# The Influence of Sea Surface Temperatures on African Climate


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**Abstract**

Establishing a relationship between anomalies in sea surface temperature (SST), perturbations in the atmospheric circulation and response in precipitation forms the physical basis of seasonal to interannual (SI) prediction. Here I: (1) review the influence of large-scale patterns of SST anomalies on the climate of tropical Africa, as interpreted from 20th century observations, (2) briefly review the influence of SST and precipitation in the tropical Atlantic and Indian Ocean on European climate, and (3) discuss the limitations of the SST forcing-rainfall response framework in interpreting the divergence of projections of precipitation change in a specific region of tropical Africa: the semi-arid margin of the Northern hemisphere monsoon and of the Saharan desert known as the Sahel.


## 1. Introduction – why is it important to "understand, anticipate and manage climate risk"[1]?

In its quest to apply science for societal benefit, the International Research Institute for Climate and Society (IRI), a unit of the Earth Institute at Columbia University, works at the intersection of predictability and vulnerability: predictability of climate and vulnerability to climate variability and environmental change. In general terms both are higher in tropical regions than in mid to high latitudes (Shukla 1998; Boko et al 2007), hence the focus of much IRI climate research and project work is in Latin America and the Caribbean, sub-Saharan Africa, and the Asia-Pacific region.

Every month the IRI releases probabilistic forecasts of the state of the El Niño-Southern Oscillation (ENSO) system and of global precipitation and temperature anomalies (see http://iri.columbia.edu). These forecasts have demonstrated skill, still very much dependent on the occurrence of extreme phases of ENSO (Barnston et al 2010). However, the usually slight tilts of the odds typical of a seasonal forecast are not straightforward to be taken advantage of. One could argue for either a reduction of losses or a slow accumulation of small benefits that in time lead to increased wealth (Patt et al 2005). For example, in agriculture, if a farmer were in a position to translate the current 40-50% probability of drier than normal conditions in the Southern Cone of South America (figure 1) into a comparable shift to planting of drought-tolerant crops, or a shift to enhanced probability of wetter

[1] From the IRI mission statement

than normal conditions into an increase in area planted, over time said farmer could benefit from such adaptation. However, not all farmers, more generally not all potential users of climate information, are born equal. It has been shown that large-scale commercial fishermen in Peru have greater access to information, and the means to take advantage of it, than smaller-scale, artisanal fishermen (Pfaff et al 1999).

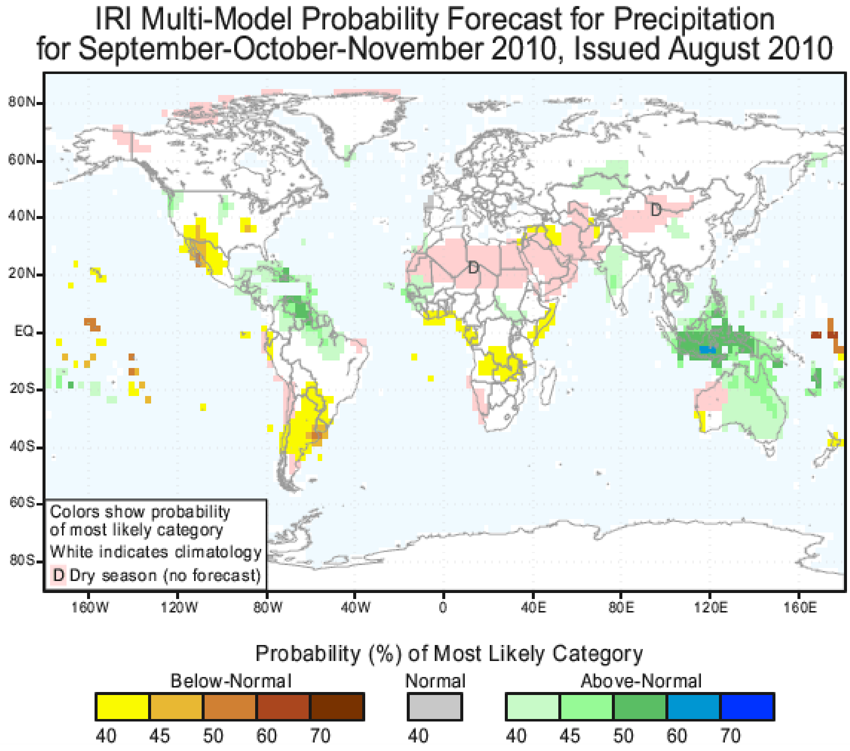


*Figure 1 – IRI net assessment, September 2010. Climatological probabilities are 33% for each of the three categories: below-normal, normal or above normal. In this case, in most places the odds are tilted in favor of below-normal (e.g. southeastern South America), or above-normal (e.g. northern South American and the Caribbean basin) precipitation due to the development of cold ENSO conditions in the central and eastern equatorial Pacific.*

