Mechanisms of Decadal Sea Level Variability in the Eastern North Atlantic and the Mediterranean Sea

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Received 14 June 2012; revised 6 August 2012; accepted 9 August 2012; published 18 September 2012.

[1] Decadal sea level variations from tide gauge records along the western European coast and in the Mediterranean Sea commencing in the late 19th and early 20th centuries are examined relative to large-scale atmospheric forcing. Recent studies have provided evidence for a link between sea level in the eastern North Atlantic and atmospheric forcing, however the nature of this relationship is still unclear. Here the outputs of a regional barotropic model and a nearly global baroclinic model are used in conjunction with wind stress and heat flux data to explore the physical mechanisms responsible for the observed sea level variability. All tide gauge records show significant decadal variability (up to 15 cm) and are highly correlated with the NAO and among themselves at decadal periods. There is a coherent sea level signal that affects the eastern boundary of the North Atlantic northward of 25°N and is limited to a narrow band of the order of a few hundred kilometers along the coast. This band tends to become narrower towards higher latitudes. We find that longshore wind and wave propagation along the boundary are the major contributors to coastal sea level variability but no significant contribution from mass redistribution linked to changes in the strength of the subtropical gyre is observed. The mass component dominates sea level in the Mediterranean and is mainly driven by mass exchanges with the Atlantic, which explains the correlation between both regions. Southward of 25°N, sea level changes are mainly driven by heat advection through Ekman fluxes.

Citation: Calafat, F. M., D. P. Chambers, and M. N. Tsimplis (2012), Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea, *J. Geophys. Res.*, *117*, C09022, doi:10.1029/2012JC008285.

1. Introduction

[2] Quantifying changes in the rate of global mean sea level (GMSL) rise, especially estimating whether a significant acceleration has occurred, is a major focus of current climate change research [e.g., *Jevrejeva et al.*, 2008; *Woodworth et al.*, 2009; *Church and White*, 2011]. While all authors agree on the long-term (50-year plus) rate of GMSL rise within ±0.5 mm/yr, their estimates of global-average accelerations are more ambiguous. *Douglas* [1992] and *Woodworth* [1990] found only a weak sea level acceleration (~0.004 mm/yr^2) in the longest tide gauge records at the European Atlantic coast but no evidence for a GMSL acceleration over the last century. *Jevrejeva et al.* [2008] used a Monte Carlo Singular Spectral Analysis to reconstruct GMSL from tide gauge records since 1700. They identified a sea level acceleration of ~0.01 mm/yr^2 starting at the end of the 18th century. *Church and White* [2011] produced a global sea level reconstruction by combining tide gauge records with empirical orthogonal functions (EOFs) from which they obtained a GMSL acceleration between 1880 and 2009 of 0.009 ± 0.003 mm/yr^2. The main two issues that affect our ability to measure GMSL accelerations accurately in tide gauge records are the limited sampling of tide gauges and the unknown interannual and decadal scale variability related to internal ocean dynamical processes.

[3] Several studies have shown that superimposed on the long-term acceleration there are shorter periods with considerable accelerations and decelerations [*Woodworth*, 1990; *Douglas*, 1992; *Holgate*, 2007; *Church and White*, 2011]. Indeed, *Jevrejeva et al.* [2008] found evidence that the main contribution to the acceleration variability is associated with decadal and multi-decadal variability. In addition, sea level changes are regionally variable, with significant differences between sea level signals at the coast and those in the ocean interior. In a recent paper, *Bingham and Hughes* [2012] have found evidence of a significant decoupling between coastal and ocean interior sea level variability, even at inter-annual time-scales. This is clearly an additional issue when using tide gauge records to estimate GMSL time series as most of them are located on the coast. Indeed, while the mean coastal trend (derived from tide gauges) agrees reasonably well with the true GMSL rate (derived from altimetry), the agreement nearly vanishes at inter-annual time-scales [e.g., *Prandi et al.*, 2009]. Our aim here is to identify the forcing mechanisms responsible for the observed decadal sea level variability on the eastern

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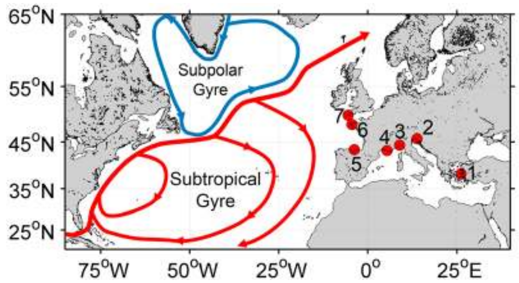

Figure 1. Sketch showing the major features of the North Atlantic circulation and the location of the tide gauge stations used in the analysis: Khios (1), Trieste (2), Genova (3), Marseille (4), Santander (5), Brest (6), and Newlyn (7).

boundary of the North Atlantic and the Mediterranean Sea and to provide further evidence of this decoupling between coastal and open ocean sea level variability.

[4] In recent years there have been several studies that have linked decadal sea level variability at the eastern North Atlantic to large-scale atmospheric changes [*Miller and Douglas*, 2007; *Woodworth et al.*, 2010; *Sturges and Douglas*, 2011]. However the precise mechanism of this relationship remains unclear. *Miller and Douglas* [2007] and *Woodworth et al.* [2010] found evidence of a link between sea level at the eastern boundary of the North Atlantic and large-scale sea level pressure (SLP) over the Atlantic, which they linked to changes in the strength of the oceanic subtropical gyre. More recently, *Sturges and Douglas* [2011] have found significant correlation between longshore wind and sea level at Cascais for periods up to a decade, which they have related to the propagation of wind-driven sea level fluctuations along the eastern boundary. Evidence for large-scale coherent sea level signals along the boundary associated with longshore wind and wave propagation has also been found in other regions [*Enfield and Allen*, 1980; *Chelton and Davis*, 1982; *Clarke and Lebedev*, 1999; *Hughes and Meredith*, 2006]. Hence it is not clear which mechanism play the most important role in driving the decadal sea level variability. In this paper, we explore the relationship between sea level and both gyre-scale circulation and longshore wind in order to clarify their contribution. Finally, it is worth commenting that a similar relationship between atmospheric forcing and sea level has also been found in other regions. *Sturges and Hong* [1995] and *Hong et al.* [2000], for instance, demonstrated that wind stress curl (WSC) in the North Atlantic forced Rossby waves that generated low-frequency sea level variability at Bermuda and along the U.S. Atlantic coast. Also, several recent papers have identified a multi-decadal change in sea level in the western Pacific [*Merrifield*, 2011; *Merrifield and Maltrud*, 2011] and the western U.S. coastline [*Bromirski et al.*, 2011] driven by changing winds.

[5] In this paper we explore decadal sea level variations on the European Atlantic coast and in the Mediterranean Sea from the late 19th century. We use the longest, most continuous tide gauge records in the region and demonstrate that they have highly correlated decadal-scale fluctuations in sea level. The physical mechanisms responsible for the observed sea level variability are explored by using the outputs of a regional barotropic model and a nearly global baroclinic model in conjunction with wind stress and heat fluxes data. We relate the observed decadal sea level variations to large-scale atmospheric changes over the North Atlantic. We show that there is a large-scale coherent sea level signal along the European Atlantic coast. This signal is significantly correlated with the North Atlantic Oscillation (NAO) index and extends only a few hundred kilometers beyond the continental shelf. We provide evidence that the main contribution to the coastal sea level variability at decadal time-scales is associated with the response of the ocean to longshore wind stress.

2. Data

[6] Monthly-averaged time series of sea level are obtained from the data archive of the Permanent Service for Mean Sea Level (PSMSL) [*Woodworth and Player*, 2003]. For the Mediterranean Sea, we use the tide gauge records at Trieste (1905–2009), Marseille (1886–2009) and Khios (1969–2009). The tide gauge record located at Marseille has been found to have faulty data during the periods 1950–1958 and 2005–2006 [*Douglas*, 1992] and data are missing for the period 1997–1998. Following *Tsimplis et al.* [2008], data at Marseille during those periods have been replaced using observations from the tide gauge record at Genova. For the eastern North Atlantic we use the tide gauge records at Santander (1944–2009), Brest (1871–2009) and Newlyn (1916–2009). The location of all tide gauges is shown in Figure 1. Since we are interested in the decadal variability, the seasonal cycle along with a linear trend are removed from all tide gauge records and a 4-year running mean applied.

[7] Monthly SLP observations are obtained from the near real time update of the Hadley Centre Sea Level Pressure (HadSLP2) dataset [*Allan and Ansell*, 2006]. HadSLP2 combines marine and land pressure observations using a reduced-space optimal interpolation analysis and is available on a 5° latitude-longitude grid from 1850 to present. Monthly wind stress data are obtained from the 20th Century Reanalysis [*Compo et al.*, 2011]. These data are available on a 2° latitude-longitude global grid from 1871 to present. Finally, surface heat flux data are obtained from the National Centers for Environmental Prediction (NCEP) reanalysis [*Kalnay et al.*, 1996]. They are monthly surface heat flux fields on a 2.5° $\times$ 2.5° global grid covering the period from 1948 to present.

[8] The barotropic response of the ocean to local wind forcing is quantified running a barotropic version of the HAMSOM (Hamburg Shelf Circulation Model) ocean model using only wind forcing. The model configuration is the same as that used to generate the HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe) sea level residual dataset [*Ratsimandresy et al.*, 2008] except that the forcing is 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° $\times$ 1/4° spatial resolution covering the Mediterranean Sea and the Atlantic coast of the Iberian Peninsula.

[9] The baroclinic component of the sea level is investigated using the German partner of the consortium for Estimating the Circulation and Climate of the Ocean (GECCO) simulation [*Köhl and Stammer*, 2008a], where the assimilation approach is essentially identical to the 11-years ECCO global data synthesis [*Köhl et al.*, 2007]. The simulation is based on the ECCO/Massachusetts Institute of Technology

(MIT) global circulation model and its adjoint, which covers the global oceans from 80°S to 80°N with a spatial resolution of 1° × 1° in the horizontal and has 23 non-uniform vertical levels, varying from 10 m at the surface to 500 m in the deep ocean. The period spanned by the simulation is 1952–2001. Because the model is still adjusting during the first decade [*Köhl and Stammer*, 2008a], this period of the simulation is excluded from the analysis.

