GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.4, PAGES 489-492, FEBRUARY 15, 1999

Nilometers, El Niño, and Climate Variability

Elfatih A. B. Eltahir and Guiling Wang

Ralph M. Parsons Laboratory, Massachusetts Institute of Technology
Cambridge, Massachusttes

Abstract. Nilometers have been used for gauging the level of water in the Nile river for more than five millennia. The written records describing some of these measurements represent the longest written records for any hydrological phenomenon. They describe interannual fluctuations in the Nile river flow which are closely associated with El Niño phenomenon. Here, we use information about long-term variability in El Niño occurrences that has been extracted from the Nilometers records to test the significance of the recent trend in the frequency of El Niño years. We show that the observed frequency of El Niño years during the last two decades is rather high compared to the long-term statistics that are computed from about a thousand years of Nilometers data; however similar levels of activity have been observed during the first millennium.

Introduction The observed increase in the frequency of El Niño years during the last few decades may be partly caused by the evident increase in the concentration of greenhouse gases (Trenberth and Hoar, 1996). This hypothesis is consistent with the results of a recent study (Meehl and Washington, 1996) that simulated the response of a numerical model describing the coupled global ocean-atmosphere system to the increase in the concentration of atmospheric carbon dioxide, and deserves further investigation. In particular, we need to evaluate accurately the statistical significance of the recent trend in El Niño occurrences. Considerable differences exist between the conclusions of the different studies on the statistical significance of the observed change in the frequency and duration of El Niño events during the last two decades (Trenberth and Hoar, 1997; Harrison and Larkin, 1997; Rajagopalan *et al*, 1997). Estimates of the corresponding return periods range from a few hundreds to a few thousands of years. These estimates are based on statistical analysis of relatively short records of El Niño indices. There is a need for a consistent analysis on a long-term record of the El Niño years in order to determine the statistical significance of the recent trend in this phenomenon.

Here, we propose to use the history of observations of water level in the Nile river to test the statistical significance of the recent trend in the El Niño phenomenon. The well established association between El Niño and the Nile river flow is supported by extensive observational evidence (Bliss, 1925; Quinn, 1992; Eltahir, 1996; Aramarasekera *et al*, 1997; Wang and Eltahir, in press). It is worth noting that the coherency between the ENSO index and the Nile flood has a distinguished peak at the time scale of 4-5 years, which is close to the ENSO time scale (see Figure 3c of Wang and Eltahir, in press). Warming in the equatorial eastern Pacific is associated with rising motion over the eastern and central Pacific ocean and sinking motion over most of the remainder of the tropics, including the sources of the Blue Nile over the Ethiopian Plateau (Eltahir, 1996; Aramarasekera *et al*, 1997). The East African monsoon is the main rainfall-producing mechanism over the Blue Nile catchment and provides the teleconnection between El Niño and the Blue Nile flow. During the flood season, from July to October, most of the water in the main Nile is supplied by the Blue Nile. Thus, a warm Sea Surface Temperature (SST) in the Pacific ocean is associated with anomalous sinking motion over the Indian ocean and surrounding land regions, less rainfall over Ethiopia (Wang and Eltahir, in press), and drought conditions in the river flow of the Blue Nile and that of the main Nile (Eltahir, 1996; Aramarasekera *et al*, 1997).

The Nile water is of critical importance to the ancient and modern civilizations of Egypt. Nilometers have been used for gauging the level of water in the Nile river for more than five millennia. Written records describing some of these measurements are available for most of the last fourteen centuries and they perhaps represent the longest written records for any hydrological phenomenon. Quinn (1992) analyzed these records carefully, with the objective of extending the recorded history of the El Niño-Southern Oscillation (ENSO) phenomenon. He developed an index that is based on the fluctuations in the Nile water level. Diaz and Pulwarty (1992) compared this Nile index to other ENSO indices and confirmed that the compilation of the Nile flood intensity record by Quinn represents a valuable contribution to ENSO studies. This recorded history of the Nile flood has been used in studying the long-term natural variability of the El Niño phenomenon (Anderson, 1992). Here, we extend the Nile flood record up to 1997 and use it to study the statistical significance of the recent trend in this phenomenon.

