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Deliverable information	
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Deliverable title	Mediterranean sea-level reconstruction spanning 1960-2018
Description	We have used spatiotemporal Bayesian methods to produce statistically rigorous estimates of sea-level trends in the Mediterranean Sea since 1960 by combining tide gauge and satellite altimetry data. Furthermore, we have also quantified the contributions from sterodynamic sea-level change, land-mass changes and glacial isostatic adjustment to the trends.
Work Package number	5
Work Package title	Coastal Resilience and Operational Services Demonstrator
Lead beneficiary	National Oceanography Centre (NOC)
Lead authors	Francisco Mir Calafat
Contributors	Thomas Frederikse (JPL, NASA), Kevin Horsburgh (NOC), Nadim Dayoub (NOC)
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Comments	

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Executive summary

Sea-level change is geographically non-uniform, with regional departures that can reach several times the global average rate of change. Characterizing this spatial variability and understanding its causes is crucial to the design of adaptation strategies for sea-level rise. This, as it turns out, is no easy feat, primarily due to the sparseness of the observational sea-level record in time and space. Long tide gauge records are restricted to a few locations along the coast. Satellite altimetry offers a better spatial coverage but only since 1992. In the Mediterranean Sea, the tide gauge network is heavily biased towards the European shorelines, with only one record with at least 35 years of data on the African coasts. Past studies have attempted to address the difficulties related to this data sparseness in the Mediterranean Sea by combining the available tide gauge records with satellite altimetry observations. The vast majority of such studies represent sea level through a combination of altimetry-derived empirical orthogonal functions whose temporal amplitudes are then inferred from the tide gauge data. Such methods, however, have tremendous difficulty in separating trends and variability, make no distinction between relative and geocentric sea level, and tell us nothing about the causes of sea level changes. Here, we combine observational data from tide gauges and altimetry with sea-level fingerprints of land-mass changes using a Bayesian hierarchical model (BHM) to quantify the sources of sea-level changes since 1960 in the Mediterranean Sea. The Bayesian estimates are provided on 1/4º x 1/4º regular grid. We find that Mediterranean Sea level rose at a relatively low rate from 1960 to 1990, at which point it started rising significantly faster with comparable contributions from sterodynamic sea level (ocean dynamics and thermal expansion) and land-mass changes.

1. Introduction

Sea-level changes in the Mediterranean Sea show large spatial variation and can deviate significantly both from the global average sea-level rise and from changes in the nearby Atlantic (Calafat and Gomis, 2009; Calafat and Jordà, 2011). Characterizing such spatial structure is crucial to improved coastal planning for climate change adaptation, but attaining this is complicated by the sparseness of the observational record in time and space. Our main source of information on long-term sea-level changes comes from tide gauge records, but those are spatially sparse, noisy, gappy, and only located on the coast. In the case of the Mediterranean, nearly all tide gauges are situated in the northern coasts with almost no stations along the African coasts. Satellite altimetry provides a much better spatial coverage but only since 1992. To address the limitations related to data sparseness in the Mediterranean region, we combine tide-gauge observations with satellite altimetry data to yield reconstructed sea-level fields with the same spatial coverage as the altimetry data and spanning the same period as the tide-gauge record (1960-2018). Furthermore, we separate the sea-level changes into their individual contributions: 1) sterodynamic changes (ocean dynamics and thermal expansion); 2) GRD (changes in Earth gravity, Earth rotation, and solid-earth deformation due to land-mass changes); 3) glacial isostatic adjustment (GIA); and 4) short-term variability (interannual to decadal).