3. Methodology

3.1. The Different Components of Sea Level

[10] From the hydrostatic relation it can be shown that changes in sea level, η, can be expressed as the sum of three components: the inverse barometer (IB) effect, η_{IB}, the steric component, η_s, and a term proportional to the change, P_b, in ocean bottom pressure; thus:

$$\eta = \eta_{IB} + \eta_s + \frac{P_b}{g\rho_0} \quad (1)$$

where g is the gravitational acceleration, and ρ_0 is a reference density.

[11] The IB effect, η_{IB}, represents the redistribution of mass within the ocean as a result of changes in the surface atmospheric pressure and can be computed as:

$$\eta_{IB} = \frac{1}{g\rho_0}\left(\overline{P}_a - P_a\right) \quad (2)$$

where P_a is sea level atmospheric pressure, and $\overline{P}_a$ is the averaged pressure over the global oceans. In this study the IB effect is computed using sea level pressure from the HadSLP2 dataset.

[12] The steric component of sea level, η_s, represents the effect of expansion and contraction of the water column associated with density changes caused by temperature (T) and salinity variations (S). It is defined as:

$$\eta_s = -\frac{1}{\rho_s}\int_{-H}^{0} \rho'(T,S)dz \quad (3)$$

where ρ_s is the surface density, H is the depth of the ocean, and ρ' represents a density deviation with respect to the time-mean of the in-situ density.

[13] The third term on the right-hand side of equation (1) will be referred to as the mass component of sea level and it includes changes in bottom pressure due to water mass addition/removal from the oceans due to melting/growing of continental ice, and to barotropic motions within the ocean.

3.2. Thermosteric Sea Level Changes Due to Surface Heat Flux Variations

[14] Surface heat and freshwater flux variations produce local density changes in the upper ocean layers that result in steric sea level changes. The thermal part of these steric variations can be written as [*Vivier et al.*, 1999]:

$$\frac{\partial \eta_s^{hf}}{\partial t} = \frac{\alpha(T,S)}{\rho_0 C_p}\left(Q_{net}(t) - \overline{Q}_{net}\right) \quad (4)$$

where α is the coefficient of thermal expansion, C_p is the specific heat of seawater, Q_{net} is the net surface heat flux, and the overbar denotes temporal averaging. The coefficient of thermal expansion, α, is estimated from the T and S fields from GECCO averaged over the mixed layer depth. The mixed layer depth is computed using a potential density criterion of 0.125 from the surface value [*Levitus*, 1982]. The procedure is as follows. First, we find the first standard level that has a potential density differing from the surface potential density by more than 0.125. A linear interpolation is then performed between this subsurface level and the preceding level to obtain the depth at which the potential density differs from the surface potential density by 0.125.

[15] Unless otherwise stated, all correlations quoted in this paper are significant at the 95% confidence level. Statistical significance is based on **t**-test at the 95% level. It is important to note that, in order to emphasize the low-frequency variability, a 4-year running mean is applied to all time series. This results in a reduction by a factor of 48 (for monthly time series) in the number of effective degrees of freedom [*Emery and Thomson*, 1998] which needs to be accounted for when estimating the significance of the correlation.

[16] In addition to correlation, we also use the explained variance, which provides a measure of the agreement between two variables in terms of both variability and magnitude. The percent of variance (*%variance*) of a variable, y, explained by another variable, $\hat{y}$, is computed as:

$$\%variance = 100\left(1 - \frac{\mathrm{var}(y-\hat{y})}{\mathrm{var}(y)}\right) \quad (5)$$

where the operator var( ) denotes variance.

4. Results

4.1. Relationship to the North Atlantic Oscillation

[17] Following recent studies that have linked the decadal sea level variability at the eastern North Atlantic to large-scale atmospheric changes [*Miller and Douglas*, 2007; *Woodworth et al.*, 2010; *Sturges and Douglas*, 2011], we begin our analysis by comparing sea level with the NAO index, as the NAO is the leading mode of low-frequency variability over the North Atlantic [*Barnston and Livezey*, 1987]. The relationship between sea level in both the eastern North Atlantic and the Mediterranean Sea and the NAO has been demonstrated previously for different time-scales [*Tsimplis and Josey*, 2001; *Wakelin et al.*, 2003; *Woolf et al.*, 2003; *Yan et al.*, 2004; *Tsimplis et al.*, 2005, 2006; *Tsimplis and Shaw*, 2008]. It has been shown that the response of the sea level to the NAO is both spatially and temporally variable. Negative correlations are found in the Mediterranean Sea and on the European Atlantic coast up to the south of the British Isles, while positive correlations are observed in the North and Baltic Seas [*Wakelin et al.*, 2003; *Woolf et al.*, 2003; *Yan et al.*, 2004]. *Woolf et al.* [2003] and *Tsimplis et al.* [2006] also found that the relationship between sea level and the NAO was stronger during the second half of the 20th century than during the first half.

[18] Here we explore the relationship between sea level and the NAO explicitly for the decadal and inter-decadal time scales. We compare smoothed (4-year running mean) winter values (DJFM) of sea level and the NAO index for the period from 1950 to 2009. Winter values are selected, as these represent the time of largest atmospheric pressure

Table 1. Correlation Between the Smoothed (4-Years Running Mean) Winter (DJFM) Values of the Sea Level From Various Tide Gauge Records (see Figure 1) and Those of the NAO Index for the Period 1950-2009[a]

Site	Correlation
Trieste	−0.89
Marseille	−0.76
Santander	−0.74
Brest	−0.65
Newlyn	−0.65

[a]All time series have been detrended prior to the computation of the correlations. All correlations are significant at the 95% confidence level.

fluctuations in the North Atlantic. Most modern NAO indices are derived either from the difference in SLP between two stations (usually Gibraltar and Iceland), or from the principal component (PC) associated with the leading EOF of the SLP over the North Atlantic sector (90°W - 40°E, 20°N - 80°N) [e.g., *Hurrell et al.*, 2003]. In this study the NAO index is computed using the EOF-based approach. All tide gauge records show significant negative correlation with the NAO index, ranging from −0.65 at Brest and Newlyn to −0.89 at Trieste (Table 1), reflecting their relationship with atmospheric forcing. It is worth mentioning that the correlation between sea level and the NAO index for whole-year values, although slightly lower, remains significant at all tide gauge stations. The correlation among tide gauge records is also significant at all tide gauge stations suggesting the existence of a large-scale coherent sea level signal along the eastern boundary of the North Atlantic and in the Mediterranean Sea (Table 2). The high correlation (0.85) between Trieste (in the Adriatic Sea) and Marseille (in the western Mediterranean) may be indicative of the existence of a uniform sea level fluctuation in the Mediterranean Sea at decadal time-scales. This possibility will be explored in the next sections.

[19] The decadal and inter-decadal sea level variability has also been examined for all tide gauge records (Figure 2). We note that all of them exhibit considerable decadal sea level variability (amplitudes of over 10 cm) with three oscillations during the period 1950–2009. Relative lows in sea level are observed in 1955, 1974 and the early 1990s at all tide gauge stations. The dips in sea level during those years coincide with maximum positive values of the NAO index. More generally there is good agreement between the time series of sea level and the NAO index, which is clearly reflected in the high correlations found between both time series

Table 2. Correlation Between Different Pairs of Tide Gauge Records in the Eastern North Atlantic and in the Mediterranean Sea[a]

	Trieste	Marseille	Santander	Brest	Newlyn
Trieste	1.00	0.85	0.73	0.54	0.70
Marseille	0.85	1.00	0.56	0.65	0.62
Santander	0.73	0.56	1.00	0.56	0.61
Brest	0.54	0.65	0.56	1.00	0.74
Newlyn	0.70	0.62	0.61	0.74	1.00

[a]Correlations have been computed using smoothed (4-years running mean) winter (DJFM) values of the sea level for the period 1950–2009. All time series have been detrended prior to the computation of the correlations. All correlations are significant at the 95% confidence level.

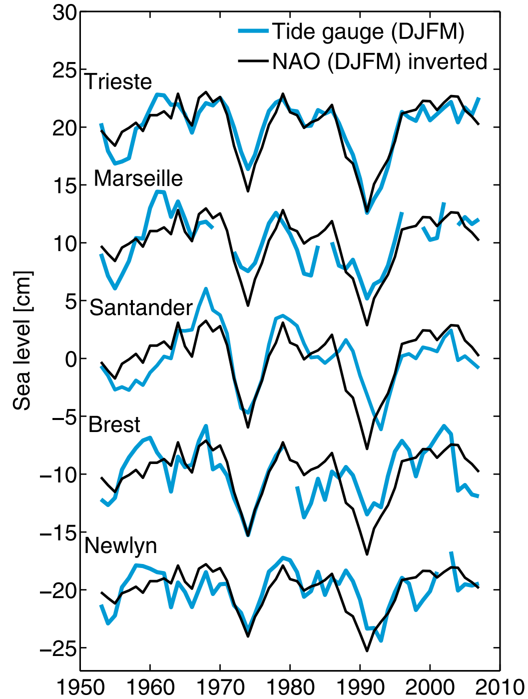

Figure 2. Comparison between the smoothed (4-year running mean) winter (DJFM) values of sea level (blue line) and those of the inverted NAO index (black line) at 5 tide gauge sites: Trieste and Marseille in the Mediterranean Sea, and Santander, Brest and Newlyn along the western European coast. All time series have been detrended.

(Table 1). The coherence of the sea level variability at the 5 tide gauge records points to the strong possibility of a large-scale coherent sea level signal affecting the western European coast and the Mediterranean basin.

