Anonymous Referee #1

The manuscript aims to investigate whether inclusion of air pressure as a force at the surface boundary may alter sea level solutions by the NEMO model in the Mediterranean at different frequency bands. The paper is nicely written and for sure deserves the publication, but after solving a major methodology problem and some small issues. The major problem with the methodology is that the authors analyse modelled high-frequency sea level oscillations (on hourly timescale), while all model runs are forced by 6-h ECMWF operational fields, including the winds and air pressure which are dominantly driving sea level oscillations on these frequencies.

- We thank the Referee#1 for the general positive comment on our manuscript. However we partially agree on the potential methodology problem regarding the forcing data frequency. Detailed comments and answers are provided in the following text.

First, I wonder how the forcing fields are interpolated from 6-h resolution to the model resolution – linear, quadratic or else?

- The 6hr frequency ECMWF data are linearly interpolated onto the model time-step, the text has been modified accordingly.

Whatever method of interpolation is used, it cannot properly describe the processes visible in air pressure and wind series that are occurring on the periods below a day (and there are a lot of them visible in air pressure and wind measurements, like rapidly moving frontal zones and cyclones, convective systems, gravity waves, squall lines, etc.), resulting in aliased forcing and therefore in aliased modeled hourly sea level series. For that reason a number of conclusions (e.g., regarding the Adriatic seiches at 21-h period, see below) in the manuscript are wrong. Therefore, the analysis in frequency domain should be cut down not at 2 h period, but on at least 24-h period.

- The reviewer is right, 6hr frequency atmospheric data under-sample atmospheric phenomena occurring at higher frequency and therefore could produce aliased model results. However, previous works have already proved the possibility to simulate spectra of high frequency oceanic oscillations (the seiches in the Adriatic Sea, or other processes in the Mediterranean basin) forcing ocean models with operational ECMWF products characterized by 6hr temporal resolution. For instance:

- Pascual et al. (2008), suggested by the referee, compare model response to atmospheric pressure and wind forcing using ECMWF fields (6hr the DAC data according the manuscript nomenclature) and higher frequency forcing data (HIPOCAS) concluding that, with the only exception of the Portuguese Atlantic coast, differences between the two simulations are negligible at frequencies higher that 20 days. See Figure 11 of the suggested manuscript.
- Wakelin and Proctor (2002), compare Storm Surge model results forced with different atmospheric data (namely UK-MetO 3hr observations, ECWMF 6hr operational and LAMBO 6hr high horizontal resolution data) and obtain good results when comparing model result with tide-gauges observations power spectra in the Adriatic Sea during occurrence of Seiches (Figure 10 and 13 of their manuscript). They have identified and underlined major limits of model run

forced with ECMWF data; however a good reproduction of the energetic content has been achieved.

In the manuscript we focus on the spectra because it is important to understand the frequencies that our NEMO-Mediterranean implementation is able to resolve on the base of the numerical formulation of the SSH and connect these frequencies to atmospheric phenomena. We are aware about ECMWF limits but the agreement between obtained results (see the new Venice power spectra) and previous studies suggest that the 6hr data could be enough for the manuscript purposes. For these reasons we think our analysis of the Mediterranean high frequency response in terms of power spectra is appropriate. However following Reviewer's suggestion we suggest to include a new sentence at the beginning of the paragraph 4.2 about the possible limitations due to the ECMWF forcing frequency as following:

"It is worth to mention that the 6 hr frequency ECMWF forcing field does not properly sample the full spectra of the atmospheric phenomena and aliasing problems may occur. Consequently the corresponding oceanic response could be only partially resolved by the NEMO configurations. Thus, some differences between modelled and observed sea level at high frequency could be due to the sampling frequency of the atmospheric data. However previous studies (Pascual et al. 2008, Wakelin and Proctor, 2002) have already proved the possibility to reproduce the energetic content of high frequency (up to 4hr) Mediterranean processes using similar atmospheric data (Wakelin and Proctor, 2002). Prior to the comparison, the tidal signal was removed from the observed dataset and steric effect superimposed on model results."

