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OPINION

# Reassessing the impact of North Atlantic Oscillation on the sub-Saharan vegetation productivity

GUILING WANG
*Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT 06269-2037, USA*

**Abstract**

**The Northern Atlantic Oscillation (NAO) has been shown to have a significant impact on the terrestrial ecosystem in the Sahelian region of Africa during the 1980s, and it has been strongly suggested that NAO may be a reliable predictor for the response of the Sahelian ecosystem to global climate variability. Using data from an extended period, we provide a reassessment for the impact of NAO on the Sahelian climate and ecosystem, and show that there is no consistent relationship between NAO and the ecosystem over Sahel. Statistical analysis on the NAO, vegetation, and precipitation data indicates that NAO influences the Sahelian vegetation productivity exclusively through its impact on precipitation. However, the relationship between the NAO index and Sahelian precipitation varies substantially with time. The correlation coefficient fluctuates between positive and negative values, and does not pass the 5% significance test during most of the twentieth century. The NAO system, although documented to govern the ecosystem dynamics over many other regions, does not have a consistent impact on the ecosystem over the Sahel. Therefore, the NAO index cannot produce a useful prediction on the ecosystem variability and changes in this region. This study provides an example that correlations based on short climate and ecological records (less than 20 years in this case) can be spurious and potentially misleading.**

*Keywords:* Africa, NDVI, North Atlantic Oscillation, precipitation, Sahel, vegetation productivity

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## Introduction

The Northern Atlantic Oscillation (NAO) is characterized by an oscillation in the atmospheric pressure difference between the Azores high and the Icelandic low (Hurrell, 1995, 1996) over the Atlantic. The same phenomenon is sometimes considered as the regional manifestation of a hemispheric annular mode known as the Arctic Oscillation (Thompson & Wallace, 1998). The positive phase of NAO is associated with a larger-than-normal meridional pressure gradient over the Atlantic Ocean, causing stronger-than-normal surface westerly winds across the Atlantic onto Europe. The opposite occurs during the negative phase of NAO. This oscillation system gives rise to the leading mode of climate variability in the Northern Hemisphere. Its impact is particularly strong over the Atlantic sector during winter, with NAO-related patterns of temperature and precipitation variability 'extending from Florida to Greenland and from north-western Africa over Europe far into northern Asia' (Visbeck *et al.*, 2001). Through its impact on climate processes with important ecological consequence, NAO influences the dynamics of both terrestrial and marine ecosystems at various levels ranging from individual to community. A rapidly increasing body of literature has documented the ecological responses to NAO, including for example changes in primary productivity, phenology, population dynamics, spatial distribution, and inter-specific relationship (Gerten & Adrian, 2000; Straile & Adrian, 2000; Ottersen *et al.*, 2001; Parsons & Lear, 2001; Thompson & Ollason, 2001; Attrill & Power, 2002; Beaugrand *et al.*, 2002; Blenckner & Hillebrand, 2002; Lucht *et al.*, 2002). The majority of these responses are observed in the northern middle and high latitudes (over both ocean and land), where strong climatic impact of NAO has been documented (Hurrell, 1996).

Correspondence: Dr G. Wang, tel. 860 486 5648,
e-mail: gwang@engr.uconn.edu

A recent study (Oba *et al*., 2001) indicated that NAO also had a significant impact on the terrestrial ecosystem in part of tropical Africa during the 1980s. It was shown that the NAO, together with some input from the El Nino Southern Oscillation (ENSO), explains more than 60% of the variance in the vegetation productivity over the Sahelian zone of Africa (i.e. the semiarid region to the south of the Sahara desert). A similarly strong response to NAO was documented in the retreat and expansion of the Sahara desert as well as the location shift of the 200 mm $yr^{-1}$ rainfall isoline. These led Oba *et al*. (2001) to suggest that the climate and ecosystem dynamics over the Sahel relate largely to natural climate fluctuations as reflected by the NAO and ENSO, and that NAO and ENSO indices may provide reliable prediction regarding the response of the Sahelian climate/ecosystem to global climate variability.

