Review of seasonal forecasting techniques and their applicability to Southern Africa

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Abstract

The development of a seasonal rainfall forecasting capability has recently become a priority of many research organisations in Southern Africa, but the methodologies used are still at an early stage of development. In other areas, high forecast skills are generally associated with tropical atmospheric variability, largely because of a thermally direct response of the tropical atmosphere to oceanic heat anomalies. Over South Africa, most current forecast skill relates to rainfall variability attributable to the tropical atmospheric circulation, including El Niño-Southern Oscillation (ENSO)-related anomalies. Consequently, highest forecastability exists in the summer rainfall region during the peak rainfall months, December to February, and is particularly high in areas that are strongly affected by ENSO activity. The extratropical atmosphere has an important influence on the rainfall of the region during the first half of the summer season, when forecast skill is relatively low. Occasionally, the extratropical atmosphere also remains dominant during the peak summer months, resulting in a poor forecast for that season. Consequently, an improved understanding of the response of the temperate atmosphere to tropical anomalies and internal blocking should result in considerably improved skill for seasonal forecasts throughout the summer season.

Introduction

The development of skilful extended-range weather prediction and seasonal forecasting capabilities has direct economic benefits (Madden, 1977; Preisendorfer and Mobley, 1984; Gilman, 1985; Namias, 1985; Brown et al., 1986; Sonka et al., 1986; Livezey and Barnston, 1988; Preisendorfer et al., 1988; Barnston and Livezey, 1989; Livezey, 1990a; Livezey et al., 1990, 1994; Palmer and Anderson, 1994). To illustrate, for the United States potential savings over ten years to the agricultural sector from seasonal forecasts, with only 60 per cent accuracy, are estimated to be between $0.5 and $1.1 bn. (O'Brien, 1992). In sub-Saharan Africa, seasonal rainfall forecasting capabilities could contribute substantially to food security and natural resource management (Hulme et al., 1992a; Mjelde et al., 1993), and benefit industry substantially (Greis, 1982; Weiss, 1982; Sonka et al., 1987; Livezey, 1990a; Harrison et al., 1991). Equally, Southern Africa should benefit considerably from skilful forecasts of rainfall and temperature. The development of such a facility has accordingly become a high priority of several research organisations within South Africa and neighbouring countries.

Techniques for predicting the future behaviour of the atmosphere are determined to a large extent by the required lead-time of the forecast (Namias, 1985). Forecast lead-times range from a few hours or days, for highly skilful numerical weather prediction, to decades, in the case of climate prediction (Fig. 1) (Lawson et al., 1984). The development of numerical weather prediction models over the last two decades has seen a remarkable improvement in the ability to predict weather conditions several days in advance (Palmer and Anderson, 1994). Several meteorological organisations make use of such models (e.g. National Meteorological Centre, NMC, and European Centre for Medium-range Weather Forecasting, ECMWF) as operational forecasting tools. These models provide short-term (up to 3 d) deterministic predictions of global weather with considerable skill.

There is, however, a theoretical limit to deterministic weather prediction of about 15 d owing to the internal chaotic variability of the atmosphere, which tends to exaggerate any initial errors in measurements and model inaccuracies (Thompson, 1957; Lorenz, 1963, 1984, 1990; Shukla, 1981; Somerville, 1987; Brankovic et al., 1990; Palmer et al., 1990; Palmer and Anderson, 1993, 1994). Beyond this theoretical limit to deterministic forecasts, extended range weather predictions of up to 30 d are based on the probability of a change in the current weather regime, within the forecast period (Legras and Ghil, 1985; Reinhold, 1987). An ensemble of forecasts is used to define the probability of a change and the nature of any subsequent regime (Mureau et al., 1993).

On the seasonal time-scale, a number of different weather regimes are likely to occur and interact. Although it is impossible to forecast this variability because of the inherent chaotic behaviour of the atmosphere, it may be possible to identify which regimes will be most probable (Legras and Ghil, 1985; Palmer and Anderson, 1994). The probability of specific weather regimes is affected by underlying boundary conditions such as sea-surface temperatures, ice cover and land-surface characteristics. The boundary conditions generally evolve relatively slowly, and so can be used to provide a forecast of different weather regime probabilities (Shukla, 1981; Legras and Ghil, 1985; Palmer and Anderson, 1994).

In this paper, a review of seasonal forecasting techniques is presented. Firstly, a review of seasonal forecasting skill for different regions of the world is presented. Secondly, an assessment of the prospects for improving forecast skill and lead times for Southern Africa is presented.

