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SAHARIAN DESERT CYCLIC EVENTS BASED ON SEASONAL TO INTERANNUAL RECURRENT SAHEL RAINFALL DIAGNOSIS.

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INTRODUCTION

The drying trend in the semiarid Sahel was attributed to warmer-than-average low-latitude waters around Africa, which, by favouring the establishment of deep convection over the ocean, weaken the continental convergence associated with the monsoon and engender widespread drought over the West Africa. Effectively, the relationship between rainfall and desert margin advances or retreats brings into focus questions regarding the interactions of global change dynamics with desertification processes. The fluctuations in the size of the Sahara Desert show a linear inverse relationship between rainfall and expansion of the desert's southern margin. There is a vast literature available on this subject.

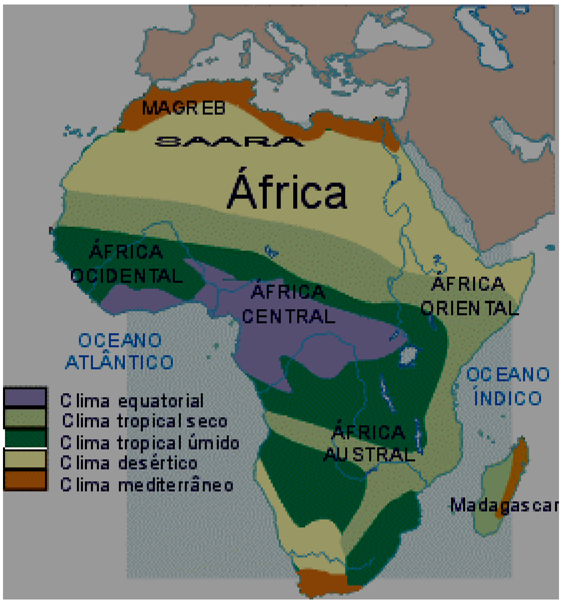

Fig.1: Climate of Africa.

In this manuscript we present statistical evidence, suggesting that variability of rainfall in the Sahel results from the temporal variability of the southern incursions of ITCZ on West Africa and its relationship with the positioning of the action centres related to the high subtropical pressures. We also analyse the relationship between the movement of the limits of the Sahara Desert with the variability of the low frequency of the configurations of the general circulation of the atmosphere, forecasting the progress and retreat of the Saharan desert.

The Sahel is the semi-arid belt in Africa between the arid to hyper-arid Sahara Desert and the humid equatorial Africa, the tropical rainforest. In the 1970's and 1908's it experienced repeated, devastating droughts, most notably in 1972-73 and in 1982-84. Since then, scientists have been debating whether the cause for this pronounced climatic shift was anthropogenic in nature, i.e. whether desertification, forced by the increasing pressure of population growth on the environment, was starting to have an impact on the regional climate (*e.g.* Charney *et al.*, 1975), or whether the recurrent droughts were related to the slower, decadal time scales of oceanic variability (*e.g.* Folland *et al*, 1986).

SAHEL EXPERIMENTAL DATASET

This study was realised considering a database of observed monthly precipitation data of the World Monthly Surface Station Climatology (WMSSC), supplied by the Joint Institute for the Study of the Atmosphere and Ocean

(JISAO) - a "Centre of Excellence" that fosters research collaboration between NOAA and the University of Washington - in the period of 1950-2000 for 14 stations of the 6 countries of the area of West Africa Sahel (see the political boundaries in Fig.1), namely, Tillabery, Tahoua, Maradi (Niger), Gao, Kita, Segou, Koutiala (Mali), Kiffa (Mauritania), Dakar, Thies, Diourbel (Senegal), Kandi,, Natitingue (Benin) and Ougihoua (Burkina Faso). Hence, for the analysis and characterization of the precipitation the observed data of WMSSC were used, giving larger focus to the periods in that were observed the northward shift in the Sahara/Sahel boundary.

Fig.2: The West Sahel Africa region.

SAHEL RAINFALL VARIABILITY.

