GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 2, PAGES 327-330, JANUARY 15, 2001

# Subtropical SST dipole events in the southern Indian Ocean

Swadhin K. Behera and Toshio Yamagata[1]

Institute for Global Change Research, FRSGC, Tokyo 105-6791, Japan

**Abstract.** Sea surface temperature (SST) anomalies in the subtropical southern Indian Ocean show interannual dipole events that are seasonally phase-locked to the austral summer. A positive phase of the event is characterized by cold SST anomalies in the eastern part i.e. off Australia and warm SST anomalies in the southwestern part, south of Madagascar. Such an event is found to produce above normal rainfall over many regions in south-central Africa. The cooling of SST in the eastern part is mainly caused by the enhanced evaporation. This is associated with stronger winds along the eastern edge of the subtropical high, which is strengthened and shifted slightly to the south during the event. On the other hand, relative decrease in the seasonal latent heat loss due to reduced evaporation dominates the warming in the southwestern part. Evolution of such subtropical dipole events shows quite a contrast to that of the tropical dipole events discovered recently in the Indian Ocean.

## 1. Introduction

Climate variations in regions around the Indian Ocean have a strong socioeconomic impact because of the large population, and are often linked to El Niño-Southern Oscillation (ENSO) phenomenon in the Pacific. Past studies suggested a statistically inverse relationship between the sea surface temperature (SST) variability in the eastern tropical Pacific and the regional rainfall *e.g.* the southern African rain during austral summer [*Ropelewski and Halpert*, 1987; *Hastenrath et al.*, 1993]. However, ENSO-related changes are not sufficient to explain all the interannual variabilities seen in the observed rainfall of the region. Due to its close proximity, the Indian Ocean may play a greater role in the regional climate scenario. Indeed some studies indicate influence of the Indian Ocean SST on summer rains of the southern Africa [*Ogallo et al.*, 1993; *Jury et al.*, 1996; *Reason and Mulenga*, 1999; *Goddard and Graham*, 1999]. In fact, a correlation between the south-central African rainfall anomaly and the SST anomalies clearly brings out a dipole pattern in the southern subtropical Indian Ocean (Fig. 1). *Behera et al.* [2000] have indicated the presence of such a subtropical dipole pattern in the SST anomalies from both data and model simulation. As it is well known, this region is dominated by the lower tropospheric subtropical high, the center of which migrates seasonally between 30°S and 35°S. Therefore, it is quite likely that atmospheric forcing plays a crucial role in the evolution of the subtropical dipole. We have analyzed such intriguing aspects using multi-source observed data sets.

## 2. Subtropical dipole pattern

In the present study we use SST data from Global Sea Ice and Sea Surface Temperature data set GISST 2.3b [*Rayner et al.*, 1996], surface wind stress and heat fluxes derived from National Center for Environment Predication reanalysis data set [*Kalnay et al.*, 1996] and rainfall data [*Xie and Arkin*, 1996]. We also examine other available datasets such as the Comprehensive Ocean-Atmosphere Data Set that produces essentially similar results. For understanding dominant modes of variability, SST anomalies are decomposed using the empirical orthogonal function (EOF) technique for the subtropical southern Indian Ocean basin between 45°S and the equator. These SST anomalies are departures from a monthly mean climatology for the period 1958-98. The leading EOF mode that explains about 26% of the total variance shows values of single polarity dominating the whole analysis domain. A good correlation between the principal component time series and the Southern Oscillation index (SOI) suggests a possible Indian Ocean warming during Pacific El Niño [*Venzke et al.*, 1997; *Wallace et al.*, 1998].

The interesting subtropical dipole pattern (SDP) oriented in the northeast-southwest direction emerges as the second EOF mode that explains 12% of the total variance (Fig. 2). The resemblance between the dipole pattern of this EOF mode and that of the correlation plot seen in Fig. 1 leads us to construct an index time series. The index (Fig. 3), which is hereafter referred to as the subtropical

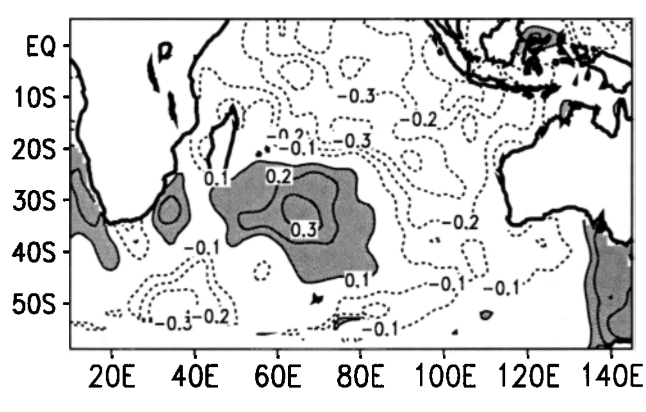


**Figure 1.** Correlation between south-central African rain (22-28°E, 18-12°S) and Indian Ocean SST anomalies for the period 1979-98. Values less than 0.1 are suppressed. A five-month running mean is applied to smooth the time series.

