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CLIMATE VARIABILITY IN MALAWI, PART 2: SENSITIVITY AND PREDICTION OF LAKE LEVELS

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ABSTRACT

Southern Africa has only a few large lakes, one of which is Lake Malawi. It forms part of the lower Zambezi catchment and the Great Rift Valley. The lake provides food, energy, transport and recreation to the local people. Inflow to the lake increases through summer (December to April) when the equatorial convection zone lies overhead. An analysis of lake levels in the period 1937–95 has been conducted and changes are related to variations in rainfall and atmospheric conditions. Interannual cycles in the time series are consistent with those found for Zambezi River streamflows, suggesting a degree of regional coherence. Years with high inflow are contrasted with mean conditions using the National Centres for Environmental Prediction reanalysis data for the period since 1958. Composite anomalies of wind fields for wet years reveal a zonal overturning circulation. Low (upper) level westerlies (easterlies) link with a sub-tropical trough in the Mozambique Channel to enhance regional convection and lake inflows. The results provide input to predictive models for Lake Malawi to plan better the management of water resources in this part of Africa. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: Malawi; lake level; climate prediction; hydrological modelling

1. INTRODUCTION

Lakes and rivers in tropical southern Africa provide much needed water resources, but the supply varies from year to year depending on prevailing climatic conditions. Summer rainfall is the main recharge system, contributed by the inter-tropical convergence zone (ITCZ) and cloud bands connecting equatorial convection with temperate troughs (Harrison, 1986). Variations in rainfall create a range of economic impacts, and observations suggest that tropical southern Africa is prone to widespread drought and flood events (Jury *et al*., 1992). Although many studies have focused on the climate of the region, few have addressed the hydrologic responses. There is recent evidence for changes in the climate of Africa based on variations in the levels of inland lakes (Maidment, 1993). Lake levels respond to rainfall and to human interference and consumption, so care is needed in relating water levels directly to climate.

Water supplies in southern Africa are relatively under-exploited for human use, either by agriculture through irrigation or for consumption through damming. Water resources of economic importance include Lake Malawi, Lake Kariba, the Zambezi River, the Orange River, and a number of smaller rivers over a 5×10^6 km^2 area of tropical southern Africa (Figure 1). The Zambezi stretches a distance of 2660 km across five countries (9–20 °S, 17–36 °E), with a drainage area of 1.3×10^6 km^2, a mean discharge of 2.5×10^3 m^3 s^{-1}, and a hydro-electricity capacity near 10^4 MW (Gandolfi and Salewicz, 1991). The Zambezi

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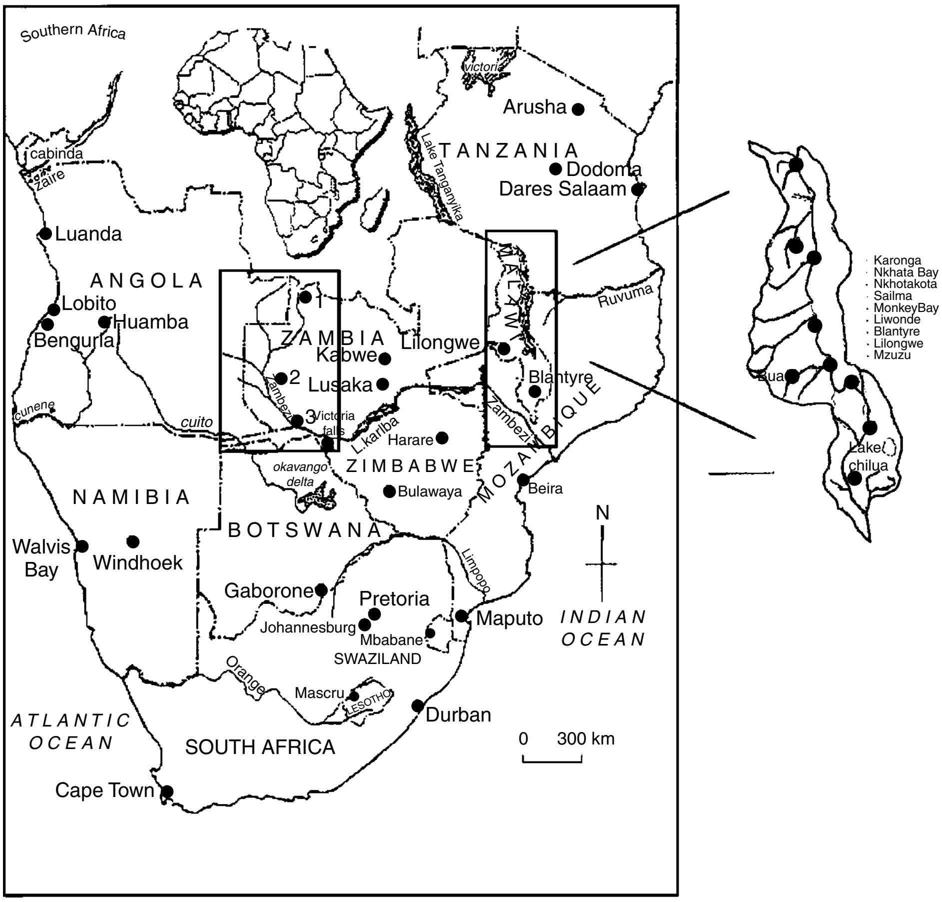