Notice that sensitivity experiments is which sea-surface temperatures in the Tropical and Subtropical Atlantic are widely prescribed to be 1°-3°C colder than today show ocean feedbacks increase monsoon rainfall in the Sahara and Sahel by enhancing evaporation from the ocean surface and increasing moisture flux to the continent. In asynchronously coupled atmosphere-ocean experiments, maximum monsoon precipitation shifts northward to 15°-20°N and precipitation over northern Africa increases by 25% compared to simulations made with prescribed modern SST. Simulations using fully-coupled atmosphere-ocean models confirm that ocean-surface feedbacks produce a significant enhancement of the orbital-induced changes in the African monsoon but again the changes are apparently insufficient to explain its observed expansion (the precipitation increase induced by the combined effect of orbital forcing and ocean feedbacks). Enhanced monsoons extended forest biomes inland in Sahelian vegetation into the Sahara, while the African rainforest was reduced consistent with a more seasonal climate in the equatorial zone.

It should be noted that the rainfall deficits discussed here represent annual rainfall amounts spatially averaged over the entire Sahelian region. Such aggregated values do not tell us anything about variations in the spatial distribution or rainfall seasonality. The latter can be as important as total rainfall amount in terms of agriculture. Agnew and Chappell (2000) point out that not all regions of the Sahel have experienced a synchronous and systematic reduction in rainfall, and that agricultural production in the Sahelian nations has increased over the course of the period generally characterised as dry. Indeed, studies have identified various different regions of coherent rainfall within the Sahelian zone, and different areas are characterised by different, and sometimes conflicting, anomaly patterns.

SEASONAL STOCHASTIC ANALYSIS.

There is a strong evidence of seasonality defining three periods: DRY, TRANS and WET. The August variability has an important contribution for the rainy periods. The dry regime corresponds to the months of November-May; the transition regime was associated for the months of June and October; and the rainy regime for the months of July-September. The rainy regime corresponds to the period in that the ITCZ reaches its more northern position in its movement to the North and the activity of the monsoon is more intense, while in the dry regime, the ITCZ migrates to the South. Over the transition regime we still have some influence of the ITCZ and of the trade winds.

The African western area is influenced by the centres of high subtropical pressures of the Azores (in the North Atlantic region) and the Santa Helena (in the South Atlantic region), which control the seasonal oscillation of the trade winds with marine influence - the marine trade winds, and of continental characteristic - the continental trade winds. In the dry regime, the trade winds of NE are more intense. During the rainy regime, they are more parallel to the coast, becoming marine trade winds. Another prominence factor is the oscillatory movement of the ITCZ, configured by the migration of the high subtropical pressure of the Azores through the North and the intensification of Santa Helena's high subtropical pressure, the trade winds of the southeast advect the wet air. This period is characterized by the penetration of the monsoon on the continent and the passage of east systems in direction to the Atlantic Ocean. These precipitation regimes are verified in overall the analysed stations.

The results reveal that the precipitation regime in the whole Sahelian stations has very marked annual cycles, with the precipitation concentrated on the months of North Hemisphere summer, which is the period of larger convection, being August the rainiest month. The annual cycle is related with the ITCZ position that seasonally migrates to the North, approximately 12°N, in August-September, to the South, approximately 4°S, in March-April.

The Sahel rainfall record provides a clear indication of the desiccation of that area since the late 1950's. The records of Sahel rainfall show a pronounced decline in rainfall level starting during the second half of the 1950's. This is the most marked precipitation trend in any part of the world during the last century. Land degradation in the Sahel itself may also be a contributing factor, altering the heat and moisture budgets of the region.

SAHEL CLIMATIC CHANGE.

Debates as to whether or not the changes in rainfall in the Sahel over the last few decades represent a desiccation or a persistent drought are largely semantic in nature, and often of limited value. It is true that not all years in the period in question have exhibited significant negative anomalies. It is also true that the downward trend in rainfall has not been continuous; indeed, the trend since 1984 has been positive. Neither has every year in this period been perceived by the inhabitants of the Sahel as being characterised by drought. However, it is certainly apparent that there have been several years since 1968 during which rainfall has been deficient enough to cause large-scale societal problems, and that these years have occurred during a period in which rainfall, aggregated across the entire Sahel, has decreased relative to earlier decades. Whichever reference period is chosen, rainfall anomalies will be more persistently negative, and more strongly negative, since 1968 than in earlier decades.

