

The Response of Sea Level to Atmospheric Forcing in the Mediterranean

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ABSTRACT

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Varying atmospheric pressure causes inversely proportional sea level changes. This is often called the “inverted barometer” effect. In cases of semi-enclosed seas, the response is limited by the configuration of the connecting straits. Three case studies demonstrating the complexity of the interaction between sea level and atmospheric forcing in the Mediterranean Sea are presented. Monthly and daily mean values of sea level, atmospheric pressure and wind components at three stations are analysed in order to provide insight on the interactions at time scales from days to decades. The response of sea level to changing atmospheric pressure is frequency dependent and is almost never the theoretically predicted isostatic response of -1 cm of sea level change for 1 mbar change of pressure. The contribution of the wind components is found to be very small for most frequencies. Nevertheless, wind is found to be the dominant parameter characterizing the annual cycle in the north coasts of the Mediterranean.

ADDITIONAL INDEX WORDS: *Isostatic response, annual cycle, semi-enclosed seas.*



INTRODUCTION

The interpretation of any sea level record requires knowledge of the interaction of several parameters. Apart from the waves that are usually filtered out of the records by the hardware and the tides that, because of their repeatability, can be accounted for, there are several other factors that influence sea level. Changes in timescales from days to decades are forced mainly by changes in the water temperature and the effect of wind and atmospheric pressure. The development of altimetry which provides continuously improving measurements of the sea surface topography has renewed the scientific interest in research on sea level response atmospheric forcing (e.g., PONTE *et al.*, 1991) in the attempt to optimise the exploitation of altimetric measurements.

The estimation of coastal sea level trends either from tide-gauges or advanced techniques like GPS also requires the study of the variability at scales from months to decades.

In general a slow increase of atmospheric pressure in the open ocean forces the water out of the affected area and thus reduces sea level; thus, the total (atmospheric + water column) pressure differences between areas will diminish. Theoretically, an increase of 1 mbar in atmospheric pres-

sure causes a 1 cm decrease in sea level; in this case the response is called isostatic. When sea level decreases (increases) more than 1 cm to 1 mbar pressure increase (decrease), the response is called over-isostatic; and when the decrease (increase) is less than 1 cm, it is called under-isostatic. The “inverted barometer” phenomenon becomes especially significant in cases where extreme low pressures travel over coastal areas where they contribute, in addition to wind effects and tides, to destructive storm surges. In these cases the changes in atmospheric pressure are fast and are also associated with wind systems.

The theoretically estimated inverse response assumes that the pressure variations take place sufficiently slow to allow for the transfer of water to the affected area. Therefore, the speed of the forcing atmospheric systems as well as their extent are factors that should be considered in predicting the resulting sea level changes. This is especially true in basins where restrictions in the flow exist due to bathymetry or configuration (e.g., the Mediterranean and the Baltic), and the -1 cm/mbar relationship is, as expected, violated. In the case of the Mediterranean, the strait of Gibraltar restricts the flow from the Atlantic to the west Mediterranean while the strait of Sicily provides a second restriction for the flow to the Eastern Mediterranean.

Table 1. Data collected over three separate periods at three different areas of the Mediterranean.

Station	Type of Data	Period	Sampling	Source
Marseille	Sea level	1886–1930	Monthly	PSMSL
	ATM. Pressure			CDIAC
Rome	ATM. Pressure			CDIAC
Vienna	ATM. Pressure			CDIAC
Trieste	Sea level	1951–1988		PSMSL
	ATM. Pressure			CDIAC
Rome	ATM. Pressure			CDIAC
Vienna	ATM. Pressure			CDIAC
Siros	Sea level	1984–1986	Daily	HNHS
Milos	ATM. Pressure			GMS
	Wind speed			
Alexandroupolis	ATM. Pressure			GMS
Heraklion	ATM. Pressure			GMS
Chios	ATM. Pressure			GMS
Hellenikon	ATM. Pressure			GMS

PSMSL: Permanent Service for Mean Sea Level; CDIAC: Carbon Dioxide Information Analysis Centre; HNHS: Hellenic Navy Hydrographic Service; GMS: Greek Meteorological Service

The exact physical mechanism by which straits control the flow has not yet been clarified, but simple models based on geostrophic control (GARRETT, 1983; GARRETT and MAJAEISS, 1984) or friction (CANDELA *et al.*, 1989; CANDELA, 1991) qualitatively describe the response of the Mediterranean Sea.

The first model indicates that the cross-strait sea level difference caused by the Earth's rotation cannot exceed the sea level difference between the adjoining seas (GARRETT and TOULANY, 1982); thus the speed of rotation (geostrophy) "controls" the flow. In the second model, frictional control is employed. Both models predict that the response of the sea level in the Mediterranean to eastward moving atmospheric systems is frequency dependent and is under-isostatic (that is 1 mbar increase of atmospheric pressure causes less than 1 cm decrease of sea level) for intermediate periods centred around 4 days. Several studies have verified these theoretical results (GARRETT and MAJAEISS, 1984; LASCARATOS and GACIC, 1990; TSIMPLIS and VLAHAKIS, 1994).

In reality changes of atmospheric pressure are accompanied with wind fields that distort the relationship. Surface wind stress and surface wind are the most important quantities in determining the forcing applied on the sea surface but continuous measurements of these parameters representative of open sea conditions are usually hard to find. Larger scale geostrophic wind, calculated from readily available pressure distributions, provides a good alternative. Surprisingly GARRETT

and MAJAEISS (1984) found the contribution of geostrophic wind to sea level fluctuations to be very small for a station in the east Mediterranean basin. The same result was derived by TSIMPLIS and VLAHAKIS (1994) using both geostrophic and spatially coherent surface wind.

In the present study, we re-examine the sea level response in the Mediterranean by comparing the results of statistical analyses based on mean monthly values as well as daily values. Both the analyses are performed with the same statistical techniques, thus providing comparable results. For convenience the sea level time series are inverted. Therefore, the isostatic response corresponds to 1 cm/mbar with larger and smaller values regarded as over-isostatic and under-isostatic respectively.

