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20/11/2019

Dear Robert Marsh,

Enclosed are replies to referee comments RC1, RC2 and RC3 on our submitted manuscript entitled *"A Model of Black Sea Circulation with Strait Exchange (2008-2018)"* in queue to be published in the journal *Geoscientific Model Development (GMD)*.

We have replied the various queries made by the referees, in the meantime few improvements on the manuscript according to the valuable suggestions given. We admit that some of the text to be updated had suffered from being hastily written. We value most of the referees' comments to lead us in the updates.

The referees' comments were mostly positive. Yet we noted some misunderstanding on the part of Referee #1, who placed some comments on the role of the present study that would be more appropriate for a research journal in place of GMD. Which is why we felt obligated to explain to the Referee the reasons for submitting the present model development paper to GMD, with appropriate title and contents. This motivated us not to leave some of specific questions un-answered, although we did not agree on the basic concepts in question, not relevant in the present context. These questions were possibly a result of some confusion created on our part, that would have been corrected in the final text. For instance, the various comments on the evolution and disappearance of Cold Intermediate Water (CIW), a climate event already detected by several authors and replicated by available observations as well as in our paper, were supplemented by appropriate references. Similarly, we had to include evidence that we should have kept private, in order to point to the advantages of our present methodology in relation to existing methods in estimating the critical role of Bosphorus fluxes.

Thank you for your support for what we foresee to be a successful publication.

Sincerely,
Murat Gündüz

Attachments: (1) Replies to comments RC1, RC2, RC3, (2) first update to the manuscript with added paragraphs and references.

Interactive comments (>> italic black) by Anonymous Referee #1 (RC1), 23/09/2019

Authors' responses are given in blue print in each section

>> The manuscript describes an implementation of the Black Sea circulation model (BSEA), which is based on the NEMO version 4.0 (Madec, 2008). The model domain includes the deep Black Sea basin (max depth: 2178 m) together with the shallow Azov Sea (depth 10m) in the north and the Marmara Sea in the south. In order to represent the Bosphorus exchange flows coupled to Black Sea, an artificial box representing the Marmara Sea and the Bosphorus Strait have been added to the domain. The manuscript focused mainly on the analysis of the 10-year (2009-2018) variations of temperature and salinity using their monthly and sub-basin averaged values.

We thank referee # 1 for valuable comments, based on brief reading of the paper.

>> The model could provide a good opportunity to improve the modelling ability of the Black Sea by incorporating the Bosphorus Strait into the simulations. However, I would like to express concerns that in its current form the manuscript focusing largely on the validation of a model rather than using the model to fully explore the processes responsible for the trends or capturing real dynamical features. This study does not focus adequately on new knowledge and instead focuses largely on developing and validating a model. I think the paper needs to be substantially revised in order to focus more on the new understanding of the processes that can be obtained, i.e. using the model as a tool to explore them. I recommend a major revision or possibly a resubmission.

Our main objective in the present study has been to achieve incremental new development of a model set-up for the Black Sea, satisfying inflow / outflow boundary conditions at the Bosphorus which allow to preserve approximate hydrological balance of the basin. This, however, is not a very simple task, technically not a well-posed problem to determine the natural limits of the model domain, subject to given constraints of ocean models. These limitations have been better appreciated in a series of past research articles carried out on the very systems of straits and basins that are in question (* references partially provided in the present paper).

In the present article, we aim for a realistic representation of the hydrometeorological fluxes of the Black Sea, with in and out fluxes created at the Bosphorus in response to an exterior box with specified seasonal hydrology. This approach allows addressing only one question at a time in an incremental way, identifying the Bosphorus climatological exchange as a missing element in earlier work on Black Sea modeling.

Otherwise we only know too well that the physical coupling between the basin-scale dynamics of the Black Sea and the energetic coastal-scale dynamics of the Bosphorus Strait would lend themselves to detailed investigations much broader in context. For instance, in the present study, we have limited ourselves to the exchange fluxes through a straight channel and smooth topography not sufficiently resolved by the present model grid, simplifying the steep topography and keeping the dynamics of hydraulic controls and exit buoyant jets etc. (* see references partially provided in the present paper) out of our focus and again circumventing the technicalities of where to set the artificial box domain to specify seasonal hydrography of the adjacent Marmara basin.

While limiting our attention to Bosphorus fluxes provided by this simple coupling scheme, we also have made use of the best available re-analyses and hydro-meteorological data sets, in order to account for missing information on interannual river and overland hydrology, finally with an objective to test which of these sources of environmental controls lead to the best comparison with in-situ data, notably with the ARGO floats data set, reflecting the closest agreement with the rapid environmental change clearly observed in the Black Sea in the recent decades (Stanev et al., 2018, 2019).

While a general overview of historical development of Black Sea modelling is not in order within the present context, we only give a short review of Black Sea modeling that indirectly has accounted for Bosphorus fluxes in the previous models. To the best of authors' knowledge, modelling of the Black Sea circulation and hydrography allowing for a system of open boundary conditions applied at the Bosphorus has not been attempted in the available literature so far, although a number of stand-alone Black Sea models have attempted indirectly accounting for fluxes at the Bosphorus (Stanev et al., 2003, 2004, 2005; Miladinova et al., 2017, 2018). Our incremental model strategy, on the other hand, could be compared to the addition of an "Atlantic Box" preferred in the early phases of Mediterranean Forecasting System, MFS (Oddo et al., 2009), which only recently have been updated to involve further refinements of coupled systems (CMEMS, 2017). Recently however, there have been various efforts to couple the entire series of straits and basins of particular characteristics together, by making use of high-resolution unstructured meshes (Ferrarin et al., 2018; Federico, 2017; CMEMS, 2017) which have yet to survive the various obstacles to properly represent coupling for each of the straits (not only Bosphorus and Black Sea but others), realistically accounting for fluxes variability between the various coastal and basin-scale elements.

In short, we do not agree with Referee #1 statement that the *"paper needs to be substantially revised in order to focus more on the new understanding of the processes"*, although we aim to improve the manuscript based on the reviews. We provide the above summary on the development of a Black Sea model with improved Bosphorus fluxes, along with other refinements keeping abreast of the recent environmental changes in the system.

We have decided to revise the abstract and some paragraphs, which may have been interpreted by the Referee as general claims we have expressed of the present model had led us to conclude. Part of these claims were derived from other new evaluations of Black Sea climate, which are now better referenced. We would also like to state that our contribution to *Geoscientific Model Development (GMD),* as implied by the name, is within the scope of the international journal, serving for geoscientific model development other than the hypothesis testing expectations of the Referee.

>> Detailed comments are provided below. Main points: In my opinion, a major weakness of the manuscript is the lack of hypothesis testing. In the Abstract the

authors suggested that "The present formulation with temperature and salinity relaxed to the observed seasonal climatology of the Marmara box and open boundary conditions are found to enable Bosphorus exchange with upper, lower layer and net fluxes comparable to the observed range. This in turn enables to capture the trend of rapid climatic change observed in the Black Sea in the last decade." I did not find in the entire manuscript how the authors test and prove the above hypothesis that their model can capture the trend of rapid climatic change. The manuscript does not present any new aspect or particular characteristic of the Black Sea hydrodynamics. For example, I would like to see how the new approach, taking into account the Bosphorus Strait in simulations, helps to gain new knowledge about the disappearance of the cold intermediate layer (CIL). Comparison with other existing Black Sea models is not presented, so I cannot decide whether the proposed model better simulated the Black Sea hydrodynamics or not.

We have edited the abstract to express better the quality of predictions based on improvements in the Bosphorus open boundary and Black Sea, as well as the data sets used in verification. Our earlier statements in the abstract may have implied that the observed environmental changes in the Black Sea system were directly connected with the methods we used; while in fact various sets of independent observations point to the particularly rapid changes in the Black Sea. We only have gotten closer to their representation in the model, thanks to the improvements we have made.

Along the same line of our earlier comments, the main purpose of the present study has not been hypothesis testing in the most general sense, but rather to search for one of the most essential Black Sea model improvements needed to account for seasonal fluxes at the Bosphorus open boundary, being one of the essential elements of overall hydro-climatology. On the other hand, we believe closing the gaps of knowledge in predictions of the present and future states of the system in question can certainly form the basis for hypothesis testing.

We aim to produce better results, choosing the most recent version of the ocean model core, as well as the best available sets of observational data sets, evaluated in the present study.

The model has been rigorously evaluated by comparison of the results with the available observations obtained by ARGO floats. The figures shown in the comparison section of the paper were constructed by using all available ARGO floats data. To the authors knowledge, very few previous attempts have been made to compare model results with the freely available data sets supplied by ARGO floats over many years. It is one of the main contributions of our novel Black Sea modelling effort that will have made its impact on reliable results.

On Referee #1 comments on whether the new model improvements had any new knowledge added on Black Sea hydrodynamics, we would like to answer with particular tests we have made during this work.

Indeed, there were some significant differences in model behavior in early runs with one grid artificial open boundary, compared with the seasonal hydrology specified in an external box. The model improvements far surpassed the short-term, seasonal and interannual variability and trends demonstrated in predictions of earlier cases which were not always in the same periods and model settings, and therefore not worthy of mention.

In-house sensitivity analyses corresponding to the model setup have been made but had to be skipped, being outside the scope of the present study. Further comparisons with most recent coupled models and observations, that in fact we should not allow to be publicly shared, are provided to counter some claims of Referee #1. We only provide them in order to show that questions of reliability and testing have been answered outside the scope of the present paper submitted to GMD.

The following figures from a follow-up study are only privately provided for comparisons between Bosphorus temperature data predicted by using the same setting as the present study with respect to observed temperatures and those predicted in the current Black Sea CMEMS context. The continuous observations have been obtained at station K2 (described in Altıok and Kayışoğlu, 2015 and Özsoy and Altıok, 2016a,b) next to the exit of the Bosphorus shown in Figure 1.

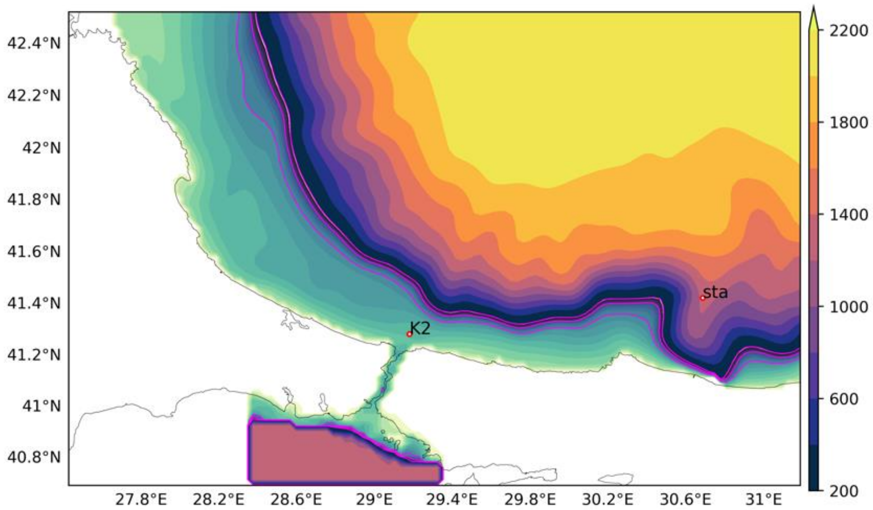


Figure 1: Location of the observation station K2.

The predicted temperature at 60 m depth compared with observations at station K2 are given in Figure 2. The red line is the observation, the black line is what is replicated by the current model and the green line is the most recent CMEMS operational Black Sea model, which seems not to have reached proper Bosphorus dynamics. The model improvements replicating those within the current study are clearly demonstrated in this figure. The temperature of the lower layer water of Mediterranean origin in the Bosphorus (well-known from many years of measurements in the Bosphorus, in literature cited in the present paper) is better represented with the current model.

