Simulating drought in Southern Africa using sea surface temperature variations

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Abstract

Changes in atmospheric circulation that produce droughts over South Africa are briefly reviewed, as too are the links between regions of homogeneous sea surface temperature variation in the oceans around Southern Africa and their correlation with rainfall over South Africa. Thereafter sea surface temperature anomaly fields known to be linked to the occurrence of droughts are used to initialise the 4-level CSIRO general circulation climate model to simulate drought over South Africa. Model results are compared with previously developed hypotheses concerning ocean-atmosphere interactions in the region and are shown to be consistent with observations in many important respects.

Introduction

The variability of South Africa's climate has been extensively investigated for many years. A detailed review and synthesis of the characteristics and mechanisms of the variability, particularly that of rainfall is available (Tyson, 1986). Variability may be ascribed to changing synoptic conditions and pressure patterns from scales of a few days to seasons and extended spells of years. Variations in the tropical easterlies and their attendant disturbances exert an important controlling influence on South African rainfall (Tyson, 1984; Harrison, 1984; 1986; Jury and Pathack, 1991; Jury et al., 1991). Likewise, the importance of the El Niño-Southern Oscillation phenomenon (ENSO) in modulating the variability of South African rainfall has been demonstrated (Harrison, 1986; Lindesay, 1986, 1988; Van Heerden et al., 1988; Mason and Lindesay, 1993). Changes in the wave configuration and frequency of westerly Rossby waves are other factors of fundamental importance in controlling the variability of rainfall south of about 20°S over the subcontinent (Tyson, 1981; Steyn, 1984; Harrison, 1986; Jury and Levey, 1993). Over the last few years increasing recognition has been given to the importance of sea surface temperature changes in regulating the atmospheric circulation and rainfall over Southern Africa (Gillooly and Walker, 1984; Walker and Mey, 1986; Nicholson, 1986, 1989; Nicholson and Entekhabi, 1987; Walker, 1989, 1990; Mey et al., 1990; Walker and Lindesay, 1989; Brundrit and Shannon, 1989). The most recent and detailed treatment of this subject has been Mason's principal components analysis of Atlantic and Indian Ocean sea surface temperatures and the linking of changes in these to rainfall variability over South Africa (Mason, 1992, 1993 a,b).

In this paper the latest findings on how sea surface temperatures in the oceans adjacent to Southern Africa affect South African rainfall will be reviewed. In addition, simulations using the Australian 4-level, mixed layer (slab ocean) CSIRO general circulation climate model, initialised with regional sea surface temperature anomalies associated with late summer (January to March) drought over Southern Africa, will be presented and compared with observations and previously developed ideas.

Links between regional sea surface temperatures and South African rainfall

Previous research has shown that during periods of within-season drought, as well as during dry spells extending over years, pressure throughout the atmosphere over Southern Africa tends to rise, while falling to the south and south-west (Miron and Tyson, 1984). At the same time anomalous divergence and subsidence occur over the subcontinent (Tyson, 1986). Upper-level standing waves in the westerlies are displaced eastward with the preferential locality for the occurrence of trough lines shifting from the west to the east coast region, or even out to sea to the east of Natal (Steyn, 1984; Harrison, 1984; Tyson, 1986; Jury and Levey, 1993). At the same time tropical easterly flow weakens (Tyson, 1981; Harrison, 1986; Jury and Pathack, 1991; Jury et al., 1991), tropical-temperate troughs occur further to the east (Harrison, 1984, 1986; Lindesay, 1988; Jury and Levey, 1993), the locus of occurrence of cloud bands associated with tropical- temperate troughs moves eastward off the continent and over the western Indian Ocean (Harrison, 1986; Lindesay, 1988), the westerlies strengthen south of Africa (Harrison, 1986; Jury and Levey, 1993), particularly in the vicinity of Marion Island (Harrison, 1986), and tracks of weaker mid-latitude storms shift northward (Harrison, 1986; Tyson, 1986). These changes are illustrated schematically in Figs. 1 and 2.

Sea surface temperatures around South Africa vary characteristically during dry summers in a pattern first identified by Walker (Walker, 1990) (Fig. 3). Principal components analysis (Mason, 1992; 1993 a,b) reveals that the pattern of warming and cooling of the oceans around South Africa (Fig. 4) is more complicated than shown by Walker. Eight principal components have been found to explain 75% of the sea surface temperature variability over the period 1910 to 1989 (Table 1). The effect of this variability on South African rainfall is, however, complicated. Those areas of the ocean in which the greatest variability in sea surface temperature occurs do not necessarily have the greatest effect on rainfall, if any effect at all. An example is the Benguela system (PC 1) which explains most ocean temperature variability (17,3%). In some areas of the Northern Transvaal the system appears to explain up to 16% of the rainfall variability when the effect of the Quasi Biennial Oscillation (QBO) is ignored and up to 49% when the QBO is in its easterly phase. (The QBO (having a periodicity of around 2 years) is associated with the periodic reversal from easterly to westerly of equatorial stratospheric winds in the region