THE DATA

Ideally, a continuous set of daily sea level, wind and atmospheric pressure data covering at least forty years and for (at least) two stations, one in the east and one in the west of the basin, would be required for a complete study. Unfortunately no such set of data was available. Moreover the existing sea level and atmospheric pressure time series include large gaps. Consequently, the analysis is narrowed down to those parts of the time series that are more than 95% complete. In those parts of the time series, gaps are linearly interpolated.

The selected data cover three separate periods at three different areas of the Mediterranean and

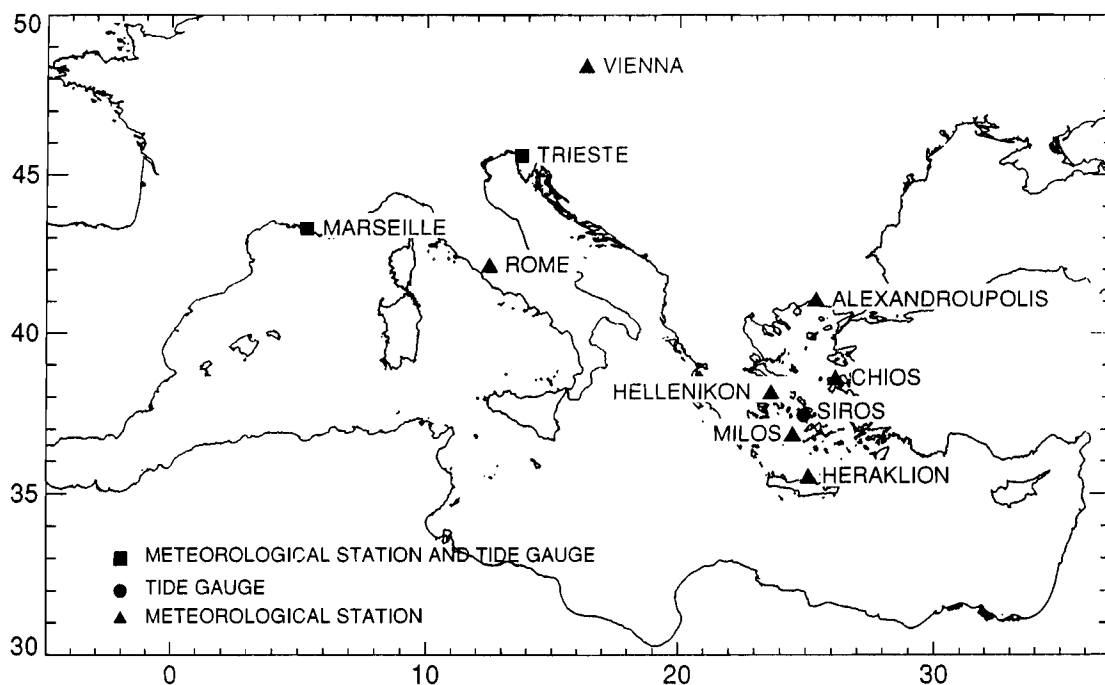


Figure 1. The position of the stations used in the present study.

are described in Table 1 while the positions of the stations are shown in Figure 1.

METHODOLOGY

Geostrophic Wind

In order to estimate the relationship between atmospheric pressure and sea level, the effect of wind has to be estimated. In the absence of reliable wind information from the open sea, the wind caused by atmospheric pressure differences under geostrophic equilibrium (geostrophic wind) is calculated.

If the atmospheric pressure distribution over an area is known, the balancing of the pressure gradient with the Coriolis terms can provide an estimate of the wind speed components u_g , v_g :

$$u_g = -\frac{1}{f\rho} \frac{\partial p}{\partial y} \quad v_g = \frac{1}{f\rho} \frac{\partial p}{\partial x} \quad (1)$$

where f is the Coriolis parameter and ρ is the air density (GILL, 1982). Usually the gradients of atmospheric pressure are approximated by differences.

In two of the present cases (Marseille and Trieste), the pressure is known at three points. To estimate the gradients of the atmospheric pressure, we assume a relationship:

$$p_j = p_0 + \frac{\partial p}{\partial x} x_j + \frac{\partial p}{\partial y} y_j \quad (2)$$

where $j = 1, 3$ and the pressure variation is assumed to vary linearly with distance between the points. The pressure gradients and P_0 are the three unknowns of the system and can be easily calculated. In the third case (Siros), where four independent pressure stations are available and are located approximately in a north-south (Alexandroupolis-Heraklion), east-west (Hellenikon-Chios) direction, Equation 1 is immediately used.

Multiple Regression Analysis in the Frequency Domain

To estimate the response of sea level to atmospheric pressure and wind in a way that takes into account their interdependency, multiple regression analysis in the frequency domain is per-