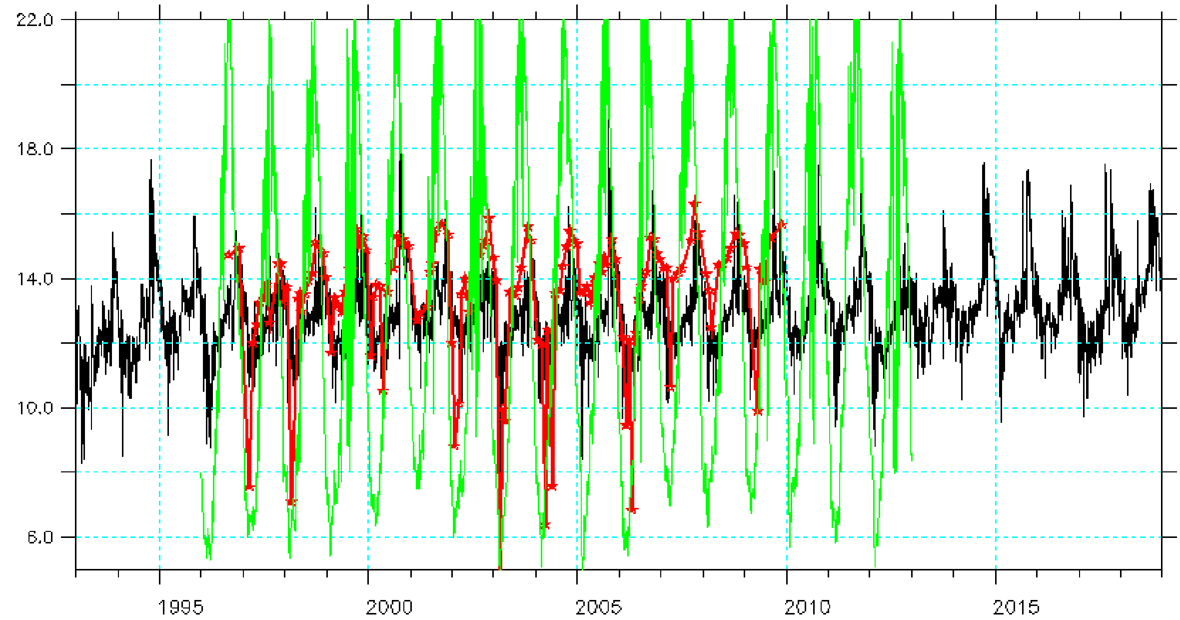


Figure 2: Time series of temperature at 60m at station K2. Red line is observation, black line is current model and the green line is CMEMS Black Sea model.

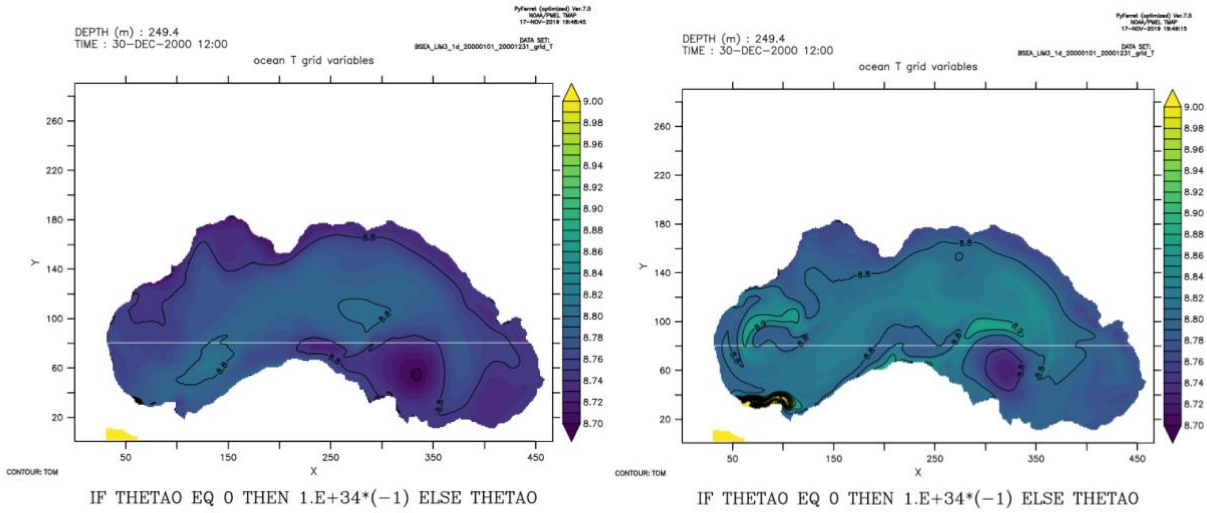


Figure 3. Comparison of model temperature at depth level 250m, for two values of the lateral viscous velocity 0.1 and 0.15 m/s.

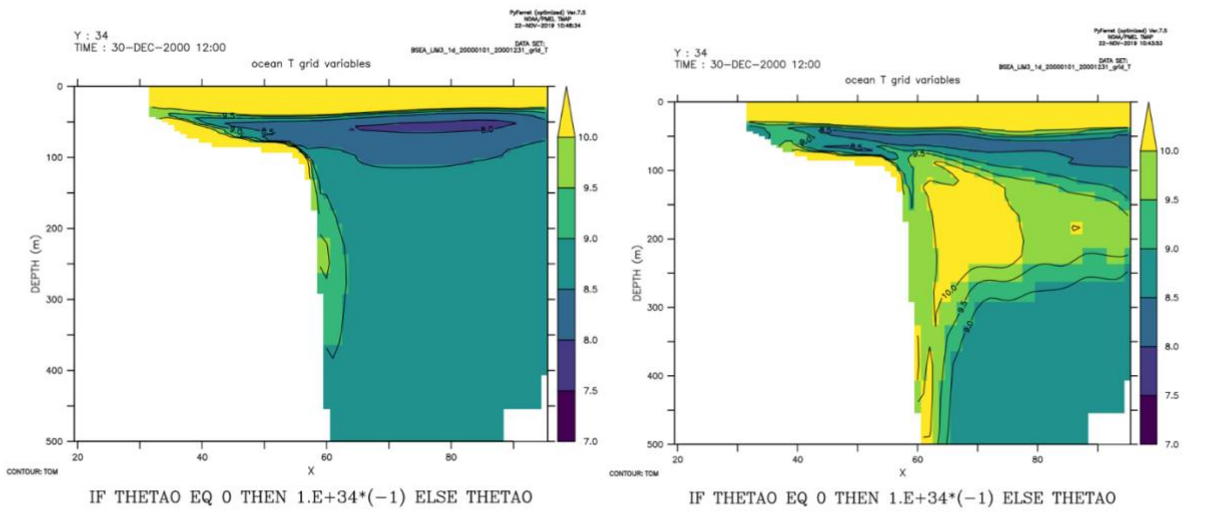


Figure 4. Comparison of model temperature across a south to north section starting from the Bosphorus mouth and the adjacent shelf and slope regions, for two values of the lateral viscous velocity 0.1 and 0.15 m/s.

The main improvements in the present study were in all time scales in question, and have been tested to produce extensive comparisons with the ARGO hydrology and sea level data, much different from the early cases, and parameter sensitivity was always tested.

The current objective of incremental model development for coupled Black Sea and Bosphorus has thus been achieved in the present study. We intend to continue scientific investigations aimed to fully understand coupled hydrodynamics of adjacent basins and straits, in addition to further investigations of climatic / environmental changes in the region with extended periods and domains.

>> I doubt that the proposed model cannot capture the CIL adequately. Figure 7 gives the average vertical distribution of temperature for the 3 regions, namely, East, West and Rim. Even the quality of the figure is very low I can see that the CIL is almost absent. Many recent studies based on ARGO float data (Stanev et al, 2013, 2014, 2017 and2018) and numerical modelling (Miladinova et al., 2017 and 2018) clearly show the presence of CIL in the period 2009-2015. CIL is eroded but exists in winter-spring. I recommend the authors to look at the figures of Stanev et al. and try to visualize their results in a similar readable way.

We are aware of the various references pointed out and indeed we have tried to test the effects of the modeling improvements on CIL, which equivocally shows reduced CIL over the recent years (in parallel with some recent results, e.g. Miladinova et al., 2017, 2018; Stanev et al., 2019). However, we only had to compare model results either on selected domain averages or at selected stations, producing the overall climatic trends captured in the references. We have changed the quality and legends of the figures for better visibility. Figure 7 has been constructed by sampling each ARGO profile at its particular location in the model domain. While the figure is seen as a basic plot, it is actually generated by using thousands of ARGO profiles. The shaded background is the model results and the black contours are from these observations. It is therefore clearly seen that there is no CIL in some years in the observations (black contours), which is also perfectly captured by the model. It is clear that the observations are confirmed by the model results.

>> Figure 7 shows many crossed lines of different meaning and the same colour. Please mark the isotherms 7, 8.5 and 15◦C. What is the meaning of the white gaps in Figure 7? The CIL is not visible in figs. 12 and 14,too. On the base of the proposed model, the authors stated ".

The warmer water at the upper surface is the 15oC isotherm, which is the boundary of the thermocline in the Black Sea. In addition, we have labeled the 7oC and 8.5oC isotherms according to the Referee's suggestion. It is most likely that the figure might have caused some confusion: since this figure is constructed by sampling of ARGO floats, the white gaps correspond to data missed by the ARGO floats, always sampled at their individual depths.

>> The abundance of CIL in the initial conditions maintained for the first two years contrasts with the single event of cold intermediate water formation in 2012, and the weaker event in 2017". The CIL is present during the period of 'spin-up' and disappears after the second year. Thus, I can conclude that the model is not able to represent the CIL adequately. Most of the figures are of poor quality. The range of variable variation is too wide to distinguish small but important variation

As stated above, the black contour in the Figure is derived from the ARGO profiles. The disappearance of the CIL after 2014, and the weaker one in 2017 are real events clearly shown in the observations. So, the model properly represents "truth" (in parallel with recent results reviewed above), with model results in good agreement with the available data from ARGO floats.

>> Validation. It is not enough to present the comparisons graphically. It is necessary to give the coefficient of correlation, the absolute values of errors, and standard deviation. It is better to substitute the figures 8 and 9 with a table containing the statistics of the comparisons.

We believe that Figures 8 and 9 contain much more information than statistics presented in tables. The seasonal and interannual variations of the temperature and salinity can easily be detected in these figures. The comparison of the model results with the numerous observations during the course of the model simulation is clearly seen in these figures. It is not clear what additional evaluation of model improvements could be provided by statistics of unevenly distributed observational data.

>> I cannot understand the following conclusion: "The reduced convection events in recent years both in the deeper central basin and near the coast stand as evidence that great changes are occurring in the Black Sea, much likely to be an amplified response to climate change in the isolated Black Sea basin severely limited in its communication with the Mediterranean Sea and eventually with the world ocean." Which their results indicate the "reduced convection" and also "great changes"? What is the meaning of the phrase "much likely to be an amplified response to climate change in the isolated Black Sea"?

These statements reflect the introductive review of the Black Sea as a deep basin fed by excess of water, in contrast in the Mediterranean, also separated by unique controls at straits, amplifying the climate change response in the isolated domain, which are well known facts from the literature reviewed in the paper as well as elsewhere. Perhaps we need to clarify and soften our sentences in the revised manuscript in order not to be misunderstood as rather unique contributions of our study. Yet we still feel our study is entitled to emphasize these facts, which are found to be enhanced in our results.

>>I strongly recommend that the authors should: a) identify the novelty of the knowledge gained; b) add the comparison with other numerical simulations; c) improve the quality and readability of the figures; d) present statistics for the model-model and model-data comparisons; e) improve the presentations of results and conclusions.

Minor points: I suggest authors to use the MEDAR climatological data (http://modb.oce.ulg.ac.be/backup/medar) for initialization of temperature and salinity. MEDAR data is freely available until 2002. The thermohaline fields in 1992 are not appropriate for initialization of simulations that start in 2008.

I couldn't understand this sentence "In this way the CIL, which is a product of convective mixing in the Black Sea, influences water mixed on the shelf and returned back to deeper layers of the Black Sea, also influencing Marmara Sea." How the return back of CIL waters is presented by the model?

We have so far commented on the purpose of our study limited to the incremental model development, essentially not negating the objective of "new knowledge gained", by providing up to date dynamics, seeking best observational support published within the scope of the *Geoscientific Model Development (GMD)*. Within this context, we have not been seeking statistical and physical comparison with other numerical models which are in fact not directly comparable and not up to date in these aspects. Improvement in results are limited only by the incremental method we have used, and will be followed up with future work that is already in the queue.