Over the Sahelian region in the last three decades of the twentieth century, a severe drought caused the worst human famine and ecosystem disruption in recent African history (Graetz, 1991; Nicholson *et al*., 1998), which motivated numerous studies that seek to understand the mechanisms governing the variability and changes of the Sahelian precipitation. According to these studies, precipitation over Sahel is subject to natural oceanic forcing such as changes of the regional and global sea surface temperature distributions (e.g. Lamb, 1978; Folland *et al*., 1991; Rowell *et al*., 1995; Ward, 1998); at the same time, anthropogenic disturbances on vegetation (e.g. desertification) and more importantly, the subsequent feedback between precipitation and vegetation, also has a significant impact on the Sahelian rainfall (e.g. Charney *et al*., 1977; Xue & Shukla, 1993; Xue, 1997; Zheng & Eltahir, 1997; Wang & Eltahir, 2000a, b, 2002; Clark *et al*., 2001). The recent study on the correlation between NAO and the Sahelian vegetation productivity (Oba *et al*., 2001) raised an interesting perspective that the atmospheric oscillation system NAO may also play an important role in the dynamics of this regional climate and ecosystem. This, if confirmed, will have significant implications regarding the prediction of agricultural yields in Africa, which can then benefit the regional economic development and societal stability.

This study tests the conclusion of Oba *et al*. (2001) using data from extended periods, including Normalized Difference Vegetation Index (NDVI) during the period 1981–2001 and precipitation as a proxy for vegetation productivity during the period 1900–1998. Precipitation is chosen as the proxy because it is the main limitation for vegetation growth and crop yields in arid to semiarid regions such as the Sahel, and existing data indicates that the NAO influences vegetation productivity in the Sahelian region entirely through precipitation. Results of this study indicate that there is no consistent correlation between NAO and vegetation productivity over the Sahel. Therefore, NAO index cannot provide a reliable prediction for the response of Sahelian ecosystem to large-scale climate variability.

## Data description and methodology

This study is based on statistical analyses on the relationships among vegetation productivity and rainfall in the Sahelian region of Africa and global climate oscillating systems including NAO and ENSO. The Sahel generally refers to the land area approximately from 16° to 40°E and from 12.5° to 17.5°N. The NDVI based on the monthly NOAA/NASA Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Land data is used as an index for vegetation productivity. These data are derived from the five-channel cross-track scanning AVHRR aboard the NOAA afternoon polar-orbiting satellite series (NOAA-7, -9, -11, and -14), and are available from the Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Center (ftp://daac.gsfc.nasa.gov/data/avhrr/continent/africa/). The Pathfinder AVHRR NDVI data used here has a spatial resolution of 8 km, and spans the period from 1981 to 2001. For rainfall index, the annual rainfall from the gridded archive of station precipitation data by Hulme *et al.* (1998) is used, which covers the period from 1900 to 1998. The CAMS–OPI data (Janowiak & Xie, 1999), a merged precipitation dataset based on both rain gauge measurements and satellite estimates for the period 1979–1999, is also used to provide a comparison between pre- and postsatellite rainfall data. The analysis presented in this paper makes use of the annual rainfall index and the growing-season (July–October) NDVI, both averaged over the approximate 200–400 mm $yr^{-1}$ long-term precipitation zone in the Sahelian region for consistency with previous studies in the area of average (Tucker *et al*., 1991; used in Oba *et al*., 2001). The location of the 200 and 400 mm $yr^{-1}$ rainfall isolines is determined based on the half-degree resolution terrestrial climatological data (for the period of 1961–1990) from New *et al*. (1999), which agrees well with that based on the CAMS–OPI climatology. It is worth pointing out that the choice of the average zone within the Sahel has little impact on the results of this study, due to the high degree of spatial coherency in the inter-annual variation of the Sahelian precipitation. For example, Fig. 1 plots the growing season NDVI average over the 200–400 mm $yr^{-1}$ precipitation zone vs. the average over the latitudinal band 12.5–17.5°N in North Africa, which shows a strong linear relationship between the NDVI averaged over these two different areas with a correlation coefficient of 0.96. Therefore, conclusions from this study should also apply to the more broadly defined Sahelian region

