Sea level in the Mediterranean Sea: The contribution of temperature and salinity changes.

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Abstract

The sea level variability produced by temperature and salinity changes in the Mediterranean is estimated from the Medar climatology. The steric heights calculated indicate that sea level in the upper 400 m is driven by temperature changes while in the deeper layers salinity also becomes important. The upper 400 m of the Eastern Mediterranean has been cooling between 1960 and the 1990s and as a result steric sea level has been reducing there. Nevertheless after 1993 upper water temperature has been increasing and consequently steric sea level has also been increasing. The Eastern Mediterranean Transient is clearly detectable in the calculated steric heights. The study of sub-regions in the Eastern Mediterranean reveals diverse behaviour at sub-basin scales and raises questions about the suitability of basin averages for the estimation either of sea level or temporal changes in temperature and salinity from climatic data. The steric sea level changes in the upper waters of the Adriatic and the Aegean Sea are correlated with the North Atlantic Oscillation index at the 99% level of significance. The comparison of the steric sea level changes to the coastal tide-gauges is not satisfactory within the Mediterranean and questions the suitability of estimating sea level changes on point measurements.

Introduction.

Global sea level has been rising by 1-2 mm/yr (Church et al., 2001) and it is expected to continue rising in the next century (mainly) due to thermal expansion of the oceans due to global warming. The question of the accuracy of these estimates which are based on a few 10s of long tide gauge records mainly in the Northern hemisphere has been re-opened by the observation that they exist in areas where enhanced trends, in relation to global mean trends, have been present (Cabanes et al. 2001). In the Mediterranean Sea before the 1960s, the relative sea level was increasing by about 1.2 mm/yr, a value within the range of the global trend. Nevertheless between 1960 and 1994 the Mediterranean Sea level trend has reversed sign (Tsimplis and Baker 2000). After the mid-1990s altimetric measurements suggest rapid rising of sea level in the Eastern Mediterannean Basin of the order of 20mm/yr which have been associated with increases of the sea surface temperature (Cazenave et al., 2001). Changes in the hydraulic conditions at the Strait of Gibraltar may also be important in the observed sea level rise during the recent years (Ross et al., 2000). Important and rapid changes in the deep water formation in the eastern Mediterranean (termed as the Eastern Mediterranean Transient (EMT) ; Roether et al., 1996) as well as decadal scale changes in the deep water characteristics (Rohling and Bryden, 1992; Bethoux *et al.*, 1990; Bethoux and Gentili, 1999; Tsimplis and Baker, 2000) may also be linked with the sea level changes.

The effects of the high NAO conditions during recent decades (Hurrell, 1995) affect the Mediterranean basin by producing increased atmospheric pressure over it and modifying the evaporation-precipitation balance of the basin (Tsimplis and Josey, 2001). Although the increase in the atmospheric pressure explains the reduction in sea level between 1960 and 1994 (Tsimplis and Josey, 2001) it does not explain the sudden change between the pre-1960 and post 1960 conditions.

In this paper we estimate the sea level changes introduced by changes in the water mass characteristics and compare them with the longer term sea level records available within the basin.

Data and Methodology

Steric sea level anomalies.

The Medar climatology (1953–1998) (http://www.ifremer.fr/sismer/program/medar/) was used to estimate the temperature and salinity variations. The T and S fields on a 1˚x1° grid were obtained using the Variational Inverse Method (VIM) developed by Brasseur (1991), extensively used in the Mediterranean context (e.g. Brasseur et al. 1996, Brankart and Brasseur 1996, 1998). This approach, statistically equivalent to traditional objective analysis is numerically more efficient and more suitable regarding the complexity of the Mediterranean geometry (Rixen et al., 2001). Calibration of the correlation length and the signal-to-noise ratio was obtained by Generalised Cross Validation (Brankart and Brasseur 1996). In order to obtain yearly values for the different standard levels, a moving gaussian weighted window of 3 years was used. We also experimented with 1 and 5 year filtering with similar results. The Medar database was then averaged spatially to produce mean T and S at 25 standard depths for the Eastern and the Western Mediterranean, an area outside the Strait of Gibraltar which represents the incoming signal from the ocean and several smaller areas (fig.1). Dynamic height anomalies and hydrostatic pressure were then calculated for each depth and integrated to produce steric heights. Three layers are presented. The upper layer extends from surface to 200m. The second layer extends between 200-400m and essentially represents the intermediate Mediterranean Waters. Finally the deep waters are represented by a layer between 400 m and the 2000m depth or the bottom in shallower areas.