What is expressed by Referee #1 as a suggestion to use climatic data from data bases such as the MEDAR is something we have always suffered from in our earlier work in Black Sea modelling. We have found that such statistical averaging of seawater properties with different instruments and within different time, geography and depth windows are bound to be defective and almost always very noisy. Because we are firm believers in initialization, we have chosen the first whole-basin coverage collaborative sampling by Black Sea riparian countries, despite the fact that the initialization data are from a different decade, allowing for some initial spin-up on the order of about two years based on our experience. We believe this is a strong point that we find to be of value in our study.

The following references and interpretations have been added in the paper:

CMEMS (2017). Copernicus Marine Environment Monitoring Service, Special Issue #56, September 2017.

Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R, Mossa, M. 2017. Coastal ocean forecasting with an unstructured grid model in the sout.hern Adriatic and

northern Ionian seas. Nat Hazards Earth Syst Sci. 17(1):45-59

Ferrarin, C., Bellafiore, D., Sannino, G., Bajo, M. and Umgiesser, G., 2018. Tidal dynamics in the inter-connected Mediterranean, Marmara, Black and Azov seas. Progress in oceanography, 161, pp.102-115.

Jorda, G., Von Schuckmann, K., Josey, S.A., Caniaux, G., García-Lafuente, J., Sammartino, S., Özsoy, E., Polcher, J., Notarstefano, G., Poulain, P.-M., Adloff, F., Salat, J., Naranjo, C., Schroeder, K., Chiggiato, J., Sannino, G. and D. Macías (2017). The Mediterranean Sea Heat and Mass Budgets: Estimates, Uncertainties and Perspectives, Progress in Oceanography, 156C, 174-208, doi: 10.1016/j.pocean.2017.07.001

Miladinova, S., Stips, A., Garcia-Gorriz, E., Macias Moy D. (2017). Black Sea thermohaline properties: Long-term trends and variations, J. Geophys. Res. Oceans, 122, doi:10.1002/ 2016JC012644.

Miladinova, S., Stips, A., Garcia-Gorriz, E., Macias Moy D. (2018). Formation and changes of the Black Sea cold intermediate layer, Progress in Oceanography 167, 11–23Stanev, E. V., M. J. Bowman, E. L. Peneva, and J. V. Staneva. (2003). Control of Black Sea inter- mediate water mass formation by dynamics and topography: Comparisons of numerical simulations, survey and satellite data. Journal of Marine Research 61:59-99.

Oddo, P., Adani, M., Pinardi, N., Fratianni, C., Tonani, M., Pettenuzzo, D. (2009). A nested Atlantic-Mediterranean Sea general circulation model for operational forecasting, Ocean Sci., 5, 461–473

Özsoy, E. and H. Altıok (2016a). A Review of Hydrography of the Turkish Straits System, in Özsoy, E. et al. (editors), The Sea of Marmara - Marine Biodiversity, Fisheries, Conservation and Governance, Turkish Marine Research Foundation (TÜDAV) Publication #42, 13-41.

Özsoy, E. and H. Altıok (2016b). A Review of Water Fluxes across the Turkish Straits System, in Özsoy E. et al. (editors), The Sea of Marmara - Marine Biodiversity, Fisheries, Conservation and Governance, Turkish Marine Research Foundation (TÜDAV) Publication #42, 42-61.

Peneva, E., Stanev, E., Belokopytov, V., Le Traon, P.-Y. (2001). Water transport in the Bosphorus Straits estimated from hydro-meteorological and altimeter data: seasonal to decadal variability, Journal of Marine Systems 31, 21–33.

Schroeder, K., Garcìa-Lafuente, J., Josey, S. A., Artale, V., Nardelli, B. B., Carrillo, A., Gačić, M, Gasparini, G. P., Herrmann, M., Lionello, P., Ludwig, W., Millot, C., Özsoy, E., Pisacane, G., Sánchez-Garrido, J. C., Sannino, G., Santoleri, R., Somot, S., Struglia, M., Stanev, E., Taupier-Letage, I., Tsimplis, M. N., Vargas-Yáñez, M., Zervakis, V., G. Zodiatis (2012). Chapter 3: Circulation of the Mediterranean Sea and its Variability, In: Lionello, P. (ed.), The Climate of the Mediterranean Region - From the past to the future, Elsevier, 592 p.

Stanev, E. V., M. J. Bowman, E. L. Peneva, and J. V. Staneva. (2003). Control of Black Sea intermediate water mass formation by dynamics and topography: Comparisons of numerical simulations, survey and satellite data, Journal of Marine Research 61:59-99.

Stanev, E. V., Staneva, J., Bullister, J. L., Murray, and J. W. (2004). Ventilation of the Black Sea pycnocline: Parameterization of convection, numerical simulations and validations against observed Chlorofluorocarbon data, Deep-Sea Research 51(12):2137-2169.

Stanev, E. (2005). Oceanography, Vol.18, No.2, June2005.

Stanev, E. V., Poulain, P.-M., Grayek, S., Johnson, K. S., Claustre, H., Murray, J. W. (2018). Understanding the dynamics of the oxic-anoxic interface in the BlackSea. Geophysical Research Letters, 45, 864–871. https://doi.org/10.1002/2017GL076206

Stanev, E. V., Peneva, E., Chtirkova, B. (2019). Climate change and regional ocean water mass disappearance: Case of the Black Sea. Journal of Geophysical Research: Oceans, 124, 4803–4819. https://doi.org/10.1029/2019JC01507

Interactive comments (>> italic black) by Anonymous Referee #2 (RC2), 23/09/2019

Authors' responses are given in blue print in each section

>> The manuscript reports development of a high resolution Black Sea circulation model, with additional coupling the basin hydrodynamics with exchange flows at Bosphorus Strait by including an artificial box on the Marmara side. It is a big effort such high resolution model to run with complicated time dependent boundary conditions that could be the case, different than actual conditions. According to the authors, the objective is to achieve coupling with Bosphorus Strait, extending the domain to include a portion of the Marmara Sea and also the Azov Sea.

We thank Referee #2 for a brief description of the paper.

>> In my opinion, this main objective of this paper is rather well met. The abstract is compact containing the purpose of the study and the most important results. The scientific approach and applied m ethods are valid. The manuscript is well organized and accomplished by briefly reviewing some of the relevant literature and explaining how the current study is related to them beginning from earlier studies up to recent researches skipping unnecessary details. On the other hand, I am not sure that this model enables to capture the trend of rapid climatic change observed in the Black Sea. Although satisfactory results, the model with current configuration is far from producing results comparable with real observations. Discrepancies can be through the time dependent boundary conditions, i.e. imposing climatological river discharges rather than actual, inaccuracies in precipitation and evaporation estimates, as well as model approximations of the free surface. All these factors could have contributed to the difference in model and observed values. While this paper entitled "A Model of Black Sea Circulation with Strait Exchange (2008-2018)" is a model development paper, could be published in the journal after technical corrections.

We thank Referee #2 for an encouraging review, based on a positive reading of the manuscript. We are aware of the problems that are mentioned in the review and intend to continue our efforts to improve the model results in the present paper as well as in future work that is already planned: To name a few, we have already constructed monthly river fluxes of main rivers, and intend to introduce corrections to shortwave radiation penetration component, based on climatological chlorophyll-a obtained from satellites. The model results have been rigorously compared with the available ARGO floats (thousands of profiles), and to the authors' knowledge, there has not been any similar effort in the Black Sea model literature, even though the ARGO observations are free for public use. We believe that this is a rather important step for the Black Sea model community.

>>Here is the list of suggested some corrections and changes:

- Page 8, by the caption of Figure 4, "Marmara box shown in the 1" can be replaced by "Marmara box shown in the Figure 1"

It is done.

- Page 10, Line 15, please change “Table 1” with “Table 2”.

It is done.

- Page 14, Line 10, the word “on” is written with double “o”.

It is done.

- Page 16, Line 11, “May 2012” is wrongly written.

It is corrected.

- Figure 7 and Figure 14 are of poor quality. The plots color scale and contour level could be changed appropriately to demonstrate the thermohaline structure of the sub-regions and stations better.

It is improved.

- Table 2 and Figure 6, no unit information of fluxes in the caption and in the label of y-axis

It is corrected.

- No units were written on the figures and also in the captions starting from Figure 8 to Figure 10.

It is corrected.

Interactive comments (>> italic black) by Anonymous Referee #3 (RC3), 23/09/2019

Authors' responses are given in blue print in each section

>> In the manuscript the authors describe the implementation of a high resolution oceanographic model for the Black Sea and validate its decadal simulations with several in situ observational data sets. The manuscript provides an important contribution for the modelling of the Black Sea and may be published in the Geoscientific Model Development.

We thank Referee #3 for a brief summary of the paper and suggestions for publication of the manuscript.

>> I have several minor comments that should be addressed by the authors before the publication of the manuscript.

>> 1. The abstract states that the boundary condition in the Marmara Sea is climatological and that this enables capturing the climatic change. Does this mean that the climatic change in the Black Sea is independent of the Mediterranean? Has this been demonstrated in the manuscript?

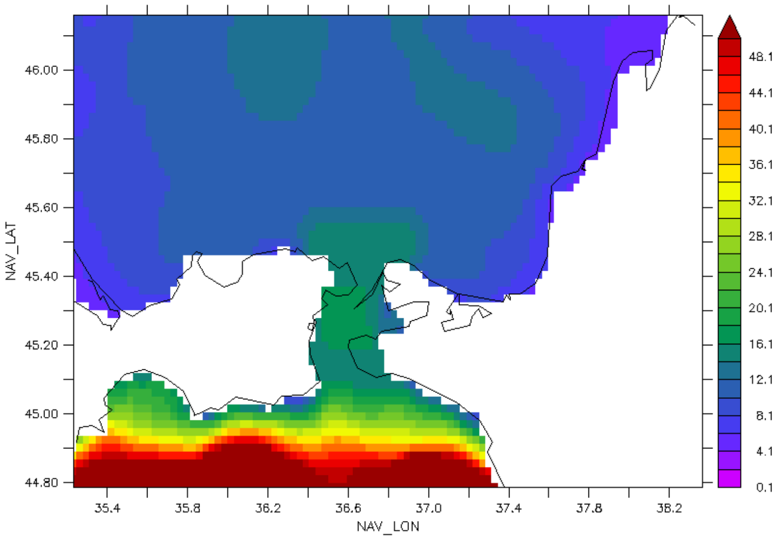
Yes, the expression was rather confusing in the abstract. We only meant that the climatic changes are now apparent in the Black Sea hydrography (with proper references in the text), although we only implied seasonal effects represented in the Bosphorus connection. In reality, of course both the Mediterranean are under the same effects, although more amplified in the Black Sea. We only try to capture the changes in the Black Sea hydro-climatology expressed in observations and model response, where the seasonally adjusted Bosphorus fluxes have a role.

>> 2. Page 1, line 20. I understand that the study cannot give the overview of all literature on the Black Sea modelling. On the other hand, the study should at least collocate itself within the most recent modelling development in the Black Sea by comparing model resolutions and forcing.

We have added new paragraphs with proper references mentioning the most recent modelling development in the Black Sea.

>> 3. Page 4, line 2: Figure 1 does not show the Kerch Strait bathymetry in detail and how it has been enlarged.

Please find below the detailed bathymetry around the Kerch Strait. We can include this figure in final text, to inform that the readers of the zoomed bathymetric information, which was only altered a little in order to avoid instabilities in the initialization and runs of the model associated with short period oscillations of the coupled Azov and Black Sea domains.



>> 4. Page 5, lines 1-3: Why is the smoothing of bathymetry implemented in this model set-up?

We had some numerical instabilities at the beginning of the model run.

>> 5. Page 5, lines 5-8: This sentence is not grammatically correct and should be corrected.

It is corrected.

>> 6. Page 11, line 11: Is it "the depth of the 21 PSU isoline"?

It is 21. The wrong text in the figure caption is corrected. Thank you for this correction.

