ON THE LONG TERM (1935 - 1976) FLUCTUATIONS
OF THE LOW FREQUENCY AND MAIN TIDAL CONSTITUENTS
AND THEIR STABILITY IN THE GULF OF ANTALYA

ANTALYA KÖRFEZİNDE ALÇAK FREKANS VE TEMEL GELGİT
BİLEŞENLERİNİN UZUN SÜRELİ (1935 - 1976) DEĞİŞİMLERİ VE
DURAĞANLIKLARI

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Key words: Sea level; Tidal constituents; Levantine Sea; Eastern Mediterranean.

Abstract

Long term and tidal characteristics of water level variations at Antalya (Northern Levantine
Sea, Eastern Mediterranean) have been investigated based upon a sequence of hourly water
level observations from 1935 to 1976.

The seasonal fluctuations of monthly mean sea level show two maxima and two minima;
the major minimum occurs in March and a major maximum in August. The range between
the extremes is about 17.4 cm. A 3.6 mm per year rise in annual sea level is computed.

Tidal oscillations are small in amplitude with a spring range of 21 cm and dominated by
semi-diurnal constituents. Tidal constituents were examined for the stability of the
harmonic constants. The result of these analyses, with a one-year shift, indicated that
diurnal (K1, O1), semi-diurnal (M2, S2, K2, N2) and some long-term (S3, S8a) constituents
for the period 1935 - 1976 were worthy to take into consideration. Most of the remaining
long period constituents were absolutely unstable and completely unreliable.

Introduction

Although the water level characteristics of the Eastern Mediterranean have been
studied in the past (Defant, 1961; Striem and Rosenan, 1972; Striem, 1974), any
literature on the tidal characteristics of Northern Levantine Sea has up till now
been rather rare. Using short data sets, Yüce and Alpar (1994) studied short (seiches) and tidal characteristics of the water level variations in the Northern Levantine Sea.

In this study, long-term characteristics and stability of water level variations were calculated for Antalya using hourly sampled tidal data compiled by the General Command of Mapping (1991). The data cover the time span from 1935 to 1976 and were collected by means of a mechanical, float type tide gauge (N36° 53' 13"; E30° 42' 09''). The gauge datum was reduced to a constant level covering the whole period of observations after the corrections of vertical shifts which occurred in the years 1938, 1942, 1955 and 1956.

Tidal analysis based on harmonic techniques is very efficient in determining tidal harmonic constants. Hourly sampled sea level data of Antalya were analysed to calculate some principal harmonic constants using a harmonic analysis software package given by Caldwell (1991). The stability of the amplitudes and phases of these constants are presented.

Analysis and Results
A. Long-Term and Secular Changes

Striem and Rosenan (1972) studied seasonal fluctuations of sea level on the coast of the Eastern Mediterranean and reported a major minimum in April, a major maximum in July/August, a minor minimum in October and a minor maximum in December with a range of 21 cm between extremes. In the present study the seasonal fluctuations were calculated using the monthly averages of the Antalya sea level data (Figure 1). A major minimum occurs in March and April followed by a major maximum in July and August. The range between these extremes is 17.4 cm. The results are similar to the Striem and Rosenan's with some slight time shifts around the extremes. The barometric pressure, thermal expansion and the piling of water onshore as a result of storm surges were considered to produce these fluctuations.

On the other hand, the annual mean sea levels were computed by taking averages of the monthly mean sea levels (Figure 2). Some distinct minimum and maximum values fluctuating around the linear trend are observed. The sea level rise in annual means for that period is computed to be 3.6 mm per year, somewhat higher than the world average.

B. Low Frequency Tidal Constituents

The constituents $S_a$ and $S_{sa}$ are known to be generated mainly by meteorological forces and steric effects. In order to detect the effects of these forces, numerical tidal analysis was carried out. The amplitudes and phases were calculated by applying the nodal corrections to the outputs from the linear least squares tidal analysis. Applying nodal corrections allows the fitted components to be used further from the actual time period used to fit the components. The phases are relative to the local reference time origin (30° E) at 00:00, 01 Jan. 1976.

Variations from year to year in the long period tides are rather large in both amplitude and phase. To understand the stability of the constituents $S_a$ and $S_{sa}$
Figure 1. The seasonal fluctuation of the monthly sea levels in the Gulf of Antalya.

Figure 2. Annual mean sea level changes in the Gulf of Antalya.
better, the vector averages (Crawford, 1982) and the standard deviations of 19 one-year analyses, which were worked out without pressure adjustment, were computed (Table 1).

