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Subtropical Indian Ocean SST dipole events and southern African rainfall

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Abstract. An atmospheric general circulation model (AGCM) is used to examine how the regional atmospheric circulation and rainfall over southern Africa respond to a recently observed dipole in subtropical sea surface temperature (SST) over the South Indian Ocean. Observations suggest that when SST is warm to the south of Madagascar and cool off Western Australia, increased summer rains occur over large areas of southeastern Africa. The model results suggest that this SST pattern leads to increased rainfall via enhanced convergence of moister than average air over the region. Increased evaporation occurs over the warm pole in the South West Indian Ocean and this moist air is advected towards Mozambique and eastern South Africa as a result of the low pressure anomaly generated over this pole which strengthens the onshore flow.

Introduction

In a recent GRL letter, *Behera and Yamagata*, [2001 -BY] use UKMO GISST2.3b data [*Rayner et al.*, 1996] to identify subtropical SST dipole events in the South Indian Ocean that are phase locked to the austral summer. Correlations with *Xie and Arkin* [1996] data suggest that when warm SST anomalies occur to the south of Madagascar and cool off Western Australia, summer rains over southeastern Africa are enhanced. BY suggest that the influence on rainfall is related to a weakening of the maritime ITCZ over the Indian Ocean and enhanced moisture transport towards southeastern Africa by stronger southeasterlies. The objective in this study is to use an atmospheric GCM to explore in more detail the atmospheric mechanisms behind the observed rainfall correlations with the SST dipole. The GCM used has previously been applied to climate variability studies in the region and there is confidence in the robustness of its results [e.g. *Rocha and Simmonds,* 1997; *Reason et al.,* 1998].

Attention is paid to the model sensitivity to the location of the warm pole in the South West Indian Ocean and to the presence of the cold pole off Western Australia. Given the significant interannual variability in rainfall over southern Africa and the associated vulnerability of the large rural population to this, there is great local interest in identifying regional SST patterns that may provide some seasonal rainfall predictability.

Model and experiment description

The model used is the Melbourne University GCM, a 9 level spectral model at R21 horizontal resolution with climatological SST forcing taken from *Reynolds* [1988]. Further details of the model and its ability to represent southern African climate are given in *Rocha and Simmonds* [1997]. Three sets of experiments were performed with the GCM forced by different SST anomalies in the South Indian Ocean. In each set, an ensemble of 11 integrations starting from different initial conditions for December 1 and ending on the following April 30 was derived. Set 1 consisted of a SST dipole anomaly with warm pole centred at 35°S, 55°E and cold pole centred at 25°S, 95°E (similar locations to the BY observed composites). In set 2, the centre of the warm pole was moved to 28°S, 42°E (i.e. closer to southern Africa) while in set 3, the cold anomaly was removed so that the SST anomaly consisted of the warm part of the set 2 forcing. In each set, the extent of the Gaussian SST anomalies was similar to BY but the central maximum increased slightly from the BY composite to ±2°C so as to make the response that much clearer. Examination of the UKMO GISST data indicated that

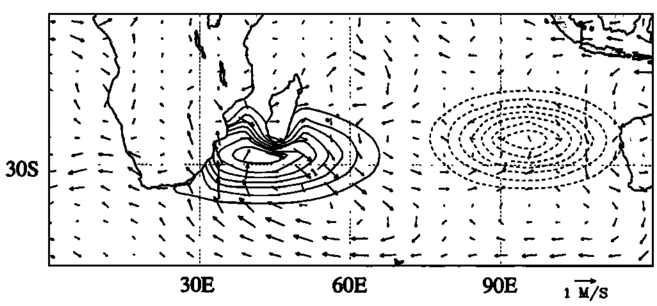

Figure 1. Difference in austral summer (JFM) 850 hPa winds between the ensemble mean of Set 2 experiments and the climatological ensemble. A scale difference vector is shown. Superimposed is the SST anomaly (contour interval 0.25°C, solid (dashed) contours denote positive (negative) anomalies) used in the Set 2 experiments. The associated MSLP difference shows statistically significant (95 %) lower (higher) pressure over the warm (cool) pole.