Figure 1. Location map of key hydrological resources over tropical southern Africa; with a detailed map for the Lake Malawi catchment showing rain gauges used

River divides the wet tropics in the north from the arid sub-tropics to the south. The mean annual rainfall over its catchment is about 1000 mm, and the potential evaporation is 870 mm. The rainfall/run-off coefficient is 13%, averaged over the basin, and at Victoria Falls the mean annual run-off is 24 km^3 (Liebaert, 1997).

Lake Malawi lies at 474 m above sea level in the African rift valley, with a surface area of 2.8×10^4 km^2, a volume of 8×10^3 km^3, a land catchment area of 9.6×10^4 km^2, a length of 550 km and a breadth of 15–80 km, and borders three countries. Six small rivers create an annual inflow of $\sim$360 m^3 s^{-1} to the lake, and one river (Shire) drains southward over a weir to the Zambezi. The vegetative cover across this region is woodland (Brachystegia, etc.) interspersed with dense savanna, some of which is cleared for cultivation to feed $\sim$20 million people. The catchment experiences potential evaporation rates around 1600 mm (Mandeville and Batchelor, 1990). The mean annual rainfall around Lake Malawi ranges from 600 to 2500 mm and its variability is the primary factor affecting inflows. In 1949–50, 1972, 1967 and 1992, low rainfall resulted in declining lake levels, whereas in 1961–63, 1978–80, and 1989, high rainfall produced elevated levels. The peak flood of 1979 resulted in many lakeshore developments being inundated.

To establish the water balance, the rate of change of lake volume with time is related to the water input and output rates: $dV/dt = (R + P + G) - (D + E + G)$, where R is runoff, P is precipitation, G is groundwater seepage, D is discharge rate, and E is surface evaporation. The equilibrium lake level is given by $L = [R + A(P - E)]$, where A is area, and D and G are neglected. Evaporative losses are controlled by the available surface energy, and dependent on temperature, humidity and wind speed. Run-off is computed by dividing the inflow by the catchment area. Estimates for the water balance in Lake Malawi according to Kidd

(1983) include: $R = +1100$ mm, $P = +1414$ mm, $E = -2264$ mm, D (Shire outflow)−418 mm, leaving a net storage of +12 mm. Departures from mean conditions are generated by cumulative effects from previous years and by fluctuations in the intensity of run-off during the rainy season. These can be decomposed into trends, quasi-cyclic variations, stochastic autoregressive properties and chaotic or random behaviour.

The regional climate is influenced by the topography and surface fluxes, and the manner in which the prevailing moisture transport is organized by weather systems (Torrance, 1972). In the winter season, from May to August, a high-pressure system dominates the area and divergent southeast trade winds induce persistently dry conditions. Mean temperatures in spring (September–October) exceed 30 °C and windy conditions enhance evaporative losses then. By summer, the ITCZ shifts southward to 10–15 °S and air masses from the Congo basin and the west Indian Ocean meet over Malawi, causing heavy rainfall at times. The terrestrial moisture flux is governed by monsoon responses over the adjacent Atlantic and Indian Oceans. A strengthening of upper easterly flow during an El Niño–southern oscillation (ENSO) cool phase and a concomitant increase in the sea-to-land temperature gradient results in an enhanced supply of moisture over tropical southern Africa (Hastenrath *et al*., 1993) and a replenishment of water resources.

