# The Anatomy of the Large Sea Level Fluctuations in the Mediterranean Sea in 2010 & 2011

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## Summary - Take Home Points

- Two large sea level anomalies of ~10 cm above the mean climatological values were observed in the Mediterranean Sea in the winters of 2009/2010 and 2010/2011.
- The anomalies were observed in sea surface height (***from Altimetry***), as well as ocean mass (***from GRACE***).
- The sea level anomalies were of barotropic nature, driven by wind.
- Basin-wide sea level anomalies in the Mediterranean correlate highly with ***wind stress anomalies on the Atlantic side, just west of Gibraltar strait***.
- Net precipitation & river discharge anomalies over and into the Mediterranean played a secondary role.
- The sea level high-stands coincided with extreme negative values of NAO index.

## 1. Overview

During the winters of 2010 and 2011, unusually large sea level changes occurred in the Mediterranean Sea. The basin-wide sea level anomalies reached amplitudes of ~10 cm, and were observed in sea surface height as well as in ocean bottom pressure. Using these observations from altimetry and GRACE, we examine and evaluate the mechanisms that led to the concurrent - apparently quasi-barotropic - sea level extremes. We find significant correlation between the sea level extremes and zonal and meridional wind stress anomalies on the western side of Gibraltar strait. In addition, we find small positive anomalies of net precipitation over the river basins that drain into the Mediterranean, as well as a small positive net precipitation anomaly over the Mediterranean Sea itself. During the winter months of 2009/2010 and 2010/2011, the North Atlantic Oscillation (NAO) was in an extreme negative phase. The overall atmospheric state led to the large sea level increase, with wind being the dominant driver, and net precipitation playing a minor role. This work will ultimately result in a better quantification of the factors and mechanisms driving Mediterranean Sea Level changes on non-seasonal time scales, using satellite and in-situ observations.

