Towards the seasonal prediction of Moroccan precipitation and its implications for water resources management

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Abstract This paper reviews the basis for our seasonal predictions of Moroccan precipitation for 1996–1997 and 1997–1998, the nature of those predictions, and their subsequent evaluation. The prediction procedures are primarily based on the month-to-month variability of the North Atlantic Oscillation and, to a lesser extent, the more persistent behaviour of the tropical Pacific sea surface temperatures. The role of this seasonal precipitation prediction capability for the management of Morocco's network of 89 dams is also assessed, as is the decadal and shorter time scale variability of Moroccan precipitation since 1932.

INTRODUCTION

In an ongoing collaborative effort with the Kingdom of Morocco that commenced in 1994, a project is being undertaken to increase our understanding of the interannual-to-decadal variability of Moroccan winter semester (November–April) precipitation, and to use this knowledge to develop a seasonal precipitation prediction capability. This project was motivated by the predominance of extremely poor Moroccan winter precipitation seasons since the late 1970s. During the third and fourth years of the project, Experimental Prediction Statements were issued to the Moroccan government for their 1996–1997 and 1997–1998 precipitation seasons. This paper reviews the research basis for, nature and utility of, and verification of those Prediction Statements.

RESEARCH BASIS FOR PREDICTION STATEMENTS

A major focus of this project is the variability of Moroccan precipitation on interannual-to-decadal time scales and its relation to the global climate system, especially the North Atlantic Oscillation (NAO). As shown in Fig. 1, the NAO control on Moroccan precipitation maximizes over the northwest and southwest regions of the country. That control increases steadily from November until January–February, after which it decreases significantly during March and then becomes non-existent in April (Fig. 1).