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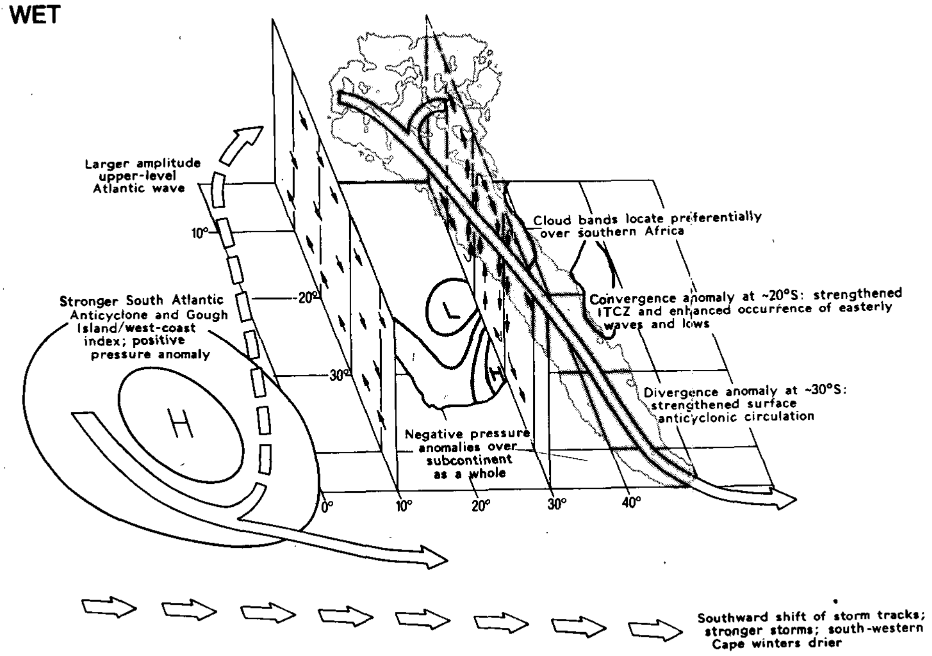


Figure 1

A model of the anomalous atmospheric circulations over Southern Africa during spells of years of predominantly wet conditions. The relative positions of the upper tropospheric Atlantic wave, preferred zones for cloud-band formation, the surface manifestations of the South Atlantic Anticyclone and locations of storm tracks are also shown (after Tyson, 1986).

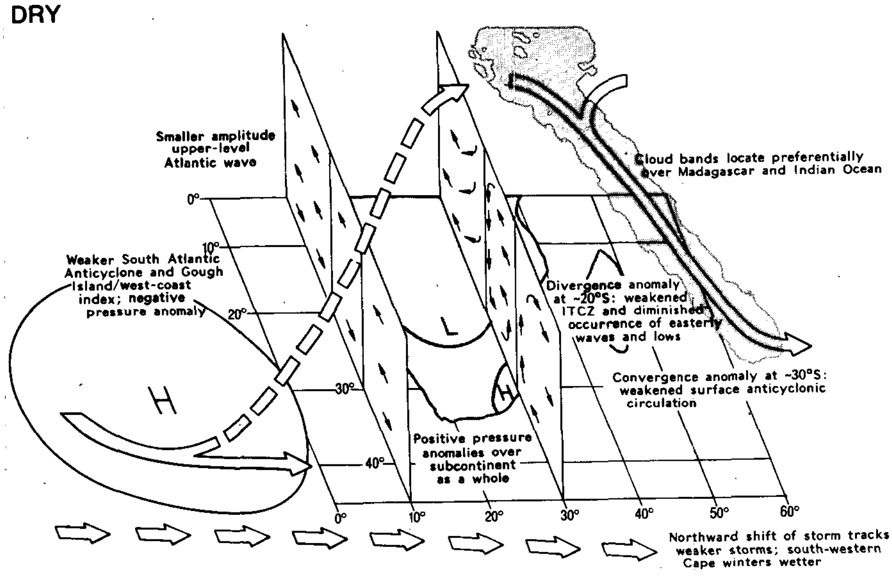


Figure 2

A model of the anomalous atmospheric circulations over Southern Africa during spells of years of predominantly dry conditions. The relative positions of the upper tropospheric Atlantic wave, preferred zones for cloud-band formation, the surface manifestations of the South Atlantic Anticyclone and locations of storm tracks are also shown (after Tyson, 1986).

of the 50 hPa level). However, the areas with an apparent rainfall response are localised. More importantly, the statistical field significance (Livezey and Chen, 1983; Mason, 1992) between PC 1 and rainfall for the summer rainfall region as a whole is less than 0,90. Thus the negative correlation between sea surface temperature variability in the Benguela system and rainfall in the summer rainfall region is not significant and must be discounted.

Ranking the rainfall response to sea surface temperature variability over all years in the period 1953 to 1989 in terms of its statistical field significance for the summer rainfall region as a whole, it is changes in the central South Atlantic Ocean temperatures (PC 5), those of the South Atlantic subtropical convergence region (PC 8) and those of the western equatorial Indian Ocean (PC 4) which have the greatest effect on South African rainfall. (Table 1). The atmospheric response to sea surface temperature anomalies in these regions is not always consistent. One possible reason for this is a modulating effect exerted by the QBO (Gray and Sheaffer, 1991). There is evidence showing that this is so over Southern Africa (Mason, 1992; Mason and Lindesay, 1993; Jury and Pathack, 1993).

