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El Niño and the natural variability in the flow of the Nile River

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Abstract. Natural variability in the annual flow of the Nile River has been the subject of great interest to the civilizations that have historically occupied the banks of that river. Here we report results from analysis on two extensive data sets describing sea surface temperature of the Pacific Ocean, and the flow of water in the Nile River. The analysis suggests that 25% of the natural variability in the annual flow of the Nile is associated with El Niño oscillations. A procedure is developed for using this observed correlation to improve the predictability of the Nile flood. A simple hypothesis is presented to explain physically the occurrence of the Hurst phenomenon in the Nile flow.

Introduction

The stories in the Bible and the Koran concerning prophet Joseph and the Pharaoh of Egypt point, among other things, to the importance of the Nile water to the ancient civilizations of Egypt (the subject of these stories is a prediction about the occurrence of a period with food surplus followed by a famine episode in Egypt). In recent history, the High Aswan Dam was constructed to control the annual flow of the Nile and to protect the region against droughts and floods. The huge structure of the dam stands as a witness to the desperate efforts by man to control the natural variability of this vital resource. Any reduction in the uncertainty about the Nile flood would represent a valuable contribution to water resources management in Egypt. This is particularly true given the natural and social conditions in this arid region, where water is by far the most important natural resource, and where the current population problem will increase the demand on water beyond the generous supply of the Nile.

Recent studies [e.g., *Ropelewski and Halpert*, 1987; *Simpson et al.*, 1993] indicate that oscillations in the state of the ocean-atmosphere system in the Pacific region are related to interannual fluctuations of rainfall and river flow in several regions of the world. These oscillations are known as El Niño–Southern Oscillations (ENSO). The early paper of *Bliss* [1925] lists the Nile flood as one of 10 geophysical variables that are related to a Southern Oscillation index. The recent study of *Quinn* [1992] explores the use of the historical record of maximum Nile flood to extend the records of the Southern Oscillation index. In a recent paper, *Moss et al.* [1994] use the Southern Oscillation index as a predictor of the probability of low streamflows in New Zealand. In this study, we test the hypothesis that the natural variability in annual flow of the Nile River at Aswan is related to ENSO and that such information can be used for improving the predictability of the Nile flood. Finally, a simple hypothesis is presented to explain some of the statistical characteristics observed in the time series of Nile flow; in particular, we propose that the relation between ENSO and the Nile flood may explain the Hurst phenomenon: the mean of the annual flow process in the Nile River varies in time following ENSO, resulting in a non-stationary process, and causing the Hurst phenomenon (the term nonstationary is used to indicate that the mean of the process is a variable function of absolute time).

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Data

The data used in this analysis consist of annual flow in the Nile River at Aswan for the century that extends between the years 1872 and 1972. The monthly distribution of the Nile flow is described by Figure 1, which shows the long-term average flow for each month. The annual flow of the Nile (the Nile flood) is defined as the cumulative flow measured from June of any year to May of the following year. A typical monthly flow in the Nile for any year follows closely a seasonal cycle, with one peak and a long recession. Hence most of the natural variability in the Nile flow is captured by the annual flow. The measured flow of the Nile has been naturalized by removing anthropogenic trends, but the findings of this paper are not sensitive to this correction. This data set on the Nile flow has been supplied by the Ministry of Water Resources of Egypt.

The index of ENSO used in this study is a homogenized monthly series of the mean sea surface temperature (SST) anomaly averaged over the regions 6°–2°N, 170°–90°W; 2°N–6°S, 180°–90°W; and 6°–10°S, 150°–110°W during the same time period, 1872–1972. This index of ENSO was published by *Wright* [1989].

