

1 **Sensitivity of the Mediterranean sea level to atmospheric**
2 **pressure and free surface elevation numerical formulation**
3 **in NEMO**

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19

1 **Abstract**

2 The sensitivity of the dynamics of the Mediterranean Sea to atmospheric pressure
3 and free surface elevation formulation using NEMO (Nucleus for European Modelling
4 of the Ocean) was evaluated. Four different experiments were carried out in the
5 Mediterranean Sea using filtered or explicit free surface numerical schemes and
6 accounting for the effect of atmospheric pressure in addition to wind and buoyancy
7 fluxes. Model results were evaluated by coherency and power spectrum analysis with
8 tide gauge data. We found that atmospheric pressure plays an important role for
9 periods shorter than 100 days. The free surface formulation is important to obtain the
10 correct ocean response for periods shorter than 30 days. At frequencies higher than
11 15 days^{-1} the Mediterranean basin's response to atmospheric pressure was not
12 coherent and the performance of the model strongly depended on the specific area
13 considered. A large amplitude seasonal oscillation observed in the experiments using
14 a filtered free surface was not evident in the corresponding explicit free surface
15 formulation case which was due to a phase shift between mass fluxes in the Gibraltar
16 Strait and at the surface. The configuration with time splitting and atmospheric
17 pressure always performed best; the differences were enhanced at very high
18 frequencies.

19 **1. Introduction**

20 The Mediterranean Forecasting System (MFS, *Pinardi and Flemmings 1989*) started
21 in the late 1980s during the years of growing interest in the operational framework of
22 applied marine science. It now provides real-time environmental information about
23 the Mediterranean Sea with continuously growing accuracy. The modelling
24 component of the MFS is the focus of the present study.

25 The Ocean General Circulation Model (OGCM), which solves the primitive equations
26 and integrates observational information for analyses and forecasts, has been
27 enhanced continuously over the past 15 years. The evolution of the model can be
28 traced back by referring to the related literature (*Demirov and Pinardi 2002* to *Oddo*
29 *et al 2009*). The current operational model consists of a NEMO (*Madec 2008*) based
30 code, under incompressible and hydrostatic approximation, with $1/16^\circ$ horizontal
31 resolution, 72 vertical levels with partial cells, fully accounting for the air-sea fluxes by

1 dedicated bulk formulae, connected to the global model (*Drevillon et al., 2008*). It also
2 takes into account the fresh water input from the major Mediterranean rivers (details
3 on the implementation of the model can be found in *Oddo et al 2009*).

4 The NEMO code solves a prognostic equation for the sea surface elevation, and the
5 induced external gravity waves (EGW) are currently treated using a filter approach
6 developed by *Roullet and Madec (2000)* which allows for longer time-step saving
7 computational time. In version 3.3, the time-splitting technique was introduced into
8 the NEMO code according to *Griffies (2004)*, allowing for an explicit representation of
9 the EGW.

10 The sea level and its variability have a strong social and economical impact which
11 explains the growing interest worldwide in the correct estimate of their evolution and
12 variability, both in time and space. The Mediterranean Forecasting System is one
13 example of the considerable effort spent in trying to achieve such accuracy.

14 In the open ocean the response of the sea level to atmospheric pressure is close to
15 the inverse barometer (IB) effect (*Wunsch, 1972; Ponte 1993*). The classical IB
16 approximation formulates the static response of the ocean to atmospheric pressure
17 forcing. Atmospheric pressure effects in numerical ocean models, especially when
18 solving large scale problems, have often been neglected because of the relatively
19 small amplitude of the horizontal gradients and following the assumption that the
20 major influence is almost stationary and can be computed by superimposing an IB
21 effect on the free surface solution without atmospheric pressure. However, oceanic
22 responses to atmospheric pressure forcing can depart from a pure inverse barometer
23 effect under specific circumstances, especially in the presence of geometrical
24 constraints (i.e. straits or channels) (*Garrett and Majaess 1984*) as in the
25 Mediterranean Sea (*Le Traon and Gauzelin, 1997; Pasaric et al 2000*). The validity of
26 this IB assumption depends also on the time and space scales considered: the ocean
27 response to atmospheric pressure generally differs from the IB for periods less than
28 three days and at high latitudes. However in closed or semi-enclosed seas, such as
29 the Mediterranean, the response is more complex.

30 Sea-level variations in the Mediterranean Sea at time scales from one to ten days
31 have been shown to be primarily due to surface pressure changes related to synoptic
32 atmospheric disturbances (*Kasumovic 1958; Mosetti 1971; Papa 1978; Godin and*

1 *Trotti 1975; Gomis et al. 2006, Pascual et al. 2008*). On the other hand, sea-level
2 variations at lower time scales have been explained as due to atmospheric planetary
3 waves (*Orlic 1983*). A significant contribution of the atmospheric pressure on the sea-
4 level seasonal and interannual variability has been also documented (*Gomis et al.*
5 *2006, Gomis et al., 2008, Marcos and Tsimplis, 2007*). It has been also observed that
6 a significant departure from a standard IB effect can occur at frequencies higher than
7 30 days^{-1} (*Le Traon and Gauzelin, 1997*). Departures from the IB response may be
8 due to either local winds (*Palumbo and Mazzarella 1982*) or to the restrictions at
9 straits on water transport between basins (*Garret 1983; Garrett and Majaess 1984*).
10 *Crepon (1965)* has also shown that the response of a rotating fluid is never
11 barometric. It may be quasi-barometric if the space scale of the atmospheric
12 disturbance is smaller than the barotropic radius of deformation. He also showed that
13 the larger the bottom friction, the closer the response to barometric pressure.
14 Furthermore, coastal Kelvin waves or other fast barotropic waves can support or
15 accelerate the barometric adjustment. Atmospheric pressure driven flows through the
16 Mediterranean straits lead to mass, momentum and vorticity exchanges between the
17 connecting basins (*Candela and Lozano, 1994*).

18 It is thus clear that the dynamics of the Mediterranean Sea forced directly and
19 indirectly by atmospheric pressure cover a large spectrum of processes with different
20 temporal and spatial scales. We thus believe that the sensitivity of the dynamics
21 induced by atmospheric pressure to the numerical formulation used to solve the
22 surface elevation equation is an important area for investigation.

23 Section 2 describes the pressure formulation adopted in NEMO, together with the
24 numerical schemes implemented to solve the sea level equation. Details on the
25 NEMO implementation and experimental set up are described in Section 3. Model
26 simulation results of the Mediterranean response to the atmospheric pressure and
27 sensitivity to the numerical scheme used to solve the sea level equation are
28 discussed in Section 4. Section 5 provides a summary and conclusions.

29

1 2. The Pressure Formulation

2 Considering the hydrostatic approximation, the pressure (p) at depth z can be
3 obtained by integrating the vertical component of the equation of motion from z to the
4 free surface (η):

$$5 \quad p(x, y, z, t) = p_{atm} + g\rho_0\eta + g\int_z^0 \rho(x, y, z, t)dz. \quad (1)$$

6 Where the first term on the r.h.s is the atmospheric pressure at the sea surface, the
7 second term is the pressure due to the free surface, η , displacement, ρ_0 is the
8 constant density value, and the last term on the r.h.s is the hydrostatic pressure
9 (where ρ is density).

10 Introducing the separation (1) requires the addition of a diagnostic or prognostic
11 equation for η . Rigid lid models use different methods to solve the diagnostic
12 problem for η (*Dukowicz et al., 1993, Pinardi et al., 1995*) but we will concentrate
13 only on the prognostic formulation. The time-dependent equation for η is obtained by
14 vertically integrating the continuity equation (under the incompressible approximation)
15 and by applying surface and bottom dynamic boundary conditions:

$$16 \quad \frac{\partial \eta}{\partial t} = -D + P + R - E \quad (2)$$

17 where

$$18 \quad D = \nabla \cdot [(H + \eta)\bar{U}_h] \quad (3)$$

19 and

$$20 \quad \bar{U}_h = \frac{1}{H + \eta} \int_{-H}^{\eta} \bar{u}_h dz \quad (4)$$

21 is the barotropic velocity field, \bar{u}_h the horizontal three dimensional velocity, H the
22 bottom depth, P is the precipitation, R the runoff divided by the river cross-sectional
23 area, and E the evaporation.

24 The atmospheric pressure influences the horizontal velocity tendency which modifies
25 the barotropic velocity field (4), which in turn changes the horizontal divergence of the

1 momentum (3); the latter affects the η tendency (2) which, again, modifies the total
2 pressure.

3 Thus it is interesting to investigate how atmospheric pressure forcing influences the
4 solution of primitive equations depending on the numerical schemes adopted to solve
5 the prognostic equation (2).

