Stable isotopes in East African precipitation record Indian Ocean zonal mode

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[1] Observational stable isotope data and model simulations show that the $\delta^{18}O$ composition of precipitation in East Africa is closely related to the coupled ocean-atmosphere system over the Indian Ocean. During the rainy seasons $\delta^{18}O$ is a very sensitive recorder of the Indian Ocean Zonal Mode (IOZM). The link between $\delta^{18}O$ and the IOZM is established through adjustments in the large-scale overturning circulation over the Indian Ocean and associated changes in convective activity and precipitation over East Africa. The IOZM is recorded as significant departures in $\delta^{18}O$ not only over East Africa but as a dipole mode with opposite sign to the east and west of the Indian Ocean. **Citation:** Vuille, M., M. Werner, R. S. Bradley, R. Y. Chan, and F. Keimig (2005), Stable isotopes in East African precipitation record Indian Ocean zonal mode, *Geophys. Res. Lett.*, *32*, L21705, doi:10.1029/2005GL023876.

1. Introduction

[2] The majority of precipitation in East Africa occurs during the long rains March–May (MAM) and the short rains October–December (OND). A number of studies have documented increased precipitation in East Africa at times when the eastern Indian Ocean is cold and the western Indian Ocean is anomalously warm. This basin-wide east-west SST-gradient, often referred to as the Indian Ocean dipole (IOD) [*Saji et al.*, 1999; *Webster et al.*, 1999], or Indian Ocean zonal mode (IOZM) [*Clark et al.*, 2003; *Black et al.*, 2003], is best developed during boreal fall, coincident with the East African short rains. The atmospheric component of the IOZM is particularly well expressed in the low-level zonal wind field over the central equatorial Indian Ocean [*Hastenrath et al.*, 1993; *Hastenrath*, 2000]. Hence long precipitation records from this region might offer the unique potential to reconstruct past changes in the large-scale atmospheric circulation over the Indian Ocean domain. Unfortunately few such long and high-resolution records are available. An alternative, however, may be provided by instead using the stable isotopic composition of meteoric waters incorporated into a variety of proxies in the region [e.g., *Krishnamurthy and Epstein*, 1985; *Ricketts and Johnson*, 1996; *Barker et al.*, 2001; *Thompson et al.*, 2002]. However, there is little agreement as to how these records should be interpreted. While they are commonly viewed as indicators of past changes in temperature or precipitation amount, recent modeling studies suggest that $\delta^{18}O$ contains important information about transport and condensation history of air masses from source to deposition and therefore primarily reflects atmospheric circulation [*Cole et al.*, 1999; *Vuille et al.*, 2003]. Hence it is of interest to investigate whether variations in $\delta^{18}O$ in East African precipitation may indeed be used to assess the state of the coupled ocean-atmosphere system over the Indian Ocean.

2. Data and Methods

[3] East African precipitation is analyzed based on Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data [*Xie and Arkin*, 1997]. In addition we use data from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data set [*Kalnay et al.*, 1996], Outgoing Longwave Radiation (OLR) data [*Liebmann and Smith*, 1996] and monthly SST data, extracted from version 2 of the extended reconstructed sea surface temperature (ERSST) data set [*Smith and Reynolds*, 2004].

[4] Stable isotope measurements from East African precipitation are sparse and the available records archived in the International Atomic Energy Agency – Global Network of Isotopes in Precipitation (IAEA-GNIP) data base (available at http://isohis.iaea.org) are short and contain significant data gaps. Nonetheless this data base provides a unique source of information. We extracted all available records (35 total) within the Indian Ocean domain (40°N–40°S, 0°–160°E), which contained at least 8 years worth of data during both the MAM and OND rainy seasons.

[5] We complement our study by employing the ECHAM-4 Atmospheric General Circulation Model (AGCM) with incorporated stable isotopic tracers [*Hoffmann et al.*, 1998]. The model was forced with prescribed monthly global SST fields between 1950 and 1994. The ECHAM-4 isotope model is based on a hybrid sigma-pressure coordinate system including 19 vertical layers from surface to 30 hPa and was run with triangular truncation at wavenumber 30 (T30 $\sim$ 3.75° lat. $\times$ 3.75° long). Further details on model setup and model performance in the tropics are given by *Vuille et al.* [2003], which analyzed data from the same simulation over the tropical Americas.

