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The Influence on Summer Rainfall in the Lesotho Lowlands from Indian Ocean SSTs

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Lesotho is located approximately at latitude 30 degrees south in the interior of Southern Africa. The mesoscale climate is complicated and governed by various weather systems. The inter-annual rainfall variability is great, resulting in low food security, since the growing of crops in the Lesotho Lowlands is almost exclusively rain-fed. Reliable forecasts of austral summer rainfall are thus valuable. Earlier research has shown that the sea surface temperatures (SST) in the Indian Ocean to some extent govern rainfall in Southern Africa. The research presented is part of an on-going project to find suitable oceanographic and meteorological predictors, which can be used in a forecast model for summer rainfall, to be developed later. The first part of this paper investigates the correlation between the average SSTs in the Equatorial Indian Ocean, the Central Indian Ocean, and the Agulhas Gyre, respectively, and rainfall two months later in the Lesotho Lowlands during early austral summer, October until December for the period 1949-1995. No significant correlations have been found, probably because the three ocean areas are too large. In the second part of this paper the monthly SST in 132 grid squares in the Indian Ocean were investigated and found to be correlated with rainfall in the Lesotho Lowlands two months later, October until March. Significant correlations have been found between the SSTs and certain ocean areas and December, January, and February rainfall, respectively. There is significant negative correlation between December rainfall and October SST in an ocean area between Kenya and Somalia across the Indian Ocean to Sumatra. In the area where the Somali Current flows there is also significant correlation between December SST and December rainfall. January rainfall is significantly negatively correlated with November SST in an ocean area northeast of Madagascar. February rainfall is significantly, but weakly, negatively correlated with SST in a narrow north-south corridor in the Eastern Indian Ocean from the equator down to latitude 40 degrees south.

Introduction

The Lesotho Lowlands are located in western Lesotho and encompass 5,000 km^2. The Lowlands have a north-south extension of 200 km and a width of 25 km. They border the plains of the eastern Free State and have an approximate elevation of 1,750 m above sea level. To the east the foothills rise into the Lesotho mountains, which rise to elevations higher than 3,000 m. It is in comparison with these elevations that western Lesotho is called Lowlands, *cf.* Fig. 1. The 1886/87-1992/93 mean annual precipitation over the Lowlands is 735 mm (Hydén 1996a). However, the mean annual precipitation varies considerably between years, the lowest being 426 mm and the highest 1, 097 mm in the mentioned 107-year series.

A majority of the Basotho live in the Lowlands from rain-fed agriculture. Rainfall variability is thus of great importance for food security. The ability to forecast rainfall in the austral summer would contribute to improving food security. This is especially true, if droughts could be forecasted so much in advance that farmers could switch to more drought resistant crops and adjust the extent of the planted area to expected rainfall. It is against this background that meteorological droughts and rainfall variability in Lesotho have been studied by this author (Hydén 1996 a, b, c and 2000) and others: De Baulny (1977, 1979, 1981); Eckert (1980); Eldredge (1987, 1993); Jayamaha (undated after 1979); Makhoalibe (1985); Molapi and Sekoli (1989); Sekoli (1981); Sene et al (1998); Sharma and Makhoalibe (1988); Sharma and Makhoalibe (undated after 1984); SWECO (1977); World Bank (1990); Zinyowera (1978).

The Lesotho Lowland is a fairly small area. It might be feared that distant teleconnections would not be discernible in the mesoscale climate of such a relatively small area. However, it has been shown (Hydén 1996a) that there is a strong correlation between Lesotho Lowlands regional rainfall and rainfall over the much larger summer rainfall region of South Africa.