If the period 1953 to 1989 (this period has been used in the principal components-rainfall correlation analyses since it is the longest period for which QBO data is available) is stratified into years when the QBO was either easterly or westerly (approximately 18 years of each), then the ocean region associated with the strongest rainfall response is the Indian Ocean south-east of South Africa (PC 7 - QBO easterly), followed by the South Atlantic subtropical convergence region (PC 8 -QBO westerly) and the Agulhas system, (PC 2 - QBO westerly). If the rainfall responses to regional sea surface temperature variations are ranked according

TABLE 1
JANUARY-MARCH RAINFALL VARIANCE IN THE SUMMER RAINFALL REGION ACCOUNTED FOR BY VARIATIONS IN JFM SEA SURFACE TEMPERATURE WITH AND WITHOUT THE PHASE OF THE QBO TAKEN INTO ACCOUNT, RAINFALL VARIANCE IS GIVEN AS THE SQUARE OF THE CORRELATION COEFFICIENT OF THE HIGHEST CONTOURS IN AREAS WHERE THE CORRELATION HAS A POINT SIGNIFICANCE GREATER THAN 0,90, THE STATISTICAL FIELD SIGNIFICANCE, SFS, FOR THE REGION AS A WHOLE IS ALSO GIVEN

Principal component	**Area of occurrence**	**% SST variance**	**% rainfall variance; sign of correlation (); sfs for region ()**		**% rainfall variance with phase of QBO (); sign of correlation () sfs for region ()**		**Area where effect most pronounced**
1	Benguela system	17,3	16 (-)	(not sig.)	49 (E) (-)	(not sig.)	N, Transvaal
2	Agulhas system	13,0	16 (+)	(not sig.)	16 (W)(+)	(>,90)	Cape, Transkei, parts of Transvaal
3	NE Brazil coast	11,3	9 (-)	(not sig.)	16 (W)(-)	(not sig.)	Scattered
4	Western equatorial ocean	7,5	16 (-)	(>,94)	49 (E)(-) 25 (W)(-)	(not sig.) (not sig.)	NE regions
5	Central S Atlantic Ocean	7,4	16 (-)	(>,97)	16 (W) (-)	(not sig.)	S Cape coastal and adjacent inland areas
6	S Brazil Coast	7,1	(16 (+)	(not sig.)	16 (E,W) (+)	(not sig.)	
7	Indian Ocean SE of S Africa	6,2	4 (-)	(not sig.)	36 (E) (-) 16 (W) (+)	(>,99) (>,90)	NW-SE band, Cape Prov NW-SE band, Cape Prov
8	S Atlantic subtropical convergence region	5,2	16 (+)	(>,96)	25 (W)(+)	(>,96)	S Cape coastal and adjacent inland areas

to the degree of significance of the correlation between sea surface temperature and rainfall for the 3 cases taken together (i.e. QBO not taken into account, QBO easterly and QBO westerly), then the strongest association between sea surface temperature variability regions and a summer rainfall response on land is that with the Indian Ocean to the south-east (PC 7 - QBO easterly), followed by the central South Atlantic (PC 5 - unstratified), the South Atlantic subtropical convergence region (PC 8 - unstratified), the western equatorial Indian Ocean (PC 4 - unstratified) and the Agulhus system (PC 2 - QBO westerly).

As the Indian Ocean to the south-east of South Africa (PC 7 region) warms and cools so the pattern of baroclinic westerly waves over the country adjusts. Anomalous warming is associated with an eastward movement of the locus of most frequent occurrence of upper-level wave troughs (Fig. 5). The summer rainfall region becomes drier to the west of the upper trough (consequent upon enhanced divergence and subsidence of air on the trailing side of the trough). The pattern of rainfall association with sea surface temperature variations in the Central South Atlantic Ocean (PC 5)

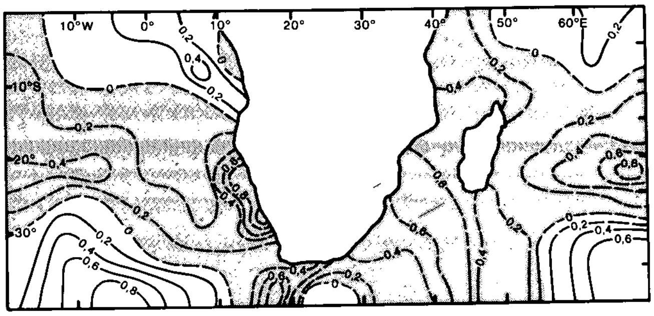


Figure 3
*Composite sea surface temperature differences, °C, between dry and wet late summer seasons in the eastern summer rainfall region (**Southern Oscillation influences excluded**). Anomalously high sea surface temperature differences are indicated by solid lines and anomalously low temperatures by broken lines. Negative differences are shaded (adapted from Walker, 1990).*

