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The effect of the NAO on sea level and on mass changes in the Mediterranean Sea

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[1] Sea level in the Mediterranean Sea over the period 1993–2011 is studied on the basis of altimetry, temperature, and salinity data and gravity measurements from Gravity Recovery and Climate Experiment (GRACE) (2002–2010). An observed increase in sea level corresponds to a linear sea level trend of 3.0 ± 0.5 mm/yr dominated by the increase in the oceanic mass in the basin. The increase in sea level does not, however, take place linearly but over two 2–3 year periods, each contributing 2–3 cm of sea level. Variability in the basin sea level and its mass component is dominated by the winter North Atlantic Oscillation (NAO). The NAO influence on sea level is primarily linked with atmospheric pressure changes and local wind field changes. However, neither the inverse barometer correction nor a barotropic sea level model forced by atmospheric pressure and wind can remove fully the NAO influence on the basin sea level. Thus, a third contributing mechanism linked with the NAO is suggested. During winter 2010, a low NAO index caused a basin sea level increase of 12 cm which was almost wholly due to mass changes and is evidenced by GRACE. About 8 cm of the observed sea level change can be accounted for as due to atmospheric pressure and wind changes. The residual 4 cm of sea level change is caused by the newly identified contribution. The physical mechanisms that may be responsible for this additional contribution are discussed.

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1. Introduction

[2] Sea level estimates for the Mediterranean basin derived from the longest tide-gauge records give a rate of sea level rise for the twentieth century of 1.1–1.3 mm/yr [*Marcos and Tsimplis*, 2008], which is lower than the global sea level rise value of 1.7 mm/yr [*Solomon et al*. 2007] over the same period. Superimposed on this long-term sea level trend, there is also significant, seasonal, interannual (year to year), and interdecadal (decade to decade) regional sea level variability, which can temporarily amplify or reduce the impact of the long-term sea level rise and that of the extreme events. Thus, during the 1990s fast sea level rise was observed in the Mediterranean Sea [*Cazenave et al.*, 2001; *Fenoglio-Marc*, 2001] linked with sea surface temperature increases [*Cazenave et al.*, 2001]. After 1999 and up to 2005, Mediterranean sea level stopped rising [*Fenoglio-Marc*, 2001; *Vigo et al.*, 2005, *Criado-Aldeanueva et al.*, 2008].

[3] The interannual and longer-term variability of Mediterranean sea level is strongly linked with the North Atlantic Oscillation [*Tsimplis and Josey*, 2001]. The anticorrelation of winter sea level with the North Atlantic Oscillation (NAO) index is part of a larger pattern covering the whole of the European coasts [*Tsimplis and Shaw*, 2008]. The winter NAO, through the barotropic effects of atmospheric pressure and wind, dominates the observed seasonal trends in the basin mean [*Gomis et al.*, 2008] and permits the reconstruction of winter mean sea level variability in the region [*Gomis and Tsimplis*, 2006]. However, the relationship between sea level and the NAO may not be entirely due to barotropic atmospheric pressure and wind effects. *Tsimplis and Shaw* [2008] showed that for some regions the correlation between sea level and the NAO index remains significant after the atmospheric pressure effects have been removed from the observed sea level. However, they did not clarify whether the basin average remains related to the NAO, why the correlation of the atmospherically corrected tide-gauge records with the NAO is statistically insignificant in the western Mediterranean, and what is the cause of the persistence in the correlation with the NAO.

[4] In this paper, we confirm that the basin mean sea level for the Mediterranean remains correlated with the NAO

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index after the barotropic atmospheric effects caused by wind and atmospheric pressure are eliminated from the observation. This is explored further by examining the various forcing parameters in order to identify the source of this residual correlation. In addition, we discuss the evolution of sea level in the Mediterranean during the last two decades (1993–2010), and we explain the contributions of the forcings that have affected sea level, examining in particular the mass component.

2. Data and Methodology

[5] Observed sea level and its separate contributions, namely steric, mass, and atmospherically induced components as well as freshwater fluxes and river runoff, were analyzed using the data sets described in the following. The mean and the seasonal cycle have been removed from all time series.

2.1. Altimetry Data

[6] Gridded monthly mean sea level anomalies with a spatial resolution of $1^\circ \times 1^\circ$ for the period 1993–2011 were obtained from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) web server (http://www.cmar.csiro.au/sealevel/sl_data_cmar.html). The gridded anomalies were produced using the combined TOPEX/Poseidon, Jason-1, and Jason-2/OSTM altimetry missions with all geophysical corrections applied, including the Global Isostatic Adjustment (GIA). The data used had the seasonal cycle removed. Two time series were used. In the first time series, the inverse barometer correction, which accounts for the effect of atmospheric pressure, has been applied. This will be called IBC altimetry (inverse barometer corrected altimetry). CSIRO also provides a data set without the inverse barometer correction, and this will be referred to simply as "altimetry." The GIA correction applied to the data is described in *Church and White* [2011]. The mean GIA trend in the Mediterranean Sea is -0.42 mm/yr and is applied to the altimetry data. Note that the GIA correction is about a third of the best estimate of 1.1–1.3 mm/yr [*Marcos and Tsimplis*, 2008] for sea level rise for the twentieth century.