As one moves from the seasonal to interannual time scale of predictions to the longer-term time scale of projections of climate change, one is faced with increased complexity in the physical processes that it is necessary to consider, so that it becomes increasingly difficult to predict net outcomes of competing processes. In the longer term, paradoxically, projections of regional rainfall change are more credible in the extra-tropics than in the tropics, perhaps understandably so. Certain processes that are crucial to getting right the tropical climate's response to increasing anthropogenic forcing, most notably processes leading to vertical instability, deep convection and rainfall, are only approximately represented in state-of-the-art climate models – because the spatial scale of processes is not resolved in models, the description of such processes relies on empirical relationships, rather than on first principles. These shortcomings are clearly borne out in maps of the intra-model coherence of the sign of rainfall change, [e.g. figure 2 in box 11.1, Chapter 11 of the contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change, hereafter IPCC AR4 (Christensen et al 2007)], where one can compare the level of agreement that the sub-tropics, e.g. the Mediterranean basin just north of the Sahara desert, are going to get drier, with the lack thereof for the tropical belt just south of the Sahara, the Sahel.

At the same time, as one considers the longer time scale, one also naturally becomes more curious about the complexity of the system at work beyond the physical climate: while famine in the Sahelian country of Niger in 2005 may have been triggered by an abrupt early demise of the rainy season, the critical reader is left to ponder why Niger is still vulnerable to recurrent food security crises [http://www.fews.net], perhaps increasingly so, despite the increased availability of food with greater integration in the global market economy. More generally, while it is important to identify the role of physical/environmental processes in driving societal change, such undertaking should not lead us to underestimate human/societal factors and solutions.

## 2. Influence of SST on African climate

On seasonal to interannual time scales the influence of sea surface temperatures defines the predictability of climate in sub-Saharan Africa. The warm phase of ENSO, the dominant pattern of variability at global scale, is associated with drought at the margins of the monsoon systems of the northern and southern hemispheres during the respective rainy seasons. These fall in the middle of the calendar year during ENSO growth in northern Africa, in the Sahelian belt stretching from the Atlantic coast of Senegal and Mauritania to the Red Sea coast of Sudan and Eritrea, and at the beginning of the calendar year after peak ENSO in southern Africa.