Studies of the persistence of Sahelian rainfall, represented mathematically by the degree of autocorrelation in the rainfall series, demonstrate that the nature of the interannual variability of the regional rainfall has undergone a profound change, with the autocorrelation of the aggregated rainfall anomalies increasing dramatically around 1950. Coupled with the start of the downward trend in rainfall in the 1950s and the association of Sahel rainfall with other changes in the global climate, these considerations suggest that the rainfall changes in the Sahel are representative of a broad systematic change in Sahelian climate which may be linked to widespread decadal-scale climate change. If the observed rainfall changes represent a systematic reduction in precipitation in the Sahel, which is linked to other patterns of global change, it seems reasonable to describe such changes in general terms as decadal-scale regional climate change.

The change in the nature of the interannual variability in Sahelian rainfall in the 1950's suggests that it is worth considering at which point after 1950 the desiccation can be said to have commenced. It may be argued that the 1950's was an anomalously wet decade, and that the reduction in rainfall between 1955 and 1968 signified nothing more than a return to "normal" conditions, after which a desiccation commenced which resulted in abnormally dry conditions replacing abnormally wet conditions. Alternatively, whatever mechanism or mechanisms have been responsible for the dry episode may have been active since the mid-1950's, perhaps at the same time as, and in opposition to, the processes which resulted in the high rainfall of that decade. A greater understanding of the mechanisms responsible for the increased aridity in the region is required before the timing of the onset of the recent drier regime can be clearly identified. Such considerations mean that the debate as to the nature and likely duration of the Sahelian dry episode is still far from closed.

An understanding of the mechanisms responsible for the recent aridification will help climate scientists to assess whether the dry period of the late twentieth century is unusual in an historical context, and whether such conditions are likely to prevail in the near-future. Many such mechanisms have been postulated. These include changes in oceanic heat transport and sea surface temperature patterns, a reduction in the size and intensity of convective disturbances over the Sahel, large-scale changes in the northern hemisphere tropospheric circulations, and anthropogenically driven changes in surface albedo in the Sahel. Despite of the large staff which has been dedicated to furthering understanding of the causes of Sahelian drought, the mechanisms which initiated and which have sustained in the Sahel are still relatively poorly understood. Debate has essentially focused on whether the observed changes in rainfall are a response to "internal" factors related to changes in the characteristics of the land surface within Sahelian regions, or "external" factors such as large-scale atmospheric forcing by variations in sea surface temperatures. Changes in global patterns of sea surface temperature and northern hemisphere tropospheric circulations which are contemporaneous with the Sahelian desiccation suggest that the changes in rainfall have been associated with variations in the global-scale atmospheric and oceanic circulation. However, the inexact relationships between these quantities and Sahel rainfall on an interannual timescale suggest that regional and local-scale processes may be important as drought-modifying mechanisms. The interannual variability of Sahelian rainfall, and especially its high level of persistence over the drought period, cannot be explained entirely by association with the general configuration of the atmospheric and oceanic circulation. Some of the interannual variations in rainfall are likely to be explained by teleconnections between the Sahel and individual oceanic regions. However, the persistence in interannual rainfall, which is absent in the first half of the twentieth century and also in modelled Sahel rainfall suggests that regional-scale feedback processes may have acted to reinforce the observed aridity. The nature and scale of the increases in dust production observed since the 1950's and 1960's, along with the potential for dust aerosols to increase atmospheric stability and thus suppress convection and ultimately rainfall, make dust a likely, but by no means sole, candidate for such a feedback mechanism.

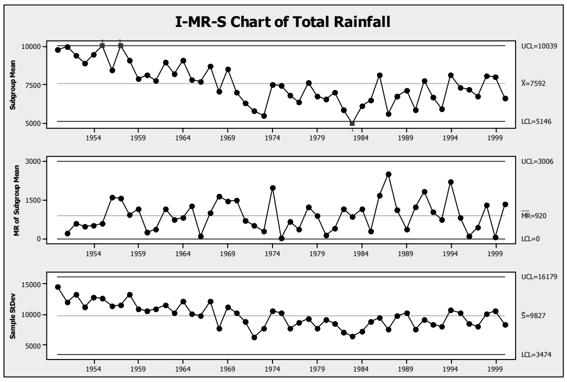

Fig.3: Statistical Quality Control Chart: The trend analysis of the annual amount of rainfall on the West Sahel Africa (1950-2000). Structural change-points can be easily observed on 1973, 1983 and 1986, which can be associated to the PDO.