The sampling of the Mediterranean is biased towards the areas of deep and intermediate water formation, while areas near the African coasts have not been sampled adequately. Moreover the data are also seasonally biased. Nevertheless the Medar dataset is presently the best dataset for the Mediterranean and therefore its use is more justified than the use of selected individual profiles in limited regions or the option of not attempting to understand the variability of the basin until a reliable observational network is developed. Previous studies in the area have suggested that the salinity measurements in the region may be of variable quality (Tsimplis and Baker, 2000). The same impression is also conveyed by the Medar data set and it appears important to flag or exclude measurements obviously wrong or dubious from any future climatology.

Sea Level Data

Mean annual values for Marseille and Genova in the north-western part of the western Mediterranean and at Trieste in the Adriatic are used as representative of the coastal sea level variability. The data are extracted from the Permanent Service of Mean Sea Level Database (Woodworth and Player, 2002). All three stations are revised local reference (RLR) stations i.e. information on the local datum is included in the database. The Marseille and Genova time series exhibit very similar trends (about 1.25 mm/yr) before 1960 while after 1960 sea level in Marseille is reducing by about 0.6 mm/yr while in Genova there is no significant trend (Tsimplis and Baker, 2000). Because both time series have gaps we form one sea level time series by averaging their mean annual values. We will consider the resulting time series as representative of the observed sea level near the coasts of the northwestern Mediterranean. The sea level time series in Trieste are complete.

Altimetric data from the TOPEX/POSEIDON mission are also used. The data are averaged to 1˚x1˚ grid squares as follows. First the mean value at each (sampling) point within the square is removed thus no spatial gradients are allowed within each grid box. Then the values are averaged monthly and from them mean annual values are extracted.

Results

The steric sea level anomalies are calculated in relation to a level of no motion at 2000 m (or at bottom where the sea is shallower), well below the sill level at Gibraltar. The total steric height anomalies are in the range from 4 to –5 cm for the Western and Eastern Mediterranean and almost double that for the Atlantic section. Increase of T or decrease of S result in increased steric heights.

The variability in the upper waters of the Eastern Mediterranean is mainly due to temperature effects (Fig.2). The reduction in steric height due to cooling around the 1990 is related to the EMT (Roether et al., 1995). The steric height of the upper waters of the western Mediterranean depends both on T and S changes. The Atlantic sector is not representative of the Atlantic ocean variability but it is presented as a comparison of what is the input in of the Atlantic to the Mediterranean Sea, if the hydraulic control at the Strait is ignored. Warming and increases in salinity appear west of Gibraltar especially after the 1980s. These are larger than the changes observed at the Western Mediterranean thus indicating that they are not directly influencing the steric heights there. The intermediate waters in the eastern and the western Mediterranean indicate cooling between 1974 and 1982 with warming after 1984 for the western basin and continued cooling up to 1993 for the eastern basin. Steric heights due to S changes appears to be reducing slightly in both basins indicating small increase in S. The Atlantic sector probably reflects measurements of different water masses. The changes in temperature in the upper and intermediate waters are based on measurements from CTD and XBTs. Thus we feel confident that the steric height changes reflect real variability rather than error in measurement.