Relation Between ENSO and the Nile Flood

The natural series of annual flow of the Nile at Aswan is shown in Figure 2. The years with El Niño events are defined according to the classification of *Rasmusson and Carpenter* [1983] and are marked in Figure 2 with solid circles. From Figure 2 we may conclude that ENSO events are associated with those years when the flow of the Nile is low compared to the long-term average. This observation prompted a more careful look at the correlations of ENSO indices and the Nile flow. The index of ENSO is averaged over four quarters of the year: December, January, and February; March, April, and May; June, July, and August; September, October, and November. Then the correlations between the annual flow of the Nile (the flow from June to May) and the average index of ENSO for each of these quarters are computed. The different quarters are denoted by negative (positive) sign when the correlation is computed between the Nile flood and SST in the

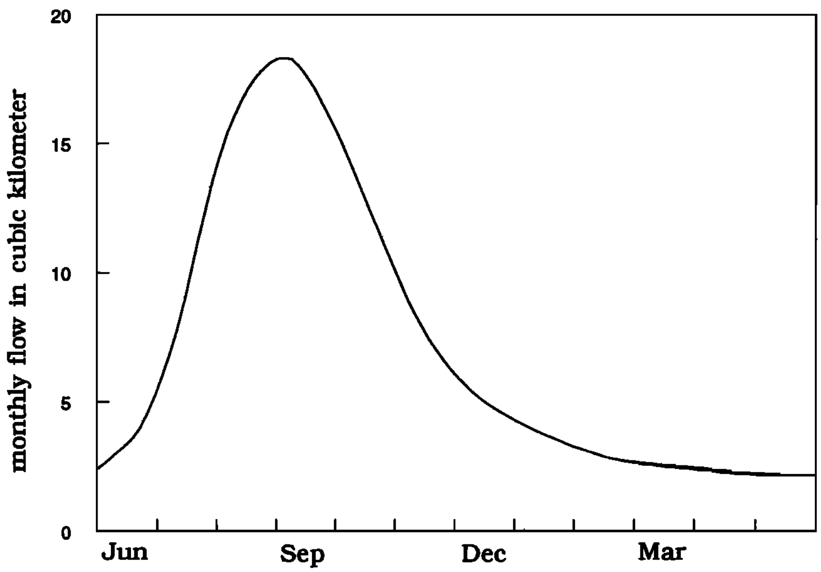

Figure 1. Seasonal cycle of the Nile flow at Aswan.

preceding (succeeding) year. The correlation coefficients are shown Table 1. The correlation between the Nile flow and ENSO index averaged for the months of September, October, and November is about 0.5. The corresponding percentage of the variance in annual flow explained by the ENSO index is 25%. The scatter plot for this relation is shown in Figure 3.

An explanation is provided for the relation between ENSO and the annual flow of the Nile based on observed correlations in the global distribution of sea level pressure. In particular, we note the observed positive correlation between the annual mean sea level pressure at the sources of the Nile, in the Ethiopian Plateau, and the annual pressure at Darwin, Australia [see *Trenberth and Shea*, 1987]. A positive anomaly in the annual surface pressure at Darwin is an indicator of the onset of an ENSO event. But according to the observations, Darwin pressure is positively correlated with pressure anomalies over the Ethiopian Plateau. The laws of atmospheric dynamics require that a positive anomaly in annual sea level pressure over the Ethiopian Plateau is associated with decreased convergence of atmospheric moisture and therefore less rainfall. The observational study of *Janowiak* [1988] confirms that ENSO events are associated with drier than normal levels of summer rainfall in a region that includes the Ethiopian Plateau. This reduction in rainfall causes a negative anomaly in the annual flow of the Blue Nile. The latter contributes most of the interannual variability in the Nile flow.

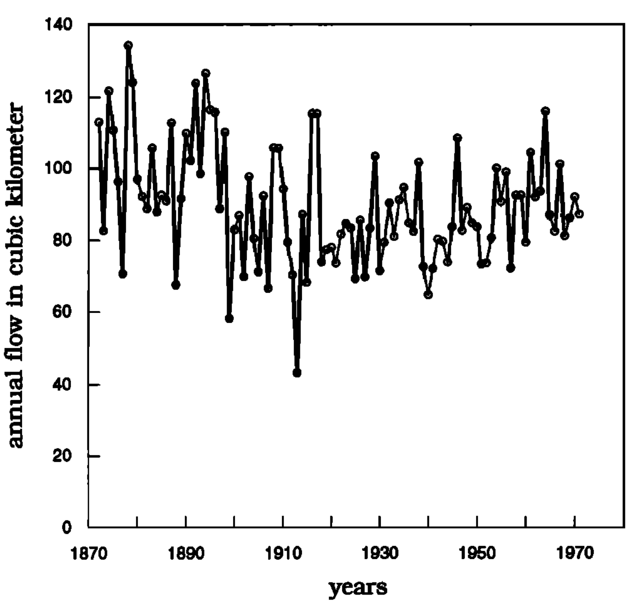

Figure 2. Annual fluctuations of the "natural" flow in the Nile at Aswan for the years 1872–1972. El Niño events are marked with solid circles.