Minor to moderate suggestions:

Page 3897/3898. There is newer literature on the inverse barometric effects in the Mediterranean, like Le Traon and Gauzelin (1997), Pasaric et al. (2000), Raicich (2003), Vilibic (2006), Pasqual et al. (2008) – the authors limit their literature mostly to a 30 of more years old papers (which should be mentioned, but not limited to). Generally, the references about IB effect in the World Ocean and the Mediterranean are pretty old and should be accompanied with some of fresh research and findings.

- We thank the Referee#1 for this important and very useful comment. More recent and most of the suggested manuscripts have been included in the discussion and therefore in the bibliography.

Page 3989. What is r.h.s?

- r.h.s means right hand side. We think it is not necessary to explicitly write the acronym, however if the reviewer insist we can easily modify the manuscript accordingly.

Page 3990, lines 5-15. They belong to introduction.

- The text has been modified accordingly and the sentence moved to the introduction.

Page 3994, lines 12-13. ": : : and the structures are more realistic in the atmospheric forcing cases". Please proof this statement with the reference!

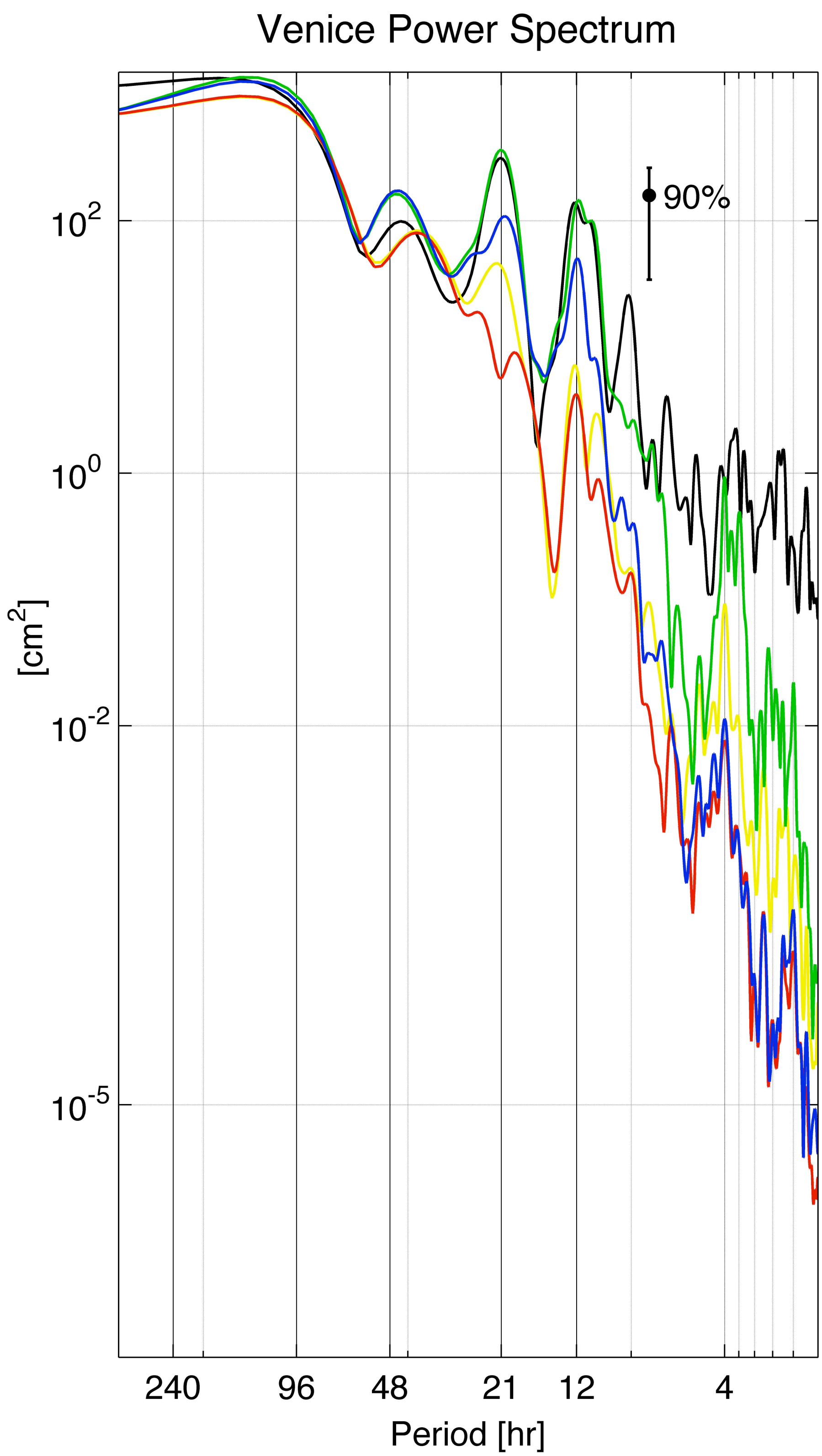
- The reference to Pinardi et al 2013 paper has been included. The paper provides a detailed description of the Mediterranean surface circulation structures based on a reanalysis dataset.