2.2. Steric Sea Level

[7] The estimates of the steric sea level component were based on gridded monthly temperature (T) and salinity (S) fields from the ENACT/ENSEMBLES version 2a (EN3_v2a) database [*Ingleby and Huddleston*, 2007]. This product spans the period 1950 onwards with a spatial resolution of $1^\circ \times 1^\circ$. Argo profiles are included in the database except those suspected of containing errors [*Willis et al.*, 2009; *Guinehut et al.*, 2009]. Expendable bathythermograph (XBT) bias corrections have been implemented in the database [*Wijffels et al.*, 2008]. Steric sea level was computed by integrating down to a specified depth the specific volume anomaly estimated on the basis of T and S. Thermosteric and halosteric sea level have been computed in the same way but with keeping S and T respectively constant at its initial value. The seasonal cycle was removed by fitting an annual and a semiannual harmonic. The gridded T, S values of the EN3_v2a database are obtained by synthesizing sparse, irregular in time, and non-uniform in space oceanographic observations. Thus, the temperature of the upper layers is more densely observed through XBTs and Argo floats, but the density of observations reduces with depth. Argo floats also measure salinity but have been in operation only for about a decade and they do not cover systematically the whole basin. Some confidence for the upper-layer temperature variability can be derived by its correlation (>0.6) to satellite-based estimates of sea surface temperature fields, after the removal of the seasonal cycle from both time series. While this gives some confidence for the near-surface temperature estimates, the uncertainty in the variations of the under-sampled deeper layers and also the uncertainty related to the salt content remain [*Tsimplis et al.*, 2011]. For these reasons, the computation of steric sea level has been restricted to the upper 300 m. Nevertheless, the computation was repeated for deeper layers. We found that increasing the depth over which the steric signal was calculated did not significantly affect our results, and therefore we do not report these results here.

2.3. Estimates of the Ocean Mass Component from GRACE

[8] For the mass component, we used the ocean monthly grids of equivalent water thickness based on the Release-04 gravity field from the Center for Space Research at the University of Texas, Austin, which cover the period August 2002 to May 2011 and are publicly available from the Gravity Recovery and Climate Experiment (GRACE) Tellus web site (http://grace.jpl.nasa.gov/data/mass/). The ocean grids provided in this web site have been processed as described in *Chambers* [2006]. In particular, a glacial isostatic adjustment (GIA) correction as given by the model of *Paulson et al.* [2007], a destriping filter, and a 300 km Gaussian filter are applied to the data. Also the leakage of land signals onto the ocean caused by both the destriping and Gaussian filters is minimized by means of an iterative procedure. Mass redistributions in the ocean caused by atmospheric pressure variations (i.e., the inverse barometer effect) have no effect on the mass variations observed by GRACE. Thus, GRACE is directly comparable to IBC altimetry minus steric sea level. Annual values are calculated for years 2003–2010.

[9] The filtering of the GRACE data causes a reduction in the signal that may be compensated by multiplying the filtered basin-averaged mass component from GRACE by a scale factor [*Fenoglio-Marc et al.*, 2012]. We have estimated the appropriate scale factor using the simulated gravity coefficients described in [*Chambers*, 2009] but extended to cover the period 2002 to 2011. The simulation includes hydrology from GLDAS, ocean bottom pressure from JPL_ECCO, ice loss from Greenland, Antarctica, and glaciers. The mass loss from land is redistributed over the ocean as an equilibrium response. The derived gravity coefficients were processed identically to the GRACE_RL04 data, using the same destriping and Gaussian smoothing algorithms, as well as using an iterative procedure to estimate the leaked signals using mapped data from the simulated gravity coefficients over land [*Chambers and Bonin*, 2012].

[10] Scaling factors were also computed from scatter plots of the monthly observations, for two cases—including the seasonal variation and with the seasonal variation removed (based on best-fit harmonic functions). The factor varied

from 1.4 for including the seasonal fit, to 1.8 for the interannual time series. The trend in the smoothed data was still biased low even after scaling in both cases. For the interannual time series, the trend bias was 1.2 mm/year too low (relative to a simulated trend of 4.2 mm/year). The GRACE trend estimated for a scale factor of 1.8 is 6.6 mm/yr and for 1.4 is 4.8 mm/yr. Because of the sensitivity of the GRACE trend to the selection of the scale factor, the confidence on the trends of GRACE is low. Here we only use GRACE for confirmation of the correlation of the mass change with the NAO. The sensitivity of the GRACE observations to the selected scale factor will also affect the regression coefficients with the NAO, discussed below, but not the correlation coefficients. For this comparison and for plotting the time series, we have selected a value of 1.5 for the scale factor but, where needed, we report values for the range 1.4 to 1.8. The seasonal cycle was removed by fitting an annual and a semiannual harmonic.