[20] Large-scale atmospheric changes can affect sea level through a variety of mechanisms. Changes in either wind stress curl or buoyancy fluxes can produce fluctuations in the strength of the oceanic gyres, which are accompanied by water mass redistributions and sea level changes. For instance, during a spin-down of the subtropical gyre water is forced out of the gyre interior and released to the margins of the North Atlantic, which result in sea level falling in the gyre interior and rising on the coast. Changes in surface buoyancy fluxes and in wind stress (via Ekman pumping and heat advection due to Ekman transport) can also produce steric sea level changes. At a side boundary (such as the coastal region) there is an additional response of the ocean to longshore wind forcing, resulting from the fact that there can be no flow normal to the boundary so a convergence or divergence is established with a corresponding change in sea level in order to conserve mass. The response can be both barotropic and baroclinic, consisting respectively of a piling-up of water on the coast and vertical movements of the thermocline.

[21] Figure 3 shows the time-mean pattern of the wind stress curl over the North Atlantic as well as the anomaly in both wind stress curl and wind stress associated with the positive phases of the winter (DJFM) NAO (positive phases are defined as the years when the NAO index exceeds one standard deviation over the period 1950–2009). The zero curl line in the time-mean pattern of the wind stress curl

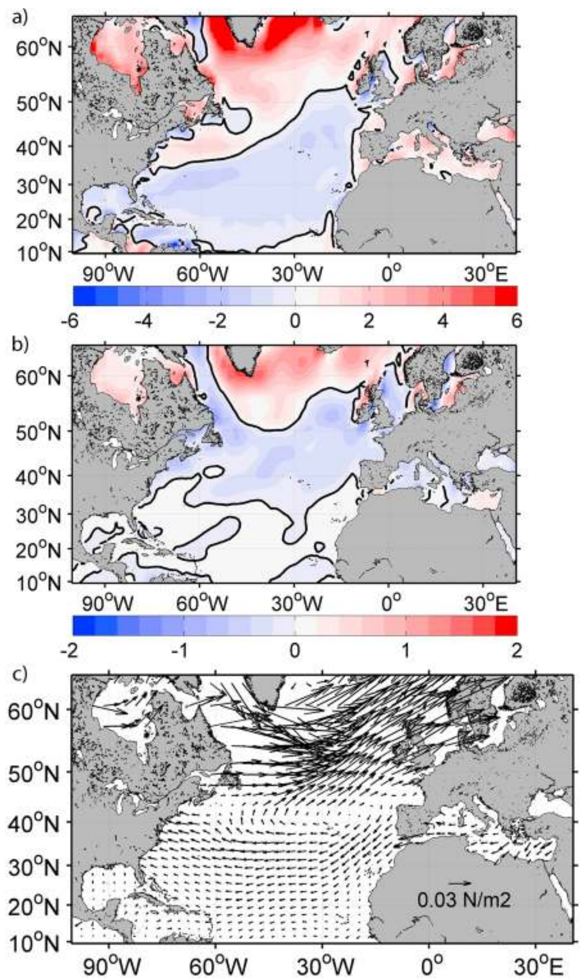

Figure 3. (a) Time-mean WSC over the North Atlantic in units of 10^{-7} N/m^3. (b) The anomaly in WSC associated with positive phases of the winter (DJFM) NAO (10^{-7} N/m^3). (c) The anomaly in wind stress associated with positive phases of the winter (DJFM) NAO in units of N/m^2 (a reference vector is shown in the bottom-right corner). The black lines in Figures 3a and 3b represent zero wind curl lines.

marks the confluence of the subpolar and subtropical gyres (see Figure 1 for a sketch of the general circulation in the North Atlantic), with positive values to its north and negative values to its south (Figure 3a). We note that the anomaly in wind stress curl represents not only a modulation in the strength of the mean pattern but also a northward shift (Figure 3b). The anomaly in wind stress (Figure 3c) shows also a northward shift as well as an enhanced southward longshore wind along the eastern boundary of the North Atlantic. These patterns of variability in air-sea interaction associated with the NAO will be an important element to help us understand and interpret the results presented in the following sections, where we quantify the contributions of the different forcing mechanisms to decadal-scale sea level variability in this region.

4.2. The Inverse Barometer (IB) Effect

[22] Because the NAO index essentially represents the difference between the sea level pressure of the subtropical high and the subpolar low, one would expect that a portion of the observed sea level variability would be explained by the IB effect. The IB effect is computed from equation (1) using SLP from the HadSLP2 data set. Its contribution to the observed decadal sea level variability is quantified by computing the percentage of variance (equation (5)) of sea level that it explains at the tide gauges of Trieste, Marseille, Santander, Brest, and Newlyn (Table 3). Both sea level and IB time series have been detrended and smoothed using a 4-year running mean prior to the computation of the explained variance. Results show that the IB effect explains only a small fraction of the sea level variance at all 5 tide gauge stations. The percentage of variance explained by the IB effect ranges from 14% at Marseille to 27% at Brest. Correlations are also rather small, although statistically significant, at all stations except at Marseille.

[23] The small contribution of the IB effect to the observed sea level variability is further demonstrated by plotting the smoothed time series of both sea level and the IB effect for the five tide gauge records (Figure 4). Although the IB effect exhibits a similar variability to that shown by the tide gauge records, its magnitude is considerable smaller than that of the sea level. It is also interesting to note that the decadal sea level variability is very similar in all tide gauge records, which indicates that the large-scale coherency in sea level exists not only for the winter values but also for the whole-year values. Correlations are high not only among Atlantic tide gauge records but also between the Atlantic and the Mediterranean. For instance, we find correlations of 0.70 and 0.66 for the pairs Marseille-Brest and Marseille-Newlyn, respectively. Marseille and Trieste, both in the Mediterranean Sea, are also highly correlated (0.70). These results are consistent with those by *Tsimplis and Shaw* [2008] who also found coherent sea level signals, although for higher frequencies than those explored here, between the western Mediterranean and the Adriatic Sea and also between those regions of the Mediterranean and the eastern North Atlantic.

4.3. The Barotropic Response to Local Wind Forcing

[24] In section 4.2, we have demonstrated that the IB effect explains only a small fraction (between 14% and 27%) of the observed sea level variability. This indicates that other forcing mechanisms are responsible for the observed decadal sea level variability as well as for its significant correlation with the NAO index. Since wind variability is closely related to pressure variations, one possibility is that the additional response of sea level to the NAO forcing (i.e., that not explained by the IB effect) may be due to the piling-up of

Table 3. Percentage of the Variance of Sea Level Explained by the IB Effect at Various Tide Gauge Records for the Period 1950–2009[a]

	Variance (%)	Correlation
Trieste	25	0.59
Marseille	14	0.40 (NS)
Santander	15	0.52
Brest	27	0.56
Newlyn	22	0.47

[a]The correlation between the sea level and the IB effect at each tide gauge station is also shown. All time series have been detrended and smoothed using a 4-years running mean prior to the computation of the explained variance and correlation. NS stands for non-significant correlation.

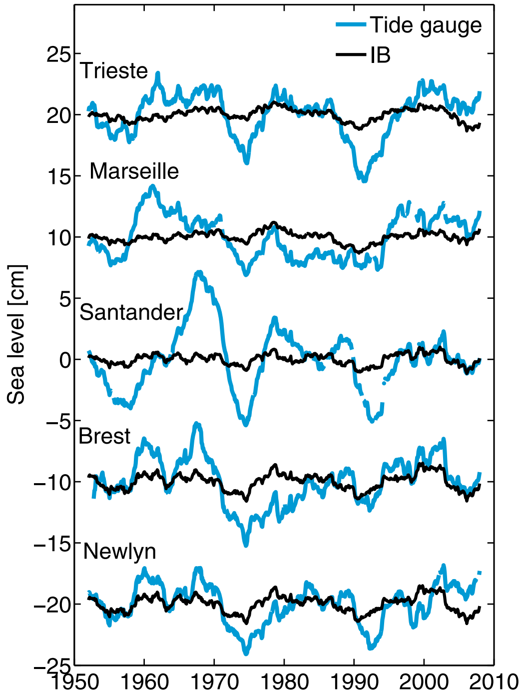

Figure 4. Comparison between the smoothed (4-year running mean) values of sea level (blue line) and those of the IB effect (black line) at 5 tide gauge sites: Trieste and Marseille in the Mediterranean Sea, and Santander, Brest and Newlyn along the western European coast. All time series have been detrended.

water against the coast caused by Ekman transport induced by the winds. Here we explore this possibility by means of a regional barotropic model covering the whole Mediterranean basin and a part of the eastern North Atlantic (see section 2 for model description). It is important to note that the model is a limited area barotropic model, and thus it only accounts for the barotropic response to local winds (i.e., the piling-up of water due to wind-driven Ekman transport toward or away from the coast). However it does not reproduce, for instance, large-scale changes in the ocean circulation of the North Atlantic or baroclinic effects.

[25] Because the model domain does not cover latitudes northward of 46°N, only the tide gauge records at Trieste, Marseille and Santander are included in the analysis. We find that the contribution of the barotropic response to local wind is even smaller than that of the IB effect. In particular, the percentage of the variance of the low-pass filtered (4-year running mean) sea level explained by this contribution for the period 1958–2008 at Trieste, Marseille, and Santander is 15%, 13% and 0% respectively. The reason why values are larger at Trieste and Marseille than at Santander is partly because, in the Mediterranean Sea, there is an additional contribution (besides that of the local wind) due to the piling up of water at the Gibraltar Strait induced by winds around the strait. Hence it turns out that the percent of sea level variance accounted for by the combined effect of the barotropic response to local wind and the IB effect is only ~35% at Trieste, ~25% at Marseille, and ~15% at Santander. A major implication of this result is that the relationship between sea level and large-scale atmospheric forcing (i.e., NAO) is, to a large extent, due to mechanisms other than the IB effect and the barotropic response to local wind.

