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# A Note on Fluctuations of the Nile River Flood Levels (715–1470)

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With 5 Figures

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**Summary**

Climate episodes, lasting a century or longer, of low and high annual Nile flood level minima (from 715 to 1470) are defined by a lowpass filter. Their relation to fluctuations of shorter or longer periodicity (less than or greater than 25 years) is deduced from the power spectral density of a hundred year window moving over the time series. Low flood climate and enhanced variance of short period fluctuations are significantly correlated characterizing reduced persistence of fluctuations during dry climate conditions. There is only a qualitative indication of enhanced long period variability (or enhanced persistence) during high flood levels.

## 1. Introduction: The Nile Flood Level Time Series

The streamflow of rivers is a good indicator of climate variations, because it provides an integral measure of the precipitation over the source regions, if other conditions remain unchanged. The flood levels of the Nile river are one example of a long time series analysed by hydrologists, climatologists and historians in order to gain information about the evolution of the systems involved and their interactions, and also to estimate future conditions which, in climatological context, means that the possibility of recurring past events provides a measure of the expected variability.

A number of these studies are concerned with the reconstruction of the data from historical sources: Toussen (1925), for example, compiled a time series of the Nile flood minima and maxima from 622 to 1921 A.D. which, since 715, documents the record of the Roda Nilometer near Cairo. These data form an almost continuous time series until 1470 when the first of the larger gaps occurs. Popper (1951) corrected this time series taking into account changes in calibration.

Other studies deal with hydrology – related statistical analyses of the Nile flood time series (Hurst et al., 1965), the results of which recently appeared to be of fundamental interest in connection with fractal processes and chaotic dynamics. The Nile flood variations have also been analysed by more standard statistical methods (power spectrum or cumulative deviations) to identify cycles (Hameed, 1984), to develop hydrological forecast models based on autoregressive processes with moving average corrections etc. (Aguada, 1987), and to define climatic episodes interpreted in terms of general atmospheric circulation anomalies over Ethiopia (Riehl et al., 1979), East Africa and Europe (Hassan, 1981).

From these studies only a brief background will be given, referring both to the present situation and to the time span analysed in this study. The Nile receives the water from the two sources of the White and the Blue Nile in equatorial Africa and Ethiopia. The Ethiopian tributaries deliver an annual mean flow rate of approximately 1 600 $m^3/s$; the flood peak of 5–6 000 $m^3/s$ is reached in the flood season between July and September. Thereafter the Nile is mostly fed by the White Nile while the Ethiopian waters contribute only a quarter to the total. The Nile flood maxima from the Blue Nile are mostly fed by the monsoonal rains in Ehtiopia associated with the northward shift of the intertropical convergence zone (ITCZ); the Nile flood minima originate in tropical East Africa. There is a recently observed coincidence between low and high Nile flood minima and East African lake levels (e.g. Lake Victoria); but the causes of the tropical climate variations are far from clear. There may be a European teleconnection: During the warm epoch (before the Little Ice Age), the Nile floods were relatively high from 1070 to 1180, but low from 1180 to 1350 which coincides with the minor advance of glaciers. The period of the Little Ice Age from 1500 to 1700 has not been analysed here because there are a number of gaps in the Nile flood record; but there is evidence of low Nile floods occurring in the periods 1470–1500, 1640–1720 and a number of low floods from 1774–1792. Finally, (recent) fluctuations of the Nile flood maxima have been related with El Niño/Southern Oscillation (ENSO) events, a climate signal affecting the global atmosphere (Whetton et al., 1990).

In this note we extend the time series analysed linking the flood related climate episodes with shorter period fluctuations during these episodes. That is, we try to identify a possible connection between a climate mean state and its related smaller scale variability due to internal dynamics. For example, in meteorology larger variances characterize the weather dynamics of the midlatitude winter climate whereas variability is reduced during summer. In this sense we expect that warm (or wet) climate episodes in the tropics may be distinguished from cold (or dry) epochs not only by their means but also by their internal fluctuations. As a first step in this direction we analyse the continuous part of the annual record of the Nile flood extrema from 715 to 1470; only the annual minimum flow data are used, because they show larger signals (Fig. 1) and they are also considered to be subject to smaller errors than the maxima (Aguada, 1984).