Naturalization of the Nile Data The interannual fluctuations in the Nile water level during the summer months should reflect the natural variability in the East African monsoon and the El Niño phenomenon. However, during this century the extent of the human impact on the natural flow of the Nile river has reached a point where direct measurements of the river flow may no longer be indicative of the natural variations in the monsoon system. In particular, the extraction of water from the Blue Nile for irrigation purposes in Sudan, and the construction of the High Aswan dam had noticeable effects on the observed fluctuations of river flow.

Careful consideration has been given in this study to the elimination of the effects of the two anthropogenic factors mentioned above. First, we use two complementary observational records from two nearby stations:

Paper number 1999GL900013.
0094-8276/99/1999GL900013$05.00

Aswan and Dongola, to characterize the recent history of the Nile flow. Dongola is located on the Nile river at about 600 kilometers upstream from Aswan. The flow records at Dongola are useful for characterizing the natural flow of the Nile after the construction of the High Aswan dam. Second, we estimate the water extraction in Sudan. The extraction of water occurred after 1925 when Sennar dam was built to supply water for the Gezira irrigation scheme. The water extraction can be estimated by the change, with reference to the period before 1925, in the difference between the observed flow at Roseris station and Khartoum station for the period 1912-1997. Both stations are located on the Blue Nile. Roseris is located near the Sudan/Ethiopia boarder, upstream from where the extraction occurred. Khartoum is located at the confluence of the Blue Nile and the White Nile, downstream from where the extraction occurred. After estimating the water extraction, the Nile flood series at both Aswan station and Dongola station can then be naturalized by adding the water extraction estimates to the observed series.

Figure 1 shows the resulting naturalized series of the summer flood at Aswan and Dongola. These two series are highly correlated, and they collectively describe the recent history of the Nile river flow for the period 1871-1997.

El Niño Index Based on Nilometer Records The normalized fluctuations of the summer flood for Aswan and Dongola are presented in Figure 2 in comparison to the normalized fluctuations of the SST within the Pacific Ocean (a standard index of El Niño). The SST data used here is from the UKMO global data set. It has been averaged for the regions 6-2N, 170-90 W; 2N-6S, 180-90 W; and 6-10S, 150-110W (same as the area used by Wright, 1989). The SST records have

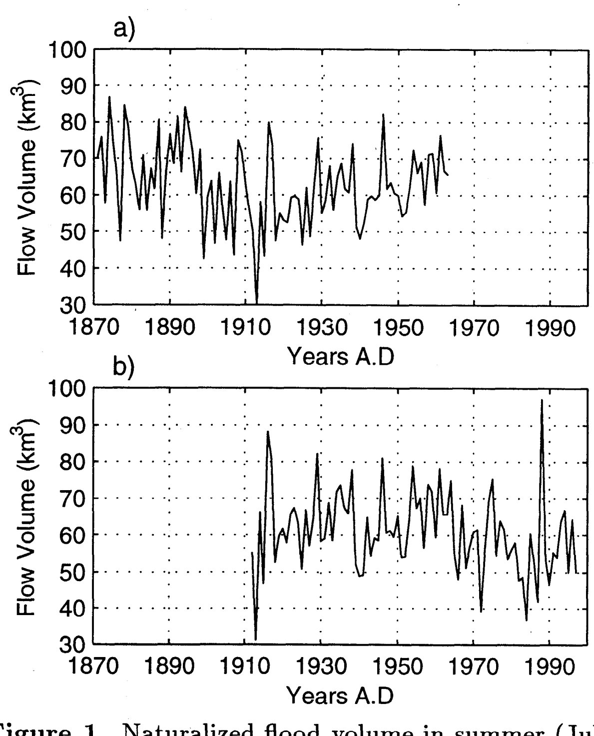


Figure 1. Naturalized flood volume in summer (July to October) at (a) Aswan for the years 1871-1964; and (b) Dongola for the years 1912-1997.

