Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Influences of ENSO and SST variations on the interannual variability of rainfall amounts in southern Africa

PATRICK VALIMBA[1], PIERRE CAMBERLIN[2], YVES RICHARD[2], ERIC SERVAT[3] & DENIS HUGHES[4]

1 *Department of Water Resources Engineering, College of Engineering and Technology, University of Dar Es Salaam, PO Box 35131, Dar Es Salaam, Tanzania*
pvalimba@hotmail.com

2 *UMR 5080 CNRS Centre de Recherches de Climatologie, Université de Bourgogne, 6 Bd Gabriel, F-21 000 Dijon, France*

3 *IRD, UMR HydroSciences, Maison de Sciences de l'Eau, Université Montpellier II, BP 64501, F-34394 Montpellier cedex 5, France*

4 *Institute for Water Research, Rhodes University, PO Box 94, Grahamstown 6140, South Africa*

Abstract Relationships between southern Africa rainfall, the El Niño-Southern Oscillation (ENSO) and sea surface temperatures (SSTs) were investigated. Principal Components Analysis (PCA) on rainfall amounts established coherent regions. Results of correlation analysis between rainfall and the Southern Oscillation Index (SOI) and regional SST anomalies indicated strong influences of ENSO and the Tropical Indian Ocean and moderate influences of the Southwest Indian Ocean. The ENSO influence was consistently, moderately negative in equatorial Southern Africa during October–January, strongly positive in the Tropical/Subtropical areas during February–April and highest for light and moderate events in the south and for intense events in the north. SSTs in the Tropical Indian Ocean influence light and moderate events, while SSTs close to the region influence heavy events. Sliding correlations indicated changing rainfall–SOI/SST relationships in the mid-1950s which improved the associations, and since the early-1970s which deteriorated or reversed the relationships.

Key words rainfall variability; ENSO; SST; Principal Components analysis; correlation analysis

INTRODUCTION

There have been significant global-scale changes in oceanic and atmospheric conditions in the 1960s through 1970s. They include warming of the tropical Pacific and Indian Oceans in the late 1970s (Wang, 1995; Trenberth & Hoar, 1996), of the southwest Indian Ocean in the 1970s (Trzaska *et al.*, 1996) and of surface air temperatures after 1960. The warming of the tropical troposphere in the 1960s could have contributed to the delayed oceanic warming in low latitudes in the 1970s (Flohn & Kapala, 1989). Some of the consequences are an increase in the frequency and amplitude of warm ENSO events since the mid-1960s (Torrence & Compo, 1998) and changes of rainfall and streamflow characteristics in eastern and southern Africa since the 1960s through to the 1970s (Valimba, 2005). The changes generally led to a declining occurrence of light rainfalls across much of southern Africa, and an increasing occurrence of intense rainfalls particularly in the eastern part of the sub-continent.

To highlight the influence of climate on identified hydrological changes, this study investigates the dynamic nature of relationships between southern African rainfall and climatic variables using seasonal rainfall amounts and the number of raindays in classes of daily amounts (Valimba, 2005). The main questions investigated are:

– In which classes of daily rainfall amounts do ENSO and SST have stronger influences?
– In which parts of southern Africa and in which seasons do ENSO and SST have stronger influences?
– Are lead–lag relationships between rainfall and ENSO/SST stable over time?

DATA AND METHODS

Data

Time series of daily and monthly rainfall at various stations were acquired from various sources: southern African FRIEND database (University of Dar Es Salaam), Department of Water Affairs (Namibia), Computing Centre for Water Research (South Africa) and Tanzania Meteorological Agency. The records were of variable quality and length and selection criteria of period of interest (1950–1990), record length (at least 30 years), continuity (<15% missing) and spatial distribution

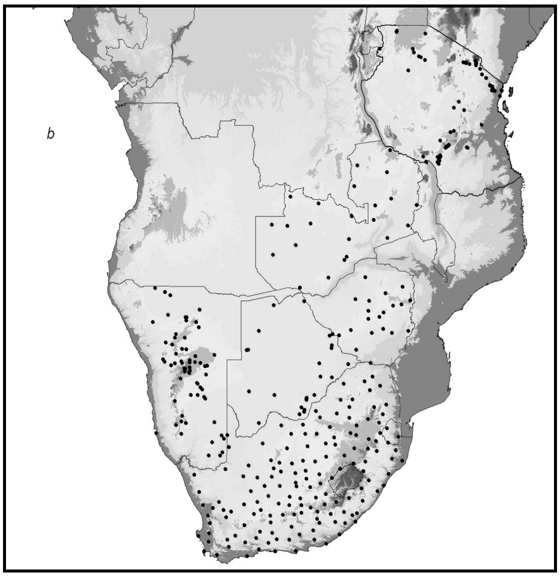

Fig. 1 Spatial distribution of rainfall stations in southern Africa selected for the study.