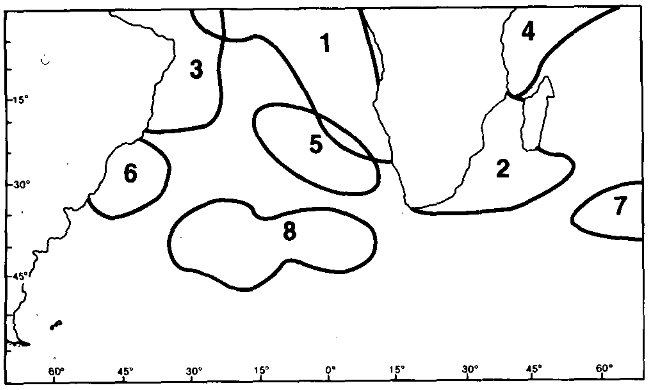
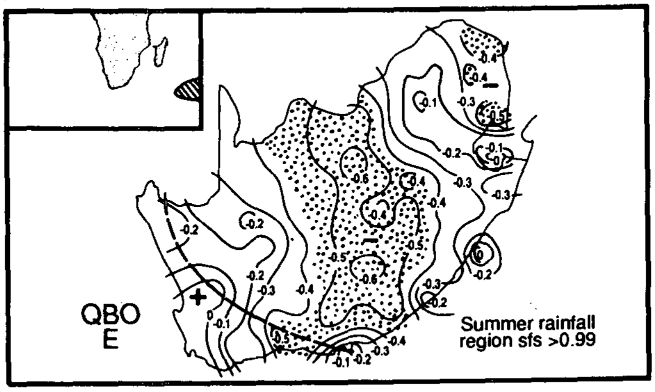


Figure 4
Core areas of sea surface temperature coherence as determined from principal components analysis with varimax rotation (after Mason 1992; 1993a).

a) Correlation between SST and rainfall



b) Circulation pattern

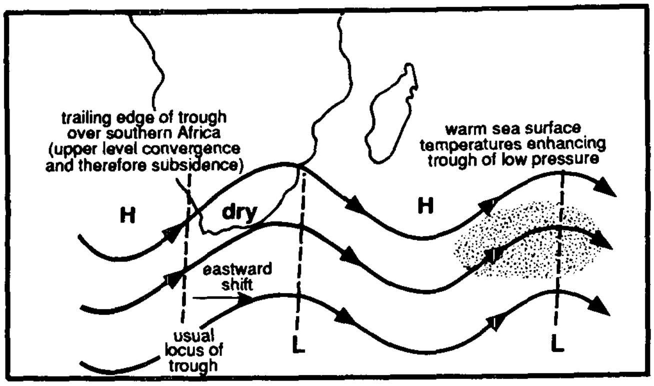
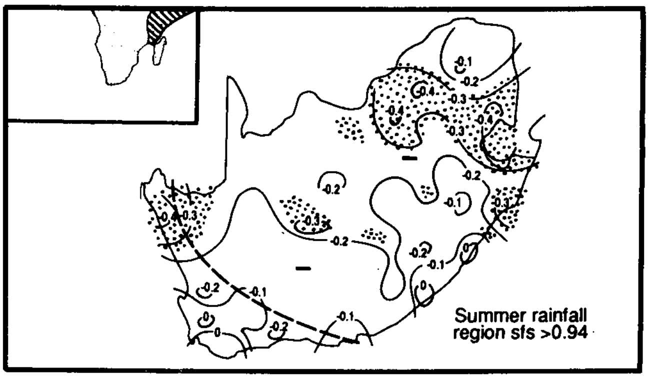


Figure 5
a: Correlations between January-February-March sea surface temperature principal component scores in the ocean to the east and south-east of South Africa (PC 7 region) and rainfall. Areas locally significant at the 90% level are shaded. Where the summer rainfall region as a whole has a statistical field significance (sfs) exceeding 0,90, this has been indicated.
b: Envisaged circulation adjustments associated with warm events in the region.

suggests that atmosphere-ocean interactions produce changes in the South Atlantic anticyclone or in baroclinic westerly wave configurations that affect rainfall over the subcontinent. Either a shift in the position of standing wave 3 of the Southern hemisphere circulation or a change from a wave 3 to a wave 6 pattern would produce a diminution of summer rainfall in association with a warming of the ocean in the specified region. Temperature change in the South Atlantic subtropical convergence region (PC 8) likewise appear to be modulated with the baroclinic westerly waves, in this case in such a way that warming of the ocean surface is linked to a significant increase in rainfall over the summer rainfall region, but only when the QBO is westerly. Warming of the western equatorial Indian Ocean (PC 4) causes pressure to fall over the ocean forming a tropical low or barotropic easterly wave situated over the area (Fig. 6). This occurs irrespective of whether the QBO is easterly or westerly and has the effect of shifting tropical convection patterns eastward. Tropical-temperate troughs form further to the east and the major cloud bands linking tropical and temperate regions and their attendant rainfall bands also shift eastward. Rainfall diminishes over South Africa and droughts may occur. Finally, as sea surface temperatures in the Agulhus region (PC 2) increase, so an enhanced moisture flux may occur over northern areas via the tropical easterlies. (Walker, 1990; Jury et al., 1993). Further to the south the strengthened sea surface temperature gradient encourages increased cyclogenesis. The question of variability of moisture fluxes over Southern Africa during wet and dry periods is considered in detail elsewhere (D'Abreton, 1992; D'Abreton and Lindesay, 1993; D'Abreton, and Tyson, 1993).