6 The free-surface elevation response to atmospheric pressure may be composed of
7 external gravity waves (EGWs). Their time scale is short compared to other
8 processes described by primitive equations and thus they require a very small time
9 step. Two methods are implemented in NEMO to allow a longer time step, solving the
10 primitive equation in the presence of EGWs: the so-called *filtered* and *time-splitting*
11 method (hereafter also referred to as FLT and TS, respectively).

12 NEMO users can decide between the two methods depending on the physical
13 processes of interest. For fast EGWs, i.e. Poincare' or coastal Kelvin waves, then
14 time-splitting is the most appropriate choice. If the focus is not on EGWs, a filter can
15 be used to slow down the fastest waves while not altering the slow barotropic Rossby
16 waves.

17 The filtering of EGWs in numerical models with a free surface is usually a matter of
18 the discretisation of the temporal derivatives. In the NEMO code however, a slightly
19 different approach developed by *Roullet and Madec (2000)* is used: the damping of
20 EGWs is ensured by introducing an additional force in the momentum equation.

21 The time-splitting formulation used in NEMO follows the one proposed by *Griffies*
22 *(2004)*. The general idea is to solve the free surface equation and the associated
23 barotropic velocity equations with a smaller time step than the one used for the three
24 dimensional prognostic variables.

25 In this study we focus on the two different NEMO methods to solve the surface
26 elevation equation (2), and on how these methods affect the reproduction of the
27 atmospheric pressure induced dynamics.

28

1 3. Experimental set-up

2 3.1. NEMO model configuration

3 Four different physical and numerical configurations of NEMO were used to test and
4 analyze the sensitivity of the model results on the atmospheric pressure forcing and
5 the numerical scheme adopted to solve the surface elevation equation. The NEMO
6 configurations used in this study are ultimately derived from the NEMO v3.2 model
7 described in *Oddo et al. (2009)*. This is the ocean modelling component of the
8 Mediterranean Forecasting System (*Pinardi et al., 2003*), hereafter NEMO-MFS-1.
9 Since the original publication of *Oddo et al. (2009)*, the NEMO model has undergone
10 a series of revisions and is now used at v3.4. However, the results described in *Oddo*
11 *et al. (2009)* can traceably be reproduced using the current v3.4 version of NEMO.

12 In this study, **NEMO-MFS-1** is based on NEMO 3.4 code version using a filtered free
13 surface with a $1/16^\circ$ horizontal regular resolution, and 72 unevenly spaced vertical z-
14 levels with partial cells to fit the bottom depth shape. **NEMO-MFS-1** covers the entire
15 Mediterranean Sea and also extends into the Atlantic (*Fig. 1, upper panel*). The
16 model is forced by momentum, water and heat fluxes interactively computed by bulk
17 formulae (*Oddo et al. 2009*) using the 6-h, 0.5° horizontal-resolution operational
18 analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF)
19 and model-predicted surface temperatures. The ECMWF fields are linearly
20 interpolated onto the model time-step. Atmospheric pressure effects are not included
21 in the model forcings. The natural surface boundary condition for vertical velocity is
22 used.

23 Only seven major rivers were implemented (*Fig.1, upper panel*): the Ebro, Nile and
24 Rhone monthly values are from the Global Runoff Data Centre (*Fekete et al., 1999*),
25 the Adriatic rivers Po, Vjose and Seman are from Raicich (*Raicich, 1996*) while the
26 Bojana River climatological flow is taken from *UNEP (1996)*. The Dardanelles inflow
27 was parameterized as a river and its monthly climatological net inflow rates and
28 salinity values were taken from *Kourafalou and Barbopoulos (2003)*.

29 The advection scheme for active tracers is a mixed up-stream/MUSCL scheme
30 (Monotonic Upwind Scheme for Conservation Laws, *Van Leer, 1979*, as implemented
31 by *Estubier and Levy, 2000*). The up-stream scheme is used in proximity of the river

1 mouths, in the Gibraltar Strait and close to the lateral open boundaries in the Atlantic.
2 In Gibraltar, the up-stream scheme, together with an artificially increased vertical
3 diffusivity, parameterizes the mixing that acts in this area due to the internal wave
4 breaking, which is not explicitly resolved by the model.

5 In **NEMO-MFS-1**, the Atlantic box is nested within the monthly mean climatological
6 fields computed from the daily output of the $1/4^\circ$ global model (*Drevillon et al., 2008*),
7 spanning from 2001 to 2005. The 2-D adaptive radiation condition (*Marchesiello et*
8 *al., 2001; Oddo and Pinardi, 2008*) was used for the active tracers (temperature and
9 salinity). Total velocities at the open boundaries are imposed by the global model
10 solution, while barotropic velocities use a modified *Flather (1976)* lateral boundary
11 condition explained in *Oddo and Pinardi (2008)*. A summary of the model
12 configuration is provided in **Table 1**, while details on the lateral open boundaries
13 conditions are provided in *Oddo et al (2009)*.

14 Three additional NEMO configurations were created for this study. **NEMO-MFS-2** is
15 identical to **NEMO-MFS-1** except for the inclusion of the atmospheric pressure
16 forcing. This forcing, like the other atmospheric fields, is taken from ECMWF
17 operational products. **NEMO-MFS-3** uses the time-splitting approach to solve the free
18 surface elevation tendency equation (2), without considering the atmospheric
19 pressure. Finally **NEMO-MFS-4** uses the time-splitting method and also takes into
20 account the atmospheric pressure effects. The differences between the four model
21 configurations are listed in **Table 1** while **Appendix A** provides details on how to
22 reproduce the physical setup used in this manuscript starting from the standard
23 NEMO code.

24 All the simulations have been initialized with climatological temperature and salinity
25 fields (*SeaDataNet, www.seadatanet.org*) on 7 January 2004 and ended on 31
26 December 2012.

27

28 **4. Results and Discussion**

29 In this section the sensitivity of the circulation response due to the atmospheric
30 pressure effect is analyzed as a function of the free surface elevation formulation in
31 NEMO. Only the different solutions for η are considered since vertical profiles of
32 temperature and salinity were not found to be significantly different among the four

1 experiments. All the model configurations have very similar baroclinic skills to each
2 other and to those ones obtained with similar NEMO experiments (*Oddo et al. 2009*).

3 To assess the accuracy of the model and to corroborate the numerical findings, sea
4 level data retrieved from several tide gauges in the Mediterranean Sea were used
5 (*Fig. 1* bottom panel).

6 Since the Mediterranean's response to atmospheric pressure forcing varies according
7 to the time scales considered (*Garret and Majaess 1984, Lascaratos and Gačić*
8 *1990*), model results are analyzed and discussed on the basis of different temporal
9 scales. Firstly the low frequency response results are discussed in terms of model-to-
10 model and models-to-observations comparisons in a period range spanning from the
11 time-invariant components of the η signal up to 5 days. The high frequency model
12 results are then analyzed in a period window from 15 days to 2hr.

13

14 **4.1. Low frequency components**

15 The two-year mean component of the sea surface height (SSH) in the four
16 experiments is shown in *Fig. 2*. At climatological time scales there are no significant
17 differences between the two η numerical formulations, however qualitative
18 differences in the circulation due to the introduction of pressure forcing are evident.
19 The major Mediterranean circulation structures (*Pinardi et al 2013*) are very similar
20 among the various numerical model formulations but different due to the introduction
21 of atmospheric pressure forcing. This forcing generally weakens all the cyclonic wind-
22 driven structures as the atmospheric pressure forces η in the opposite way from the
23 wind stress curl, i.e. the wind strengthens the cyclonic structures, whereas the
24 associated atmospheric pressure weakens them. The Adriatic and the Rhode
25 cyclonic gyre circulations illustrate the atmospheric pressure effects well, and the
26 structures are more realistic and closer to recent Mediterranean circulation reanalysis
27 studies (*Pinardi et al. 2013*) in the atmospheric forcing cases.

28 The maps showing differences between the experiments with and without
29 atmospheric pressure are also similar. A large-scale zonal gradient in the free surface
30 is observed due to atmospheric pressure which produces higher η values in the
31 Levantine basin and lower η values in the western Mediterranean Sea. Similar

1 standard deviations maps (not shown) also indicate that, by introducing atmospheric
2 pressure, the Levantine basin has larger seasonal oscillations than the remaining part
3 of the Mediterranean Sea. In the various experiments, small-scale differences, i.e.
4 eddy-like structures, were observed. These structures have horizontal scales that are
5 much smaller than the atmospheric pressure scales and are probably due to the
6 displacements of oceanic features as a consequence of instabilities induced by the
7 new forcing.