The research presented in this paper is part of an on-going project to find suitable oceanographic and meteorological predictors to forecast rainfall in the Lesotho Lowlands. In an earlier paper (Hydén 2000) the possibilities to forecast early summer rainfall in the Lesotho Lowlands from the El Nino/Southern Oscillation were investigated. Rainfall during October, November, December, October+November, November +December and October+November+December was correlated with the Southern Oscillation Index during preceding months from May to October. The results indicated that it would be possible to make forecasts that would be significant-

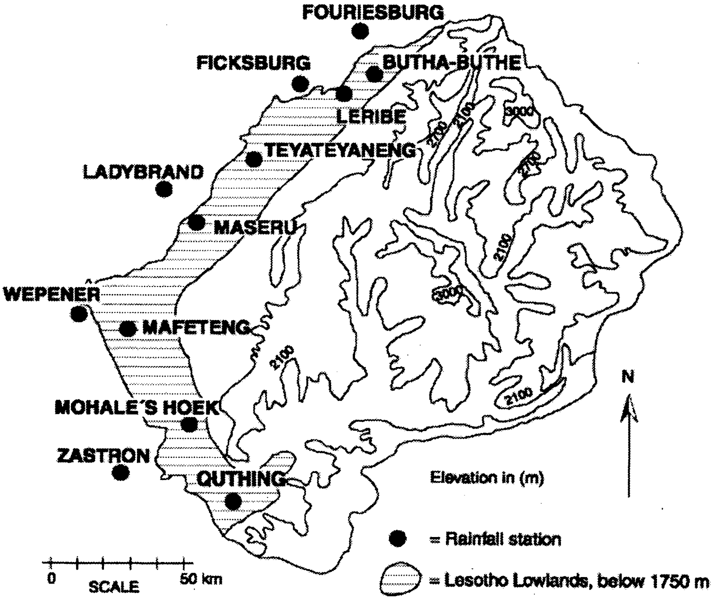

Fig. 1. Topographic map of Lesotho and location of rainfall stations

ly better than chance for all six rainfall periods. The highest correlation achieved was +0.53 between July Southern Oscillation Index and November rainfall.

The purpose of this paper is to study the impact of the Indian Ocean SSTs on Lesotho Lowlands austral summer rainfall. In Southern Africa the only attention paid to defining optimal forecast periods has been to divide the austral summer season into the early, mainly temperate half and the later, tropical half (Mason 1997). This paper deals with all the summer months, i.e. the months of October, November, December, January, February, and March. Once relevant Indian Ocean predictors have been established, it is anticipated that a forecasting model can be developed using both the Southern Oscillation Index and Indian Ocean SSTs in one model to predict Lesotho Lowlands summer rainfall.

In the 1990's a vast amount of research was carried out, mostly in South Africa, to study the impact of the sea surface temperatures (SSTs) of surrounding oceans, i.a. the Indian Ocean, on rainfall in South Africa. This included work by Hastenrath et al (1995), Jury (1992, 1995 and 1996), Jury and Pathack (1995), Jury et al (1996), Landman (1997) Landman and Klopper (1998), Mason (1995), Pathack (1993), Rautenbach (1997), Walker (1990) and Walker and Shillington (1990) (Table 1).

The most detailed analysis has been carried out by Pathack, who used summer rainfall data in six zones in South Africa for the period 1950-1986. Pathack's results for Zone 3, located in the eastern regions of the Cape Province and covering areas to the south and west of Lesotho, are summarized by this author in Fig. 2.

Table 1 – Impact of Indian Ocean SST on Summer Rainfall in Southern Africa. Literature review.