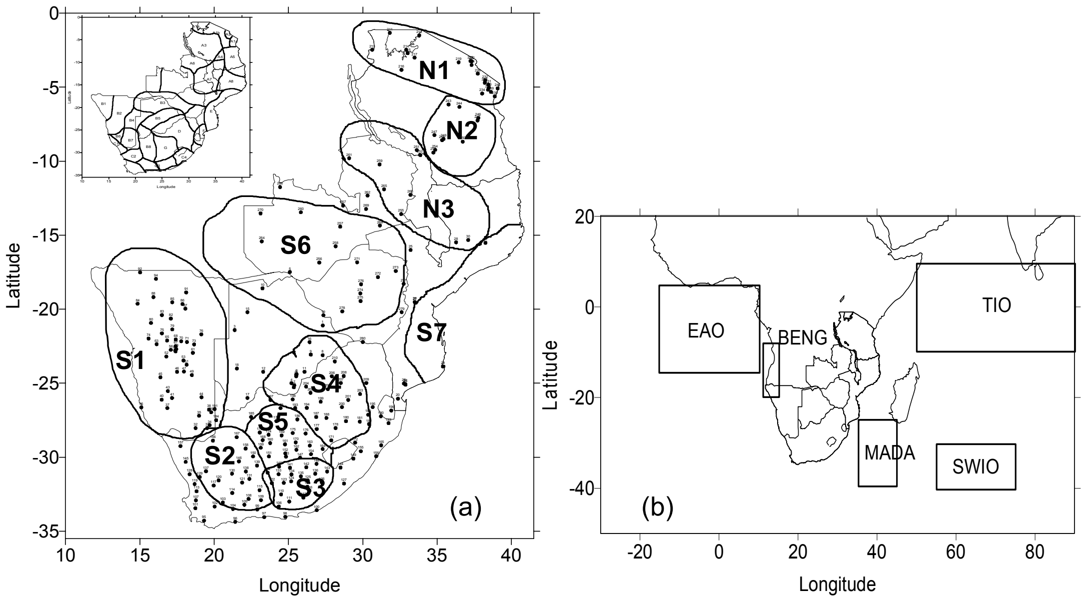

Fig. 2 (a) General coherent clusters from PCA and correlation analysis (Valimba, 2005). (b) Selected oceanic regions in the Atlantic and Indian oceans (Valimba, 2005).

of the stations resulted in 280 stations (Fig. 1) being retained for analysis. Classes of daily rainfall were adopted from Valimba (2005) and include the light rainfall events (class 2; 1–9.9 mm), moderate (class 3; 10–19.9 mm), moderate heavy (class 4; 20–29.9 mm), heavy (class 5; 30–39.9 mm) and extreme heavy (or intense) (class 6; ≥40 mm) events.

ONDJ and FMA seasons were used to define early and late summer seasons. May is omitted from the latter season as atmospheric circulations responsible for rainfall in northern Tanzania at this time resemble those in early summer and differ from March–April (Mutai & Ward, 2000; Camberlin & Okoola, 2003) and May rainfall in the southwestern and southern part of South Africa is predominantly frontal.

Areal average indices of SST anomalies in the key basins of the Atlantic and Indian oceans were used (Valimba, 2005). The regions (Fig. 2(b)) are the Tropical Western Indian Ocean (TWIO), Southwest Indian Ocean (SWIO), Mozambique/Agulhas Currents (MADA), Equatorial Atlantic Ocean (EAO, Phillipon *et al.*, 2002) and Angola/Benguela Front region (BENG), approximately defining the core of extreme warmer SST anomalies during the Benguela Niños (see e.g. Rouault *et al.*, 2003). ENSO seasons (SON, DJF, MAM and JJA; Trenberth & Caron, 2000) were used to compute seasonal SOI values while seasonal SST anomalies were computed for 3-month rainfall (OND, FMA and JJA) ENSO seasons. In the southern regions, correlations between seasonal rainfall and SOI for ENSO seasons (SON/MAM) were slightly less than for rainfall seasons (OND/FMA). Therefore, only correlations between seasonal rainfall and SOI (defined for ENSO seasons) are presented.