## 2. Climate and Fluctuations of the Nile Flood Minima

*Climate*: Climate episodes of low and high annual Nile flood level minima can be deduced after suitable time averaging (or filtering) which does not suppress the long term climate variations. The averaging process used here is a 50-point lowpass filter (Duchon, 1979) with a cut-off frequency corresponding to a 100 year period; this time scale is chosen to filter out the significant 77 year cycle which is the longest period of fluctuations analysed by Hameed (1984). The results (Fig. 2) show fluctuations between climatic episodes of high and low flood levels which last between 80 and 170 years. These episodes are similar to those obtained by Hassan (1981, Table 1) applying the method of cumulative deviations; only the first major high and low flood epochs have been classified by a sequence of minor high and low floods of shorter duration (20–50 years) which are smoothed by the lowpass filter during 715 to 930 A.D. These results are relatively stable if the cut-off is changed by ± 30 years or if a 100 ± 30 year running mean is applied.

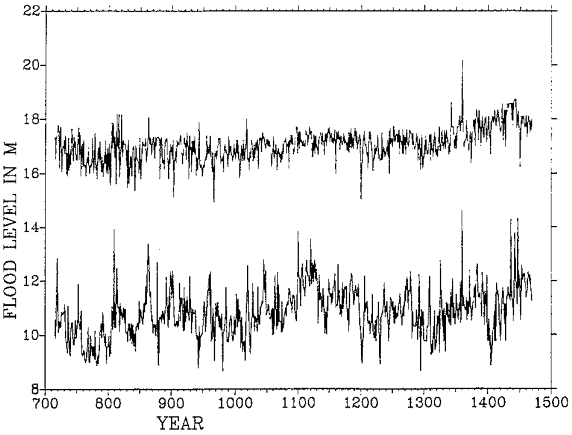

Fig. 1. Nile flood level maxima and minima at Roda Island

*Fluctuations*: Internal fluctuations of timescales with periods less than 100 years are associated with the high and low flood episodes. Such fluctuations can be visualized by (a sequence of) variance density distributions (power spectra) of a 100-year window shifted over the time series in annual time steps. Plotted in a frequency-time diagram, the isolines of variance contributions pro-

Table 1. *Major High and low Flood Episodes of the Lowpass Filtered Levels of the Nile's Annual Flow Minima*

| | | | |
|---|---|---|---|
| Major low floods: | <760–820 | 940–1030 | 1200–1370 |
| Major high floods: | 820–940 | 1030–1200 | >1370 |

vide the frequency dependent spectral densities changing with time and thus lead to a dynamical spectrum (or spectrogram; Olberg and Rakoczy, 1984). As a spectral estimator, the maximum entropy method is applied with an autoregressive process of relatively high order, AR(33), to resolve the low frequency end within the window (as a rule of thumb: the order of the AR process should be about 1/3 of the size of the data set). Furthermore, a red noise process, AR(1), is deduced to define the associated null-hypothesis for the significance test (see Appendix). The contour of the 95% level of significance is chosen (and not the variance density values) to present the behaviour of the (window-related) power spectrum changing with time. The results are shown in Fig. 3 together with the overall power spectrum of the total time series, which may be interpreted as a suitable time average of the spectrogram (or dynamical maximum entropy spectrum). The following results are noted:

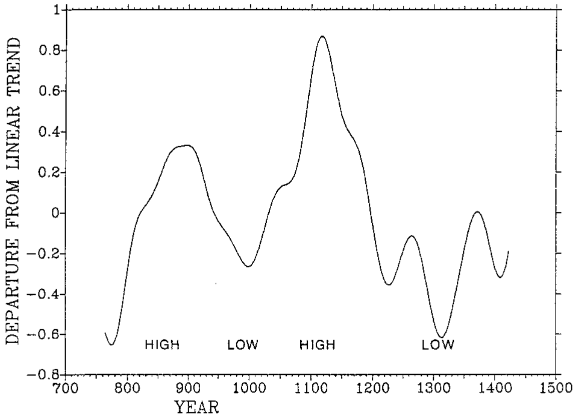

Fig. 2. Lowpass filtered minimum flood levels and flood climate episodes (high/low)