## 2. Sea Level observations from *Altimetry* and *GRACE*

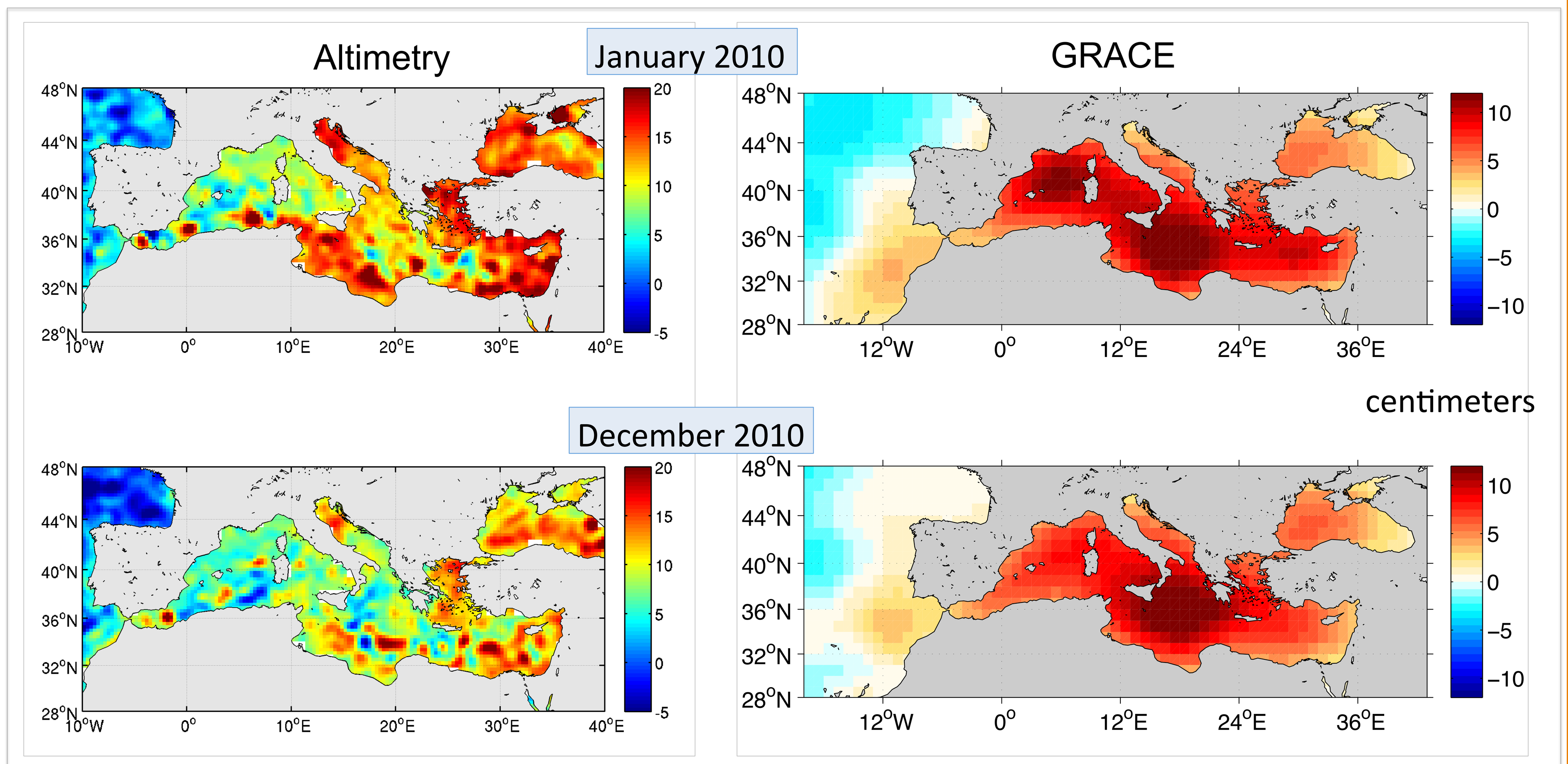


**Fig. 1:** The Sea level anomalies from altimetry (left) and GRACE (right) over the Mediterranean Sea and Black Sea from in January and December to 2010 show distinctly different patterns. Satellite altimetry can resolve SSH-features at much fine scale than GRACE. The focus of our analysis is thus on basin-mean variations.