ENSO and Predictability of the Nile Flood

The observed correlation between ENSO and the flow in the Nile has important implications on the predictability of the annual flow in the river. A simple probability table is developed for use in predictions of the Nile flood. This table is based on the classification that is described in Figure 4 and Table 2. An average flood is defined as the annual flow that has a magnitude between 80 and 100 km^3. The long-term average for the

Table 1. Coefficients of Correlation Between the Annual Flow of the Nile and the Index of ENSO Averaged for Different Quarters of the Year

Quarter of the Year	Coefficient of Correlation
Sept.,$^-$ Oct.,$^-$ Nov.$^-$	−0.15
Dec.,$^-$ Jan., Feb.	−0.20
March, April, May	−0.36
June, July, Aug.	−0.45
Sept., Oct., Nov.	−0.50
Dec., Jan.,$^+$ Feb.$^+$	−0.49
March,$^+$ April,$^+$ May$^+$	−0.42
June,$^+$ July,$^+$ Aug.$^+$	−0.06

A negative (positive) sign following any month indicates that the correlation is performed between the Nile flood and SST in the year preceding (following) the peak of the Nile's flow.

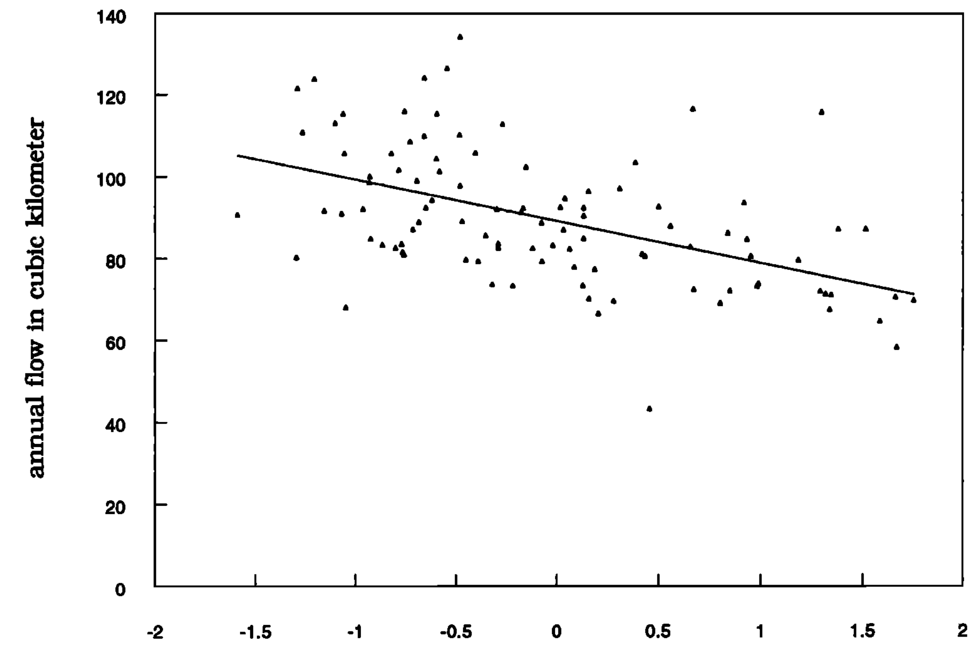

Figure 3. Scatter plot of the data showing the relation between the annual flow of the Nile and the index of ENSO for the months of September, October, and November, for the years 1872–1972. The coefficient of correlation is −0.5. The straight line is the regression line.