(a) Three major continuous outbreaks of longer period fluctuations ($25 < p < 100$ years) are significant. They occur before 765 and last until 910, between 1050 and 1150, and from 1350 to 1420 or later; note that ± 50 years needs to be added to extend the limits of the time intervals because the frequency spectra of the moving hundred year window are centered at the window-year 50. The first outbreak shows the fluctuation periods decreasing from more than 70 to about 40 years. This coincides with the sequence of minor high and low flood level episodes (Hassan, 1981) whose durations diminish from 50 to 20 years during the epoch between 700 and 930 A.D.

(b) Enhanced activity of shorter periods ($p < 25$ years) characterizes the breaks between the spells of long period fluctuations; the significant peaks are shown in Fig. 3. These dominate during climate episodes of low flood levels and show some variability in the periods ($p < 25$ years). By visual inspection the Nile flood climates (Fig. 2) and the internal fluctuations (Fig. 3) appear to be related: The major low flood levels are associated with shorter period fluctuations whereas the opposite holds for the major high flood levels and the longer period fluctuations:

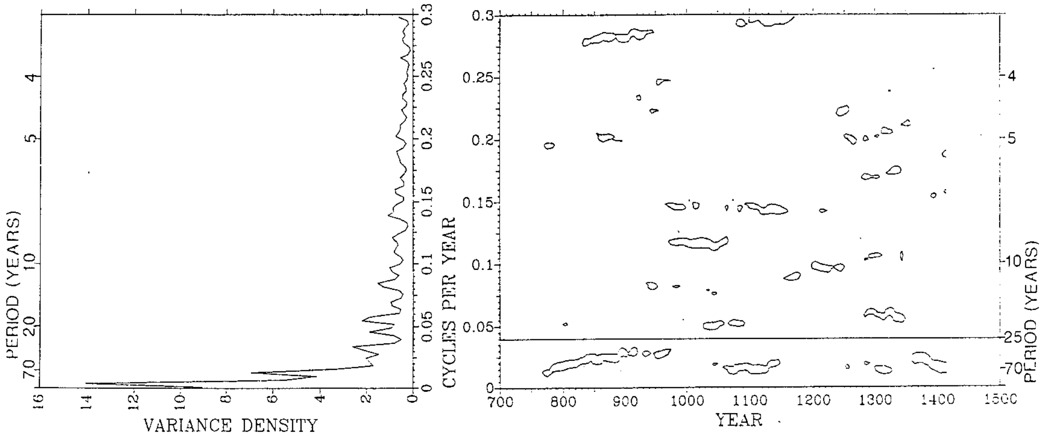

Fig. 3. Dynamical maximum entropy spectrum (spectrogram) composed by power-spectra from 100-year-windows showing the 95% significance-level against red noise; the boundary between short and long period fluctuations is indicated at 25 years. The power spectrum of the total time series is shown for comparison (left)

Table 2. *Qualitative Association Between the Major Climate Episodes of the Nile Flood Minima and the Fluctuations During These Episodes*

| Fluctuations (periods) | Short<br>($p < 25$) | Long<br>($25 < p < 100$) |
|---|---|---|
| Major low floods | strong | weak |
| Major high floods | weak | strong |

The variance contributions of the shorter and longer period fluctuations within the hundred year window are shown in Figs. 4 a and b. Note that these time series are obtained from the dynamical power spectral densities (after Blackman-Tuckey) within the moving hundred year window, and subsequent integration over the short and the long period intervals, respectively; the Blackman-Tuckey power spectra provide good estimates of the integrated variance contributions whereas the maximum entropy method provides a high resolution of the frequency estimates of the spectral peaks. These time-series are used for the following analysis.