In this study we analyse variations in the level of Lake Malawi and the flow of the Zambezi River at Victoria Falls, and establish the nature and context of water resource variability in terms of regional climate. Our objective is to study climatic patterns contributing to flood events and to develop forecast models for hydrological resources over tropical southern Africa.

2. DATA AND METHODS OF ANALYSIS

Monthly lake-level data were obtained from the Malawi Water Resources Department for the period 1916–95 for three stations along Lake Malawi. Levels are measured above a reference, the Shire Weir Datum. Although water level records started then, the period prior to 1937 exhibits a linear upward trend as the lake filled to the weir level. Thereafter, a more cyclical, climate-impacted behaviour is noted. In our analysis, an inflow index is computed from the difference in the level from the month with the lowest data for the year (around November) to the month with the highest level (usually May). The data are then standardized to produce anomalies by subtracting the long-term mean from each year and dividing by the standard deviation. Annual stream flow totals for the Zambezi at Victoria Falls were obtained from the Namibian Department of Hydrology for the period 1915–96. Annual standardized departures for a matching period were computed. From conventional surface weather data, monthly rainfall was obtained for a group of stations along the shores of Lake Malawi. Monthly potential evaporation was computed using the Penman formulae.

The lake-level time series is analysed for variability using various techniques: autocorrelation for persistence, linear regression for trends, and spectral analysis for cyclic behaviour. The remaining variance is assumed to have both stochastic and chaotic components. The lake inflow index is cross-correlated with various environmental indices to determine which part of the variability is predictable and linked with global and regional climate.

To investigate regional climate patterns contributing to lake inflows, National Center one season in advance for Environmental Prediction (NCEP) reanalysis data are utilized to derive composite fields of wind and precipitable water. The data are at 2.5° resolution and suitable for use in describing the regional climate over tropical southern Africa. Years for inclusion in the composite analysis are selected by ranking the inflow index time series. On consideration of the composite and correlation results, a group of candidate 'predictors' is extracted for comparison with the lake inflow index. A multivariate model is developed using step-wise insertion to forecast changes in lake inflow at a one season lead-time.

3. RESULTS

3.1. Time variability of water resources

The seasonal cycle of inflows and inter-annual variability for Lake Malawi is illustrated in Figure 2 over the 1937–95 period. The 58 year mean incremental increase in lake level is typically +0.17 m in January,