[1]Also at Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan



Paper number 2000GL011451.
0094-8276/01/2000GL011451$05.00

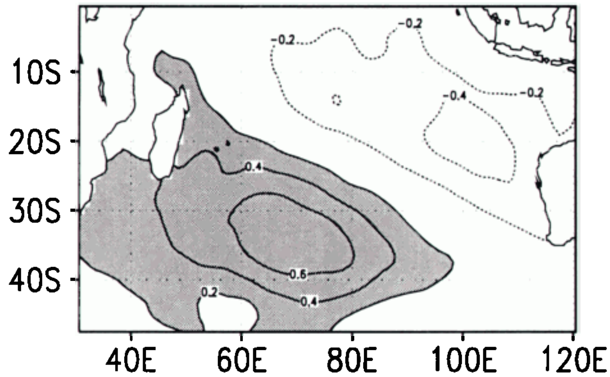


**Figure 2.** Spatial pattern of the second EOF mode. Unit is arbitrary,zero contour is suppressed and positive values are shaded.

dipole index (SDI), is obtained from the SST anomaly difference between the western (55-65$^0$E, 37-27$^0$S) and eastern (90-100$^0$E, 28-18$^0$S) subtropical Indian Ocean. It reproduces the time series of the second EOF mode quite faithfully with a correlation of 0.8. *Reason* [1999] has recently shown warm/cold SST patterns in the southern Indian Ocean. However, the SST pattern described here differs considerably in the location as well as in the orientation. Further, years of positive and negative events are quite different in both the studies. This is mainly because the pattern in his case is close to EOF modes 3 and 4, whereas in our case the pattern is close to the EOF mode 2.

## 3. Evolution of the dipole mode

The positive SDP event is characterized by occurrence of a cold (warm) SST anomaly in the southeastern (southwestern) Indian Ocean (Fig. 4) during the austral summer. The phenomenon itself is quite robust in the subtropical region, although both the place and the time of occurrences vary slightly among individual events. Usually, it develops in December-January, peaks in February and dies down by May-June. However, during certain occasions the event does not die down completely and revives again to become the second consecutive event (*e.g.,* the positive events of 1980-81 and 1981-82).

The mean surface winds in the southern Indian Ocean north (south) of 35$^0$S are predominantly easterly (westerly) in association with the subtropical high. These winds are, however, more southeasterly off Australia during January. This is because the center of the subtropical high shifts eastward during austral summer. Since the Australian landmass is warm with low surface pressure, the resulting pressure gradient along the edge of the subtropical high gives rise to southeasterlies. During the mature phase of the positive SDP event, the subtropical high is strengthened and shifts slightly southward. Moreover, the West Coast Trough that forms over the western Australia during summer months migrates near to the west coast during January-March. This is reflected in the February sea level pressure anomalies shown in the upper left panel of Fig. 5. Therefore, the resultant pressure gradient at the eastern edge of the subtropical high further enhances the southeasterlies (Fig. 4) off the coast of Australia. These pressure anomalies also produce anomalous southwesterlies southwest of Australia. The anomalous southeasterlies in the eastern part (Fig. 4) cause cooling due to increased evaporation (lower left panel of Fig. 5) and upper ocean mixing. It may be noted that a change of 10 W m$^{-2}$ in latent heat loss could lead to a local change of 0.5$^0$C in the SST over a season for a typical mixed layer depth of 50 m, even in absence of other processes.

The deformation in the subtropical high also causes anomalous easterlies around 40$^0$S in February (Fig. 4), leading to the weakening of seasonal midlatitude westerlies. Thus, the related reduction of the seasonal latent heat loss (lower left panel of Fig. 5) leads to the warming of the southwestern part (Fig. 4). In addition, the reduction in the seasonal westerlies may decrease the equatorward Ekman transport of colder high latitude waters, thereby, contributing to the warming. As the austral summer ends, the seasonal atmospheric subtropical high migrates to northwest i.e. south of Madagascar when the Australian landmass cools and an anticyclone establishes over the continent. The associated shift in westerlies and easterlies causes decay of the SDP (Figs. 4 and 5). The situation is just opposite during a negative phase of the SDP (not shown).