In designing the reconstruction strategy, it is important to recognize that while tide gauges measure sea level relative to the land on which they reside (what is termed relative sea level), satellite altimetry measures geocentric sea level. This means that the sea level observed by tide gauges is affected by changes both in sea surface height (SSH) and in the underlying solid Earth (i.e., vertical land movements - VLMs) and so it is not directly comparable to the sea level measured by altimetry. Therefore, combining tide gauge data with altimetry observations requires a physically consistent framework that explicitly models the contributions from SSH and VLM. However, existing reconstructions of Mediterranean sea level (Calafat and Gomis, 2009; Calafat and Jordà, 2011; Meyssignac et al., 2011) have typically made the assumption that tide gauge and altimetry observations are equivalent, except for VLMs associated with GIA. In this task, we have taken a step forward and consistently modelled the SSH and VLM components of sea level while combining tide gauge observations, altimetry data, and fingerprints of land-mass changes through a spatiotemporal BHM. The investigation of the new sea-level reconstruction allows us to answer fundamental questions such as: How much has sea level risen in the Mediterranean Sea over the past several decades? Has the rate of change been constant? What are the contributions from ocean dynamics, land-mass changes and other processes?

2. Observational data

Monthly time series of mean sea level (MSL) from tide gauge records spanning the period 1960-2018 were obtained from the Permanent Service for Mean Sea Level (PMSL) Revised Local Reference data base (Holgate et al., 2017). A seasonal cycle (annual and semiannual) was removed from the monthly time series along with the effect of atmospheric pressure (assuming an inverse barometer effect) calculated using sea-level pressure data from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996). The monthly data were then averaged into annual values of MSL. The locations of the tide gauges are shown in Figure 1.

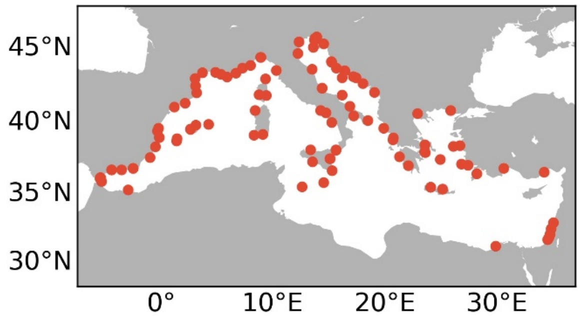

Figure 1. Locations of the tide gauge stations used in the reconstruction.

Satellite altimetry sea-level anomalies (SLAs) spanning the period 1993-2018 were obtained from the multi-mission gridded sea surface heights product provided by the Copernicus Marine Environment Monitoring Service[1]. The altimetry data are made available as daily fields on a quarter-degree near global grid spanning the period from January 2004 to May 2018. These daily sea-level fields were averaged into annual fields for our analysis. The data are provided with all standard corrections applied, including corrections for tropospheric (wet and dry) and ionospheric path delays, sea state bias, tides (solid earth, ocean, loading, and pole), and atmospheric effects (sea-level pressure and high-frequency winds). We have also used a second altimetry dataset derived using a dedicated coastal retracking algorithm called ALES which has been developed at the National Oceanography Centre. Our results based on these two altimetry products are very similar. Here we focus on the results derived using the multi-mission gridded product.

[1] http://marine.copernicus.eu/

The fingerprints of land-mass changes for the period 1960-2018 were produced by Frederikse et al. (2020) and downloaded from Zenodo[2].

3. Bayesian hierarchical model

We build a spatiotemporal BHM that combines tide gauge observations and altimetry data with fingerprints of land-mass changes. We model sea level as the sum of four contributions, namely short-term variability (interannual to decadal), sterodynamic changes (ocean dynamics and thermal expansion), GRD (changes in Earth gravity, Earth rotation, and solid-earth deformation due to land-mass changes), and GIA:

$$\mathrm{SL}_{Rel} = \mathrm{a} * \mathrm{EOF} + \mathrm{Sterodyn} + \mathrm{GRD}_{Rel} + \mathrm{GIA}_{Rel} + \mathrm{S}_{Rel} \quad (1)$$

$$\mathrm{SL}_{Geo} = \mathrm{a} * \mathrm{EOF} + \mathrm{Sterodyn} + \mathrm{GRD}_{Geo} + \mathrm{GIA}_{Geo} + \mathrm{S}_{Geo} \quad (2)$$