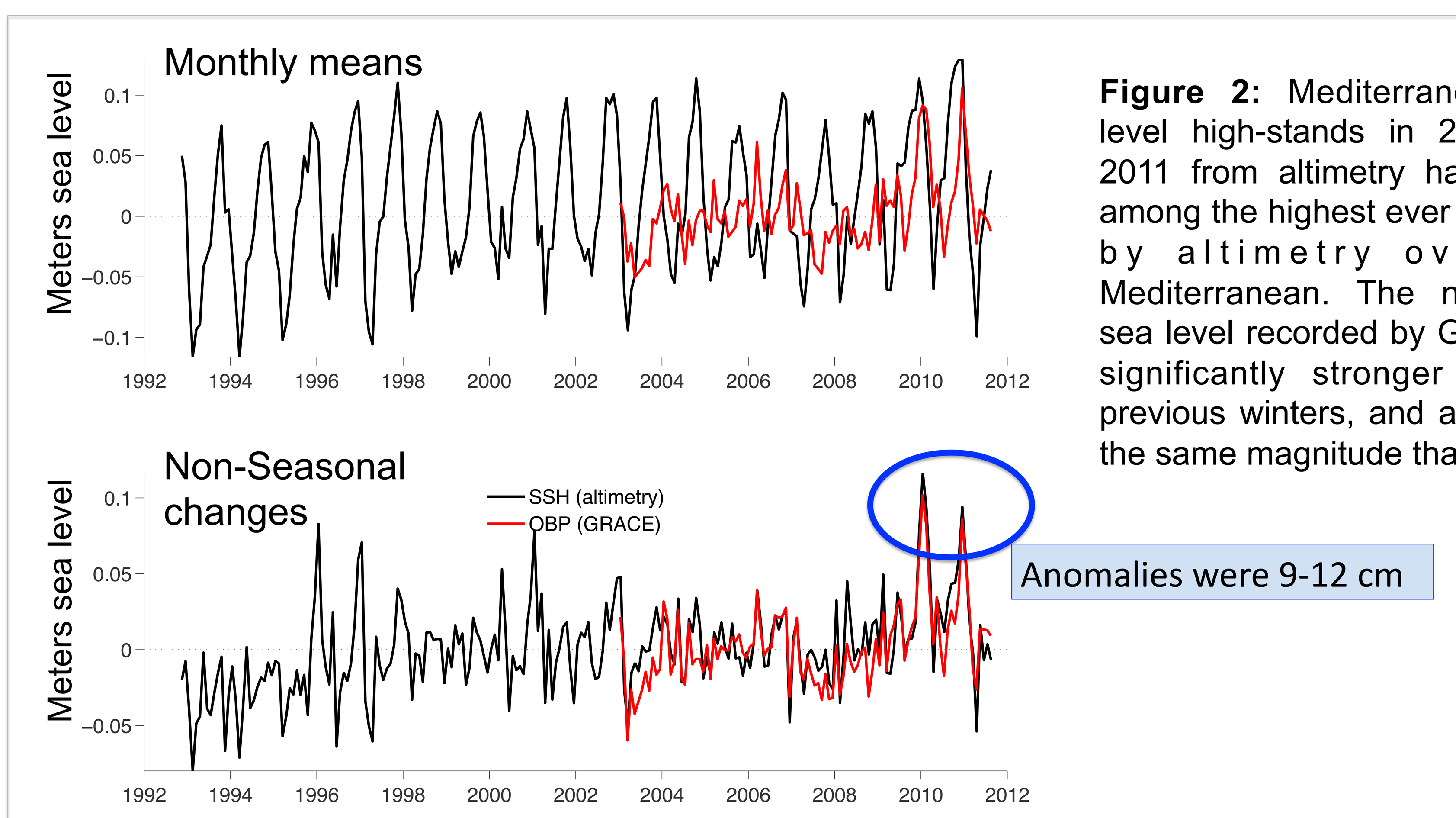


**Figure 2:** Mediterranean sea level high-stands in 2010 and 2011 from altimetry have been among the highest ever recorded by altimetry over the Mediterranean. The non-steric sea level recorded by GRACE is significantly stronger than in previous winters, and at least of the same magnitude than SSH.