Approaches to seasonal forecasting

Predictions of the seasonal behaviour of the atmosphere are made using both empirically- and physically-based models. Physical models attempt to forecast the time-averaged future atmospheric

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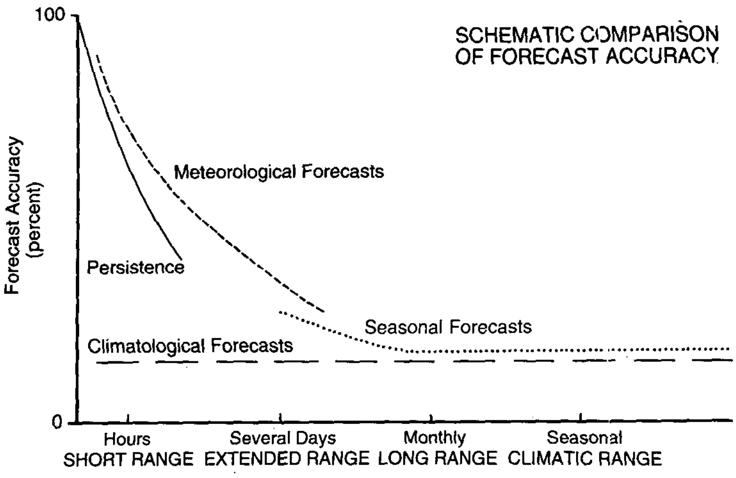

Figure 1

A schematic comparison of forecasting accuracy using various forecast types (after Lawson et al., 1984)

conditions by simulating the dynamic and thermodynamic processes which determine the state of the overlying atmosphere. In contrast, empirical models rely on past statistical associations between lower-boundary forcing or atmospheric precursors and the climatic variable being forecasted and generally provide probabilistic seasonal predictions (Hansen et al., 1984; Namias, 1985; Barnett and Preisendorfer, 1987; Hastenrath, 1990a; b, 1991; Chu and He, 1994). Empirical models for seasonal predictions are used operationally for several regions within the global tropics (Hastenrath, 1991).

In the tropics, coupling between the atmosphere and the ocean is more direct and the atmospheric internal variability is relatively small (Gill, 1980; Campbell et al., 1983; Livezey, 1990a; b). For this reason, the potential for seasonal predictability associated with surface boundary forcing in the tropics is high. The potential for seasonal prediction in the extratropics is, however, relatively poor because of the greater inherent chaotic instability of the extratropical atmosphere (Palmer and Anderson, 1994), especially during the winter (Roads, 1985; Barnston and Livezey, 1987; Palmer and Anderson, 1994). Nevertheless, the predictability of the extratropics, at least during the winter months, may be dependent, in part, on predictability of the tropical atmosphere (Bengtsson et al., 1993; Barnston et al., 1994); planetary-scale circulation patterns within the tropics are known to exert an influence on extratropical circulations through teleconnections induced by Rossby-wave dynamics (Ropelewski and Halpert, 1987; Livezey, 1990b; Palmer and Anderson, 1993; Hunt et al., 1994). In general, therefore, forecast skill in the extratropics is regionally and seasonally specific, with highest skill in late winter and spring and lowest skill in autumn (Wolter, 1989; Buchmann et al., 1990; Zeng, 1990; Palmer and Anderson, 1994).

Examples of seasonal forecasting

Attempts to forecast the Indian summer monsoon represent the earliest efforts to relate weather to global climate anomalies (Walker, 1923; 1924; Walker and Bliss, 1930). More recently, significant seasonal predictability of the Indian monsoon has been identified using a variety of statistical modelling techniques (Kung and Sharif, 1980; Dhar and Rakhecha, 1983; Shukla and Paolina, 1983; Bhalme et al., 1986; Shukla and Mooley, 1987; Hastenrath, 1988; Hastenrath and Greischar, 1993). General circulation models (GCMs) provide less accurate forecasts of the Indian monsoon circulation and rainfall than empirical techniques (Anderson and Carrington, 1993; Palmer and Anderson, 1994). The Asian landmass acts as an elevated heat source that drives the boreal summer monsoon circulation, and so the inability of the models to represent orography and land-surface processes adequately is an important shortcoming (Barnett et al., 1989; Brankovic et al., 1990; Fennessy et al., 1994; Sperber et al., 1994).

Because of the coarse resolution of most GCMs, the simulation of rainfall over the Southern African region, as in the Asian monsoon area, illustrates a high sensitivity to model topography (Mason and Joubert, 1996). In the absence of a monsoon, however, land-sea contrasts and the dramatic changes in topography associated with the escarpment are probably not as important in influencing the annual cycle of rainfall as over the Indian subcontinent (Kung and Sharif, 1980). Consequently, prospects for the successful development of seasonal forecasts using GCMs may be greater for the Southern African region.