Where S_{Rel} and S_{Geo} are the contributions from small-scale processes to relative and geocentric sea-level changes, respectively. Equation (1) describes relative sea level changes from tide gauges while Equation (2) represents geocentric sea-level changes from satellite altimetry. These two equations form a couple system in our BHM. The first term on the right-hand side of each equation captures the short-term variability through a linear combination of empirical orthogonal functions (EOFs), which are extracted from the altimetry data prior to fitting the BHM (we use five EOFs). The amplitudes of the EOFs, a, are quantities to be estimated as part of the BHM. We note that the two first terms on the right-hand side are the same in both equations, while the last two terms are different. The sterodynamic, GRD, and GIA contributions to sea-level changes are modelled as spatiotemporal random walks using Gaussian processes.

To fit the BHM we use the No-U-Turn Sampler (Hoffman and Gelman, 2014) as implemented by the Stan probabilistic programming language (Carpenter et al., 2017). We run the sampler with four chains of 1250 iterations each (warm-up=500) for a total of 3000 post-warm-up draws.

4. Results

Our BHM provides gridded estimates of historical relative sea-level changes (i.e., all contributions, including short-term variability) as well as gridded estimates of the instantaneous (yearly) rate of sea-level change associated with all the contributions for the period 1960-2018. Here we present a few results based on the Bayesian solutions. We begin by showing estimates of changes in relative sea level averaged over the Mediterranean basin (Figure 2), which we compare with estimates from a traditional EOF reconstruction (Calafat and Gomis, 2009). We note that relative sea-level changes show substantial interannual variability, even when averaged over the basin, with peak-to-peak fluctuation as large as 4 cm. Focusing on long-term changes, we note that Mediterranean sea level was relatively flat between 1960 and 1990 while a clear positive trend is noticeable after 1990. Finally, we note that the two estimates of relative sea level from the BHM and an EOF reconstruction show both similar interannual variability and similar long-term changes, giving us additional confidence in the robustness of our estimates.

[2] https://zenodo.org/record/3862995#.X9JiPdj7SUk

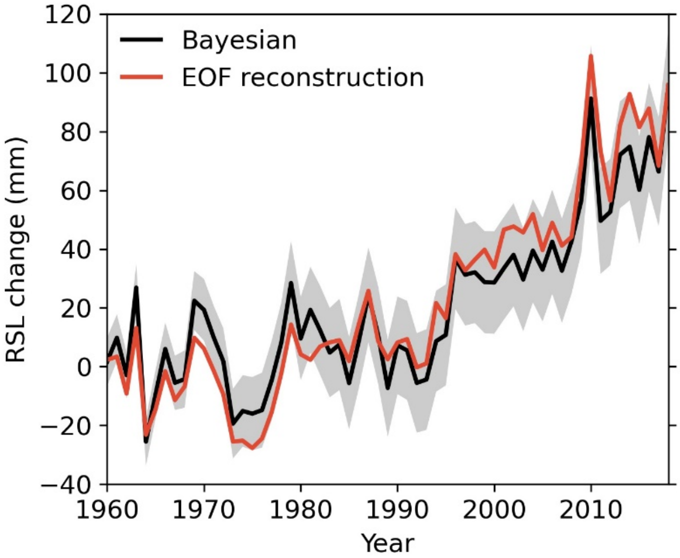

Figure 2. Changes in relative sea-level since 1960 averaged over the Mediterranean basin as given by the Bayesian model (black) and an EOF reconstruction (red).

The long-term evolution of the relative sea level can be better quantified by looking at the rate of change through time (Figure 3). We see that the rate of change was relatively small before 1990 at which point it started to increase rapidly reaching a value of about 3 mm/yr in 2000 that has persisted to this day. For the period before 1990, we note that all contributions are relatively small (i.e., they do not cancel one another out to yield a small rate of total sea-level change). For the period after 1990, the acceleration of relative sea level has comparable contributions from sterodynamic changes and land-mass changes (GRD). The contribution from GIA, which is linear over the period considered here, is relatively small with a spatially averaged value of 0.2 mm/yr. The uncertainty associated with our estimates of the rate of change is larger in the first decades because of the relatively small number of tide gauge stations in that period.