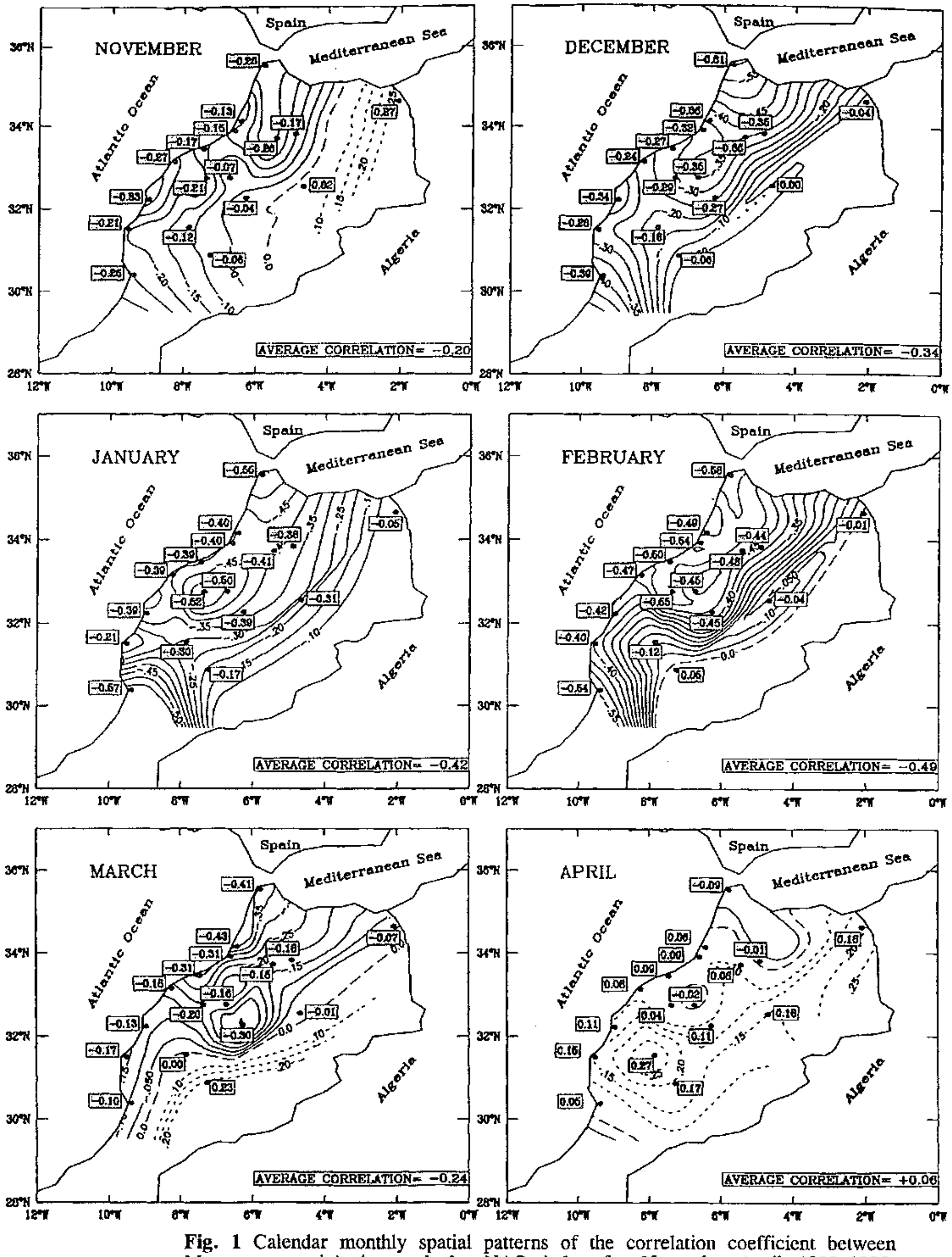

Fig. 1 Calendar monthly spatial patterns of the correlation coefficient between Moroccan precipitation and the NAO index for November–April 1932–1995. Precipitation stations are located by solid circles, with their associated correlation coefficients being enclosed within adjacent shaded rectangles. Continuous/broken lines are negative/positive correlation isopleths at 0.05 intervals. The average correlations given for individual months are for all stations except the four southeastern most ones, where precipitation is weakly related to the NAO.

Since the NAO Index is much less persistent (1 month lag autocorrelation = +0.13, January 1874–April 1998) than the Southern Oscillation Index (+0.64, 1933–May 1998), it is especially challenging to use the NAO as a tool for the seasonal prediction of Moroccan precipitation. However, the evolution of the NAO in