a) Correlation between SST and rainfall



b) Circulation pattern

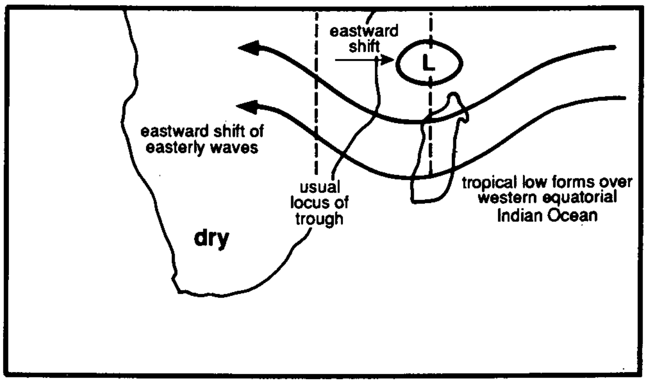


Figure 6
a: Correlations between January-February-March sea surface temperature principal component scores in the western equatorial Indian Ocean (PC 4 region) and rainfall. Areas locally significant at the 90% level are shaded. Where the summer rainfall region as a whole has a statistical field significance (sfs) exceeding 0,90, this has been indicated.
***b**: Envisaged circulation adjustments associated with warm events in the region.*

Simulating droughts over South Africa

The conceptual model given in Figs. 1 and 2 and the subsequent hypotheses arising from observed links between sea surface temperature anomalies and rainfall over Southern Africa may be tested using general circulation models. One such model now being used in South Africa is the Australian CSIRO 4-level R21 general circulation model (Gordon and Hunt, 1991), which couples the atmosphere to a mixed layer ocean in which heat transport occurs. The model is by modern standards not a particularly complex one in that it only uses a limited number of layers and is not fully coupled to a circulating ocean. Thus it cannot begin to address the full complexity of ocean-atmosphere interactions in the real world. However, it is useful for testing hypotheses and has the benefit of being able to run on small super computers such as the Convex C-120 and C-210. It remains a useful, indeed powerful, tool in the quest for a better understanding of the South African climate system. In the model a moist convective adiabatic adjustment is used to treat the convective process and a diurnal cycle is incorporated. Clouds are given fixed properties which are determined by relative humidity or condensation. Further details of the model are available (Gordon and Hunt, 1991; Smith and Gordon, 1992). The model has been used to simulate the atmospheric effect of perturbing sea surface temperature fields around Southern Africa (Lindesay, 1992) and for simulating rainfall responses to sea surface temperature changes (Lindesay and Smith, 1993; Tyson et al., 1993; Lindesay et al., 1993).

The model was initialised using sea surface temperature anomaly fields that represent an annual cycle with peak anomalies in February. The sea surface temperature is presented as a boundary condition and the ocean does not react subsequently to any induced anomalous atmospheric circulation or wind stress. The complexity in the interaction and feedbacks between the atmosphere and ocean thus is not fully addressed by the model. The anomaly fields used in the modelling experiment described here are based on those reported initially by Walker (1989). Following the example of Pitcher et al. (1988), the magnitude of the anomalies has been exaggerated slightly to highlight the resulting atmospheric conditions. An example of the February boundary conditions is given in Fig. 7 (upper left). The reason for using initial conditions based on Walker's work and not Mason's more recently derived sea surface temperature anomaly fields (Mason, 1992; 1993a,b) is that the latter were completed only after the model experiments had been initiated. Indicators of climate such as temperature, pressure, wind, cloud, rainfall, heat flux and soil moisture have been obtained for the late summer (January to March). Each simulation was repeated several times with independent initial atmospheric fields to test the stability of the results and the significance of the derived anomaly fields. Simulations of air temperatures, geopotential heights, heat fluxes, wind components and vectors and soil moisture have been analysed at lower, middle and upper tropospheric levels to assess their consistency with observed features of the climate and its mode of variability as well as for consistency with simulated rainfall anomalies.