As it is seen from the table, the amplitudes of the constituent $S_a$ seem to be decreasing from 1935 to 1976, with some fluctuations. The variations of the phases also decrease. Both amplitude and phase lags, especially the latter, exhibit considerable variations. For the $S_{Sa}$ constituent, standard deviations of the amplitude exceed the amplitude itself. These statistical results show that $S_a$ and $S_{Sa}$ should not be taken for tidal predictions for this port.

In theory these tidal constituents can be resolved by choosing a sufficiently long record. Therefore, it will be better to handle data that covers a nodal period (18.61 years, the period of rotation of the lunar node).

The long period of oscillations can be exemplified by examining the variation in the mean sea level (MSL). For this purpose, the time series of hourly heights were low passed by applying the $A_2A_2^2/(24^2+25)$ tide-killing filter (Godin, 1972) to remove the diurnal and semi-diurnal tides. The record was almost free of gaps, and its low passed record has no gaps at all. Data points at 24 hour intervals were chosen from the low passed record, starting at 0100 January 1, 1935. Twenty-two 19-year analyses with one year shifts were computed for the constituents $S_a$ and $S_{Sa}$.

The amplitudes of $S_a$ tend to increase for that period of time, showing some fluctuations (Figure 3). This is contrary to what is calculated above. On the other hand, the variations of phase lags decrease. But there is a constant phase advance (+177.16° 1.72°) between the phases given in Table 1 and the resampled data for $S_a$, while a constant phase delay (-14.36° 1.48°) was calculated for $S_{Sa}$. This is because of the difference between the zero reference points of hourly raw data and 24-hourly sampled low pass data.

Barometric pressure correction can be applied to the sea level data in order to obtain data that may possibly represent the low frequency constituents better. Franco and Harari (1993) who examined the variations of harmonic constants ($H$ and $g$) after barometric pressure corrections on sea level data did not find any difference for $S_{Sa}$. However, they found some different characteristics for $S_a$, such as a decrease in fluctuations of the amplitudes after correction. In other words, the deviations of the harmonic constants from their linear trends are smaller while they keep a very similar pattern with that of the uncorrected data. Because the comparative barometric pressure data covering the observation period were not available, it could not be possible to adjust the sea level data to test this problem for Antalya.

C. Main Tidal Constituents

Tides in Eastern Mediterranean is characterised by semi-diurnal tides in the east; mixed but mainly semi-diurnal tides in the west (Defant, 1961). Semi-diurnal tidal patterns with a spring ranges of 52 cm largest, 42.8 cm average and 35 cm smallest on Israel's Mediterranean coast were reported by Striem (1974) based upon a set of
Table 1. Vector average amplitudes (H), phases (g) and standard deviations of long period harmonic constituents \( S_a \) and \( S_{sa} \) at Antalya. Amplitudes and standard deviations are in centimetres, g is the 030 epoch expressed in degrees.