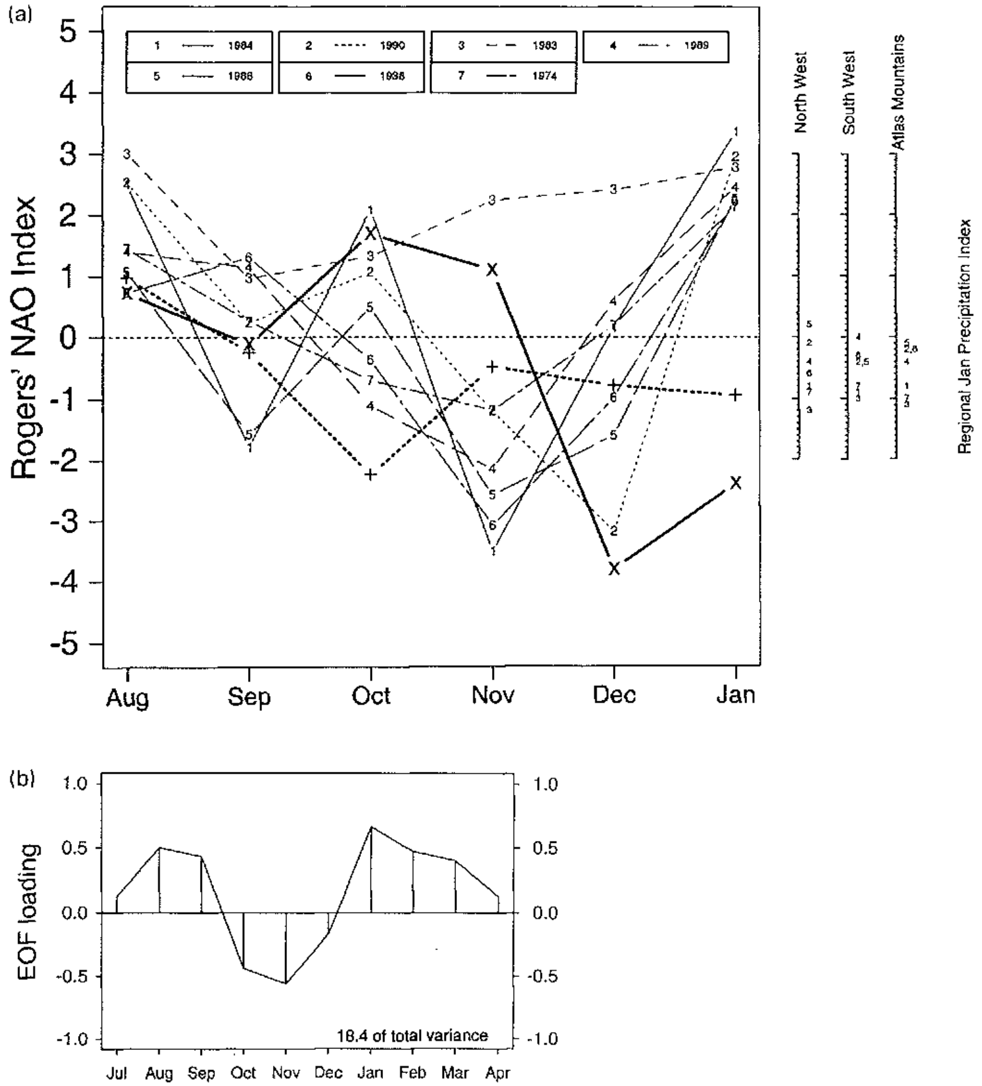

Fig. 2 (a) Evolution of NAO (Al Moubarak, σ) from August to January in the seven years (numbered 1–7) since 1932 when the January NAO value was most positive. Also shown are the NAO evolutions during 1996–1997 (thick solid line with ×) and 1997–1998 (thick broken, line with +). The scales on the right indicate the January standardized precipitation anomaly (σ) in each of the seven extreme (numbered) NAO years for the Northwest, Southwest, and Central Mountain regions of Morocco. These Moroccan regions have been identified by our research as having spatially coherent precipitation.

(b) The first correlation eigenvector (Empirical Orthogonal Function, EOF) of the seasonal NAO evolution from July to April for 1922–1995.

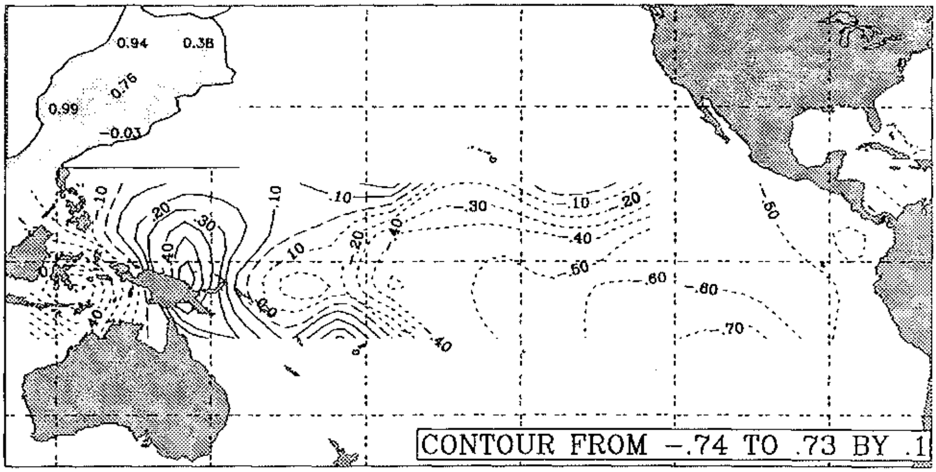

Fig. 3 The first coupled mode identified by the Canonical Correlation Analysis of November–January tropical Pacific SST and February–April Moroccan precipitation (1951–1995). The tropical Pacific SST was represented by its first 11 EOFs (84.5% of the total variance) and Moroccan precipitation was represented by five EOFs (~100% of the total variance).

extreme years offers some promise in that regard. For example, Fig. 2(a) documents the August–January evolution of the NAO during seven seasons since 1932 that culminated in the most extreme positive January NAO values. A distinct August–November–January NAO oscillation is evident for six of these seven seasons, and its inverse is also partly characteristic of the evolution of the seven most extreme negative January NAO values (not shown). Extreme positive/negative January NAO values tend to be associated with contemporary Moroccan precipitation that is below-average-to-very-deficient/above-average-to-abundant (e.g. Fig. 2(a), right-hand axis). These NAO and related precipitation anomalies also tend to persist into February–March. The development/non-development of the above oscillation or its inverse during a particular August–November period, thus provides a basis for the prediction/elimination of an extreme January NAO value (and its accompanying and persisting Moroccan precipitation) with some level of confidence. Furthermore, Fig. 2(b) establishes that the above August–November–January NAO oscillation is a major mode of the NAO's seasonal evolution.