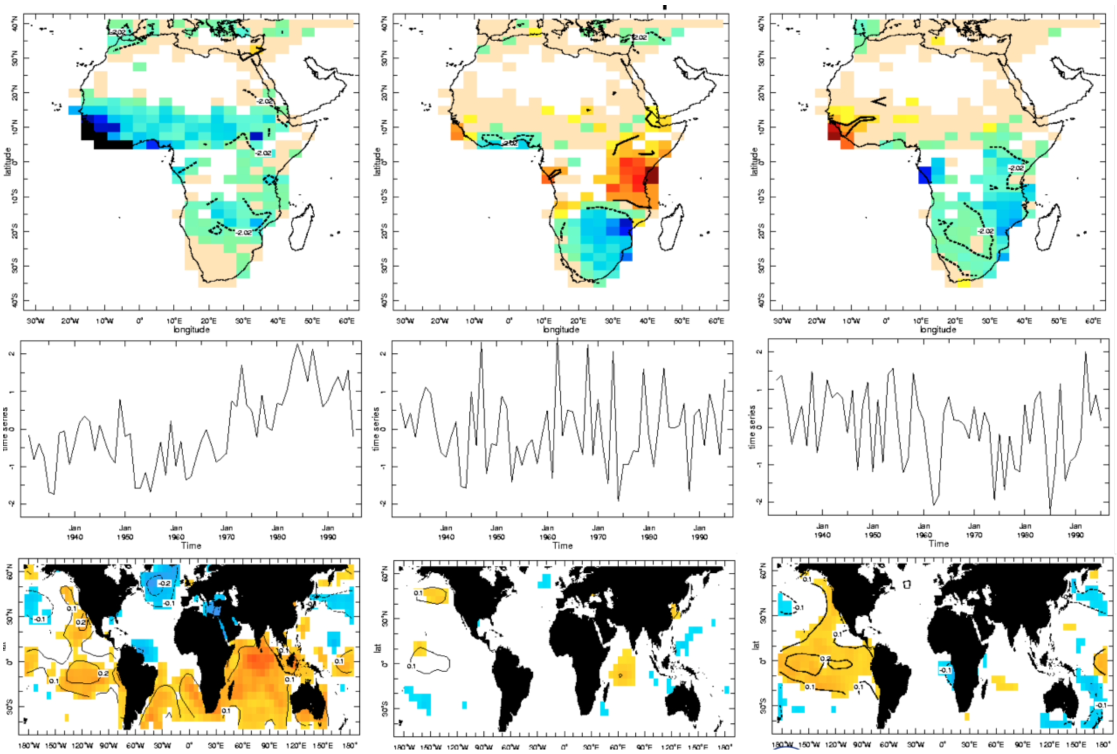

*Figure 2 (from Giannini et al 2008): leading spatial patterns of annual mean (July-June) rainfall variability at continental scale, their associated time series, and regression with sea surface temperatures (1930-1995).*

How does a warm ENSO event generally cause tropical drought? It is worth discussing the theory in some detail, because similar processes will be invoked in interpretations of future climate change related to oceanic warming.

The increased energy that is extracted by positive feedbacks in the coupled ocean-atmosphere system in the central and eastern equatorial Pacific (Bjerknes 1969; Cane 1991) not only increases heat content and sea surface temperatures, but is also carried upward through the atmosphere by deep convection, warming up the tropical upper troposphere (Yulaeva and Wallace 1994). The upper-level warming in turn engenders a transient anomaly in vertical stability when the surface outside of the core ENSO region, especially the oceanic surface, takes a finite amount of time to warm up in response to such energy imbalance. This situation leads to a transient top-down increase in vertical stability in regions remote from the core ENSO region, hence a reduction in precipitation (Chiang and Sobel 2002). As a result, ENSO is correlated with the global extent of drought (Lyon 2004).

At times this purely atmospheric response to ENSO that dominates the monsoon regions of the world, including Africa, also affects eastern equatorial Africa, making the association between warm ENSO and increased rainfall that is typical of this region (Ogallo 1989; Schreck and Semazzi 2004) somewhat less reliable than other ENSO teleconnections. Though below-normal precipitation is the less frequent, least expected outcome in warm ENSO years in eastern equatorial Africa, such response to ENSO can be interpreted in the same framework detailed above. It can be found in analyses of observations (e.g. figure 2, taken from Giannini et al 2008), and in simulations. In models (Goddard and Graham 1999), when SSTs are prescribed to evolve as observed in the tropical Pacific basin, and held fixed to climatology in the Indian and Atlantic Oceans, the atmosphere responds with generalized drought in eastern equatorial Africa. The additional prescription of observed variations in the Indian Ocean, or their simulation with a fully coupled ocean-atmosphere model (Bracco et al 2005), results in the more frequent ENSO teleconnection, i.e. increased rainfall in eastern equatorial Africa. In sum, this pattern of increased rainfall can be understood as the integrated response of the upper-level and near-surface temperatures coming into equilibrium, with ENSO fueling the warming of the equatorial Indian Ocean during the “short rains” of October-December, and the attendant increases in moisture convergence over land, and in probability of above-normal rainfall and flooding.

This last description, of the complex interaction of remote and local, atmospheric and oceanic influences associated with the response to ENSO in eastern equatorial Africa, is a good example of the more general situation in tropical Africa, and in regions outside of the core dynamical ENSO region: while ENSO influence is discernible, it rarely stands alone. At times and in places predictability can be improved by consideration of additional patterns of variability tied to oceanic variability. At other times, unpredictable weather patterns give rise to unexpected situations.

Among the latter, the most notable case unfolded during the warm ENSO event of 1997-1998, the warmest of the century. The drought that had been predicted in southern Africa did not happen, due to internal atmospheric variability with origins in the South Atlantic basin (Lyon and Mason 2009). Nevertheless, in the anticipation of drought, farmers were denied loans to buy seed and fertilizer, an example of the perverse, unintended consequences that the asymmetric dissemination of climate information can generate.

An example of the former, i.e. of additional predictability coming from patterns of tropical SST other than ENSO, is the Sahel. Drought did occur In the Sahel in 1997 – the association between warm ENSO and drought in this region has become clearer since the 1970s, as the region shifted to persistently dry conditions. More generally, the influence of ENSO on the Sahel is clearest throughout the 20th century when care is taken to separate it from the SST pattern associated with the long-term shift to dry (Giannini et al 2003): warming of the equatorial Indian Ocean coupled with the development of a north-south gradient in SST in the Atlantic Ocean.