METHODS

Principal components analysis (PCA) and correlation analysis were used to establish coherent rainfall regions from seasonal rainfall. For each season, PCA established a few general coherent regions across southern Africa and a comparison of the regions for all seasons retained only eight main coherent regions (Fig. 2(a); Valimba, 2005). Regional seasonal rainfall amounts were computed as arithmetic averages of standardized anomalies at each station. Pearson's correlation coefficients, computed between regional seasonal rainfall indices and monthly/seasonal SOI and SST anomalies for the 1955–1985 period, were used to assess the ENSO/SST–rainfall lead–lag relationships. Absolute correlations exceeding 0.39 and 0.49 are significant at the 95% and 99% levels, respectively.

The stability of ENSO/SST southern African rainfall associations was investigated for the period 1950–1994, using long Namibian and South African records. Since major changes in oceanic and atmospheric variables had occurred in the late-1970s and only 18 years are available for analysis in the post-1977 period, a 15-year window is used to compute sliding correlations between SOI/SST indices and seasonal rainfall indices. Absolute correlations exceeding 0.5 and 0.43 are significant at the 95% and 90% levels, respectively.

RESULTS

ENSO–southern African rainfall relationships

Results show similar influences of ENSO on seasonal rainfall amounts and number of raindays. In general, the results of the correlation analysis between SOI and seasonal rainfall amounts indicate the seasonality of rainfall responses to an ENSO signal and the spatial variation of the responses. This is summarised according to the strength of the response (Fig. 3(a)) and the nature and seasonality of the relationships (Fig. 3(b)). The results further indicate:

(a) **The consistent influences of ENSO on all classes of daily rainfall** The correlations between SOI and rainfall amounts (Table 1) indicate identical responses of rainfall in the different classes to an ENSO signal with the highest influences on classes III and II.

(b) **The spatial variation of rainfall responses to an ENSO signal** The magnitude and significance of the correlations (e.g. Table 1) indicate the strongest ENSO signals in southern African rainfall in the western parts of southern Africa (Fig. 3(a)) and moderate/weak signals in the northern and eastern parts of the region. These results are consistent with those in the past studies (Nicholson & Kim, 1997; Landman & Mason, 1999; Indeje *et al.*, 2000).

(c) **The seasonality of the influences of ENSO** ENSO signals in early summer rainfall are strong in the eastern regions (*S4* and *N1*) and in late summer in the western (*S1* and *S2*) and southern regions (*S3*). An exception is the central interior of South Africa (*S5*) where the influence is significant in both early and late summer. The influence on late summer rainfall in the northern (*N*) regions is low.

(d) **The lead–lag influences of ENSO** It was found that the SON SOI values produced the highest correlations in both early and late summer. Correlations usually peak in SON (Table 1) and decay thereafter. Correlation peaks are found in October (for early summer rainfall), November (late summer class IV–VI), January (late summer, *S* regions) or April (late summer, N2) for the lower classes.

(e) **Changing influence of ENSO on Southern Africa rainfall** The results of sliding correlation analysis indicate significant changes in the ENSO-southern Africa rainfall relationships. The changes are summarized as:

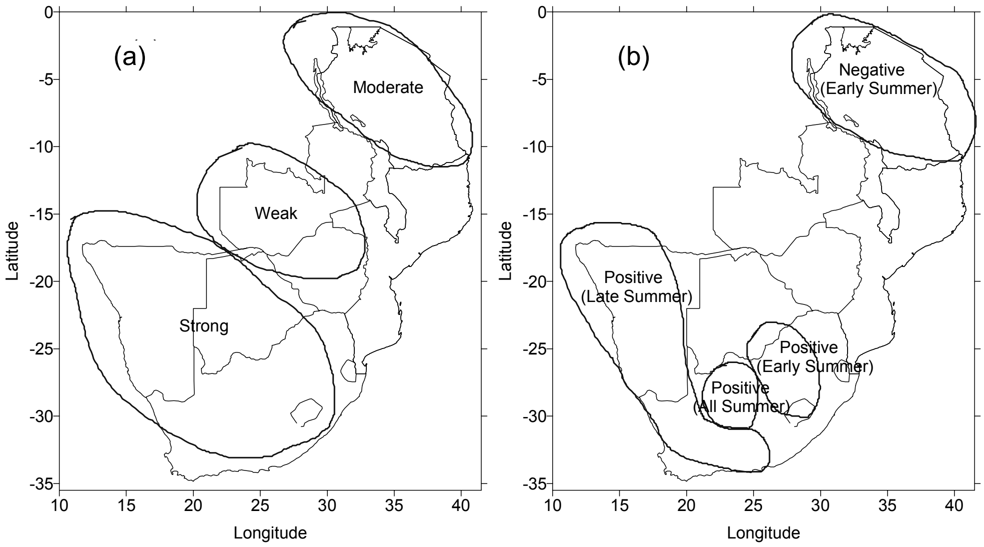

Fig. 3 Generalization of the ENSO-southern African rainfall relationships according to: (a) strength and (b) seasonality and sign of the association with SOI.

Table 1 Correlations between ONDJ and FMA seasonal amounts in southern Africa and seasonal SOI values. Significant correlations at 95% are in bold italics.

Region	Class	ONDJ seasonal amounts against				FMA seasonal amounts against			
		SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF
S1	II	0.12	0.22	0.25	0.04	0.38	***0.50***	***0.67***	***0.54***
	III	0.12	0.27	0.33	0.03	0.38	***0.45***	***0.68***	***0.65***
	IV	0.11	0.27	0.39	0.00	0.35	***0.43***	***0.62***	***0.61***
	V	0.16	0.28	***0.40***	–0.02	0.31	0.36	***0.54***	***0.54***
	VI	0.13	0.27	0.35	0.03	0.14	0.29	***0.48***	***0.43***
	Overall	0.13	0.27	0.35	0.02	0.36	***0.45***	***0.66***	***0.61***
S5	II	0.07	0.31	0.34	–0.08	***0.41***	0.29	***0.54***	***0.57***
	III	0.30	***0.51***	***0.58***	–0.05	***0.50***	0.36	***0.57***	***0.61***
	IV	0.20	***0.42***	***0.47***	–0.06	***0.43***	***0.42***	***0.46***	***0.53***
	V	0.39	0.29	***0.41***	0.14	***0.40***	***0.52***	***0.58***	***0.55***
	VI	0.20	0.22	***0.43***	–0.04	***0.42***	***0.58***	***0.56***	***0.54***
	Overall	0.29	***0.43***	***0.55***	–0.03	***0.49***	***0.50***	***0.60***	***0.63***
N1	II	–0.18	***–0.40***	***–0.41***	0.11	0.09	–0.07	–0.12	0.08
	III	–0.33	***–0.48***	***–0.53***	0.12	0.18	–0.15	–0.14	–0.08
	IV	–0.34	–0.33	–0.38	–0.09	0.17	–0.17	–0.13	–0.10
	V	–0.27	–0.37	***–0.46***	0.07	0.02	–0.29	–0.19	–0.15
	VI	–0.32	***–0.42***	***–0.52***	0.07	–0.06	–0.38	–0.31	–0.25
	Overall	–0.32	***–0.42***	***–0.49***	0.06	0.06	–0.31	–0.24	–0.16

– *Dates and direction of changes*: Significant changes were mainly observed in the mid-1950s and mid-1970s indicating strong ENSO-summer rainfall association in the period 1956/57–1975/76. The relationships weakened or reversed around 1975/76 (Fig. 4(a)). The two extreme dates correspond to periods of re-occurrence of an active ENSO phase in the late-1950s and warming of the tropical Indian and Pacific Oceans around 1976/77.
– *The changing period of influences of ENSO*: Sliding correlations further indicate weakening or reversing influence of ENSO during September–December on early summer rainfall affecting significantly the three higher classes (class IV–VI) (Fig. 4(a)) and steadily increasing influence of ENSO during June-August (e.g. Fig. 4(b)) on late summer rainfall.
– *Implications of the changes*: The change from positive to negative SOI-early summer rainfall associations suggest that post-1975/76 decaying SOI (warm ENSO) corresponds to enhanced early summer rainfall and reduced late summer rainfall.