2.4. Wind and Atmospheric Pressure Forced Sea Level

[11] The barotropic effects of wind and atmospheric pressure on Mediterranean sea level variability were quantified using the HAMSOM ocean model in its 2-D version. The model configuration was the same used to generate the HIPOCAS sea level residual data set [*Ratsimandresey et al.*, 2008] except that the forcing was provided by the ARPERA atmospheric hindcast for the period 1958–2008 [*Jordà et al.*, 2012]. The model outputs are hourly sea level fields at 1/6° 1/4° spatial resolution. The model has been demonstrated to successfully represent the atmospheric component of sea level variability at interannual and interdecadal scales [*Tsimplis et al.*, 2005]. For this work, the HAMSOM model has also been run with wind forcing only, in order to isolate local wind effects from atmospheric pressure effects. It is important to highlight that the model is a limited area barotropic model. Therefore, it can only account for the barotropic effects of the local winds. The seasonal cycle was removed from the model time series by fitting an annual and a semiannual harmonic.

[12] The HAMSOM simulation ends in 2008. To estimate the sea level change due to the atmospheric component for 2009–2010, we combine an inverse barometer estimation based on atmospheric pressure data with an estimate of the wind contribution to the basin average sea level change. The wind contribution is obtained by fitting a linear function of winds at Gibraltar to the basin-averaged atmospheric component of sea level [*Menemenlis et al.*, 2007] using the available data. The best-fit regression model obtained using the ARPERA winds and the HAMSOM sea level outputs is as follows:

$$h(t) = 0.50\tau_x + 0.95\tau_y$$

where, $h(t)$ is the sea level difference between the two sides of Gibraltar, (τ_x, τ_y) are the wind stress components (meridional and zonal) at the Gibraltar strait, and t is the time in days. The correlation of the reconstructed sea level with the directly modeled sea level (in both cases the seasonal signal was removed) was 0.53. This relationship was then used to estimate wind-induced sea level changes for the period 2009–2010 using ERA-INTERIM winds. ERA-INTERIM products are provided with 1.5° spatial resolution, which is coarser than the ARPERA product, but the values of these data sets are comparable.

2.5. Sea Level from a Global Ocean Model

[13] Monthly sea level, temperature, and salinity fields were obtained from the GLORYS (Global Ocean Reanalysis and Simulation) reference simulation for the period 1993–2009 (www.myocean.eu). GLORYS relies on the ORCA025 global model configuration of the NEMO3 ocean/sea ice GCM. The model has a horizontal resolution of 1/4° and 75 vertical levels and is configured both for operational and climate applications [*Barnier et al.*, 2006]. GLORYS is forced with atmospheric surface variables from ERA-INTERIM atmospheric reanalysis. Among the different GLORYS simulations, we have selected the one where no data assimilation is performed. This is important for our purposes as far as any similarity between model outputs and observations will come from the ocean response to the forcing and not imposed through the assimilation of data.

[14] Two features must be commented on GLORYS sea level. The first one is that the steric component shows a spurious trend that is removed when we analyze the interannual variability. The second feature to be noted is that GLORYS is not forced by atmospheric pressure. Therefore, the mass component of sea level changes accounted for by the model is due to mass redistributions induced by the geostrophic adjustment and by the wind forcing. The latter include the barotropic effect of the wind and the eventual ageostrophic component of the baroclinic circulation.

[15] In order to compare with other data sources, we have averaged the T, S, and sea surface height model fields in the Mediterranean (5°–40°E/30°N–45°N) and the nearby Atlantic (20°W–5°W/30°N–43°N). The GLORYS mass component of sea level has been estimated from the difference between the deseasoned sea surface height and the steric component for the top 775 m.

2.6. Precipitation, Evaporation, and River Runoff

[16] Freshwater fluxes in the Mediterranean Sea have been estimated on the basis of the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] and river runoff data obtained from the five longest rivers covering the period 1930–1982. We note that these five rivers account for about $4 \cdot 10^3\,m^3/s$ of water which represents only a fraction of the best estimate for river runoff ($10.4 \cdot 10^3\,m^3/s$) given by *Struglia et al.* (2004). Thus, the runoff of the five rivers was multiplied by 2.5 to adjust the obtained values and the associated variability to the mean suggested by *Struglia et al.* [2004]. The mean seasonal cycle was removed.

3. Results and Discussion

[17] Monthly mean sea level (the seasonal cycle has been removed from all time series used) in the Mediterranean Sea between 1993 and the end of 2011 is shown in Figure 1a for altimetry and IBC altimetry. Three aspects of this plot are of interest and will be discussed in detail. First, sea level in the Mediterranean Sea has increased over the period under study. Although a linear trend can be used to describe the overall increase over this period, Figure 1a shows that sea level does not increase linearly in time but that the largest

