Tidal Gauge Data in Deducing Secular Trends of Relative Sea Level and Crustal Movements in Portugal

João Alveirinho Dias† and Rui Taborda‡

‡Instituto Hidrográfico
Rua das Trinhas, 49
1296 Lisboa Codex, Portugal

†Museu e Laboratório Mineralógico e Geológico
da Universidade de Lisboa
Rua da Escola Politécnica 58
1294 Lisboa Codex, Portugal

ABSTRACT


Along the Portuguese coast there are four tide-gauge data series that exceed 10 years. However, only those of Cascais and Lagos can be considered reliable indicators of long-term changes in relative sea level. A rise in relative sea level of $1.3 + 0.1$ mm/year and $1.5 + 0.2$ mm/year, respectively, can be found. The comparison of Cascais data with the evolution of sea surface temperature of North Atlantic Ocean suggests that thermal expansion of ocean is responsible for a large part of the observed rise. The reversal in the Cascais long-term trend detected around 1920 might be connected with the end of the “Little Ice Age”.

The determination of land elevation changes using Cascais and Lagos data was tried. The results point to a possible relative uplift of the Lagos station at a mean rate of $0.3 + 0.2$ mm/year.

ADDITIONAL INDEX WORDS: Relative sea level, tide-gauges, Portugal, land elevation changes.

INTRODUCTION

Analysis of tide-gauge records is of special value in the assessment of the present day trend of mean sea level. Studies using tide-gauges throughout the world indicate a “global” sea level rise of 1 to 3 mm/year (Table 1). Thus far, a serious drawback in accepting these numbers has been the large geographic variability of the observed rates of sea level rise and the high non-uniformity of the tide-gauge network (for example, coverage of the southern oceans with tide-gauges of sufficient longevity is poor).

However, when tide-gauge data are filtered in order to remove the contamination due to the ongoing influence of glacial isostatic adjustment, the global pattern thereby revealed does have spatial coherence (PELTIER and TUSHINGHAM, 1989). This signal is mainly due to thermal expansion of oceans and to the action of ongoing glacier and ice sheet melting, and can be a first indicator of global climate warming (that might be related to the greenhouse effect). Nevertheless, there is still a remaining variability due to a conjunction of factors such as: (a) tectonic movements, sediment loading and flexure, pore-fluid removal, and sediment compaction, which are responsible for the movement of the fixed bench-marks; and (b) long-term changes in the patterns of oceanographic and atmospheric circulation, responsible for changes of local mean sea level. For this reason, recent studies have examined relative sea-level changes on a regional scale often using data composed of different records. The study of long, continuous records, obtained in single tide-gauge stations and their comparison with records of other stations located nearby, are still powerful methods in determining relative sea-level oscillations on a local or micro-regional basis. These kinds of studies are fundamental to the mega-regional studies and can perhaps lead to a better understanding of the sea level constraints and variability.

The purpose of this study is to determine how eustatic, isostatic, and geologic factors produce the spatial and temporal variability of the relative sea level in Portugal. The records of Cascais and Lagos, of 104 and 78 years duration, respectively, have been the most important tide-gauge stations analyzed. The data from the Cascais station have been often used in global studies of sea level (e.g., Maksimov, 1971; Gornitz et al., 1982; Barnett,
Table 1. Estimates of "global" sea level increase (after Barnett (1983) and Braatz and Aubrey (1987)).

<table>
<thead>
<tr>
<th>Author</th>
<th>Rate (mm/year)</th>
<th>Method</th>
</tr>
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<tbody>
<tr>
<td>Thorarinsson (1940)</td>
<td>&gt;0.5</td>
<td>Cryologic aspects</td>
</tr>
<tr>
<td>Gutenberg (1944)</td>
<td>1.1 ± 0.8</td>
<td>Tide Gauges, 69 stations, 1880-1939</td>
</tr>
<tr>
<td>Kien (1950)</td>
<td>1.2-1.4</td>
<td>Different methods combined</td>
</tr>
<tr>
<td>Listz (1958)</td>
<td>1.12 ± 0.36</td>
<td>Tide Gauges, 6 stations, 1800-1943</td>
</tr>
<tr>
<td>Wexler (1961)</td>
<td>1.18</td>
<td>Cryologic estimates</td>
</tr>
<tr>
<td>Fanning and Kiefer (1962)</td>
<td>1.2</td>
<td>Tide Gauges, 1900-1950</td>
</tr>
<tr>
<td>Emery (1980)</td>
<td>3.0</td>
<td>Tide Gauges, 247 stations, 1850-1973</td>
</tr>
<tr>
<td>Gornitz et al. (1982)</td>
<td>1.2</td>
<td>Tide Gauges, 193 stations</td>
</tr>
<tr>
<td>Barnett (1983)</td>
<td>1.5 ± 0.15</td>
<td>Tide Gauges, 9 stations, 1903-1969</td>
</tr>
<tr>
<td>Barnett (1984)</td>
<td>1.43 ± 0.14</td>
<td>Tide Gauges, 155 stations, 1880-1980</td>
</tr>
<tr>
<td>Aubrey and Emery (Aubrey, 1985)</td>
<td>0-3.0</td>
<td>Tide Gauges</td>
</tr>
<tr>
<td>Gornitz and Lebedeff (1987)</td>
<td>1.7</td>
<td>Tide Gauges, 231 stations</td>
</tr>
<tr>
<td>Peletier and Tushingham (1989)</td>
<td>2.4 ± 0.9</td>
<td>Tide Gauges, 40 stations</td>
</tr>
</tbody>
</table>