This same pattern of global change – oceanic warming most pronounced in the tropics and southern oceans – is actually part in the continental-scale declining trend in rainfall in Africa: the tendency towards less rainfall that is visible in figure 2, left, not only in the Sahel (in July-September), but also in the Guinea highlands and along the Gulf of Guinea coast (in April-June), and in southern Africa, can be related to this pattern.

## 3. A brief excursus on tropical influences on European climate

Variations in the tropical oceans are also related to shifts in European climate (e.g. Cassou 2010; Scaife 2010; Vitart 2010 in this collection). Are these two independent phenomena, meaning – are tropical SST anomalies at the same time the forcing for anomalies in Sahel precipitation and in the atmospheric circulation over Europe? If one considers the warming of the Indian Ocean, that seems to be the case. The dynamical association between Indian Ocean warming, long-term drying tendency in the Sahel, and persistence of the positive phase of the North Atlantic Oscillation (NAO) that characterized the end of the 20th century has been successfully simulated (Bader and Latif 2003; Hoerling et al 2004). (However, the NAO returned to negative values in the mid-1990s, and was significantly negative this past winter, too, despite continued warming of the Indian Ocean.) In the case of the north Atlantic, there seems to be something more than a statistical relationship between summertime NAO and precipitation anomalies across the Sahel and over Europe (e.g. Folland et al 2009). Cassou et al (2005) report of the evidence for a dynamical relationship between tropical convection and extra-tropical atmospheric circulation in a modeling study: prescribing anomalies in convection in the tropical Atlantic/West African sector as observed during spring and summer of 2003 leads to shifts in the probability of occurrence of regimes that are consistent with the persistence of dry, hot weather over Europe that gave rise to the phenomenal “2003 heatwave”.

## 4. SSTs and projections of rainfall change

Let us now go back to tropical Africa, to consider the relationship between patterns of sea surface temperature and the alternation of wet and dry years, wet and dry decades in the Sahel, because it is exemplary of current efforts to exploit our physical understanding of seasonal predictability to make sense of uncertainty in climate change projections.

We understand the 20th century evolution of Sahelian climate to have been dominated by changes in the oceans, which means that we have the basics for seasonal prediction in this region, institutionalized in the Regional Climate Outlook Forum process (Patt et al 2007). Consideration of the persistence of drought in the Sahel in the context of climate change is justified by two observations: 1) the shift from wet to dry that characterized this region’s climate toward the end of the

20th century was of exceptional severity – an overall~15% decrease in seasonal rainfall total sustained for decades across a region thousands of kilometers wide east to west ("detection" of a signal that lies outside the bounds of "normal" climate variability), and 2) this shift can in no negligible part be linked to warming of the Indian Ocean (Bader and Latif 2003; Hagos and Cook 2008), which is interpreted as an example of the direct effect of greenhouse gases on surface temperatures (Levitus et al 2000; Barnett et al 2005; Du and Xie 2008) ("attribution" of the signal to anthropogenic causes).

The issue is how to reconcile understanding of past drought with divergent projections of future change, especially in light of a recent partial recovery of rains (Nicholson 2005; Ali and Lebel 2009). These inconsistent projections were obtained with the atmospheric components of state-of-the-art models forced with a homogeneous 2K warming (Held et al 2005) and in the IPCC scenarios run with coupled ocean-atmosphere models (Douville et al 2006; Biasutti and Giannini 2006; Cook and Vizy 2006). An atmospheric model that successfully simulates the historical shift from wet to dry when forced with observed SST (Lu and Delworth 2005), also responds with drier conditions to the 2K warming of the global oceans. When in its coupled ocean-atmosphere configuration, it projects drier conditions in the future. Conversely, a model that responds with wetter conditions to the 2K warming of the oceans, in its coupled configuration also projects a wetter future.

One can envision two extreme behaviors (Giannini 2010). If one follows the ENSO analogue argument, then for as long as the system is in a transient state characterized by an imbalance between the upper-level warming and the near-surface response, then dry conditions prevail: greater vertical stability, reduced convection and rainfall, reduced moisture convergence and weakened circulation – the increased net solar radiation and surface warming cannot compensate for the moisture deficit. The complementary situation is an overall wetter state, where vertical stability is determined from the surface – for example, instability driven by increased evaporation forced by an increase in net terrestrial radiation into the surface – the direct influence of anthropogenic greenhouse gases.