The model simulations suggest that as Atlantic and Indian ocean temperatures change in the manner defined in Fig. 7 (upper left), so at 900 hPa a cyclonic circulation anomaly develops to the north-east of Madagascar and the westerlies to the south of the

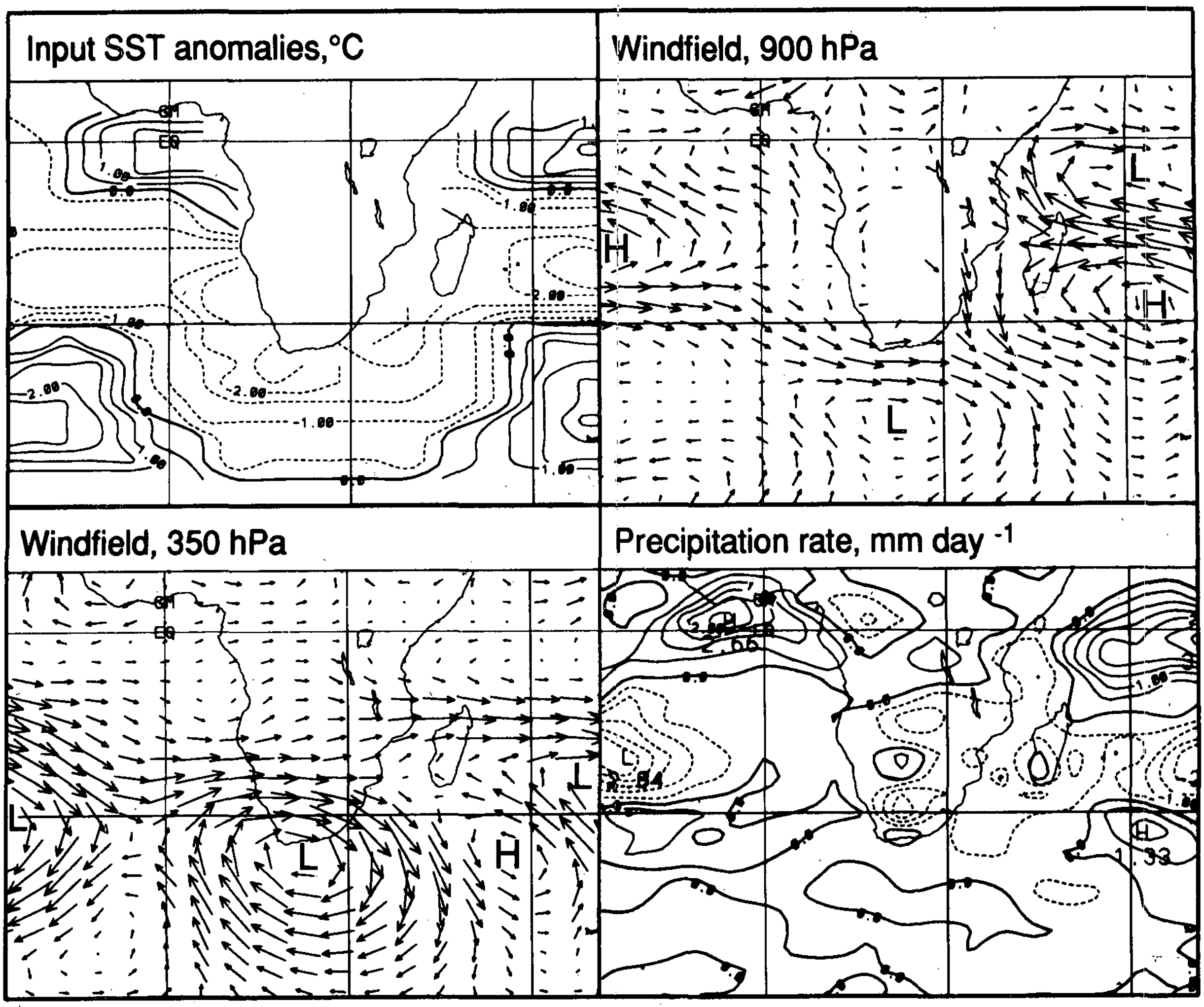


Figure 7

Late summer (January-March) near-surface and upper-level circulation anomalies and consequent drought over the same period simulated using the Australian CSIRO 4-level model initialised with sea surface temperature anomalies exemplified by those for February (upper left) (Lindesay, 1992). In the case of precipitation rate anomalies, solid lines indicate positive and broken lines negative anomalies. The length of wind vector anomalies is proportional to wind speed.

continent strengthen (Fig. 7, upper right). At 350 hPa anomalous westerlies develop in tropical latitudes to the north of Madagascar, a major cyclonic anomaly develops to the south of the continent and the westerly jet strengthens over the subcontinent (Fig. 7, lower left). The cyclonic anomaly to the north-east of Madagascar is consistent with an enhancement of convection over the warmer tropical Indian Ocean waters (Jury, 1993; Jury and Pathack, 1991, 1993). The development of a westerly anomaly in the tropical easterlies to the north of South Africa accords with findings of Harrison (1986) and Lindesay (1986).

The simulated mid-latitude circulation anomalies in both the lower and upper troposphere show increased westerly flow over the southern part of South Africa during drought conditions, a result consistent with earlier observations of Harrison (1986), Lindesay (1986) and Tyson (1986). The tendency for a positive geopotential anomaly to develop throughout the troposhere in the vicinity of Gough Island (Miron and Tyson, 1984) is not replicated; nor is the recent suggestion by Jury and Pathack (1993) that there is relatively little change in the 850 and 200 hPa flow fields over southern South Africa between wet and dry summers. The anticyclonic anomaly found during dry summers by Jury and Pathack (1993) to the east and south-east of Natal is simulated by the model, but is displaced to the north-east. The movement of the locus of cloud band occurrence (and hence rainfall) during droughts to the east of Southern Africa and over Madagascar as postulated initially by Harrison (1986), does not appear to be replicated by the model. Nonetheless, and most importantly, the model simulates below-normal rainfall over much, if not most, of the subcontinent (Fig. 7, lower right). On the whole, the model has performed well in replicating observed conditions, both in the tropics and mid-latitudes.