>> 7. Page 11, line 13: This statement should be rewritten to provide a quantitative comparison instead of an opinion.

This sentence is changed.

>> 8. Conclusion: How does this model implementation differ from the others?

A sentence was added to the introduction section to explain this. Thank you very much.

A Model of Black Sea Circulation with Strait Exchange (2008-2018)

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Abstract. The Bosphorus exchange is of critical importance for hydrodynamics and hydro-climatology of the Black Sea. In this study, we report on the development of a medium resolution circulation model of the Black Sea, making use of surface atmospheric forcing with high space and time resolution, climatic river fluxes and strait exchange, enabled by adding elementary details of strait and coastal topography and seasonal hydrology specified in an artificial box on the Marmara Sea side. Particular attention is given to circulation, mixing and convective water mass formation processes in the model, which are then compared with observations. Open boundary conditions relaxed to seasonal hydrology specified in the artificial box are found to enable Bosphorus exchange with a proper upper, lower layer and net fluxes comparable to the observed ranges. These improvements at the artificial boundary and in the interior evolution of the Black Sea allows the study to capture daily, seasonal to decadal climatic variability and change observed in the Black Sea in the last few decades.

1 Introduction

1.1 A Short Review of Black Sea Oceanography and Recent Modeling Development

The Black Sea is a part of the Old World's seas that has limited communication with the world ocean. Its unique oceanographic characteristics, natural and environmental history have been subject to a number of reviews by (Özsoy and Ünlüata, 1997, 1998; Oğuz et al., 2005; Kosarev, 2007; Sorokin, 2002; Grinevetsky et al., 2002; Vespremeanu and Golumbeanu, 2017). On the other hand, there is clear observational evidence of rapid environmental change in the Black Sea in the recent decades (Capet et al., 2016; Stanev et al., 2019). Fluxes of momentum, water and buoyancy at the sea surface and at coastal and open boundaries dominate the hydrodynamics of semi-enclosed seas. Lateral fluxes, especially articulated in the Black Sea, by inputs from major rivers and the Bosphorus Strait exchange flows demand their adequate representation in this almost totally enclosed sea. Despite relatively small net flux on the order of 0.01 Sverdrup across the strait, strong coupling between the Bosphorus and the Black Sea is suggested by observations, in terms of circulation and mixing in either region.

Various modeling studies of the Black Sea circulation often with objectives similar to ours have considered realistic model configuration, initialization and time-dependent forcing elements aiming to generate results verifiable by observations.

To the best of authors' knowledge, modelling of the Black Sea circulation and hydrography allowing for a system of open boundary conditions applied at the Bosphorus has not been attempted in the available literature so far, although a number of stand-alone Black Sea models have attempted indirectly accounting for fluxes at the Bosphorus (Stanev et al., 2003, 2004; Stanev, 2005; Miladinova et al., 2017, 2018). Previous modeling efforts in the Black Sea considered the Bosphorus exchange fluxes by using different open boundary condition techniques. For example, Staneva et al. (2001) expressed the Bosphorus fluxes by spreading the exchange over five horizontal and five vertical grid points with specified upper and lower salinity in their DieCAST ocean model. (Kara et al., 2008) expressed the imbalance of water budget by adding negative river precipitation (i.e., a river evaporation) at the Bosphorus exit on their HYCOM ocean model. Miladinova et al. (2017) described the Bosphorus inflow/outflow as a river flow by using 3D General Estuarine Transport Model (GETM) model. None of the previous studies did include the Bosphorus exchange dynamics under the real-time atmospheric forcing and circulation, while in the present study we aim to achieve coupling with Bosphorus Strait under real time forcing by extending the domain to include a portion of the Marmara Sea, as will be detailed in the following sections.

Our model strategy, on the other hand, could be compared to the addition of an "Atlantic Box" preferred in the early phases of Mediterranean Forecasting System, MFS (Oddo and Pinardi, 2008), which only recently have been updated to involve further refinements of coupled systems (CMEMS, 2017). Recently however, there have been various efforts to couple the entire series of straits and basins of particular characteristics together, by making use of high-resolution unstructured meshes (Ferrarin et al., 2018; Federico et al., 2017; CMEMS, 2017) which have yet to survive the various obstacles to properly represent coupling for each of the straits (not only Bosphorus and Black Sea but others), realistically accounting for fluxes variability between the various coastal and basin-scale elements.

We skip further review of the voluminous literature on stand-alone modeling of the Black Sea, while in the present study we aim to achieve coupling with Bosphorus Strait, extending the domain to include a portion of the Marmara Sea and also the Azov Sea, as will be detailed in the following sections.

1.2 Interaction with Straits

A unique regime of hydraulically controlled, turbulent and strongly stratified flow is well documented by observations in the Bosphorus (Gregg et al., 1999; Özsoy et al., 1995, 1996; Özsoy and Ünlüata, 1998; Özsoy et al., 2001; Gregg and Özsoy, 2002).

Observations in the Marmara Sea have revealed two-layer stratified flow details, fluxes and circulation in this small internal sea (Ünlüata et al., 1990; Beşiktepe et al., 1993, 1994; Özsoy et al., 2016), connected to the Black Sea and Aegean Sea respectively by the Bosphorus and Dardanelles Straits.

Estimates of Bosphorus fluxes contributing to the Black Sea have been made based on satellite observations and numerical models (Peneva et al., 2001; Staneva et al., 2001; Stanev et al., 2004). Often these indirect methods have yielded inaccurate estimates of the net and layer averaged two-way fluxes through the Bosphorus by deforming the statistics of the short-term variability often displayed at coastal scales of the strait.

In addition to estimates of annual and seasonal fluxes by in-situ measurements obtained throughout the years, recent observations based on instrumental measurements continued for extended periods have been of great value to establish better statistical reliability in these estimates (Özsoy et al., 2001; Jarosz et al., 2011b, a). Collective re-evaluation of these recent observations have led to better estimates that are typical of the seasonal fluxes through the Bosphorus with relatively small trends and observational uncertainties within the last decades (Schroeder et al., 2012; Altıok and Kayışoğlu, 2015; Özsoy and Altıok, 2016a, b; Jordà et al., 2017).

Recent advances in modeling (Ilıcak et al., 2009; Sözer and Özsoy, 2017a, b; Sannino et al., 2017) have provided details of the dynamics and mixing as well as the essential verification of the experimental synthesis of hydraulic controls, also providing evidence for "maximal exchange" special conditions satisfied in the Bosphorus. The Bosphorus Strait has been found to be a special environment that supports maximal exchange, even more strictly than the Gibraltar Strait for which the theory originally has been developed (Farmer and Armi, 1986, 1988). Later developments in modeling have enabled resolving the coupled dynamics of the Turkish Straits System (TSS) including the Bosphorus and Dardanelles Straits as well as the Marmara Sea in the model domain (Sannino et al., 2014, 2017; Aydoğdu et al., 2018a, b).

There is evidence that the interaction between the Black Sea and the TSS occurs in both ways and in different realms. For instance in the Black Sea, located in a strong climate gradient between the warm Mediterranean and continental Eurasia, an upper ocean cold water mass is formed in winter (the Cold Intermediate Layer, CIL), which formerly used to prevail throughout the year, although recent evidence (additionally in the present study) shows it to be fast disappearing. The CIL resides just above the halocline and provides fundamental contribution to static stability of the water column. At the same time, the CIL resides partially above the wide southern continental shelf and continental slope regions (Figure 1) where it is responsible to modify the characteristics of the bottom Mediterranean plume exiting from the Bosphorus into the Black Sea. The CIL penetrates into the Bosphorus, coming into contact with the Mediterranean waters that it overlies, influenced by turbulent mixing and entrainment between waters of Mediterranean and Black Sea origin, transformed towards the sharply stratified surface and bottom waters that emerge respectively on the Marmara and Black Sea sides of the strait (Gregg et al., 1999; Özsoy et al., 1995, 1996; Özsoy and Ünlüata, 1998; Özsoy et al., 2001; Gregg and Özsoy, 2002). In this way the CIL, which is a product of convective mixing in the Black Sea, influences water mixed on the shelf and returned back to deeper layers of the Black Sea, while also influencing the Marmara Sea.

In correspondence to the above example of Black Sea influence on the TSS, the TSS also predetermines what would later become of its waters flowing to the Black Sea. The Mediterranean water plume exiting onto the Black Sea shallow continental shelf spreads along the shelf and canyon finally dipping down the continental slope, where it creates intrusions (Latif et al., 1991; Murray et al., 1991; Özsoy et al., 1993; Özsoy and Beşiktepe, 1995) leading to double diffusive convection (Özsoy et al., 1991; Özsoy and Beşiktepe, 1995; Kelley et al., 2003) and in extreme situations can penetrate throughout the Black Sea interior (Falina et al., 2017), interestingly found responsible for fast penetration of chemical signals such as the Chernobyll radiation fallout in the interior Black Sea (Rank et al., 1999; Özsoy et al., 2002; Delfanti et al., 2014). Novel features detected in the region of spreading along canyon topography of the Black Sea shelf adjacent to the Bosphorus have led to detailed description of density currents along undersea channels with new hypotheses proposed on their turbulent dynamics (Dorrell et al., 2016, 2019). Based on the above literature, it is evident that the evolution of water properties and currents through the TSS influence mixing and water mass formation processes in the Black Sea shelf and continental slope boundary layers as well as the interior region.

As regards coupled modeling of Black Sea and the TSS, we can quote Sannino et al. (2017) results showing the changes in circulation of the Marmara Sea in response to net flows through the Bosphorus, finally leading to switching of the modes of circulation in response to extreme cases of flow blocking in the Bosphorus. Similarly Stanev et al. (2017) showed significant changes in coupled circulations of the Black Sea and Marmara Sea in response to changes in flow through straits.

2 Model Configuration

We aim to closely reproduce the circulation and hydrography of the Black Sea during the last decade by developing a unique high-resolution model prototype that relies on high fidelity forcing data sets available today on atmospheric reanalysis and climatological riverine fluxes, also considering coupling with the external ocean by including a "Marmara box" and the Bosphorus Strait in communication with the Black Sea. In this respect, the model aims truthful reproduction of the interplay between thermo-haline circulation, water mass formation dynamics and inter-basin exchange in coupled fashion. Our renewed effort aims to improve the great number of previous modeling studies that have simulated some characteristics of the Black Sea circulation without reference to Bosphorus exchange, thereby to close gaps in predictability of the physical response of this complex basin on scales from days to a decade by introducing the essential strait coupling.

It is with worth noting that the original configuration of NEMO version 3.3.1 we used earlier had horizontal resolution of 1/12^o grid and 42 vertical levels. Having a coarser grid, using an earlier version of GEBCO topography, Levitus gridded climatology for initial conditions, atmospheric fluxes based on ECMWF ERA-interim reanalyses and only major rivers Danube, Dniestr, Dniepr and Don included, the strait exchange not sufficiently representative, an update seemed in order as we moved to the present model configuration for improved results.

2.1 Model Domain, Grid and Bathymetry

The present Black Sea circulation model (BSEA) is based on the NEMO version 4.0 (Madec, 2008) with advanced features of a community model accounting for complex physics of the marine environment. The model domain between 40.69 °-47.30 ° N and 27.43 °-42.00 ° E includes the deep Black Sea basin (max depth: 2178 m) together with the shallow Azov Sea (depth 10m) in the north and the Marmara Sea in the south. The bathymetry for the model displayed in Figure 1 is based on the General Bathymetric Chart of the Oceans GEBCO08 grid version 20100927 released in 2010, which we find the most up-to-date and accurate data set for the Black Sea, with 30 arc-seconds resolution.

