PERIODICITIES IN SEA-LEVEL CHANGES AT STOCKHOLM

R. P. KANE and D. GOBBI
Instituto Nacional de Pesquisas Espaciais, INPE, C.P. 515, 12201 São José dos Campos, SP, Brazil

Abstract. The annual mean sea-level time series for Stockholm (Sweden) for 1825–1984 (160 data points) had a large long-term negative (almost linear, only slightly quadratic) trend. After correcting for the same, the detrended series was subjected to maximum entropy spectral analysis (MESA). Choosing selected periodicities for further multiple regression analysis, series for the first 80 yr (1825–1904) showed periodicities at $T = 2.40, 5.0, 6.1, 13.5, 14.8$ and 32 yr, significant at a 2$\sigma$ level. The three largest peaks (italicized) had amplitudes of approximately $(2.5-3.0) \pm 0.8$ cm. The latter 80 yr (1905–1984) showed significant periodicities at $T = 2.05, 2.7, 3.0, 3.6, 4.4, 5.5, 6.3, 7.7, 9.8, 20.5$ and 33 yr. The three largest peaks (italicized) had amplitudes of approximately $(2.0-2.5) \pm 0.7$ cm. The whole period of 160 yr (1825–1984) showed significant periodicities at $T = 2.05, 2.9, 3.2, 4.5, 4.9, 5.6, 6.4, 7.8, 11.0, 13.7, 14.8, 29$ and 43 yr. The three largest peaks (italicized) had amplitudes of approximately $(1.6-1.9) \pm 0.6$ cm. All these significant peaks explained a variance of only about 30% or less, indicating a large random component of approximately 70%. Peaks at $T = 11$ yr (sunspot cycle) or $T = 18.6$ yr (lunar nodal term) were either absent or very weak. Most of the other peaks were transient (present in the first 80 yr or the latter 80 yr) except an uncertain quasibiennial oscillation (QBO) ($T = 2-3$ yr) and $T = 5-6$ yr and $T \approx 30$ yr, which seemed to be persistent throughout the whole period. Some periodicities seem to resemble those seen in the Southern Oscillation (SO) index.

1. Introduction

Regional and global sea-level changes have been studied by many researchers. Earlier results have been summarized in Lisitzin (1974) and some recent results in Emery (1980). Barnett (1983) presented a new analysis of global sea level which largely avoided the space/time bias of previous works and reported a relative sea-level (RSL) increase of approximately 15 cm/century. Barnett (1984) developed an objective method of estimating regional averages of coherent sea-level change and applied it to a large set of sea-level data representative of most of the world’s continental margins. For the 100-year period 1881–1980, an average trend of $14.3 \pm 1.4$ cm/century was obtained, though it consisted of a period of little change (1881–1920) and a period of steady increase thereafter (1920–1980). The linear trend for 1930–1980 was $22.7 \pm 2.3$ cm/century and was considered a good fit. However, there was also a concern that the rate of rise may be increasing and may increase significantly over the next few decades as a result of the ‘greenhouse effect’. Hence, Woodworth (1990) examined evidence for previous accelerations or quadratic trends in European sea levels and, in general, found no evidence for such accelerations for the period 1870 to the present but did find a positive acceleration of...
approximately 0.4 (mm yr\(^{-1}\)) per century over the last few centuries for the European Atlantic coast and the Baltic mean sea level.

Apart from these trends, another interesting aspect of the sea-level time series is the presence of periodicities. Rossiter (1967) applied regression analysis to annual means of sea level for European stations to estimate secular variations, air-pressure variations and the lunar nodal tide (18.6 yr) and obtained only weak evidence for the nodal tide. Using maximum entropy spectral analysis (MESA), Currie (1975) studied the monthly mean values of tide gauge records from 126 stations and detected the Chandlerian-induced pole tide signal (period 433.16 ± 0.41 mean solar days) on a world-wide basis. Also, using monthly mean values of sea level of the 33 longest time series for approximately 75 yr (1890–1964), mostly at locations along the coasts of Denmark and the Netherlands, Currie (1976) presented evidence for the presence of a lunar nodal term (18.5 ± 1.1 yr) and a solar cycle signal (10.9 ± 0.6 yr) and additionally, a signal of unknown origin at approximately 6.3 yr. Currie applied high-pass and low-pass filters and finally used 34 twice-yearly data points for spectrum analysis.