Author	**Analysis**	**Results**
1. Hastenrath and Greischar, 1995	Correlation analysis DJF rain in Transvaal region correlated with N SST, 25-30S, 45-85E, 1954-1978	r=+0.34 Not significant at 95% level (Table 1)
2. Jury, 1992	Correlation analysis SE Africa summer rainfall index (JF) and SST NE of Madagascar, 1950-1984	Lags -2 to -6 months: r>-0.50 Significant at 95 % confidence level for N=35
	Composite analysis Wet-Dry JF	South of Madagascar, max + 0.86 C; 70 E, 32 S, max +0.94 C (Fig. 6)
3. Jury and Pathack, 1993	Correlation analysis Southern Africa rainfall index (JF) and Indian Ocean SST 0-10 S, 60-80 E	r=-0.60 at lags -3 to -4 months
	Composite analysis ND SST differences during the 4 wettest and the 4 driest summers (JF) 1975-1984	Max +0.86 C difference around 32 S, 50 E. Max -0.97 C around 12.5 S, 85 E (Fig. 5)
4. Jury, 1995	Correlation analysis DJF rain correlated with 0-lag SST in the Central Indian Ocean 0-10 S, 60-80 E, 40 years	r=0.3-0.6, 0.6 closest to the equator (Fig. 2)
5. Jury, 1996	Correlation analysis South Africa rain 24-28 S, 24-29 E correlated with SST in Central Equatorial Indian Ocean 0-10 S, 60-80 E:	
	*Jan rain vs Jan SST	*r exceeding -0.6 (Fig. 4 Top)
	*Jan rain vs N SST	*Insignificant r:s (Fig 3 Top)
	*NDJFM rain in Transvaal vs 3 month CEI SST, lags -1 to -5 months	*Max r=-0.81 for NDJ SST (Fig. 12)

cont.

6. Jury, Pathack, Rautenbach and VanHeerden, 1996	Correlation analysis 25 station rainfall over South Africa 25-30 S, 24-30 E correlated with SST data, 1950-1988:	
	*F rain vs F SST	*r=-0.4 to -0.5 in 5 N-5 S, 75-90 E (Fig. 4 Bottom) r=-0.5 in 30 S, 40 E (Fig. 4 Bottom)
	*F rain vs O SST	*r=-0.4 to -0.5 in 0-10 S, 60-75 E (Fig. 4 Top)
7. Landman, 1997	First canonical maps of district December rainfall in western Lesotho predicted from Sept-Nov SST in the Indian Ocean	r=0.82-0.89
8. Landman, and Klopper, 1998	Forecasts into three categories of DJFM rain in district F, northwest of Lesotho, from the four predceeding three month SST seasons, using global oceans between 45 N and 45 S, including the Indian Ocean	8 forecasts out of 15 correct
9.Mason, 1995	0-lag correlation between SST seasonal principal component scores and 1910-1989 rain totals over South Africa	PC2 (south of Madagascar): JFM and AMJ barely significant in Lesotho (Figs. 4a and 4b)
10. Pathack, 1993	Rainfall in north-eastern Cape, southern Lesotho and eastern Free State is correlated with 0-lagged and lagged Indian Ocean SST	See text and Fig. 2 in this paper.
11. Rautenbach, 1997	DJ rain PC1 1961-1990 correlated with 0-lag global SST	r=>+0.4; 0-15S, 60-90E (Fig. 4a)
12. Walker, 1990	JFM rain correlated with OND SST	r:s significant at 90 % level in 0-40S, 20-60E. Max r=+0.47 at 38S, 32E (Fig. 9 top)
13. Walker and Shillington, 1990	JFM rain in SE South Africa 0-lag correlated with SSTs (n=22)	r:s significant at 90 % level in 10-35S, 20-70E. Max r= +0.53 in the southern Mozambique Channel (Fig. 2 top)