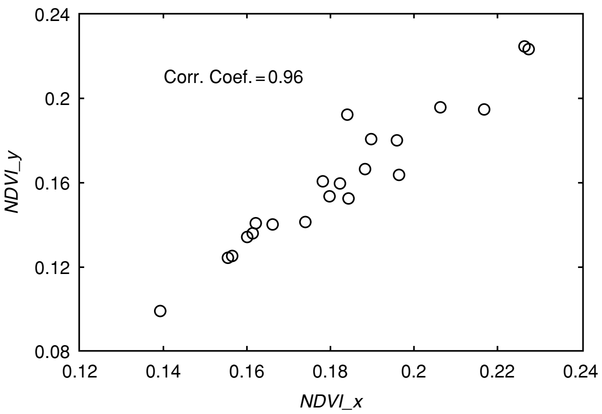


**Fig. 1** The growing-season NDVI averaged over the 200–400 mm yr$^{-1}$ precipitation zone (labeled as *NDVI_y*) vs. the growing season NDVI average over the 12.5°–17.5°N latitudinal band in Africa (labeled as *NDVI_x*), during the period 1981–2001. Each open circle represents the NDVI averages during the growing season (July–October) of an individual year for two different areas, with its *x*-coordinate and *y*-coordinate corresponding to the values of *NDVI_x* and *NDVI_y*, respectively.

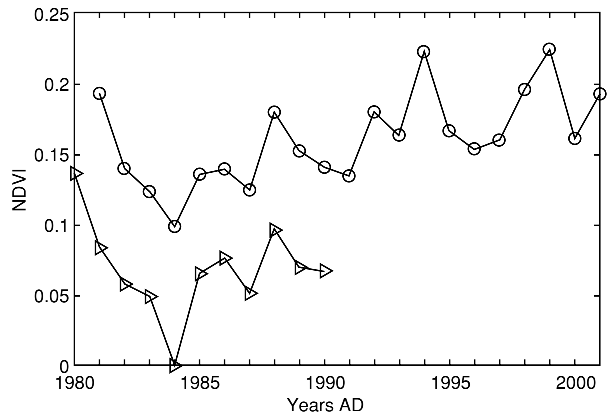


**Fig. 2** Growing-season NDVI averaged over the area between 200 and 400 mm annual rainfall isolines in the sub-Saharan region. Solid line with open circles represents the NDVI time series used in this study, and solid line with triangles represents that derived by Tucker *et al*. (1991) and used in Oba *et al*. (2001). The correlation coefficient between these two time series during the overlapping period (1981–1990) is 0.94.

(e.g. the Sahel defined as the latitudinal band between 12.5° and 17.5°N in Africa).

Compared with the Oba *et al*. (2001) study using NDVI data over the period 1980–1990, the longer NDVI record used here (1981–2001) can provide more reliable statistical information. The Pathfinder NDVI data starts from July 1981, after the launch of NOAA-7 in June 1981. Pre-1981 NDVI data was derived from the AVHRR aboard the morning polar orbiter NOAA-6, while measurement from afternoon polar orbiters (e.g. NOAA-7, -9, -11, and -14) is preferred for producing NDVI data for its low solar zenith angle. As shown in Fig. 2, for the overlapping period 1981–1990 in the Sahelian region, the NDVI used here (from Pathfinder) follows the same pattern of inter-annual variability as that derived by Tucker *et al*. (1991) (which was used by Oba *et al*., 2001), with a high correlation coefficient of 0.94 between these two time series. Differences in absolute magnitude arise mainly from differences in the algorithm used to process the AVHRR record into NDVI products and from differences in data calibration over desert. For example, the NDVI value over desert was set to zero in the product used by Oba *et al*. (2001) but varies approximately between 0.0 and 0.1 in the Pathfinder NDVI product used here. Despite the magnitude difference, however, over arid and semiarid regions such as the Sahel, the impact of different algorithms on the seasonal and inter-annual variability as well as long-term trend of NDVI is negligible, as evidenced in Fig. 2.