Recently, Ekman (1988) published the world’s longest continued series of sea-level observations. The observations are for Stockholm for about a 200-yr period (1774–1984) and are claimed to be very reliable. Using them, Ekman estimated the eustatic rise of sea level as 1 mm/yr (10 cm/century), caused by the change from the colder climate at the end of the ‘Little Ice Age’ around 1700/1800 to the milder climate of our own century, which is characterized by the melting of glaciers (Lisitzin, 1974; Lambeck and Nakiboglu, 1984), mainly from the Northern Hemisphere (Lambeck, 1980; Meier, 1984). Using monthly means for the period 1825–1984, Ekman and Stigebrandt (1990) performed a Fourier analysis and examined in detail the semiannual and annual variations as well as the pole tide (Chandler period of 14.3 months) and reported secular changes in the amplitudes of these periodicities. In the present communication, we present the MESA results of Ekman’s (1988) long time series, using annual means of sea level at Stockholm.

2. Method of Analysis

Maximum entropy spectral analysis (MESA) was developed by Burg (1967, 1975) and critically reviewed by Ulrych and Bishop (1975). MESA is superior to the Blackman and Tukey (1958) method of autocorrelation. However, MESA has a major defect, viz. the amplitude (or power) estimates are not reliable (Kane, 1977; Kane and Trivedi, 1982). Hence, Kane (1977) introduced the procedure of using MESA only for detecting possible periodicities \(T_k\) \((k = 1, \ldots, n)\) and then using these \(T_k\) in the expression

\[
f(t) = A_0 + \sum_{k=1}^{n} a_k \sin(2\pi t/T_k) + \sum_{k=1}^{n} b_k \cos(2\pi t/T_k) + E
\]
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\[ \begin{align*}
    f(t) &= A_0 + \sum_{k=1}^{n} r_k \sin(2\pi t/T_k + \phi_k) + E,
\end{align*} \]

where \( f(t) \) is the observed time series and \( E \) is the error factor. A multiple regression analysis (Bevington, 1969; Johnston, 1960) is then carried out to obtain (by a least-square fit) the best estimates of \( A_0, (a_k, b_k) \) and also their standard errors. From these, the amplitudes \( r_k \) and their standard errors \( \sigma_{r_k} \) can be calculated. Also, the percentage variance explained (PVE) by every \( r_k \) is given by \( 100 \times \left( \frac{r_k^2}{\sigma^2} \right) \), where \( \sigma^2 \) = variance of the series \( f(t) \). For a 100-data-point sample, the accuracy of peak location in MESA is better than 5% near \( T = 2-3 \) but errors become larger for larger \( T \), with errors as large as 20% when \( T \) approaches the data length 100 (Chen and Stegan, 1974; Kane, 1977, 1979).

3. Data and Long-Term Trend

Ekman (1988) gave annual mean sea levels for Stockholm for 1774–1984. However, the initial data had some gaps. Data for 1778–1784, 1786, 1792–1800, 1812–1824 were missing. Hence, we have used data only for 1825–1984 (160 annual means), which are shown in Figure 1 (a). As can be seen, there was a continuous decrease of about 60 cm during the last 160 yr. This seems to be completely out of phase with most of Europe and Africa, for which Barnett (1983, 1984) reported an increase for the same period. The reason for this discrepancy is, however, well-known: mean sea-level changes can occur due to a variety of physical processes, e.g. changes in water temperature and salinity, local and non-local currents, winds, waves and atmospheric pressure, etc., and these can be conflicting with each other (Lisitzin, 1974). But a still more complicating factor is tectonic land uplift/subsidence. This effect is most pronounced in regions of glacial rebound (high latitudes, e.g., Hicks and Shofnos, 1965, for the Alaskan region) and near the mouths of large rivers (e.g., Gulf of Mexico). This effect is known to be strong in Scandinavia; what is seen in Figure 1 (a) is the land uplift at Stockholm, overshadowing the sea-level rise. Ekman (1988) divided the data into two parts of roughly 100 yr each and estimated the land uplift (millimeters/year) as 4.93 ± 0.23 for 1774–1884 and 3.92 ± 0.19 for 1885–1984, from which he obtained a change of the apparent land uplift as −1.01 ± 0.30 and interpreted it as an eustatic rise of sea level of approximately 1 mm/yr. Woodworth (1990) used the same data and fitted a quadratic of the type \( y = a - bt + ct^2 \) and obtained for the acceleration \( c \) a small value (0.0043 ± 0.0014 mm/yr \(^2\)) for the period 1774–1984 (210 yr). Our quadratic fit for the period 1825–1984 (160 yr) gave \( c = 0.0015 ± 0.0005 \) mm/yr \(^2\), somewhat lower than the value obtained by Woodworth. Since sea-level changes can occur due to a variety of causes, an interpretation of this result is not unambiguous, especially for a single station. In this communication, our purpose is not to attempt such an interpretation but to study other periodicities. Hence, the (slightly) quadratic fit was used to correct the original data. In Figure 1 (a) the trend is shown
Fig. 1. Annual mean sea level at Stockholm for 1825–1984 (160 data points). (a) Original data. The superposed smooth line represents long-term (only slightly non-linear) trend. (b) Detrended data.