3. $\delta^{18}O$ and the Indian Ocean Zonal Mode (IOZM)

[6] We first focus on the short rain season (OND), which tends to show a closer relationship with the large-scale atmospheric circulation. In a second step we expand our analysis by including the long rains (MAM), and consider whether an IOZM signal is still present in $\delta^{18}O$

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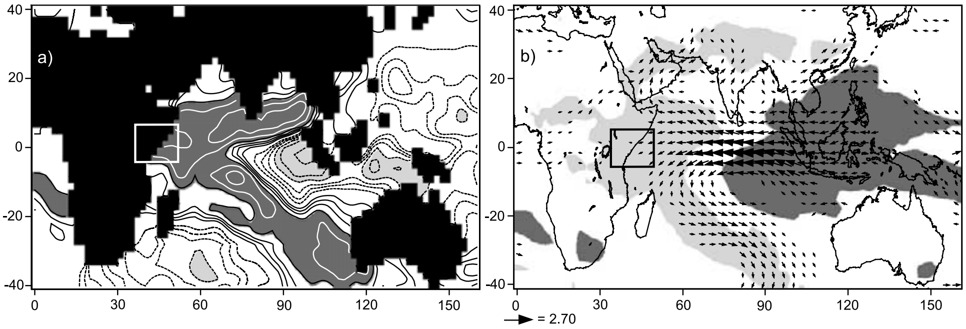

Figure 1. a) Correlation field of CMAP OND precipitation in East Africa (5°N–5°S, 35°–50°E, white box) with ERSST between 1979 and 2003. Contour interval is 0.1, 0-contour is omitted and negative contours are dashed. Significant positive (negative) correlations ($p < 0.05$) are shaded in dark (light) gray. b) as in a) but for regression with NCEP-NCAR 850 hPa wind field and correlation with OLR. Wind field is only plotted where correlation of East African rainfall with either meridional or zonal wind component is significant at $p < 0.05$. Scale for wind field is shown in lower left. Light (dark) gray shading indicates where East African precipitation is significantly negatively (positively) correlated with OLR.

of precipitation, when both rainy seasons are analyzed jointly.

[7] The connection between East African short rains, SSTA and the atmospheric circulation over the Indian Ocean domain is depicted in Figure 1. Increased precipitation over East Africa is associated with above normal SST in the western Indian Ocean and below average SST in the eastern part of the basin (Figure 1a). The OLR correlation field (Figure 1b) is an almost perfect mirror image of the correlation with SST, indicating that the anomalously warm and cold SST in the western and eastern part of the basin lead to anomalous convection over the centers of the two poles respectively. In the lower troposphere the anomalous east-west pressure gradient leads to a weakening or even a reversal of the equatorial low-level westerlies (anomalous easterlies) in the central Indian Ocean during periods of increased precipitation in East Africa (Figure 1b).

[8] It is evident from Figure 1 that interannual fluctuations in East African short rains are very closely tied to the large-scale atmospheric circulation and the associated east-west SST-gradient over the Indian Ocean domain. This gradient is often referred to as the Indian Ocean dipole mode and captured in a dipole mode index (DMI) [*Saji et al.*, 1999] defined as the difference in SST between the western (50°E–70°E; 10°N–10°S) and the eastern Indian Ocean (90°E–110°E; 0°–10°S). During a typical dipole mode event the anomalous east-west SST gradient coincides with the reversal of the Walker circulation, manifested as a weakening or even a reversal of the lower tropospheric zonal winds in the central equatorial Indian Ocean. Since the 850 hPa zonal wind component is more closely related to the stable isotopic composition of precipitation than SST and unlike SST, this variable is simulated in our atmosphere-only GCM, we make use of a zonal wind index (ZWI) defined as the 850 hPa zonal wind averaged over the central equatorial Indian Ocean (5°N–5°S, 60°–90°E, black box in Figure 2) rather than the DMI to describe the IOZM. Studies by *Hastenrath et al.* [1993] have shown that the ZWI is a very powerful index, which accurately describes the zonal circulation over the Indian Ocean and is closely associated with East African short rains. Indeed the correlation of the ZWI in OND with the large-scale precipitation field reveals the exact same dipole pattern, characteristic of the IOZM (Figure 2a). Easterly low-level wind anomalies over the central equatorial Indian Ocean during boreal fall are associated with significantly increased precipitation over East Africa and the western Indian Ocean, extending northeastward and southeastward to the midlatitudes. At the same time anomalously dry conditions prevail over the eastern Indian Ocean, the maritime continent and parts of Southeast Asia and Australia. During periods with anomalous westerly equatorial winds in the