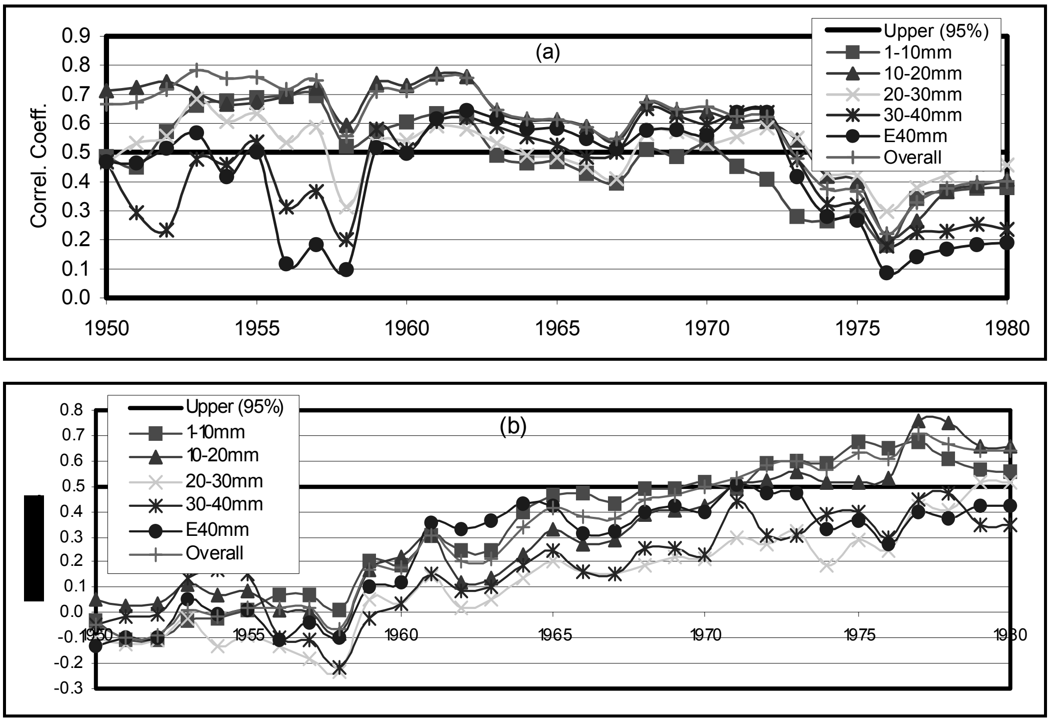

Fig. 4 Temporal evolution of correlations between seasonal rainfall and SOI: (a) FMA seasonal number of events and DJF SOI in S5 and (b) FMA seasonal number of events and MAM SOI in S2. Absolute correlations exceeding 0.50 are significant at 95%.

Table 2 Correlation coefficients between seasonal rainfall amounts in southern Africa and seasonal SST anomalies. Significant correlations at 95% ($r > 0.39$) are bolded. MA = MADA, SW = SWIO, TW = TWIO, EA = EAO and BE = BENG.