4.4. Baroclinic Effects and Large-Scale Atmospheric Forcing

[26] So far we have shown that the IB effect and the barotropic response to local winds can explain only a small part of the variance in sea level at decadal scales. This indicates that the observed coastal sea level variability in the eastern North Atlantic must be driven by either steric changes or mass redistributions associated with large-scale changes in the ocean circulation of the North Atlantic. As commented above, steric sea level changes can be produced by changes in the surface heat flux but also by water movements induced by the changing wind stress. The contribution of each of those physical mechanisms is explored in this section with the help of the nearly global GECCO simulation (see section 2 for model description). The GECCO estimate exactly satisfies the model equations without artificial sources or sinks of momentum, heat, and freshwater [*Köhl et al.*, 2007], and thus it is reasonable to assume that processes present in the simulation are not an artifact of the data assimilation procedure. It has been successfully used to study decadal sea level changes [*Köhl and Stammer*, 2008a] and the variability of the Meridional Overturning Circulation (MOC) in the North Atlantic [*Köhl and Stammer*, 2008b].

[27] Before beginning with the analysis of sea level from GECCO, it is necessary to ensure that the sea level from GECCO is in good agreement with observations (i.e., tide gauges) at decadal time-scales. This is achieved by comparing the sea level from GECCO with the IB-corrected sea level at various tide gauge stations (Figure 5). For the Mediterranean Sea we have averaged the tide gauge records at Trieste and Marseille to obtain a single time series of the Mediterranean sea level. The agreement between the modeled and observed sea level variability is remarkably good with correlations ranging from 0.64 at Brest to 0.88 in the Mediterranean Sea. The modeled sea level is also comparable in magnitude to the

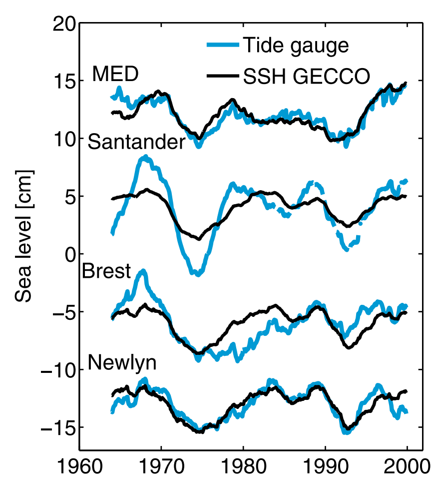

Figure 5. Comparison between the smoothed (4-year running mean) values of the sea level from GECCO (black line) and those of the IB-corrected sea level (blue line) from various tide gauge records: the average of Trieste and Marseille (MED), Santander, Brest, and Newlyn. All time series have been detrended.

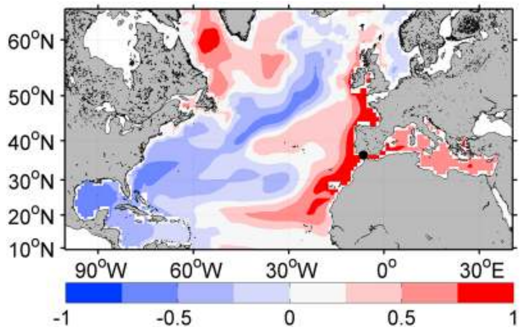

Figure 6. Map showing the correlation between the sea level from GECCO at the Atlantic side of Gibraltar (black dot) and the sea level at each grid point. All time series have been detrended and smoothed using a 4-year running mean prior to the computation of the correlation.

observations. The percent of variance accounted for by the model is ~75% in the Mediterranean Sea, ~60% at Santander, ~41% at Brest, and 73% at Newlyn. Given the similarity between the observed and modeled sea level at decadal scales, the model provides a useful means to explore the forcing mechanisms of the decadal sea level variability.

[28] The significant correlation among tide gauge records along the eastern boundary of the North Atlantic points to the existence of a coherent sea level signal along the boundary. The existence of such a coherent signal is confirmed by plotting the correlation between the sea level from GECCO at a particular coastal point of the eastern boundary and the GECCO sea level at each grid point (Figure 6). The model shows a large band of high correlation (>0.8) along the eastern boundary of the North Atlantic extending from the Canary Islands up to the British Isles. We also note that the band extends only a few hundred kilometers beyond the shelf edge and tends to become narrower towards higher latitudes, where it is nearly limited to continental shelf. This is consistent with the findings of *Bingham and Hughes* [2012], who found that coastal sea level becomes progressively decoupled from the interior sea level at higher latitudes. They attributed this to a decrease in the Rossby wave speed towards higher latitudes, which results in a larger lag between coastal and deep ocean sea level. The fact that the region of high correlation is nearly confined to the coast and occupies a substantial portion of the western European coast is highly suggestive of wave propagation along the coast. Evidence for boundary wave propagation in the GECCO simulation was found also along the western boundary of the North Atlantic [*Köhl and Stammer*, 2008b]. They found that the southward propagation of density anomalies as boundary Kelvin waves from the Labrador Sea to the subtropical region explained over 30% of the MOC variability. Nevertheless, the large-scale coherent sea level signal along the eastern boundary could be also due to mass redistributions related to changes in the strength of the subtropical gyre associated with large-scale atmospheric changes, since tide gauges are located along the peripheries of the gyre. These and other possible mechanisms are explored in the next sections. Finally, we also note a significant correlation (>0.6) between the sea level at the eastern boundary and that in the Mediterranean basin in agreement with observations. The nature of the relationship between the sea level in the Atlantic and in the Mediterranean Sea is also investigated in the next sections.

4.4.1. The Steric and the Mass Components of Sea Level

[29] In this section we explore the relative contribution of the steric and the mass components to total sea level. The steric component is computed by means of equation (3). Figure 7 shows a map of the variance of the total sea level from GECCO explained by the steric component of sea level. The most interesting feature is that the steric sea level explains most of the sea level variance everywhere except in two regions, where it explains less than 20% of the variance: the Mediterranean basin and the eastern boundary of the North Atlantic northward of about 45°N. The dominance of the mass component in the Mediterranean Sea is consistent with the findings of previous studies [e.g., *Calafat et al.*, 2010]. Also it is well established that steric sea level variations dominates sea level in the deep ocean at long time-scales [*Cabanes et al.*, 2006; *Köhl and Stammer*, 2008a], in good agreement with the results shown in Figure 7. However, as described in a recent paper by *Bingham and Hughes* [2012], in the real ocean the steric component must vanish at the coast because so does depth, which is in contrast with the results shown in Figure 7. The fact that the steric component from GECCO does not vanish along the eastern boundary southward of 45°N suggests that the model poorly resolves the narrow shelf. Northward of 45°N, where the shelf becomes notably wider, the steric component from GECCO almost vanishes at the coast as it should, which indicates that, in this region, the shelf may be better resolved by the model. Also, the fact that GECCO performs well in reproducing the coastal sea level in spite of its poor resolution of the topography, suggests that topographic effects are not important.

[30] Figure 7 also provides information on the contribution of large-scale circulation changes. While the model has a poor resolution of the continental shelf in some regions, it should reproduce large-scale circulation changes and mass redistribution properly, which should be reflected in the mass component. The nearly negligible contribution of the mass component everywhere at the latitudes of the subtropical gyre indicates that changes in the strength/position of the subtropical gyre play no role during the studied period. Note that although the mass component dominates in

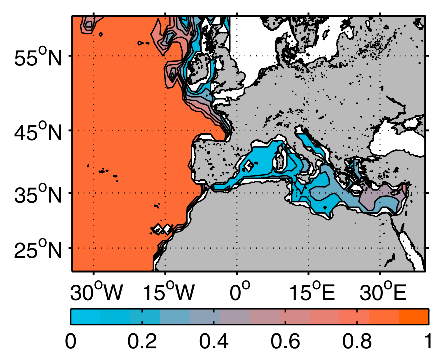

Figure 7. Map showing the fraction of variance of the total sea level from GECCO explained by the steric component of sea level. All time series have been detrended and smoothed using a 4-years running mean prior to the computation of the explained variance.

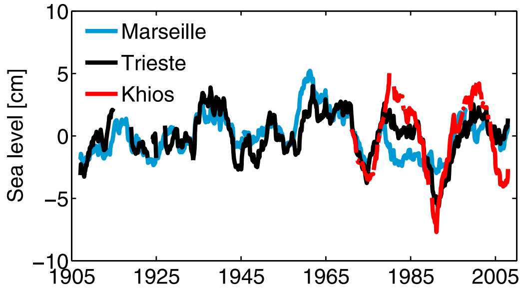

Figure 8. Comparison of the smoothed (4-year running mean) sea level from the tide gauge records at Trieste (black line), Marseille (blue line), and Khios (red line). All time series have been detrended.

the Mediterranean, we do not expect it to be related to changes in the large-scale ocean circulation either since, if it were, then this signal would also be seen in the nearby Atlantic, which is not the case. It is also worth noting that the coastal mass signal shown by GECCO northward of 45°N is in fact a baroclinic signal transformed into a mass signal to maintain the required dynamical constraint [*Bingham and Hughes*, 2012], and hence it is unrelated to large-scale ocean circulation changes.

[31] To confirm that mass redistributions linked to changes in the strength of the subtropical gyre play only a minor role, we have compared changes in the strength of the subtropical gyre from GECCO with sea level at the eastern boundary and in the Mediterranean Sea. The transport in the subtropical gyre can be represented by its barotropic streamfunction, ψ,

$$\psi(x, y, t) = \int_{-H}^{0} \int_{x_e}^{x} v(x', y, z, t) dx' dz \qquad (6)$$

where v is the meridional velocity from GECCO. A measure of the strength of the subtropical gyre is then given by the value of the streamfunction, ψ, just at the center of the gyre. We find no significant correlation between sea level and the strength of the subtropical gyre, neither at the eastern boundary nor in the Mediterranean Sea. This result provides further evidence that the contribution of mass redistribution linked to changes in the strength of the subtropical gyre, if any, is small. The forcing mechanism of the sea level variability along the eastern boundary as well as the nature of the mass changes shown by GECCO in the Mediterranean Sea are investigated in the next sections.

