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Coherency detection of multiscale abrupt changes in historic Nile flood levels

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[1] A scanning algorithm based on the classical Student *t*-test is extended to detecting the presence and coherency of multiscale abrupt changes in two time series. It functions similarly to the Haar wavelet transform, but also provides thresholds of the statistical significance for testing change-points. The algorithm is applied to the historic series (AD 622–1469) of the maximum and minimum flood levels of the Nile River using the "Table-Look-Up Test" for correction of dependence in the series. The results reveal several abrupt changes, and separate wet/dry episodes on 30–160 year time-scales. Most of the episodes coincide with historic records of catastrophe in Egypt. Some changes correspond to changes in China and Europe, and to reconstructions of fish stocks off the west coast of North America, indicating that they are driven and linked by global teleconnection processes. *INDEX TERMS:* 1833 Hydrology: Hydroclimatology; 9820 General or Miscellaneous: Techniques applicable in three or more fields; 1860 Hydrology: Runoff and streamflow; 1821 Hydrology: Floods; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] The flood level of a river is usually influenced by changes in climate. For the Nile River, its maximum flood level is influenced mainly by monsoonal precipitation over the Ethiopia Highlands, the source of one major tributary—the Blue Nile. The minimum flood level is influenced mainly by equatorial rains over the watershed of Lake Victoria, the source of the other major tributary—the White Nile [*Said*, 1993]. Due to its long historical record, international researchers have analyzed the fluctuations of the Nile flood levels since *Poper* [1951] corrected the data sets of the maximum and the minimum flood levels at Rode Island (Cairo, Egypt). However, most of these investigators examined the difference between the minima and the maxima, or examined the minimum flood level series only [e.g. *Hassan*, 1981; *Hameed*, 1984; *Fraedrich and Bantzer*, 1991]. Few have analyzed the maximum flood level series [*Riehl and Meitin*, 1979]. The periods suggested by these authors unfortunately do not correspond with the famine chronologies of Egypt. This is because the minima reflect the variations in river levels in the low season, which had a minor role in Egyptian life and culture until the beginning of the nineteenth century [*Said*, 1993].

[3] Here we introduce a scanning algorithm for detecting the presence and coherency of multi-scale abrupt changes in two time series, and apply the algorithm to both the maximum and the minimum Nile River flood levels. The series are then partitioned into comparatively wet/dry episodes on the scale of 30–160 years for comparison to the famine chronologies of Egypt. In addition, the results are briefly compared with related changes in China and Europe during the same time periods, and with fish scale deposits, a proxy of fish population size, off the west coast of North America. These comparisons suggest that climate episodes in Nile River floods are linked to climate variability in disparate locations via global teleconnection processes.

2. Methodology

[4] Most methods used previously to objectively detect abrupt changes in time series, such as the Mann-Kendall rank test [*Goossens and Berger*, 1987], and *Yamamoto et al.* [1986] criterion, search for a single abrupt change in a short time series [*Jiang and You*, 1996]. The wavelet transform recently has been applied in various fields as a decomposition tool and as a technique for the detection of multiscale fluctuations in a long time series [*Kumar and Foufoula-Georgiou*, 1994]. Wavelets calculate contrasts (usually linear) between subsets of the data centered at the time (or location) b for a time scale a, where the time-scales are integer powers of 2 for discrete series. In particular the Haar wavelet coefficient $W(a, b)$ is proportional to the difference in the means of the two subsets of the data; but how to determine a threshold for the wavelet coefficients to test for statistically significant abrupt changes is still an open question [*Jiang et al.*, 1997].

[5] As an alternative to techniques based on the wavelet transform, we extend the classical Student *t*-test, which tests the difference between two subsample means, to a scanning test and coherency detection. We can define a statistic $t(n, j)$ of the scanning *t*-test for subsample size n at point j as:

$$t(n,j) = \left(\bar{x}_{j2} - \bar{x}_{j1}\right) \cdot n^{1/2} \cdot \left(s_{j2}^2 + s_{j1}^2\right)^{-1/2} \tag{1}$$

where,

$$\bar{x}_{j1} = \frac{1}{n}\sum_{i=j-n}^{j-1} x(i), \quad \bar{x}_{j2} = \frac{1}{n}\sum_{i=j}^{j+n-1} x(i);$$

$$s_{j1}^2 = \frac{1}{n-1}\sum_{i=j-n}^{j-1}\left(x(i) - \bar{x}_{j1}\right)^2;$$

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$$s_{j2}^2 = \frac{1}{n-1}\sum_{i=j}^{j+n-1}\left(x(i) - \bar{x}_{j2}\right)^2.$$

Here the subsample size n may correspond to the scale parameter a in the Haar wavelet for $n = 2, 3, \ldots < N/2$, or n may be selected as a suitable interval. The j is a reference point at which an abrupt change may occur, and is comparable with the time (or location) parameter b in the wavelet transform for $j = n + 1, n + 2, \ldots, N - n$. Thus the statistic $t(n, j)$ not only has the capacity to detect multiscale abrupt changes like the Haar wavelet coefficient, but also provides a test of statistical significance for these changes. The n is also not limited to be integer powers of 2.