8 A comparison between the time-series of daily values of η for the four experiments
9 and corresponding observed data are shown in *Fig. 3*. Prior to the comparison, the
10 steric effect was superimposed on the SSH model outputs, following Mellor and Ezer,
11 (1995). A time interval from July 2010 to July 2012 was selected, since a significant
12 number of station data are available. The results were also evaluated by a power
13 spectra comparison and coherency analysis with observations. For the coherency
14 analysis smoothing was performed over eight adjacent frequencies. Model results
15 were first interpolated into the tide-gauge positions (*Fig. 1*, bottom panel) and then
16 averaged. In order to evaluate potential sampling errors deriving from the relatively
17 short time interval analyzed and statistical robustness of the model results, a
18 preliminary spectral analysis has been carried out considering the entire model runs
19 period. In terms of the energetic content and differences between the different
20 models configurations no significant differences have been observed between the
21 two time periods considered. Results are shown for periods between 360 and 5,
22 days. However results for periods shorter than 15 days were shown to be sensitive to
23 specific sampling positions and/or tide gauge locations (in agreement with *Garret and*
24 *Majaess* 1984, *Lascaratatos and Gačić* 1990). On the other hand the modelled
25 response to the atmospheric pressure in the period band between 360 and 15 days
26 was shown to be geographically coherent within the Mediterranean basin.

27 In agreement with *Molcard et al. (2002)* and *Oddo et al. (2009)* and irrespective of the
28 experiment considered, both observational and modelled data are characterized by a
29 large seasonal cycle modulated by inter-annual variability (the inter-annual variability
30 is not shown since only a two-year interval series was selected from the model
31 results in order to be consistent with the observational dataset available).
32 Qualitatively, the longer time scales of the inter-annual variability have larger

1 amplitudes in the winter than the summer. At very low frequencies the major
2 difference in the results deriving from the two free surface methods is the amplitude
3 of the seasonal cycle, i.e. the filtered formulation has a larger amplitude.

4 Comparing the power spectra (*Fig. 3* left-middle panel), it is evident that the filtered
5 formulation overestimates the energy content in the spectral window between 360
6 and 120/100 days. The introduction of the atmospheric pressure slightly reduces this
7 model behaviour (*Fig. 3* right-bottom panel). For shorter periods, between 120 and 5
8 days, the filtered formulation generally underestimates the energy content. Also in
9 this case, by introducing the atmospheric pressure in the filtered formulation, there
10 was a considerable improvement in the reproduction of the energy content.

11 Overall, the two experiments with the time-splitting formulation improved the
12 reproduction of the observed energy content. At seasonal scales, the energy content
13 is considerably lower than the filtered simulations and is closer to the observation.
14 However in the window between 180 and 30 days, **NEMO-MFS-3** significantly
15 underestimated the observed variability due to the missing contribution of
16 atmospheric pressure in this period range.

17 At frequencies between 100 and 5 days⁻¹ **NEMO-MFS-3** and **NEMO-MFS-1** without
18 atmospheric pressure forcing have very similar energy contents and both
19 underestimated the observed values.

20 As for the filtered formulation, by introducing the atmospheric pressure in the time
21 splitting experiments, the energy content of η increases in the spectral window
22 between 120 and 5 days, reaching generally closer values to the observations. In
23 terms of energy content, introducing the atmospheric pressure has a significant
24 impact for periods shorter than 120/100 days (see the gain panel in *Fig.3*). For
25 periods longer than 120/100 days, the numerical scheme used to solve Eq. (2) plays
26 a major role in determining the ocean dynamic (irrespective of the additional forcing
27 introduced), while for periods shorter than 120/100 days, the effect of atmospheric
28 pressure dominates over the effect of the specific numerical solution method for η .

29 In all the experiments, the coherence is fairly high (*Fig. 3* right middle panel). There
30 were significant improvements with the introduction of the atmospheric pressure,
31 irrespective of the numerical solution methods, for periods shorter than 50 days. The
32 phase difference is always small and generally below 30°. There was a significant

1 phase shift between observations and model simulation values between 40 and 25
2 days in the absence of atmospheric pressure forcing. For periods shorter than 180
3 days, all the gains are generally smaller than 1, which means that the model
4 underestimated the amplitude of η oscillations. However there was a significant
5 improvement by introducing the atmospheric pressure forcing for periods shorter than
6 90 days.

7 The analysis so far was performed for the model and observed average sea level at
8 the 25 tide gauge stations (*Fig. 1*). This can be considered as a good estimate of the
9 mean sea level of the Mediterranean Sea for periods between 360 and 15 days
10 because no significant differences were observed, at these time scales, averaging
11 over the whole Mediterranean Sea or by only sampling at tide gauge locations.

12 To better understand the observed differences between the results of the four
13 experiments in terms of these basin averaged oscillations, *Fig. 4* shows the time
14 series of net transport at the Gibraltar Strait together with the corresponding power
15 and cross power (with atmospheric pressure) spectra. The mean net transport in the
16 four experiments does not vary significantly, i.e. the time averages are all about 0.05
17 Sv (in agreement with previously modelled and observed findings *Oddo et al. 2009*).
18 On the other hand in agreement with *Lacombe (1961)*, by introducing the
19 atmospheric pressure there was a significant increase in the amplitude of the
20 transport oscillations for periods shorter than 100 days. Furthermore important sub-
21 inertial variability in the period band of 10-5 days is observed, while annual or semi-
22 annual signals have small amplitudes, confirming previous studies results (*Lafuente*
23 *et al. 2002*)

24 For periods longer than 270 days, introducing the atmospheric pressure dampens the
25 amplitude of the transport whichever numerical formulation is used for the free
26 surface elevation, but this effect was larger using the filtered scheme (*Fig. 4* middle
27 panel). In the range of 270 and 120 days, the ***NEMO-MFS-1*** and ***NEMO-MFS-2***
28 simulated transport had a larger energy content than the corresponding ***NEMO-MFS-***
29 ***3*** and ***NEMO-MFS-4***. Between 70 and 30 days, the introduction of atmospheric
30 pressure produced a similar increase in energy content in both the configurations
31 (filtered and time-splitting formulation).

1 For periods shorter than 25 days, there were clearer differences in atmospheric
 2 pressure effect in the two formulations. In these spectral windows, the oscillation in
 3 the Gibraltar transport was totally due to the atmospheric pressure-induced
 4 dynamics. Peaks in the spectra and in the cross power spectra simulated with the
 5 time-splitting match peaks simulated using the filtered formulations. However using
 6 time-splitting, the energy content doubled, meaning that the atmospheric pressure
 7 effect in the Gibraltar Straits must occur in the form of fast processes filtered out
 8 using the filtered formulations.

9 Note that the different amplitude of the seasonal cycle of the average sea surface
 10 elevation in the two model formulations is not completely explained by the
 11 corresponding energy content of the Gibraltar transport. Similarly to *Pinardi et al*
 12 (2014), by integrating (2) into time and into a semi-enclosed basin such as the
 13 Mediterranean Sea, we obtain an equation for the mean sea level tendency:

$$14 \quad \frac{\partial \langle \eta \rangle}{\partial t} = \frac{Gib_tr}{A} - \langle qw \rangle \quad (5)$$

15 where Gib_tr is the integral of the mass divergence D in (3) resulting in the net
 16 transport at Gibraltar, A is the Mediterranean Sea area, and qw is the basin average
 17 of the surface mass fluxes, which is identical (not shown) in the four simulations.
 18 What modulates the mean sea surface elevation seasonal oscillation differently in the
 19 four experiments is the phase shift between the two terms on the right hand side of
 20 (5). *Pinardi et al (2014)* call this difference the stochastic component of the sea
 21 surface elevation tendency.

22 In *Fig. 5* (top panel) the phases between the Gibraltar net transport and the surface
 23 mass flux (qw) for the four experiments are shown. The main differences derive from
 24 the introduction of the time splitting scheme, while the atmospheric pressure plays a
 25 minor role in modulating the phase of the two signals at seasonal time scales. At
 26 higher frequencies (periods shorter than 100 days) the atmospheric pressure effect
 27 dominates. In the middle panel of *Fig. 5*, the Gib_tr and qw reconstructed signals
 28 considering only the seasonal frequencies are shown together with the corresponding
 29 stochastic sea surface elevation component (*Fig. 5* bottom panel). Only one time-
 30 series of qw is drawn since no significant differences among the experiment are
 31 observed. The amplitude of the Gibraltar net transport annual cycle is very similar in

1 all the considered model experiments and its value is about 0.07 Sv, the *qw* seasonal
2 cycle has an amplitude of about 0.06 Sv. Both, *Gib_tr* and *qw*, modelled seasonal
3 oscillations are in agreement with previous studies (Lafuente et al. 2002). The phase
4 shift produced using the time splitting scheme amplifies the phase difference between
5 *qw* and *Gib_tr* (from 120 degrees to 150 degrees), and the resulting stochastic
6 component has a smaller amplitude. This could have a profound influence on the
7 long-term trend in the sea level in the Mediterranean, as explained by *Pinardi et al.*
8 (2014).