* The authors attempt a correction for crustal motion and find 1.0 mm/year sea level rise.
* After a correction for crustal motion the authors found rates of 1.2 and 1.0 mm/year.
* The data were filtered to remove the contribution of ongoing glacial isostatic adjustment.

1983, 1984; Lambeck and Nakiboglu, 1984; Gornitz and Lebedeff, 1987; Peletier and Tushingham, 1989) due to the high quality of continuous, long term measurements and the location away from areas of intensive tectonic movement. However, thus far, there are no published studies specifically analyzing the tide-gauge records of Cascais and Lagos.

METHODS

The data sets from all continental Portuguese tide-gauge stations with a minimum time span of 10 years were studied (Leixões, 30 years; Cascais, 106 years; Lisboa, 14 years; and Lagos, 80 years) (Figure 1). Tide-gauge data were obtained from the Portuguese Hydrographic Institute. The analyses of these records have shown a background of interannual variability superimposed on the trends. This background is due to changes in weather patterns and in ocean circulation, and it causes trend analyses based only on a few years of observations to be potentially misleading (Pugh, 1987). In order to avoid this problem and to give prominence to the secular trends, stations with temporal lengths less than 50 years were discarded. Thus, only the long continuous and warrantable records of Cascais and Lagos were analyzed.

The most objective methods in estimating the secular trend entangled on long tide gauge records are probably those based on least squares calculations (Pirrazolla, 1986). All data were, therefore, subjected to linear regression analysis. The Cascais data were also fitted to other models, such as exponential, logarithmic, and power curves, which allow rates to change with time, but no significant statistical improvement was found.

In order to look for long periodic oscillations, a 19-year running mean was used. This procedure allows the elimination of the 18.6 year nodal cycle and, therefore, retains only long term changes.
RESULTS

Linear regression of the Cascais and Lagos series reveals trends of $+1.3 \pm 0.1$ and $+1.5 \pm 0.2$ mm/year changes in mean sea-level in relation to the fixed tide-gauge benchmarks (Figure 2). These results clearly indicate an effective and significant rise of the relative sea-level (at least during the last half-century) in Portugal. These values are in the range of most estimates of global sea level rise for this century (Table 1). It might thus be reasonable to admit that most of the signal detected in these stations is of global origin. This global rise is due mainly to thermal expansion of oceans and melting of alpine and continental glaciers (Gornitz et al., 1982; Gornitz and Lebedeff, 1987). However, the relative importance of these two factors in present sea-level rise is not yet well known. One clue to solve this problem lies perhaps in the background of short term variability, usually regarded as "noise" in the studies of long term sea level changes.

There is a significant agreement between the Cascais sea level curve and the variation of sea surface temperature (SST) of the North Atlantic Ocean (Figure 3) presented by Barnett (1983). There is a minimum between 1910 and 1920, followed by three peaks and 3 secondary minimums, within the same temporal periods. Since 1940, a five-year lag seems to be present. In order to confirm and to quantify the similarity of these curves, as well as to test the existence of the temporal lag visually determined, the correlation coefficient between the mean sea level in Cascais and the North Atlantic Ocean sea surface temperature was computed. A value of $+0.82$ was obtained, and when a time lag of five years was considered, this value rises to a maximum of $+0.86$.

Since 1920, the SST of the North Atlantic Ocean has risen almost $1^\circ$ C. According to Barnett (1983), if this warming were vertically distributed, thermal expansion of ocean would be responsible...
for a total elevation of 11 cm in the sea-level. This value is similar to the observed relative sea-level rise during the same period in the Portuguese stations of Cascais and Lagos. These results show that a large part of sea level rise can be accounted for in terms of the thermal expansion of the ocean.