Page 3999, line 15. "sea level" not "seal level".
-Thanks, text modified accordingly.

Page 4000, lines 16-17. 21 h-1 is not inertial frequency of the Adriatic Sea (it is seiches frequency), but 17 h-1.
- We apologize for the mistake, and thank the Referee#1 for pointing out this error in the manuscript. The corresponding sentence has been corrected.

Page 4000, lines 17-22. The existence of seiches on the Venice measured series is reproduced by the model when introducing air pressure forcing, but in my opinion not because of realistic forcing but because of introduction of aliased air pressure high-frequency energy due to 6-h forcing resolution. The Adriatic seiches are normally generated by rapid changes in winds (from sirocco towards lebicchio and tramontana/bora) after pronounced pushing up of waters in the northern Adriatic by strong and long-lasting sirocco wind (e.g., Cerovecki et al. 1997; Raicich et al., 1999), and air pressure is of minor importance for the process – this is also wrongly stated in page 4003, lines15-19. Again, the effects of 6-h forcing to the modeling of 21-h process should be carefully assessed. As suggested above, it would be wise to rise the lower period of analysis to 24 h (and not to only Nyquist's 12 h), to avoid these problems and not to discuss the frequency range which is affected with aliasing problems.
- Cerovecki, I., Orlic, M., Hendershott, M.C., 1997. Adriatic seiche decay and energy loss to the Mediterranean. Deep-Sea Res. I, 44, 2007-2029.
- Raicich, F., Orlic, M., Vilibic, I., Malacic, V., 1999. A case study of the Adriatic seiches (December 1997), Il Nuovo Cimento C, 22, 715-726

- The possibility to simulate Adriatic seiches with ECMWF 6hr forcing data has been evaluated in previous scientific studies (Wakelin and Proctor 2002). Based on this manuscript and on our results we think that the analysis provided in our manuscript is correct. The Referee is right about the sentence at page 4003 lines 15-19 where the effect of the Atmospheric pressure seems to be overestimated. The sentence has been rephrased. We tried also to include the references suggested by the Referee#1. Moreover redrawing the Venice power spectra according the Referee#2 suggestions the occurrence of Adriatic Seiches and the model skill in reproducing this phenomenon is more evident. A new Figure for the Venice (also Mahon and Valencia) power spectra have been added where it is now more evident that the model configurations with time-splitting both simulate the seiches but the one with atmospheric pressure ameliorate the model results. On the other hand the NEMO configuration using the filtered free surface without the atmospheric pressure forcing does not capture the 21 hr peak. The text describing the figure has been modified accordingly.