<table>
<thead>
<tr>
<th>Years</th>
<th>( S_a ) H</th>
<th>( S_a ) g</th>
<th>( S_{sa} ) H</th>
<th>( S_{sa} ) g</th>
</tr>
</thead>
<tbody>
<tr>
<td>1935 - 1954</td>
<td>7.20</td>
<td>70.63</td>
<td>4.19</td>
<td>72.78</td>
</tr>
<tr>
<td>1936 - 1955</td>
<td>7.56</td>
<td>72.44</td>
<td>4.07</td>
<td>70.96</td>
</tr>
<tr>
<td>1937 - 1956</td>
<td>7.74</td>
<td>72.84</td>
<td>4.41</td>
<td>69.37</td>
</tr>
<tr>
<td>1938 - 1957</td>
<td>7.83</td>
<td>68.41</td>
<td>4.24</td>
<td>66.77</td>
</tr>
<tr>
<td>1939 - 1958</td>
<td>7.82</td>
<td>66.37</td>
<td>4.72</td>
<td>62.65</td>
</tr>
<tr>
<td>1940 - 1959</td>
<td>7.27</td>
<td>65.24</td>
<td>4.76</td>
<td>66.87</td>
</tr>
<tr>
<td>1941 - 1960</td>
<td>7.67</td>
<td>64.88</td>
<td>4.70</td>
<td>66.56</td>
</tr>
<tr>
<td>1942 - 1961</td>
<td>7.67</td>
<td>64.88</td>
<td>4.41</td>
<td>66.76</td>
</tr>
<tr>
<td>1943 - 1962</td>
<td>7.61</td>
<td>65.19</td>
<td>4.72</td>
<td>60.74</td>
</tr>
<tr>
<td>1944 - 1963</td>
<td>7.68</td>
<td>66.43</td>
<td>4.75</td>
<td>61.40</td>
</tr>
<tr>
<td>1945 - 1964</td>
<td>7.41</td>
<td>67.38</td>
<td>4.97</td>
<td>61.39</td>
</tr>
<tr>
<td>1946 - 1965</td>
<td>7.46</td>
<td>63.43</td>
<td>4.66</td>
<td>64.44</td>
</tr>
<tr>
<td>1947 - 1966</td>
<td>7.56</td>
<td>64.62</td>
<td>4.68</td>
<td>65.54</td>
</tr>
<tr>
<td>1948 - 1967</td>
<td>7.69</td>
<td>64.98</td>
<td>4.67</td>
<td>64.63</td>
</tr>
<tr>
<td>1949 - 1968</td>
<td>7.63</td>
<td>65.31</td>
<td>4.39</td>
<td>64.33</td>
</tr>
<tr>
<td>1950 - 1969</td>
<td>7.32</td>
<td>68.32</td>
<td>4.55</td>
<td>62.54</td>
</tr>
<tr>
<td>1951 - 1970</td>
<td>6.82</td>
<td>68.46</td>
<td>4.81</td>
<td>64.54</td>
</tr>
<tr>
<td>1952 - 1971</td>
<td>6.71</td>
<td>68.02</td>
<td>4.91</td>
<td>64.41</td>
</tr>
<tr>
<td>1953 - 1972</td>
<td>6.69</td>
<td>63.15</td>
<td>4.82</td>
<td>64.64</td>
</tr>
<tr>
<td>1954 - 1973</td>
<td>6.78</td>
<td>62.52</td>
<td>4.27</td>
<td>63.02</td>
</tr>
<tr>
<td>1955 - 1974</td>
<td>6.67</td>
<td>58.67</td>
<td>4.28</td>
<td>64.23</td>
</tr>
<tr>
<td>1956 - 1975</td>
<td>6.76</td>
<td>58.31</td>
<td>3.79</td>
<td>62.98</td>
</tr>
<tr>
<td>1957 - 1976</td>
<td>6.74</td>
<td>61.05</td>
<td>4.07</td>
<td>63.84</td>
</tr>
</tbody>
</table>
six-year data. These amplitudes decrease towards the west with a mean Spring range of 36.6 cm at the East coast of Cyprus. In the Gulf of Antalya, the mean Spring range is 20.8 cm and the tidal regime is mixed but mainly semi-diurnal in nature (Yüce and Alpar 1984). The semi-diurnal lunar ($M_2$) constituent is the major tidal component and secondary contribution comes from solar ($S_2$) component, being typical of Mediterranean.

As many as 68 tidal constituents can be separated by the 366 day hourly data analysis. But because the tidal amplitudes are rather small in the Gulf of Antalya, the accuracy of the results becomes an important factor. To estimate the accuracy of the results, the major constituents ($K_1$, $O_1$, $M_2$, $S_2$) and $N_2$ and $K_2$ with amplitudes greater than 1 cm, were selected. By considering only the linear regression analyses of their variations, mean amplitudes ($H_0$) and phase lags ($g_0$) with their average yearly variations (AYV) and standard deviations (SD) were calculated (Table 2).

### Table 2. Accuracy of the results

<table>
<thead>
<tr>
<th>Constituent</th>
<th>$H_0$ (cm)</th>
<th>AYV (cm)</th>
<th>St. Dev. (cm)</th>
<th>$g_0$ (deg)</th>
<th>AYV (deg)</th>
<th>St. Dev. (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_1$</td>
<td>1.50</td>
<td>0.00469</td>
<td>0.12</td>
<td>292.40</td>
<td>-0.47011</td>
<td>10.20</td>
</tr>
<tr>
<td>$K_1$</td>
<td>2.30</td>
<td>0.00892</td>
<td>0.21</td>
<td>321.29</td>
<td>-0.40599</td>
<td>10.44</td>
</tr>
<tr>
<td>$N_2$</td>
<td>1.08</td>
<td>0.00116</td>
<td>0.14</td>
<td>290.99</td>
<td>-0.70159</td>
<td>10.03</td>
</tr>
<tr>
<td>$M_2$</td>
<td>6.35</td>
<td>0.04077</td>
<td>0.81</td>
<td>291.73</td>
<td>-0.86720</td>
<td>17.68</td>
</tr>
<tr>
<td>$S_2$</td>
<td>3.98</td>
<td>0.02308</td>
<td>0.44</td>
<td>307.69</td>
<td>-0.81365</td>
<td>17.30</td>
</tr>
<tr>
<td>$K_2$</td>
<td>1.14</td>
<td>0.00992</td>
<td>0.18</td>
<td>296.17</td>
<td>-0.50572</td>
<td>14.84</td>
</tr>
</tbody>
</table>