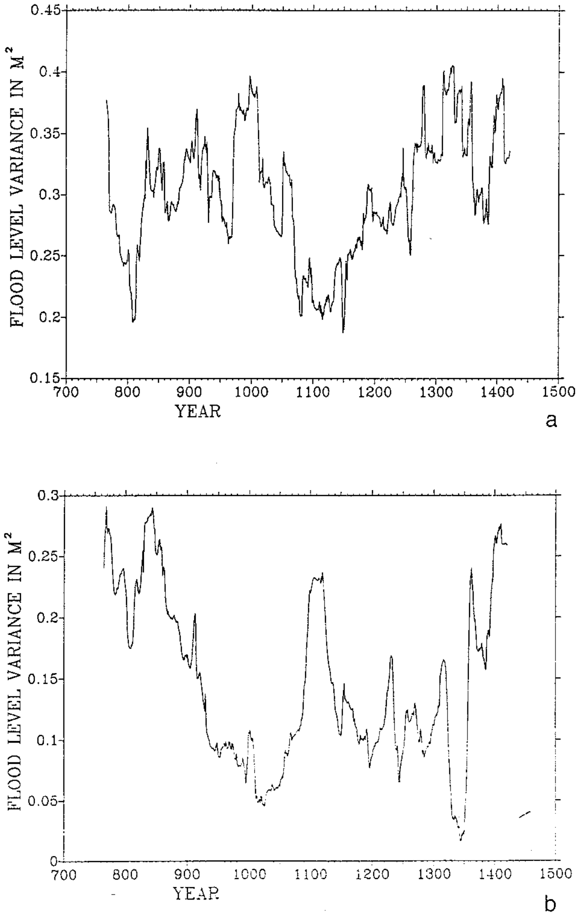

Fig. 4. Variances of minimum flood levels contributed by periods shorter (a) and longer (b) than 25 years

*Climate and Fluctuations*: The hypothesised qualitative association between the Nile flood climate and the fluctuations can be quantified by a cross-correlation analysis between the lowpass filtered time series (Fig. 2) and the time series provided by the variance contributions from the shorter ($p < 25$ years) or longer ($25 < p < 100$) periods (Figs. 4 a, b). The corresponding lag cross-correlations between the flood climates and its fluctuations (presented in Fig. 5) only partially substantiate the qualitative results of Table 2:

(a) The negative lag correlation between flood level climate and short-period fluctuations is maximum at zero lag showing the almost simultaneous occurrence of low flood minima and enhanced short period fluctuations (or high levels of the flood minima and reduced short period variability). This correlation reaches the 95% level of significance (see Appendix), whereas the lag correlation between flood level minima and long period fluctuations does not.

(b) The first zero-crossing of the lag-correlation occurs at about 80 years which gives an estimate of the characteristic quarter-period of the climate episodes to which both the climate means and its

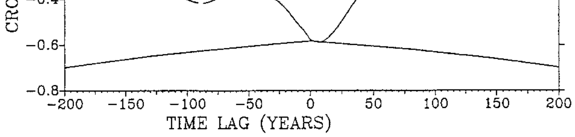

Fig. 5. Lag cross-correlations between lowpass filtered minimum flood levels and variances contributed by short (full) and long (dashed) periods. The climate leads variances for positive time lags. The 95% levels of significance are also plotted

associated fluctuations contribute. In this sense both the short period fluctuations and the mean characterize the flood level climate of the Nile.

## 3. Discussion

The Nile flood climates of low and high flood level minima are characterized by episodes of about a century or longer. They can be related to their internal fluctuations of shorter ($< 25$ years) or longer periodicity ($> 25$ years) quantified by the dynamical power spectral densities of a hundred year window moving over the time series. The significant correlation (at zero lag) between the low flood climate and the enhanced short period fluctuations characterizes reduced persistence of the fluctuations during dry climate conditions in tropical Africa. During high flood levels there is a qualitative but not significant indication of enhanced persistence associated with long period internal variability. A discussion of the mechanisms is beyond the scope of this note, but the following aspects should be mentioned: The internal climate dynamics of the atmosphere (and ocean) may indeed be different during wet and dry climatic episodes affecting tropical Africa. In particular this may be the case as dry climates are characterized by a large variance induced by occasional short interruptions of wet periods. On the other hand, during wet climate conditions a large water storage system may respond with a large inertia whereas dry climates with smaller water reservoirs may be characterized by short response times. Thus the internal fluctuations of the climate system during wet or dry periods need not necessarily be different in order to generate the hydrological response observed for the Nile flood levels.