The deep waters of the eastern basin follow mainly the salinity curve up to the end of the 1980s. After the mid 1980s the EMT is marked by a small reduction of the steric sea level as part of the salinity variation which has been partly counter balanced by increases in T. Notably in the 1970s a salinity increase appears which if true would be more important than the EMT for the steric sea level. We feel that the salinity values in the Eastern Mediterranean especially in the deeper waters before the 1980s may include significant errors and therefore we would suggest that the consequential steric variations are treated with care.

Thus in the Eastern Mediterranean most of the variability during the last 5 decades is due to steric changes in the upper waters directly linked with cooling. The western Mediterranean appears less variable but with warming after the 1960s accompanied by increased S.

The Atlantic input is not expected to affect the Mediterranean waters below the Gibraltar sill depth. Nevertheless it is worth noting that warming and salinification of deeper waters appears to counter balance each other giving a small increase in the steric sea level west of Gibraltar. Whether this is due to changes in the outflowing Mediterranean Water is not clear from this dataset.

Satellite altimetry records show areas of differential trends within the Ionian and the Levantine basin (see for example figure 1 in Cazenave et al., 2001). Thus we repeat the estimation of steric sea level for four smaller areas (fig. 1). Heating remains the dominant parameter in the upper levels while salinity becomes important in the deeper waters (fig. 3). Moreover significantly different regional behaviour can be identified at each of the four regions analysed. In fact the basin average is not representative for any of the four regions. The area near Sicily exhibits in the upper waters strong heating between 1985 and 1990 and subsequent cooling afterwards. In the same period in the Levantine there is gradual cooling which is especially strong after 1990 and reaches its minimum in 1994. Between 1994 and 1998 sea level has been rising in all but the area east of Sicily. As T/P data are available after 1993 what the altimeter has been recording as differential rates of sea level rise are qualitatively in agreement to what we see in the climatology and what Cazenave et al. (2001) have identified in sea surface temperature. Nevertheless the impression one takes by considering the satellite data alone can be misleading as the sea level difference between the two regions appears to be returning to the pre mid-1980s situation rather than developing a strong spatial gradient in the 90s.

The cooling in the upper and intermediate waters of the Adriatic and the Aegean Sea is of the same rate and reversed sign around 1993. Nevertheless important differences appear to exist in the salinity records. In the Adriatic the whole of the water column became fresher after 1989 while the salinity over the Aegean increased by about 0.2 psu. These changes fit in with the picture of deep water formation in the South Aegean due to cooling as the salinity increases during the period 1987-1992 appear to be important only within the Aegean Sea. In addition the interruption in deep water formation in the Adriatic during the same period (Roether et al., 1995) appears to be accompanied with strong reduction in salinity. The reduction in salinity in the Adriatic surface and intermediate water is larger than that in the Intermediate waters thus indicating that changes in the local forcing play a significant role.

An intriguing feature is the deep water steric height changes in the Levantine basin around the 1973. These are linked with strong changes in salinity of 0.05 psu and do not appear to be documented in the literature. It is unclear how these changes took place and we cannot exclude the possibility of problems with the salinity data quality during this period and in this region (Nadia Pinardi, personal communication). For this reason we compare the steric effects above 400 m with the coastal data.

The annual mean sea level records at three tide gauges Lagos (Atlantic sector), Trieste (Adriatic) and a combined record of Marseille and Genova (west Mediterranean) are plotted together with the sum of the corresponding regional steric estimates for the upper and intermediate waters (fig. 4). Although both time series of Lagos (Portugal) appear in good agreement with the tide-gauge data the records of Trieste and Marseille-Genova are not consistent with the coastal tide gauge record for most of the time. For Trieste the atmospheric correction for pressure difference is also shown to indicate how its inclusion further increases the observed sea level trend. The Topex/Poseidon annual averages for the region are also plotted to demonstrate that the agreement with the tide gauge data is generally good. Although one can not claim agreement between the calculated steric heights and the coastal measurements, all of them appear to indicate an increase in sea level after the 1990.