Nile flood is about 90 km^3. If the annual flow is larger than 100 km^3, it is classified as high. If the same flow is smaller than 80 km^3, then it is classified as low. The data on SST are classified similarly into cold, normal, and warm conditions. The boundaries between these three conditions are temperatures of −0.5°C and 0.5°C, respectively. The choices of the boundaries between the different conditions for SST as well as the Nile flood are subjective. Indeed, the same exercise can be performed using any alternative reasonable choices. Table 2 describes the prediction probabilities for the Nile flood. This

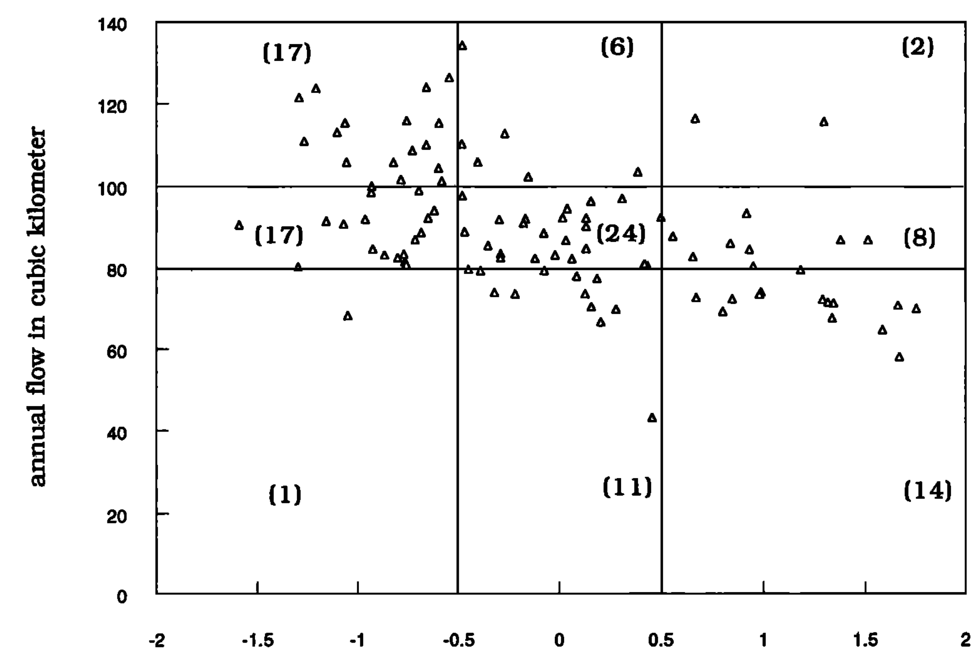

Figure 4. Categories of the Nile flood and ENSO index. The number of data points in each group is also shown.

Table 2. Conditional Probability of the Nile Flood Given the SST Index of ENSO Based on Observations of 1872–1972

	Flow		
SST	Low	Average	High
Cold	0.02	0.49	0.49
Normal	0.27	0.58	0.15
Warm	0.58	0.34	0.08

table consists of the conditional probability of having a Nile flood in a certain category (low, average, or high) given a certain observed SST condition (cold, normal, or warm). For example, the probability of having a low flood given a cold SST condition is 2%; and the probability of having a high flood given a warm SST conditions is 8%. In order to appreciate the information content in the relation of ENSO and the Nile flood, we note that in absence of any information about SST, the probability of having a low flood in any year is 26%, and the corresponding probability for having a high flood is 25%. These estimates are based solely on the past records of Nile floods. Hence knowledge of SST conditions could potentially be very useful in prediction of the Nile flood.

Recent studies presented optimistic conclusions about the predictability of ENSO events, suggesting that these events could be accurately predicted 1 or 2 years ahead using a coupled model of the ocean-atmosphere system [see *Cane et al.*, 1986]. In this study, we utilize predictions of SST in the Pacific Ocean, which are obtained using a coupled ocean-atmosphere model, for the purpose of making predictions about the Nile flow. The predictions of SST are obtained using an improved version of the model described by *Cane et al.* [1986]. These predictions are issued 9 months in advance and were supplied to us by Stephen E. Zebiak of Lamont-Doherty Geological Observatory of Columbia University. Table 3 shows predictions of the SST index of ENSO for the years 1973–1989. These predictions are used to make similar predictions for the Nile flood in the same years. These flood predictions are made as early as the February that precedes the Nile flood of interest. The observed floods for the same years are shown in Table 2 for verification purposes. In 12 of the 17 years the prediction of the most probable flood matches the observations. For example, the prediction for the most probable flood for 1984 is a low flood level that matches the observation for that year. Since the autocorrelation coefficient at lag 1 in the Nile flood series is insignificant (~0.22), there is very little persistence that can be used for forecasting purposes. Hence in absence of any information about SST, the prediction of the most probable flood for any of the years will be the average flood. According to the observations for 1973–1989, this prediction matches the observations in 9 out of the 17 years. From this comparison, we conclude that the use of ENSO predictions could improve the Nile flood predictions significantly.