Region	Class	ONDJ Seasonal amounts against					FMA Seasonal amounts against				
		MA_OND	SW_OND	TW_OND	EA_OND	BE_OND	MA_FMA	SW_FMA	TW_FMA	EA_FMA	BE_FMA
S1	II	0.21	0.10	–0.18	0.01	0.04	0.34	0.11	***–0.59***	0.05	0.18
	III	0.11	0.05	–0.19	0.00	0.06	0.39	0.20	***–0.57***	–0.04	0.11
	IV	0.09	0.08	–0.22	–0.04	0.04	0.36	0.19	***–0.52***	–0.10	0.04
	V	0.04	0.09	–0.20	–0.03	0.00	0.28	0.18	***–0.40***	–0.29	–0.15
	VI	0.04	0.10	–0.23	–0.03	0.05	0.28	0.04	–0.36	***–0.47***	–0.27
S5	II	0.28	0.04	*–0.36*	–0.02	0.20	0.14	0.13	–0.36	–0.18	–0.06
	III	0.15	0.14	***–0.53***	–0.20	0.12	0.26	0.22	–0.38	–0.02	–0.03
	IV	0.01	0.04	***–0.52***	–0.05	0.11	0.18	0.30	–0.29	0.02	0.00
	V	0.11	0.22	***–0.44***	0.04	–0.05	0.29	0.37	–0.31	–0.24	–0.12
	VI	0.14	0.10	*–0.32*	–0.19	–0.05	0.24	0.19	–0.34	–0.19	–0.08
N1	II	–0.24	–0.05	*0.35*	0.10	–0.04	–0.27	–0.11	0.23	–0.15	–0.08
	III	–0.09	0.02	***0.57***	0.23	0.05	–0.38	–0.29	0.14	–0.21	–0.02
	IV	–0.03	0.06	***0.47***	0.19	0.11	–0.07	–0.08	0.14	–0.24	–0.18
	V	–0.09	0.04	***0.47***	0.16	0.08	–0.06	–0.12	0.25	–0.35	–0.29
	VI	–0.02	–0.04	***0.60***	0.20	0.10	–0.14	–0.24	0.32	–0.13	–0.14

SST–southern African rainfall relationships

Results of correlation analysis between classed seasonal amounts and SST in the Atlantic and Indian Ocean basins (e.g. Table 2) mainly indicate the dominant influence on heavy rainfall events of SST in the Tropical Western Indian Ocean (TWIO) and moderate influence of SST in the south Madagascar (MADA) basin. The influence of TWIO SST are positive in the northern regions and negative in the southern regions while that of MADA is generally the opposite. SST in other oceanic basins show low correlations with southern African rainfall. In the northern regions, the influence of SST is almost consistent for all classes but peaks for the higher classes. In the southern regions, the lower classes of daily intensities are predominantly influenced by the SST in

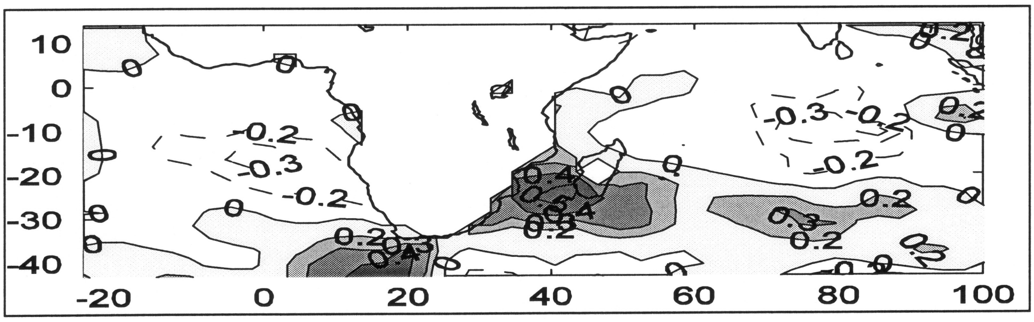

Fig. 5 Correlations between OND SST and S6 (Zambezi) regional ONDJ seasonal amounts. All correlations exceeding 0.39 are significant at 95%.

the tropical Indian Ocean, which are known to modulate regional scale atmospheric dynamics, notably the Walker and Hadley cells. However, the influence generally decreases with increasing intensities suggesting the increasing role of local or regional scale influences on heavy rainfall events (e.g. Fig. 5).

The results of sliding correlation analysis are almost identical to those obtained with SOI which indicate changes in the SST-rainfall associations in the 1956–1966 and 1970–1978 periods. In general, the changes which involve SST in the Indian Ocean basins occurred mainly in the 1970s. The changes in the early-1970s were evident in the relationships involving JJA SST in the TWIO basin and OND SST in the MADA basin. The post-1970 relationships are predominantly positive.

In late summer, the changes involving TWIO SST led to positive associations after the mid-1970s while those involving SST in the two southwest Indian Ocean basins (MADA and SWIO) led to generally negative associations for FMA SST. The influence of SST in the two Atlantic Ocean basins (BENG and EAO) has remained generally insignificant and relatively unaltered.

Increasing influences of the austral winter (JAS) SST and decreasing influences of the austral spring (OND) SST in these three Indian Ocean basins on summer rainfall in southern Africa were observed. This is suggesting a probable shift of the influence from the austral spring to austral winter, increasing the SST lead favourable for forecasting purposes.