## 3. The Role of Wind Stress on Mediterranean Sea Level – Coupled EOF Analysis with Ocean Bottom Pressure and Sea level

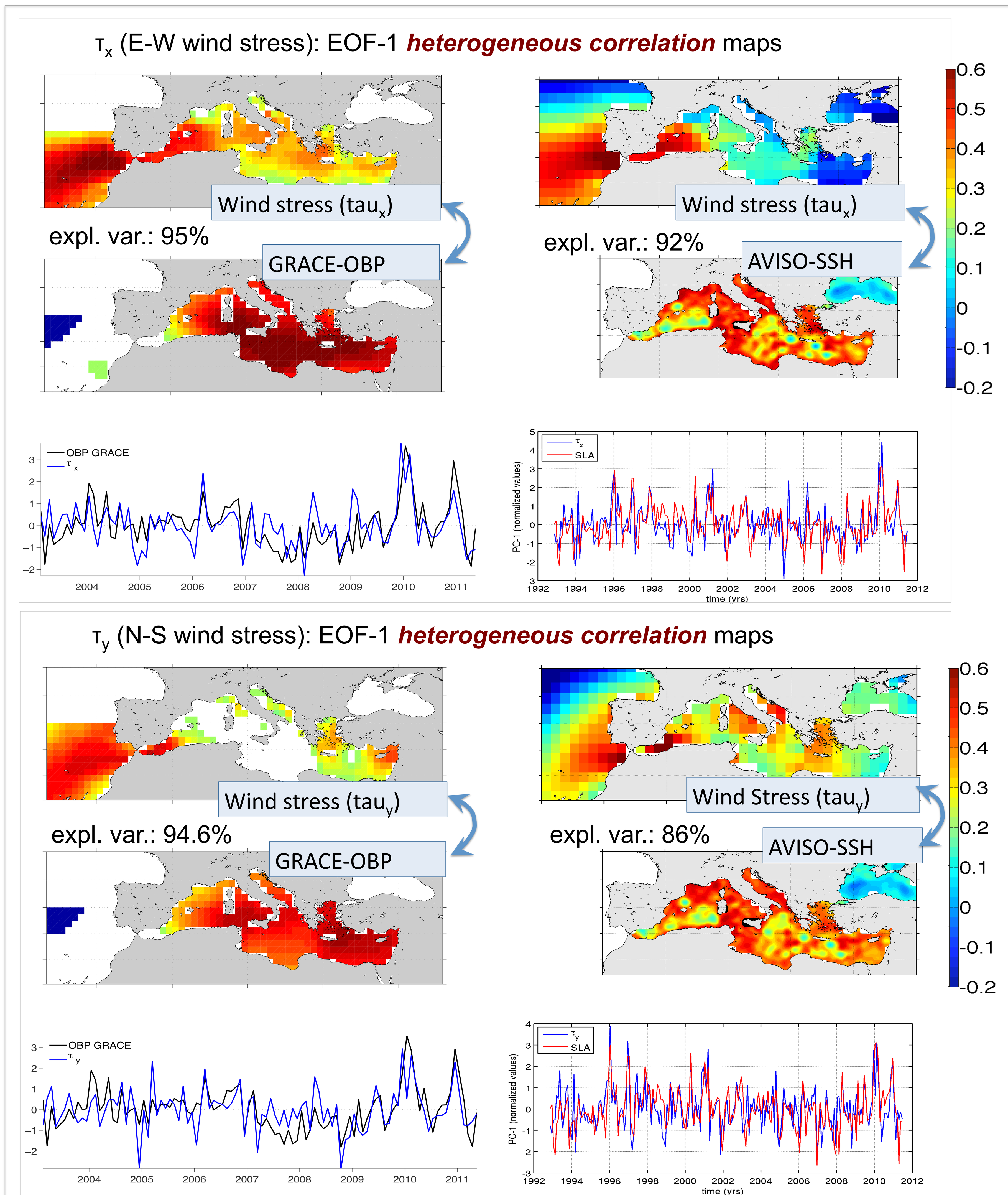


**Figure 4:** The coupled EOF-Analysis of the non-seasonal surface wind stress components $\tau_x$ (left), and $\tau_y$ (right) with the bottom pressure field from GRACE and the SSH field from altimetry reveals that for both $\tau_x$ and $\tau_y$, the most contribution is from outside and to the West and South-West of Gibraltar Strait, largely consistent with model results (e.g., Fukumori et al. 2007). The principal components of the wind stress reveal that the two OBP anomalies 2010 and 2011, which are nearly equal in amplitude, may have been forced by varying contributions from the wind stress vector components.
Note that the sea surface height and OBP have been corrected for the inverted barometer effect; however, since IB and wind stress are correlated, the residual sea level anomalies are still correlated with IB, but this *does not* constitute a deviation from an IB-response.

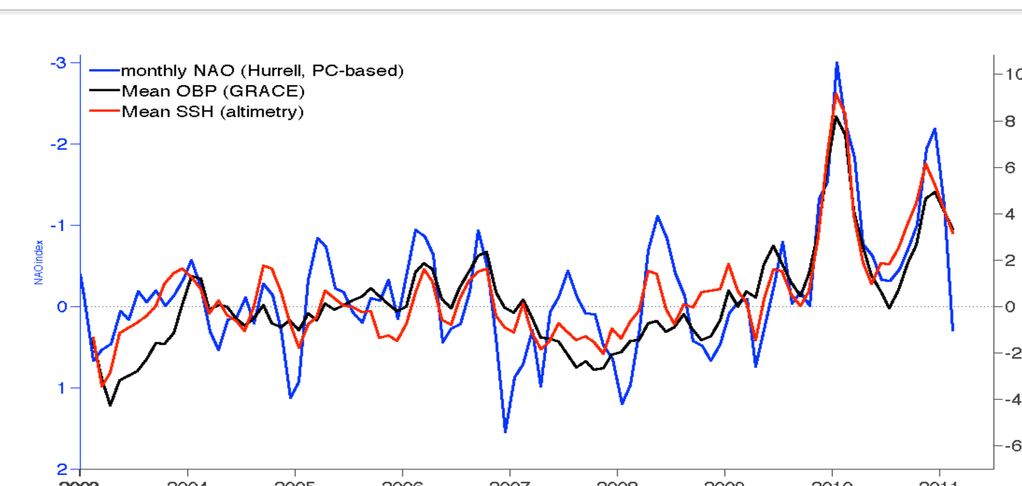


**Figure 6:** The non-steric (or barotropic) Mediterranean Sea level (from GRACE), is closely correlated with the NAO index (R=0.64). Similarly, SSH is correlated at 0.68, indicating that the SSH anomalies are largely wind driven, and that steric processes play only a minor role. Precipitation over the Mediterranean and surrounding regions tends to be anti-correlated with the NAO, such that a low NAO is typically accompanied by higher than average net precipitation over the Mediterranean and its the drainage regions. Our analysis of net precipitation and land water storage changes (not shown here) indicates a positive, albeit small contribution to the 2009/2010 and 2010/2011 sea level anomalies.

Acknowledgements

- Sea Surface Height: altimetry observations, processed by SSALTO/DUACS, distributed by AVISO with support from CNES.
- Non-steric Sea Level: based on time-variable gravity observations from GRACE, provided by CSR.
- Monthly wind-stress: ERA-Interim Re-analysis provided by the European Centre for Medium Range Weather Forecast (ECMWF).
- This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration (NASA).

Data Sets & Methods

- Sea Surface Height: altimetry observations, processed by SSALTO/DUACS, distributed by AVISO with support from CNES;
- Ocean Bottom Pressure: derived from time-variable gravity observations from GRACE (CSR-RL04); we apply a de-striping filter, and a Gaussian filter of 300 km for the spatial maps;
- Monthly wind-stress: ERA-Interim Re-analysis provided by the European Centre for Medium Range Weather Forecast (ECMWF);