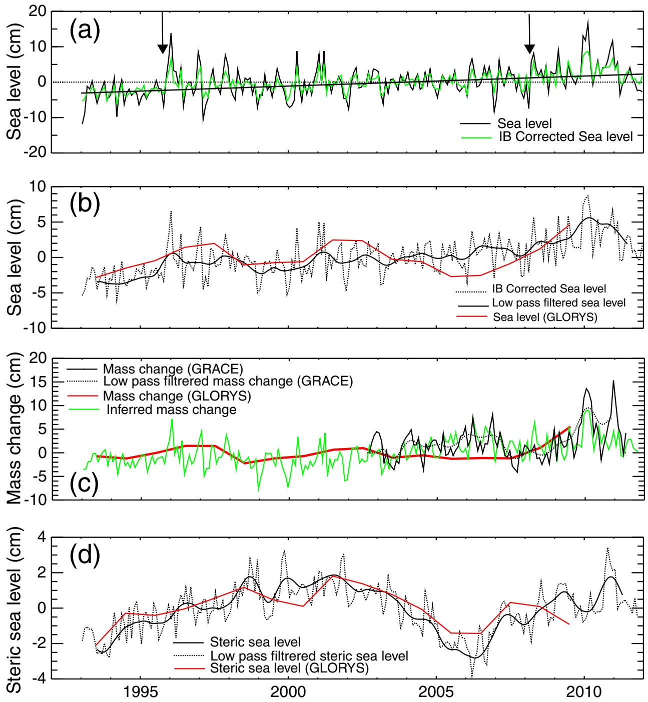

Figure 1. (a) Sea level from altimetry and IBC altimetry (green line). The linear trend for altimetry is also shown. (b) IBC altimetry (dotted line), 12 month moving average filtered values (solid line) and sea level from the oceanic model used in GLORYS (red line). (c) Mass change from GRACE (solid line), filtered values (dotted line), inferred mass change from IBC altimetry minus steric sea level (green line) and mass estimate from the oceanic model used in GLORYS estimated from sea level minus steric effect (red line). (d) Steric sea level (dotted line), filtered values (solid line), and detrended steric sea level from the model used in GLORYS (red line). The arrows indicate the periods during which sea level increased in the basin. The seasonal cycle and the mean have been removed from all time series; monthly values are shown.

changes occur during short periods of time. Identifying the source of the interannual variability will be the second aspect that will be discussed. The third aspect relates to the very strong sea level signals during winter 2010 primarily and 2011 and their cause.

3.1. Linear Trends of Sea Level and Its Components

[18] The linear trends for sea level change and its components are shown in Table 1. The sea level trend for the period 1993–2011 is 3.0 ± 0.5 mm/yr for the altimetry record. It reduces to 2.8 ± 0.5 mm/yr for the IBC altimetry. The uncertainty of the sea level trend is based on the length of the time series as suggested by *Tsimplis et al.* [2011]. Thus, the sea level rise rate in the Mediterranean Sea over the last two decades is more than double the long-term trend of 1.2 mm/yr. The steric sea level trend in the upper waters is significantly smaller than the trend of the total sea level, and in fact its magnitude is smaller than its uncertainty. The mass component inferred as IBC altimetry minus steric sea level is 2.6 ± 0.5 mm/yr, more than twice the long-term trend estimated by *Calafat et al.* [2010] for the period 1948–2000.

3.2. Interannual Variability

[19] The sea level increase is not linear in time but is dominated by two periods of change. This is particularly evident in the low-pass (12 month moving average) filtered signal (Figure 1b). The first period is one where a step change of 2–3 cm occurs during 1995–1996. The second period of change is between 2008 and 2011. Mean sea level for the period 2008–2011 is 2–3 cm above the average for the period 1996–2008. The 2008–2011 signal includes the most prominent peak in winter 2010, which is 16.6 cm above the average of the total period in the altimetry record (8.6 cm above the average for the IBC altimetry). The sea level estimate from GLORYS is also shown. The available data stop in 2009. The curve deviates from the altimetry sea level record; however, it includes the increase in 2008–2009.

[20] The mass component of Mediterranean sea level as derived from GRACE data (August 2002 to May 2011) is plotted in Figure 1c. The winter 2010 signal is very strong. There is an even stronger monthly signal in winter 2011. Significant monthly and interannual variability is also evident. The annual signal for the last 2 years is much stronger than the earlier period. The GLORYS mass component is also shown estimated as the difference between the model sea level and the model steric signal after the removal of the steric trend from the model values. The model reproduces the observed increase towards the end of the record, although it appears in the model a year earlier than in the observations. Note also that while the low frequency pattern looks very similar in the mass changes inferred by GRACE and altimetry, the high-frequency signal agrees well only between the end of 2009 and the first 6 months of 2010. It is unclear whether this is coincidental or not.