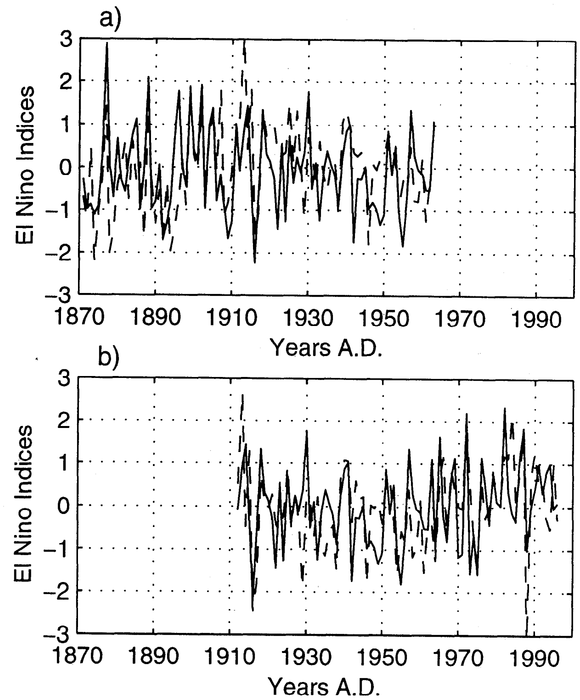


Figure 2. A comparison between two indices of El Niño based on SST in the Pacific Ocean (continuous line) and the summer flood of the Nile river (dashed line) at (a) Aswan; and (b) Dongola.

also been averaged from September through November, which has the most significant correlation with the Nile flood (Eltahir, 1996). The coefficient of correlation between Nile flood and SST in the Pacific ocean is about -0.54. This coefficient is quite significant, especially if we compare it to the corresponding coefficient for the correlation between the SST index of El Niño and the Southern Oscillation Index (SOI) which is about - 0.78. However, examination of Figure 2 reveals the non-stationary nature of the association between the Nile floods and ENSO. During the decades of the 1930s and 1940s, this correlation is less significant than in other periods. Hence, we emphasize that the analysis described in this report assumes that the correlation between the two phenomena remains always significant (Allan *et al*, 1998). We have analyzed the naturalized series of the Nile river flow for the last 127 years using the same criterion that has been developed by Quinn (1992). This analysis estimates the order of El Niño in each year based on the departure of summer (July-October) flood volume at Aswan station from the 50-year moving average. Order 1 corresponds to a departure of somewhere between 5.5 km^3 to 10.9 km^3; order 2 corresponds to a departure between 10.9 km^3 and 16.4 km^3; order 3 corresponds to a departure between 16.4 km^3 and 21.8 km^3; order 4 corresponds to a departure between 21.8 km^3 and 27.3 km^3; order 5 corresponds to a departure larger than 27.3 km^3. The estimated El Niño order time series is shown in Figure 3, which reflects the recent increase in frequency of El Niño years that has been reported by other studies (Trenberth and Hoar, 1996).

El Niño is not the only factor that affects the river flow in the Nile. In fact, it only explains about 30%

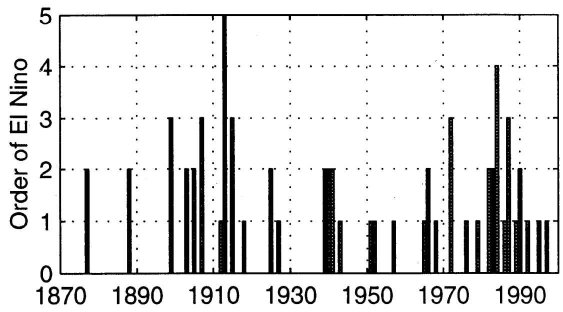
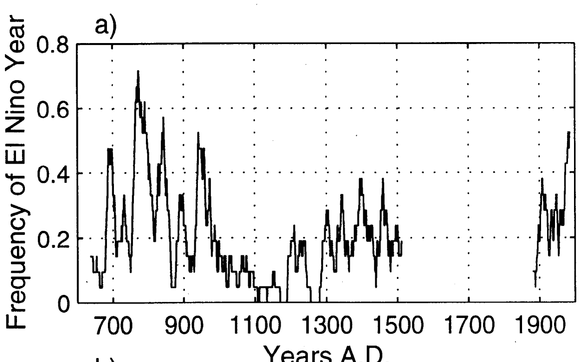


Figure 3. Order of El Niño years estimated based on the Nile flow series of Figure 1.