## 4. Discussion

The intertropical convergence zone (ITCZ) in the western Indian Ocean lies around 10$^0$S in the mean field during austral summer as the Northern Hemisphere trades intrude into the Southern Hemisphere. The continental ITCZ is

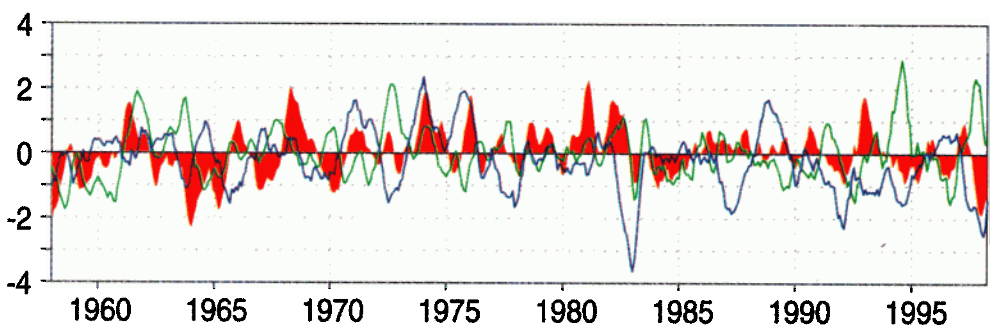


**Figure 3.** Time series of SDI (red), TDM (green) and SOI (blue) from January 1958 to April 1998. Normalized time series are smoothed by a five-month running mean.

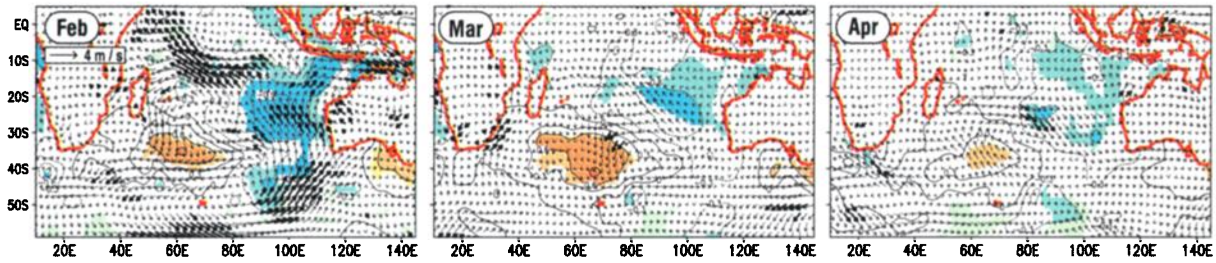


**Figure 4.** Monthly composite of SST anomalies and wind anomalies in February, March and April for six strong recent positive events during 1968, 1974, 1976, 1981, 1982 and 1993. Contour interval is 0.5$^{0}$C. SST anomalies exceeding 90% and wind anomalies exceeding 80% of confidence limits using a two-tailed t test are shaded and represented by bold arrows respectively.

found between Tanzania and central Mozambique during December-February and the SDP event coincides with the principal rainy season. In fact, the SDP events are found to be related with anomalous precipitation in southern Africa. The dipole pattern as found in the correlation plot of Fig. 1 is further confirmed through quite a reciprocal pattern obtained by correlating the SDI with the rainfall anomalies [*Xie and Arkin*, 1996] over the southern Indian Ocean (upper panel of Fig. 6). Positive (negative) correlation is seen over a wide region of southern African landmass (Indian Ocean), which includes parts of Zambia, Mozambique, Zimbabwe, Botswana and South Africa. Studies with atmospheric general circulation model experiments also indicate such positive influence of subtropical Indian Ocean SST anomaly on the African summer rainfall [*Reason and Mulenga*, 1999; *Goddard and Graham*, 1999].