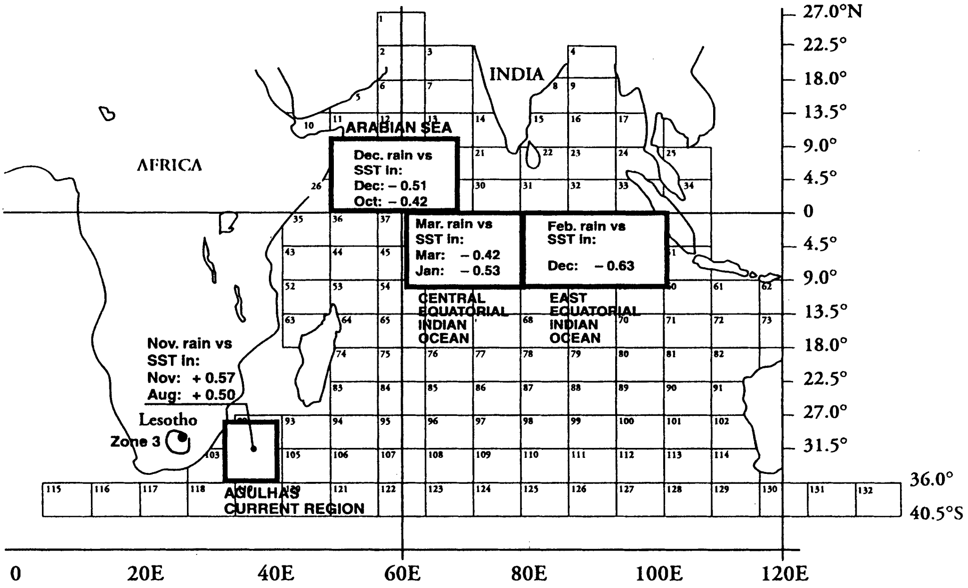

Fig. 2. Some of Pathack's findings, 1993. Correlation coefficients between rainfall in Pathack's Zone 3 and SSTs.

Pathack proposed the following physical grounds to justify the negative association between the variations of South African summer rainfall and Equatorial Indian Ocean SST. When the SST over the Equatorial South Indian Ocean is above average, there is a tendency for intense tropical cyclones in the area to be more frequent during the southern summer. Moisture convergence and convective activity then become anomalously intense over these oceanic areas, depriving the southern African subcontinent of moisture influx. There is a statistically significant positive correlation between the September-November SST in the South West Indian Ocean and the total number of intense tropical cyclones forming in the following summer months, December to March. (Pathack 1993)

These findings of Pathack, but also of particularly Jury, Landman and Walker, *cf.* Table 1, make it likely that the SST of certain areas in the Indian Ocean might be used to forecast rainfall in the Lesotho Lowlands. The main purpose of this paper is to identify the ocean areas best suited to make such forecasts.

Methods

The SST data in degrees centigrade were supplied by the South African Weather Bureau for the period 1949-1996. The grid for the Indian Ocean consists of 132 squares, 7.5 degrees longitude by 4.5 degrees latitude in size. The data are described by Landman (1997). For the period 1949-1985 Landman used Global Ocean Global Atmosphere (GOGA) SST data. Blended and Optimum Interpolation SST data were obtained for the 1986-1996 period. The Blended data (2 degree latitude by 2 degree longitude) and the Optimum Interpolation data (1 degree latitude by 1 degree longitude) were interpolated to the GOGA grid, using cubic interpolation.

Monthly rainfall records in millimetres were made available through the Lesotho Meteorological Services for the following seven stations in the Lesotho Lowlands: Butha-Buthe, Leribe, Teyateyaneng, Maseru Old Airport, Mafeteng, Mohale's Hoek and Quthing. For October, November, and December data for the 47-year period 1949-1995 were used, for January, February, and March data for the 47-year period 1950-1996. The rare gaps in the records were filled with data from adjacent rainfall stations in South Africa, for which data were provided by the South African Weather Bureau. The location of the stations is shown in Fig. 1. The quality of the data has been checked and found adequate (Hydén 1996a). The start of the time series was set to 1949 to coincide with the start of the SST data.

Eckert (1980) computed a Lowlands rainfall series 1920/21-1978/79 as an arithmetical mean for these stations. It was shown (Hydén 1996a) that the method gave almost identical results as with using station weights as outlined by Thiessen (1911). The Lesotho Lowlands regional rainfall was therefore computed as a seven station arithmetical mean. The mean rainfalls are 68, 86, 92, 111, 104, and 94 mm for the six months, respectively. The coefficients of variation are 0.61, 0.41, 0.43, 0.52, 0.43 and 0.43, respectively.