The NAO and ENSO indices are obtained from the National Center for Atmospheric Research website: http://www.cgd.ucar.edu/. The ENSO index is based on SST anomaly averaged over the Nino 3.4 region (Trenberth & Stepaniak, 2001), and the NAO index is defined as the difference in normalized sea level pressure anomalies between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland (e.g. Hurrell, 1995). Correlation analyses based on NDVI and NAO/ENSO indices for various seasons with different time lags indicate that vegetation productivity in the Sahelian region is most strongly correlated with NAO index in the previous winter and ENSO index in the previous fall. Therefore, this study focuses on the NAO winter index (December–March) (similar to Oba *et al*., 2001) and the ENSO fall index (September–November), and examines the impact of NAO and ENSO on the Sahelian eco-hydrological system based on their correlation with precipitation during the period 1900–1998.

This study first examines the significance of the correlation between NDVI and NAO during the period when reliable NDVI data is available from 1981 to 2001. The large difference found in the significance of NDVI–NAO correlation between different portions of this period warrants the need for further analysis. Over the Sahelian region, in addition to livestock grazing and anthropogenic land cover changes, water availability is the primary controlling factor for vegetation growth and productivity. Therefore, it is expected that large-scale climate processes such as the NAO and ENSO influence the Sahelian vegetation productivity through their impact on precipitation. This is further confirmed using the partial correlation analysis among NDVI, precipitation, and NAO/ENSO indices. Since precipitation is the mechanism linking Sahelian ecosystem to large-scale climate forcing, the impact of NAO and ENSO on the dynamics of this regional ecosystem at longer time scales can be studied by examining their impact on precipitation, the record of which dates back much further than the NDVI data. In this study, the correlation, or the lack of it, between Sahelian precipitation and NAO/ENSO indices is documented based on data spanning the period 1900–1998. Instead of lumping together the data from the whole time series in one regression, the correlation is analyzed using 11-year and 21-year data in a moving window, which can clearly demonstrate the variation of this relationship with time.

## Results and discussion

The Sahelian vegetation productivity as described by the area-averaged NDVI data during 1981–2001 does not show a significant correlation with the hemispheric atmosphere oscillation mode described by the NAO index. In fact, the correlation is negligible, as shown by the coefficient of determination (0.03) in Table 1. This seems to contrast the strong correlation shown by Oba *et al*. (2001) using data from 1980 to 1990, especially since the same NAO index and similar NDVI data are used. Further analysis indicates that the difference in correlation significance is caused by the strong variation of this relationship with time. Linear regression on the NAO and NDVI data during 1981–1990 (the overlapping period between the NDVI data used here and that derived by Tucker *et al*. (1991) used in the Oba *et al*. (2001) study) indicates that the two NDVI time series are similar in their correlation with NAO. During this overlapping period, the NAO index explains 26% of the NDVI variance in the Tucker *et al*. data, and 22% in the Pathfinder data used for this study, as shown in Table 1. While these coefficients of determination based on the 10 years of data (1981–1990) are both significantly higher than that based on the 21 years of data (1981–2001), none of them exceeds the 5% significance level. When the NDVI for the year 1980 from the Tucker *et al*. data is included as Oba *et al*. did, this coefficient of determination increases to 46% for the period of 1980–1990 (Table 1), which is approximately the same as what Oba *et al*. (2001) showed. Therefore, the difference between this study and the Oba *et al*. (2001) study in the correlation significance is mainly due to the difference in the period of data coverage rather than differences in the derived NDVI data. The fact that one data point makes a dramatic difference regarding whether the correlation is significant necessitates more careful study of this relationship. At the same time, the substantial decrease of determination coefficient from 0.22 in 1981–1990 to 0.03 in 1981–2001 raises the question of whether the correlation between Sahelian productivity and NAO is abnormally high in the 1980s or abnormally low in the 1990s, a question that can only be addressed with a longer data record. Since reliable direct record for vegetation before 1981 is not available, an alternative way of addressing this issue is to use proxy data, which can be identified based on the mechanism through which the NAO system influences vegetation productivity in the Sahel. Similar analysis on the relationship between Sahelian NDVI and ENSO index is also carried out, but the results (not shown here) indicate that the correlation is weak in both 1980s and 1990s.