9

10 **4.2. High Frequency components**

11 To analyze the high frequency response of the model to atmospheric pressure forcing
12 and its sensitivity to the sea level formulation for short periods, three tide gauge
13 stations (Valencia, Mahon and Venice) were selected on the base of data availability.
14 The data have a frequency of an hour and were analyzed for a period of one month.
15 The tide gauge positions are shown in *Fig. 1* (bottom panel). The Mediterranean's
16 response to atmospheric pressure varies spatially, as different processes
17 characterize different areas of the basin. It is worth to mention that the 6 hr frequency
18 ECMWF forcing field does not properly sample the full spectra of the atmospheric
19 phenomena and aliasing problems may occur. Consequently the corresponding
20 oceanic response could be only partially resolved by the NEMO configurations. Thus,
21 some differences between modelled and observed sea level at high frequency could
22 be due to the sampling frequency of the atmospheric data. However previous studies
23 (Pascual et al. 2008, Wakelin and Proctor, 2002) have already proved the possibility
24 to reproduce the energetic content of high frequency (up to 4hr) Mediterranean
25 processes using similar atmospheric data (Wakelin and Proctor, 2002). Prior to the
26 comparison, the tidal signal was removed from the observed dataset and steric effect
27 superimposed on model results. Modelled and observed sea level data time-series
28 were also compared by analyzing individual power spectra.

29 In *Fig. 6* and *Fig.7* the sea level time-series and power spectrum are shown for the
30 station in Valencia. At relatively low frequencies (lower than 50 hr^{-1}), the experiments
31 without the atmospheric pressure underestimated the amplitude of the oscillations. In
32 the range between 2 (48 hr) and 1 days all the experiments performed in a similar

1 way. Differences between model results are more evident for periods lower than 24
2 hr. For these periods (lower than 24 hr), differences between numerical schemes and
3 additional forcing effects are more evident. Experiments without the atmospheric
4 pressure forcing, **NEMO-MFS-1** and **NEMO-MFS-3**, strongly underestimated the
5 amplitude of the signal. By introducing the atmospheric pressure, the energetic level
6 increased in both **NEMO-MFS-2** and **NEMO-MFS-4**. In addition, by introducing the
7 atmospheric pressure, generally the time-splitting formulation improved the
8 reproduction of the energetic content of the observed signals, although it tended to
9 overestimate the 4 hr oscillation.

10 The use of the time-splitting formulation and the introduction of the atmospheric
11 pressure (**NEMO-MFS-4**) produced significantly different model results from the other
12 simulations for periods shorter than 6hr. These very high frequency oscillations are
13 evident in the observed time-series and represent the main difference between the
14 sea level observed in Mahon (*Fig. 8*) and in Valencia. These oscillations also have a
15 higher frequency than the atmospheric forcing used in the simulations (6 hr^{-1}), thus
16 we argue that some high frequency barotropic processes excited by the introduction
17 of the atmospheric pressure forcing may interact with bathymetry (the narrow
18 continental shelf in front of Valencia) and background velocities, resulting in very high
19 frequency barotropic waves. This is evident when comparing the different power
20 spectra for the four experiments and the observations with periods lower than 6 hr.
21 This process was filtered out in **NEMO-MFS-2**.

22 As already highlighted, at Mahon a very similar sea level behaviour was observed
23 (*Fig. 8*), the only significant difference with Valencia being the very high frequency
24 oscillations and the corresponding energetic levels for periods between 24 and 4 hr
25 (*Fig.9*). The models generally failed to reproduce this part of the observed sea level
26 variability. By introducing the atmospheric pressure, there was a slight improvement
27 for periods shorter than 12 hr although the modelled values remain lower than the
28 observed ones. The η formulation seems to play a minor role in the analyzed spectral
29 window, while the introduction of the atmospheric pressure forcing was responsible
30 for the differences between the model results. In the spectral windows between 6 and
31 2 hr the energetic levels obtained with **NEMO-MFS-4** were slightly higher and closer
32 to the observed values than the energetic levels simulated by the other experiments.

1 The November 2011 high frequency sea level data and corresponding power spectra
2 for the Venice station are shown in *Fig. 10 and Fig.11 respectively*. For most of the
3 observed days, the sea level was characterized by the presence of seiches (*Leder
4 and Orlić 2004*). This was also confirmed by the power spectra maxima at 21 hr^{-1} and
5 12 hr^{-1} frequencies (the frequency of the main fundamental longitudinal oscillation in
6 the Adriatic Sea, Raicich 1999). By introducing the atmospheric pressure, the model
7 was able to reproduce the observed seiches in both the η formulations. This is
8 probably due to the relatively shallow water characterizing these areas and the
9 corresponding low values of gravity wave phase speed which are also resolved using
10 the filtered free surface. However the energy content in the time-splitting formulation
11 better matches the observed values. Without the atmospheric pressure, both the η
12 formulations clearly fail to simulate this process. The signal is only partially present in
13 the model results (***NEMO-MFS-1*** and ***NEMO-MFS-3***) due to the wind effect which is
14 also a driver for the seiches dynamic (*Leder and Orlic, 2004*).

15 The differences between the two η formulations become more evident and account
16 for greater differences in the results of the models for periods shorter than 10 hr. Both
17 the simulations using the time-splitting formulation reached higher energetic levels
18 than ***NEMO-MFS-1*** and ***NEMO-MFS-2***. The high frequency oscillations induced by
19 the atmospheric pressure are filtered out using the filtered formulation and the
20 corresponding energetic levels between ***NEMO-MFS-1*** and ***NEMO-MFS-2*** were
21 similar. On the other hand the differences in power spectra between ***NEMO-MFS-3***
22 and ***NEMO-MFS-4*** were significant, reaching a relative maximum at a 4 hr^{-1}
23 frequency.

24

25 **5. Summary and Conclusions**

26 The sensitivity of the Mediterranean Sea ocean dynamics to the free surface
27 elevation numerical formulation in NEMO was evaluated for cases with and without
28 atmospheric pressure forcings. Four different NEMO configurations were created and
29 the results compared with each other and with available observations. All the NEMO
30 configurations were implemented using the same horizontal and vertical meshes.

31 The reference NEMO configuration, ***NEMO-MFS-1***, uses a filtered formulation of the
32 free surface equation (*Roullet and Madec, 2000*) and does not take into account the

1 atmospheric pressure effects. This model setup is currently used in the framework of
2 the Mediterranean Forecasting System (*Pinardi and Flemmings 1989*).

3 **NEMO-MFS-2** differs from **NEMO-MFS-1** due to the introduction of the atmospheric
4 pressure forcing. The free surface equation is solved using a time-splitting approach
5 (*Griffies, 2004*) which either does or does not account for the atmospheric pressure
6 effect in **NEMO-MFS-3** and **NEMO-MFS-4** configurations, respectively.

7 The spatial variability induced by the introduction of the atmospheric pressure in the
8 two-year mean component of the *sea level* was not influenced by the different
9 numerical formulations used to solve the free surface equation (*Fig. 2*). However the
10 introduction of the atmospheric pressure induced a basin scale zonal sea level
11 negative gradient (higher values in the east and lower in the west) and a weakening
12 of all the cyclonic wind-driven structures irrespectively of the free surface formulation
13 adopted. The structure of the sea level and the corresponding circulation could be
14 considered as more realistic with atmospheric pressure forcing although
15 observational evidence is lacking at the basin scale.

16 At low frequencies, the major difference between the two numerical free surface
17 formulations is the amplitude of the seasonal cycle. The filtered formulation
18 overestimated the energy content in the spectral window between 400 and 120 days.
19 The amplitude of the seasonal cycle in the time-splitting NEMO formulation was
20 considerably smaller than it was in the filtered simulations and was closer to the
21 observations. The introduction of atmospheric pressure slightly improved the filtered
22 solution, but did not influence the time-splitting simulation results. With shorter
23 periods (between 120 and 50 days), the simulations without the atmospheric
24 pressure forcing generally underestimated the energy content.

25 For periods longer than 120/100 days, differences in the model numerical schemes
26 led to quantitative differences in the sea level (irrespective of the atmospheric
27 pressure), while for shorter periods, atmospheric pressure effects dominated.

28 In the analyzed frequency windows, the time-splitting and the filtered formulation
29 responses to the introduction of atmospheric pressure were very similar; higher
30 energy levels were reached with the time-splitting scheme and atmospheric pressure
31 for short periods.

1 The mean net transport at the Gibraltar Strait in the four experiments did not vary
2 significantly. At seasonal time-scales, the introduction of the atmospheric pressure
3 dampened the amplitude of the net transport in both the free surface numerical
4 formulations. This effect was greater using the filtered scheme. In the periods longer
5 than and 120 days, the **NEMO-MFS-1** and **NEMO-MFS-2** simulated transport had a
6 larger energy content than the corresponding **NEMO-MFS-3** and **NEMO-MFS-4**
7 values. In addition by introducing the atmospheric pressure, there was a significant
8 increase in the amplitude of the transport oscillations for periods between 70 and 30
9 days.