The value of the probability table for prediction purposes can be further appreciated by considering the extreme flood conditions. A prediction of a warm SST translates into a very low probability (8%) of having a high flood. On the other hand, a prediction of a cold SST translates into an even smaller probability (2%) of having a low flood. It is encouraging that for the years 1973–1989, none of the years had cold SST/low flood or a warm SST/high flood conditions. For the purpose of water resources management, the ability to (almost) rule out the possibility of occurrence of a high flood (or a low flood), 9 months ahead, could be of great economic value.

ENSO and the Hurst Phenomenon

Hurst [1951] observed that the time series of annual flow in the Nile River exhibits statistical characteristics that are not compatible with a series of purely random fluctuations: Hurst phenomenon. This observation is most relevant to the hydrologic design of interannual storage reservoirs. For example, the size of a reservoir on the Nile River, which on average, fails once every n years in supplying exactly the long-term mean flow, is roughly proportional to $n^{0.72}$. In contrast, for any purely random river flow the same reservoir size is proportional to $n^{0.5}$. Hence for any specific design criteria, a reservoir on the Nile has to be of a relatively large size.

Table 3. Predictions of SST and Predictions and Observations of the Nile Flood 1973–1989

	Predicted SST		Predictions of Flood (Probability), %			Observed Flood	
Year	°C	Category	Low	Average	High	km^3	Category
1973	−0.6	cold	2	49	49	83	average
1974	−0.6	cold	2	49	49	90	average
1975	−0.1	normal	27	58	15	102	high
1976	0.9	warm	58	34	8	80	average
1977	1.3	warm	58	34	8	92	average
1978	−0.3	normal	27	58	15	86	average
1979	0.0	normal	27	58	15	69	low
1980	−0.3	normal	27	58	15	82	average
1981	0.0	normal	27	58	15	85	average
1982	2.5	warm	58	34	8	69	low
1983	2.1	warm	58	34	8	72	low
1984	1.7	warm	58	34	8	53	low
1985	0.5	normal	27	58	15	82	average
1986	1.0	warm	58	34	8	73	low
1987	1.9	warm	58	34	8	68	low
1988	0.2	normal	27	58	15	115	high
1989	0.4	normal	27	58	15	81	average

The flood predictions are described by the probabilities of having a certain flood level.