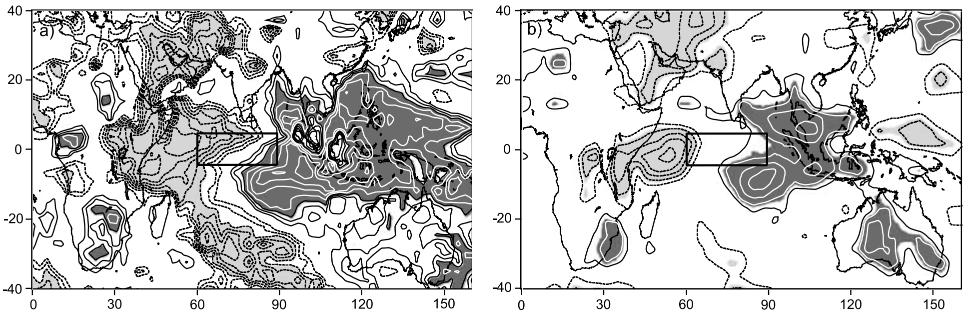

Figure 2. a) Correlation field of OND ZWI (averaged over 5°N–5°S, 60°–90°E, black box) with CMAP precipitation (1979–2003). Contour interval is 0.1; contours 0.1, 0 and −0.1 are omitted and negative contours are dashed. Significant positive (negative) correlations ($p < 0.05$) are shaded in dark (light) gray. b) as in a) but based on ECHAM-4 simulation (1950–1994).