Venice Power Spectrum
90%
10^2
10^0
10^{-2}
10^{-5}
[cm^2]
240
96
48
21
12
4
Period [hr]

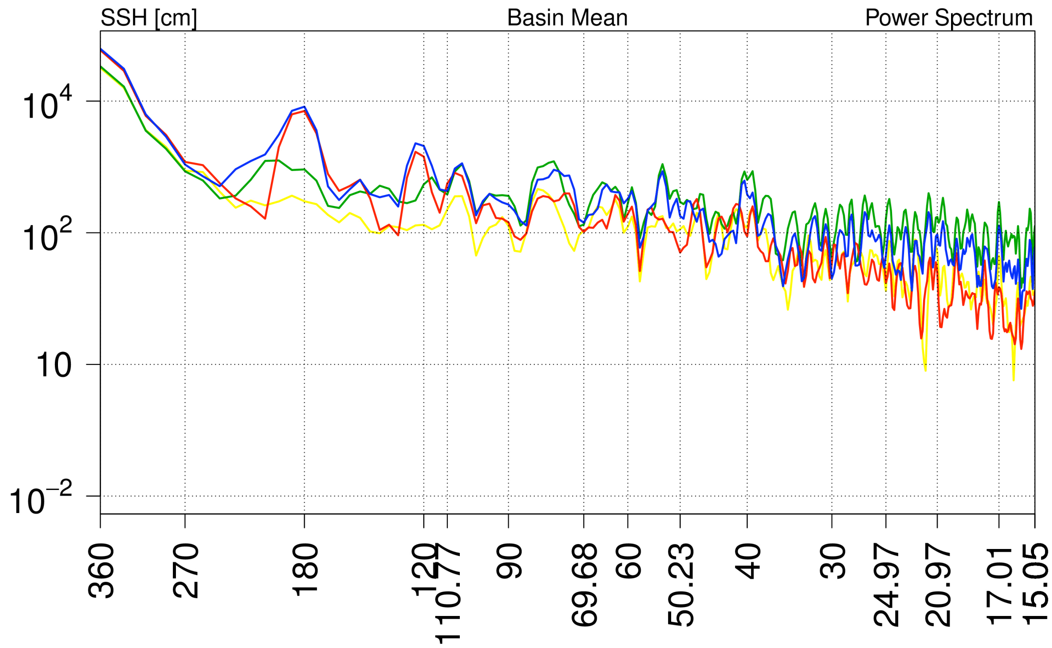
References:

- Pascual, A., Marcos, M., Gomis, D., 2008. Comparing the sea level response to pressure and wind forcing of two barotropic models: Validation with tide gauge and altimetry data. J. Geophys. Res., 113, C07011, doi: 10.1029/2007JC004459.
- S.L. Wakelin, R. Proctor. 2002. The impact of meteorology on modelling storm surges in the Adriatic Sea. Global and Planetary Change 34 (2002) 97– 119

Referee #2

(1) The model runs are from 7 January 2004 to 31 December 2012, yet all comparisons are done with tide gauge data from July 2010 to July 2012. Comparison should be done with tide gauge data covering the whole of studied interval. There is not much point in discussing spectral energy at periods longer than 200 days, when there are only 2-3.5 oscillations of these period in the modeled time series. These tide gauge data (at least at a hourly sampling interval) are certainly available for a number of the Mediterranean stations. If there is a problem with using longer time series because of model spin up time (but is it 6.5 years?), I either suggest starting model earlier, or refraining from discussing too much these long periods.