But only major constituents ($K_1$, $O_1$, $M_2$, $S_2$) were selected to study their long-term behaviors (Figure 4). It is evident that both the amplitudes and phase lags oscillate around the values which are not strictly constant. In fact, the straight lines clearly indicate drifts in the results of subsequent analyses. All of the phase lags were decreasing, but with different rates. On the other hand, all of the amplitudes were increasing. But the amplitudes of the semi-diurnal constituents increase at a higher rate than those of diurnal ones. An increase is detected in the $M_2$ amplitude (0.041 cm per year), while the $O_1$ is almost stable at a rate of 0.005 cm per year. However,
Figure 3. Variation of $H$ and $g$ for $S_a$ and $S_{sa}$ in the Gulf of Antalya.

Variation of $H$ for $S_a$ and $S_{sa}$

Variation of $G$ for $S_a$ and $S_{sa}$

Degrees
Figure 4. Variation of H and g for M$_2$, S$_2$, K$_1$ and O$_1$ in the Gulf of Antalya.
the linear regression lines in Figure 4 seem not to be the best fits to the variations. Some sinusoidal waves with a nodal period may give better polynomial fits especially for phases and amplitudes of semi-diurnal constituents.

The reason of these long-term variations should have an explanation. Long-term changes of the physical characteristics of the water masses and also geophysical medium may cause some slow rate changes on the sea level systems. We may tentatively assume that these fluctuations are due to a possible displacement of the amphidromic system located at the southern Aegean Sea.

Conclusion

The seasonal sea level fluctuations in the Gulf of Antalya show two maxima and two minima; the major minimum occurs in March and a major maximum in August. These are fairly in good agreement with the general fluctuations of mean sea level for Eastern Mediterranean. An annual sea level rise of 3.6 mm per year is computed. The tidal regime is mixed, but predominantly semidiurnal.

The amplitudes and the phase lags of the main harmonic tidal constituents are not strictly constants. From the scientific point of view, the determination of constituents $S_a$ and $S_{sa}$ from one year data is far from being perfect. Therefore $S_a$ and $S_{sa}$ should not be included in the harmonic analysis of one-year tidal records of this port.

The variations in the tidal analyses results may be explained by some displacement of the amphidromic systems in the vicinity, depending upon the physical characteristics of the water masses and the geophysical medium.

Özet


Ortalama aylık su seviyeleri mevsimsel değişimleri yıl süresince iki maksimum ve iki minimum göstermektedir. Esas minimum Mart ayında, esas maksimum ise Ağustos ayında oluşmaktadır. En büyük ve en küçük ortalama değerler arasındaki fark yaklaşık olarak 18 cm bulunmaktadır. Belirtilen zaman diliminde ortalama su seviyesinde gözlenen yükselme miktarı yıllık bazda 3.6 mm olarak hesaplanmıştır.

Gelgit değişimleri yarım günlük karakteristikte olup, küçük genliklidir ve ortalama yüksek gelgit 21 cm olarak bulunmuştur. Ayrica 1935 - 1976 yılları arasında gelgit bileşenleri harmonik sabitlerin durağanlığı araştırılmıştır. Bir yıllık kayımlarla yapılan bu analizin neticesinde, günlük ($K_1$, $O_1$), yarım günlük ($M_2$, $S_2$, $K_2$, $N_2$) ve bazı uzun süreli ($S_a$, $S_{sa}$) bileşenler dikkate alınmaya değer bulunmuştur. Kalan uzun peryodlu bileşenlerin çoğu zaman boyutunda kararsız olup, güvenilir değildir.

Acknowledgement

The authors gratefully acknowledge the tidal data support of the General Command of Mapping of
Turkey. The authors wish to express their sincere thanks to their colleagues, especially Mr. Nazmi POSTACIOĞLU for his data processing contributions and to Miss. B. İşıl ALPAR for her patient help in typing and producing the figures of this manuscript.

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Accepted 23.2.1995