The model domain includes Azov Sea in the north, the shallowest sea in the world, with a maximum depth of 14m in the middle, separated from the main body of the Black Sea by the narrow Strait of Kerch. The river Don joins Azov Sea at its head,

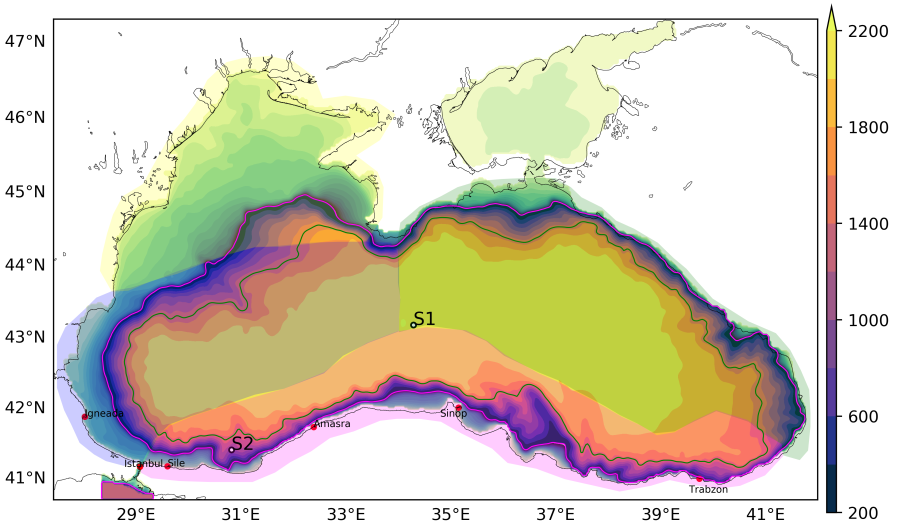

Figure 1. Model domain and bathymetry. The polygons show three subregions of the Black Sea (namely "east", west","rim") used to sample the ARGO floats. Five tide gauges along the Turkish coast are shown by red dots (İğneada, İstanbul, Şile, Amasra, Sinop and Trabzon). Contours in the range 100-2300 m (contour interval 200 m) correspond to the colour scale on the right. Contours in the depth range 0-100 m (contour interval 10 m) are superimposed with different colour scale (not shown) and 100m contour marked in magenta. Two stations (S1 and S2) shown in white dots are used to construct time series plots.

while the river Kuban joins near the Kerch Strait. The bathymetry and width of Kerch Strait has been artificially increased in the model (Figure 1), in order to have unobstructed exchange with the Black Sea, necessitated by the high river discharges into this relatively small, shallow domain with very sensitive response to wind stress forcing.

In order to represent the Bosphorus exchange flows coupled to Black Sea, an artificial box representing the Marmara Sea and the Bosphorus Strait have been added to the domain. The Marmara box is bounded by the northern coast of the Marmara Sea including the Bosphorus entrance and three open boundaries (i) along 40.74° N (ii) 28.403 °E (iii) 29.28° E, with the depth limited to 1200m at the bottom and true bathymetry elsewhere.

The model nominal grid resolution is $\Delta x \equiv \Delta y \equiv$ 2.5km (0.03133° longitude by 0.02286° latitude) along both horizontal directions resulting in an equally spaced horizontal grid of dimension 466 x 280, and a vertical grid with 60 z-levels of partial steps configuration. The resolution of the vertical grid has been adjusted so as to be compatible with the topography and density variations. The minimum vertical grid size of 2m at the surface, increasing to about 3m at a depth of 40m, then to about 10m at a depth of 110m is designed to adequately represent the surface mixed layer which is typically shallower than 25m, and the main halocline which is usually shallower than 100m in the Black Sea. There are 20 levels in the first 50m of depth, followed by 10 in the next depth range until 100m (Figure 2). The wide shelf areas especially of the western Black Sea typically limited by the 100m depth contour at the shelf edge are sufficiently resolved by this vertical grid. The model integration was carried out with a baroclinic time step of $\Delta t_i = 240s$.

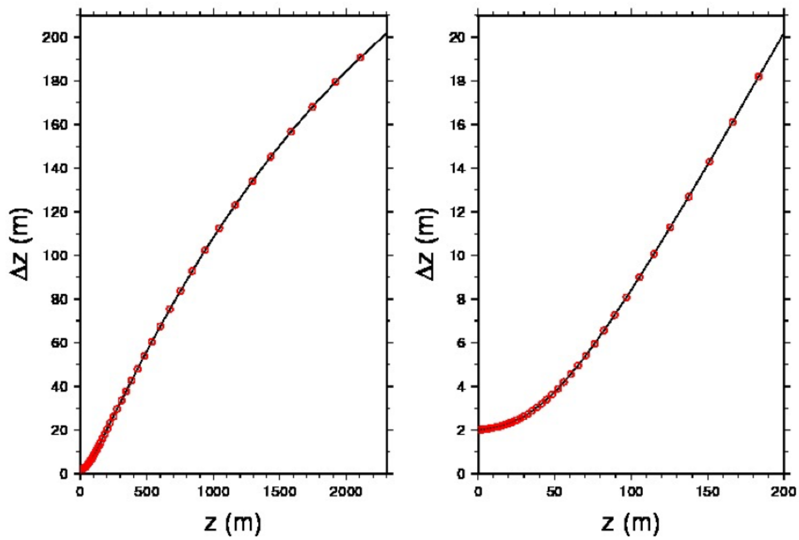

Figure 2. Model vertical grid spacing Δz (meters) as a function of the vertical coordinate z displayed for (a) maximum depth of 2300m, (b) in the upper 200m.

The model bathymetry represented in Figure 1 has been moderately smoothed using scale selective filters, satisfying the slope criterion of ROMS (Song and Haidvogel, 1994) so as to have $rx0 = \max(\Delta h/h) < 0.3$ between any neighboring grid points, where h is the depth.

In regard to the Bosphorus coupling, it should be clear that the present horizontal and vertical grid resolution needed to represent the complicated bathymetry at the Strait is less than what would be needed. It is therefore to be expected that the present configuration insufficiently resolving the strait topography would not be capable to reproduce the full range of nonlinear dynamical behavior of the Bosphorus Strait. The present choice is made in recognition of this fact in order to include strait coupling to the lowest order of approximation, saving the required effort for the future.

2.2 Parametrization

The numerical values of the horizontal viscosity length and velocity are taken $1km$ and $0.1m/s$ respectively. The horizontal diffusive length scale and velocity are $2km$ and $0.01m/s$ respectively. Values for vertical eddy viscosity and eddy diffusivity are selected as $A_v m = 1.e{-}7m^2/s$ and $A_v t = 1.e{-}8m2/s$. Turbulent Kinetic Energy (TKE) turbulent closure scheme (Blanke and Delecluse, 1993) is applied in the vertical with default settings in NEMO version 4.0 configuration. Bi-laplacian diffusivity schemes are used for both tracer and momentum.

Table 1. Climatological monthly river runoff for major Black rivers (m3/s)

River	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Danube	6365.0	5818.6	6091.6	7215.7	8397.7	8754.2	8144.7	6976.1	5405.6	4607.1	4355.1	4893.3	5719.8
Dnieper	1630.8	1505.0	1757.6	1839.1	2723.8	3180.6	1777.2	1162.7	1035.5	925.1	1077.2	1221.9	1364.2
Don	850.7	345.3	295.2	292.2	482.2	1284.9	2913.6	1532.6	1144.6	827.7	465.8	335.0	289.4
Rioni	409.7	303.3	346.3	431.1	654.8	611.9	535.2	428.2	326.4	240.9	294.6	357.6	386.2
Kuban	350.8	268.2	240.6	318.6	380.2	548.7	524.3	473.2	371.3	288.0	256.8	233.1	306.1
Dniestr	326.3	180.2	256.3	479.0	535.1	400.2	437.4	413.6	303.4	250.8	215.1	226.9	217.6
Sakarya	217.3	301.9	306.7	332.7	304.2	206.3	165.3	138.4	124.9	126.2	139.3	246.2	216.2
Kizilirmak	202.2	212.9	255.4	328.4	308.2	231.2	157.0	118.2	123.8	147.4	167.6	173.4	202.6
Southern Bug	110.4	86.8	124.0	258.6	215.2	86.3	71.0	89.6	66.5	67.3	88.5	85.2	85.8
Kamtehiya	22.4	30.4	43.0	45.7	32.3	25.8	20.4	11.2	8.4	8.3	6.6	14.4	22.4

2.3 River Input

The inputs of fresh water from major rivers, Danube in Romania, Dniester, Southern Bug and Dnieper in the Ukraine, Don, Kuban in Russia, Rioni in Georgia, Kizilirmak and Sakarya in Turkey, and Kamtehiya in Bulgaria have been accounted for, by using climatological monthly discharges reported by the RivDIS data base. Climatological monthly discharges of the rivers are given in Table 1.

The total annual river inflow represented with 11 rivers in the model amounts to $10570m^3/s(=333km^3/yr)$. (Kara et al., 2008) have found little difference in comparing different sources of river runoff, including a budget based on 6 major rivers of the Black Sea, totaling $9160m^3/s(=289km^3/yr)$.

More importantly, additional land-based sources of water other than rivers may be more important, though often neglected. If the overland runoff were to be taken into account, the total freshwater inputs apparently would increase by another 30%, amounting to a total of $13825m^3/s(=436km^3/yr)$ according to Black Sea data displayed at the GRDC web portal ($http://geoportal.bafg.de/mapapps/resources/apps/GRDC_FWF/index.html?lang=en$) "fresh water fluxes to the world oceans", although the monthly data for the overland flows could not be separately accessed, and therefore not included in our account.

According to the same source (GRDC), the total freshwater runoff has significant inter-annual variability. As it can be observed in Figure 3, the total discharge of freshwater into the Black Sea by rivers plus the overland runoff varies by almost two fold from one year to the other. Considering seasonal variability within each year this variability is even higher on inter-annual time scales, as demonstrated by Özsoy and Ünlüata (1998), based on long term data provided by Simonov and Altman (1991).

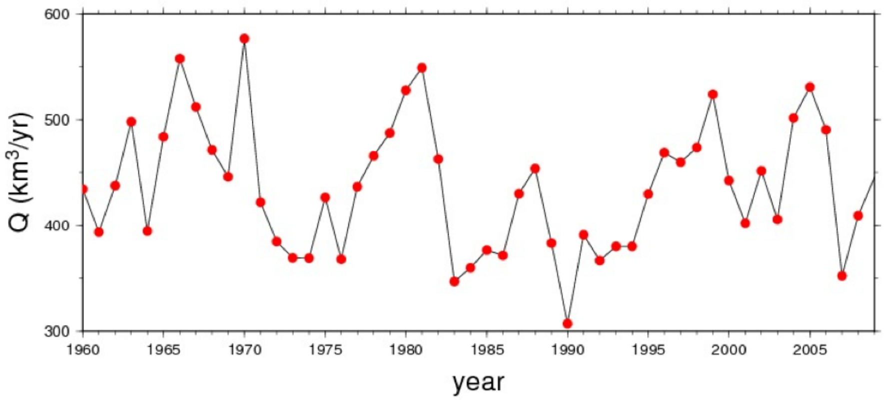

Figure 3. Inter-annual variations of mean annual freshwater inflow to the Black Sea – source: GRDC $(http://geoportal.bafg.de/mapapps/resources/apps/GRDC_FWF/index.html?lang=en)$.

The Danube river discharge monitored since last two centuries clearly displays this great interannual / interdecadal variability (Bondar, 1986; Sur et al., 1996). The air sea exchange of water by precipitation and evaporation adds further variability to the water exchange.

From the above discussion it is obvious that the water budget of the Black Sea is highly variable on inter-annual and seasonal time scales because of climatological factors and is influenced by insufficient accounting of all freshwater sources such as overland runoff, implying that the model response to freshwater inputs is expected to vary greatly at any instance. For the moment we use the climatological monthly river fluxes as lateral sources of freshwater in the model, although we fully recognize the future need to account for the net water exchange regulated by the Bosphorus Strait.

2.4 Open Boundary Conditions

Within the Marmara box domain external to the Black Sea, temperature and salinity were relaxed to climatological values, which were a function of depth only, along a buffer zone that is 5 grids wide in parallel to the open boundary, only leaving out a very small area near the Bosphorus entrance quickly adjusted to the rest of the domain shortly after initialization. The depth and time dependent values imposed at the open boundary were obtained from historical data sets as daily climatology, by averaging over corresponding dates of years with suitable smoothing and static stability checks among available archives of CTD data at IMS-METU. The averaging of the data that was finally applied at the Marmara box was done over the entire Marmara Sea for increased statistical reliability of the observational daily T,S profile time series, which are shown in Figure 4. The data were used to initialize and later to relax for the properties within the Marmara box.