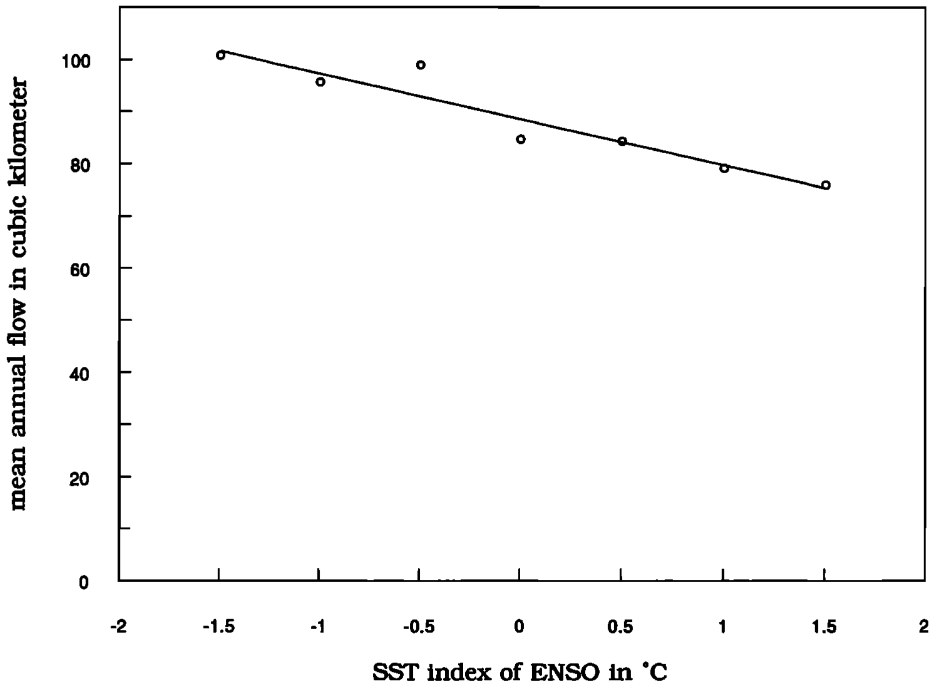

Figure 5. The relation between ENSO index and the varying mean of the annual flow in the Nile River. The annual flow of the Nile is averaged over a small window of ENSO indices, each with a width of 0.5°C centered around (−1.5°, −1.0°, −0.5°, 0.0°, 0.5°, 1.0°, and 1.5°C). The number of points within each of these windows are 4, 19, 25, 21, 11, 9, and 11, respectively.

Several studies attempted to explain the Hurst phenomenon based on statistical arguments and models. *Bras and Rodriguez-Iturbe* [1985] summarize the different lines of thought in explaining the Hurst phenomenon as due to (1) a transitory behavior due to the short records of observed geophysical variables [see *Salas et al.*, 1979, Figure 5], (2) nonstationarity of the underlying mean of the process [see *Klemes*, 1974; *Potter*, 1976; *Boes and Salas*, 1978; *Bhattacharya et al.*, 1983], and (3) a stationary process with very large memory.

A physically based explanation for the Hurst phenomenon in the Nile flow is hypothesized. The above analysis indicates that the occurrence of ENSO events excites similar oscillations in the tropical climate, which are then teleconnected to the Nile flow through the rainfall-producing mechanisms at the sources of the Nile. The relation of the ENSO index and the Nile flood suggests that the Nile flood responds to natural variability in SST of the Pacific Ocean. This variability occurs at several timescales ranging from annual to decadal and even longer. As a result, variability in SST of the Pacific Ocean causes significant nonstationarity in the mean of the annual flow process in the Nile River. Natural climatic factors (other than ENSO) dictate the variability of the Nile flow around the varying mean of the process.

The relation between ENSO index and the nonstationary mean of the annual flow in the Nile is estimated. This relation is shown in Figure 5. The annual flow of the Nile is averaged over a small window of ENSO indices, each with a width of 0.5°C centered around −1.5°, −1.0°, −0.5°, 0.0°, 0.5°, 1.0°, and 1.5°C. The number of points within each of these windows are 4, 19, 25, 21, 11, 9, and 11, respectively. Each group of points is treated as a sample from a different population. Although some of these samples have only few data points, the nonstationary mean of the Nile flood is clearly related to ENSO index. The resulting relation is described by

$$\text{mean of the annual flow of the Nile} = 88.5 - 8.7\ (\text{ENSO index}) \quad (1)$$

The coefficient of correlation in this relation is −0.9. The varying mean of the annual flow in the Nile River is computed in Figure 6 using (1) and the series of observed ENSO indices. Figure 6 shows the varying mean for the years 1872–1972. These random oscillations represent the contribution of the ENSO index to the natural variability in the flow of the Nile River.

Based on this analysis, we propose the following hypothesis: the mean of the annual flow process in the Nile River varies in time following ENSO, resulting in a non-stationary process, and causing the Hurst phenomenon. The statistical characteristics of nonstationary processes have been studied extensively, and their ability to reproduce the Hurst phenomenon has been proven [see *Potter*, 1976; *Boes and Salas*, 1978]. In order to exclude effects due to the transitory behavior of the process, the hypothesis presented in this paper can only be rigorously tested when long time series ($\sim 10^3$ data points) of the annual flow in the Nile River becomes available.

Our hypothesis about the Hurst phenomenon is similar to the argument offered by *Potter* [1976]. He analyzed precipitation records from North America and pointed to the potential role of oscillations in the state of the global ocean-atmosphere-land system in providing a physical explanation for the Hurst phenomenon. However, this analysis has focused on a specific global oscillation, the ENSO, and the hypothesis presented is relevant to a different natural variable, the Nile flood.