During a positive SDP event, cold SST anomalies are found to be elongated obliquely from the eastern subtropical region to the western tropical region in the southern Indian Ocean (Fig. 4). These cold anomalies weaken the maritime ITCZ by suppressing the atmospheric convergence as inferred from the correlation of rainfall anomalies (upper panel of Fig. 6). Thus, anomalous southeasterlies spread even to equatorial regions off Somalia as seen in the February plot of Fig. 4. The anomalous condition leads to increased tropospheric moisture divergence from the eastern subtropical Indian Ocean during the peak phase (lower panel of Fig. 6). Enhanced lower tropospheric southeasterlies then transport the surplus moisture to the far fetched continental regions in south-central Africa, leading to the moisture convergence there (lower panel of Fig. 6). This gives rise to increased convective activity and anomalous rainfall over those regions.

The situation is just opposite during a negative phase of the SDP. The warmer water associated with anomalous northwesterlies strengthens the maritime ITCZ giving rise to increased precipitation in the maritime region. Further, the cold western pole and the opposite anomalies in lower tropospheric flow result in less precipitation over the regions of southern Africa and southern Madagascar. Here, we presented a chain of events that happen in consequence to each other and suggested that the SDP is a regional phenomenon locked to seasonal march in the southern Indian Ocean. Some recent studies suggest that anomalies in the subtropical high and the associated changes in meridional winds west of Australia and the easterly anomalies in the midlatitude region might actually be related with the Antarctic circumpolar wave [*White and Peterson*, 1996; *Peterson and White*, 1998], which definitely needs further investigation.

It is also interesting to compare the SDP evolution with other tropical phenomena e.g. the ENSO and the recently discovered Indian Ocean tropical dipole mode (TDM)

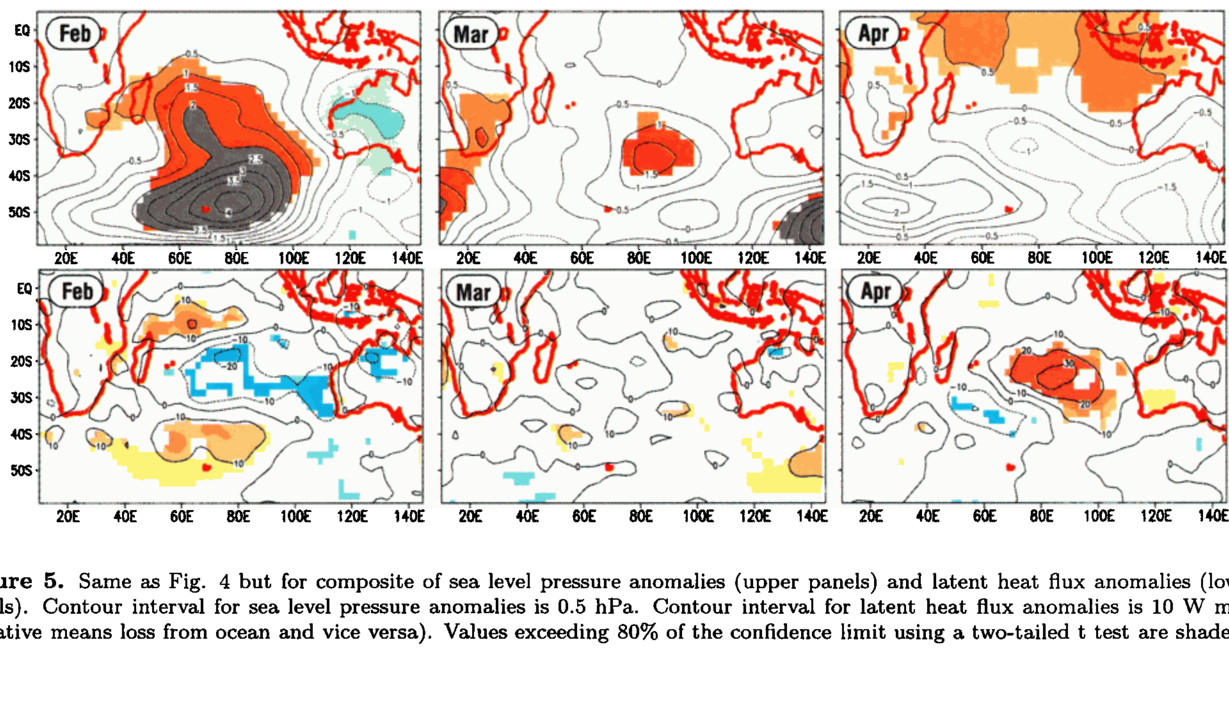


**Figure 5.** Same as Fig. 4 but for composite of sea level pressure anomalies (upper panels) and latent heat flux anomalies (lower panels). Contour interval for sea level pressure anomalies is 0.5 hPa. Contour interval for latent heat flux anomalies is 10 W m$^{-2}$ (negative means loss from ocean and vice versa). Values exceeding 80% of the confidence limit using a two-tailed t test are shaded .