10 At higher frequencies, the differences in the atmospheric pressure effect in the two
11 sea level formulations are more evident. In these spectral windows, the oscillation in
12 the Gibraltar transport was totally due to the atmospheric pressure induced dynamics.
13 Using time-splitting, the energy content doubled.

14 An interesting finding of this study is the effect of the numerical scheme on the phase
15 shift between Gibraltar transport and surface mass fluxes. This phase shift modulated
16 the η seasonal oscillation differently in the four experiments. The main differences in
17 the four experiments derive from the introduction of the time splitting formulation,
18 while atmospheric pressure forcing plays a minor role in modulating the phase of the
19 two signals at seasonal scales. The phase shift produced using time-splitting
20 amplifies the phase opposition between surface mass fluxes and the Gibraltar
21 transport, and the resulting stochastic component of the sea level tendency has a
22 smaller amplitude.

23 An analysis of the observed and modelled high frequencies datasets in three different
24 locations in the Mediterranean Sea (although two locations are relatively close to
25 each other: Valencia and Mahon) highlights that the interaction between atmospheric
26 pressure and barotropic dynamics follows different dynamics. In Mahon, an open
27 ocean station in the western Mediterranean Sea (*Fig. 1*, bottom panel), the
28 introduction of the atmospheric pressure forcing in the model represents the
29 fundamental step in reproducing the observed η variability and energetic content. In
30 Venice, located in the northernmost part of a semi-enclosed basin and characterized
31 by very shallow water, the introduction of the atmospheric pressure clearly improved
32 the models capability to correctly simulate the seiches which, in addition to wind

1 regimes, are also driven by the atmospheric pressure differences between the north
2 and south Adriatic. However it is the explicit resolution of the barotropic processes
3 (using the time-splitting) that allows the model to correctly simulate the η dynamics at
4 high frequencies. Finally in Valencia, it is the combination of both the atmospheric
5 pressure and the time splitting, that enabled the model to reach the correct energetic
6 levels at high frequencies.

7

1 **Appendix A**

2 The NEMO model is freely available under the CeCILL public license. After
3 registering at the NEMO website (<http://www.nemo-ocean.eu>), users should follow
4 the procedure described in the "NEMO Quick Start Guide" section to access and run
5 the model. The physical setup of the configurations used in the present manuscript
6 can be obtained starting from the GYRE standard configuration and modifying the
7 following parameters.

8 **CPP keys:**

9 **GYRE:**

10 key_gyre key_dynspg_ft key_ldfslp key_zdftke key_iomput

11 **NEMO-MFS-3 and NEMO-MFS-4:**

12 key_myconfig key_mpp_mpi key_obc key_zdfric key_dynspg_ts key_iomput

13 **NEMO-MFS-1 and NEMO-MFS-2:**

14 key_myconfig key_mpp_mpi key_obc key_zdfric key_dynspg_ft key_iomput

15

16 Namelist values should be modified according table A1

17

18 Namelist:

	GYRE	MFS-1	MFS-2	MFS-3	MFS-4
In_zco	True			false	
In_zps	False			true	
In_ana	True			false	
In_blk_mfs	False			true	
In_rnf	False			true	
In_bfrimp	True			false	
nn_eos	2			0	
In_traadv_tvd	True			false	
In_traadv_muscl	False			true	
In_traldf_lap	True			false	
In_traldf_bilap	False			true	
In_traldf_hor	False			true	
In_traldf_iso	True			false	
In_hpg_zco	True			false	
In_hpg_zps	False			true	

In_dynldf_lap	True	false			
In_dynldf_bilap	False	true			
rn_ahm_0_blp	0	-5.e9			
rn_aht_0	1000	-3.e9			
In_apr_dyn	False	false	false	true	true

1

2 **Acknowledgements**

3 This work was supported by the European Commission MyOcean 2 Project (FP7-
4 SPACE-2011-1-Prototype Operational Continuity for the GMES Ocean Monitoring
5 and Forecasting Service, GA 283367) and by the Italian Project RITMARE, la Ricerca
6 iTaliana per il MARE (MIUR-Progetto Bandiera 2012-2016).

7

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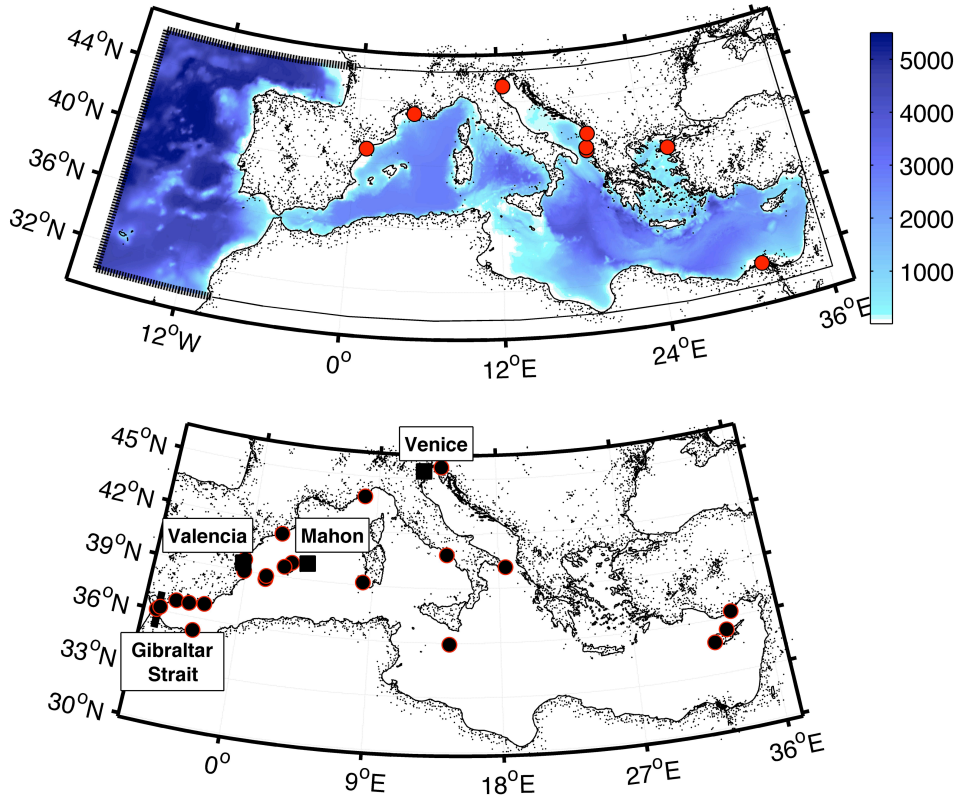
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- 21
- 22

NEMO				
	MFS-1	MFS-2	MFS-3	MFS-4
Horiz. Resolution	1/16 Degree			
Vertical Discretization	72 z levels with partial cells. (<i>ln_zps = .true.</i>)			
Horiz. Viscosity	Bi-Laplacian $A_{mh} = -5e.9 \text{ m}^4\text{s}^{-1}$ (<i>ln_dynldf_bilap = .true.</i>)			
Horiz. Diffusivity	Bi-Laplacian $A_{th} = -3.e9 \text{ m}^4\text{s}^{-1}$ (<i>ln_traldf_bilap = .true.</i>)			
Vertical Visc. scheme	Pacanowski & Philander (<i>key_zdfric</i>)			
Free-surface formulation	Filtered (<i>key_dynspgflt</i>)		Time-Splitting (<i>key_dynspgts</i>)	
Time-step	600s		Number of barotropic sub-time steps <i>nn_baro</i> =100	
Initial Condition	MedAtlas Climatology			
Air-sea fluxes	MFS-Bulk formulae (<i>ln_blk_mfs = .true.</i>)			
Atmospheric press. <i>ln_apr_dyn =</i>	No <i>.false.</i>	Yes <i>.true.</i>	No <i>.false.</i>	Yes <i>.true.</i>
Runoff	As Surface boundary condition for S and w (<i>ln_rnf = .true.</i>)			
Solar radiation	2 Bands Penetration (<i>ln_qsr_2bd = .true.</i>)			
Lateral momentum B.C.	No-sleep (<i>rn_shlat = 2.</i>)			
Bottom momentum B.C	Non linear friction (<i>nn_bfr = 2</i>)			
EOS	UNESCO - Jackett and McDougall (1994) (<i>nn_eos = 0</i>)			
Tracer Advection	Up-stream / MUSCL (<i>ln_traadv_muscl = .true.</i>)			
Momentum Advection	Vector form (energy and enstrophy cons. scheme) (<i>ln_dynadv_vec = .true. ln_dynvor_eeen = .true.</i>)			
Back. Vertical Visc.	$A_{mv} = 1.2e-5 \text{ m}^2\text{s}^{-1}$			
Back. Vertical Diff.	$A_{tv} = 1.2e-6 \text{ m}^2\text{s}^{-1}$			
Vertical visc/diff Scheme	Implicit (<i>ln_zdfexp = .false.</i>)			