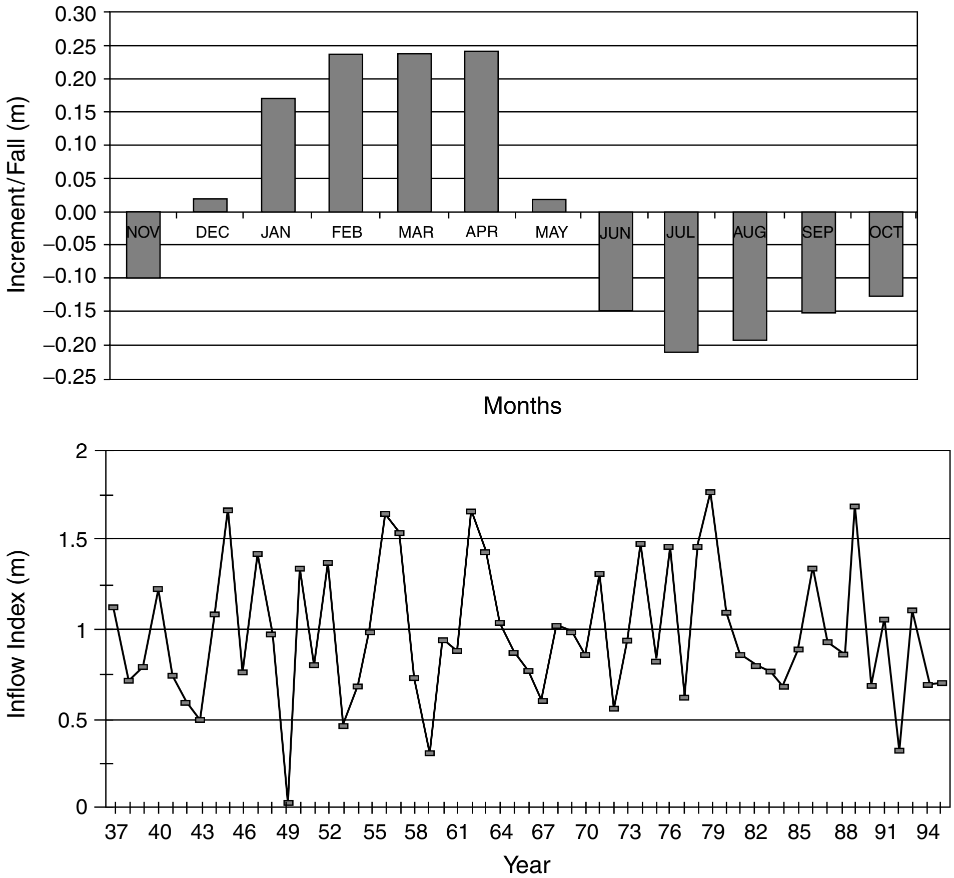

Figure 2. Mean monthly incremental changes in Lake Malawi (top) and summer inflows (bottom) in the period 1937–95

and +0.24 m in each of the three months of February, March and April. December and May exhibit small increases, whereas lake levels fall during winter and spring, June through November, peaking at −0.21 m in July. The inter-annual variability exhibits a biennial oscillation (2.0–2.6 years) and a weaker oscillation around 5.6 years in the period 1937–95. Lake inflows were at a minimum in 1949 and a maximum in 1979 (an outlier). The years with high lake inflows, in the period of data overlap with NCEP, include 1962, 1963, 1974, 1978, and 1989. A frequency distribution of inflow years (not shown) indicates a prevalence of cases in the range 0σ to -1σ (standard deviation), and a smaller group of cases in the $+1\sigma$ to $+2\sigma$ range. The autocorrelation of the inflow time series at +1 year lag is near zero, indicating that persistence is limited by biennial oscillations and the intervening dry winter season. Comparing an average of all lakeside summer rainfall data with the inflow index, a correlation of +0.77 is achieved. The degrees of freedom is 56, so the r value is significant at the 99% confidence level. The strong relationship indicates that lake inflows are useful in gauging climate variability in the region. The lake acts as a rain gauge, when incremental changes are considered. Incremental decreases in lake level and outflows via the Shire River were similarly analysed, but for the sake of brevity will not be reported here. In summary, Lake Malawi has a 'short memory' and is quite sensitive to inter-annual rainfall variability. The relation of Shire outflows to absolute lake levels is high due to hydraulic pressure, but is relatively low compared with the inflow (incremental) index, as expected.

The temporal nature of Zambezi River streamflow is illustrated in Figure 3. Farquharson and Sutcliffe (1998) suggest that its high amplitude of variability is attributable to erratic rainfall and high evaporation, owing to warm temperatures and the elevated topography. Flows decline as low as 14×10^9 m^3 in 1915 and peak at 73×10^9 m^3 in 1958. 1958 appears as an inflection point, with a rising trend before and a decline

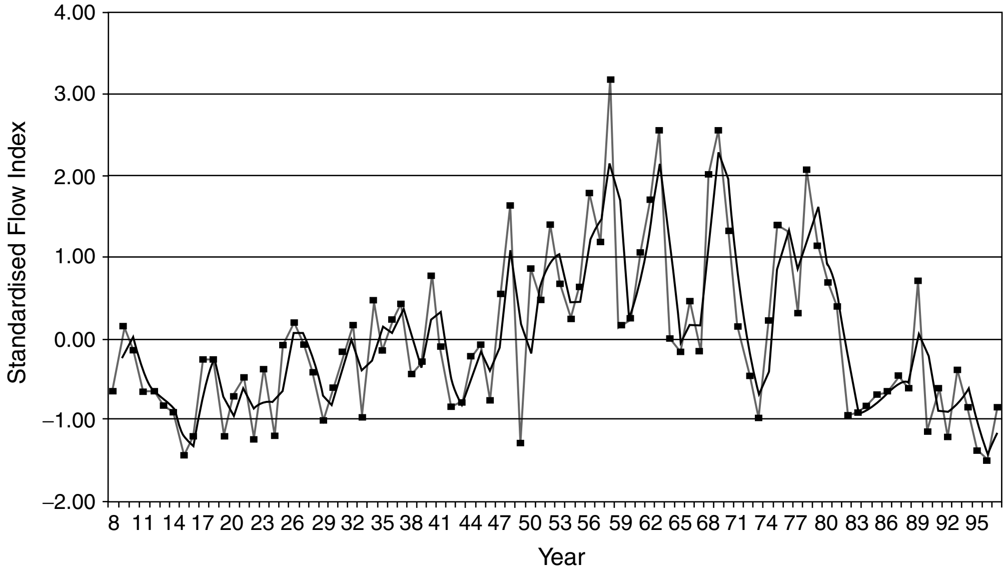

Figure 3. Zambezi River annual streamflows at Victoria Falls (grey) and filtered with three-point running mean (black)