[21] The steric sea level component (Figure 1d) is dominated by a decadal oscillation with amplitude of about 2 cm. The winter 2010 steric sea level is not markedly different from the other parts of the record, i.e., it does not show any significant increase as in total sea level or the mass component. Thus, as far as the 2010 sea level signal is concerned, the mass component was the dominant forcing. However, in winter 2011 a very strong steric signal is observed earlier than the mass signal, followed by a sudden decrease by the time that the mass component reaches its maximum. The result of this combination is that the 2011 maximum in total sea level is weaker than

Table 1. Linear Trends in the Sea Level Time Series for the Period 1993–2011[a]

	Period	Sea Level Trend (mm/yr)	Error (mm/yr)
Altimetry	January 1993 to December 2011	3.0	0.5 (0.1)
IBC-altimetry	January 1993 to December 2011	2.8	0.5 (0.1)
Steric sea level	January 1993 to December 2010	0.2	0.5 (0.5)
Inferred mass change	January 1993 to December 2010	2.6	0.5 (0.5)

[a] The error stated is the empirical estimate of *Tsimplis et al.* [2011]. The errors in parenthesis are the statistical errors from the linear regression.

the 2010 maximum (see the altimetry record in Figure 1a). Further work is needed to understand the difference in the character of the 2010 and 2011 events.

[22] The steric sea level estimate from GLORYS, with spurious steric trend removed, is also shown. The decadal oscillation present in the data is well described in GLORYS except for the final year of the model.

[23] The relationship of the estimated and observed mass variability with the NAO index is shown in Figure 2. Figure 2a shows the variation of the mean annual values of the mass component inferred as IBC altimetry-steric sea level and of the mass component observed by GRACE together with the winter NAO index (inverted). Figure 2b shows the variation of the winter values of these parameters which are larger than for the annual values. For 2010, the inferred mass estimate from altimetry-steric is 12 cm (not shown in Figure 2), of which about 4 cm of the total mass change due to pressure difference (see Figure 1a). The GLORYS estimate of mass change produced by subtracting the detrended steric sea level from the model sea level is also shown. The mass increase after 2008 is well captured by GLORYS.

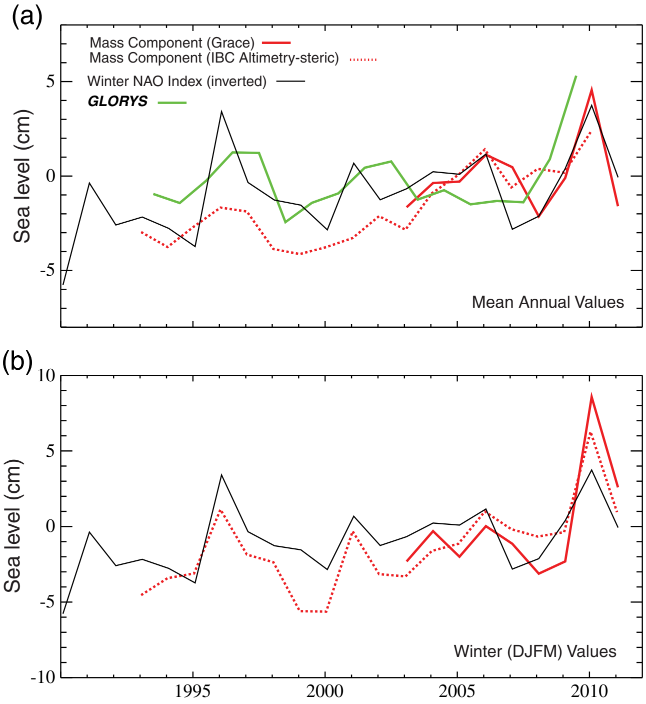

Figure 2. (a) Mean annual mass change from GRACE (red continuous) and from the difference between IBC altimetry and steric sea level (red dotted). The inverted NAO Index (black continuous) is multiplied by 1.5. The GLORYS mass component derived from the sea level minus the detrended steric signal are also shown (green); (b) as in Figure 2a but for winter (December-January-February-March (DJFM)) values. The seasonal cycle and the mean have been removed from all time series.

[24] The good agreement between the mass time series, especially for the winter values, and the NAO index, suggests that the mass changes in the Mediterranean Sea both during the GRACE period and during the altimetry period are mostly associated with changes over the North Atlantic. Moreover, the fact that local atmospheric pressure variations cause no changes in the mass component observed by GRACE indicates that the good agreement with the NAO index is due to mechanisms other than the inverse barometer response.

[25] In order to better quantify the agreement between the different time series of the mass component and the winter NAO index, we have computed their correlations (Table 2). The reported correlation coefficients refer to annual and winter averages of the various sea level time series and the winter NAO index. The correlation of basin-averaged altimetry for winter with the winter NAO index is −0.9. The correlation coefficient for NAO and IBC altimetry is −0.79, still statistically significant. On the basis of the available data the steric changes in sea level are uncorrelated with the NAO ($r = -0.10$ for annual values and −0.24 for winter values).