2 Table 1 NEMO –MFS configurations with corresponding cpp keys and namelist
3 variables.

4

1



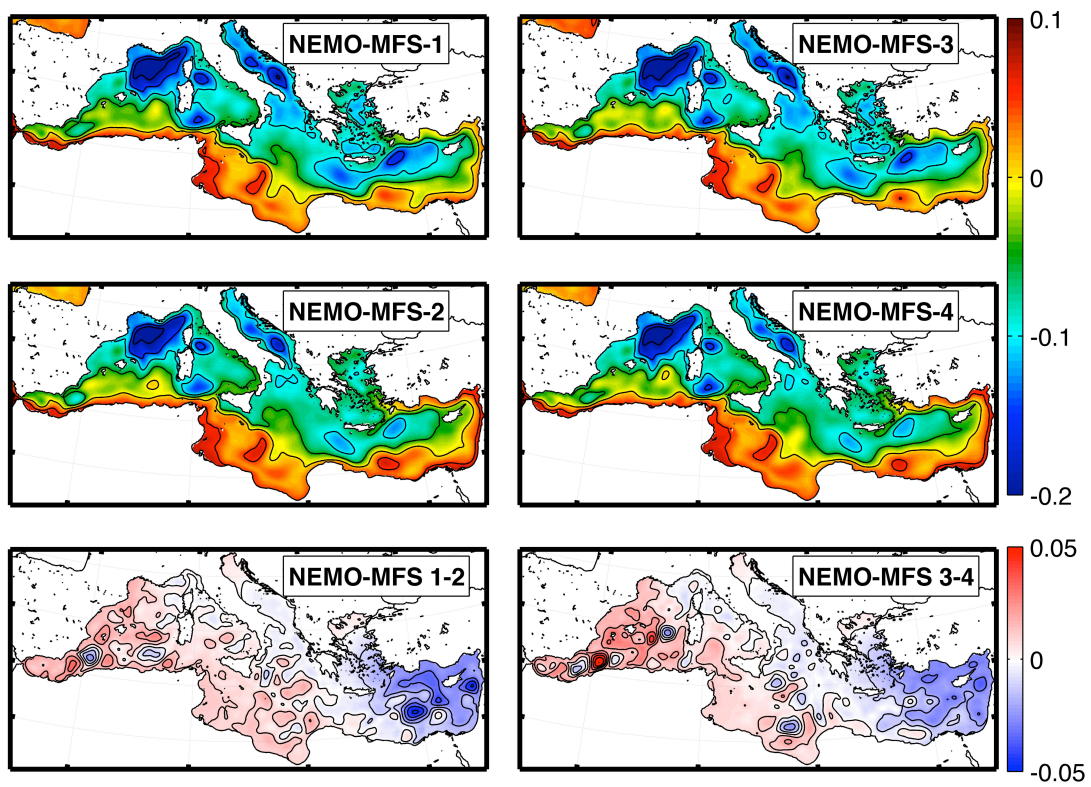
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3 Figure 1 **Upper Panel**: Model domain. Bold dashed lines in the Atlantic indicate the
4 location of the lateral boundaries of the model. Red circles indicate river locations and
5 Dardanelles inflow. **Bottom Panel**: Black circles indicate tide gauge positions. Dark
6 squares indicate the positions of the tide gauges collecting high frequency data. The
7 Gibraltar Strait is also shown.

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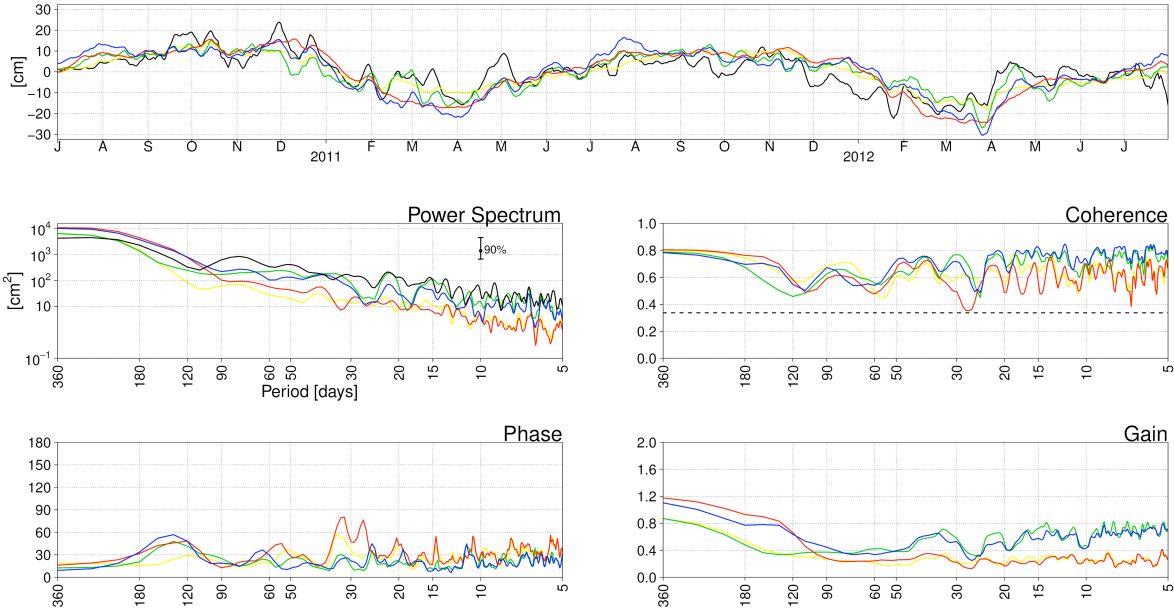
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Figure 2 Horizontal maps of the two-year mean component of the sea surface elevation in the four experiments (units are meters). The two bottom panels represent the sea surface elevation differences between the experiments with and without atmospheric pressure forcing for the time-splitting (right) and the filtered free surface (left) cases.

1



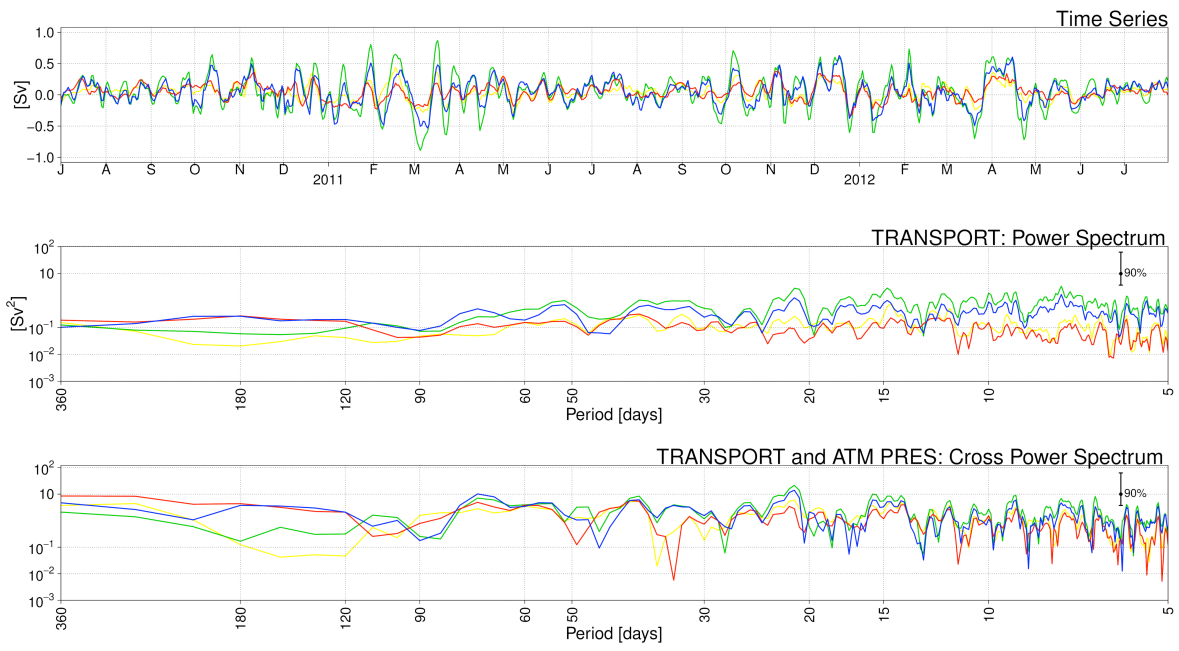
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3 Figure 3 **Top Panel:** Mediterranean mean sea level time-series from the four
4 experiments and observations averaged over the tide gauge positions shown in Fig.
5 1. The black line represents observational data, the red line represents NEMO-MFS-1
6 results, the blue line represents NEMO-MFS-2 results, the yellow line represents
7 NEMO-MFS-3 results, and the green line represents NEMO-MFS-4 results. **Left**
8 **Middle Panel:** η power spectra for observations and model results, units are cm².
9 **Right middle, left bottom and right bottom panels:** coherence, phase (degrees)
10 and gain computed between observations and model, respectively. Units in the x axis
11 are periods in days.