Large-scale climate oscillations such as NAO and ENSO influence the productivity of various ecosystems through their impact on climate variables such as temperature and precipitation. Over the Sahelian region in Africa, due to extreme aridity, vegetation productivity is mainly limited by water availability. As a result, at the inter-annual time scale, precipitation explains more than 65% of the NDVI variance for both 1980s and 1990s (Table 1). Similar to the NDVI–NAO relationship, the correlation of annual rainfall based on the Hulme precipitation data with the NAO index is strong ($R^2 = 0.42$) for the period of 1981–1990, but becomes relatively weak when data from the 1990s is included ($R^2 = 0.12$) (Table 1). The significant temporal variation in its correlation with NAO is not unique to rainfall index derived from the Hulme station precipitation data. Rainfall index derived from the CAMS–OPI precipitation data (which includes input from satellite measurement) correlates with the

**Table 1** Coefficients of determination ($R^2$)

| Time period | $NDVI_T$ vs. NAO | $NDVI_W$ vs. NAO | Rainfall vs. NAO | $NDVI_W$ vs. Rainfall | $NDVI_W$/Rainfall vs. NAO |
|---|---|---|---|---|---|
| 1981–2001* | – | 0.03 | 0.12 | **0.69** | < 0.01 |
| 1981–1990 | 0.26 | 0.22 | **0.42** | **0.66** | < 0.01 |
| 1980–1990 | **0.46** | – | – | – | – |

$NDVI_T$ stands for the Sahelian NDVI time series of Tucker *et al*. (1991), which is used in the Oba *et al*. (2001) study; $NDVI_W$ stands for the Sahelian NDVI time series used in this study. $NDVI_W$/Rainfall stands for the residual $NDVI_W$ variance that cannot be explained by the rainfall information. A value in bond face indicates that a correlation passes the 5% significance test.
*When correlation with rainfall is involved, only the data before 1998 is used.

NAO index in a similar manner, with an $R^2$ of 0.58 for the 1980s and $R^2$ of 0.01 when data from the 1990s is included. Moreover, as evidenced by the close-to-zero partial correlation coefficients in Table 1, the NAO index does not explain any of the residual variance in the vegetation productivity that cannot be explained by the rainfall fluctuations (Table 1). Therefore, NAO influences the Sahelian ecosystem productivity exclusively through its impact on precipitation. Consequently, based on the correlation between NAO index and rainfall (the available record of which is much longer than that of NDVI), one can address the question of whether the stronger correlation in the 1980s or the weaker correlation in the 1990s is more representative of the relationship between NAO and Sahelian vegetation productivity.