In the first part of the study it is attempted to establish the SSTs of fairly large ocean areas as predictors. The following three ocean areas were tried: Equatorial Indian Ocean, Central Indian Ocean and the Agulhas Gyre. The locations are shown in Fig.3. For each ocean area the lagged Pearson correlation coefficient between the average area SST in degrees centigrade and the Lesotho Lowlands rainfall in mm in the appropriate time period was computed. Actual data in degrees centigrade and millimetres of rainfall were used to detect more easily the effect of any threshold in SSTs. If the correlation coefficient is larger than 0.29 for the 47 observations, then one can reject on the 95 % level of significance the hypothesis that the correlation coefficient is zero. October rainfall was correlated with ocean area SST for May, June, July, August, May-August, June-August and July-August. Similar computations were made for the five other rainfall periods (November, December, January, February, and March), giving 42 cases in all.

In the latter part of the study all 132 grid squares were used as predictors, hopefully catching some of the impact of the energy transport in the currents in the Indian Ocean, shown in Fig. 3. Pearson correlation coefficients lagged two months were computed, on the assumption that it is the persistence of ocean SSTs that explains the forecasting potential. For those grid squares with significant correlation the zero lagged correlation was also computed. This approach was used for all summer months from October to March.

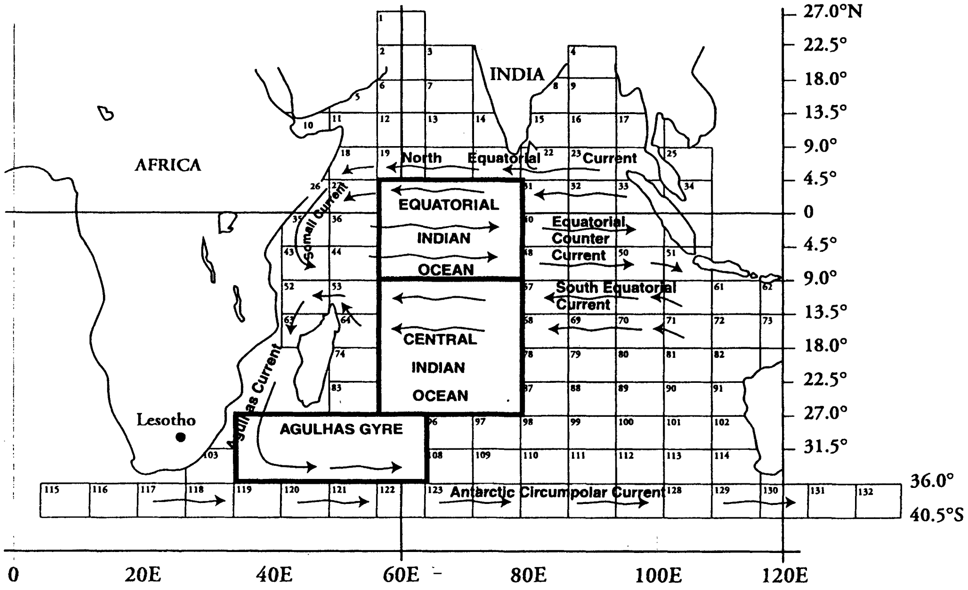

Fig. 3. Indian Ocean. Currents during north-east monsoon (November to March) and large ocean areas used in the first part of this study.