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3 Figure 4 (**Top Panel**) Gibraltar transport time-series from the four experiments.

4 **Middle Panels** Gibraltar transport power spectra.. **Bottom Panels** Cross power

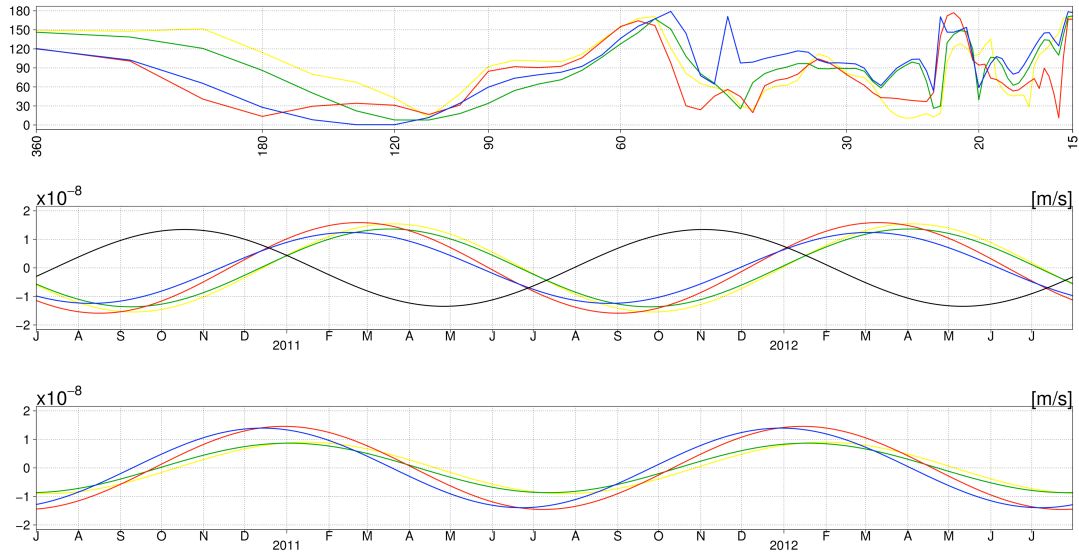
5 spectrum between Gibraltar transport and atmospheric pressure. Colours as in Fig.

6 03.

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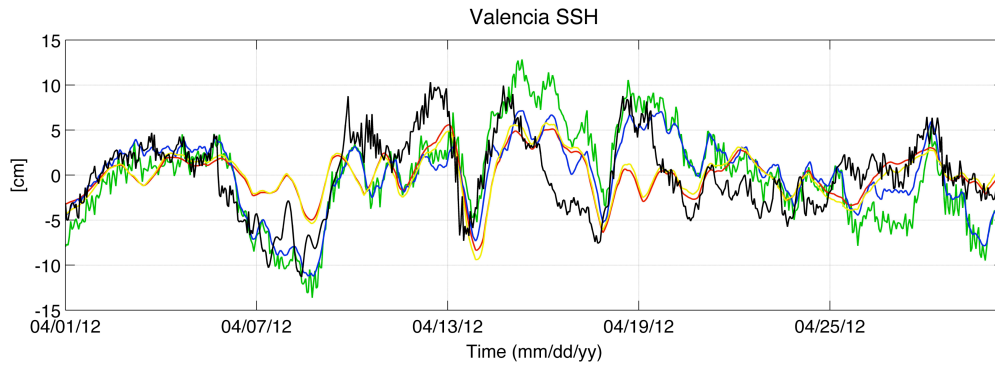
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Figure 5 **Top Panel:** Phase analysis between Gibraltar transport and surface mass
fluxes. **Middle Panel:** Gibraltar Transport for the four experiments and surface mass
flux reconstructed using only seasonal frequencies. The solid dark line indicates the
surface mass fluxes (identical in all the model simulations), coloured lines indicate
model results as in Fig. 3. **Bottom panel** Seas Surface Height stochastic component
reconstructed using only seasonal frequencies.

9

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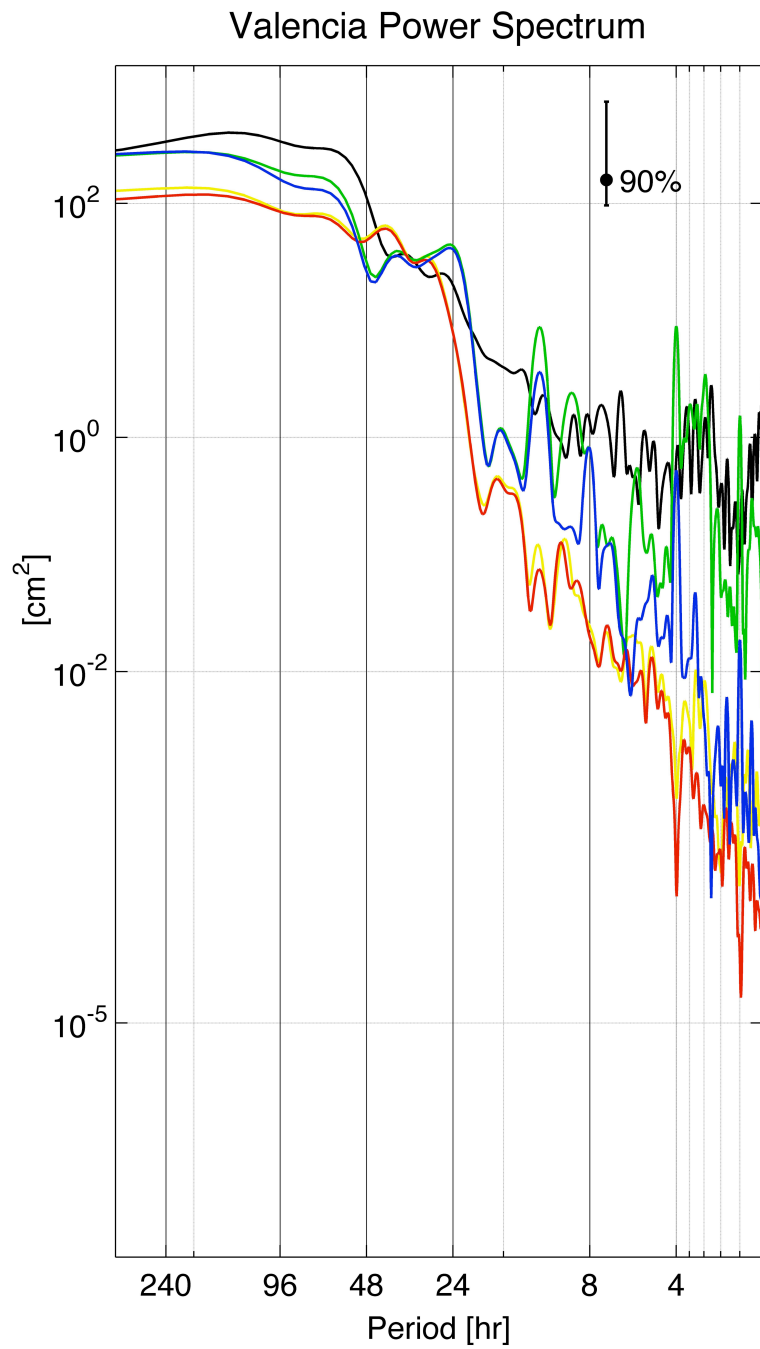
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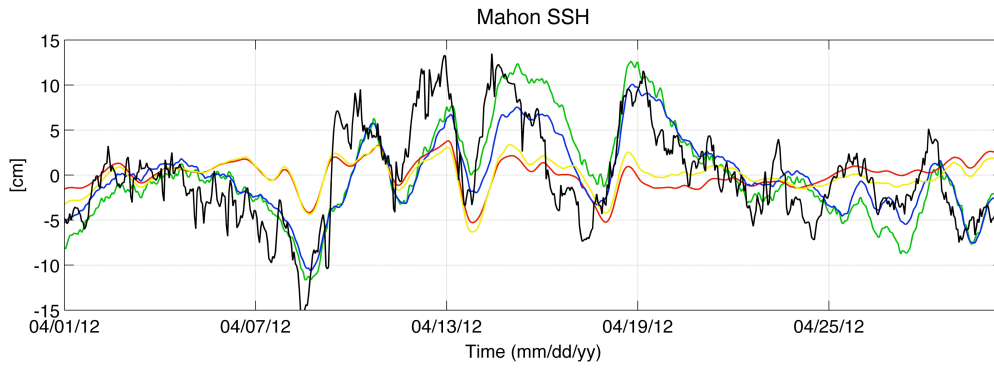
3 Figure 6 Valencia sea surface elevation time-series from observations and models

4 results. Colours as in Fig. 3.