- To our knowledge tide-gauge stations data spanning the entire period covered by model runs can be retrieved only through the Permanent Service for Mean Sea-Level (PSMSL, 2014; Holgate, 2014), as monthly or annual time-series. In general, for the Mediterranean area, higher frequency long time-series data availability is an issue. In this study high frequency data (1 day or 1hr) have been obtained from the MyOcean Mediterranean Med-MFC only since 2010. However, also in this case, most of the recorded series have gaps potentially affecting the statistics. The selected stations are the only ones providing long enough series without significant data gaps.
Moreover, we agree with the Referee#2 about the sampling error and potential differences deriving from the time coverage in particular analyzing the lower frequencies. In order to evaluate potential sampling problems deriving from the relatively short time interval analyzed a preliminary analysis have been carried out. A dedicated spectral analysis has been carried out considering the entire model runs period. Basin averaged time-series have been considered. The power spectra obtained (Figure below) are similar and comparable with those shown in Figure 3 in terms of the energetic content associated to the annual (360 days) and semi-annual (180 days) frequencies, and those that characterize the medium frequencies processes (i.e. from 120 to 15 days). A sentence has been included in the manuscript. Similar results have been obtained also for the Gibraltar Transport Spectra. It is also worth to mention that using longer time-series we obtained smaller confidence intervals ensuring the correctness of the results presented in the manuscript. However we think is important to focus on the comparison with the observations available.



(2) I fully agree with reviewer 1 that periods shorter than 12 hours should not be analyzed due to aliasing problems; and would also, to be on a safe side, suggest cutting analysis at least at the 24 hours period. In any case, I suggest the authors to create spectra for the modeled time series at three selected stations for the whole modeling time interval for periods shorter than 48 hours, and to check whether or not they get some spurious spikes which could be due to aliasing. E.g. all of your spectra of model time series have strong peaks at 4 hours, likely at 2.5 hours also, and at some other periods as well. Also whatever you reproduce at the Adriatic has a spectral peak centered at 23-24 hours, and not at 21 hours.

- See answer to Referee#1 about the possibility to model spectra of oceanic phenomena with frequency higher than the atmospheric forcing. Moreover previous manuscripts (Leder and Orlic 2004) have already proved the possibility to study high frequency oceanic processes in the Mediterranean analyzing hourly frequency time series shorter than one month. We agree with the Referee#2 that spectral analysis spanning longer temporal windows could provide additional and more robust information, however we believe that the current analysis clearly show the differences between the different numerical schemes and the effect of the atmospheric pressure which is the main scope of the manuscript. Since the strong peaks mentioned by the Referee#2 are often in agreement with the observations we think that the suggested additional analysis would not bring additional info and the major manuscript results will be unchanged.

We therefore prefer to maintain the current temporal windows for the high frequency spectral analysis having overlap with observations in order to better validate the model results.

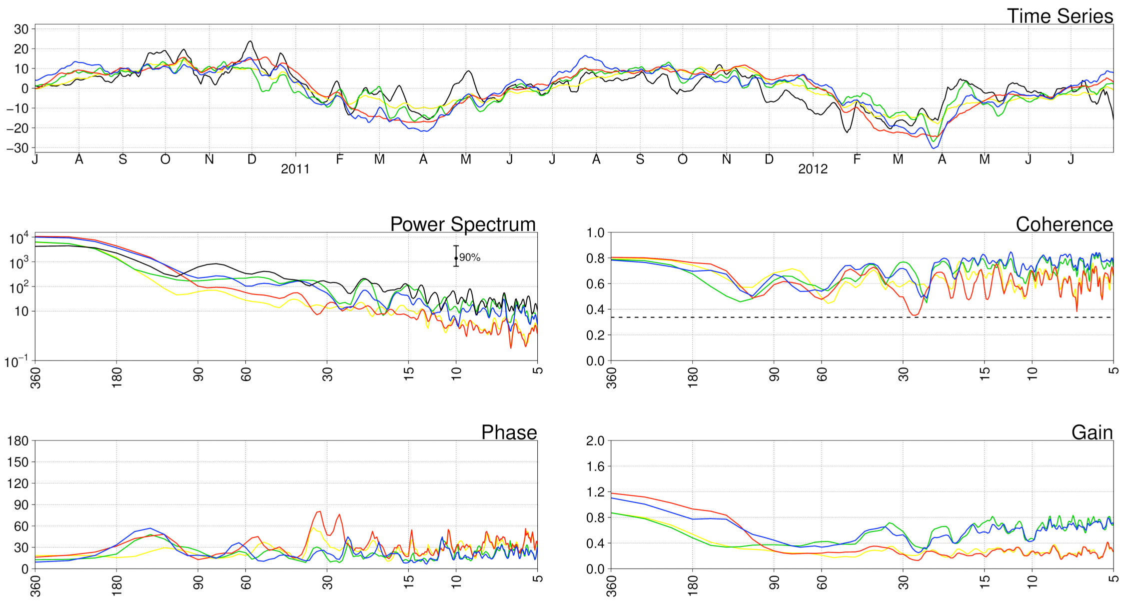
For what concerns the Adriatic seiches peaks, we have redone the figures changing the X/Y aspect ratio and filtered the spectra partially following the Referee suggestion. It is easier now to read the exact peaks period which is 21 hr. The new figure has been provided in the answers to the Referee#1 and will substitute the present one.