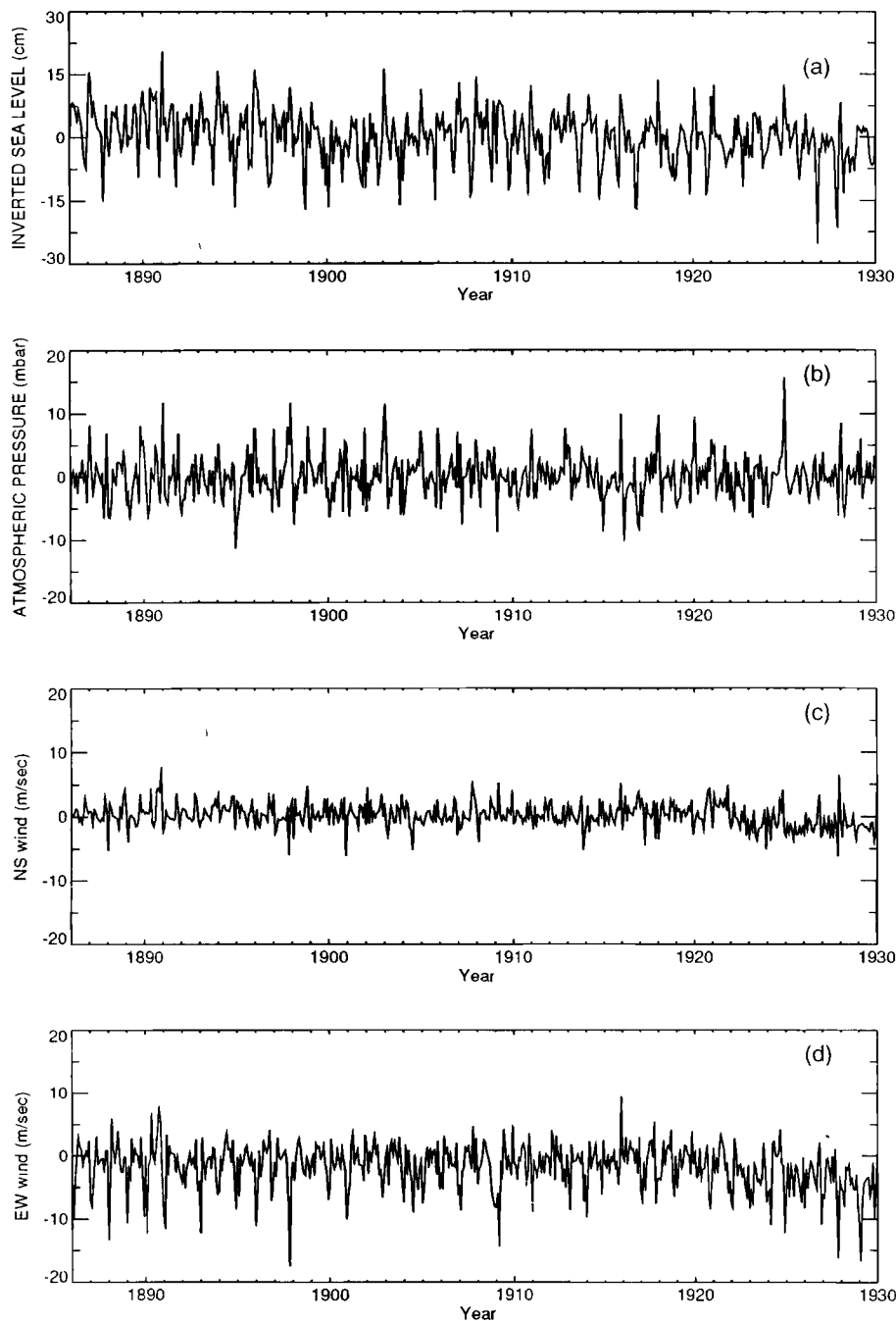


Figure 2. The time series used for Marseille (1885–1930). Inverted sea level (a), atmospheric pressure (b), north-south and east-west geostrophic wind, (c) and (d) respectively.

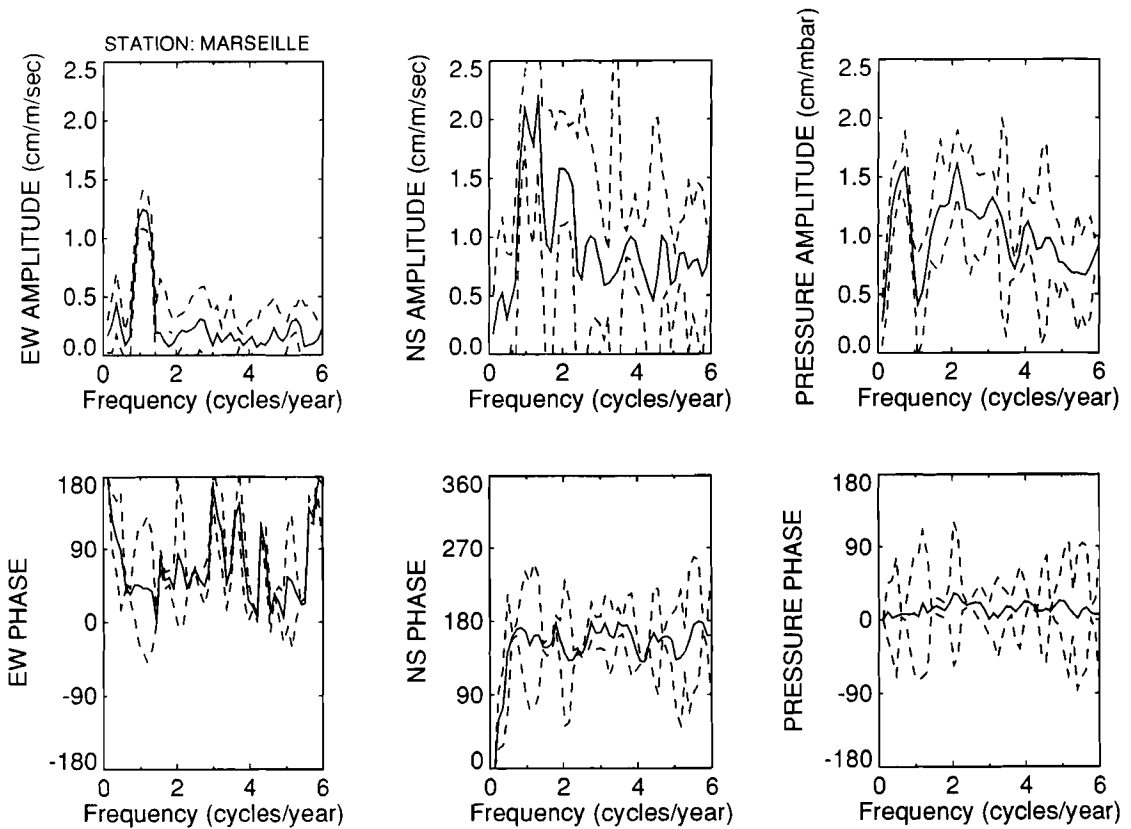


Figure 3. Amplitude and phase of the regression coefficients of inverted sea level on EW wind, NS wind and local atmospheric pressure for Marseille. The dashed lines are the 90% confidence limits. The phase values are meaningful only when the corresponding amplitude values are significantly different than zero.

formed (WUNSCH, 1972; GARRETT and TOULANY, 1982; GARRETT and MAJAESS, 1984).