[6] The t-test, however, assumes that the time series is of independent, identical, and normal distribution. Here, we use the "Table-Look-Up Test" [*Storch and Zwiers*, 1999] as a correction for dependence in the raw data series. For every sub-sample the critical t-value is adjusted based on the pooled sample lag-1 autocorrelation coefficient and sub-sample size. We found that these critical values are highly restrictive for short sub-samples, thus chose those values $t_{0.10}$ at 90% confidence level to reveal abrupt changes on time scales of 20 or more years.

[7] For convenience in analysis, we use the ratio:

$$t_r(n,j) = t(n,j)/t_{0.10} \tag{2}$$

as the index of critical t-test for scanning detection of multi-scale abrupt changes. It is obvious that an abrupt change is significant at the confidence level $\alpha = 0.10$ when $|t_r(n, j)| > 1.0$, where $t_r(n, j) < -1.0$ denotes an abrupt decrease, and $t_r(n, j) > 1.0$ indicates an abrupt increase.

[8] Finally the statistic

$$t_{rc}(n,j) = sign[t_{ru}(n,j)t_{rv}(n,j)]\{|t_{ru}(n,j)t_{rv}(n,j)|\}^{1/2} \tag{3}$$

is defined as the index of coherency of abrupt changes between two series u and v. Usually, when the statistic $t_{rc}(n, j) > 1.0$ with both $|t_{ru}(n, j)|$, $|t_{rv}(n, j)| > 1.0$ the two series have abrupt changes in the same direction, while if $t_{rc}(n, j) < -1.0$ the two series have abrupt changes in opposite directions.

3. Analysis and Results

[9] The Nile River maximum and minimum flood level datasets are the same as those used in *Fraedrich and Bantzer* [1991], originally made available to the authors by R. Said. These are yearly records from AD 622 to AD 1469, with a few missing data points that were linearly interpolated. Statistical analysis (not shown here) shows that the minima are nearly normally distributed, while the maxima are slightly skewed toward higher values.

[10] Smoothed contours of the results of the scanning algorithm using the "Table Look-Up Test" are presented in Figures 1a and 1b for the maxima and the minima, respectively. Figure 1c shows the smoothed contours of the coherency test $t_{rc}(n, j)$, computed from formula (3) above. The changes in riverbed sediment level were ignored because its trend is relatively small [*Riehl and Meitin*, 1979].

[11] The abrupt changes in each series are described in more detail in *Fraedrich et al.* [1997]. Here, the interest is focused on the coherence of abrupt changes in both series. An outstanding feature seen in both series is an abrupt increase around AD 1020–1070 on a time scale (subsample size) of approximately 388 years (Figure 1). This increase continues in the later years in the maxima (Figure 1a), while the minima decrease from AD 1120 to AD 1300, then increase thereafter (Figure 1b). The minus center in AD 1230 on a 194-year scale (Figure 1c) reflects the

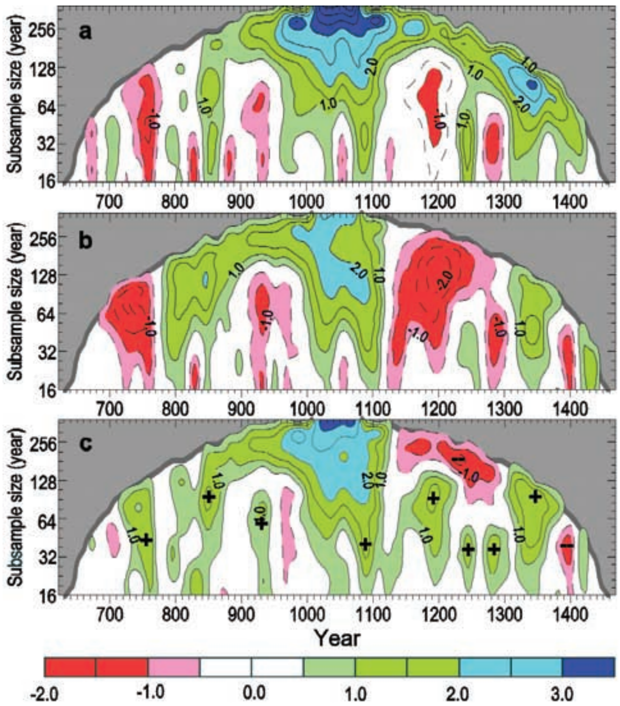

Figure 1. Contours of the scanning t-test: (a) for the Nile River maxima; (b) for the Nile River minima; and (c) coherency $t_{rc}(n, j)$ between both. (Shadows indicate changes passed the threshold of statistical significance at the confidence $\alpha = 0.10$ based on the "Table Look-Up Test". The '+' in Figure 1c represents a same direction change while '−' denotes an opposite direction change. Contours estimated using the program Surfer, with a contour interval of 0.5).

fact that the minima declined while the maxima increased during this period.