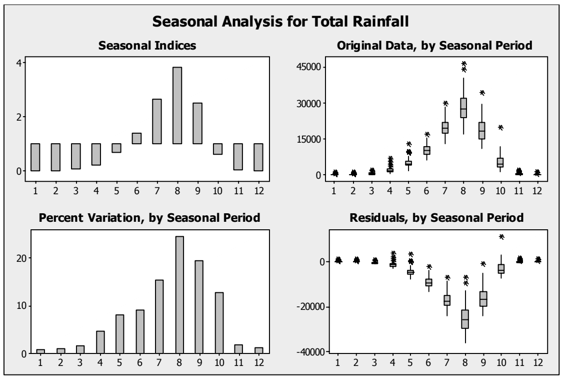

Fig.4: The monthly rainfall climatology assembling overall meteorological stations. The evidence of seasonality is remarkable, defining the important contribution of August (8), July (7) and September (9) for the rainy periods.

SAHEL TELECONNECTIONS.

The Western Africa as well as close regions can be less sensitive to the ENSO events compared with other mid-latitude areas. However, exceptions exist for the phases of warm and intense ENSO, when Western Africa can suffer relative climatic impacts indicating drastic reduction of the southwest monsoon precipitation amount. There is a significant correlation between the La Niña predominance (El Niño) and the increase (decrease) trend of precipitation. In the period in which La Niña prevails, there is a positive tendency of the precipitation that reveals larger precipitation. In the period of El Niño's predominance, there is a negative tendency, decreasing the precipitation amount. During the La Niña, the circulation east-west is stronger than the normal, there is a fort ascending movement on West Africa that can intensify the convective activity provoking rains above the average.

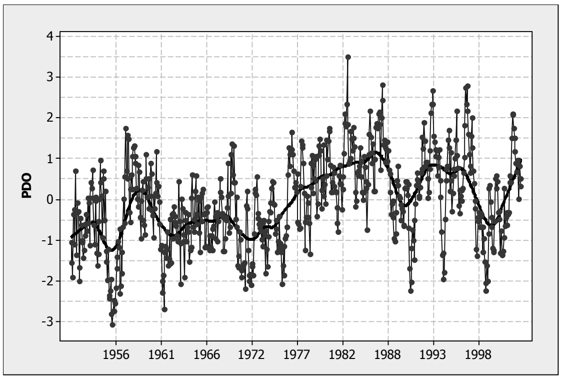

Fig.5: Chronological time series of the Pacific Decadal Oscillation (PDO) - (1950-2000). Structural change period can be easily detected between 1972 and 1986.

The precipitation anomalies recorded, during the target years of this study (1950-2000), can be linked to the variability of the southwest monsoon of the West Africa. For drought years it is noticed a delay of the movement through the north of the southwest monsoon, displacements through the south of the ITCZ, of the subtropical pressures high of the Azores and the Santa Helena, and anomalous cooling of the northwest waters or anomalous cooling of the southeast waters of the line that ties West Africa.

Analysing thee time series we can define the existence of two cycles (with one structural change-point), in terms of the annual amount of precipitation. In the first cycle (1950-1975) the precipitation was superior compared to the second cycle (1976-2000) the precipitation went inferior that to climatological average. Notice that anomalies can be associated to climatic alterations related with the variation of the atmospheric structures in planetary and synoptical scale as the positioning of the high subtropical pressures and the ITCZ.

In the period from 1950 to 1975 there was a prevalence of the cold phase of the ENSO (La Niña) while from 1976 to 2000 there was a predominance of the warm phase (El Niño). Here the clear correlation between La Niña (El Niño) pervasiveness and the positive (negative) anomaly of precipitation over the Sahel region is evident - atmospheric teleconnections exists, particularly in the fields of atmospheric pressure, that produce climatic anomalies in so far away areas of the phenomena that gave them origin.

The tendency of the precipitation for the three regimes reveals that, for the studied stations, the dry regime not recorded tendency of precipitation variation, while the transition regimes and rainy present weak negative tendency, and strong and significant negative, respectively. Fig.2 illustrates the annual rainfall for the whole meteorological stations on the West Sahel Africa (1950-2000), where structural change-points can be easily observed of about 1973 and 1983. Fig.4 illustrates the Pacific Decadal Oscillation (PDO) index (1950-2000), where also structural change period can be easily detected between 1972 and 1986.