CONCLUSIONS

Results show that interannual variability of rainfall in southern Africa is mostly influenced by ENSO and SST in both the tropical Indian Ocean basin and south/southwest Madagascar Ocean basins. The influences of ENSO are consistent in all types of rainfall events and highest in the light (<20 mm) events, and form a dipole-like response of rainfall between the northern and southern part of southern Africa, are moderately negative during the early summer in the north and strongly negative in late summer in the south and have changed since the mid-1970s leading to an increasing influence of the austral winter SOI and decreased or changed associations for austral spring SOI.

The influences of SST in the Indian and Atlantic Oceans indicated the dominance of SST in the tropical Indian Ocean on the interannual variability of rainfall in the region, that the interannual variability of the light/moderate (<20 mm) daily rainfalls is modulated by large-scale influences of the Indo-Pacific signals while regional SST in the south/southwest Madagascar were found to have a considerable influence on heavy daily events. SST in the tropical Indian Ocean have an inverse relationship with rainfall in the southern part and a direct relationship with rainfall in the north, while SST in the south Madagascar basin show the opposite influence

Evolving long-lead SOI/SST–summer rainfall associations in Namibia and South Africa offer the possibility of using SOI and SST as predictors of summer rainfall in these countries. But one should also be cautious when constructing summer seasons as the early and late summers displayed opposing interannual patterns of variability.

Acknowledgements This paper is an extract from the PhD Thesis of Patrick Valimba and the senior author wishes to thank the Institut de Recherche pour le Developpement (IRD, France) for providing financial assistance.

REFERENCES

Camberlin, P. & Okoola, R. E. (2003) The onset and cessation of the long rains in eastern Africa and their interannual variability. *Theor. Appl. Climatol.* **75**, 43–54.

Flohn, H. & Kapala, A. (1989) Changes of tropical sea-air interaction processes over 30-year period. *Nature* **338**, 244–246.

Indeje, M., Semazzi, F. H. M. & Ogallo, L. J. (2000) ENSO signals in east African rainfall seasons. *Int. J. Climatol.* **20**, 19–46.

Landman, W. A. & Mason, S. J. (1999) Change in the association between Indian Ocean sea-surface temperatures and summer rainfall over South Africa and Namibia, *Int. J. Climatol.* **19**, 1477–1492.

Mutai, C. C. & Ward, N. M. (2000) East African rainfall and the tropical circulation/convection on intraseasonal to interannual timescales. *J. Climate* **13**, 3915–3939.

Nicholson, S. E. & Kim, J. (1997) The relationship of the El Niño-southern oscillation to African rainfall. *Int. J. Climatol.* **17**, 117–135.

Phillipon, N., Camberlin, P. & Fauchereau, N. (2002) Empirical predictability study of October–December East African rainfall. *Quart .J. Royal Met. Soc*. **128**, 2239–2256.

Rouault, M., Florenchie, P., Fauchereau, N. & Reason, C. J. C. (2003) Southeast tropical Atlantic warm events and southern African rainfall. *Geophys. Res. Lett.* **30**(5), 8009, doi: 10.1029/2002GL014840.

Torrence, C. & Compo, G. P. (1998) A practical guide to wavelet analysis. *Bull. Am. Met. Soc.* **79**, 61–78.

Trenberth, K. E. & Hoar, T. J. (1996) The 1990–1995 El Niño-Southern Oscillation event: longest on record. *Geophys. Res. Lett.* **23**, 57–60.

Trenberth, K. E. & Caron, J. M. (2000) The Southern Oscillation revisited: sea level pressure, surface temperatures and precipitation. *J. Climate* **13**, 4358–4365.

Trzaska, S., Moron, V. & Fontaine, B. (1996) Global atmospheric response to specific linear combination of the main SST modes. Part I: Numerical experiments and preliminary results. *Ann. Geophys*. **14**, 1066–1077.

Valimba, P. (2005) Rainfall variability in southern Africa, its influences on streamflow variations and its relationships with climatic variations, PhD Thesis, Rhodes University, Grahamstown, South Africa.

Wang, B. (1995) Interdecadal changes in El Niño onset in the last four decades. *J. Climate* **8**, 267–285.