(based on the correlation coefficient of -0.54) of the variability in the Nile flood. There must be some other factors that influence the rainfall generation over the Nile river watershed. Consequently, certain degree of discrepancy exists between the Nilometer-based El Niño record in Figure 3 and the standard El Niño record based on the Pacific SST. For example, a weak La Niña was observed in 1984, while the Nile flood record signaled a strong El Niño in that year. Discrepancy in El Niño strength also exists in some El Niño years. However, in general, the Nilometer record still captures most of the variability of El Niño phenomena.

In order to study the low frequency variability of any phenomenon we need to consider records that are long enough to resolve those low frequencies. Otherwise, we have to assume that the conditions experienced in the



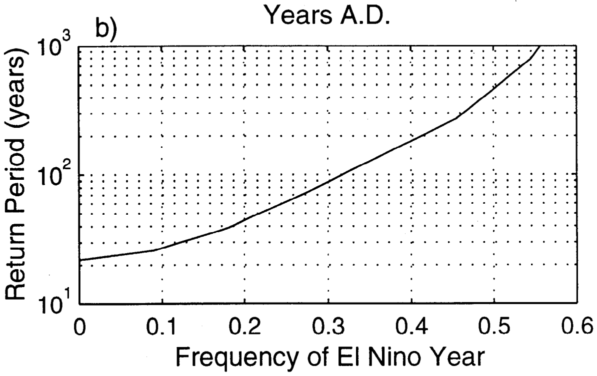
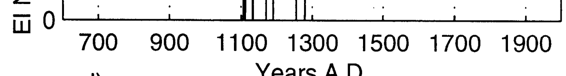


Figure 4a. Frequency of El Niño years based on the estimation of the El Niño order by Quinn (1992) for the period 622-1522 A. D., and based on the El Niño order series of Figure 3 for the period 1871-1997 A. D..
Figure 4b. The return period describing the frequency of El Niño years.

short record are representative of longer periods. In order to avoid such assumptions, we use the recorded history of the Nile river flow as a long-term record of the El Niño phenomenon. By taking this approach, we gain additional information about the low frequency variability of this phenomenon at the expense of sacrificing some of the accuracy in our estimates of the frequency of El Niño years. In the following analysis, the El Niño order by Quinn (1992) based on Nilometer records are used for the period 622-1522 A.D., and the El Niño order series of Figure 3 are used for the period 1871-1997 A.D.. The Nilometer records between 1522-1870 A.D. have not been included here since for political reasons those records include several gaps.

Results and Conclusions Figure 4a describes consistent estimates of the frequency of El Niño years that are based on the relatively recent and short record of observations on the Nile river flow (Figure 3) as well as long-term Nilometers records. Any year for which the order of El Niño is greater than zero is identified as an El Niño year. The frequency of El Niño years is computed using a 21-year moving average. Figure 4b shows the return period of the El Niño years, derived empirically using the frequency record of Figure 4a. In Figure 4c, the frequency of the El Niño events are calculated. An El Niño event is defined as a continuous series of one or more El Niño years. The 21-year moving average of the duration of El Niño events is shown in Figure 4d.

Examination of Figures 4a-d reveals several important observations. The long-term variability in the frequency of El Niño years is the result of two factors: variability in the frequency of El Niño events (Figure 4c), and variability in the average duration of El Niño events (Figure 4d). The former reflects changes in the wavelength of the ENSO phenomenon. The recent increasing trend in the frequency of El Niño years is largely due to



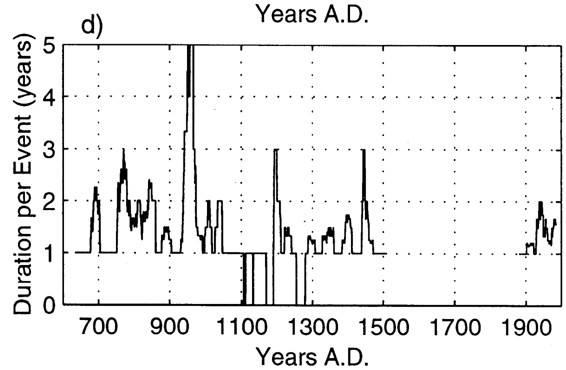


Figure 4c. Frequency of El Niño events.
Figure 4d. Average duration of El Niño events.

an increase in the frequency of El Niño events. The frequency of El Niño events within the last two decades is similar to the observed frequency in the first few decades of this century. However, the average duration of the recent events is longer than those experienced in the early decades of this century. As a result, the frequency of El Niño years during the last two decades is the highest for this century. The same frequency is also significantly high compared to the long-term statistics; however such a burst of El Niño years is not entirely unprecedented. Similar levels of activity were experienced during the last three centuries of the first millennium.