[26] The correlation coefficients of the annual values of altimetry and IBC altimetry with the winter NAO are −0.72 and −0.65, respectively. These correlations are smaller than those for winter values. In addition, the corresponding regression coefficients are much smaller for the regression on annual values than for the regressions on winter values. Thus, we consider that the relationship of sea level with the NAO is dominated by the influence of the latter during the winter period. The correlation of GRACE with the NAO index is the same for the annual and winter values, but the regression coefficient for winter is almost twice the one obtained for the annual values. Thus, all time series agree that the annual

Table 2. Correlation and Regression Coefficients between the Various Detrended Sea Level Estimates and the Winter NAO[a]

		Annual Values		Winter Values	
Parameter	Period Covered	Correlation with NAO	Regression coefficient cm/unit NAO	Correlation with NAO	Regression Coefficient cm/unit NAO
Altimetry	1993–2011	−0.72	−1.20	−0.90	−3.05
IBC-altimetry	1993–2011	−0.65	−0.89	−0.79	−1.65
Altimetry-steric	1993–2010	−0.67	−1.18	−0.89	−3.03
IBC altimetry-steric	1993–2010	−0.56	−0.87	−0.77	−1.57
GRACE	2003–2010	−0.77	−1.19	−0.78	−2.23
HAMSOM (pressure)	1958–2008	−0.70	−0.38	−0.83	−1.36
HAMSOM (Wind)	1958–2008	−0.51	−0.14	−0.76	−0.60
Reconstructed sea level [*Calafat et al.* 2010]	1948–2000	(−0.12)	−0.25	−0.50	−1.31
Inferred mass change [*Calafat et al.* 2010]	1948–2000	(−0.18)	(−0.13)	−0.28	−1.22

[a] Values in parenthesis are not significant. Steric sea level does not show any significant correlation with the winter NAO.

correlation with the NAO is dominated by the winter relationship. However, the winter and annual correlations for GRACE do not change, while the correlations for altimetry do change. Whether this difference in behavior is related to the processing of GRACE and/or altimetry or it is due to the variations of the steric signal is unclear and requires further research.

[27] We confirm the NAO correlation with coastal sea level by using two tide-gauge records: Trieste, in the Mediterranean Sea, and Bonanza in the Atlantic side of the Strait of Gibraltar. The wind + pressure effect was estimated for each tide gauge from the closest grid point of the HAMSOM model, and the pressure effect was estimated as the difference between the wind + pressure effect and the wind effect alone again at the closest grid point of the model. The correlation between winter sea level obtained from these tide gauges and the winter NAO index was computed prior to and after the removal from the tide gauges of (a) the wind + pressure effect and (b) the pressure effect alone.

[28] The observed sea level is significantly correlated with the winter NAO index at both stations. When only the pressure effect is removed, the correlation with the NAO remains significant at both stations ($r = 0.5$). This is consistent with the work of *Tsimplis and Shaw* [2008], who found a reduction of the correlation with the NAO index after the removal of the atmospheric pressure but the persistence of residual significant correlation in the Adriatic and the Eastern Mediterranean. The correlation is reduced after the removal of the wind + pressure effect for Trieste where it remains statistically significant ($r = 0.39$). For Bonanza, the removal of the wind + pressure effect makes the correlation of the residual sea level with the NAO statistically insignificant.

[29] Thus, the NAO influence remains statistically significant for pressure corrected tide gauges as well as for the IBC altimetry. In other words, the residual correlation with the NAO index identified by *Tsimplis and Shaw* [2008] for pressure corrected tide-gauge data in the eastern Mediterranean and the Adriatic Sea is also present for the basin-averaged sea (Table 2).

[30] The regression coefficients for winter values are -3.05 ± 0.35 cm/unit NAO for altimetry and -1.65 ± 0.37 cm/unit for IBC altimetry. Thus, sea level in the Mediterranean basin changes by -1.65 ± 0.37 cm per unit NAO caused by processes other than atmospheric pressure changes. This will be discussed further later.

[31] We also used an altimetry product corrected for the effect of both atmospheric pressure and wind as estimated by a barotropic model [*Carrere and Lyard*, 2003]. The results obtained do not differ significantly from those presented here and will not be discussed further. They confirm that the omission of the high-frequency wind when correcting the altimetry measurements is not the reason for the residual correlation with the NAO index.

[32] Both the GRACE mass estimate and the inferred mass estimate (IBC altimetry-steric) show correlation with the winter NAO (Table 2). The regression of the winter GRACE data (2003–2010) to the winter NAO index gives a basin average value for the Mediterranean of -2.23 ± 0.28 cm/unit NAO (-1.19 ± 0.28 cm/unit NAO for the yearly value). The regression values for GRACE are sensitive to the selected scale component. The reported values are for scale factor 1.5. A scale factor of 1.8 gives -2.66 ± 0.28 cm/unit NAO for winter and -1.42 ± 0.28 cm/unit NAO for the annual values, respectively.

[33] In Figure 3, the inferred mass change estimated from *Calafat et al.* [2010] is plotted together with a linear regression model in which the NAO index and time are the independent parameters. The linear trend was found to be 1.5 mm/yr for the period 1948–200, and the regression coefficient for the winter values with the NAO is -1.22 ± 0.40 cm/unit NAO. These results suggest that the correlation between the interannual variability of mass change and the NAO index is not particular for the altimetric period, but it extends at least back to 1950 for the winter season.