4.4.2. The Mediterranean Sea

[32] The significant correlation between the tide gauge records of the eastern North Atlantic and those of the Mediterranean Sea together with the fact that the mass component dominates in the Mediterranean Sea suggests that the correlation is achieved via a water mass exchange between the Atlantic and the Mediterranean basin. In other words, the sea level coherent signal, which extends several thousands of kilometers along the eastern boundary of the North Atlantic, gets into the Mediterranean as a mass signal through the Strait of Gibraltar. The result that the mass component is a major contributor to the Mediterranean sea level variability is not new. *Calafat et al.* [2010] have used satellite altimetry and tide gauge data in conjunction with hydrographic observations to quantify the contribution of the mass component to Mediterranean sea level variability. They have shown that this component dominates the sea level variability in the Mediterranean basin at annual and inter-annual scales, at least for the period 1948–2000. What is new here is that we provide evidence that a considerable fraction of the mass component entering the Mediterranean Sea through the Strait of Gibraltar seems to have its origin in a large-scale coherent sea level signal extending along the eastern North Atlantic coast from the Canary Islands up to the British Isles.

[33] If there is indeed a nearly uniform barotropic sea level fluctuation in the Mediterranean Sea at decadal time-scales, tide gauge records from stations in the Mediterranean Sea should show similar decadal variability regardless of their location within the basin. In previous sections we have shown that this is the case for Trieste (in the Adriatic Sea) and Marseille (in the western Mediterranean), at least for the period 1950–2009. In order to further demonstrate the presence of a basin-wide fluctuation at decadal time-scales we have extended the comparison between the tide gauge records at Marseille and Trieste to a much longer period (1905–2009), and we have added the tide gauge record at Khios (in the Aegean Sea) to the comparison (Figure 8). Unfortunately observations at Khios or at any other tide gauge record in the eastern Mediterranean (excluding the Adriatic Sea) begin no earlier than 1969, and hence the consistency of sea level at Khios can be demonstrated only after 1969. Examining Figure 8 shows that the agreement between Trieste and Marseille is very good and it exists for the whole period 1905–2009, which is reflected in the high correlation (0.70) between the two tide gauge records. We also note that the sea level variability in the eastern Mediterranean (i.e., at Khios) is also in good agreement with that in both the Adriatic and the western Mediterranean, at least from 1969 onwards. The lows in sea level in 1974 and the early 1900s as well as the two peaks in 1980 and 1990 are especially remarkable in Khios. It is worth noting that the amplitude of the variability is larger at Khios than at the other tide gauge stations. This could be related to the larger contribution of the steric component in the eastern Mediterranean (see Figure 7) and to its relationship with the NAO index. *Tsimplis and Rixen* [2002] found a strong negative correlation between the NAO index and temperature changes in the upper and intermediate waters of the Aegean Sea (where Khios is located) at decadal time-scales.

[34] Our hypothesis is that the mass changes in the Mediterranean and its correlation with sea level along the western European coast is due to water mass exchanges between the Atlantic and the Mediterranean. In order to explore this possibility, we have compared the sea level from GECCO and its mass component averaged over the whole Mediterranean basin with the sea level from GECCO at the Atlantic side of Gibraltar (Figure 9). The sea level at the Atlantic side of Gibraltar agrees much better with the mass component of the Mediterranean sea level than with the total sea level. The mass component deviates significantly from the curve of sea level at Gibraltar only at the beginning of the period and during the late 1980s and early 1990s. The large discrepancy shown by the total sea level between 1980 and 1990s is significantly reduced when considering the mass component. This suggests that the mass component (and the total sea

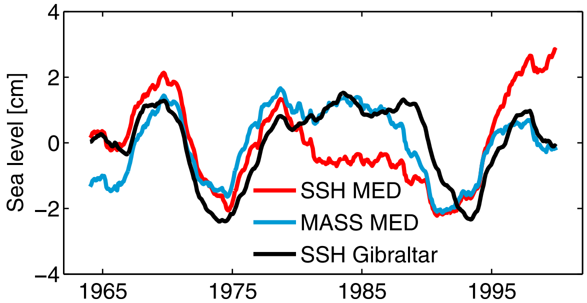

Figure 9. Comparison of the sea level and its mass component from GECCO averaged over the whole Mediterranean basin with the sea level from GECCO at the Atlantic side of the Strait of Gibraltar. All time series have been detrended and smoothed using a 4-years running mean.

level) in the Mediterranean Sea is mostly driven by sea level changes in the nearby Atlantic in the following way. Sea level changes in the Atlantic side lead to changes in the Atlantic inflow through Gibraltar until the along-strait slope is eventually restored to its equilibrium value. Hence if sea level in the nearby Atlantic rises (falls) then the Atlantic inflow will increase (decrease) and so will sea level in the Mediterranean Sea until equilibrium is restored. This is consistent with the results found by *Calafat et al.* [2012] who have shown that regional ocean models of the Mediterranean Sea that do not account for mass exchanges with the Atlantic do not properly reproduce sea level within the basin. At these time-scales any significant difference between the Mediterranean and the Atlantic is rapidly compensated by mass exchanges through Gibraltar. In this sense, sea level changes in the Mediterranean can be considered to follow quite closely those in the nearby Atlantic, which explains the observed correlation between tide gauge records in both regions.

[35] Nevertheless some differences between the time series of the mass component in the Mediterranean basin and the sea level at Gibraltar are still noticeable. Such differences are partly explained by the fact that the mass component in the Mediterranean Sea is not only affected by sea level changes in the nearby Atlantic but also by the effect of the local winds around Gibraltar that induce piling-up of water at the Strait and can lead to barotropic sea level changes affecting the whole basin [*Fukumori et al.*, 2007; *Menemenlis et al.*, 2007]. This contribution has been investigated in section 4.3 and it has been estimated to account for about 15% of the variance of the sea level in the Mediterranean Sea at decadal time-scales. At higher frequencies (i.e., annual) the contribution of this wind-driven fluctuation can increase significantly and explain up to 50% of the variance of the sea level in the Mediterranean basin [*Fukumori et al.*, 2007]. Another possible effect of the local winds at Gibraltar is to induce an Atlantic and Mediterranean sea level difference [*Menemenlis et al.*, 2007]. Therefore local winds around Gibraltar may prevent or reduce the influence of sea level changes in the Atlantic on the Mediterranean sea level. Finally, changes in the E-P-R (evaporation - precipitation-river runoff) budget over the Mediterranean basin could also contribute to the differences between the mass component in the Mediterranean basin and the sea level in the Atlantic side, although, due to the much larger area of the Atlantic Ocean, such changes should theoretically be rapidly compensated by changes in the Atlantic inflow through Gibraltar in order to restore equilibrium, hence having only a minor impact on the averaged Mediterranean sea level. This is consistent with the results of *Calafat et al.* [2010] who found that the annual cycle of the mass component in the Mediterranean Sea accounts for only a small fraction of the variance despite the fact that the E-P-R budget shows a large seasonal cycle signal.

4.4.3. The Role of the Longshore Wind

[36] The analysis of the different components of sea level from GECCO (see section 4.4.1) has shown that the steric component dominates the sea level variability nearly everywhere at decadal time-scales. Steric sea level changes, which in the real ocean appear as mass changes at the coast, can be produced by changes in the surface heat fluxes and by water movements induced by changes in the wind stress. Returning to Figure 6 we can see that there is a long but relatively narrow band of high correlation following the coast. The fact that the band extends only a few hundred kilometers in to the ocean suggests that boundary effects are an important factor and that offshore processes have only little influence. A plausible driving mechanism that would lead to a response consistent with that shown in Figure 6 is longshore wind stress, as it produces a baroclinic response that affects mainly the coastal region and which can propagate large distances along the coast in the form of coastally trapped waves. This possibility will be examined here. However, before going on it is convenient to rule out other forcing mechanisms that could also contribute to the steric changes.

[37] The steric response to surface heat flux variations is expected to be uniform over relatively large areas and not confined to the coast, contrary to what GECCO shows. Hence we expect this contribution to play only a minor role. This is confirmed by plotting the correlation between the steric changes from GECCO and the thermosteric contribution induced by local surface heat forcing computed from equation (4) (Figure 10). The correlation is significant in most parts of the Mediterranean Sea and also in some regions of the North Atlantic, however it is rather small near or at the eastern boundary where density variations explain the majority of the sea level signal (see Figure 7). This suggests that the steric changes driving the decadal sea level variability at the eastern boundary of the North Atlantic are

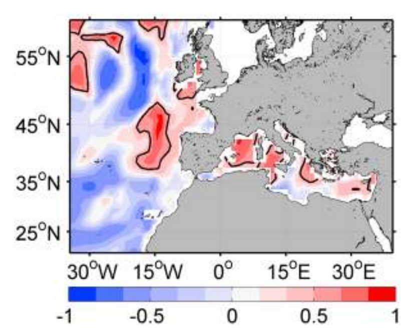

Figure 10. Map showing the correlation between the steric contribution due to local surface heat flux forcing and the total steric contribution from GECCO. All time series have been detrended and smoothed using a 4-years running mean prior to the computation of the correlation. The black line indicates the 95% confidence level.

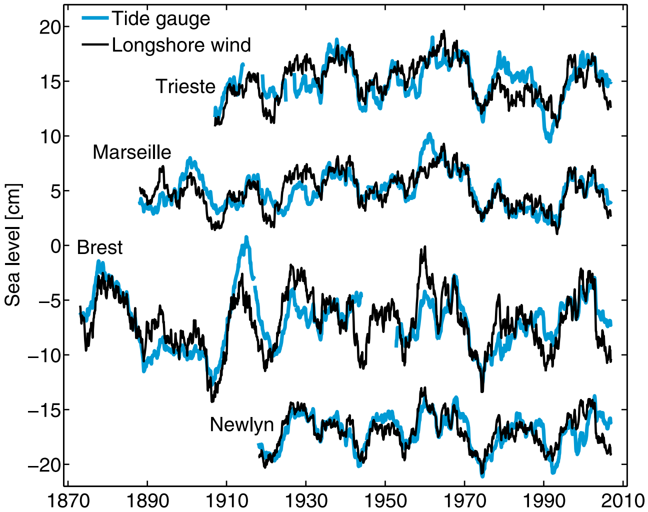

Figure 11. Comparison between the (scaled) integrated longshore wind and the sea level from the tide gauge records at Trieste, Marseille, Brest, and Newlyn. All time series have been detrended and smoothed using a 4-years running mean.

not due to local heat fluxes, but rather due to changes associated with wind stress. Finally, we also compared the variability of the surface heat fluxes (i.e., the time integral) with the sea level from all tide gauge records for the period 1950–2009, but found no significant correlation.