Figure 3 plots the correlation coefficients of two individual correlation analyses, one between the Sahelian rainfall index and the NAO index of the previous winter and one between the Sahelian annual rainfall index and the ENSO index of the previous fall, conducted based on data in a moving window of 11 years (Fig. 3a) and 21 years (Fig. 3b). The coefficient of correlation between Sahelian rainfall and NAO index varies significantly with time, and fluctuates between positive and negative values. In other words, there is no consistent relationship between NAO and Sahelian rainfall (therefore vegetation productivity). In addition, the correlation of precipitation with NAO index does not exceed the 5% significance level during most of the twentieth century except in the 1930–1940s and 1980s. However, these two periods differ in the nature of the relationship – positive NAO phase in the 1930–1940s corresponds to wetter-than-normal conditions, while the same NAO polarity in the 1980s corresponds to drier-than-normal conditions. The relationship between Sahelian rainfall and ENSO index is not temporally consistent either. The correlation is strongest in the 1930–1940s, and is not significant during a substantial portion of the twentieth century. Increasing the width of the moving window from 11 to 21 years does not change these results (Fig. 3b). It is worth mentioning that the NDVI–NAO correlation tends to be even weaker than the rainfall–NAO correlation (as shown in Table 1), perhaps as a result of vegetation being subject to external disturbances such as anthropogenic land use/land cover changes and livestock grazing. Note that during the late 1960s and early 1970s when the onset of a severe drought caused catastrophic human famine in the Sahel, the correlation between Sahelian rainfall and the NAO/ENSO index was extremely weak. This excludes the NAO and ENSO indices from the pool of causal factors for the 20th century drought and famine in the Sahelian region.

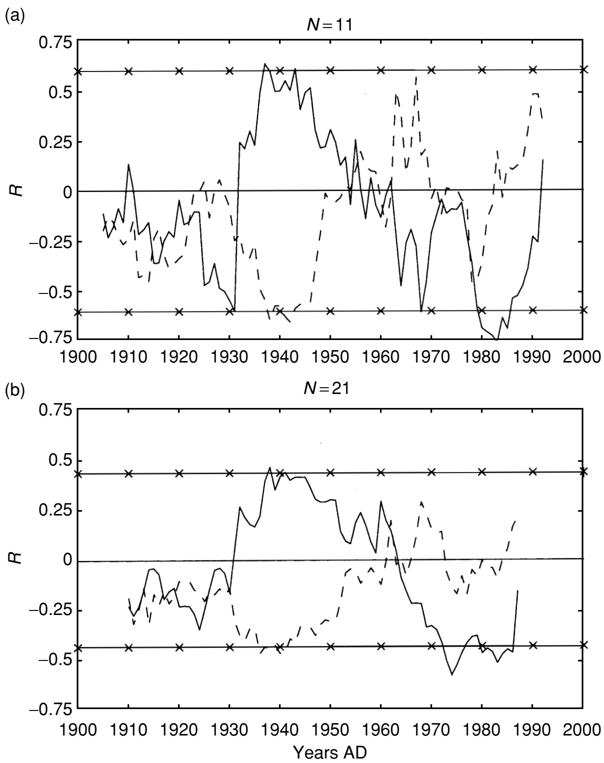


**Fig. 3** Temporal variation of the correlation coefficients between Sahelian rainfall and the NAO index in the previous winter season (solid line), and between Sahelian rainfall and the ENSO index in the previous fall season (dashed line). Each correlation coefficient is calculated based on $N$ years of data in a sliding window: (a) $N = 11$; (b) $N = 21$. Solid lines with crosses indicate the threshold values for correlation coefficient at 5% significance level.

What may have caused the substantial fluctuation in the NAO/ENSO–rainfall correlation is beyond the scope of this study. However, the analysis presented here clearly demonstrates that the impact of NAO and ENSO on Sahelian ecosystem productivity is not as strong as previously suggested. The strong correlation between NAO and NDVI during the 1980s does not reflect the normal state of their relationship.

To examine the combined effect of NAO and ENSO on rainfall and ecosystem productivity in the Sahelian region, stepwise multiple linear regression analysis has been conducted. Figure 4 shows the fraction of precipitation variance that can be explained by the NAO and ENSO indices combined, as well as the coefficient of determination by NAO index alone. The difference between them measures the contribution from ENSO that is additional to the NAO contribution. Similar to the individual analysis on the NAO impact, the coefficient of determination of precipitation by NAO and ENSO combined exceeds the 5% significance level only in part of the1930–1940s and 1970–1980s, and is not significant during the rest of the twentieth century. The NAO and