### Acknowledgement

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### Appendix (Significance Tests)

*Dynamical Maximum Entropy Spectrum (Spectrogram)*: The red-noise or AR(1)-process fitted to the time series defines the null-hypothesis, $E$. Spectral estimates exceeding the value $S = E + u(\beta)^* E^*(2/\mathrm{DOF})^{1/2}$ are plotted (Fig. 3) as significantly different from a red-noise process at the $\beta = 95\%$ level; $u(\beta = 95\%) = 1.96$ is the 95%-significance limit of the Gaussian distribution with zero mean and unit variance; the degrees of freedom, $\mathrm{DOF} = N/M$, where $N$ is the length of the time series and $M$ is the order of the auto-regressive process used for the maximum entropy spectral estimate, in this case, AR(33).

*Lag Cross-Correlation*: The variance, VAR, of a cross-correlation estimate, $\mathrm{cor}(x, y, k)$ at lag $k$ between two uncorrelated time-series, $x$ and $y$, can be approximated by the individual lag $i$ auto-correlations, $\mathrm{cor}(x, i)$ and $\mathrm{cor}(y, i)$, after Bartlett 1955 (see also Box and Jenkins 1976):

$$\mathrm{VAR} = \Sigma\,\mathrm{cor}(x, i)^* \mathrm{cor}(y, i)/(N-k) \text{ for } i = -\infty, \ldots, +\infty$$

$N$ is the length of the time series. The null-hypothesis that both time series are uncorrelated, can be rejected on the $\beta = 95\%$ level, if $\mathrm{cor}(x, y, k) > u(\beta)^*[\mathrm{VAR}]^{1/2}$; $u(\beta = 95\%) = 1.96$ is the 95%-significance limit of the Gaussian distribution with zero mean and unit variance.

### References

Aguado, E., 1987: A time series analysis of the nile river low flows. *Ann. Assoc. Amer. Geogr.*, **72**, 109–119.

Duchon, C. E., 1979: Lanczos filtering in one and two dimensions. *J. Appl. Meteor.* **18**, 1016–1022.

Evans, T. E., 1990: History of Nile flows. In: Howel, P. D., Allan, J. A., (eds.) *The Nile – Resource Evaluation, Resource Management, Hydropolitics and Legal issues.* Conference at Roy. Geogr. Soc., Univ. of London, 5–40.

Hameed, S., 1984: Fourier analysis of Nile flood levels. *Geophys. Res. Lett.*, **1**, 843–845.

Hassan, F. A., 1981: Historical Nile floods and their implications for climatic change. *Science*, **212**, 1142–1144

Hassan, F. A., 1987: Nile floods and climatic change. In: Rampino, M. R., Sanders, J. E., Newman, W. S., Königsson, L. K., (eds.) *Climate: History, Periodicity and Predictability.* New York: Van Nostrand and Reinhold Inc., 37–46.

Hurst, H. E., Black, R. P., Sinaika, Y. M., 1965: *Long Term Storage in Reservoirs.* An Experimental Study. London: Constable, 145 pp.

Jenkins, G. M., Watts, D. G., 1968: *Spectral Analysis and its Applications.* San Francisco: Holden-Day, 525 pp.

Olberg, M., Rakoczi, F., 1984: *Informationstheorie in Meteorologie und Geophysik.* Berlin: Akademie Verlag, 181 pp.

Riehl, H., Meitin, J., 1979: Discharge of the Nile River: A barometer of short-period climate variation. *Science*, **206**, 1178–1179

Popper, W., 1951: *The Cairo Nilometer.* Berkley: University of California Press, 269 pp.

Toussoun, O., 1925: Memoire Sur L'Histoire du Nil. Mem. Inst. Egypte. Vol. 8–10, Cairo.

World Meteorological Organization, 1966: Climatic Change. Techn. Note 79, WMO-No. 195.TP.100, 79 pp.

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