[12] Eight other same-signed abrupt changes were detected on shorter time scales in both series. These are denoted by positive centers in the coherency plot (Figure 1c), and by the same signed centers in Figures 1a and 1b. Abrupt changes toward lower flood levels were detected in AD 759 (on a 42-year time scale), AD 935 (74-year), AD 1195 (97-year), and AD 1282 (30-year). Changes toward higher flood levels occurred in AD 849 (on a 84-year scale), AD 1096 (37-year), AD 1246 (30-year), and AD 1341 (97-year). The changes in AD 759, AD 1246, and AD 1282 are similar to the results of *Poper* [1951], and the changes in AD 849 and AD 1282 are very close to *Riehl and Meitin* [1979]. An oppositely-signed change on a 32-year scale happened in AD 1395, when the maxima increased while the minima declined, until about AD 1427 when both records rose again.

[13] Based on the above nine change-points, we divided the Nile River flows into long episodes of roughly coherent dry (low-water), normal, and wet (high-water) conditions. These are shown in Table 1 and Figure 2. Change points around AD 935, 1095, 1194 and 1341 are roughly in agreement with *Said*'s [1993] classification of wet/dry periods, based on ten-year averages from Poper's data series.

3.1. The Egyptian Historical Record

[14] The timing of most episodes identified here is well verified by historical records from Egypt. For the longest and exceptionally dry epoch of AD 935–1095 (Figure 2), *Said* [1993] states that "The years 945–977 had a lower than average discharge. The low Niles of this episode were exceptionally destructive of the economy as several successive failures of the River Nile left the larger

Table 1. Coherent Wet, Normal and Dry Episodes

Wet episodes	Normal	Dry episodes
	622–758 (137 yrs)	759–848 (90 yrs)
	849–934 (86 yrs)	935–1095 (161 yrs)
	1096–1194 (99 yrs)	1195–1245 (51 yrs)
	1246–1281 (36 yrs)	1282–1340 (60 yrs)
1341–1394 (54 yrs)		
1395–1427[a] (33 yrs)		
1428–1469 (42 yrs)		

[a] Represents a period with out-of-phase changes between the maxima and minima.

part of the land of Egypt uncultivated. Raids by tribes from north Africa, driven by the droughts of the period, finally led to the Fatimid take over of Egypt in the year of AD 969.'' The period from AD 1052 to 1090, he states: ''saw the Egyptian population reduced from 2.4 million... to 1.5 million'' due to persistent droughts leading to '' ...starvation, death from hunger, spread of disease and plague, and even cannibalism.'' An eyewitness account in AD 1068 states that ''for seven consecutive years people ate cadavers.''

[15] Said continues that ''...the opening years of the thirteenth century were tragic and disastrous,'' leading to the end to the Fatimid Dynasty. This coincides with the dry spell AD 1195–1245 in our analysis. During the last three exceptionally wet phases from AD 1341 to 1469, Said states that during the high Niles of the years AD 1359–1360 ''... people went out to the desert beseeching God to reduce the level of the Nile.'' For the asynchronous period AD 1395–1427, Said notes that ''Several years of low Nile alternated with these years of high flood causing famines such as those reported in the years 1374, 1394, and 1403.'' He adds that ''The high floods, famines and the plague reduced the population of Egypt from about 4 million in around 1300 to 3 million at the end of fifteenth century....''

[16] However, it remains an open question why no famine records were found for AD 759–848, which was the driest spell during the 848-year record.

3.2. Related Evidence in Asia and Europe

[17] *Yao et al.* [1991] analyzed ice cores from the Guliya Ice Caps in the western Kunlun Mountains in China, and concluded that around AD 1100 a key change-point occurred in which the climate shifted toward wet and warm conditions. Another investigation of sediments in the Kunming Lake of the Summer Palace in Beijing also suggests a large climate shift in the 11th century. As severe droughts caused the lake's bottom to become bare, the concentration of sporophytes in the sediment decreased abruptly, and mussels and shrimps are found in the sediment [*Zhang and Ge*, 1997].

[18] Evidences of an abrupt change in the 11th century is also found in Germany. The dry mass of sediments of the Holzmaar (Eifel, Germany) increased sharply, and tree-ring growth and the number of warm and dry summers showed dramatic changes [*Fraedrich et al.*, 1997].