thereafter. An 80–100 year cycle is found in proxy data for the Zambezi and other African rivers (Nicholson and Yin, 1998: Tyson *et al*., 2000). Our 1958 inflection point appears to be a part of this low-frequency cycle. The histogram of Zambezi streamflows is skewed toward the 0σ to -1σ range, and flood events above $+2\sigma$ are rare. Spectral analysis of the time series of annual streamflows reveals weak cycles at 2.5, 5.8 and 9.7 years. Relationships with Zambezi basin-averaged rainfall are strong, with an r value of +0.74. The cross-correlation of Zambezi streamflow with Lake Malawi inflow is relatively high at +0.53, suggesting that hydrological impacts occur on continental scales, in agreement with Sutcliffe and Knot (1987). The Zambezi's higher degree of persistence (autocorrelation at +1 year lag of +0.42) is distinct from that found for Lake Malawi. We attribute the persistence to the larger basin scale and to inflow from Angola being partially governed by Atlantic decadal variability (Tourre *et al*., 1999).

3.2. Composite analysis of high lake inflow years

A composite analysis is conducted using NCEP reanalysis data for the 'wet' summers (December–February (DJF)) of 1962, 1963, 1974, 1978, 1979, and 1989, i.e. those with high inflow to Lake Malawi. The historical mean is subtracted to produce anomaly fields for precipitable water and winds over the domain 10 °N–40 °S, 30 °W–90 °E. It should be noted that the composite sea-surface temperature (SST) anomaly pattern is relatively weak around Africa. The precipitable water pattern for wet summers is shown in Figure 4(a) and illustrates a broad moist tongue extending from east to southern Africa. Its axis of orientation is along the eastern escarpment and northeastern monsoon flow. Within this moist anomaly, a smaller northwest–southeast-oriented positive axis is observed over Mozambique around 25 °S, 35 °E. This 'Mozambican trough' extends toward Zimbabwe and Malawi, and is a regular feature of the summer climate of southern Africa (Washington and Todd, 1999). The precipitable water composite results suggest that wet summers are contributed by steady monsoonal inflows triggered by a sub-tropical standing wave.

The wet composite circulation patterns are described using 3 and 12 km level data. Composite winds at the 700 hPa level (Figure 4(b)) reveal a low-pressure cell in a clockwise circulation over the central plateau (Botswana). Northerly flow on its eastward flank corresponds with the Mozambican trough axis. A westerly flow anomaly occurs along 10 °S, whilst easterlies are found at higher latitudes. Together, these zonal flows create cyclonic vorticity in the lower troposphere over tropical southern Africa. At the upper level (Figure 4(c)), an axis of easterly winds occurs along 20 °S, with an outflow channel branching poleward