The underlying mechanisms leading to the development and sustaining of the sea surface temperature anomalies that produce the model responses remain unresolved. It is probable that atmospheric circulation fluctuations are involved in the development of large sea surface temperature anomalies, as well as in their temporal evolution and spatial propagation. Elucidation of this issue awaits further research.

Conclusions

The simulated atmospheric circulation adjustments associated with sea surface temperature variation in the oceans adjacent to Southern Africa are consonant in varying degrees with the observed changes associated with drought conditions that were reported earlier in the paper and elsewhere. It remains to report in full on the modelling of the separate individual effects that sea surface changes in the different parts of the Atlantic and Indian Oceans have in modulating rainfall over Southern Africa. This is in the process of being done (Lindesay and Smith, 1993; Lindesay et al., 1993). From the work done to date it is clear that the use of global climate models initialised using sea surface temperature changes in the South Atlantic and Indian Oceans in the African region holds promise in the timeous forecasting of drought conditions over Southern Africa. However, it is necessary to add a cautionary note. The uncertainties associated with climate modelling, though being reduced as more research is done, remain considerable. Models of the kind presented in this paper need to be used with circumspection. Much more research is needed before such forecasts can be considered sufficiently reliable or spatially resolved to be useful in an operational sense. In the meantime, further work must be done to reduce the uncertainties associated with the use of global climate models to predict seasonal or within-season rainfall.

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References

BRUNDRIT, GB and SHANNON, LV (1989) Cape storms and the Agulhas Current: a glimpse of the future? *S. Afr. J. Sci.* **85** 619-620.

D'ABRETON, PC (1992) The dynamics and energetics of tropical-temperate troughs over southern Africa. Unpublished Ph.D. Thesis, University of the Witwatersrand. 231pp.

D'ABRETON, PC and LINDESAY, JA (1993) Water vapour transport over southern Africa during wet and dry early and late summer months. *Int. J. Climatol.* **13** 151-170.

D'ABRETON, PC and TYSON, PD (1993) Divergent and non-divergent water vapour transport over southern Africa during wet and dry conditions. *Meteorol. Atmos. Phys.* In press.

GILLOOLY, JF and WALKER, ND (1984) Spatial and temporal behaviour of sea-surface temperatures in the South Atlantic. *S. Afr. J. Sci.* **80** 97-100.

GORDON, HB and HUNT, BG (1991) Droughts, floods and sea surface temperature anomalies: a modelling approach. *Int. J. Climatol.* **4** 347-363.

GRAY, WM and SCHEAFFER, JD (1991) El Niñoand QBO influences on tropical activity. In: Glantz, MH, Katz, RW and Nicholls, N (eds.) *Teleconnections Linking Worldwide Climate Anomalies*. Cambridge University Press, Cambridge. 535 pp.

HARRISON, MSJ (1984) A generalised classification of South African summer rain-bearing synoptic systems. *J. Climatol.* **4** 547-560.

HARRISON, MSJ (1986) A synoptic climatology of South African rainfall variations, Unpublished Ph.D. Thesis, University of the Witwatersrand. 341pp.

JURY, MR (1993) A preliminary study of climatological associations and characteristics of tropical cyclones in the SW Indian Ocean. *Meteorol. Atmos. Phys.* **51** 101-115.

JURY, MR and PATHACK, B (1991) A study of climate and weather variability over the tropical southwest Indian Ocean. *Meteorol. Atmos. Phys.* **47** 37-48.

JURY, MR, PATHACK, B, CAMPBELL, G, WANG, B and LANDMAN, W (1991) Transient convective waves in the tropical Southwest Indian Ocean. *Meteorol. Atmos. Phys.* **47** 27-36.

JURY, MR and PATHACK, BMR (1993) Composite climatic patterns associated with extreme modes of summer rainfall over southern Africa: 1975-1984. *Theor. Appl. Climatol.* **47** 137-145.

JURY, MR and LEVEY, K (1993) The Eastern Cape drought. *Water SA* **19** 133-137.

JURY, MR, VALENTINE, HR and LUTJEHARMS, JRE (1993) Influence of the Agulhas current on summer rainfall along the southeast coast of South Africa, *J. App. Meteorol.* **32** 7 1282-1287.

LINDESAY, JA (1988) Southern African rainfall, the Southern Oscillation and a Southern Hemisphere semi-annual cycle. *J. Climatol.* **8** 17-30.

LINDESAY, JA (1986) The Southern Oscillation and atmospheric circulation changes over southern Africa. Unpublished Ph.D. Thesis, University of the Witwatersrand. 284pp.

LINDESAY, JA (1992) Modelling the influence of sea surface temperature anomalies on summer rainfall in southern Africa. Paper presented to the International Geographical Union Commission on Climatology, Pennsylvania State University. 3-7 August 1992.