The temporal structure of the data recorded in the station of Cascais suggests that relative sea level has not been rising consistently. From the end of last century until the 1920’s, mean sea level has apparently dropped at a rate of 0.5 ± 0.4 mm/year, and it is only from that period that relative sea level has had a net upward trend (+1.7 ± 0.2 mm/year). Although not very clearly shown, this minimum recorded around 1920 in Cascais could also be present in the Lagos data. The coincidence with the beginning of the observations in this station prevents any conclusive inference. Because the small climatic oscillation known by the name of “Little Ice Age” in Western Europe terminated by the end of the last century (Lamb, 1982), and because statistical correlations between sea level and global atmospheric temperature have suggested a 18-year lag of sea level in relation to atmospheric temperatures (Gornitz et al., 1982), it is possible that this shift in sea-level trend is connected to the end of the Little Ice Age. This shift can also be observed in several other tide-gauge stations. Even the composite sea-level curves presented by Gornitz and Lbedeff (1987), namely those corresponding to the “global” curve and the “Fennoscandia” and the “Rest of Europe” curves, present a different behavior before and after the decade of the 1920’s. This points to a mega-regional (or global) origin, which agrees with the possible relationship between the referred inflection in the sea-level curves and the transition from the “Little Ice Age” to the present climatic phase.

Beside providing information on movements of the sea surface, tide-gauge data can also be used as an indicator of neo-tectonic movements (including isostatic adjustments) amongst different stations. This can be determined by monitoring the differences between mean sea level at nearby stations, and by disregarding differences resulting from geoidal and long-term current changes. By applying this technique to the stations of Cascais and Lagos, it has been possible to deduce a possible 0.3 ± 0.2 mm/year relative uplift of Lagos station in relation to Cascais during the period 1908 to 1987 (Figure 4). Notwithstanding the high dispersion of the computed values and the impossibility of reaching conclusive results previously, the provisional conclusion is generally compatible with several well-defined factors, such as the present relative movements of the African plate in relation to Iberia. However, further investigation using more refined analysis techniques is required in order to achieve more consistent results.

CONCLUSIONS

Relative sea level is rising in both Cascais and Lagos stations at a mean rate of 1.3 ± 0.1 mm/year and 1.5 ± 0.2 mm/year, respectively (considering the entire data set of 106 and 80 years). Analysis of the temporal patterns of relative sea-level changes reveals a shift around 1920. This shift might be connected with the termination, in Western Europe, of the “Little Ice Age”, by the turn of the century. Considering only the period 1920–1987, mean sea level in Cascais has risen at a rate of 1.7 ± 0.2 mm/year.

The comparison of Cascais tide-gauge data with sea surface temperature of North Atlantic Ocean suggests that thermal expansion of the ocean plays an important role in the observed sea-level rise. The differences between sea-level curves from Cascais and Lagos stations show a possible relative uplift of the Lagos station at a mean rate of 0.3 ± 0.2 mm/year.
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LITERATURE CITED


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SUMARIO

Na costa Portuguesa existem 4 estações marégraficas com mais de 10 anos de registro. No entanto, só as de Cascais e Lagos podem ser consideradas indicadores seguros de variações de longo período no nível relativo do mar. Os resultados obtidos para estas duas estações apontam para uma elevação do nível referido a taxa média de $1.3 \pm 0.1 \text{ mm/ano}$ e $1.5 \pm 0.2 \text{ mm/ano}$, respectivamente. A comparação dos dados de Cascais com a evolução da temperatura superficial do Oceano Atlântico Norte sugere que a expansão térmica é responsável por uma grande parte da subida observada. A inflexão no comportamento na tendência secular detectada na série de Cascais por volta do ano 1920 poderá estar relacionada com o fim da "Pequena Idade do Gelo". Foi ensaiada a determinação de movimentos crustais usando as estações de Cascais e Lagos. O resultados apontam para um possível levantamento relativativo da estação de Lagos (em relação à de Cascais) à taxa média de $0.3 \pm 0.2 \text{ mm/ano}$.

SUMMARY

Sur la côte portugaise quatre stations marégraphiques ont plus de 10 ans d’enregistrements, mais seules elles de Cascais et Lagos indiquent des variations relatives du niveau de la mer. Les résultats de l’analyse des séries marégraphiques montrent une élévation du niveau de la mer de $1.3 \pm 0.1 \text{ mm/an}$ à Cascais et de $1.5 \pm 0.2 \text{ mm/an}$ à Lagos. Le comparaison des données de Cascais avec l’élévation de la température superficielle de l’Océan Atlantique Nord sugère que l’expansion thermique est le facteur principal, responsable de l’élévation du niveau de la mer qui s’y verifie. Sur la courbe de Cascais, l’inflexion observée vers 1920 doit se rapporter à la fin de la période du Petit Âge Glaciaire. La determination des mouvements de soulevement du continent entre Cascais et Lagos sugère que Lagos s’élève de $0.3 \pm 0.2 \text{ mm/an}$, relativement à Cascais.