Canonical Correlation Analysis (CCA) of historical data, and Global Climate Model (GCM) experimentation using the ECHAM4 model, are also being performed to investigate the association of Moroccan precipitation with global sea surface temperatures (SSTs). The results indicate that tropical Pacific SSTs can be used to predict late-season Moroccan precipitation (February, and especially March–April) several months in advance, with a level of skill well above that achievable by chance. Figure 3 shows the first CCA mode that couples midwinter tropical Pacific SSTs and late winter Moroccan precipitation. The strongest relationship (negative) is between the central-to-eastern tropical Pacific SSTs and precipitation in the western regions of Morocco.

NATURE OF PREDICTION STATEMENTS: EXAMPLES

The Experimental Precipitation Prediction Statements that we provided to the Moroccan government for the 1996–1997 and 1997–1998 precipitation seasons had a narrow primary focus: the likelihood of extreme NAO values and associated precipitation in the heart of the November–April season. This focus was made possible by the above newly discovered August–November–January NAO oscillation for years with extreme January values.

For example, Fig. 2(a) (which was included in the 1996–1997 Prediction Statement no. 2 issued on 13 December 1996, except for the December 1996–January 1997 and August 1997–January 1998 curves) clearly indicates that the November 1996 NAO value had left the typical "evolution envelope" for an extreme positive January NAO outcome. This indication of a non-drought scenario for the winter season was supported by an historical analogue analysis that focused on the ten years that had the most similar August–November NAO evolutions to 1997. Only 20% of these years had large positive NAO indices ($>+1.5\sigma$) occurring during January–March. There were even fewer cases (0–20%) of extreme precipitation deficits ($<-1.0\sigma$) for those months. The 1996–1997 Prediction Statement no. 2 therefore concluded that there was a significantly reduced probability of a large positive January NAO, with its accompanying non-abundant Moroccan precipitation. This Statement also specifically did not rule out the possibility of an extreme negative January NAO outcome. Probabilistic precipitation predictions were issued for each of the Moroccan regions that had been delineated from Principal Component and Cluster Analyses of a 22-station set of monthly Moroccan precipitation data for 1932 to present. These predictions stated that there was a strong possibility of near-average precipitation in January and February of 1997, with 50–70% of the analogue years having precipitation between $+0.40\sigma$ and -0.40σ.

Using a refined version of the above procedure, the sole 1997–1998 Prediction Statement (issued on 1 November 1997, and which never needed to be modified) indicated that "there is a moderate-to-high probability that Moroccan precipitation will be in the below-average-to-very-low range for much of the upcoming precipitation season. Conversely, there is a low probability that Moroccan precipitation will be abundant for extended periods during this season ... (even though) the early season Moroccan precipitation may not be deficient". This prediction was based on the low probability of the extremely large negative October 1997 NAO Index value (Fig. 2(a)) persisting through December–February.

The secondary focus of the Prediction Statements was the above association of late winter Moroccan precipitation with midwinter tropical Pacific SSTs in the standard El Niño monitoring regions. Specifically, this exploited the tendency for late season Moroccan precipitation to be more/less plentiful in years when La Niña/El Niño conditions prevail. Given the essentially complete international consensus during November 1996–January 1997 that weak La Niña conditions would persist through the following late winter and early spring, all three of our 1996–1997 Prediction Statements (issued between mid-November and mid-February) indicated an increased possibility of near-to-above normal Moroccan precipitation for March–April 1997. Conversely, our prediction of an increased likelihood of below-average

Moroccan precipitation for March–April 1998 was primarily based on a comparable consensus that the strong El Niño that developed during mid-1997 would persist through the 1998 spring.

VERIFICATION OF PREDICTION STATEMENTS

The month-to-month evolution of the NAO during the 1996–1997 winter, and the contemporary precipitation anomalies for the northwest (NW), southwest (SW), and mountain (MT) regions of Morocco, are shown in Fig. 4(a). It is clear that there was a strong negative NAO control on the 1996–1997 Moroccan precipitation season, which followed a pattern that has been especially characteristic of the 1990s. As we predicted, there was a large negative January NAO value (−2.39σ) and above average (but not extreme) January precipitation (NW = +0.83σ; SW = +0.69σ ; MT = +0.96σ). However, rather than peaking in January and persisting into February, as we had anticipated—based on Fig. 2(b) and the inverse counterpart of Fig. 2(a)—this large negative NAO event maximized in December and then persisted