[38] In a stratified ocean, in addition to the barotropic response to local wind (quantified in section 4.3), there is also a baroclinic response of the same form, especially when the Ekman transport is away from the coast. In this case, the surface water that is moved offshore needs to be replaced by denser water from lower levels to maintain mass balance, which results in an upward movement of the thermocline and a decrease in the steric sea level. However, it should be pointed out that the response is not purely local because if the thermocline is raised at one latitude, that information is carried poleward by coastally trapped waves, and so steric sea level changes are also observed at all points poleward of the latitude of forcing [*Gill*, 1982]. *Gill and Clarke* [1974] showed that the low-frequency response can be expressed as a sum of modes (coastally trapped waves) with the amplitude of each mode, A, satisfying a first-order wave equation whose solution takes the form:

$$A(y,t) = \int_{y_0}^{y} B\tau^s\left(y', t - \frac{y-y'}{c}\right)dy' \tag{7}$$

where c denotes the speed at which internal waves propagate for the mode in question, τ^s is the wind stress parallel to the coast, y_0 is the latitude from which we begin the integration (i.e., the equator), and B is a coefficient that defines how much the mode in question is stimulated.

[39] The response of sea level to longshore wind is studied by computing the integral on the right-hand side of equation (7). The integration is carried out from the equator up to the latitude where the solution is wanted. Here, the coefficient B is set equal to one, which implies that we are obtaining an estimate of the variability of the response but not the right magnitude. Concerning the propagation speed, it is known that, theoretically, Kelvin waves (for the first baroclinic mode) travel at speeds between 1 m/s and 3m/s [*Gill and Clarke*, 1974]. Studies have shown that the speed of boundary Kelvin waves is sensitive to model resolution for models formulated on an Arakawa B-grid but not for those formulated on an Arakawa C-grid [*Hsieh et al.*, 1983]. Since the ECCO-MIT model is formulated on an Arakawa C-grid, we expect wave speeds close to those quoted above.

[40] Figure 11 shows a comparison between the integrated longshore wind and the sea level from tide gauge records at Trieste, Marseille, Brest, and Newlyn. For the comparison with the Mediterranean tide gauge records (i.e., Trieste and Marseille) the longshore wind has been computed integrating from the equator up to the Gibraltar Strait (36°N), while for the other two tide gauge records the integration has been carried out from the equator up to their respective locations. The comparison is conducted over the longest period for which wind and sea level data were available: 1905–2008 (Trieste), 1886–2008 (Marseille), 1871–2008 (Brest), and 1916–2008 (Newlyn). The agreement between the integrated longshore wind and the sea level is very good at all tide gauges, with correlations that range from 0.71 at Trieste to 0.74 at both Marseille and Newlyn. Examining Figure 11 shows that the correlation is high over the whole period and it does not deteriorate as we go backward in time. It is worth noting several other aspects of the variability. First, all tide gauge records show large decadal oscillations with amplitudes of up to 10 cm. Second, the variance exhibited by the tide gauge records remains approximately constant over the whole period. That is to say, the amplitude of the oscillations appears to be relatively constant over time. Third, we note that Mediterranean and Atlantic tide gauge records show similar variability, although there are certain years in which significant differences are observed. The reason is simply that sea level fluctuations continue to be forced by the wind while propagating northward from the Gibraltar Strait. Finally, from Figure 11 there is no apparent phase delay between longshore wind and sea level. We performed an analysis of the lead-lag relationship between longshore wind and sea level and found a phase delay of ∼1 month, with the wind leading, in agreement with the results from *Sturges and Douglas* [2011]. However, the difference in terms of correlation between the cases of using a delay of 1 month and no-delay is not statistically significant. It is also worth mentioning that, after correcting for the IB effect, the correlation between sea level and wind remains significant at all tide gauge records.

[41] As a complementary test, we have calculated the correlation between the integrated longshore wind and the sea level from the GECCO simulation at the eastern boundary of the North Atlantic for all coastal points between 20°N and 55°N (Figure 12). High correlation values of about 0.8 are found at all coastal points poleward of about 25°N. Southward of 25°N the correlation between longshore wind and coastal sea level becomes non-significant. These results confirm that, in agreement with observation, the large coastal band of high correlation shown by GECCO (see

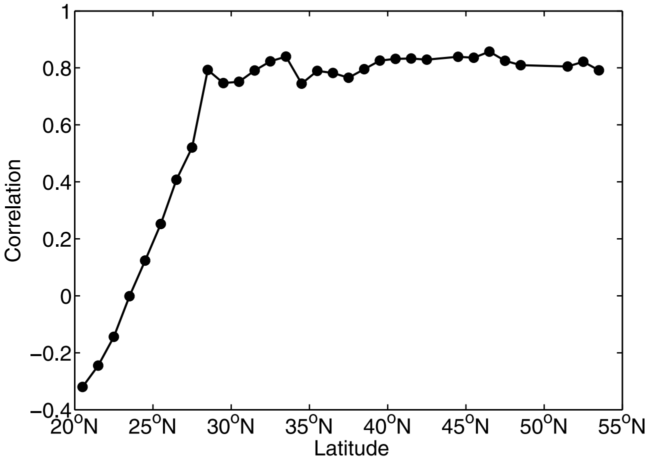

Figure 12. Correlation between the integrated longshore wind and coastal sea level from GECCO along the eastern boundary of the North Atlantic for all coastal points between 20°N and 55°N. All time series have been detrended and smoothed using a 4-years running mean prior to the computation of the correlation.

Figure 6) in the eastern North Atlantic is likely due to the response of the ocean to longshore wind.

4.4.4. Sea Level Changes Southward of 25°N

[42] Finally, in section 4.4.3 we have shown that, southward of ~25°N, the correlation of coastal sea level from GECCO with the longshore wind deteriorates rapidly as we move southward (see Figure 12). Unfortunately, in this region, there are no observations (i.e., tide gauges) to compare with and to validate this result. Here we assume that model results are a good approximation to reality and we investigate which mechanisms other than the longshore wind could contribute to the decadal sea level variability shown by GECCO.

[43] Since we found that the steric changes southward of 25°N are not due to changes in the local surface heat fluxes nor to longshore wind variations (section 4.4.3), we focus our attention on steric changes produced by water movements and heat transport induced by changes in wind stress. In particular we explore steric changes due to advection of heat through Ekman fluxes. Following *Marshall et al.* [2001], the advection of heat through Ekman transport is expressed as a pseudo air-sea heat flux:

$$H_{Ek} = C_p\left(-\vec{k} \times \frac{\vec{\tau}}{f}\right) \cdot \vec{\nabla} SST \qquad (8)$$

where $\vec{k}$ is a unit vector in the vertical, and SST is sea surface temperature.

[44] Figure 13 shows a map of the Ekman heat transport computed from equation (8) associated with periods of low sea level (defined as the years when negative sea level anomalies exceeds one standard deviation over the period 1962–2001) at the eastern boundary southward of 25°N. The dominant feature is the significant cooling induced by the Ekman fluxes at the coastal areas southward of 25°N, which can reach over 10 W/m^2. This magnitude can lead to variations in the steric sea level of several centimeters in a few years. In order to confirm a possible relationship between the

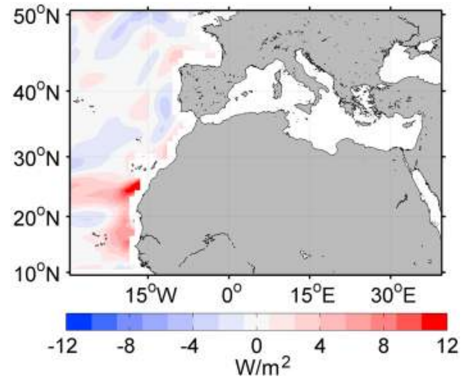

Figure 13. Pseudo air-sea Ekman heat flux associated with periods of low sea level at the eastern boundary southward of 25°N, computed from equation (8). Positive fluxes are directed out of the ocean.

advection of heat through Ekman fluxes and the coastal sea level changes at those latitudes, we have computed the correlation between the pseudo air-sea Ekman heat flux averaged over the coastal points between 10°N and 25°N and the sea level from GECCO at each grid point (Figure 14). We find correlations larger than 0.9 all over the eastern boundary of the North Atlantic between 10°N and 25°N. The influence of heat advection through Ekman transport on sea level has been previously demonstrated for other regions and timescales. *Köhl and Stammer* [2008a], for example, found that the horizontal advection of heat linked to WSC changes explains a major fraction of the regional sea level trends from GECCO for the period 1962–2001. Another interesting feature is the westward extension of the band of high correlations to the open ocean. An analysis using a simple Rossby-wave baroclinc model has shown that the band reflects the westward propagation of Rossby waves radiated from the eastern boundary and also forced by the interior WSC. This is consistent with the finding by *Sturges and Hong* [1995] and *Hong et al.* [2000], which showed that much of the sea level variability at Bermuda (i.e., interior of the ocean) and also at the western boundary of the North

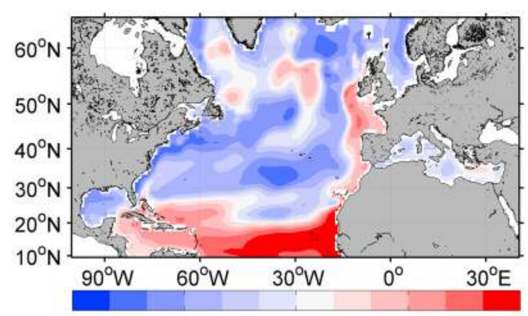

Figure 14. Map showing the correlation between the pseudo air-sea Ekman heat flux averaged over the coastal points between latitudes 10°N and 25°N and the sea level from GECCO at each grid point. All time series have been detrended and smoothed using a 4-years running mean prior to the computation of the correlation.