3.3. The Forcing of Interannual Variability

[34] One important question arising regards the physical mechanism that causes IBC altimetry in the Mediterranean to be linked with changes in the NAO index. The inverse barometer correction is applied to the altimetry product globally, so that redistribution of water masses over the Atlantic as a response to changes in atmospheric pressure gradients are accounted for. However, sea level may also be affected by the large-scale wind field and the associated oceanic circulation. In addition, local wind effects at the Atlantic side of the Strait of Gibraltar may also be responsible for the correlation with the NAO.

[35] The output of the HAMSOM simulation covering the period 1958–2008 provides sea level change caused by changes in atmospheric pressure and local wind (we call this pressure + wind effect). Running HAMSOM solely with the wind forcing, a separate estimate of sea level changes driven by local wind forcing alone is obtained. The difference between the two runs (pressure + wind and wind alone) provide the sea level change caused by pressure changes. The basin averages of the atmospheric pressure contribution and the local wind forcing contribution are both correlated with the NAO index (Table 2), and both have significant trends: -0.4 mm/yr and -0.2 mm/yr, respectively.

[36] The sum of the regression coefficients obtained from HAMSOM estimates of pressure and wind-driven sea level is, for winter, -1.96 cm/unit NAO. This is less than the regression coefficient obtained for altimetry which was -3.05 cm/unit NAO. Thus, the observed change in the NAO between 2008 and 2010 (~4 NAO units) would translate in a sea level change of 5.4 cm due to pressure and 2.4 cm due to wind, a sum of 7.8-cm, which is less that the 12 cm obtained from the altimetry regression with the NAO. That is, about 4 cm of sea level change linked with the NAO remains unexplained. The point is illustrated in Figure 4.

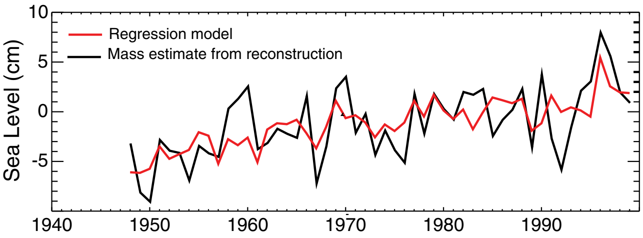

Figure 3. Winter mass changes from *Calafat et al.* [2010] inferred from reconstructed sea level for the Mediterranean basin with the steric sea level contribution subtracted (black line). The linear regression model based on the inverted winter NAO index and a linear trend is also shown (red line). The mean has been removed from the time series.

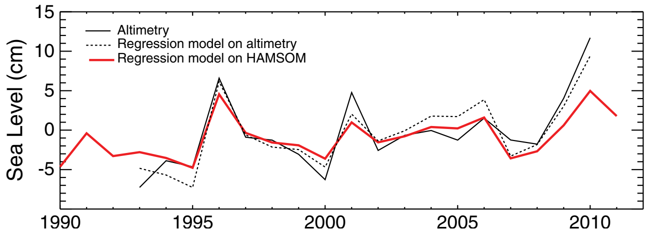

Figure 4. Winter values for altimetry (continuous line); the regression model based on the winter NAO with regression coefficient -2.8 cm/unit NAO and a trend of 1.9 mm/yr (dotted line); the regression model on the basis of the relationship of the total atmospheric forcing (pressure and wind) with regression coefficient of -2 cm/unit NAO (red line). The seasonal cycle and the mean have been removed.

[37] Because our estimates for the contributions of local wind and pressure are based on the statistical relationship between HAMSOM, which stops at 2009, and the NAO index and thus does not cover the 2010 event, we further explore the wind contribution by using the formula of *Menemenlis et al.* [2007]. From this, we derive that winds in 2009 have contributed an increase in sea level of ~1.2 cm by comparison to 2008 and an increase of 1.8 cm in 2010. These values are slightly lower than the 2.4 cm of wind contribution we estimated on the basis of the regression coefficient of wind on NAO. Thus, the local wind contribution, although significant, cannot explain the observed differences.

[38] As shown, the HAMSOM model does not reproduce the whole of the sea level signal associated with the NAO. There are several mechanisms that may separately or jointly explain the discrepancy. The HAMSOM model has the inverse barometer effect imposed as boundary condition, but the sea level changes at the boundary caused by oceanic circulation are not accounted for. Thus, one possibility is that sea level change caused by the large-scale wind and linked with the oceanic circulation outside the modeled domain is not accounted for. *Calafat et al.* [2012] have shown that the contribution of changes in the strength of the subtropical gyre to the sea level in the Eastern North Atlantic and the Mediterranean Sea is very small at decadal time scales. At the decadal time scales, the propagation of baroclinic sea level fluctuations along the eastern boundary caused by changes in the longshore wind are the most important forcing factor [*Calafat et al.*, 2012]. The mechanism described by *Calafat et al.* [2012] is missing from the barotropic HAMSOM model we use in this study to resolve the atmospheric forcing effects as it does not account for the effects of stratification within the ocean. Thus, it is possible that steric sea level signals propagating along the eastern boundary and driven by the integrated longshore wind stress may contribute in explaining the observed discrepancy. However, as the *Calafat et al.* [2012] study concerns decadal time scales, it will require further work to resolve its influence on sea level at shorter time scales.