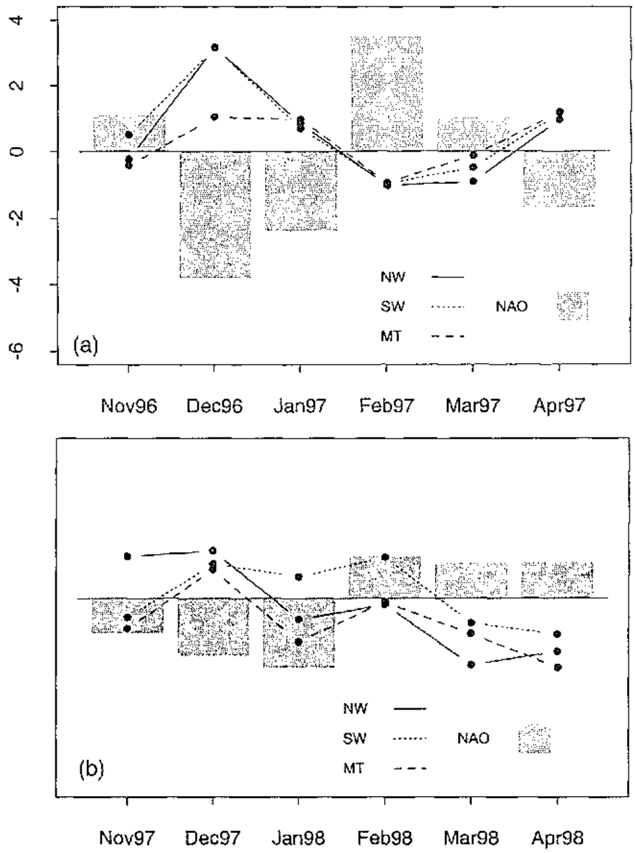

Fig. 4 Monthly NAO index values (grey bars, σ) and Moroccan precipitation anomalies (σ for same regions as Fig. 2(a)) for (a) November 1996–April 1997, and (b) November 1997–April 1998.

with some weakening into January. By February the NAO had reverted to extremely high positive values (Fig. 4(a)) and was accompanied by substantial precipitation deficiencies across the NW, SW and MT regions of Morocco. We failed to predict both of these developments. Verification of our predictions of near-to-above normal March–April precipitation, which assumed the persistence of weak La Niña conditions, is somewhat equivocal. Although such precipitation did occur in April and the second half of March, the weak La Niña was replaced by developing El Niño conditions during those months.

Figure 4(b) is a counterpart to Fig. 4(a) for the 1997–1998 winter. The negative NAO control on this Moroccan precipitation season was weaker than for 1996–1997 and most other winters during the 1990s. However, as we predicted, the early season (November–December) precipitation was not deficient, the extremely large negative October 1997 NAO Index value (–2.24σ, Fig. 2(a)) did not persist through December–February, and Moroccan precipitation was not abundant for extended periods during the season. Furthermore, with the exception of ~10 days overlapping January and February 1998, the mid-December through February precipitation was consistent with our prediction of the "below-average-to-very-low range for much of the upcoming precipitation season". The latter was also characteristic of March–April 1998, the prediction for which was based (correctly) on the persistence of the 1997–1998 El Niño.

UTILITY OF PREDICTION STATEMENTS: WATER RESOURCE MANAGEMENT EXAMPLE

During the last 30 years, Morocco has significantly improved its water resource management through the construction of 89 large dams (with 14×10^9 m^3 storage capacity) that impound runoff from Atlas and Rif Mountain precipitation. Since these dams are drawn down during the mid- and late-dry seasons, the Moroccan Direction Générale de l'Hydraulique (DGH) is faced with especially crucial water resource management decisions before the start of each precipitation (and agricultural production) season in November. Specifically, on the basis of current dam levels and expectations about the upcoming winter precipitation, the DGH must decide on the amounts of water that are released for irrigation (10^6 ha), hydroelectricity generation (average of 2×10^3 GWH year^{-1}), and domestic consumption (average of 2×10^9 m^3 year^{-1}), and conversely at what levels the dams should be maintained prior to the start of the precipitation season. Additionally, the recently developed capability to transfer water from previously hydrologically wet to dry regions further complicates the water management decision process. Since an imbalance between the initial dam levels and the subsequent precipitation can lead to severe flooding or water shortages, the potential value of seasonal predictions of Moroccan precipitation of the type discussed above is very high (M. Jellali, Director General, Moroccan "Direction Générale de l'Hydraulique", personal communication 1995, 1996). Recent international surveys have identified Morocco as a country that will need continued water resource development to meet the increasing needs of future generations (e.g. *Water International* **20**, p. 177, 1995).