Atlantic could be explained by a Rossby-wave model forced by WSC.

5. Discussion and Conclusions

[45] In this paper we have found that tide gauge records along the western European coast and in the Mediterranean Sea exhibit significant decadal variability (up to 15 cm) and are highly correlated with the NAO and among themselves at decadal time-scales. All tide gauge records show three oscillations with amplitudes of up to 10 cm between 1950 and 2009, which are characterized by 3 marked dips in sea level in the 1950s, the 1970s and the early 1990s. Such oscillations appear to be related to large-scale atmospheric changes associated with changes in the NAO. The variability of the NAO at decadal time-scales is known to be linked, at least to a certain extent, to the coupling between the ocean and the atmosphere [*Marshall et al.*, 2001; *Bellucci et al.*, 2008; *Fan and Schneider*, 2012]. Such coupling is achieved first by the response of the ocean gyres and the thermohaline circulation to NAO forcing and later by their effect in modulating sea surface temperature anomalies. Because baroclinic modes respond only at low frequencies (related to the time required for Rossby waves to propagate across the basin), changes in the ocean gyres and in the thermohaline circulation tend to occur at much lower frequencies than those of the forcing. In consequence the coupled interaction between ocean dynamics and the NAO becomes especially important at decadal time-scales, which explains the large variability shown by the NAO index at these time-scales. Changes in the wind stress, air-sea heat fluxes, Ekman transport and ocean circulation related to NAO variations are all potential contributors to the observed sea level variability. In this study we have explored the contribution of each forcing mechanism to the decadal sea level variability at the eastern boundary of the North Atlantic and in the Mediterranean Sea.

[46] We have found that while the IB effect shows significant correlation with the sea level at the eastern boundary and in the Mediterranean, it explains only a small fraction of the decadal sea level variance (between 14% and 27%). This is consistent with the results of previous related studies, which also found that the observed sea level variability was too large by a factor of over 3 to be explained directly by the IB effect [*Miller and Douglas*, 2007; *Woodworth et al.*, 2010; *Sturges and Douglas*, 2011]. The barotropic response to local wind forcing has been investigated by means of a regional barotropic model. Results show that this contribution likewise plays only a minor role in explaining the observed sea level variability (it explains only between 0% and 15%).

[47] The baroclinic response to atmospheric forcing has been explored using wind stress and surface heat flux data in conjunction with the outputs of a baroclinic model. Our analysis confirms that there is a large-scale coherent sea level signal along the eastern boundary of the North Atlantic and in the Mediterranean Sea. In the baroclinic model, the region affected by this signal extends only a few hundred kilometers beyond the shelf edge and tends to become narrower towards higher latitudes, which suggests that coastal sea level is hardly representative of the open ocean at these time-scales. We have found that much of the coastal sea level variability is consistent with variability in the longshore wind forcing. The important role played by the longshore wind is reflected in its high correlation (0.74) with the sea level from the tide gauge records at Brest and Newlyn for the periods 1871–2008, and 1916–2008, respectively. It is important to emphasize that maximum correlations are found only when taking into account the cumulative effect of the longshore wind along the eastern boundary. This suggests that sea level variability is, at least partly, the result of the poleward propagation of sea level fluctuations along the eastern boundary as coastally trapped waves. Hence, we conclude that the correlation between sea level and the NAO is, to a large extent, due to the correlation between changes in wind stress and changes in pressure. Our results are consistent with those found by *Sturges and Douglas* [2011], which showed significant correlation between the integrated longshore wind and the tide gauge record at Cascais (Portugal). Results from the GECCO model confirms that sea level is highly correlated with the longshore wind at all point along the eastern boundary from 25°N to 55°N.

[48] There is no evidence in our results for a significant contribution from mass redistribution linked to changes in the strength of the subtropical gyre. This result seems to be in contrast with the conclusions made by *Miller and Douglas* [2007] and *Woodworth et al.* [2010], who found significant correlation between sea level pressure at the center of the subtropical gyre and sea level at the eastern boundary of the North Atlantic from Cascais (39°N) to Brest (48°N), and which they attributed to large-scale ocean circulation changes. Our analysis suggests that the correlation between sea level pressure in Azores and coastal sea level reflects the correlation between changes in wind stress and changes in pressure.

[49] Our results suggest that the correlation between sea level in the Mediterranean Sea and that at the eastern North Atlantic is achieved by means of mass exchanges between the Atlantic and the Mediterranean basin through the Strait of Gibraltar. The GECCO model shows that the mass component dominates the sea level variability in the Mediterranean Sea, which is in agreement with previous findings [*Calafat et al.*, 2010]. Hence we conclude that it is the mass component, and not the steric, that is correlated with the sea level at the eastern North Atlantic. At these long time-scales, whenever the sea level at the Atlantic side of Gibraltar changes, that information is transferred to the Mediterranean Sea as a barotropic signal through Gibraltar, which adjusts uniformly across the entire basin. The presence of a basin-wide coherent signal in the Mediterranean Sea is confirmed by the high correlation between the tide gauge records at different locations of the Mediterranean Sea. For instance, the correlation between Trieste (in the Adriatic) and Marseille (in the western Mediterranean) is 0.70 for the period 1905–2009, and 0.79 between Trieste and Khios (in the Aegean Sea) for the period 1969–2009. The correlation between different regions of the Mediterranean Sea and between the Mediterranean and the Atlantic has also been demonstrated for higher frequencies in previous studies [*Tsimplis and Shaw*, 2008]. Both tide gauge records (i.e., Trieste and Marseille) show a high correlation (>0.70) with the longshore wind integrated from the equator to the Strait of Gibraltar, which explains their correlation with sea level at the eastern North Atlantic and suggests that part of the sea

level signal traveling poleward along the eastern boundary gets into the Mediterranean through the Gibraltar Strait.

[50] Finally, it is useful to summarize the main results of this study.

[51] 1. There is significant decadal sea level variability (up to 15 cm) in the tide gauge records in the western European coast and in the Mediterranean that is highly correlated. The correlation between sea level and the NAO index is also high at all tide gauges, ranging from 0.65 to 0.89. The GECCO model shows that this coherent sea level signal extends thousands of kilometers along the eastern boundary from 25°N to 55°N but only a few hundred kilometers beyond the shelf edge.

[52] 2. The decadal sea level variability is too large by a factor of 3–4 to be explained directly by the IB effect, both in the eastern North Atlantic and in the Mediterranean Sea. The contribution of the barotropic response to local wind forcing is even smaller.

[53] 3. The influence of diabatic steric changes (i.e., due to surface heat fluxes) appears to play only a minor role at all tide gauges at decadal time-scales.

[54] 4. The longshore wind seems to be the major forcing mechanism. The correlation between the longshore wind and the sea level is higher than 0.7 at all tide gauges. This relationship has been demonstrated for periods beginning at the end of the 19th century. Results from GECCO confirm this relationship for all point along the eastern boundary from 25°N to 55°N.

[55] 5. There is no evidence for a significant contribution from large-scale mass redistributions due to changes in the strength of the subtropical gyre.

[56] In conclusion, coastal sea level variations are found to be consistent with large-scale atmospheric variations at decadal time-scales, which causes high correlation along most of the eastern boundary and the Mediterranean Sea. Because this coherent coastal sea level signal extends only a few hundred kilometers beyond the continental shelf, especially at higher latitudes, it is not reflective of open ocean sea level variability. Moreover, *Bingham and Hughes* [2012] have shown that the decoupling between deep ocean and coastal sea level is even more severe for western boundaries. This clearly suggests that reconstructing global mean sea level time series from tide gauge records alone or in combination with altimetry may not provide a reliable measure of the true decadal-scale variability in global mean sea level.

[57] **Acknowledgments.** F. M. Calafat was supported under a Marie Curie International Outgoing Fellowship (IOF) within the 7th European Community Framework Programme (grant agreement PIOF-GA-2010-275851). D. P. Chambers was supported under a grant from the NASA Interdisciplinary Science Sponsored Research program. This research would not have been possible without the tide gauge records from the Permanent Service for Mean Sea Level, housed at the National Oceanography Centre, Liverpool, UK. The authors wish to thank three anonymous reviewers for their comments on an earlier draft of this paper which helped improve it.

References

Allan, R. J., and T. J. Ansell (2006), A new globally complete monthly historical mean sea level pressure data set (HadSLP2): 1850–2004, *J. Clim.*, *19*, 5816–5842, doi:10.1175/JCLI3937.1.

Barnston, A. G., and R. E. Livezey (1987), Classification, seasonality and persistence of low frequency atmospheric circulation patterns, *Mon. Weather Rev.*, *115*, 1083–1126, doi:10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2.

Bellucci, A., S. Gualdi, E. Scoccimarro, and A. Navarra (2008), NAO–ocean circulation interactions in a coupled general circulation model, *Clim. Dyn.*, *31*, 759–777, doi:10.1007/s00382-008-0408-4.

Bingham, R. J., and C. W. Hughes (2012), Local diagnostics to estimate density-induced sea level variations over topography and along coastlines, *J. Geophys. Res.*, *117*, C01013, doi:10.1029/2011JC007276.

Bromirski, P. D., A. J. Miller, R. E. Flick, and G. Auad (2011), Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration, *J. Geophys. Res.*, *116*, C07005, doi:10.1029/2010JC006759.

Cabanes, C., T. Huck, and A. C. de Verdière (2006), Contributions of wind forcing and surface heating to interannual sea level variations in the Atlantic Ocean, *J. Phys. Oceanogr.*, *36*(9), 1739–1750, doi:10.1175/JPO2935.1.

Calafat, F. M., M. Marcos, and D. Gomis (2010), Mass contribution to the Mediterranean Sea level variability for the period 1948–2000, *Global Planet. Change*, *73*, 193–201, doi:10.1016/j.gloplacha.2010.06.002.

Calafat, F. M., G. Jordà, M. Marcos, and D. Gomis (2012), Comparison of Mediterranean sea level variability as given by three baroclinic models, *J. Geophys. Res.*, *117*, C02009, doi:10.1029/2011JC007277.