Finally correlation coefficients between the T and S time series and a 5-yr averaged winter (December-March) NAO index (Jones et al., 1997) have been calculated (Table 1). Deciding which of the correlation coefficients are statistically significant it far from easy. The T and S time series are annual mean values based on irregular sampling in time and space and filtered with a 3-yr gaussian filter. The time series used for the correlation are 51 points long. Dividing by 5 (the longest averaging period) we get a conservative estimate of 10 degrees of freedom. Thus only correlation coefficients of 0.7 and higher would be consider significant at the 99% level of significance. The temperature of the upper and intermediate waters in the Aegean as well as the upper waters of the Adriatic are anti-correlated with the NAO. This is consistent with the observations of Tsimplis and Josey (2001). Because of the uncertainties with S especially in the deep parts of the Levantine Sea we would not like to claim that the anticorrelation observed at the intermediate waters both in the Levantine and the Aegean is true. Nevertheless the low frequency part of the signal looks very similar.

Discussion

Our results and those of Cazenave at al (2001) indicate increases in sea level in the Mediterranean driven by warming of the upper waters. In fact Cabanes et al. (2001) comparing the global records suggest that during this period the temperature changes are the dominant ones globally and no other forcing parameter seems to matter. This is indeed the impression one can get by looking at the short altimetric records.

In the Mediterranean the lack of correlation between the tide gauge data and the steric effects in the regions we explored over the last 50 years indicates that this correspondence between the steric heights and the coastal measurements has been only taking place during the last decade. Thus at least for the coastal sea level in the Mediterranean we cannot conclude that the direct effect of heating is the only factor responsible, although this appears to be true for the last decade. It is, of course, possible that one of the forcing parameters of sea level may become particularly important for some period of time but it appears that this is linked with changes in the NAO i.e. regional rather than global scale changes. Thus our assessment is that the dependency of sea level on the various forcing factors is not only complicated but it also varies with time and that a good understanding of the oceanic circulation is needed in order to interpret it. For example we demonstrate that the significant sea level rise observed in altimetry records south of Crete and the sea level reduction east of Sicily (Cazenave at al., 2001) is in reality part of longer term variability of the signal and is probably linked with changes in mesoscale variability in the region driven by meteorological forcing. The location of the changes and the period during which they appear to be happening (1985-1995) indicate that these changes may be linked with the Eastern Mediterranean Transient (Roether et al. 1995) possibly reducing the transport of LIW and thus salt to the north Adriatic.

The hydrographic dataset for the Mediterranean is far from complete or free of dubious measurements but in comparison with other regions of the world, especially in the southern hemisphere it can be considered as a long and dense dataset of measurements. Our inability to account of sea level changes from steric height calculations alone is indicative that estimates of long term variation of steric heights in the southern hemisphere should be treated with care.

We believe that it is of paramount important to establish a good observational network for the Mediterranean and to link it with models which will include the sea level response of the region. The role of the Strait hydraulics must also be clarified (Ross et al., 2001) as this may be able to explain the discrepancy between the Mediterranean coastal sea level and the steric effects which contrasts with the agreement of the Lagos sea level data and the steric heights outside the Strait of Gibraltar.

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Table 1. Correlation coefficients between a 5-yr averaged winter NAO index and the time series of temperature T (bold) and salinity S.

	Adriatic	Aegean	Ionian	Levantine
Upper Waters	**-0.70**/0.14	**-0.79**/0.54	**0.04**/-0.52	**-0.56**/0.07
Intermediate Waters	**-0.55**/0.29	**-0.79**/-0.59	**-0.34**/0.27	**-0.42**/-0.68
Deep Waters	**-0.62**/0.30	**0.13**/0.42	**-0.32**/0.15	**0.60**/-0.47

List of Figures.