Sea-surface temperature and wind vector anomalies have been successfully used to provide statistical seasonal forecasts of rainfall over the Sahel (Palmer, 1986; Owen and Folland, 1988; Parker et al., 1988; Ward et al., 1991; Owen and Ward, 1989; Folland et al., 1991; Hulme et al., 1992b), other areas of sub-Saharan Africa (Farmer, 1988a; b; Ogallo, 1988) and the Brazilian North-Nordeste (Ward et al., 1988; Folland et al., 1991; Hastenrath, 1984, 1990a, 1991).

Skill has also been demonstrated in modelling inter-annual variations in rainfall over the Sahel and North-East Brazil using observed sea-surface temperatures (Moura and Shukla, 1981; Folland et al., 1986, 1991; Druyan, 1988; Owen and Folland, 1988; Hulme et al., 1992b; Rowell et al., 1992). More accurate simulation of rainfall is dependent upon a higher resolution and parameterisation of surface moisture flux (Brankovic et al., 1990; Hulme et al., 1992b).

The high forecast skill for inter-annual rainfall variability over the Sahel and North-East Brazil are examples of high predictability in the absence of any strong ENSO signal: highest forecast skills globally are generally found in areas with a strong ENSO influence. In areas of Southern Africa where rainfall is poorly correlated with the Southern Oscillation Index (SOI), correlations with Atlantic and Indian Ocean sea-surface temperatures may provide useful forecast skill (Mason, 1995). An important finding from modelling studies is that the combined influences on Sahelian rainfall of sea temperatures in different oceans can be non-linear. As a result, it is imperative that the global effects of ocean anomalies on Southern African rainfall are modelled when producing seasonal forecasts for this area using a GCM.

Almost all seasonal forecasting models have been designed to give a prediction for a specific atmospheric variable, most frequently rainfall or temperature (Brankovic et al., 1994). The exceptions generally involve attempts to forecast intense synoptic disturbances such as tropical cyclones and storms (Nicholls, 1979, 1985; Chan, 1994; Landsea et al., 1994; Gray et al., 1992, 1993, 1994). A multiple regression model for the prediction of tropical cyclone activity in the Atlantic Ocean basin based on 13 separate predictors has recently been developed (Gray et al., 1992, 1993, 1994). These predictors appear to be successful at forecasting the number of cyclones with an acceptable accuracy. The predictors include stratospheric winds, west African rainfall, sea level pressure and temperature data, ENSO and information for the Caribbean Basin. The model is able to predict cyclone frequencies from the start of the season (1 June) with reasonable skill scores. Similar statistical models have been developed for forecasting tropical cyclone frequencies in the south-west Indian Ocean (Jury, 1993).

Seasonal predictions for the extratropics are usually based on a combination of known lagged correlations between antecedent mid-latitude sea-surface temperatures and upper-air circulation anomalies (Ferranti et al., 1994). Because the extratropics have a low signal to climate noise ratio, seasonal forecasting has proven to be more difficult than for the tropics (Madden, 1981; Christensen and Eilbert, 1985). However, at least in the Northern Hemisphere, large-scale circulation patterns originating in the tropics can influence the extratropical atmosphere through Rossby-Wave teleconnections, particularly during the winter (Wallace and Gutzler, 1981; Hamilton, 1988; Palmer and Anderson, 1993). Consequently, ENSO-related winter temperature predictions have recently been developed on the basis of an improved understanding of variations in the strength, timing and type of ENSO events (Barnett and Preisendorfer, 1987; Livezey and Mo, 1987; Hamilton, 1988; Barnston et al., 1991, 1994; Halpert and Ropelewski, 1992).