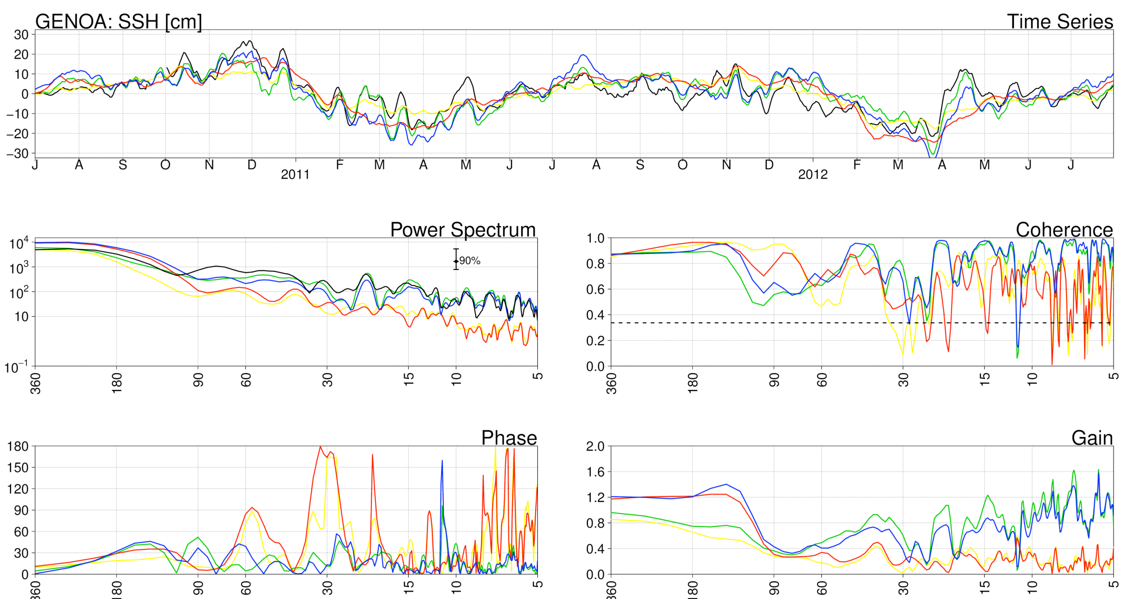
(3) Analysis of water mass transport through Gibraltar is interesting. But this should be compared with some measurements, or, if these are not available, at least with existing literature. What is real amplitude of seasonal oscillations of transport through the Gibraltar strait?

- We thank the Referee for this positive comment. To our knowledge few studies focused on the annual frequencies of the Gibraltar transport mostly due to the scarcity of long enough observation time series. One of the few and most recent papers addressing the issue and providing estimates of the investigated quantity is Lafuente et al. 2002. Our results fit within the confidence interval provided by the Authors. The reference has been included in the text and the manuscript modified accordingly.