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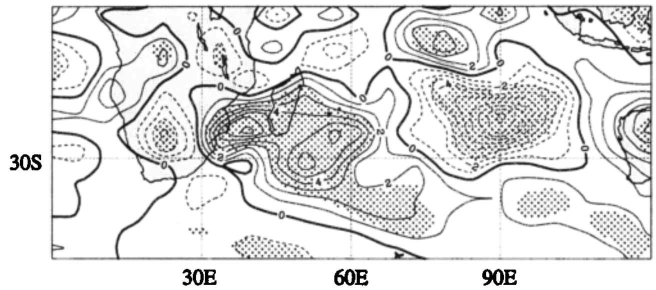

Figure 2. As for Fig. 1 except mixing ratio at 850 hPa. Contour interval is 1×10^{-4} kg/kg and stippling indicates significance at the 95 % level.

some of the six individual austral summers that went into the BY composite had maxima of about 2°C.

Results

The results from the Set 1 and Set 2 experiments are broadly similar except that the response over southern Africa is considerably enhanced in Set 2 in which the centre of the warm pole is just to the southwest of Madagascar (Figure 1) rather than well southeast of this island (Set 1). This result is consistent with previous observational studies [e.g., *Walker,* 1990; *Jury et al.,* 1993] which show significant statistical links between SST in the Agulhas Current region and local rainfall. Attention is therefore focused on Set 2 and on comparison of these with the Set 3 results. Given that the dipole reaches maximum in February [BY], results in each case are presented as the austral summer (JFM) difference between the ensemble mean of SST perturbation runs from an ensemble climatology. Gridpoint t tests are applied for statistical significance of all fields at the 95% level.

Consistent with linear quasigeostrophic theory and previous GCM results [e.g., *Reason,* 2001], a low (high) pressure anomaly which decays with height is generated over, and downstream of, the warm (cold) SST pole. The associated cyclonic wind anomaly over the South West Indian Ocean (Figure 1) evaporates more moisture over the warm pole and enhances the mean summer onshore advection of moisture over eastern South Africa and Mozambique (Figure 2). The divergence field indicates negative anomalies (or relative convergence) of the low level moist airflow over the Mozambique region (Figure 3). The large scale velocity potential field suggests that there is relative enhancement of the local Walker circulation over the western Indian Ocean / southern African region and relative weakening of this cell over northern Australia / Indonesia (Figure 4). At 200 hPa, there are anomalously strong easterlies over low latitude Africa (not shown), a situation that is known from observations [*Tyson,* 1986] to be associated with increased summer rainfall over southeastern Africa.

Although the model is not ideally suited to simulate precipitation since its resolution does not capture the strong local topographic (e.g. Drakensberg) and SST (e.g. Agulhas Current) gradients as well as one would like, this field is presented since it is of much interest to the local community (Figure 5). Consistent with the BY rainfall/SST correlations, the model indicates enhanced summer rainfall over coastal eastern South Africa, Mozambique and Zimbabwe. Accumulated over the season, maximum rainfall anomalies are of order 150-180 mm which is a significant fraction of the seasonal total for summer. Analysis of the surface latent heat flux (not shown) indicates that most of the increased precipitation arises from enhanced evaporation off the warm SST pole and relatively little from either local land-surface evaporation or remote oceanic sources.

For Set 3, the SST forcing differs from Set 2 in that the cold part of the dipole off Western Australia is removed so that the forcing consists only of the warm anomaly east of South Africa. The pattern of the Set 3 circulation changes over the South West Indian Ocean is very similar to Set 2; however, the magnitude is enhanced. Consistent with the strengthened onshore flow of moist air towards the region, the model precipitation anomaly over eastern South Africa and Mozambique is increased over that in the Set 2 experiments. Recall also that the Set 1 results in which the warm SST pole was

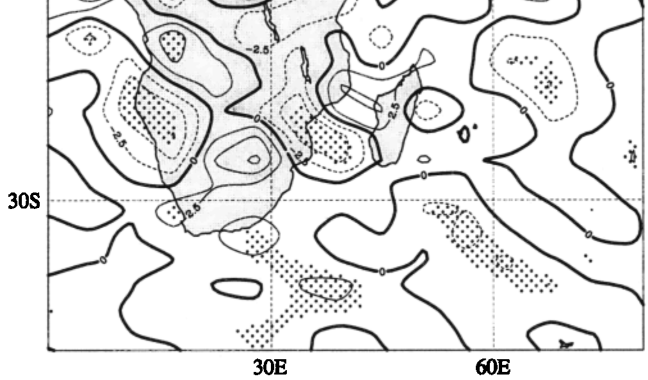

Figure 3. As for Fig. 2 except divergence at 850 hPa. Contour interval is 2.5×10^{-7} s^{-1}.