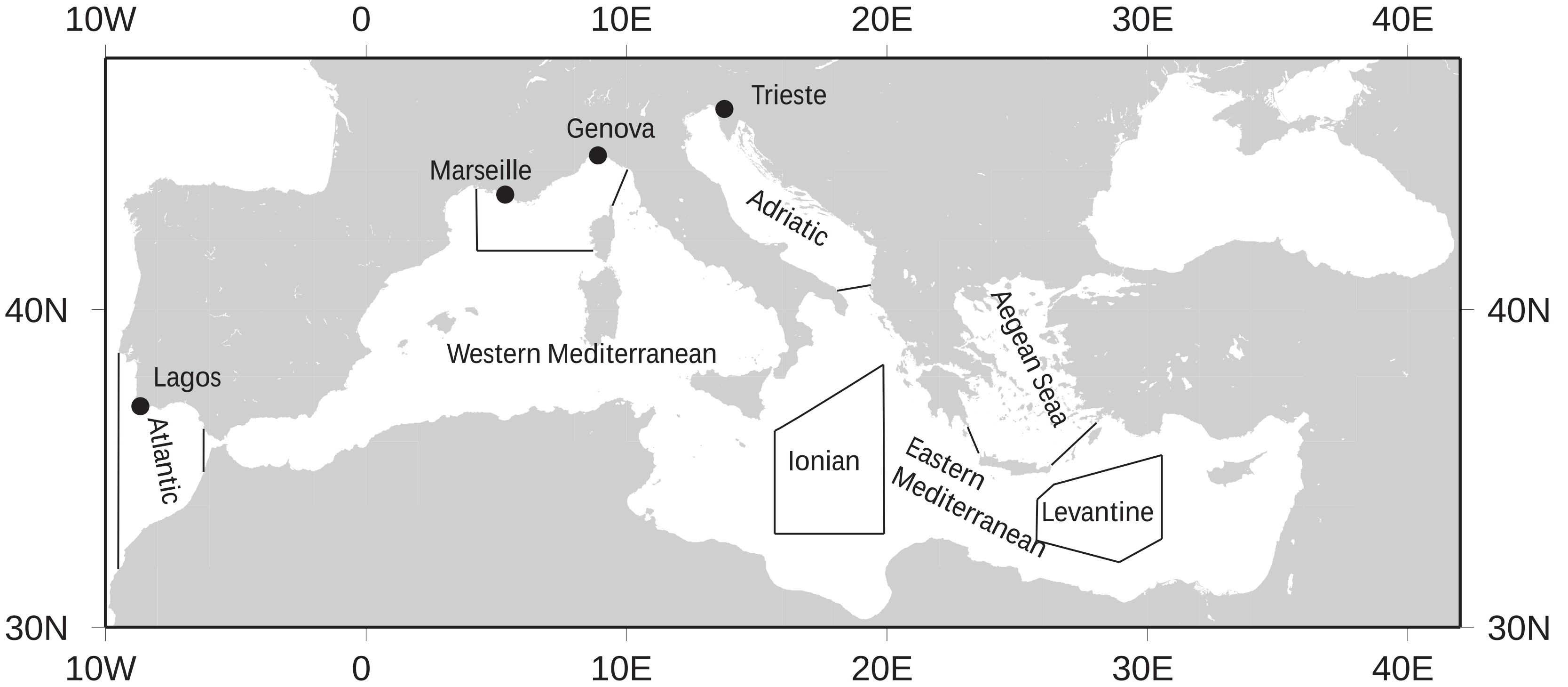

Figure 1. The areas of the Mediterranean Sea for which the steric height variations have been estimated. The location of the long-term, high quality tide-gauges available at the Permanent Service for Mean Sea Level are also shown.