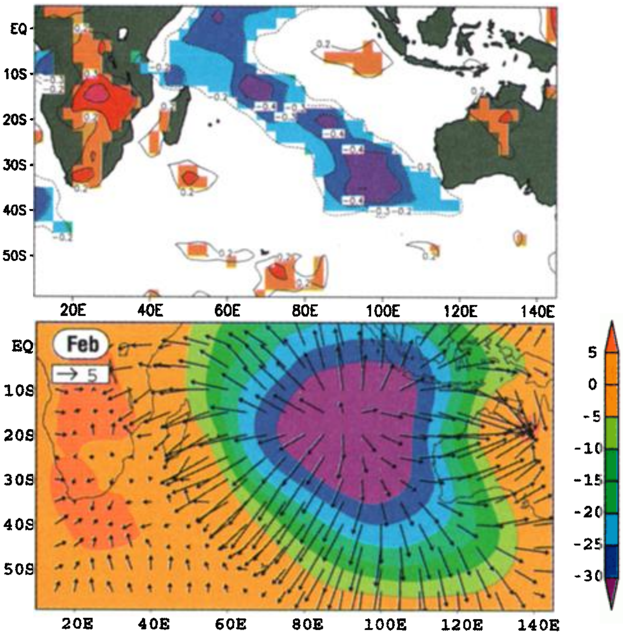


**Figure 6.** Upper panel: Correlation between rainfall anomalies for the period 1979-98 and the corresponding time series of SDI. Values exceeding 99% of confidence limit (with a two-tailed t test) are shaded. Lower panel: The composite of moisture divergence in February for the six events as in Fig. 4. Arrows are divergent ($\vec{Q}_\chi = \nabla\chi_Q$) component of the anomalous tropospheric (surface to 300 hPa.) moisture transport $\vec{Q}$ expressed as kg $m^{-1}$ $s^{-1}$. The scalar $\chi_Q$ (shaded) is the velocity potential expressed in kg $s^{-1}$.

[*Saji et al.*, 1999]. As can be seen from the time series shown in Fig. 3, there is quite a contrast in the evolution of SDI and TDM. However, the positive SDP coincided with La Niña during 1973-74 and 1975-76 and El Niño during 1992-93. Interestingly, during 1997-98, the SDP changed the phase from positive to negative when both TDM and El Niño occurred. On the other hand, strong positive SDP events are seen in absence of the ENSO event during 1967-68, 1980-81 and 1981-82. We also note that a SDP event preceded the strong TDM during 1960-61 when there was no ENSO in the Pacific. These four events, in addition to the SDI's overall weak correlation (~ 0.2) with SOI, suggest that there is a mechanism unique to the southern Indian Ocean. Though external forcings such as that from ENSO could affect some of the SDP events through chain reactions among various atmospheric and/or oceanic processes, it is beyond the scope of the present paper to provide the exact nature of such influences.

The seasonal rainfall in southern Africa is very important for the regional ecosystem and the human population. Therefore, skillful prediction of the interannual variability in the summer rain has a potential value for the crop and water management. Recent studies show the skill of the Indian Ocean SST for the prediction of the crop production in southern Africa [*CLIVAR Africa*, 1999]. The SDP we presented here should provide a meaningful guideline in this context.

**Acknowledgments.** Authors thank T. Matsuno, N. Saji, H. Nakamura, Y. Masumoto, A.S. Rao, Y. Tanimoto and M. Honda for many usefull sugestions. SKB also thanks J.P. McCreary, G. Meyers and W. White for stimulating discussion during the course of the work. H. Watanabe and Y. Yasunaka helped in preparing the figures. An anonymous reviewer provided very useful comments that helped in improving the manuscript.

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S.K.Behera, and T.Yamagata, Institute for Global Change Research, FRSGC, SEAVANS N 7F, 1-2-1 Shibaura, Minato-ku, Tokyo 105-6791, Japan. (e-mail: skb@frontier.esto.or.jp; yamagata@eps.s.u-tokyo.ac.jp)

(Received January 28, 2000; revised June 23, 2000; accepted October 24, 2000.)