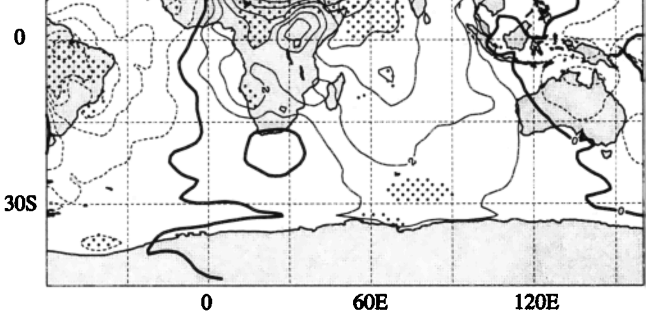

Figure 4. As for Fig. 2 except velocity potential at 850 hPa. Contour interval is 1×10^{5} m^{2}s^{-1}.

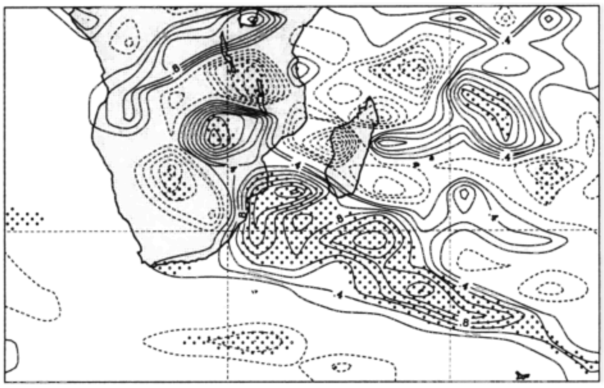

Figure 5. As for Fig. 2 except precipitation. Contour interval is 0.2 mm/day.

located much further east in the South Indian Ocean led to a considerably smaller response in circulation and rainfall over southern Africa.

The model results therefore suggest that it is the warm part of the BY SST dipole, and particularly its proximity to land, that is important for the response over eastern South Africa / Mozambique. Furthermore, these results reinforce previous observational work [e.g. *Walker*, 1990; *Mason*, 1995] which found significant statistical links between South African summer rainfall and SST in the Agulhas Current region.

Further north (i.e. Zimbabwe), comparison of the Set 2 and 3 results suggests that there may be some sensitivity to the cold part of the SST dipole. Set 3 (without the cold pole) shows a weak increase or even a decrease in model rainfall here whereas Set 2 showed a statistically significant increase (Figure 5). The important difference in the circulation fields between these 2 sets is that the relative enhancement of the ascending branch of the Walker circulation is noticeably stronger over tropical southern Africa in Set 2. This results because the dipole SST forcing in Set 2 enhances the zonal SST gradient across the tropical South Indian Ocean and thereby facilitates a relative strengthening (weakening) of the maritime ITCZ over the western (eastern) part of the basin.

Concluding remarks

Three sets of SST anomaly experiments have been performed with an atmospheric GCM. These have been motivated by recent observations [BY] of SST dipole events in the South Indian Ocean which are significantly correlated with summer rainfall over large parts of southeastern Africa. The model results reinforce the [BY] findings but suggest that the response over southeastern Africa is stronger if the warm pole is located closer to the subcontinent, and that the response over the tropical (subtropical) landmass is sensitive (not sensitive) to the cold part of the dipole off Western Australia. In all cases, the model response includes a near-surface low over the warm SST forcing in the South West Indian Ocean, increased evaporation there, and transport of a moister marine airmass towards southeastern Africa where relative convergence and uplift leads to statistically significant increased rainfall.

Although the model grid does not allow fine resolution of the significant topographic and SST gradients in the region, the mechanisms through which the increased rainfall comes about are consistent with observations and provide further support for the [BY] results. Better understanding of the links between rainfall variability and regional SST patterns is of great importance for agriculture and the livelihoods of the large rural population in southeastern Africa and the results of this study help in that goal. To improve the representation of local SST and topographic gradients, future work is aimed at applying a regional climate model to the southern African domain.

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