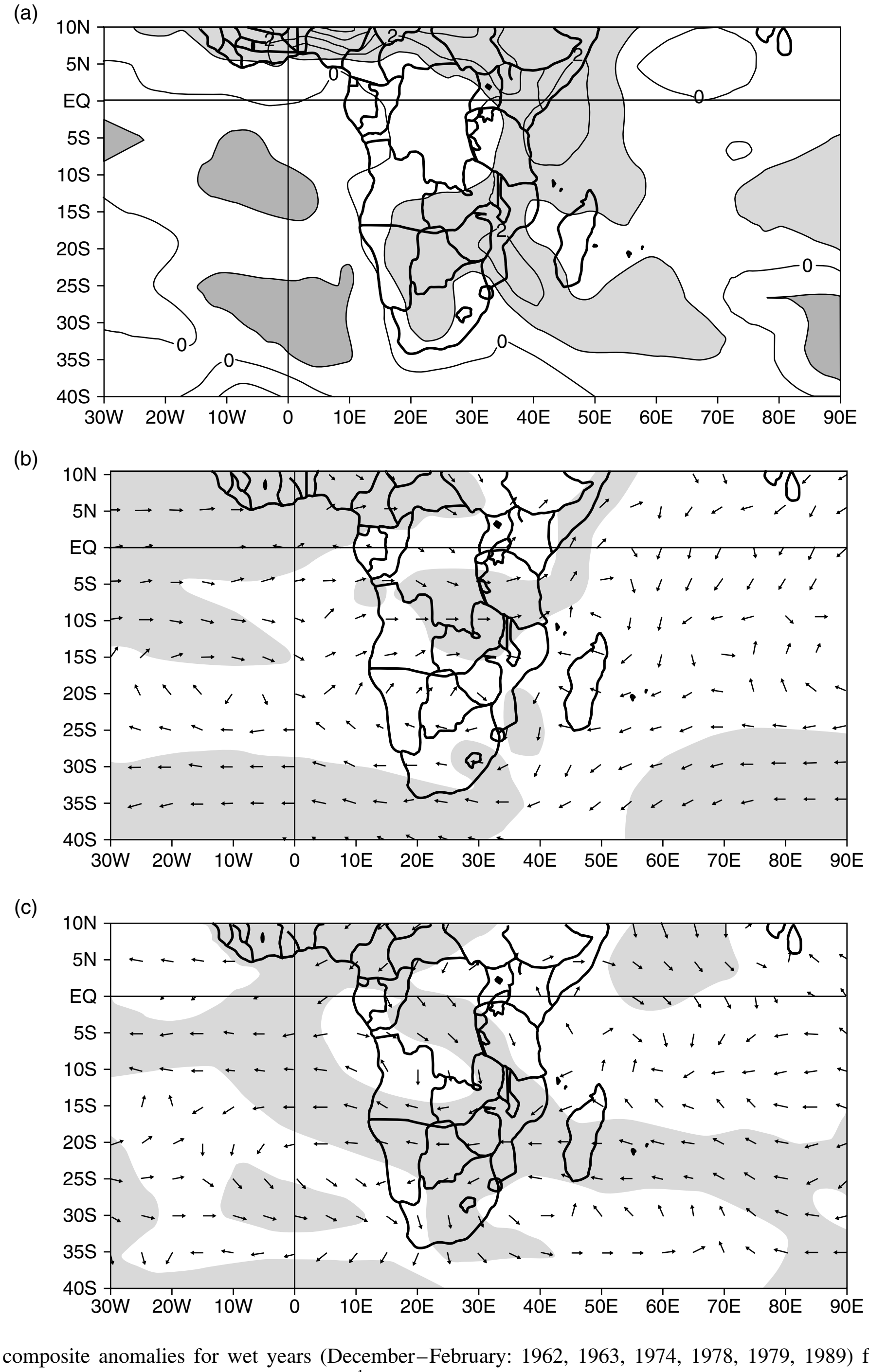

Figure 4. NCEP composite anomalies for wet years (December–February: 1962, 1963, 1974, 1978, 1979, 1989) for (a) precipitable water (kg m^{-2}), (b) 700 hPa and (c) 200 hPa winds (m s^{-1}). Light shading in (a) represents positive anomalies, dark indicates negative; contour interval is 1 mm. Shading in (b) and (c) refers to wind anomalies >1 m s^{-1}

over South Africa. The easterly axis extends into the tropical Atlantic and is indicative of ENSO cool phase conditions (Jury and Mason, Submitted).

Vertical sections of the composite circulation anomaly are given in Figure 5. The east–west zonal wind section reveals a deep layer of westerly flow over tropical southern Africa and a shallow layer of easterlies

aloft. The zonal overturning appears connected to the Atlantic, where precipitable water anomalies are negative. The north–south meridional wind section illustrates poleward flow induced by the Mozambican trough. Maximum negative values occur around 25 °S in the 300–500 hPa layer. V-wind anomalies are weak elsewhere, and suggest that the Hadley circulation is a lower-order determinant of wet summers.