The information about the long-term variability in El Niño years is then used to test the statistical significance of the recent trend in the frequency of El Niño years. The rate of El Niño years during the last two decades is about 5 years per decade. The corresponding return period, based on Figure 4b, is about 450 years. According to Figure 4a such a high frequency of El Niño years was never sustained for more than a few decades. It remains to be seen if the current episode of rather frequent El Niño years will be sustained for more than a few decades. If that happens, then such an episode would present a clear sign of a significant change in the global climate.

Acknowledgments. The authors would like to thank the two anonymous reviewers for their helpful comments. Their suggestions improved the quality of this paper.

References

Allan R., J. Lindesay, and D. Parker, El Niño Southern Oscillation and Climatic Variability. 405pp., CSIRO Australia Publications, 1998

Amarasekera, N. A., R. F. Lee, E. R. Williams, and E. A. B. Eltahir, ENSO and the natural variability in the flow of tropical rivers, *Journal of Hydrology*, 200, 24-39, 1997

Anderson R. Y., Long-term changes in the frequency of occurrence of El Niño events. In *El Niño: Historical and Paeoclimatic Aspects of the Southern Oscillation*, edited by Diaz, H. F., and Markgraf, V. , 193-200, 1992

Bliss, E. W., The Nile flood and world weather, *Memoirs Roy. Meteorol. Soc.*, 4(23), 53-84, 1925

Diaz, H. F., and R. S. Pulwarty, A comparison of Sounthern Oscillation and El Niño signals in the tropics. In *El Niño : Historical and Paeoclimatic Aspects of the Southern Oscillation*, edited by Diaz, H. F., and Markgraf, V., 175-192, 1992

Eltahir, E. A. B., El Niño and the natural variability in the flow of the Nile river, *Water Resources Research*, 32 (1), 131-137, 1996

Harrison, D. E., and N. K. Larkin, Darwin sea level pressure, 1876-1996: evidence for climate change? , *Geophysical Research Letters*, 24(14), 1779-1782, 1997

Meehl, G. A., and W. M. Washington, El Niño-like climate change in a model with increased atmospheric CO_2 concentrations, *Nature*, 382, 56-60, 1996

Popper, W., The Cairo Nilometer. 269pp., Berkeley and Los Angeles, University of California Press, 1951

Quinn, W. H., a study of Southern Oscillation-related climatic activity for A.D. 622-1990 incorporating Nile River flood data, In *El Niño : Historical and Paeoclimatic Aspects of the Southern Oscillation*, edited by Diaz, H. F., and Markgraf, V. , 119-149, 1992

Rajagopalan, B., U. Lall, and M. Cane, Anomalous ENSO occurrences: an alternate view, *Journal of Climate*, 10(9), 2351-2357, 1997

Tousson, O., Memoire sur l'Histoire du Nil, in Memoirres a L'Institut D'Egypte. Cairo. 544pp., Imprimerie de l'Institut Francaise d'Archeologie Orienta, 1925

Trenberth, K. E., and T. J. Hoar, The 1990-1995 El Niño-Southern Oscillation event: longest on record Trenberth, Kevin E. – Hoar, Timothy J., *Geophysical Research Letters*, 23, 57-60, 1996

Trenberth, K. E., T. J. Hoar, El Niño and climate change, *Geophysical Research Letters*, 24(23), 3057-3060, 1997

Wang, G., and E. A. B. Eltahir, Use of ENSO information in medium- and long-range forecasting of the Nile floods, *Journal of Climate*, in press

Wright P. B., Homogenized long-period Southern Oscillation indices, *International Journal of Climatology*, 9, 33-54, 1989

E. Eltahir, Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Room 48-207, Cambridge, MA 02139. (e-mail: eltahir@mit.edu)

G. Wang, Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Room 48-208, Cambridge, MA 02139. (e-mail: glwang@mit.edu)

(Received October 21, 1998; revised December 21, 1998; accepted January 5, 1999.)