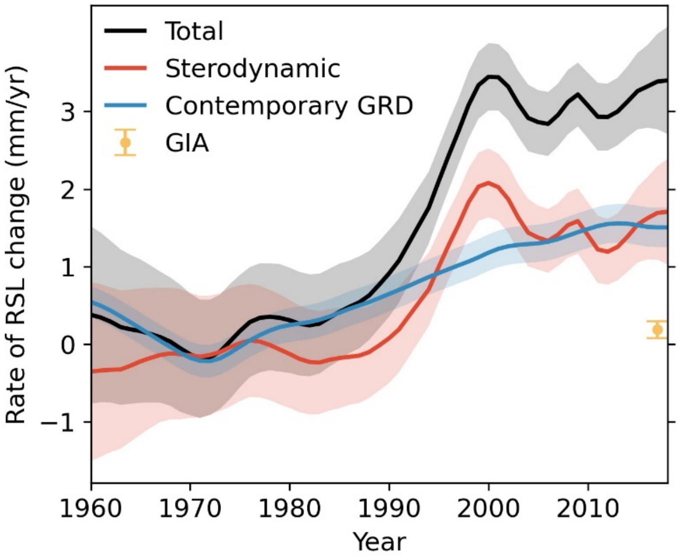

Figure 3. Instantaneous rate of relative sea-level change averaged over the Mediterranean basin and the contributions from sterodynamic changes, GRD, and GIA for the period 1960-2018. The shading denotes the 1-sigma uncertainty band.

Our Bayesian solution also provides estimates of the local rate of relative sea level change and its individual contributions on a 1/4° x 1/4° regular grid. In this case, it is interesting to look at local deviations from the basin-mean trend for the sterodynamic and GRD contributions for the period 1993-2018 (Figure 4). We note that both contributions show spatial variations in the rate of change, however, such variations are much more significant in the sterodynamic contributions, with deviations from the mean ranging from -2.5 to 1.5 mm/yr. The largest trends are found in the eastern part of the Mediterranean Sea, particularly around Cyprus, and in the Aegean Sea, while the smallest trends are found in the Ionian Sea and south of the island of Crete.

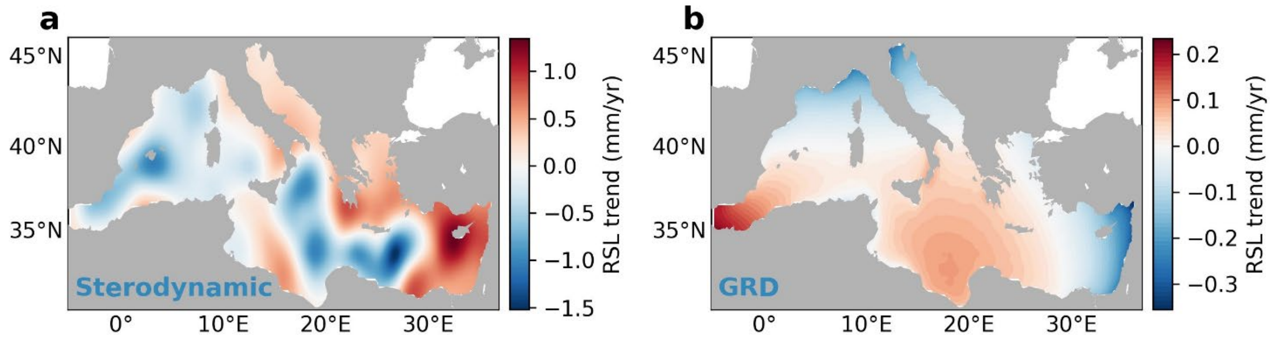

Figure 4. Deviation of the rate of relative sea-level change from the basin-mean rate of change associated with (a) sterodynamic sea level and (b) GRD for the period 1993-2018.

