seen, is partly driven by IOD. As stressed in this review, the current understanding between IOD and hydrological variability is quite limited – an area that is crucial for our understanding of East African climate viability and the various management options, and policy development this knowledge can fuel. There are a variety of long-term hydrological data sets available from East Africa, primarily from river gauging stations, and increasingly from palaeoecological records that document lake level and ecosystem response to environmental change; how these can be used to investigate hydrological variability is an essential way forward to improve forecasting and feed into appropriate policy.

In addition to better observational data there is a need for model developments, Rao *et al.* (2001) and Vinaychadran *et al.* (2002) have been successful in simulating the evolution of the positive IOD events of 1982, 1994, 1997, and the negative IOD events of 1984 and 1996 using an ocean general circulation model driven by the NCEP wind

fluxes for the period 1975–1998. However, the IOD is dynamic and there is a need to take a longer perspective. Model results, particularly those for precipitation, need to be viewed in context, as given the poor spatial resolution they cannot resolve details of strong SST regional gradient (Reason, 2001) and topography (e.g. the Eastern Arc Mountains). Another area of continued uncertainty is the role to which changes in land cover may feedback to IOD variability, and indeed how changes in the IOD may influence terrestrial ecosystems and associated land-ocean feedbacks. One area of focused research is to assess the behaviour of the IOD over the recent geological past and the likely climatic impacts this will impart in East Africa. These developments need to take place in the context of developing regional models to investigate ecosystem response to climate change as part of a broader initiative to understand the past, present and future ecosystem dynamics of Eastern Africa and societal implications of these changes.

Conclusions

The Indian Ocean, through IOD and other circulatory changes, undergoes significant physical variability that has far-reaching influence on East African ecosystems, biogeochemistry the associated services these ecosystems can provide. The IOD is an under-researched and relatively unknown phenomenon, in terms of its spatial and temporal character and strong impact. The mechanism of IOD variability in the past, present and future is not well understood and needs to be focused on over the coming years. Consequently, much more research into the behaviour and variation of IOD is warranted. At present, most computer climate-forecasting models ignore the Indian Ocean, or operate at a scale that is inappropriate to develop policy – new studies need to address these issues, in particular developing regional climate models so that we can understand better how climate and ecology interact in Africa.

Acknowledgements

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