The power spectrum of sea level, ζ , is used as the dependent variable, while the power spectrums of atmospheric pressure, P , the north-south, N , and the east-west, E , components of the wind are the independent variables. Therefore for each frequency ω , we find the optimum fitting of the independent variables in the equation:

$$\zeta = aE + bN + cP + \text{variability incoherent with } E, N, P \quad (3)$$

where a , b , c are frequency dependent complex parameters.

The regression coefficients a , b , c in Equation 3 are determined at each frequency ω as the solutions of:

$$\begin{aligned} G_{EE}a + G_{EN}b + G_{EP}c &= G_{E\zeta} \\ G_{NE}a + G_{NN}b + G_{NP}c &= G_{N\zeta} \\ G_{PE}a + G_{PN}b + G_{PP}c &= G_{P\zeta} \end{aligned} \quad (4)$$

where $G_{ij}(\omega)$ is the cross-spectrum estimate for variables i and j .

The 90% confidence limits $\delta l_{\text{amplitude}}$, δl_{phase} for the regression coefficient l ($l = a, b, c$) are approximated by:

$$\begin{aligned} |\delta l_{\text{amplitude}}| &= \sqrt{1.8 f_{2,n-2} (n-2)^{-1} G_{ii} D_j} \\ \delta l_{\text{phase}} &= \pm \sin^{-1} \frac{|\delta l_{\text{amplitude}}|}{|l_{\text{amplitude}}|} \end{aligned} \quad (5)$$

where D_j is the j th diagonal of the inverse of the cross-spectral matrix in equation 4 and $f_{2,n-2}$ is

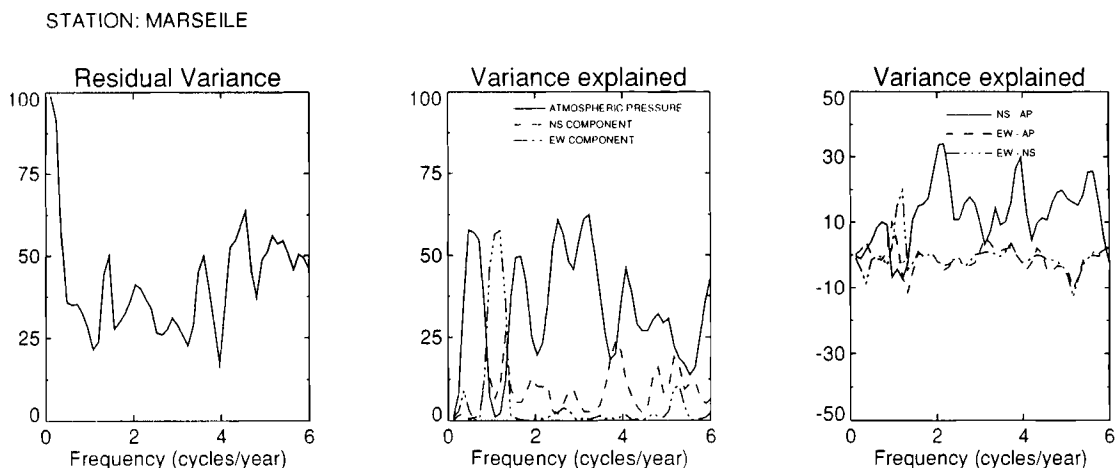


Figure 4. The residual variance and the percentage of sea level accounted for by the various inputs and their combinations (see equation 6).

the value of the Fishers distribution with 2, $n - 2$ degrees of freedom (GARRETT and TOULANY, 1982).

When Equation 3 is multiplied by its complex conjugate (denoted for each variable by $*$) on both sides, then one obtains:

$$\begin{aligned} \zeta\zeta^* = & aa*EE^* + bb*NN^* + cc*PP^* \\ & + (ab*EN^* + a*bE*N) \\ & + (ac*EP^* + a*cE*P) \\ & + (bc*NP^* + b*cN*P) \\ & + \text{residual variance.} \end{aligned} \quad (6)$$

By dividing both sides of Equation 6 by $\zeta\zeta^*$, and multiplying by 100, we have an estimate of the percentage of variance explained by each of the factors in Equation 6.

As an overall description of the methodology, when atmospheric pressure at three stations is available Equation 2 is used to estimate the pressure gradients. Then Equation 1 is used to calculate the NS and EW component of the geostrophic wind. Mean values and trends are removed from the time series of sea level, atmospheric pressure and NS and EW wind components. The resulting time series are used as input to the multiple regression analysis in the frequency domain (Equations 3–6) where inverted sea level is the dependent variable.

RESULTS

Marseille 1886–1930

The atmospheric pressures differences between Vienna and Rome (NS) and Marseille and Rome (WE) are used to estimate monthly values of geostrophic wind. The resulting time series are plotted in Figure 2 together with the inverted sea level and the atmospheric pressure in Marseille. Some extreme values of sea level are associated clearly with extreme values of atmospheric pressure. Nevertheless, the sea level signal seems more variable than a simple inverse barometer effect would imply. The EW wind component is clearly more energetic than the NS one. Of course one should keep in mind that the two wind components and the local atmospheric pressure are not independent measurements since the latter has been used in the calculation of the former. The power spectrums of the resulting wind components and the local atmospheric pressure are subsequently regressed in the frequency domain on the power spectrum of inverted sea level.

The results of the regression are shown in Figure 3. The coefficient of the EW wind is significantly different to zero only around the annual frequency, while the NS component gives significant values at the annual frequency and its harmonics. The response of sea level to atmospheric pressure seems to be around the inverted barom-