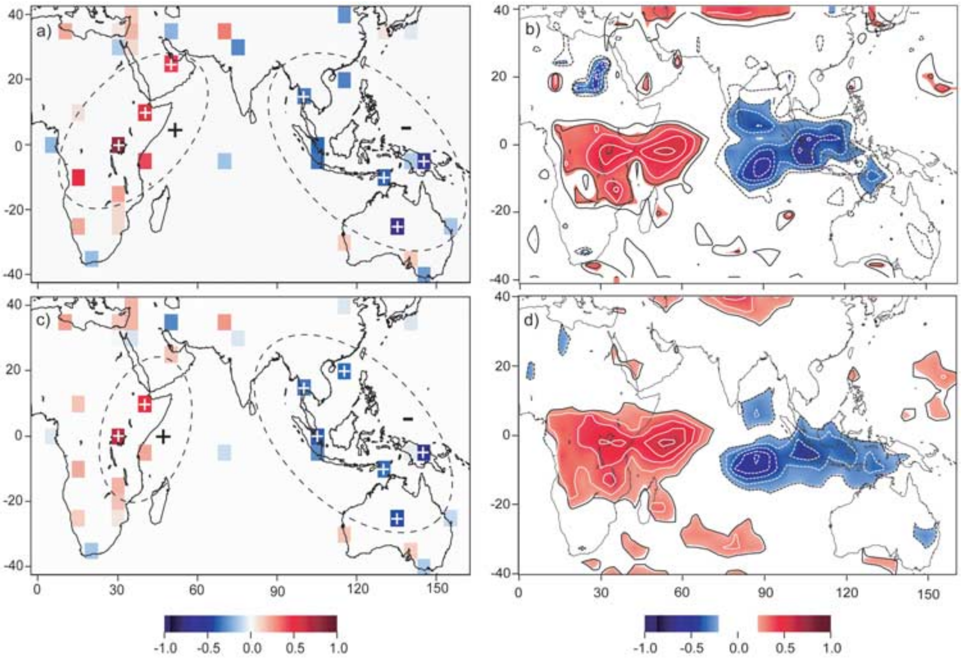

Figure 3. a) Correlation of OND ZWI anomalies with $\delta^{18}O$ anomalies from IAEA-GNIP stations (varying record length). Significant correlations ($p < 0.05$) are indicated by a white cross. b) as in a) but for ECHAM-4 simulation (1950–94). Contour interval is 0.1; contours 0.1, 0 and −0.1 are omitted and negative contours are dashed. Significant positive (negative) correlations ($p < 0.05$) are shaded in red (blue). c) as in a) but MAM and OND anomalies. d) as in b) but for OND and MAM anomalies.

central Indian Ocean, this pattern is reversed. The characteristic east-west precipitation dipole over the Indian Ocean is accurately reproduced in the ECHAM-4 simulation (Figure 2b), although the north-south extent of the regions with significant correlations is underestimated in the model.

[9] During boreal fall this coupled ocean-atmosphere mode also significantly affects the stable isotopic composition over the entire basin. The same east-west dipole pattern that is so characteristic of the IOZM can also be found in the sparse $\delta^{18}O$ data scattered throughout the Indian Ocean domain (Figure 3a). Strong positive IOZM events, and hence a negative ZWI lead to significantly depleted $\delta^{18}O$ in East African precipitation. At the same time $\delta^{18}O$ in precipitation over Australia, the maritime continent and Southeast Asia is significantly more enriched. During negative IOZM events the pattern is reversed. Unfortunately not very many $\delta^{18}O$ records exist from this region and several of those used in Figure 3a are rather short. What makes the $\delta^{18}O$ – IOZM relationship so convincing, however, does not hinge on individual records, but is based on the entire basin-scale pattern with its clear east-west differentiation, which is exactly what one would expect based on the OLR anomalies depicted in Figure 1b. Additional support for the notion that this correlation pattern is real comes from our simulation with the ECHAM-4 model. The model (Figure 3b) produces a correlation pattern between $\delta^{18}O$ and the ZWI which is entirely consistent with the observations and shows the exact same $\delta^{18}O$ dipole. Unlike the observations however, the model result is based on 45 years of spatially complete data. Hence it is unlikely that the result based on observations in Figure 3a is in any way biased by the temporal or spatial sampling. Interdecadal variations in the relationship between the IOZM and precipitation, described by *Clark et al.* [2003], are not apparent in our simulation.

[10] A significant correlation between the ZWI and $\delta^{18}O$ does not yet guarantee that this relationship is visible in proxy archives. The size of the signal needs to be resolvable in records which incorporate $\delta^{18}O$. This is particularly important for coral records where the precipitation signal is not directly incorporated, but mixes into the surface ocean. Figure 4a shows that the amplitude of the precipitation $\delta^{18}O$ signal is indeed large; extremes in the ZWI are associated with a difference in $\delta^{18}O$ of 5.3 permil in East Africa (Entebbe) and 11.8 permil in Australia (Alice Springs). Another concern is that the OND short rains only account for approximately 30–40% of the annual precipitation total in East Africa; hence it is not a priori clear that the IOZM signal can be identified in proxy records that lack sub-annual resolution. In a second step we therefore analyze both rainy seasons, MAM and OND, jointly. These six months account for 65–85% of the annual precipitation over East Africa (CMAP, 1979–2003). Hence any climate signal apparent in the stable isotopic composition of the two rainy seasons will likely be recorded in annually resolved proxies. Indeed the correlation field between $\delta^{18}O$ and the ZWI is not significantly different when both rainy seasons are analyzed jointly. The correlation over East Africa is somewhat weaker in the observational data, but it is actually stronger in most records from Southeast Asia (Figure 3c). Again the ECHAM-model simulates a relationship between $\delta^{18}O$ and the ZWI which is entirely consistent with the IAEA/GNIP data (Figure 3d).