superposed on the original data. When subtracted from the original data, the trend-corrected data were as shown in Figure 1(b). These data were divided into two equal parts of 80 data points each (1825–1904, 1905–1984), and these as well as the whole data set of 160 points (1825–1984) were subjected to MESA.

4. Maximum Entropy Spectral Analysis

Figure 2 (a) shows the spectra for the first 80 yr (1825–1904) and Figure 2 (b) for the latter 80 yr (1905–1984). In each case, the lengths of the prediction error filter (LPEF) used were 27, 40, and 53, corresponding to 33%, 50%, and 67% of the data length 80. From these spectra, the following periodicities were selected for further multiple regression analysis:

For 1825–1904: \( T = 2.19, \ 2.40, \ 2.64, \ 3.17, \ 3.64, \ 4.28, \ 4.95, \ 5.30, \ 6.10, \ 6.50, \ 7.10, \ 8.00, \ 8.70, \ 11.3, \ 13.5, \ 14.8, \ 20.5, \ 26.4, \ 31.7 \) yr (19 peaks).

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Fig. 2. Maximum entropy spectra for the Stockholm annual mean sea level time series for (a) first 80 yr, 1825–1904; (b) latter 80 yr, 1905–1984; (c) whole period (160 yr) 1825–1984, for lengths of the prediction error filters (LPEF) 27, 40 and 53 for (a) and (b) and 53, 80 and 107 for (c), corresponding to 33%, 50% and 67% of the data lengths 80 for (a) and (b) and 160 for (c).
Fig. 3. Amplitudes (cm) of the various periodicities obtained by a multiple regression analysis for the spectra of the Stockholm annual mean sea level series for (a) first 80 yr, 1825–1904; (b) latter 80 yr, 1905–1984; (c) whole period (160 yr) 1825–1984. The shaded portion represents the 2 sigma limit. Numbers represent periodicities (years) and the three circled numbers in each case indicate the three most prominent periodicities. The two arrows at the top indicate locations where periodicities at $T = 11$ yr (sunspot cycle) and $T = 18.6$ yr (lunar nodal term) were expected but are not seen at a significant level.

For 1905–1984: $T = 2.05, 2.35, 2.70, 3.03, 3.56, 3.90, 4.40, 4.90, 5.50, 6.30, 7.70, 8.20, 9.80, 11.3, 13.8, 20.5, 25.0, 33.2$ yr (18 peaks).

The amplitudes (in centimeters) are shown in Figures 3 (a) and (b). The shaded area represents the 2 $\sigma$ level, where $2\sigma = 1.5$ cm for Figure 3 (a) and 1.3 cm for Figure 3 (b). Some amplitudes are significant at a 2 $\sigma$ level, more so for the data for the latter 80 yr (figure 3 (b)). Periodicities having the three largest amplitudes are marked with circles and together explain approximately 30% of the total variance. However, there are no significant common periodicities except $T \approx 32$ yr. This would imply that the periodicities are probably of a transient nature. Also, the two prominent periodicities at $T = 18.6$ yr (lunar nodal term) and $T = 11$ yr (sunspot cycle) reported by Currie (1976) do not seem to be present in any of the two 80-yr samples.