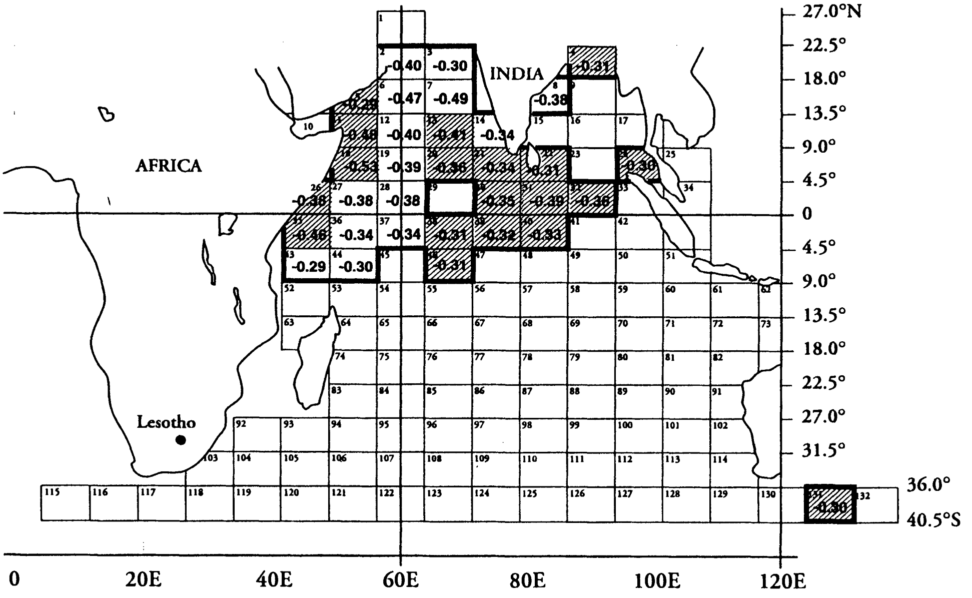

Fig. 4. Significant correlation between October SST and December rainfall in the Lesotho Lowlands. Legend: Shaded grid squares also have significant correlation between December SST and December rainfall.

Results

The results of the first part of the study regarding large ocean areas as predictors were discouraging. For the Equatorial Indian Ocean area only four significant lagged correlations were found, all of them pertaining to December rainfall. The highest correlation was -0.33 between December rainfall and October SST. For the Central Indian Ocean area and the Agulhas Gyre no significant correlation coefficients were found. Probably the chosen ocean areas were too large.

The results for the second part of the study for all 132 grid squares were somewhat more encouraging, although no significant correlations were found between August SST and October rainfall, between September SST and November rainfall and between January SST and March rainfall, except for a few single grid squares.

Correlation coefficients were computed between grid square SST in October and December rainfall. The results are shown in Fig. 4. There is one major coherent ocean area with significant correlation coefficients, all of them negative. It stretches from Kenya and Somalia across the Indian Ocean to Sumatra and encompasses 30 grid squares. For these 30 grid squares the zero lagged correlation was also computed. That correlation is significant for 18 grid squares, which are shaded in Fig. 4. There are basically two shaded regions. One covers the Indian Ocean area closest to Kenya and Somalia, approximately coinciding with the area where the Somali current flows, *cf.* Fig. 3. The other area extends west and south of Sri Lanka. It is interesting to note that all significant correlations are negative, implying that a relatively cold equatorial Indian Ocean leads to relatively wet conditions in the Lesotho Lowlands. A relatively warm equatorial Indian Ocean leads to relatively dry conditions in the Lesotho Lowlands.

The highest lagged correlation is -0.53 between December rainfall and October SST in grid square 18, off the Horn of Africa. The linear equation is

$$R = 1018.4 - 36.43\,SST \qquad (1)$$

where

R = rainfall in the Lesotho Lowlands during December in millimetres

SST = sea surface temperature in grid square 18 during the preceding October in degrees centigrade

Similarly, correlation coefficients were computed between grid square SST during November and January rainfall. The results are shown in Fig. 5. There is only one major area with significant correlation coefficients, all of them negative. It is located northeast of Madagascar and extends as far north as the equator, encompassing 12 grid squares. Relatively cold Indian Ocean conditions northeast of Madagascar thus imply relatively wet conditions in the Lesotho Lowlands. The highest lagged correlation is -0.47 between November SST and January rainfall in grid square 54. Of the 12 grid squares with significant lagged correlation four grid squares also have significant zero lagged correlation, but grid square 54 is not among them.