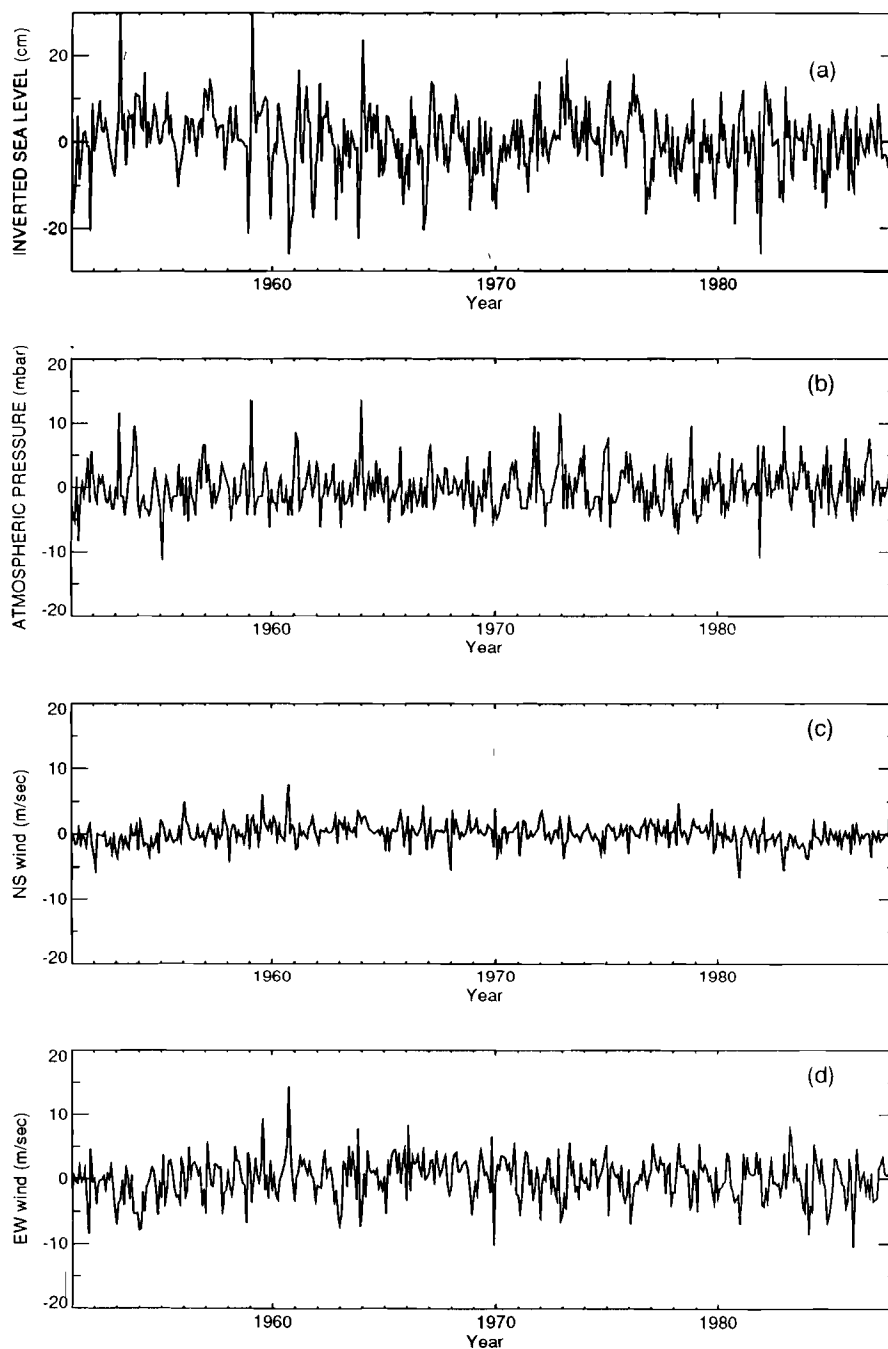


Figure 5. The time series used for Trieste (1851–1988). inverted sea level (a), atmospheric pressure (b), north-south and east-west geostrophic wind, (c) and (d) respectively.

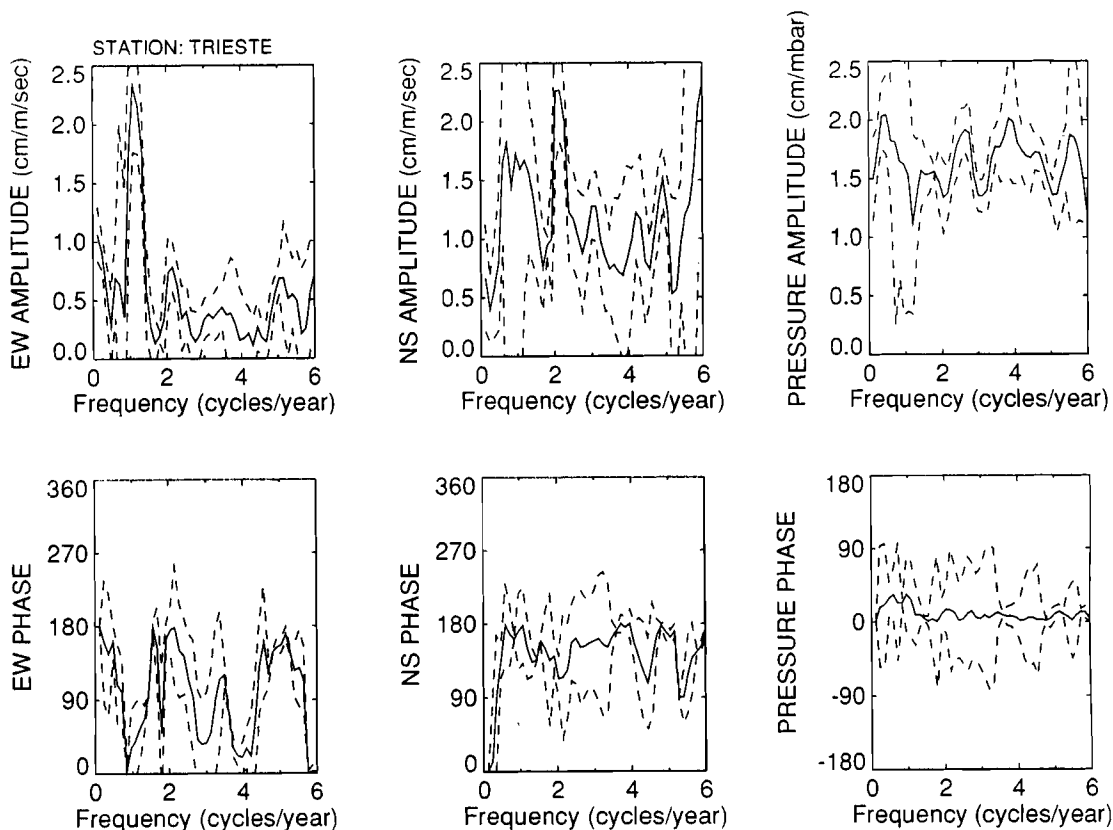


Figure 6. Amplitude and phase of the regression coefficients of inverted sea level on EW wind, NS wind and local atmospheric pressure for Trieste. The dashed lines are the 90% confidence limits. The phase values are meaningful only when the corresponding amplitude values are significantly different than zero.

eter effect value for frequencies higher than 3 cycles/year; while for lower frequencies, it is more than the isostatic value (remember we are looking at inverted sea level) with the exception of the annual frequency where it is strongly under-isostatic. The phase difference is in all cases very close to zero.