Chelton, D., and R. Davis (1982), Monthly mean sea level along the west coast of North America, *J. Phys. Oceanogr.*, *12*, 757–784, doi:10.1175/1520-0485(1982)012<0757:MMSLVA>2.0.CO;2.

Church, J. A., and N. J. White (2011), Sea-level rise from the late 19th to the early 21st Century, *Surv. Geophys.*, *32*, 585–602, doi:10.1007/s10712-011-9119-1.

Clarke, A. J., and A. Lebedev (1999), Remotely driven decadal and longer changes in the coastal Pacific waters of the Americas, *J. Phys. Oceanogr.*, *29*, 828–835, doi:10.1175/1520-0485(1999)029<0828:RDDALC>2.0.CO;2.

Compo, G. P., et al. (2011), The Twentieth Century Reanalysis Project, *Q. J. R. Meteorol. Soc.*, *137*, 1–28, doi:10.1002/qj.776.

Douglas, B. C. (1992), Global sea level acceleration, *J. Geophys. Res.*, *97*(C8), 12,699–12,706, doi:10.1029/92JC01133.

Emery, W. J., and R. E. Thomson (1998), *Data Analysis Methods in Physical Oceanography*, 634 pp., Pergamon, Oxford, UK.

Enfield, D. B., and J. S. Allen (1980), On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America, *J. Phys. Oceanogr.*, *10*, 557–578, doi:10.1175/1520-0485(1980)010<0557:OTSADO>2.0.CO;2.

Fan, M., and E. K. Schneider (2012), Observed decadal North Atlantic tripole SST variability. Part I: Weather noise forcing and coupled response, *J. Atmos. Sci.*, *69*, 35–50, doi:10.1175/JAS-D-11-018.1.

Fukumori, I., D. Menemenlis, and T. Lee (2007), A near-uniform basin-wide sea level fluctuation of the Mediterranean Sea, *J. Phys. Oceanogr.*, *37*, 338–358, doi:10.1175/JPO3016.1.

Gill, A. E. (1982), *Atmosphere-ocean Dynamics*, 662 pp., Academic, San Diego, Calif.

Gill, A. E., and A. Clarke (1974), Wind-induced upwelling, coastal currents and sea-level changes, *Deep Sea Res. Oceanogr. Abstr.*, *21*, 325–345.

Holgate, S. J. (2007), On the decadal rates of sea level change during the twentieth century, *Geophys. Res. Lett.*, *34*, L01602, doi:10.1029/2006GL028492.

Hong, B. G., W. Sturges, and A. J. Clarke (2000), Sea level on the U.S. east coast: Decadal variability caused by open ocean wind-curl forcing, *J. Phys. Oceanogr.*, *30*, 2088–2098, doi:10.1175/1520-0485(2000)030<2088:SLOTUS>2.0.CO;2.

Hsieh, W. W., M. K. Davey, and R. C. Wajsowicz (1983), The free Kelvin wave in finite-difference numerical models, *J. Phys. Oceanogr.*, *13*, 1383–1397, doi:10.1175/1520-0485(1983)013<1383:TFKWIF>2.0.CO;2.

Hughes, C. W., and P. M. Meredith (2006), Coherent sea-level fluctuations along the global continental slope, *Philos. Trans. R. Soc. A*, *364*, 885–901, doi:10.1098/rsta.2006.1744.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (2003), An overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser*, vol. 134, edited by J. W. Hurrell et al., pp. 1–35, AGU, Washington, D. C., doi:10.1029/134GM01

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

Jordà, G., D. Gomis, and E. Álvarez-Fanjul (2012), The VANI2-ERA hindcast of sea level residuals: Atmospheric forcing of sea level variability in the Mediterranean Sea (1958–2008), *Sci. Mar.*, *76*, 133–146.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*(3), 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Köhl, A., and D. Stammer (2008a), Decadal sea level changes in the 50-year GECCO ocean synthesis, *J. Clim.*, *21*, 1876–1890, doi:10.1175/2007JCLI2081.1.

Köhl, A., and D. Stammer (2008b), Variability of the meridional overturning in the North Atlantic from the 50-year GECCO state estimation, *J. Phys. Oceanogr.*, *38*, 1913–1930, doi:10.1175/2008JPO3775.1.

Köhl, A., D. Stammer, and B. Cornuelle (2007), Interannual to decadal changes in the ECCO global WOCE synthesis, *J. Phys. Oceanogr.*, *37*, 313–337, doi:10.1175/JPO3014.1.

Levitus, S. (1982), *Climatological Atlas of the World Ocean*, *NOAA/ERL GFDL Prof. Pap. 13*, 173 pp., Geophys. Fluid Dyn. Lab., Princeton, N. J.

Marshall, J., H. Johnson, and J. Goodman (2001), A study of the interaction of the North Atlantic Oscillation with the ocean circulation, *J. Clim.*, *14*, 1399–1421, doi:10.1175/1520-0442(2001)014<1399:ASOTIO>2.0.CO;2.

Menemenlis, D., I. Fukumori, and T. Lee (2007), Atlantic to Mediterranean sea level difference driven by winds near Gibraltar Strait, *J. Phys. Oceanogr.*, *37*, 359–376, doi:10.1175/JPO3015.1.

Merrifield, M. A. (2011), A shift in western tropical Pacific sea-level trends during the 1990s, *J. Clim.*, *24*, 4126–4138, doi:10.1175/2011JCLI3932.1.

Merrifield, M. A., and M. E. Maltrud (2011), Regional sea level trends due to a Pacific trade wind intensification, *Geophys. Res. Lett.*, *38*, L21605, doi:10.1029/2011GL049576.

Miller, L., and B. C. Douglas (2007), Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise, *Geophys. Res. Lett.*, *34*, L16602, doi:10.1029/2007GL030862.

Prandi, P., A. Cazenave, and M. Becker (2009), Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007, *Geophys. Res. Lett.*, *36*, L05602, doi:10.1029/2008GL036564.

Ratsimandresy, A. W., M. G. Sotillo, J. C. Carretero, E. Álvarez-Fanjul, B. Pérez Gómez, and H. Hajji (2008), A 44-year (1958–2001) sea level residual hindcast over the Mediterranean Basin, *Phys. Chem. Earth*, *33*, 250–259, doi:10.1016/j.pce.2007.02.002.

Sturges, W., and B. C. Douglas (2011), Wind effects on estimates of sea level rise, *J. Geophys. Res.*, *116*, C06008, doi:10.1029/2010JC006492.

Sturges, W., and B. G. Hong (1995), Wind forcing of the Atlantic thermocline along 32°N at low frequencies, *J. Phys. Oceanogr.*, *25*, 1706–1715, doi:10.1175/1520-0485(1995)025<1706:WFOTAT>2.0.CO;2.

Tsimplis, M. N., and S. A. Josey (2001), Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic, *Geophys. Res. Lett.*, *28*(5), 803–806, doi:10.1029/2000GL012098.

Tsimplis, M. N., and M. Rixen (2002), Sea level in the Mediterranean Sea: The contribution of temperature and salinity changes, *Geophys. Res. Lett.*, *29*(23), 2136, doi:10.1029/2002GL015870.

Tsimplis, M. N., and A. G. P. Shaw (2008), The forcing of mean sea level variability around Europe, *Global Planet. Change*, *63*, 196–202, doi:10.1016/j.gloplacha.2007.08.018.

Tsimplis, M. N., et al. (2005), Towards a vulnerability assessment of the UK and northern European coasts: The role of regional climate variability, *Philos. Trans. R. Soc. A*, *363*, 1329–1358, doi:10.1098/rsta.2005.1571.

Tsimplis, M. N., A. G. P. Shaw, R. A. Flather, and D. K. Woolf (2006), The influence of the North Atlantic Oscillation on the sea level around the northern European coasts reconsidered: The thermosteric effects, *Philos. Trans. R. Soc. A*, *364*(1841), 845–856, doi:10.1098/rsta.2006.1740.

Tsimplis, M. N., M. Marcos, S. Somot, and B. Barnier (2008), Sea level forcing in the Mediterranean Sea between 1960 and 2000, *Global Planet. Change*, *63*(4), 325–332, doi:10.1016/j.gloplacha.2008.07.004.

Vivier, F., K. A. Kelly, and L. Thompson (1999), Contributions of wind forcing, waves, and surface heating to sea surface height observations in the Pacific Ocean, *J. Geophys. Res.*, *104*(C9), 20,767–20,788, doi:10.1029/1999JC900096.

Wakelin, S. L., P. L. Woodworth, R. A. Flather, and J. A. Williams (2003), Sea-level dependence on the NAO over the NW European continental shelf, *Geophys. Res. Lett.*, *30*(7), 1403, doi:10.1029/2003GL017041.

Woodworth, P. L. (1990), A search for accelerations in records of European mean sea level, *Int. J. Climatol.*, *10*, 129–143, doi:10.1002/joc.3370100203.

Woodworth, P. L., and R. Player (2003), The Permanent Service for Mean Sea Level: An update to the 21st century, *J. Coastal Res.*, *19*, 287–295.

Woodworth, P. L., N. J. White, S. Jevrejeva, S. J. Holgate, J. A. Church, and W. R. Gehrels (2009), Evidence for the accelerations of sea level on multi-decade and century timescales, *Int. J. Climatol.*, *29*, 777–789, doi:10.1002/joc.1771.

Woodworth, P. L., N. Pouvreau, and G. Wöppelmann (2010), The gyre-scale circulation of the North Atlantic and sea level at Brest, *Ocean Sci.*, *6*, 185–190, doi:10.5194/os-6-185-2010.

Woolf, D., A. G. P. Shaw, and M. N. Tsimplis (2003), The influence of the North Atlantic Oscillation on sea level variability in the North Atlantic Region, *Global Atmos. Ocean Syst.*, *9*(4), 145–167, doi:10.1080/10236730310001633803.

Yan, Z., M. N. Tsimplis, and D. Woolf (2004), An analysis of relationship between the North Atlantic Oscillation and sea level changes in NW Europe, *Int. J. Climatol.*, *24*, 743–758, doi:10.1002/joc.1035.