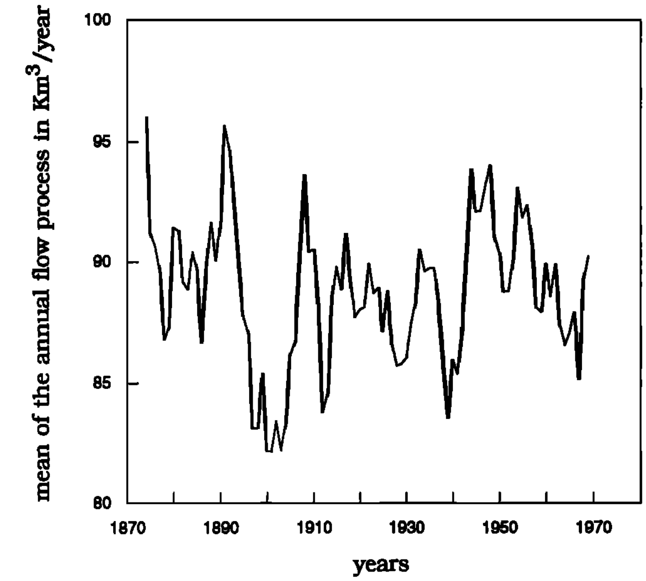

Figure 6. The varying mean of the annual flow process estimated from observed ENSO indices and using (1).

In summary, the hypothesis described in this section is motivated by the following.

1. The analysis presented in this paper confirms the existence of a significant relation between the mean of the Nile flood and SST of the Pacific Ocean (see Figure 5).

2. The SST of the Pacific Ocean exhibits oscillations at several timescales, ranging from annual to decadal and even longer [see *Wang and Ropelewski*, 1995, Figure 5]. Hence the mean of the Nile flood process oscillates in time too (see Figure 6). As a result, SST of the Pacific Ocean (ENSO index) and the Nile flood represent a weakly coupled bivariate nonstationary stochastic process.

3. Several of the studies listed above have shown that nonstationary stochastic processes are capable of simulating the Hurst phenomenon.

The combination of these three factors suggests that offering the connection between SST of the Pacific Ocean and the Nile flood as a potential candidate for explaining the Hurst phenomenon is a reasonable hypothesis.

Conclusions

The analysis of the Nile flow and ENSO index suggests that natural variability in the annual flow of the Nile River can be decomposed into two components: a mean that varies in time following ENSO, and a random fluctuation that occurs around the varying mean due to climatic factors other than ENSO. The nonstationary mean and the random fluctuation explain 25% and 75% of the observed natural variability, respectively.

The relation between ENSO and the Nile flood has important implications on two important problems: predictability of the Nile flood, and explanation of observed statistical characteristics of the Nile flood series (the Hurst phenomenon). The fact that ENSO events can be predicted with reasonable accuracy at a lead time of about 1 year suggests that the correlation between ENSO and the Nile flood should be used to improve the predictability of the annual flow in the Nile River. The finding that the Nile flood series can be decomposed into a varying nonstationary mean and a random fluctuation favors the line of thought that the Hurst phenomenon may be due to nonstationarity in the mean of the process. For this reason, we present the hypothesis that ENSO is the causal factor for the Hurst phenomenon in the annual flow of the Nile River.

A simple procedure for prediction of the Nile flood is proposed and illustrated by application for the years 1973–1989. The conditional probabilities of having a low, average, or high flood in the Nile River are computed given the SST conditions in the Pacific Ocean. The new procedure is designed to utilize model predictions of SST in the Pacific Ocean. In the absence of this procedure, the best practical prediction of the Nile flood would be the mean flow (~90 km^3). The analysis presented in this paper suggests that the proposed procedure improves on this prediction. Such an improvement in the Nile flood prediction should have a positive impact on water resources management in Egypt, particularly in operation of the High Aswan Dam.

Future research will focus on further development of the flood prediction procedure. The emphasis will be in combining SST measurements and predictions with other inputs, such as hydrological measurements of rainfall and streamflow to improve the prediction of the Nile flood.

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