To begin to unravel this apparent irreconcilable situation, I should note that warming of the oceans in the real world can lead to contrasting influences on continental climates (figure 3). In the same way that cooling of the north Atlantic contributed to drying of the Sahel, its warming is a beneficial influence. Warming of the Indian Ocean, on the other hand, contributed to the rapid drying observed at the end of the1960s. However, the divergence of model projections in regional rainfall change in the Sahel cannot be explained by differences in the projections of sea surface temperature patterns (Biasutti et al 2008). All IPCC models project a warming of the Indo-Pacific sector, which would contribute a drying tendency in the Sahel following the analogy with ENSO. While such tendency is contrasted in some models by an enhanced warming of the North compared to the South Atlantic, this Atlantic tendency is not consistent with tendency in Sahel rainfall.

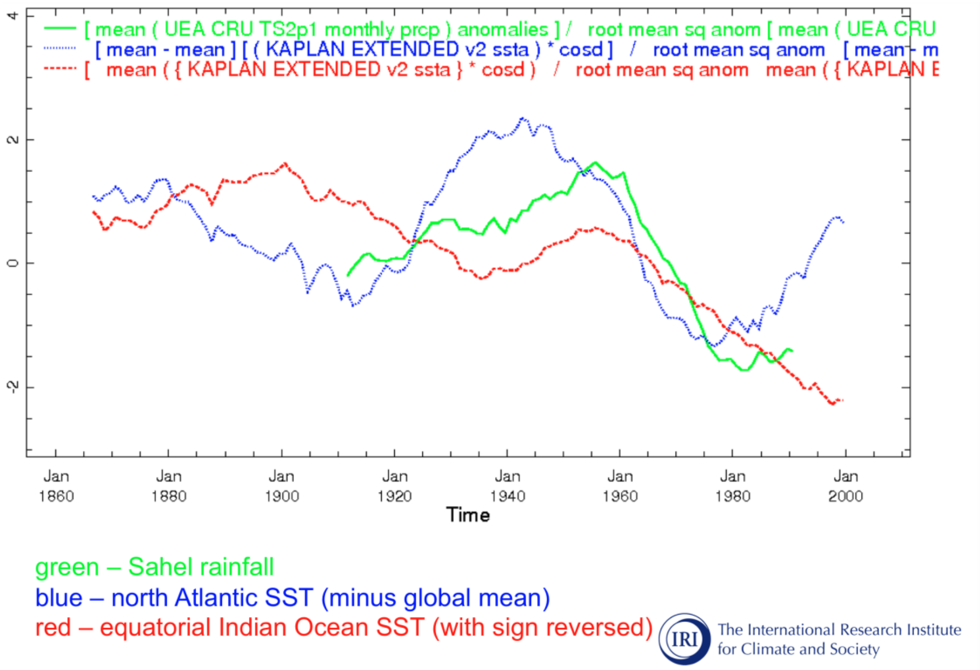


*Figure 3: 21-year running averages of Sahel rainfall (in green), north Atlantic Ocean SST (in blue: averaged over 0-60N, 60W-0E with global mean removed), and Indian Ocean SST (in red: averaged over 15S-15N, 50-90E, with sign reversed). The long-term evolution of Sahel rainfall can be reconstructed satisfactorily given knowledge of north Atlantic and Indian Ocean SST evolutions.*

I propose the following alternative interpretation, yet to be tested, to relate the roles of (north) Atlantic and Indian Oceans to the dynamics of climate change:

- Alternation of warm and cold phases of the Atlantic Ocean affects surface evaporation and moisture supply to the Sahel. If the near-surface atmospheric circulation stays the same in a warming climate, a change in atmospheric moisture content driven by oceanic evaporation may result in changes in near-surface vertical stability and in intensity of rainfall events.

- Warming of the Indian Ocean changes vertical stability from the top down, in a way analogous to the impact of a warm ENSO event discussed above: it leads to oceanic enhancement of convection, to warming of the upper troposphere, and to remote enhancement of vertical stability, or stabilization, over land. This situation may result in reduced frequency of rainfall events in the Sahel.

The fact that despite the uncertainty in projections of total seasonal or annual rainfall there is greater agreement among models that the start of the rainy season may be delayed in the future, resulting in an overall shorter season (Biasutti and Sobel 2010; Seth et al, in preparation) is consistent with the hypothesized dynamics relating the relative influences of Atlantic and Indian Ocean origin with intensity and frequency of events. If the warming of the Indo-Pacific reduces the frequency of rainfall events, then projection of seasonal totals clearly hinges on changes in intensity, or, on the ability of the atmospheric circulation to converge more moisture into the region from the Atlantic. The uncertainty is explained by the competition of mechanisms – will the balance of fewer, but more intense events lead to overall drier or wetter conditions?

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