Figure 2 (c) shows MESA for the whole period 1825–1984 (160 data points). From these, the following periodicities were selected for multiple regression analysis:
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For 1825–1984: $T = 2.05, 2.96, 3.24, 4.50, 4.90, 5.14, 5.60, 6.40, 6.90, 7.80, 8.50, 10.0, 11.0, 12.6, 13.7, 14.8, 18.7, 22.4, 28.9, 43, 65, 80$ yr (22 peaks).

The amplitudes are shown in Figure 3 (c). Several periodicities are significant above the $2\sigma$ level (shaded area, $2\sigma = 1.1$ cm), and now there exists a peak at $T = 11$ yr (sunspot cycle) of amplitude $1.4 \pm 0.6$ cm, explaining approximately 3% variance. However, this is not the most prominent peak. It is the 6th peak in order of amplitude. The three largest peaks are $T = 29$ yr (amplitude $1.9 \pm 0.6$ cm), $T = 4.9$ yr (amplitude $1.9 \pm 0.6$ cm) and $T = 14.8$ yr (amplitude $1.7 \pm 0.6$ cm), each explaining only about 5% of total variance (total variance 15%). The lunar nodal term ($T = 18.6$ yr) exists but with a small amplitude of $1.0 \pm 0.6$ cm, explaining only about 1.4% of variance.

5. Conclusion

Maximum entropy spectral analysis of the annual mean sea-level time series for Stockholm (Sweden) showed several periodicities significant at a $2\sigma$ level, viz.

For 1825–1904 (first 80 yr): $T = 2.40, 5.0, 6.1, 13.5, 14.8, 32$ yr.

For 1905–1984 (latter 80 yr): $T = 2.05, 2.70, 3.0, 3.6, 4.4, 5.5, 6.3, 7.7, 9.8, 20.5, 33$ yr.

Thus, only $T = 2–3, T \approx 6$ and $T \approx 32$ yr were common to both, indicating that the others were probably of a transient nature. Also, no significant peaks were noticed at $T = 11$ yr (sunspot cycle) or at $T = 18.6$ yr (lunar nodal term).

For the whole period, periodicities significant at a $2\sigma$ level were:

For 1825–1984 (160 yr): $T = 2.05, 2.96, 3.2, 4.5, 4.9, 5.6, 6.4, 7.8, 11.0, 13.7, 14.8, 29, 43$ yr.

Amongst these, $T = 11.0$ appears only as a weak peak and $T = 18.6$ is absent.

It would thus seem that the sunspot cycle signal ($T = 11$ yr) and the lunar nodal term ($T = 18.6$ yr) are very weakly represented in the sea-level series at Stockholm. There are other stronger signals; but most of these are transient, i.e., present in the earlier 80 yr but not in the latter 80 yr, or vice versa. Besides an uncertain QBO (quasibiennial oscillation, $T = 2–3$ yr), only $T \approx 6$ yr and $T \approx 30$ yr seem to be persistent throughout the whole period. However, the amplitudes of these are small (2–3 cm) and the total variance explained by these is only about 30%, indicating that the random component is still very large (about 70%). Thus, prediction possibilities are nil.

The physical mechanisms responsible for the various periodicities are not always known. The annual and semiannual cycles are due to similar variations of the atmospheric pressure and changes in the specific volume of the water column (the steric effect) (Ekman and Stigebrandt, 1990). The ocean tide corresponding to the polar motion with the Chandler period of 14.3 months is well identified (Currie, 1975). The QBO ($T = 2–3$ yr) is well established in the 50 mb winds in the tropics and in surface winds, also (Rasmusson et al., 1990). Periodicities at $T = 3–4$ yr may be related to the El Niño/Southern Oscillation phenomenon (ENSO) (Rasmusson

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and Carpenter, 1982). $T = 6 \text{ yr}$ could be the second harmonic of the solar cycle, though the solar cycle signal ($T = 11 \text{ yr}$) is rather weak in the present series. Larger periodicities may be related to atmospheric pressure changes that are reflected in the Southern Oscillation (SO) index (atmospheric pressure difference between Tahiti and Darwin), for which Kane (1989) reported periodicities at $T = 2-3, 3.7, 4.3, 9, 18$ and $28 \text{ yr}$ for the time series $1851-1974 (124 \text{ yr})$.

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