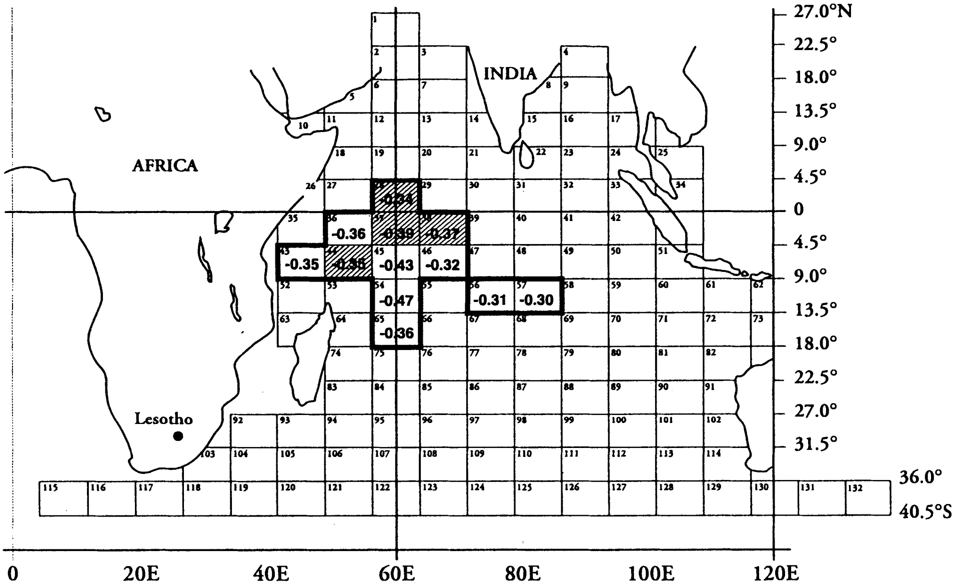

Fig. 5. Significant correlation between November SST and January rainfall in the Lesotho Lowlands. Legend: Shaded grid squares also have significant correlation between January SST and January rainfall.

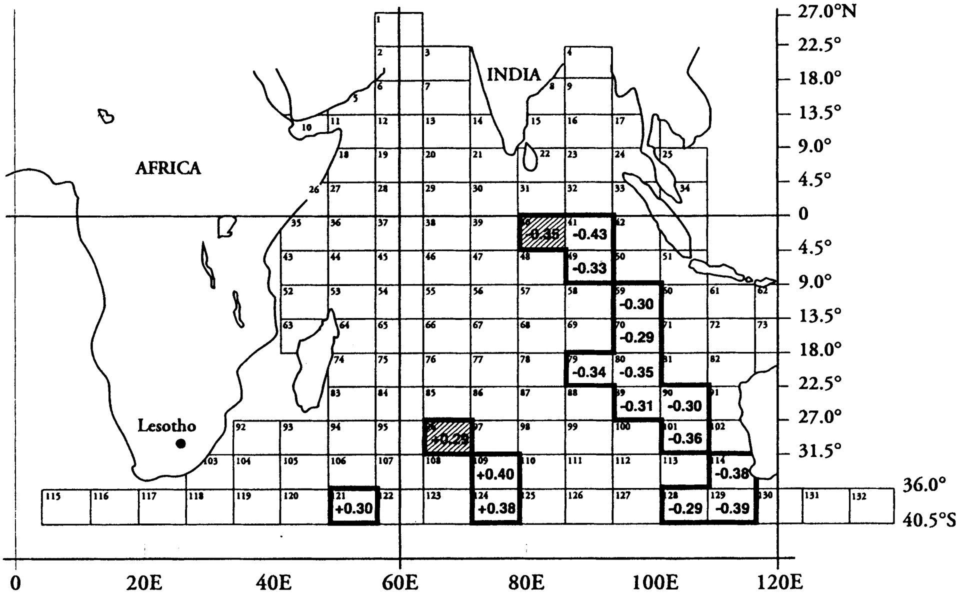

Fig. 6. Significant correlation between December SST and February rainfall in the Lesotho Lowlands. Legend: Shaded grid squares also have significant correlation between February SST and February rainfall.