LINDESAY, JA and SMITH, IN (1993) Modelling southern African rainfall responses to SST anomalies in the South Atlantic and Indian Oceans, Preprints of the 4th International Conference on Southern Hemisphere Meteorology and Oceanography. *Am. Meteorol. Soc.* Boston. 526-527.

LINDESAY, JA, TYSON, PD and SMITH, IN (1993) Modelling the influence of ocean temperatures on the late-summer rainfall of southern Africa. In preparation.

LIVEZEY, RE and CHEN, WY (1983) Statistical field significance and its determination by Monte Carlo techniques. *Mon. Weather Rev.* **111** 46-59.

MASON, SJ (1992) Sea surface temperatures and South African rainfall variability. Unpublished Ph.D. Thesis, University of the Witwatersrand. 235pp.

MASON, SJ (1993a) The effects of sea surface temperature variability on South African rainfall. Preprints of the 4th International Conference on Southern Hemisphere Meteorology and Oceanography. *Am. Meteorol. Soc.* Boston. 530-531.

MASON, SJ (1993b) Sea surface temperature - South African rainfall associations 1910-1989. *Int. J. Climatol.* Submitted.

MASON, SJ and LINDESAY, JA (1993) A note on the modulation of Southern Oscillation-South African rainfall associations with the Quasi-Biennial Oscillation. *J. Geophys. Res.* **98** (D5) 8847-8850.

MEY, RD, WALKER, ND and JURY, MR (1990) Surface heat fluxes and marine boundary layer modification in the Agulhas Retroflection region. *J. Geophys. Res.* **95** (C9) 15997-16015.

MIRON, O and TYSON, PD (1984) Wet and dry conditions and pressure anomaly fields over South Africa and the adjacent oceans, 1963-1979. *Mon. Weather Rev.* **112** 2127-2132.

NICHOLSON, SE (1986) Rainfall variability in southern and equatorial Africa: its relation to Atlantic sea surface temperatures and the Southern Oscillation. Preprints of the 2nd International Conference on Southern Hemisphere Meteorology. *Am. Meteorol. Soc.*, Boston. 472-475.

NICHOLSON, SE and ENTEKHABI, D (1987) Rainfall variability in equatorial and southern Africa: Relationships with sea surface temperatures along the southwestern coast of Africa. *J. Clim. and Appl. Meteorol.* **26** 561-578.

NICHOLSON, SE (1989) Rainfall variability in southern Africa and its relationship to ENSO and the Atlantic and Indian oceans. Preprints of the 3rd International Conference on Southern Hemisphere Meteorology and Oceanography. *Am. Meteorol. Soc.*, Boston. 366-367.

PITCHER, EJ, BLACKMON ML, BATES, GT and MUñOZ, S (1988) The effect of north Pacific sea surface temperature anomalies on the January climate of a general circulation model. *J. Atmos. Sci.* **45** 173-188.

SMITH, IN and GORDON, HB (1992) Simulations of precipitation and atmospheric circulation changes with warm SSTs: Results from an ensemble of idealized anomalies. *Clim. Dyn.* **7** 141-153.

STEYN, PCL (1984) The relationship between the 300 hPa circulation pattern and rainfall classification in the Bethlehem region, Bethlehem Precipitation Research Project Report, No. 24, South Africa Weather Bureau, Pretoria. 19pp.

TYSON, PD (1981) Atmospheric circulation variations and the occurrence of extended wet and dry spells over southern Africa. *J. Climatol.* **1** 115-130.

TYSON, PD (1984) The atmospheric modulation of extended wet and dry spells over South Africa, 1958-1978. *J. Climatol.* **4** 621-635.

TYSON, PD (1986) *Climatic Change and Variability in southern Africa.* Oxford University Press, Cape Town. 220pp.

TYSON, PD, MASON, SJ and LINDESAY, JA (1993) Modelling the influence of ocean temperatures on the rainfall of southern Africa. Preprints of the 4th International Conference on Southern Hemisphere Meteorology and Oceanography. *Am. Meteorol. Soc.* Boston. 528-529.

VAN HEERDEN, J, TERBLANCHE, DE and SCHULTZE, GC (1988) The Southern Oscillation and South African summer rainfall. *J. Climatol.* **8** 577-597.

WALKER, ND and MEY, RD (1986) Preliminary observation of seasonal and interannual heat fluxes of the Agulhas Current and its retroflection region. Preprints of the 2nd International Conference on Southern Hemisphere Meteorology. *Am. Meteorol. Soc.* Boston. 396-399.

WALKER, ND (1989) Sea surface temperature-rainfall relationships and associated ocean-atmosphere coupling mechanisms in the southern African region. CSIR Research Report, Stellenbosch. 173pp.

WALKER, ND and LINDESAY, JA (1989) Preliminary observations of oceanic influences on the February-March 1988 floods in central South Africa. *S. Afr. J. Sci.* **85** 164-169.

WALKER, ND (1990) Links between South African summer rainfall and temperature variability of the Agulhas and Benguela current systems. *J. Geophys. Res.* **95** (C3) 3297-3319.