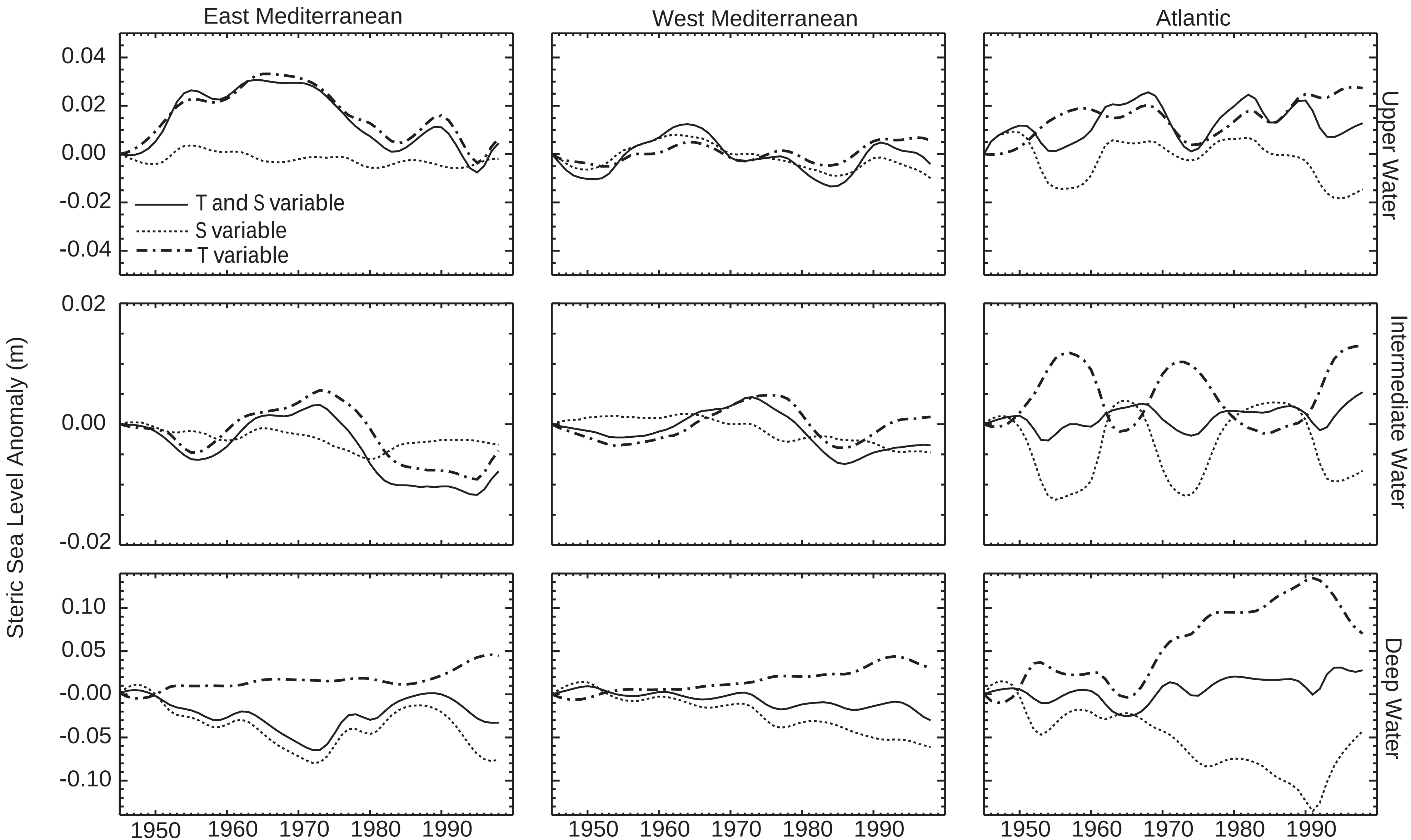

Figure 2. Steric sea level anomalies with time for the Eastern Mediterranean, the Western Mediterranean and the Atlantic sector. The variability due to temperature variation alone and the salinity variation alone has been calculated by keeping the other variable (i.e. S and T respectively) constant.