[39] The attribution of the discrepancy to another mechanism is further supported by the fact that the GLORYS model, which finishes in 2009, does show an increase in sea level as well as in the inferred mass. As explained, the steric variability of the model, after the removal of the steric trend, also appears consistent with the historical observations. Because the model is not forced by atmospheric pressure, the presence of the sea level and mass increases indicates an origin linked with wind forcing.

3.4. The Effect of the Freshwater Fluxes

[40] For completion, we assess the effect of the freshwater fluxes on the mass component. We compare the indirect estimate of mass change in the Mediterranean Sea by *Calafat et al.* [2010] and estimates of the fresh water budget data for the common period of 1951–1981 dictated by the restricted availability in river outflow data. It is known that the NAO affects Mediterranean precipitation, especially in winter, by modulating sea level pressure directly over the Mediterranean and by reorganizing large-scale moisture fluxes into the region [*Mariotti and Arkin*, 2007; *Fenoglio-Marc et al.*, 2013].

[41] Winter values of the month-to-month derivative of the mass component and the precipitation (P) + runoff (R) − evaporation (E) for the period 1951–1981 were found to be significantly correlated. The correlation between the two time series is 0.43 for the period 1951–1981, and it increases up to 0.76 when the period 1963–1981 is considered. Both values are significant at the 95% confidence level. The P + R E contribution also accounts, on the basis of linear regression, for a considerable percentage of the derivative of the mass component, being 15% for the whole period but higher for the period 1963–1981. The correspondence of the time series is due to the association of P, R, and E with the NAO index. However, we do not suggest that P + R − E is dominant in explaining the derivative of the mass addition component.

4. Conclusions

[42] The development of sea level in the Mediterranean Sea during the period 1993–2010 is assessed. The fitting of linear trends shows that the increase in sea level is 2.8 ± 0.5 mm/yr and that this is primarily due to mass addition as the steric contribution is insignificant to this increase. However, we find the fit of linear trends as unsatisfactory because most of sea level rise in the Mediterranean Sea during the period under study is due to two increases of 2–3 cm each that happened in shorter periods of time. We find that both periods of change coincide with changes in the NAO index.

[43] The analysis of altimetry and tide gauges suggests that the NAO influence on Mediterranean Sea level is primarily expressed by the local atmospheric pressure effects and secondarily by an effect of winds over the basin. Both effects are approximated by the two-dimensional modeling of the basin through the HAMSOM model. However, there is a third contribution of the NAO to sea level change in the Mediterranean Sea which can be important and was detected in winter 2010. GLORYS without data assimilation does simulate the increase in sea level at the end of its record. In addition, the HAMSOM model is unable to describe this part of the variability. Thus, it is suggested that this third component of the NAO influence is due to a change in the oceanic baroclinic circulation driven by the wind in the Atlantic Ocean which cannot be accounted for in the HAMSOM model. Further work is needed to model accurately this process which is important for the accurate

determination of the interannual sea level variability as well as for the determination of sea level trends.

[44] The Mediterranean basin mass change is highly correlated with the NAO and is driven by all three processes described above, namely, atmospheric pressure-driven redistribution of mass, wind-driven mass changes, and the third and yet fully unresolved contribution. However, on the basis of the data available, the Mediterranean average steric signal is not correlated with the NAO, which is consistent with the analysis of *Josey et al.* [2011]. Other studies have found local correlations of the steric signal with the NAO in the Adriatic and the north Aegean Sea [*Tsimplis and Rixen*, 2002]. This suggests that the NAO could locally affect the steric component through the local atmospheric forcing, but such effects would not be significant enough as to affect the basin mean steric signal.

[45] The sea level increase in winter 2010 is consistent with the lowest NAO value over the last decade. The processes linked with this NAO change caused around 12 cm of basin sea level rise. The tidal signal in the Mediterranean basin is in most parts low, and moreover sea level has been rising slower than in the rest of the world during the last decades. These factors have led to the development of infrastructure assuming a nearly stable sea level. This makes, in our view, the coastal Mediterranean areas more vulnerable to sea level changes than areas where sea level variability in tides and storm surges is much higher. Thus, the 12 cm variation in winter 2010 posed a significant risk and contributed to floods in some islands at the Aegean Sea. GRACE also shows the same peak indicating that it is primarily a mass-related change. About 5.4 cm of this change is estimated to be due to atmospheric pressure effects, 2.4 cm due to the wind effects, and 4 cm is not yet clarified, although it appears that they are linked to processes not present in the barotropic model we used but present in the GLORYS model.

[46] There are several remaining open questions to understand sea level change in the Mediterranean Sea for the observed period. Resolving the role of the barotropic and baroclinic oceanic circulation in the Atlantic and its relationship with the NAO is one. Clarifying whether the mechanisms identified by *Calafat et al.* [2012] as dominant in the decadal scales are also contributing at the interannual scale is also a priority. The significant improvement achieved through the use of satellite observations provides a solid background against which further modeling work and improved oceanographic observations can build in order to resolve these issues in the near future.

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