(4) Finally, if you are to discuss influence of including air pressure effect into numerical model, you should include tide gauge stations which are influenced by the largest horizontal pressure gradients into analysis - like Genoa (but here it's important to use periods shorter than 15 days), and then stations for which there are largest pressure differences between model runs (as seen from Figure 2).

- We thank the Referee for this important comment. Individual tide-gauge data analysis has been performed during our study. As also mentioned in the manuscript, it is evident that for period shorter than 15 days the response to the atmospheric pressure varies within the Mediterranean Basin, with some areas more sensitive to the forcing than others. Following the Referee suggestion we have analyzed the Genoa time-series individually and produced an analysis equivalent to current Fig.3 of our manuscript. The analysis confirms that for frequencies lower than 15 days the behaviour is very similar to the current Fig.3 of the manuscript. For frequencies up to 5 days the atmospheric pressure effects become more evident and differences between model configurations' are significant. Further investigation of this issue produced a new Fig.3 where the abscissa now reaches 5 days showing the similarity between the model and the Genoa tide gauge station (even if less pronounced because other stations have different behaviour). Therefore we suggest to modify the abscissa limit in Fig.3. We also mention that the amplitude of the effect of the atmospheric pressure for period shorter than 15 days varies within the basin.





More specific comments:

Figure 3. Is this data from all tide gauge stations? Authors should smooth their spectral estimates (using window averaging); all these peaks in the middle left figure are distressing. Also, level of confidence should be added to all spectral plots.

- We have better specified the data sources (all the tide-gauge stations) and we have already created new figures with smoothed spectra and level of confidence. The new figures will be used in the final manuscript version.

Figure 4. Authors should add levels of confidence, and when crossing from left to right column in plots, authors should continue their plots where they've stopped them (at 72 hours period). X-label should be given (or written in Figure caption).

- The figure has been redrawn including levels of confidence and X-label provided in the corresponding Figure Caption.

Figure 5. What is black line in middle plot, i.e. from which experiment is it originating from?
- The black line in the middle plot is the surface mass flux (Evaporation – Precipitation - Runoff) which is identical in all the experiments. The text has been be modified accordingly, explaining that all the model experiments have identical mass flux at the air-sea interface.

Figure 6-8. Restrict to periods longer than 24 hours (you can filter short periods out from tide gauge time series), estimate spectra for whole modeling interval, add confidence levels. I would even do spectral analysis for periods of 1 - 360 days for selected stations.
- Figures 6-8 have been modified (see previous answer) smoothing high frequencies and changing the X/Y axes aspect ratio to better identify peaks in the spectra. However, as also explained in the previous answers to Referee#1, we think that the analysis at frequencies higher than 24 hr is appropriate and correct. Estimated spectra for the whole modelling interval would be difficult to validate due to the observational gap.
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<u>References:</u>

Lafuente J. G., Delgado, J., Vargas, J. M., Sarhan, T., Vargas, M. and Plaza, F. Low frequency variability of the exchanged flows through the Strait of Gibraltar during CANIGO. Deep Sea Research, 49, 19, 4051-4067. 2002

Permanent Service for Mean Sea Level (PSMSL), 2014, "Tide Gauge Data", Retrieved 21 Jul 2014 from http://www.psmsl.org/data/obtaining/.

Simon J. Holgate, Andrew Matthews, Philip L. Woodworth, Lesley J. Rickards, Mark E. Tamisiea, Elizabeth Bradshaw, Peter R. Foden, Kathleen M. Gordon, Svetlana Jevrejeva, and Jeff Pugh (2013) New Data Systems and Products at the Permanent Service for Mean Sea Level. Journal of Coastal Research: Volume 29, Issue 3: pp. 493 – 504. doi:10.2112/JCOASTRES-D-12-00175.1.