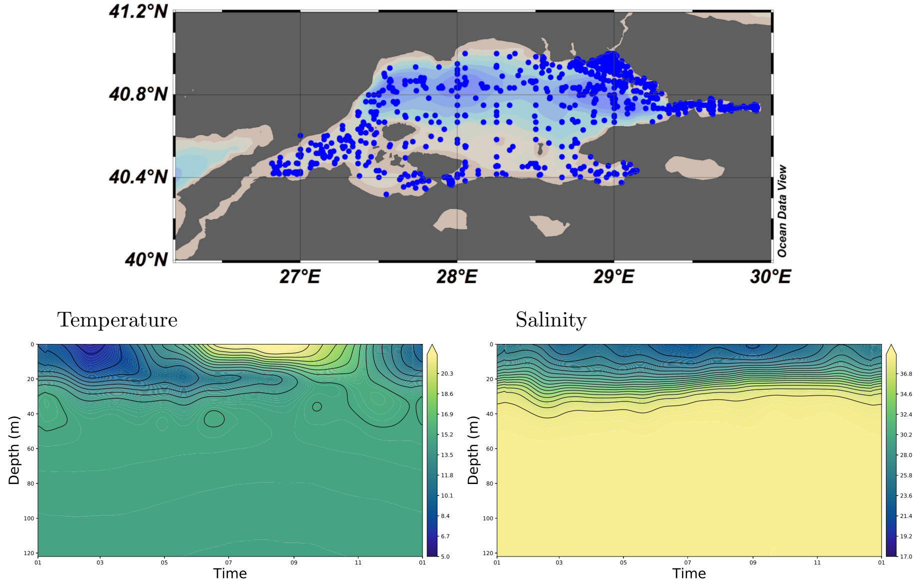

Figure 4. Time series of daily climatological salinity (left) and temperature (right) profiles and location of the CTD stations (top) applied for relaxation at the Marmara box shown in the 1.

2.5 Initialization and Atmospheric Forcing

The initial conditions of the model are constructed from intercalibrated temperature and salinity data from the 1992 CoMSBlack cruise, a multi-national collaborative oceanographic survey which quasi-synoptically covered the entire Black Sea in maximum possible extent and detail (http://www.grid.unep.ch/bsein/descript/cblack92.htm), carried out during 2-26 July 1992 by five research vessels from the riparian countries, as quoted in Oğuz et al. (1993) and (Sur et al., 1994, 1996). The data obtained from a total of 394 hydrography stations at nominal spacing of 20’ (=1/3°) in longitude and latitude have been screened to eliminate few stations contributing to anomalous properties in the analyzed fields. The objectively analyzed temperature and salinity fields at the surface (model level 1) and at a depth of 89m (model level 28) respectively are shown in Figure 5.

The model was initialized with the July 1992 analysis fields substituted for the July 1, 2008 initial conditions and run for about 10.5 years from 01/07/2008 to 31/12/2018, subject to the atmospheric forcing and surface and lateral flux boundary conditions as specified above. The substitution of the July 1992 analysis for initial conditions is misplaced by more than two decades from the modeling period, but it was justified in the absence of other reliable initial data, providing the best possible synthesis of the entire basin hydrography ever made. Although the model would need a few years of spin-up time for adjustment to the initial and boundary conditions, the adjustment run was not carried out, as the objective of model performance testing prevailed. Results obtained so far illustrate rather fast adjustments of the model fields without much vertical displacements or oscillations encountered, although this remains to be finally tested in the future by persistence runs or multi-decadal runs from actual initial conditions. We choose to start from a representative initial condition, albeit the fact that it is misplaced in time,

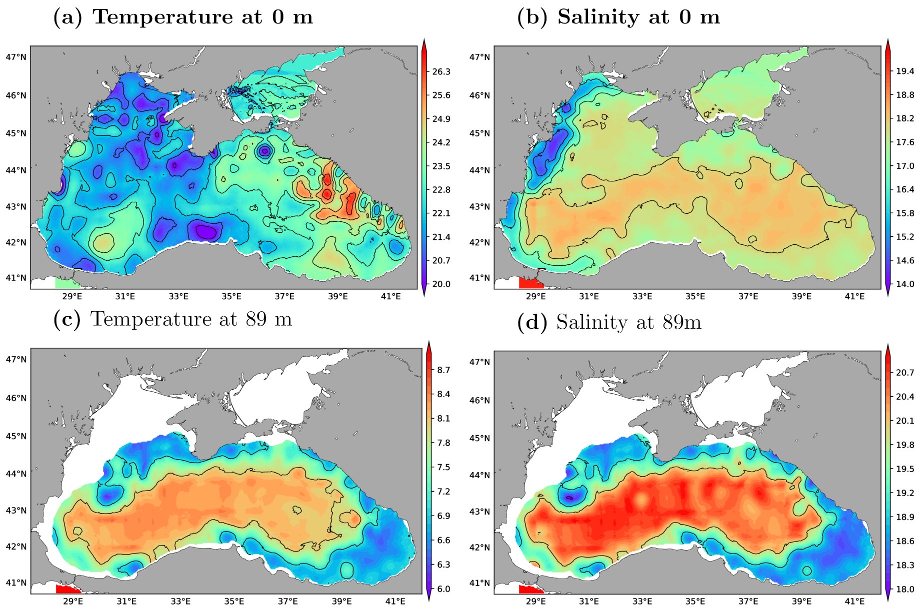

Figure 5. Model initial conditions of temperature (lhs) and salinity (rhs) at the surface (upper row) and at a depth of 89m (lower row), based on the objective analyses of data from a total of 394 CTD measurement stations obtained during the July 1992 CoMSBlack cruise.

and allow the model dynamics with realistic forcing alone to set up the circulation, without any climatological adjustments of the initial or evolving fields.

Surface fluxes are computed using the core algorithm of NEMO, based on the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis product ERA5 Re-Analysis data set. The ERA5 high space and time resolution atmospheric data at 1 hr intervals and $31km$ horizontal grid spacing of the atmospheric model is interpolated on-the-fly by the NEMO ocean model and applied at the surface using the COARE 3.5 bulk formulae (Madec, 2012).

First model runs have been carried out with the ERA5 precipitation. However, the comparison of model salinity with ARGO floats showed a difference in trends between model and observations at the end of model simulation. Detailed analysis have revealed that the ERA5 precipitation is significantly lower than the ERA-Interim precipitation in the Black Sea with a ratio of about 2. Therefore, we decided to replace the ERA5 with ERA-Interim precipitation for the rest of model runs, keeping the source for other variables the same.

3 Model Evaluation

3.1 Bosphorus Fluxes

The extension of the Black Sea to the Marmara "box" through the Bosphorus Strait aimed to represent strait and basin coupling in the model. This is achieved through relaxation of properties to climatological daily stratification in the box and Flather

Table 2. Water Transport km^3/yr

	analysis		observations		
	(1)	(2)	(3)	(4)	Model result
	South/North	mid-strait	South/North	South/North	South/North
upper layer	-653/-603	-540	-420/-395	-444/-374	-508/-492
lower layer	353/303	115	249/255	333/252	298/281
net	-300/-300	-425	-171/-140	-111/-122	-209/-210

(1)Ünlüata et al. (1990); (2) Özsoy et al. (1996); Özsoy and Ünlüata (1998); (3) Altıok and Kayışoğlu (2015); (4) (Jarosz et al., 2011b, a)

boundary conditions Oddo and Pinardi (2008) applied at the Marmara box open boundaries. Although the Flather open boundary conditions imply that the sea surface height and normal velocity are adjusted to values specified at the boundary with some radiation of the disturbances, we set these to zero and let the model calculate them in accordance with wave radiation and with the help of upstream boundary conditions for outflowing components. As the temperature and salinity near the boundary (effectively in the greater part of the small box) are relaxed to climatological boundary conditions, the outflow and inflow at the artificial boundaries are verified to approach approximate volume conservation apart from a small inconsistency, but ensuring two way exchange at the Bosphorus approaching realistic values with a net barotropic component.

Comparison of the time series for upper, lower layer and net fluxes in the Bosphorus Strait obtained from the model and observations from August-2008 to Jan -2009 are superposed in Figure 6. The experimental fluxes are based on Jarosz et al. (2011b) measurements. We observe that the model results are in the same range of mean fluxes obtained from observations, although there are differences in the oscillatory part of the signals. We also observe that the lower layer fluxes are in better agreement between the model and observations, while the upper layer fluxes outwards from the Black Sea are less compliant, most likely because the outflow is directly related to the surface water balance of the Black Sea.

The various historical estimates of Bosphorus fluxes based on mass budgets and direct observations in the literature, re-evaluated by Özsoy and Altıok (2016a) are listed in Table 2, compared with the model computed values in the last column.

It is noted in Figure 6 that the longer term model fluxes of the upper, lower layer and net flows in magnitude and direction are in better agreement with the observations, while the short-term components on the order of few days to a week have greater amplitude in the observations compared to the model, possibly because of the insufficient model resolution to fully duplicate hydrulically controlled, turbulent flow dynamics of the strait at this resolution, as remarked earlier in the model configuration section.

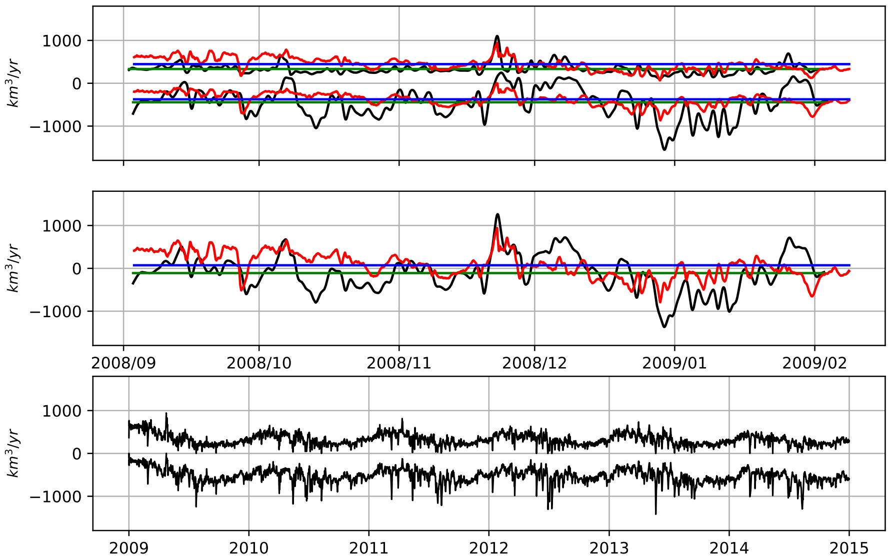

Figure 6. Time series of water transport at Bosphorus Strait. Upper panel: Upper and lower fluxes from the model (red line) and from observations (black line) compared for the August-2008 to Jan -2009 period. Middle panel : Net water transport from model (red line) and observation (black line). Lower panel : Upper and lower layer fluxes from the model for the entire model run period.

3.2 Comparison with ARGO Floats

Model generated temperature and salinity profiles were compared with the available ARGO floats data in the Black Sea. For this purpose, the model results were sampled at each ARGO float location and depth within each of the polygons shown in Figure 1. Figure 7 shows profiles of salinity (left column) and temperature (right column) averaged over the three sub-regions. To construct this plot, a total number of 8167 profiles were used for "east" region, 6230 profiles for the "west" region and 5820 profiles for the "rim" region. Model results are shown in color shading in the background, and ARGO samples are contoured in black. There is good correlation between model results and ARGO salinity for each of the three sub-regions, indicating that the model is able to reproduce salt conservation under the created mass fluxes and mixing events during the model integration period. The red line shows the 21 salinity contour obtained by the model.