RECENT CHANGES IN MOROCCAN PRECIPITATION

The recent series of very dry years, covering approximately 1977/1978 to 1994/1995, appears very unusual and may not be solely attributable to the NAO. The NAO does contain a strong upward winter-time trend, but the trend is centred on the month of March (not shown). Along the northwest and southwest coasts where the NAO explains the most precipitation variance, the precipitation downtrends are centred on December (Fig. 5), for which there has been no pronounced NAO trend.

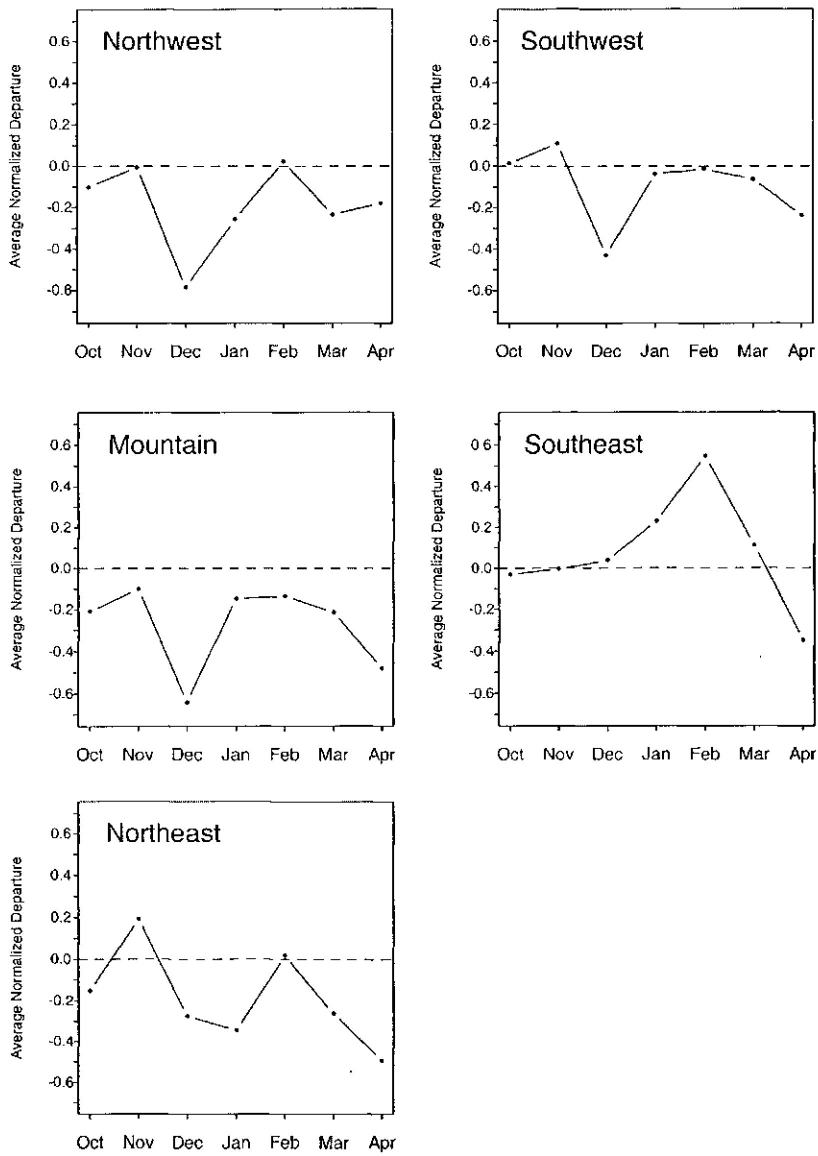

Fig. 5 Calendar monthly average of normalized precipitation departures for all five Moroccan regions for 1979–1994, with reference to the 1932–1998 base period.

Farther inland, in the Atlas Mountains, the December precipitation decreased by 64% during this period. In the southeast, there has been a dramatic increase in February precipitation. Our supporting research is starting to focus on the origin and predictability of the fraction of Moroccan precipitation variance that is not explained by the NAO. If we can identify and understand the evolution of other large-scale climate system controls, this will further enhance the developing seasonal prediction capability that is so important for Moroccan water resources management.

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