A year running mean of the Sahel rainfall neatly separates interdecadal variability, which includes the negative trend in Sahel rainfall (hereafter referred to as the *low-frequency* component of Sahel rainfall variability), from interannual variability (hereafter referred to as the *high-frequency* component, which can be associated to warm/cold ENSO events. The role of ENSO in shaping Sahel climate variability on the interannual timescale is undeniable, as seen in the relationship between the high-frequency components of the Sahel rainfall with surface temperature. SST variability in the oceans around Africa is responsible for the low frequency variability. It seems that the warming trend in the equatorial Indian Ocean may have favoured the local establishment of deep convection, and that the atmospheric response to SST/convection anomalies in the

equatorial Indian Ocean may have weakened the African monsoon.
Notable features of this atmospheric response are: (a) tropospheric warming centred over the SST convection region in the equatorial Indian Ocean, and a weakened Tropical Easterly Jet; (b) precipitation anomalies of opposite sign over the Sahel and over the equatorial Indian Ocean; (c) equatorial westerly wind anomalies to the west of the equatorial Indian Ocean SST anomalies, and north-easterly anomalies over Africa. Climatic variations can result in shifts in the isohyets in sub-Saharan North Africa of the order of hundreds of kilometres. If definitions are based on rainfall amounts then the Sahel must be seen as a mobile geographic entity. The Sahel is characterised by steep latitudinal rainfall gradients and, as with other semi-arid regions, by high interannual rainfall variability. The bulk (80-90%) of Sahelian rainfall occurs between the months July and September and is associated with the northward movement of the ITCZ.

The ITCZ is characterised by a surface pressure trough within which is embedded a band of convergence produced by flow discontinuity where the trade wind systems of the northern and southern hemispheres meet. Over the Eastern Atlantic the pressure trough broadly coincides with a zone of maximum sea surface temperature (SST). It should be noted that the surface wind discontinuity, surface pressure trough and the zones of maximum SST, convergence, cloudiness and precipitation do not necessarily coincide, and that the ITCZ has a more complex structure than some studies may have suggested.

The northward migration of the ITCZ in boreal summer brings moisture from the equatorial Atlantic over continental North Africa in the form of the West African monsoon. Most of the rainfall is generated from this moist air over the Sahel by disturbance lines, otherwise known as disturbances or squall lines, which are organised lines of approximately westward travelling convective cells, oriented in a northsouth direction and tens to hundreds of kilometres in length. The disturbance lines are associated with easterly waves, which are manifest as variations in the zonal flow at altitudes in the vicinity of the 700hPa pressure level.

DISCUSSION

Concern about aridification of the Sahelian environment arose in the early 1970's, when consecutive rainfall-deficient years culminated in the widespread Sahelian droughts of 1971, 1972 and 1973. As early as the mid-1970's it was postulated that the Sahel may be experiencing a shift to a generally more arid climatic regime. Although the Sahel recovered from the droughts of the early 1970's, rainfall continued to be low with respect to 1950's and 1960's, reducing again in the early 1980's. The years of 1983 and 1984 were extremely dry, with 1984 exhibiting the largest rainfall deficit of the twentieth century (30% below the long-term mean). Are suggestions that the Sahel "drought" would end in 1985 proved to be unfounded? Rainfall was low in 1985 and 1986, while the rainfall deficit in 1987 was comparable to that of 1973 (20% below the long-term mean).

After the relatively wet year of 1988, rainfall anomalies remained negative with respect to the twentieth century mean until 1993, with rainfall in 1990 again being comparable to that of 1987 and the early 1970's. Rainfall in 1994 was similar to 1962 and represented the largest aggregated total since the onset of dry conditions. 1995-1997 and 2000 were also dry, and rainfall in 1998 was above to the century-mean. Rainfall was deficient in 2000, but July and August were wet, with widespread floods in many Sahelian countries in August. Within the context of the post-1968 aridity, it is worth noting that the only other year in the twentieth century to exhibit a rainfall deficit comparable to driers years: 1971-1973, 1983, 1987, 1990-1993 and 2000.