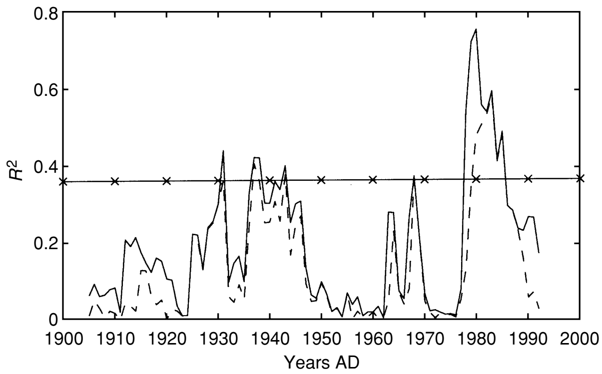


**Fig. 4** Temporal variation of the determination coefficients from the multiple regression analysis between the Sahelian rainfall, NAO, and ENSO indices (solid line), based on 11 years of data in a sliding window. For comparison, the dash line shows the coefficients of determination for the individual correlation analysis between Sahelian rainfall and NAO index. The solid line with crosses indicates the threshold value at the 5% significance level.

ENSO indices cannot provide a consistent prediction of precipitation or ecosystem productivity in the Sahel.

## Conclusions

This study provides a reassessment regarding the impact of large-scale climate oscillating systems on the terrestrial ecosystem dynamics in the Sahelian region of Africa, and focuses on the NAO. It is concluded that the correlation between Sahelian vegetation productivity and the NAO index is not as strong as previously suggested. The relationship between NAO index and vegetation productivity in the Sahelian region differs significantly between 1980s and 1990s, and substantial temporal variation of this relationship is also evident during the rest of the 20th century. Specifically, the correlation coefficient between the NAO index and eco-hydrological conditions in the Sahelian region fluctuates between positive and negative values, and does not pass the 5% significance test during most of the twentieth century. In other words, the NAO does not have a temporally consistent impact on Sahelian ecosystem and climate. The same holds true for the impact of ENSO. Large-scale climate variability as described by the NAO and ENSO indices cannot provide a consistent prediction for the ecosystem productivity in the Sahel. Findings of this study also disqualify NAO and ENSO as possible candidates for causes of the desertification, severe drought and famine that took place over the Sahelian region in the recent past.

The regional biosphere–atmosphere system in the Sahel are known to be sensitive to certain large-scale climate forcings such as regional and global sea surface temperature distribution changes (e.g. Ward, 1998) and local processes such as anthropogenic land cover changes and livestock grazing (e.g. Xue, 1997; Wang & Eltahir, 2000a,b; Clark *et al.*, 2001). NAO has been shown to influence precipitation in the Mediterranean region and part of North Africa, with drier conditions corresponding to the positive phase of NAO (Hurrell, 1995, 1996). However, the region of such impact usually does not reach far south enough to include the Sahelian region. Even though an abnormal southward shift of this impact region would link the Sahelian biosphere–atmosphere system to NAO, the fluctuation between negative and positive correlations is rather intriguing.

Although the focus of this study is on the Sahelian ecosystem, the finding is of general importance. Statistical investigation of ecological processes and their response to large-scale climate variability such as NAO requires long-term data (Wunsch, 1999). A strong relationship based on short records can be of potential use within its calibration period (e.g. to fill missing data in a retrospective manner). However, its application beyond the calibration period (e.g. for prediction purpose) can be potentially misleading.

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Comments and suggestions from the subject editor and three anonymous reviewers significantly improved this paper. Data for the NAO index was obtained from the web site of Dr James Hurrell at NCAR, and the ENSO index was made available at the NCAR website by Dr Kevin Trenberth. Thanks also go to Dr Molly Brown at the NASA/GSFC Biospheric Science Branch for very insightful discussion and to Dr Tong Zhu at the NASA/GSFC Global Land Biosphere Data support team for her help with the Pathfinder AVHRR NDVI data. The AVHRR data were provided by the Earth Observing System Data and Information System (EOSDIS), Distributed Active Archive Center at Goddard Space Flight Center which archives, manages, and distributes this data set.

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