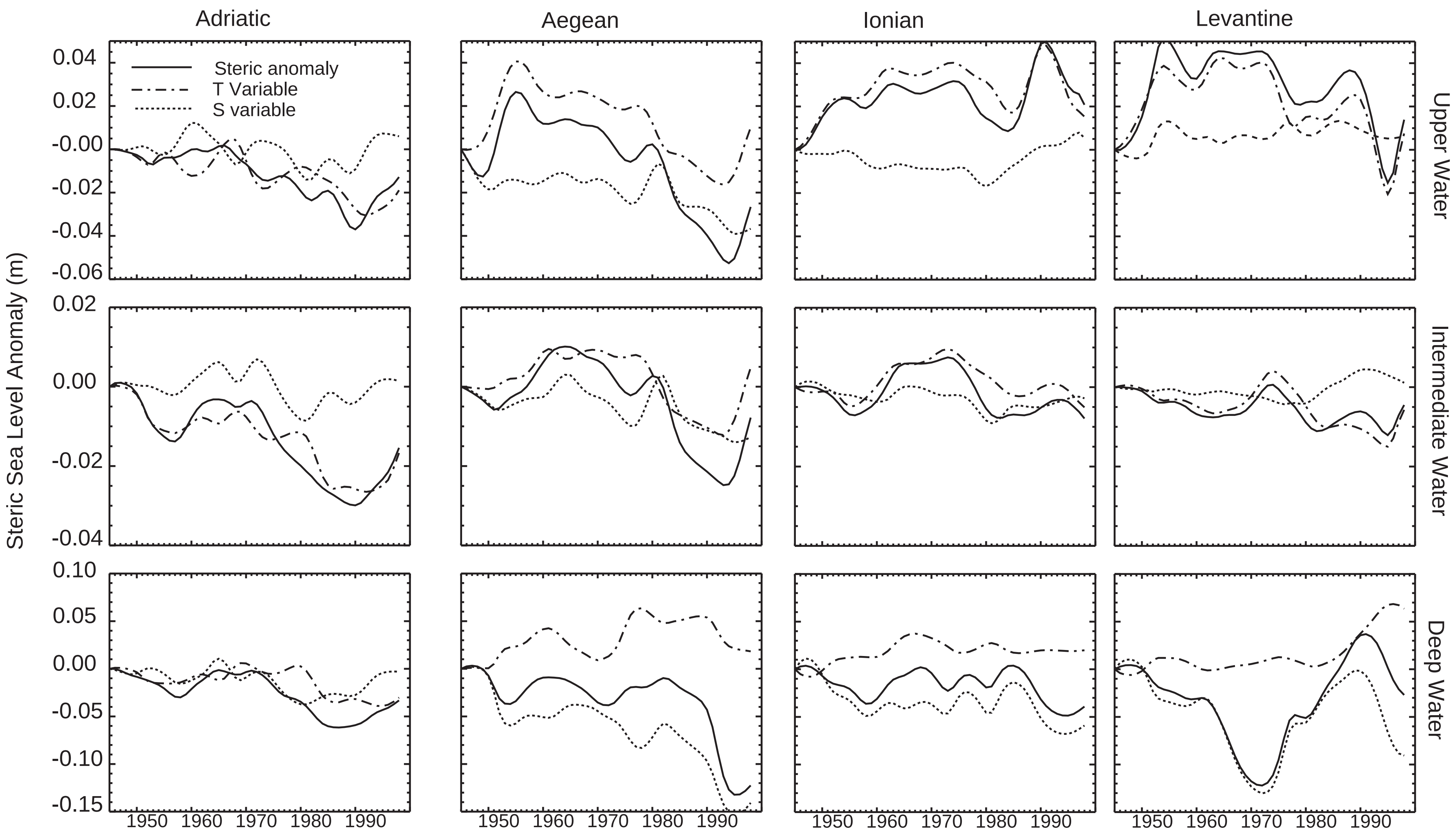

Figure 3. As figure 2 but for the smaller areas shown in Figure 1.