5. Conclusions and Discussion

Our new estimates of sea-level changes in the Mediterranean Sea show that Mediterranean Sea level barely changed between 1960 and 1989 (Figure 3), even though the global mean sea level is estimated to have changed at a rate of about 0.7 mm/yr during that period (Frederikse et al., 2020). Past studies emphasized this relatively low rate of change in the Mediterranean Sea and attributed it to a positive anomaly in sea-level pressure over the Mediterranean Sea over the same time period. Our results show that the low rate of change was also due to almost negligible sterodynamic and GRD contributions. Since the late 1990s, Mediterranean sea level has been rising at a rate of about 3.1 mm/yr (Figure 3), which is similar to the rate of global mean sea-level rise for that period (Frederikse et al., 2020). Furthermore, we show that sea level in the Mediterranean basin does not change uniformly but instead shows high geographical variability (Figure 4). These results highlight the fact that the rate of sea-level change is highly non-uniform spatially and demonstrate the importance of robust estimates of regional changes, such as those provided here.

The key deliverable of this project task is a reconstruction of sea-level changes in the Mediterranean provided as gridded (1/4° x 1/4°) estimates of relative sea-level changes and their instantaneous rates for 1960-2018, separated into the individual contributions of sterodynamic changes, contemporary GRD, GIA, short-term variability (interannual to decadal). Thinking about the impact of the outputs arising from this task, our estimates will be relevant and significant to researchers from a broad array of disciplines, including not only specific research on sea level changes, but also more generally on oceanography and climate sciences. Separation of the sea-level changes into their individual contributions, including short-term variability, will enable researchers to advance our understanding of the effects of internal climate variability on sea level in the Mediterranean Sea and will allow them to better distinguish between temporal fluctuations and sustained human-induced changes. This, in turn, will make it possible to detect accelerations in regional sea-level rise much earlier than it would be feasible using tide gauge records alone, providing increased lead time to implement the necessary adaptation. It is also important to recognize that accurate projections of regional sea-level rise are crucial to the success of coastal adaptation strategies for sea-level rise, yet such projections are still subject to large uncertainty. Our estimates will allow researchers to gain new insights into the relative roles of the various underlying causes of Mediterranean sea-level change in the recent past, contributing to efforts to reduce model uncertainty and benefiting downstream applications such as coastal planning and decision making. In short, we expect our reconstruction to be very valuable not only to scientists but also to policymakers, coastal planners, and coastal communities at large.

6. Data availability

The Bayesian estimates of Mediterranean sea-level changes and contributions for 1960-2018 are available via Zenodo[3]. Additionally, these estimates were presented at the EGU General Assembly 2021[4].

References

Carpenter, B. et al. Stan: A probabilistic programming language. *J. Stat. Softw.* 76(1), (2017).

Calafat, F. M., and D. Gomis. Reconstruction of Mediterranean sea level fields for the period 1945–2000. *Global Planet. Change* 66, 225–234 (2009).

Calafat, F. M., and G. Jordà. A Mediterranean sea level reconstruction (1950–2008) with error budget estimates. *Global Planet. Change* 79, 118–133 (2011).

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. The causes of sea-level rise since 1900. *Nature* 584(7821), 393–397 (2020).

Holgate, S. J. et al. New data systems and products at the Permanent Service For Mean Sea Level. *J. Coast. Res.* 29, 493–504 (2013).

Kalnay, E., et al. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Meteorol. Soc.* 77(3), 437–471 (1996).

Meyssignac, B., F. M. Calafat, S. Somot, V. Rupolo, P. Stocchi, W. Llovel, and A. Cazenave. Two-dimensional reconstruction of the Mediterranean sea level over 1970–2006 from tide gauge data and regional ocean circulation model outputs. *Global Planet. Change* 77, 49–61 (2011).

[3] https://doi.org/10.5281/zenodo.5562985
[4] https://doi.org/10.5194/egusphere-egu21-15087