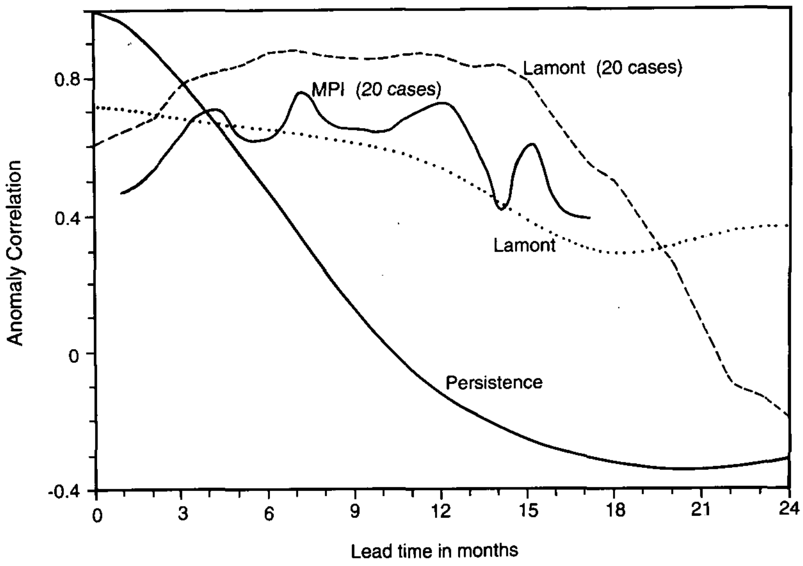

Figure 2

Anomaly correlation of sea-surface temperatures in the NINO3 region for 20 hindcasts for the MPI GCM (solid) and Lamont (CZ) model (dashed). In addition the skill over all CZ forecasts for a 30-year period is shown by the dotted curve, and persistence by the solid curve. The model hindcasts do not beat persistence for the first few months. This is partly a reflection of the way the models are initialised (after Latif et al., 1994).

El Niño - Southern Oscillation events

Recent developments in seasonal forecasting globally are largely a result of improvements in the predictability of ENSO events (Cane and Zebiak, 1985; Cane et al., 1986; Zebiak and Cane, 1987; Barnett et al., 1993; Barnston et al., 1994; Latif et al., 1994). ENSO events are characterised by the development of above average sea-surface temperatures in the central and eastern equatorial Pacific Ocean and are associated with an eastward displacement of convective activity and rainfall away from the Indonesian region. ENSO-related teleconnections are responsible for rainfall and temperature anomalies in several regions around the globe (Ropelewski and Halpert, 1987; Trenberth, 1991; Halpert and Ropelewski, 1992).

The potential for seasonal predictability of ENSO events is high because of direct coupling between the atmosphere and the ocean in the tropical Pacific Ocean, with little internal chaotic variability (Gill, 1980; Livezey, 1990a; b). The near-linear nature of the coupled ocean-atmosphere system ensures that ENSO is predictable with lead-times of several seasons (Fig. 2) (Cane et al., 1986; Zebiak and Cane, 1987; Latif et al., 1994). The simulation of ENSO variability has been most successful with coupled hybrid models, although statistical models also have useful skill at lead times of 6 to 12 months (Latif et al., 1994). In most cases, the models comprise a fully integrated, non-linear ocean circulation model and a simplistic atmospheric model (Cane et al., 1986; Barnett et al., 1993).

The Cane and Zebiak ocean model has recently been run in combination with the Commonwealth Scientific and Industrial Research Organisation 9-level GCM (Hunt et al., 1994). Rainfall hindcasts for Australia and Southern Africa for 1991 and 1992 were generated using predicted sea-surface temperatures for the Pacific Ocean. Both Southern Africa and Australia experienced severe droughts in 1991 and 1992. The GCM displayed statistically significant skill in hindcasting such marked rainfall anomalies in both regions. The results suggest that GCMs may be used successfully to provide operational forecasts.

Seasonal forecasting in Southern Africa

A South African Long-Lead Forecast Forum (SALFF) was founded in October 1994 with the purpose of developing the seasonal forecasting capabilities of the country. There are four group members of the SALFF involved in seasonal foreasting, namely the South African Weather Bureau and the Universities of Cape Town, Pretoria and the Witwatersrand. Considerable progress has been made by the SALFF members in developing statistical forecast models for summer season rainfall, with useful forecast skill. The forecasts are largely based on statistical associations between tropical Pacific, Atlantic and Indian Ocean sea-surface temperatures, out-going long-wave radiation and atmospheric circulation indices in the tropics, subtropics and mid-latitudes (Mason, 1995; Jury, 1996). Upper-atmospheric circulation indices are used in addition to surface features and include the Quasi-biennial Oscillation of stratospheric equatorial zonal wind (Jury et al., 1994; Mason et al., 1994) and the zonal component of upper-tropospheric winds over the equatorial Atlantic Ocean (Jury, 1996) . Each group uses different sets of predictors and statistical techniques. The Research Group for Statistical Climate Studies of the South African Weather Bureau relates rainfall variability over South Africa to sea-surface temperatures globally using canonical correlation, while the Climatology Research Group at the University of the Witwatersrand uses a non-linear discriminant analysis model. The Universities of Cape Town and Pretoria both make more extensive use of atmospheric data to produce forecasts using regression-based techniques. To date, seasonal forecasting efforts for South and Southern Africa have concentrated on rainfall; attempts at the University of Cape Town to provide seasonal forecasts for temperature are in the early stages of development.