The correlation coefficients were finally computed between grid square SST during December and February rainfall. The results are shown in Fig. 6. There are two major regions with significant correlation. The largest area is located in the eastern Indian Ocean, extending from the equator down to approximately latitude 40 degrees south in a narrow corridor, encompassing 13 grid squares, all with negative correlation. Relatively cold eastern Indian Ocean conditions thus imply relatively wet conditions in the Lesotho Lowlands. The highest correlation is -0.43 in grid square 41, west of Sumatra, just south of the equator. Of the 13 grid squares with significant lagged correlation only grid square 40 has significant zero lagged correlation.

The other major area with significant lagged correlation is located in the central part of the southernmost region of the Indian Ocean, just north of latitude 40 degrees south, encompassing four grid squares, all with positive correlation. The highest correlation is +0.40 in grid square 109. Of the four grid squares only grid square 96 also has significant zero lagged correlation.

Discussion

The ocean area off Kenya and the Horn of Africa shows the highest correlation coefficient between December rainfall and October SST in grid square 18, -0.53. This is encouraging since one might expect that the Hadley circulation closest to the African continent influences rainfall conditions around the southern tropical circle, over the Indian Ocean and over Lesotho. Grid square 18 is also located in Pathack's Arabian Sea Area, where Pathack found that the corresponding correlation coefficient was -0.51, *cf.* Fig. 2. It is more difficult to explain the influence of the SST in the region south of India. Maybe it is the influence of the North Equatorial Current, flowing westwards in the area from 8 degrees north latitude to the equator during the northeast monsoon (November to March), *cf.* Fig. 3.

The ocean area north-east of Madagascar with significant lagged correlation between November SST and January rainfall, *cf.* Fig. 5, is also included to a large extent in the area with significant lagged correlation between October SST and December rainfall, *cf.* Fig. 4; grid squares 28, 36-38, 43-44 and 46 are significant in both figures. The significant area in Fig. 5 is basically a reduction and movement southwards of the significant area in Fig. 4, as the southern summer progresses.

The influence of December SSTs on February rainfall in the eastern Indian Ocean shows a complete change of influence regions, when one compares Fig. 6 with Fig. 4 and 5. It is difficult to conceive a physical explanation how this corridor extensively elongated from the equator to latitude 40 degrees south should influence rainfall in the Lesotho Lowlands. It should be noticed, however, that most of the correlations are weak, just barely above 0.29. The three northern-most grid squares, including grid square 41, all fall within the region in Eastern Equatorial Indian Ocean, where Pathack found the corresponding correlation to be -0.63, *cf.* Fig. 2.

In summary it can be said that it is the large-scale influence of the equatorial and to some degree the eastern Indian Ocean which governs wet or dry conditions in the Lesotho Lowlands. Temperature conditions in the Indian Ocean areas closest to southern Africa do not appear to have any significant influence. Recent research has shown that the phase relationship between Indian Ocean SST and southern African rainfall is shifting almost continuously. In the 1960s the ocean was leading, in the 1970s the relationship was simultaneous and in the 1980s the ocean was lagging behind rainfall conditions by two seasons. (Jury, personal communication, 2001) Future research might against this background develop different relationships for different time periods. Judging from the results of this paper and the previous paper on the influence of the Southern Oscillation, one can anticipate that a forecasting model based on both Indian Ocean SSTs and the Southern Oscillation Index can yield correlations greater than 0.53, at least for the month of December. Forecasting of summer rainfall is done already for different regions in South Africa by several institutions for the benefit of dry land farmers all over South Africa.

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