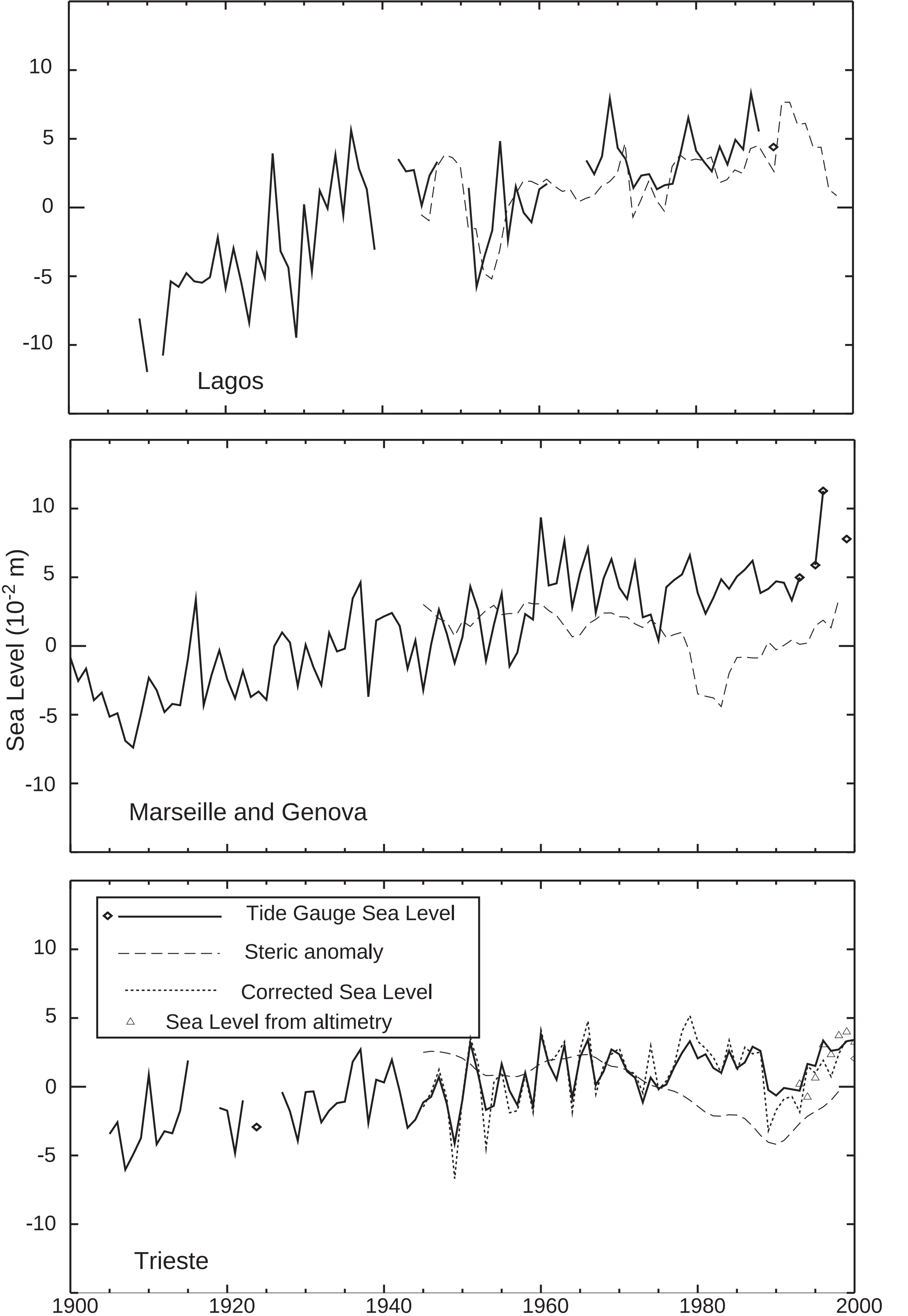

Figure 4. The comparison between the tide gauge data (continuous line) and the regional steric height (dashed line). The effect the atmospheric correction has on the comparison and the satellite values are shown for Trieste as an example.