Although model results closely follow observations, with amplitude of the mixing events coinciding remarkably well, it seems that there is a slight increase of the 21 salinity depth especially in the eastern sub-region after 2017. The evolution of temperature in the model versus observational data shown on the right hand side of Figure 7 shows good agreement over a decade-long integration.~~leaves little doubt that the model is able to reproduce observed variations remarkably well over a decade-long integration.~~

The model performance evaluated on its ability to reproduce CIL water mass and in capturing the thermocline depth, seems also satisfactory. The model temperature is shown in background color while contour lines show incremented values of 7 to

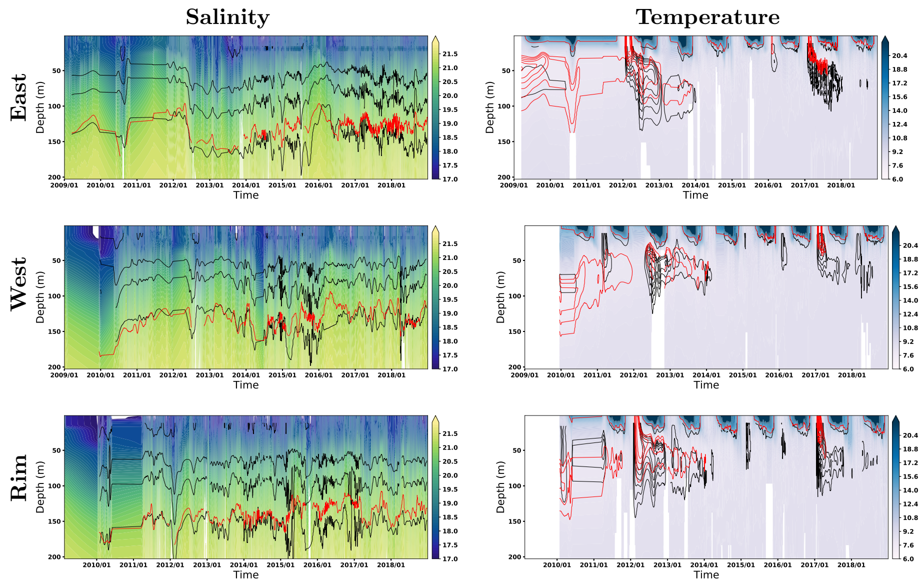

Figure 7. CTD profiles of salinity (left column) and temperature (right column) for the three subregions shown in the Figure 1. Top panel for the "east" region, middle panel "west" region and bottom panel "rim" region. Model results were shown as background fill image for each figure. Argo and model results were also shown in contour line (17 to 21 for ARGO salinity, 21 for model salinity, 7 to 8.5 and 15 ° C for the temperature), black line for the argo, red line for the model.

8.5°C for the ARGO (black line) and for the model (red line). It is seen that the model is able to generate the CIL water for each of the investigated sub-regions. The model is also able to reproduce the interannual variation of the thermocline. The contour at the upper 50m marks the 15 ° C temperature (red line model, black line ARGO) for reference.

In Figure 8, the time series of ARGO float samples and model temperature at 25 m depth are compared for those samples in the east, west and rim regions. Considerably good visual agreement between the observed and modeled temperature suggests that the surface heat flux in the model and mixed layer dynamics are appropriate for maintaining the surface temperature close to reality over the last decade.

In Figure 9 both the observed and the model salinity time series at 25 m depth display increasing trends over the 10 year period, while the model trend appears slightly larger than the observed one in all regions, but especially in the east. These trends are evidence that increased environmental change are in due course in the Black Sea as has been recently shown by (Stanev et al., 2017). We also note that the trend in model salinity has been significantly reduced by choosing ERA-interim precipitation in place of ERA-5 since the latter source was found to result in much smaller total precipitation and had produced higher salinity trend as well as a much reduced net transport through the Bosphorus (not shown), as discussed in the earlier sections.

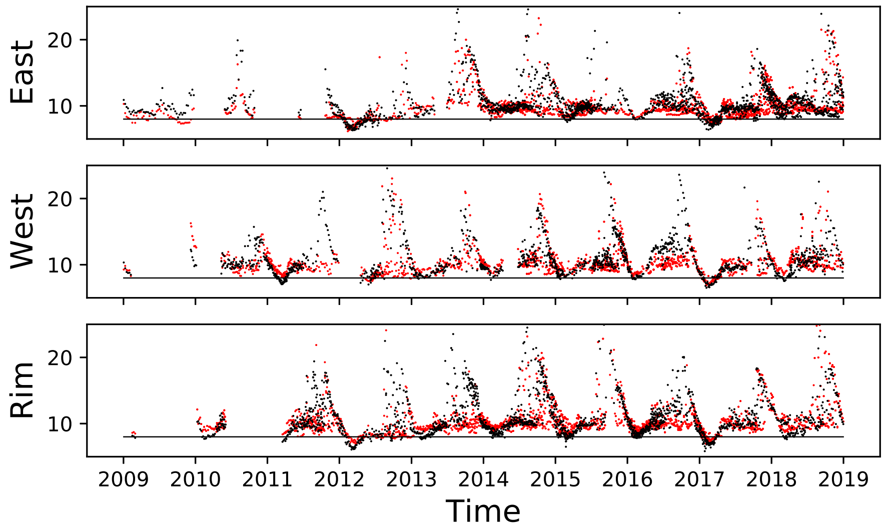

Figure 8. Time series of model and argo temperature (°C) at 25 m sampled over the three regions shown in the Figure 1. upper: east, middle:west, lower:rim. Black dots from argo floats, red dots from model results.

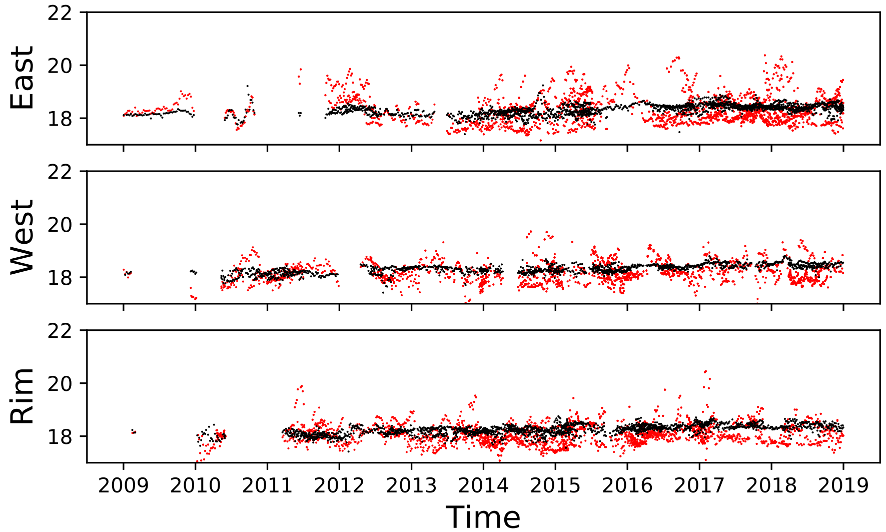

Figure 9. Time series of model salinity at 25 m sampled over the three regions shown in the Figure 1. upper: east, middle:west, lower:rim. Black dots from ARGO floats, red dots from model results.

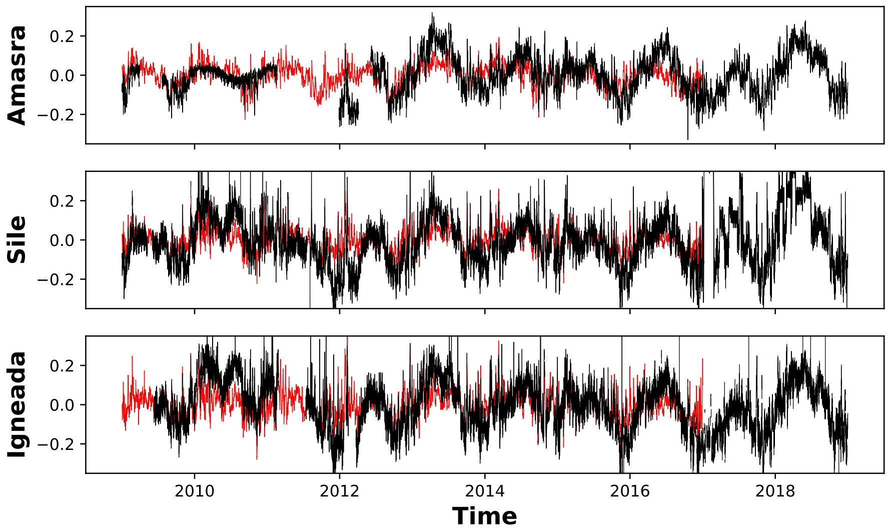

Figure 10. Time series of sea surface height anomaly (m) for the three tide gauge stations shown in the Figure 1. Upper: Amasra, Middle: Şile, Lower:İğneada. Model result is black line and tide gauge record is red line.

3.3 Comparison with the Tide Gauges

Model generated sea surface height (SSH) was compared with the six tide gauges located along the western and southern Black Sea coast. For this purpose, SSH anomaly was computed for model and observations, given in Figure 10 for the run period. The model results are in general agreement with the observations especially at higher frequencies, except for the irregular seasonal variation of greater amplitude evident in the observations.

It is yet immature to explain this difference at present, given the possible deficit in closing the Black Sea water budget, e.g. by imposing climatological river discharges rather than actual, inaccuracies in precipitation and evaporation estimates, as well as model approximations of the free surface. Especially in regard to the latter, first we note that we have used the linear free surface assumption in the present runs, with plans to use the nonlinear free surface option in future runs. Secondly, the seasonal, spatially variable steric component of sea level in the Black Sea reported to have an amplitude on the order of 2 cm by (Tsimplis et al., 2004), but estimated to reach 6 cm at some locations by (Arkhipkin and Berezhnoi, 1995), often are not properly accounted for by ocean circulation models at present. All these factors could have contributed to the difference in model and observed SSH anomalies .

Samples of annual comparisons between model and observed SSH anomalies in Figure 11 are more optimistic however, as they display better agreement between the higher frequency components in the range of daily to weekly and fortnightly oscillations, leaving aside the longer term and seasonal, possibly steric or fresh-water induced components.

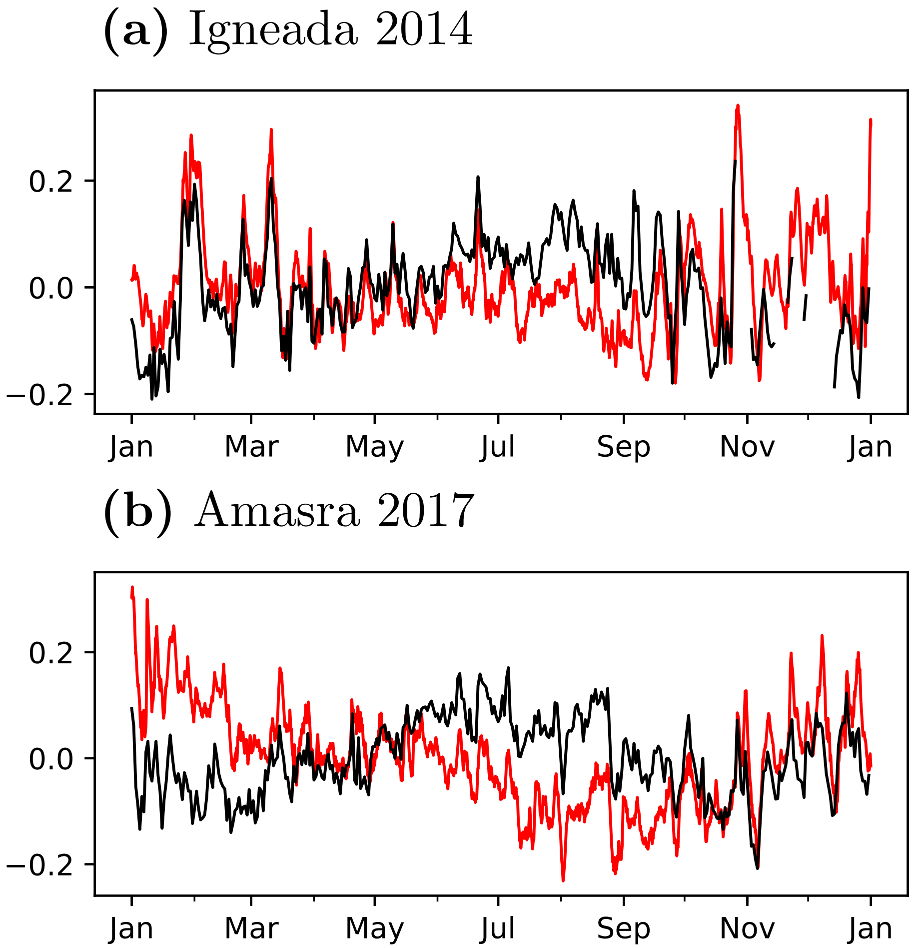

Figure 11. Time series of sea surface height anomaly (m) for three tide gauge station shown in the Figure 1. Upper: Amasra, Midde: Sile, Lower:Igneada. Model results is black line and tide gauge results are red line.