The analysis of the variance is shown in Figure 4. The multiple regression used explains 50–60% of the sea level signal in most frequencies. Notably the atmospheric pressure is the major parameter in all frequencies except the annual where the EW wind component can explain more than 50% of the variability. The coupling of atmospheric pressure with the NS wind component is also a significant factor in most frequencies.

Trieste 1951–1988

The atmospheric pressures differences between Vienna and Rome (NS) and Marseille and Rome (WE) are again used to estimate monthly values of geostrophic wind. The resulting time series are plotted in Figure 5 together with the inverted sea level and the local atmospheric pressure in Trieste. Most of the extreme events of atmospheric pressure are associated with extreme events in the sea level record but the reverse is not true. The power spectrums of the calculated wind components and the local atmospheric pressure are subsequently regressed in the frequency domain on the power spectrum of inverted sea level exactly as for Marseille.

STATION: TRIESTE

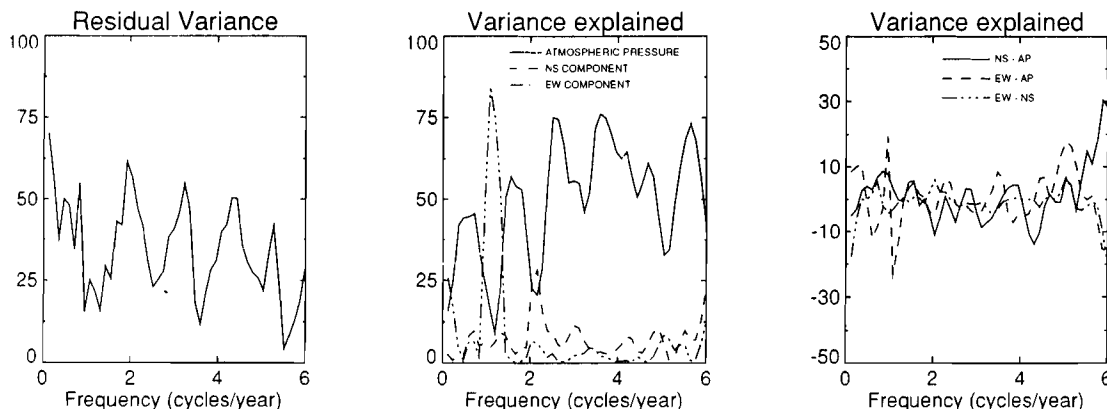


Figure 7. The residual variance and the percentage of sea level accounted for by the various inputs and their combinations (see equation 6) for Trieste.

The results are shown in Figure 6. The resulting situation is somewhat different to Marseille. The response to atmospheric pressure is over-isostatic without significant phase differences even for the annual frequency. The response to the wind components is in general larger than Marseille and is significant at the same frequencies, that is at the annual cycle and its harmonics. Note though that the results for Trieste refer to a different period than those of Marseille and therefore may only be qualitatively comparable. In Figure 7, the variance explained by the regression and by each parameter is shown. Atmospheric pressure is the sole contributor in all but the annual frequency where again the EW wind component becomes dominant. Another marked difference is also that the NS-atmospheric pressure term seems not to be significant in the case of Trieste and for this period.

Siros 1984–1986

To investigate the response of sea level frequencies higher than 6 cycles/year, daily sea level data from Siros located in the centre of the Aegean Sea are used. The geostrophic wind is estimated from atmospheric pressure differences between Alexandroupolis and Heraklion (NS) and Hellenikon and Chios (WE). The power spectrum of the atmospheric pressure at Milos, the local NS and EW winds or the geostrophic wind components, is regressed on inverse sea level in Siros. The use

of geostrophic winds is more successful than the use of local winds either due to localized sheltering effects to certain wind directions or just because an “average” wind estimate over a larger area is more relevant to sea level response than the local wind. The time series used are shown in Figure 8. The time series of inverted sea level and atmospheric pressure are remarkably similar, although the response of sea level to atmospheric pressure events seems larger than the isostatic value. The seasons are easily distinguished in these time series with the summers corresponding to the quieter periods.

The results of the multiple regression in the frequency domain are shown in Figure 9. The response of sea level to atmospheric pressure is under-isostatic for periods between 2–10 days, and it seems to approach the isostatic value for shorter periods and a clearly over-isostatic value for lower frequencies. The phase difference is around 30 degrees though the error bars are large enough to make this statistically insignificant. The response to the wind is an order of magnitude less than that of the monthly values and for most frequencies is very close to zero. Most of the explained variance is due to the atmospheric pressure factor (Figure 10) while the wind components cannot explain much of the variability.