1
 2 Figure 7 Valencia sea surface elevation power spectra from observations and models
 3 results. Colours as in Fig. 3.
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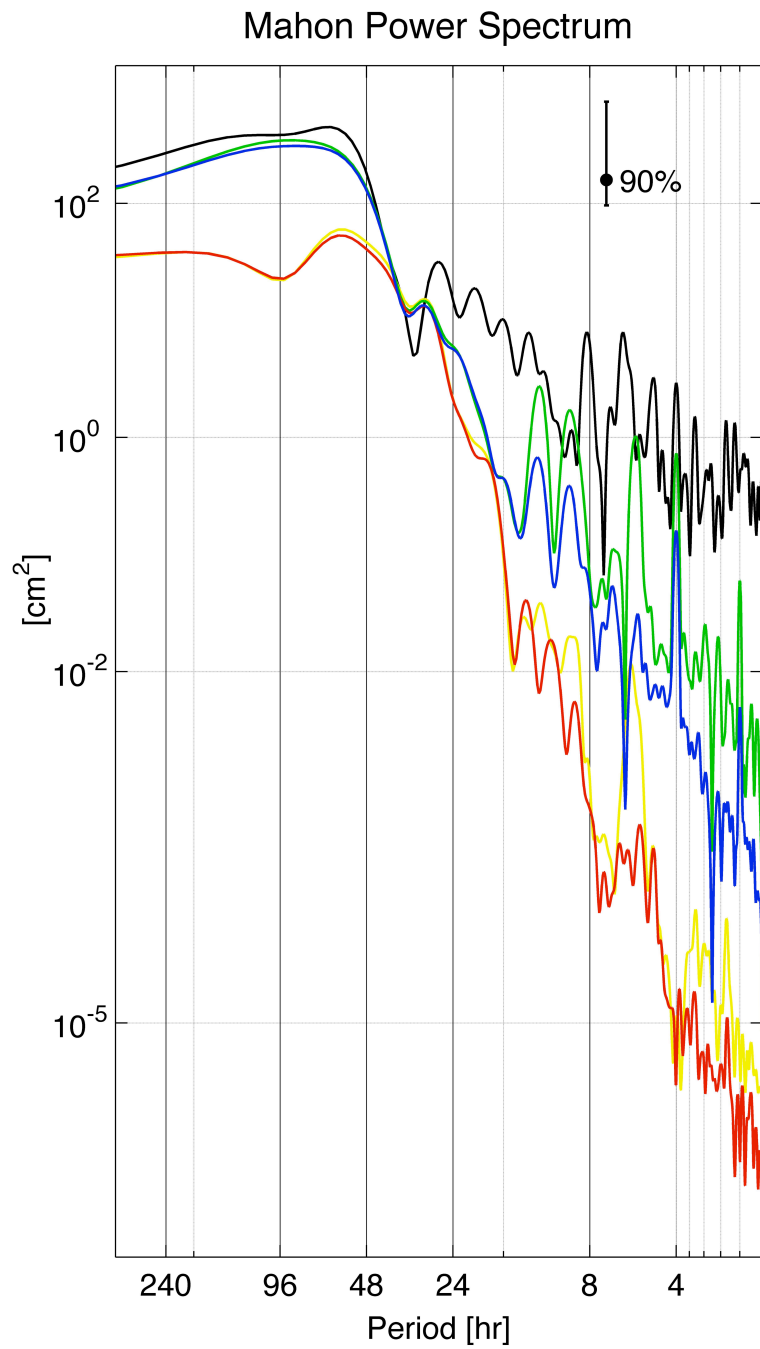
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3 Figure 8 Mahon η time-series from observations and model results. Colours as in Fig.

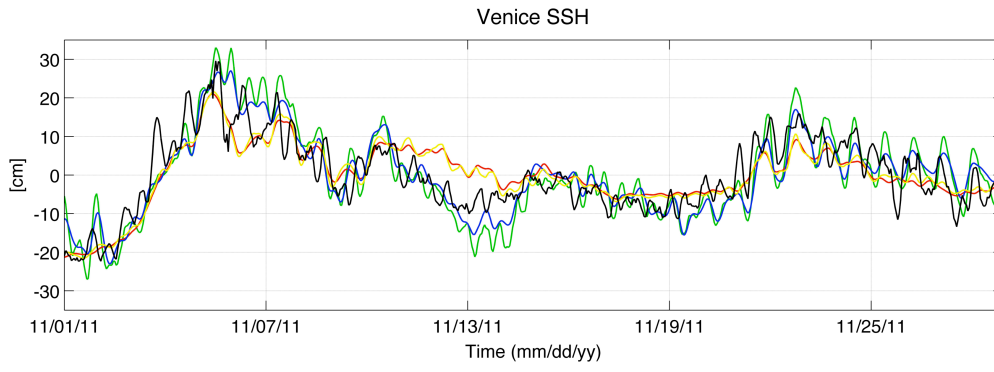
4 3.



1
 2 Figure 9 Mahon η power spectra from observations and model results. Colours as in
 3 Fig. 3.

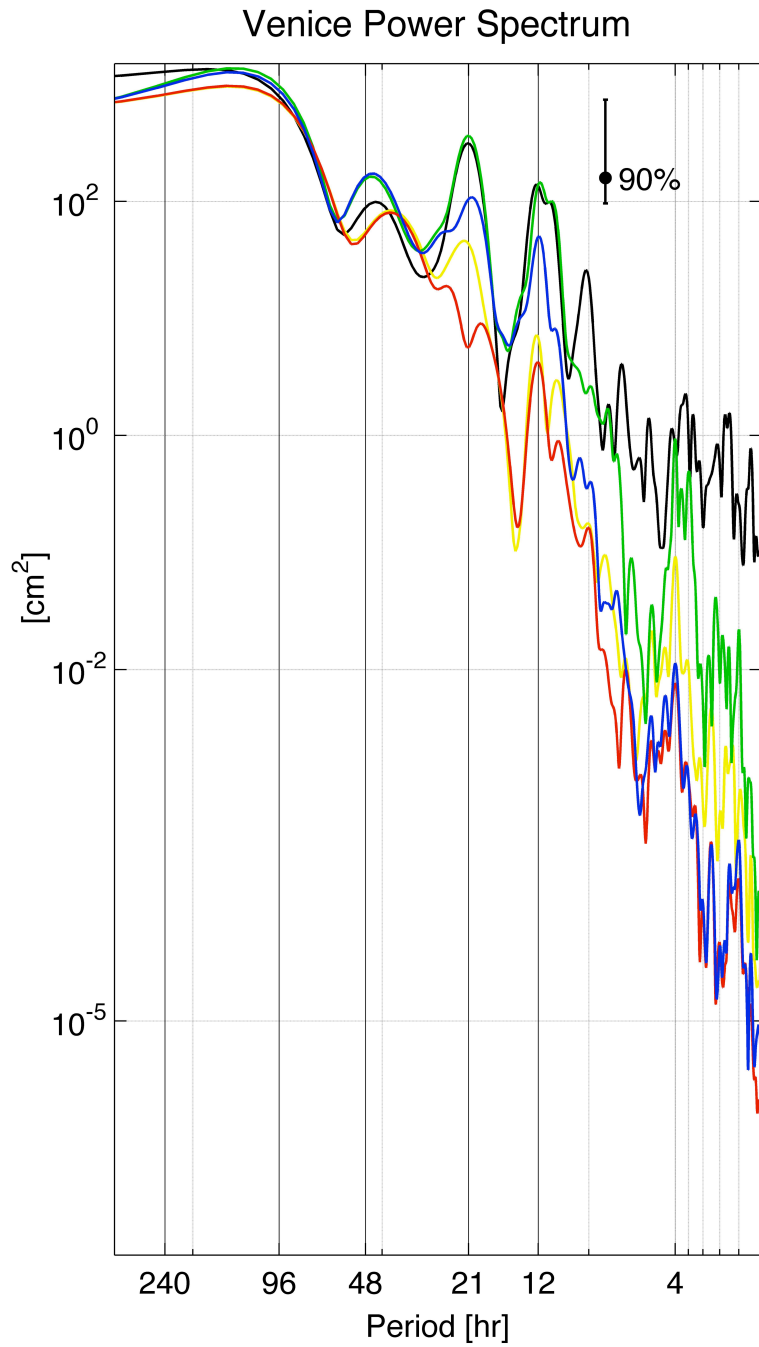
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Figure 10 Venice η time-series from observations and model results. Colours as in Fig. 3.



1
 2 Figure 11 Venice η power spectra from observations and model results, Colours as
 3 in Fig. 3.