4. DISCUSSION AND DEVELOPMENT OF PREDICTIVE MODEL

With increasing concern about climate variability in tropical southern Africa, regional climatic factors underlying the temporal fluctuations have been assessed with respect to key hydrological resources. Changes in the level of Lake Malawi and Zambezi River streamflows, driven by basin-averaged rainfall, exhibit spectral energy in 2–10 year periods consistent with cycles found in the stratospheric quasi-biennial oscillation (QBO), the global ENSO phenomenon, and the solar cycle. Incremental inflows in Lake Malawi are offset by evaporation during the dry season. Biennial fluctuations ensure that each rainy season commences with little residual effect from previous years. Based on a suite of six cases, composite NCEP reanalysis fields provide a number of clues to climatic conditions underlying wet summers. Foremost amongst these is a tropical circulation pattern comprised of low-level westerlies, upper easterlies and a moist trough over Mozambique. The climatic patterns are tracked to the precursor spring season, and variables are extracted for inclusion in multivariate forecast models, designed to 'fit' changes in Lake Malawi inflows. Following a careful screening process from analysis of precursor season July–September (JAS) environmental fields (Gwazantini, 1999), candidate predictors are extracted: swAst, eAst, eAp, cAu_{200}, eIp, swIp, cIu, cIst, sIst, where the first letter refers to the quadrant within the ocean basin, the second letter to the ocean (i.e. A: Atlantic; I: Indian) and the third letter to the parameter (st: SST; p: pressure; u: zonal wind). In addition, the global indices SOI, QBO and nino3 (Pacific SST) are utilized. These are combined into regression formulae using a forward step-wise insertion technique (Jury *et al.*, 1999). The following set of rules are applied in the formulation process.

- Statistical models should be developed for 'large' area-averages (catchments), e.g. $>3^\circ \times 3^\circ$. Regionalization (e.g. rotated principal component analysis, etc.) should be performed on continental and ocean-basin scale.
- Predictors should be drawn from 'large' areas, e.g. $>10^\circ \times 10^\circ$ and confined to the tropics ($<15^\circ$ lat.) where convective responses are exponential. Predictors other than SST may be used, e.g. SLP, U/V winds, global indices, etc.
- Target and predictor data should be filtered to 3-month averages to remove intra-seasonal oscillations. The lead time prescribed by users is 3 months, e.g. JAS for summer (DJF).
- The training period should exceed 30 years and the number of candidate predictors should be less than half this (e.g. 15), to minimize artificial skill.
- The number of predictors in the algorithm cannot exceed three and should not be cross-correlated >20%.
- A hindcast r^2 fit >40% should be achieved. If the model falls below this level, then confidence in its use must be limited.
- Independent validation tests are conducted by excluding a number of years and predicting those based on the remainder of the data. Performance is judged by tercile categories 'hit'.

Applying these rules to our set of JAS season predictors and the Lake Malawi inflow index (Lm from Figure 2(b)), two algorithms are produced:

$$\text{Lm} = -0.34(\text{nino3}) + 0.34(\text{sIst}) - 0.29(\text{swIp}) \tag{1}$$

$$\text{Lm} = -0.50(\text{cAu2}) - 0.47(\text{eAp}) + 0.35(\text{swAst}) \tag{2}$$

The model in Equation (1) gives an r^2 fit of 43% and a Durbin–Watson value of 2.2 in the period 1958–93. The predictors in order of appearance include the nino3 SST in the eastern Pacific, southern Indian Ocean SST and southwest Indian Ocean surface pressure. The sign of the coefficient indicates how the predictor contributes to increased lake levels (e.g. cooler Pacific, warmer south Indian Ocean and lower pressure over