[19] These examples from Africa, Asia, and Europe may be regional appearances of global climate variability on the scale of decades to centuries. Although the yearly correlation between the maximum and the minimum flood levels of the Nile is poor because of different sources [*Conway and Hulme*, 1993], fluctuations on scales longer than 30 years are roughly in coherence for both. This suggests that climate changes at various geographical locations are teleconnected, on certain temporal and spatial scales, while that on shorter scales may be controlled by different physical factors, possibly of a more regionalized nature. The reasons for this will be the topic of future investigation.

3.3. Variations with Northern Anchovy

[20] *Baumgartner et al.* [1992] present counts of northern anchovy scale depositions off southern California for the period AD 270–1970, which they used to estimate variations in anchovy population size. Comparison of the low-passed filtered anchovy counts with the alternating wet and dry periods identified in Table 1 reveal a reasonable agreement between centers of the peaks and valleys of the two series (Figure 3). *Baumgartner et al.* [1992] found a spectral peak in the anchovy data of about 100 years, which agrees with the average period of the wet and dry episodes in the Nile. *Cayan et al.* [1998] showed that decadal variations in precipitation in the southwest U.S. and northern Africa are aligned and oppositely phased. Further, they found that decadal precipitation is strongly correlated with global atmospheric pressure and sea surface temperature fields, particularly in the anchovy habitat off the west coast of North America. This again suggests a global teleconnection between climate changes that incorporates Nile River flood cycles and climate signals in widespread geographical locations.

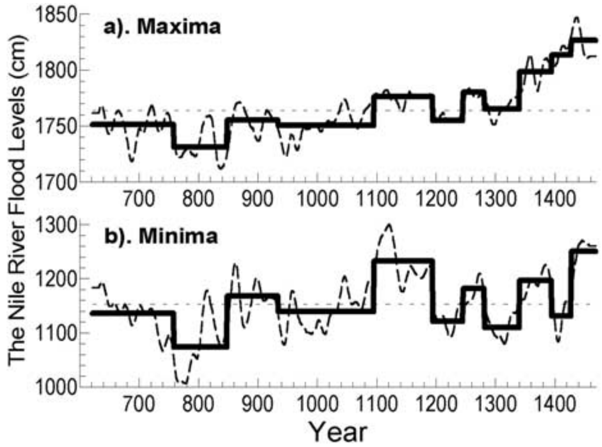

Figure 2. The episode average (thick solid line), the original series smoothed with a Gaussian filter on 21-year scale (dashed line), and the overall series mean (thin dot line), for (a) the maximum and (b) the minimum flood levels. The episodes are estimated based on the contour centers in Figure 1.

4. Summary

[21] In this article, we extend the classical Student *t*-test into a scanning and coherency detection of multiscale abrupt changes based on the wavelet technique, and apply to both historical time

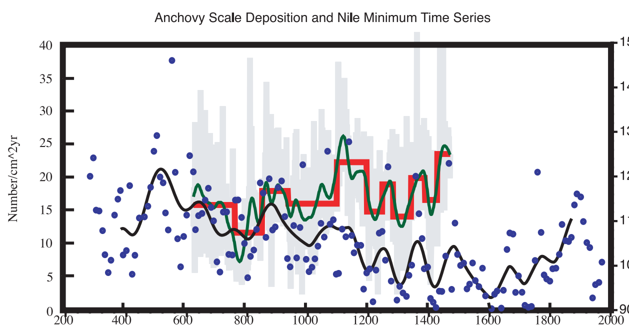

Figure 3. Estimates of the raw (blue dots) and low-pass filtered (dark solid line) Northern Anchovy scale deposition counts from *Baumgartner et al.* [1992], versus the Nile minimum series (solid gray line), a non-parametric estimate of the trend of the Nile minimum (green line) and the mean level in the Nile series during the alternate wet and dry periods identified by the multiscale scanning *t*-test (red line).

series of the maximum and minimum Nile flood levels. It is shown that the scanning *t*-test holds not only an ability similar to the Haar wavelet transform for detecting multi-scale changes, but also gives the threshold of statistical significance. It also detects abrupt changes on various time scales, because the subsample size is not limited to be integer powers of 2 like in the wavelet transform for a discrete series. In general, this algorithm may be applied to various time series for detecting multiscale abrupt changes of the first moment.

[22] The application of this algorithm to historical time series of the Nile flood levels objectively shows synchronously abrupt changes in both the maxima and minima on time scales between 30 and 160 years. The relatively dry/wet episodes in the river basin coincide well with historical records of catastrophic events in Egypt.

[23] A comparison to climate changes in Asia and Europe, and to proxy fishery population data off the U.S. west coast, suggest there exists a relationship between the temporal scales and spatial scales of climate variability. Roughly synchronous changes in larger areas usually occur on longer time scales, with strong evidence that multi-centurial climate events are globally teleconnected.

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