The Sahel rainfall record provides a clear indication of the aridness of that area since the late 1950's. The records of Sahel rainfall show a pronounced decline in rainfall level starting during the second half of the 1950's. This is the most marked precipitation trend in any part of the world during the last century. On the year-to-year timescale, drought in the Sahelian region is clearly associated with a difference in sea surface temperature between the northern and southern tropical Atlantic Ocean and, more widely, between the Northern and Southern Hemispheres. This relationship, which is used as a basis for a seasonal forecasting scheme, appears to be related to a shift in the atmospheric circulation over the Sahelian region. The rain-bearing winds fail when the northern tropics are relatively warm. The causes of the long-term decline in rainfall are unclear. There is, again, a link with the temperature gradient across the tropics. Land degradation in the Sahel itself may also be a contributing factor, altering the heat and moisture budgets of the region.

CONCLUSION

The analysis was carried out in two steps: (1) the annual cycle and migrations of the weather zones characterizing the climate of West Africa are considered. This leads to evidence of a sudden and synchronous rain onset between 9°N and 13°N, which does not follow the classic scheme of a progressive migration of the rain zones, north and south with the sun; (2) the differences in the rainfall regimes between the two succeeding periods 1951–1975 being wet and the period 1976-2000 being dry. The interannual rainfall between the wet and the dry periods is 180mm/yr. This difference is relatively evenly distributed in space, with no clear meridional gradient. Between these two periods, the parameter measure of the occurrence rate displays a systematic decrease, which appears well correlated to the decrease of the mean interannual rainfall.

The variations of the magnitude of the convective storms are, by contrast, smaller in amplitude and more erratically distributed in space. When looking at the intraseasonal scale, it appears that the rainfall deficit of the dry period is primarily linked to a deficit of the number of events occurring during the core of the rainy season over the Sahel, and during the first rainy season for the region extending south to 9°N–10°N. It is also shown that, in the south, the dry period is characterized by a shift in time of the second rainy season. All these characteristics have strong implications in term of agricultural and water resources management. They also raise questions about the traditional scheme used to characterize the dynamics of the West African monsoon.

Desertification is still often viewed as an irreversible process triggered by a deadly combination of declining rainfall and destructive farming methods. There is also a strong confusion over why the Sahel is becoming green. Scientists believe the main reason is increased rainfall since the great droughts of the early 1970’s and 1980’s. But farmers have also been adopting better methods of keeping soil and water on their land.

It is clear that Sahel climate variability is inextricably tied to global climate variability. Further work is required to test the dynamical hypotheses on ENSO's impact on Northern Hemisphere summer climate. Likewise, a warm ENSO event is associated with: (a) tropic-wide tropospheric warming, and a weakening of the tropical easterly jet between Africa and India; (b) negative precipitation anomalies over the northern summer monsoon regions of Central/North America, Africa, and the Indian subcontinent; (c) westerly wind anomalies to the west of the equatorial Pacific SST anomalies, and north-easterly wind anomalies over the Sahel, indicating a weakened monsoonal flow; (d) the Madden-Julian Oscillation and the North Atlantic Oscillation; (e) the Atlantic Ocean Dipole in Western Africa precipitation. It is expected that this work will lead to improvements in the interpretation of seasonal climate prediction, and in our dynamical understanding of the impact of climate change.

REFERENCES.

Agnew, C. T. and Chappell, A., 2000: Drought in the Sahel. *GeoJournal*, **48**: 299-311.

Giannini, A., Saravanan, R. and Chang, P. 2003: Ocean forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, **302**: 1027-1030.

Grist, J. P., Nicholson, S. and Barcilon, A., 2002a: Easterly waves over Africa. Part I: The seasonal cycle and contrast between wet and dry years. *Mon. Weather Rev.*, **130**: 197-211.

Grist, J. P., Nicholson, S. E. and Barcilon, A. I., 2002b: Easterly waves over Africa. Part II: Observed and modeled contrasts between wet and dry years *Mon. Weather Rev.*, **130**: 212-225.

Sagrans, E. 2002: Africa's deserts are in "spectacular" retreat. *New Scientist*, **September 18**.

Texier, D., de Noblet, N. and Braconnot, P., 2000: Sensitivity of the African and Asian monsoons to mid-Holocene insolation and data-inferred surface changes. *J. Climate*, **13**: 164-181.