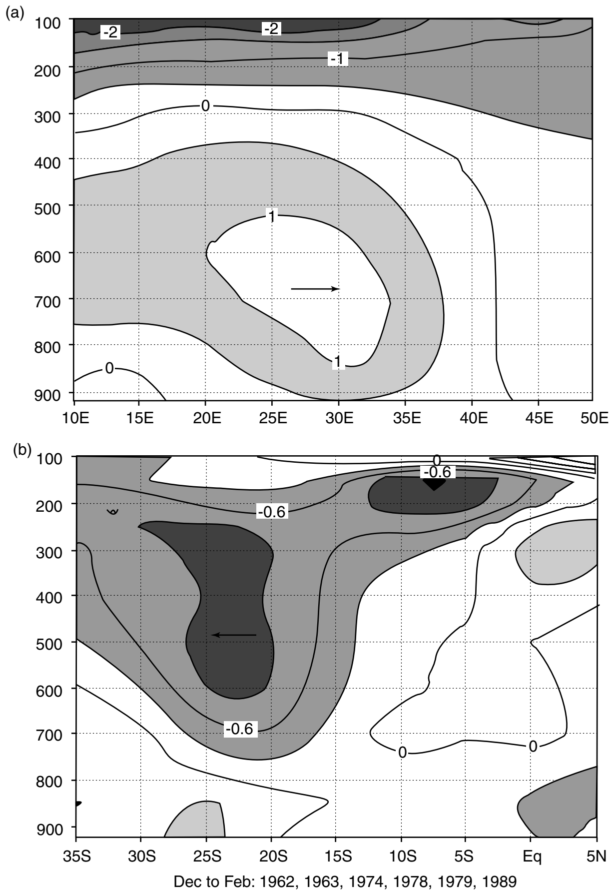

Figure 5. Composite circulation anomalies for wet years (December–February: 1962, 1963, 1974, 1978, 1979, 1989), indicating Walker-type overturning and trough activity. (a) East–west (-20 to $-7\,^{\circ}$S) and (b) north–south (28–30 °E) vertical sections of zonal and meridional winds (m s^{-1}) respectively. Contour intervals: (a) 0.5 m s^{-1}; (b) 0.4 m s^{-1}

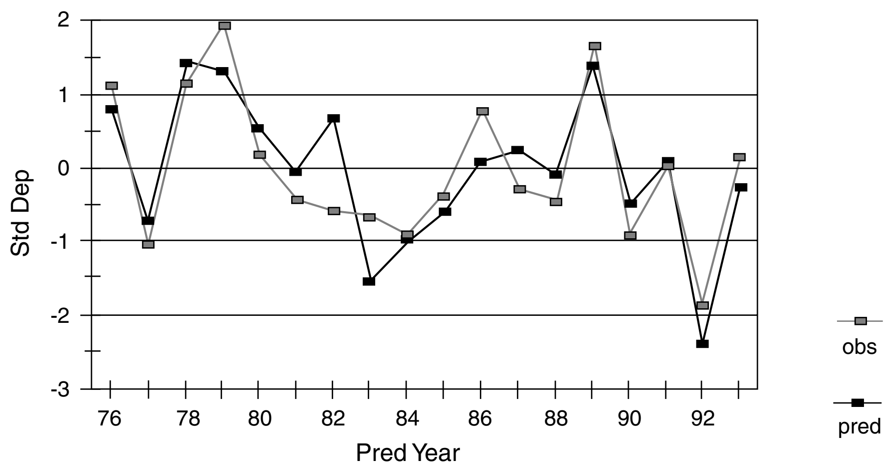

Figure 6. Validation test for model given by Equation (1) predicting inflows to Lake Malawi at one season lead-time

the southwest Indian Ocean). Performing an independent test on the last 18 years (Figure 6), Equation (1) produces a high r^2 fit of 70%. The model in Equation (2) gives an r^2 value of 53%, but its fit in the independent test period is not as good at 60%. The variables in Equation (2) include the central Atlantic upper zonal wind, east Atlantic surface pressure and the southwest Atlantic SST. Increased lake levels correspond with upper easterly winds over the tropical Atlantic, lower pressure over the east Atlantic, and higher SST in the southwest Atlantic. Interestingly, all predictors in Equation (1) are from the Indo-Pacific domain, and all predictors in Equation (2) are from the Atlantic.

5. SUMMARY

In this paper we have analysed variations in key water resources in tropical southern Africa. Close relationships were found for lake inflows, river streamflows and catchment rainfall, as expected. Inflows to Lake Malawi exhibited little persistence and weak cyclical behaviour at periods of 2–10 years. Hydrological resources were found to be sensitive to inter-annual variations of climate and the regional structure of moisture and circulation. Wet years were examined and found to be characterized by an influx of moist monsoonal air from the northeast, a zonal overturning cell connected to the tropical South Atlantic, and a subtropical trough over Mozambique. Predictor indices were extracted from environmental fields exhibiting precursor signals at one season lead-time. An outcome was the development of predictive models to forecast changes in the level of Lake Malawi. A more general outcome of this work was the generation of meaningful information on the relative influence of climatic fluctuations on water resources across tropical southern Africa.

Many issues raised in this study deserve further examination. For example, a detailed analysis of flood events, coupled with an objective technique to pinpoint climatic signals and refine statistical models, would be of benefit. Such research would improve the uptake of forecasts by hydrological managers. In addition to further statistical analyses, conceptual and numerical modelling of hydrological variability is a necessity in tropical southern Africa, where less than 10% of rainfall is converted to run-off and where water demand by a growing population will result in shortages in a few decades.

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