In Figure 11, the regression coefficients of the response of sea level to atmospheric pressure from the analysis above for Trieste and Siros are re-

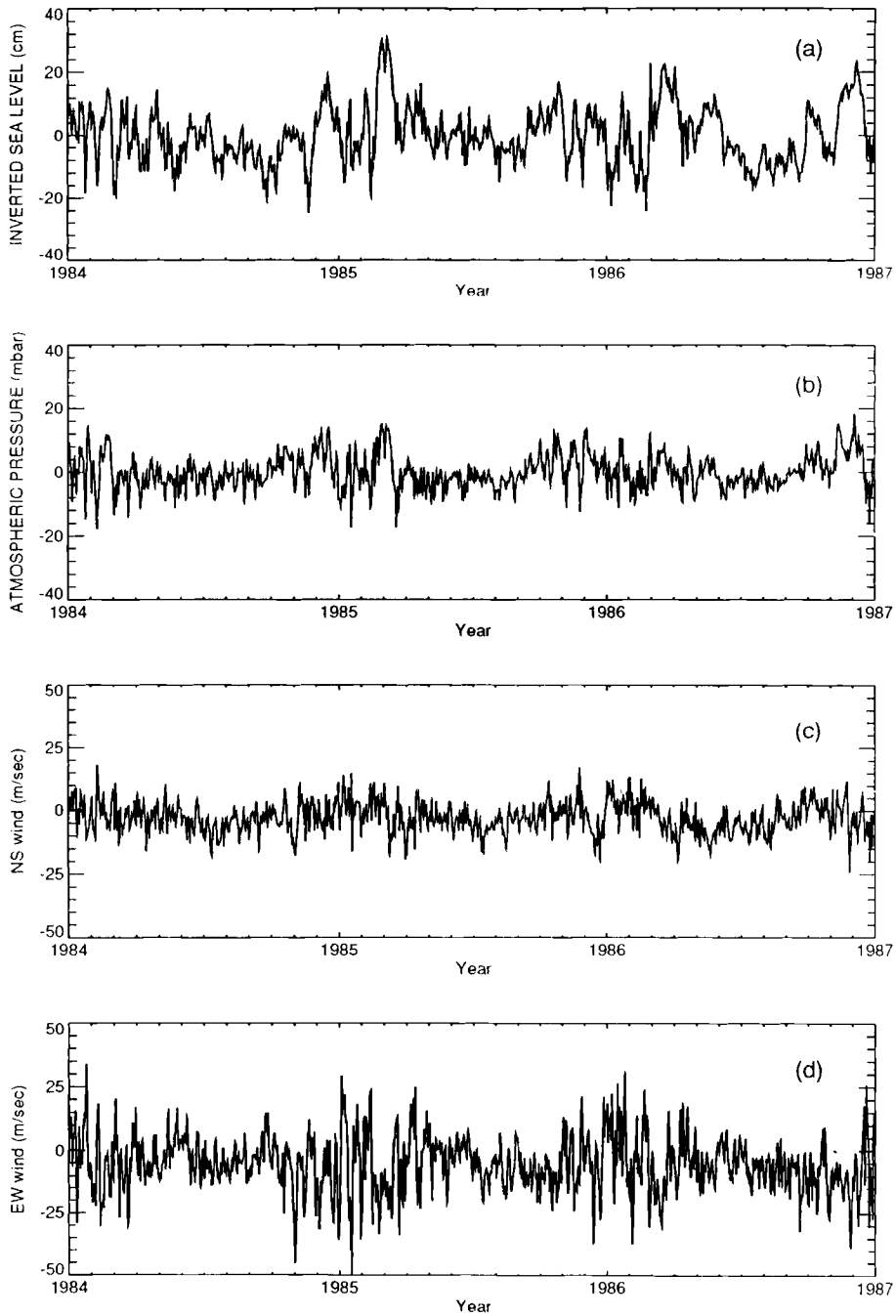


Figure 8. The time series used for Siros (1984–1986 daily values). Inverted sea level (a), atmospheric pressure (b), north-south and east-west geostrophic wind, (c) and (d) respectively.

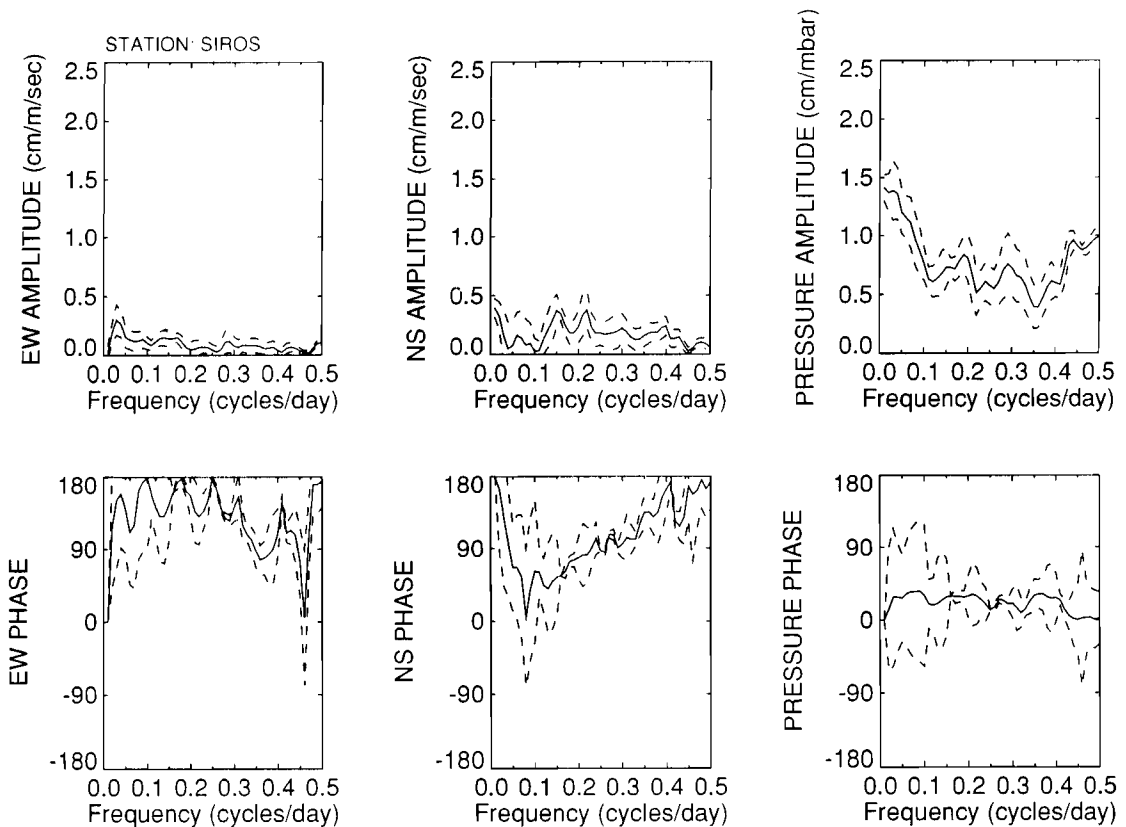


Figure 9. Amplitude and phase of the regression coefficients of inverted sea level on EW wind, NS wind and local atmospheric pressure for Siros. The dashed lines are the 90% confidence limits. The phase values are meaningful only when the corresponding amplitude values are significantly different than zero.

plotted. The results of the two analyses agree at the overlapping segment within the estimated error-bars. The results are found to be under-isostatic for periods of up to 15 days and are over-isostatic at longer periods. This sort of behaviour at low frequencies has been observed in other studies (PALUMBO and MAZZARELLA, 1982; PASARIC and ORLIC, 1992; TSIMPLIS and VLAHAKIS, 1994) but has yet to be accounted for.