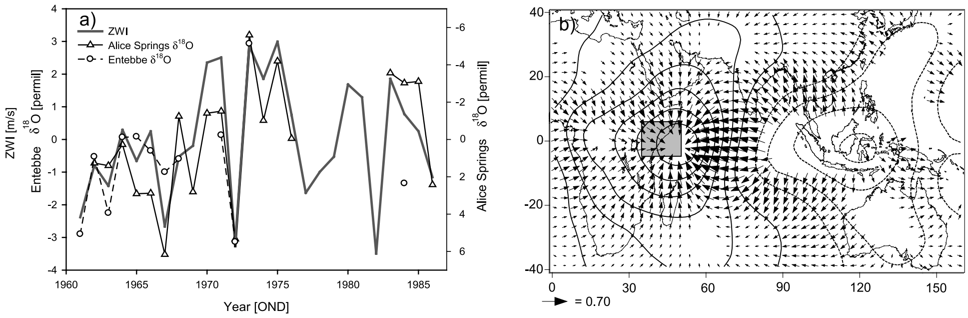

Figure 4. a) Time series of ZWI and δ^{18}O anomalies from Entebbe and Alice Springs in OND. Scale of right-side y-axis is reversed. b) ECHAM-4 MAM and OND seasonal δ^{18}O anomalies in East African precipitation (5°N–5°S, 35°–50°E, gray box) regressed against 250 hPa velocity potential and divergent wind. Wind vectors are only shown where either zonal or meridional divergent wind component is significantly correlated ($p < 0.05$) with δ^{18}O. Scale for divergent wind vector (m s^{-1} per stdev.) is shown in lower left. Contour interval for velocity potential is 2×10^5 m^2 s^{-1} per stdev.; 0-contour is omitted and negative contours are dashed.

[11] The fact that δ^{18}O records in the eastern and western part of the Indian Ocean are so closely related to the IOZM during the spring and fall transition seasons, yet out of phase with one another, suggests that they are linked through adjustments in the large-scale overturning circulation over the Indian Ocean domain. This relationship is documented in Figure 4b, which shows the regression field between simulated δ^{18}O anomalies in East African long and short rains and 250 hPa velocity potential and divergent wind field. More enriched δ^{18}O during the East African rainy seasons is related to anomalous upper-air convergence and low-level divergence (not shown) over East Africa. At the same time anomalous low-level convergence, ascending motion and upper level divergence prevails over the eastern part of the basin. Such conditions lead to enhanced rainout and more intense distillation processes and thus more depleted δ^{18}O values over the eastern Indian Ocean. Hence δ^{18}O in precipitation is more enriched in regions where vertical ascent and convective activity are subdued, while the opposite pattern occurs over regions of enhanced convection.

4. Summary and Conclusion

[12] Observational data and simulations with the ECHAM-4 AGCM indicate that δ^{18}O in East African rainfall during the spring and fall rainy seasons is a very good indicator of the IOZM. This link between δ^{18}O and the IOZM is established through adjustments in the large-scale overturning circulation over the Indian Ocean. The anomalous Walker circulation leads to changes in the upper- and lower-level convergence and convective activity, which in turn influence distillation processes and the degree of rainout in convective clouds. These changes lead to significant departures in the δ^{18}O composition of precipitation, expressed as an east-west dipole across the Indian Ocean domain.

[13] The results presented here indicate that δ^{18}O records from ancient meteoric waters deposited in East Africa may hold the potential to reconstruct climate variability in the Indian Ocean domain, in particular when used in conjunction with records from the eastern Indian Ocean, the Maritime continent or northern Australia [e.g., *Charles et al.*, 2003]. Such analyses may offer new avenues to explore Indian Ocean climate variability based on multi-proxy reconstructions (e.g. ice cores, corals, speleothems, lake sediments and tree rings) and because of the dipole nature of this relationship, records from both sides of the Indian Ocean domain may be compared and tested against each other.

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