Spatial and temporal variability of forecast skill over Southern Africa is largely a reflection of the fundamental differences in forecastability between the tropical and extratropical atmosphere. South Africa is situated within the subtropics, and its climate is influenced by systems of both tropical and extratropical origin (Tyson, 1986; Levey, 1993). The higher skills during the peak summer months of the summer rainfall region are directly related to the predominantly tropical atmospheric circulation influence at this time of year. One of the most important influences on the tropical atmospheric circulation over Southern Africa are ENSO events. Variations in forecast skill are partly a reflection of the spatial and temporal variability of the influence of ENSO events on Southern African rainfall, which occurs predominantly through the tropical atmosphere. Their influence on the temperate atmosphere is much less predictable. Consequently, relatively high forecast skills are found in those areas that are strongly correlated with the SOI, for example over the central and eastern plateau. Correlations with the SOI peak during January-February when similar peaks in forecast skill are also evident. High forecast skills at this time of year, especially in the Northern Province, are also attributable to a strong correlation with sea-surface temperatures in the Northern and Central Indian Ocean (Jury and Pathack, 1991; Mason, 1995), providing a further important source of tropical predictability.

An important exception to the relatively high forecast skill over the summer rainfall region is the Lowveld. Most seasonal forecasting models typically perform badly over the Lowveld at all times of the year. The poor performance of the models for this area is partly a result of the influence of tropical cyclones over the east coast, which contribute to a significant proportion of the inter-annual rainfall variability of the Lowveld. Over the south-western Cape, skill scores are relatively low because of the year-round extratropical influence. However, given that some forecast skill is evident for mid-latitude areas in other parts of the world, there are prospects for improving forecast skill over the winter rainfall region.

Prospects for increasing forecast skill are generally good for most regions of Southern Africa, but greatest prospects for improvements are for extending lead-times. Lead-times for skilful forecasts of up to 18 months have been shown for the ENSO phenomenon (Cane et al., 1986; Zebiak and Cane, 1987; Latif et al., 1994). Although it is unlikely that similar lead-times will be found for other atmospheric phenomena, the ability to forecast trends in the sea-surface temperatures of the Western and Northern Indian Ocean, for example, should provide an immediate improvement in rainfall forecasting lead-times for a significant proportion of the summer rainfall region (cf. Bengtsson et al., 1993). Lead times of about six months may be a limit with developments of present methodologies (Hulme et al., 1992b).

Conclusions

The development of skilful extended range weather prediction and seasonal forecasting capabilities can have significant value to a large sector of the economy. In Southern Africa a number of organisations are involved in developing such capabilities, but there is considerable scope for increasing forecast skill and most notably in extending forecast lead times.

Most of South Africa lies within the subtropical latitudes of the southern hemisphere and receives rainfall from both tropical and temperate synoptic systems. The potential for seasonal forecast skill is higher within the tropics than the extratropics because of the direct coupling between the tropical ocean and atmosphere. Consequently, some skill has been identified in the seasonal forecasting of December to February rainfall over the summer rainfall region, when the tropical atmospheric circulation is dominant. Much of the high forecast skill can be attributed to an association between rainfall and the ENSO phenomenon. Globally, highest forecast skills and longest lead-times are generally associated with ENSO teleconnections.

Experience of seasonal forecasting in Southern Africa has demonstrated consistently poor skill over the Lowveld region, despite a dominant tropical atmospheric influence, because of the occurrence of tropical cyclones. Rainfall from a single tropical cyclone may account for a large proportion of the annual rainfall total in the Lowveld. The ability to forecast these features successfully is imperative for improved forecast skill for the region. Some success has been achieved in providing seasonal tropical cyclone forecasts for other areas in the global tropics. The development of a similar capability for Southern Africa would be of great benefit and should result in a much improved overall forecast skill for the Lowveld.

Little skill has been developed for the first few months (September-December) of the rainfall season because of the dominant influence of temperate rainfall-producing systems which are inherently difficult to forecast. Occasionally, the temperate influence on Southern Africa's rainfall continues throughout the entire season, usually resulting in poor hindcasting skill for such years. It is important to be able to develop an improved forecasting skill of the temperate circulation of the region. This would enable an improvement in the ability to forecast occasional wet El Niño and dry La Niña years, for example. In the Northern Hemisphere, some success has been achieved in forecasting the summer mid-latitude circulation and so prospects for Southern Africa are promising.

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