It would have been better if Figure 11 had been produced as the result of a single analysis. It can be considered, to some extent, as representative of the east Mediterranean in view of the results of LASCARATOS and GACIC (1990). They found an in-phase mode of the atmospheric pressure in the Adriatic and the Aegean explaining 83% of the variance (daily values are used), with an associ-

ated major mode for sea level explaining 73% of the variance. The behaviour of the west Mediterranean is different to that of the east Mediterranean, at least at the frequencies where the straits of Sicily restrict the flow to the eastern basin (GARRETT, 1983; CANDELA, 1991); and therefore such a plot for the western basin cannot be produced on the basis of the present results.

DISCUSSION

Atmospheric pressure is the dominant factor associated with sea level variability in the Mediterranean in all frequency ranges examined with the exception of the annual cycle. The response of inverse sea level to changes in atmospheric pressure is in most frequencies different to the theoretical value of 1 cm/mbar. Consequently, such

STATION: SIROS

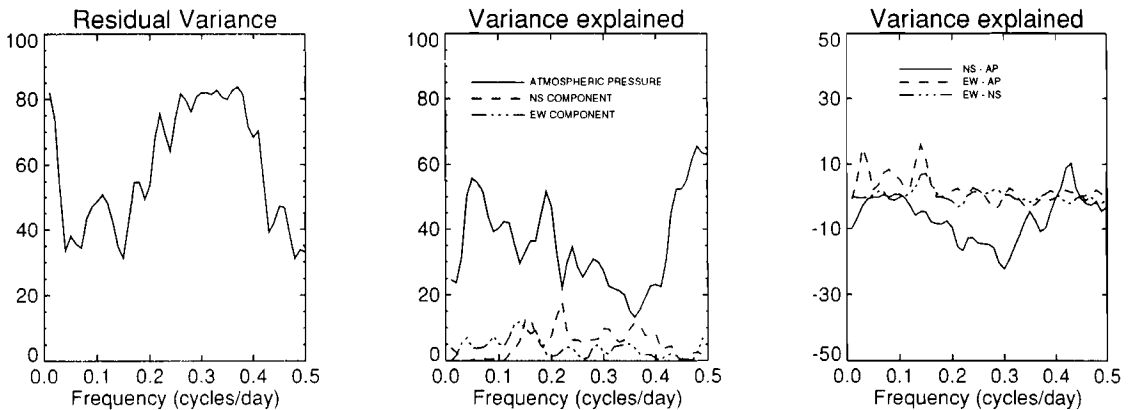


Figure 10. The residual variance and the percentage of sea level accounted for by the various inputs and their combinations (see equation 6) for Siros.

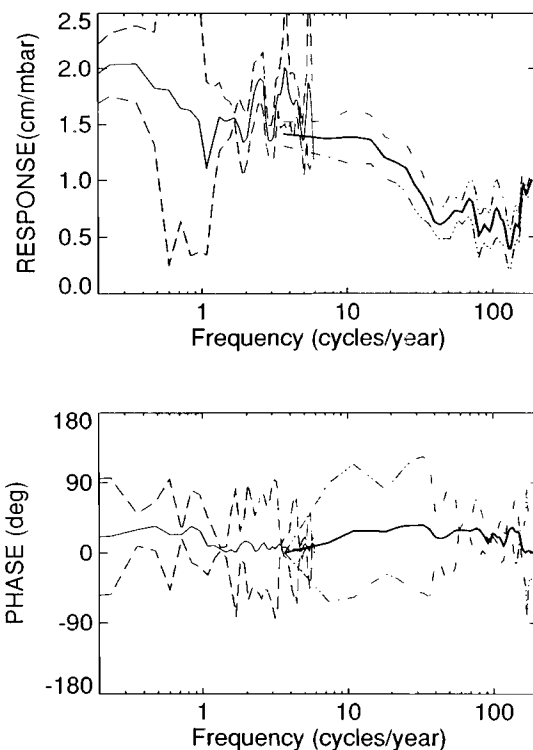


Figure 11. The response of inverted sea level to atmospheric pressure in the eastern Mediterranean as calculated by the combination of the regression results for Trieste (continuous line, 90% errors dashed line) and Siros (continuous heavy line, 90% errors dashed-dotted line).

a correction applied for altimetric or other analysis of sea level can introduce an erroneous, spatially coherent signal on a scale with atmospheric pressure patterns.

The role of the wind in determining the annual cycle is predominant for the two stations examined. The east-west component of the geostrophic wind used in the present analysis essentially represents the pressure differences between the Mediterranean coast and a station in central Europe. If indeed this difference is a good indicator of the variability of the annual sea level cycle, then it may also be used as a factor connecting climatic variability over Europe and sea level in the Mediterranean Sea.

The correlation to wind may be due not only to its dynamic effects but also to its effect on the rate of evaporation. Indeed inclusion of other variables such as precipitation, evaporation, steric effects, as well as exchange through the strait of Gibraltar, may improve the statistical analysis. It should be kept in mind though that statistical correlation may be used to identify relation between physical variables but it is not proof of causality. Hydrodynamical models are probably more appropriate to resolve the role of each of the physical parameters which are in most cases interrelated. Finally, it must be pointed out that the relevant importance of each parameter may itself vary between periods and that statistical studies provide only time averaged effects.

ACKNOWLEDGEMENTS

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