4 Initial results and applications

4.1 Circulation and mixing

The main characteristics of the Black Sea general circulation have been rather well established based on a multitude of experimental investigations, numerical modeling studies and reviews (e.g. (Stanev, 1990; Oğuz et al., 1993; Oğuz and Malanotte-Rizzoli, 1996; Özsoy and Ünlüata, 1997, 1998; Sarkisyan and Sündermann, 2009)). Our purpose is not to provide an exposé of the seasonal circulation expected, but rather to briefly demonstrate model realizations of well known circulation features through some examples.

In Figure 12 we present an exemplary selection of monthly average circulation and temperature fields at the surface (left) and at depth of 50 m (right) developed from December 2011 to March 2012. It can be noticed by from the plots on the right hand side that downwelling exists all along the continental slope region of the closed basin of the Black Sea, where higher temperature near the periphery occur and where the cyclonic rim current also roughly resides. In fact a well-developed cyclonic surface circulation with meandering currents and anticyclonic eddies along the periphery of the deep basin are evident. On the left hand side, the greater temperatures in December are reduced until March, where a cold patch surviving in the north central part of the western basin is advected to the south eastern basin near the Bosphorus, while at the same time cold water is formed in the shallow northeast shelf and the Azov Sea, preserved there until March. The cold water on the shelf is later seen in February and March to leak out of the northwest shelf area to appear on the slope of the Danube delta at 50m depth and circulated around the basin. Well noted circulation elements of the Sevastopol eddy trapped west of the Crimean peninsula and Batumi eddy in the southeastern corner are in development.

In Figure 13 we present an exemplary selection of monthly average surface currents for the months of July, September 2011, February, May 20112 (left) and July, September 2014, February, May 2015 (right), where rapid changes occur in terms of the strength of the rim current, the creation and destruction of eddies, the propagation of eddies alon the rim current and across the basin, filaments of jets separating from the main rim current and their roles in weakening and re-organization of ordered fast currents following the periphery, which show a series of dynamic events that rapidly change the structure and sequence of circulation elements that are all too important in the short and long term changes in the environment under the evolving climate.

4.2 Time Evolution at Stations

We examine the temperature and salinity evolution in the system. In particular, we examine in Figure 14 the upper ocean properties at stations 1 and 2 of Figure 1, to observe the typical seasonal / inter-annual response pattern of the forced system started from the initial condition during the relatively short period of about 10 years.

At station 1 at the very center of the basin, in Figure 14.a, we see cycles of summer warming that develops thermal stratification within the mixed layer region up to a depth of about 25-30 m followed by winter time convective mixing. The Cold Intermediate Layer (CIL) conveniently defined as the layer of intermediate depth water of temperature less than 8 $^\circ$ C is present at depths of up to 80 m below the mixed layer in the initial conditions imposed on 1 July 2008. The CIL survives until the summer of 2012 and disappears afterwards at this station. While convection seems to occur every winter, fresh cold intermediate water contributing to the core with T < 8 $^\circ$ C principally occurs only in the winter of 2012, in fact when cold water with T < 7 $^\circ$ C evidently creating convective overturning extends from the surface down to the core of the CIL at about 40 m. In the following years the cooling seems to be reduced with new cold water formed, but evidently not cold enough as the CIL has been characterized in the not so distant past, and intermediate waters in later years undergo warming. The salinity time series in Figure 14.a shows the halocline at depths of around 50m, at just about the CIL lower depth limit. Both the temperature and the salinity records show many fine scale features and oscillations associated with the eddying and small-scale motions.

At station 2 (Figure 1) near the southern boundary of the basin, in Figure 14.b, we observe that the thermal and salinity stratification are much deeper than the central basin station 1, evident by the increased depth of the halocline to about 80 m, and the depth of the mixed layer also deeper compared to the central region. The deeper structure near the coast, in comparison

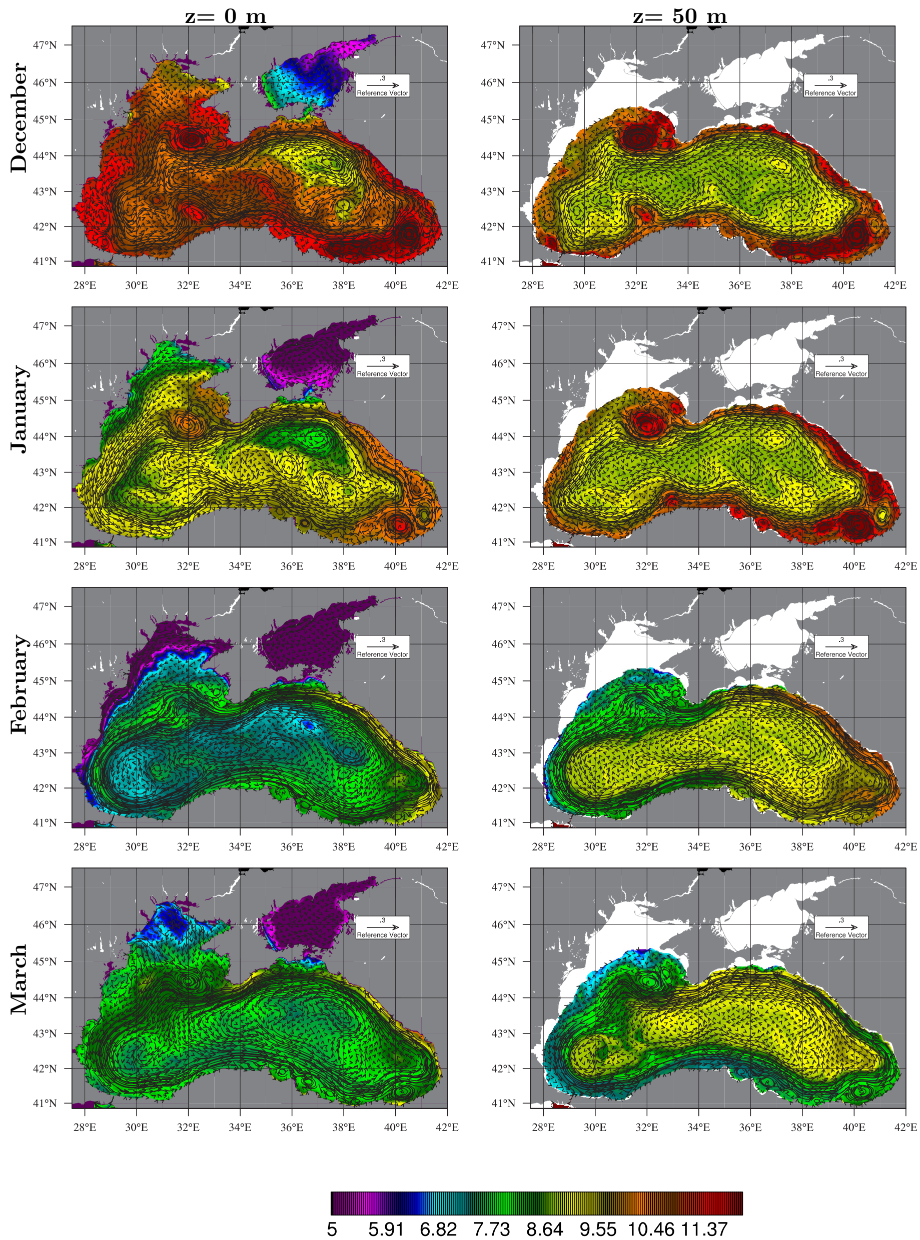

Figure 12. Monthly average currents and temperature at the surface (left) and at depth of 50 m (right) developed from December 2011 to March 2012 (ordered down the page).

to the central area of doming in the Black Sea are also evident in (Figures 12 and 13. The CIL is thicker at the near coastal station 2, its lower limit reaching a depth of about 100m at this mainly anticyclonic region. The convective overturning in the

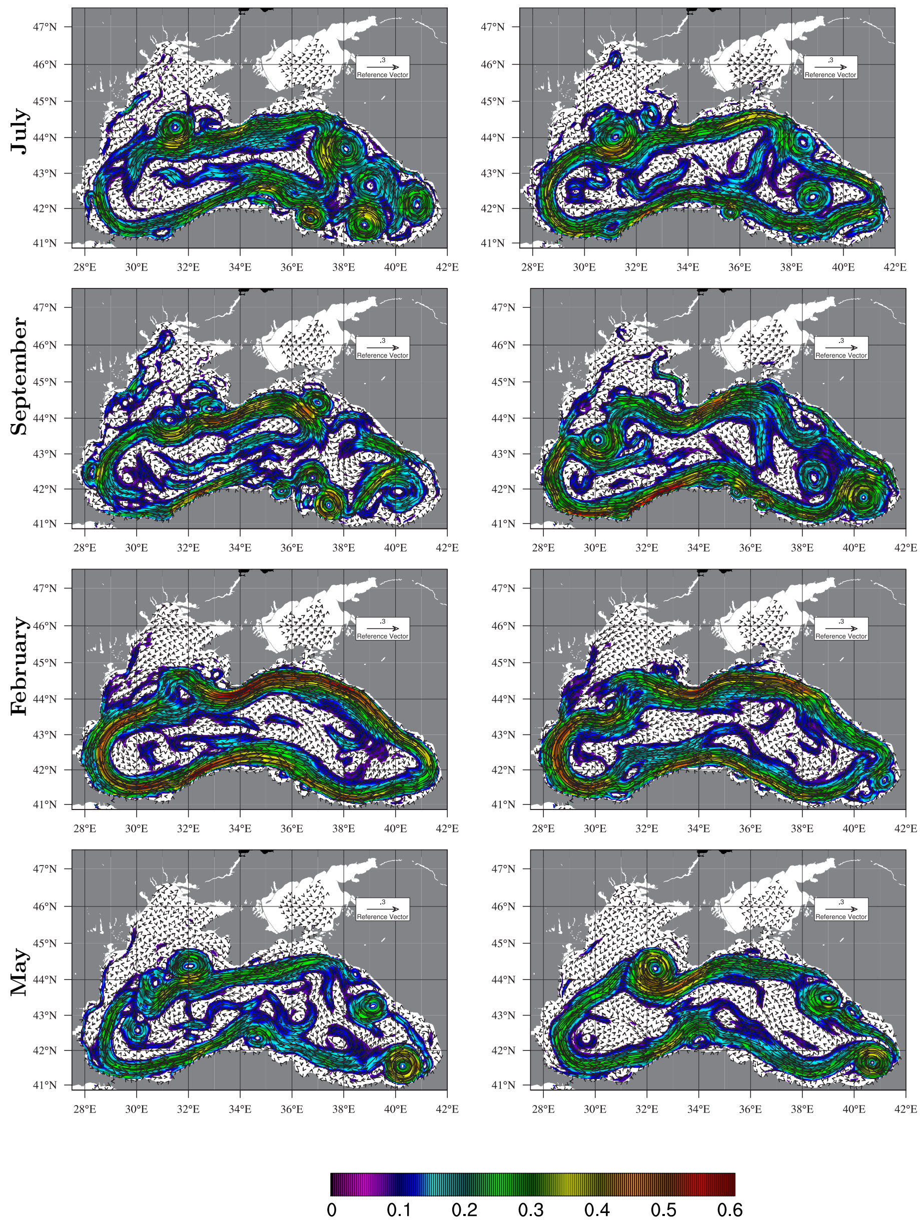

Figure 13. Monthly average current vectors and magnitude in color shading for the months of July, September 2011, February, May 2012 (left) and July, September 2014, February, May 2015 (right) (ordered down the page).

winter of 2012 therefore also becomes deeper, reaching the lower depths of the CIL core. The increased oscillatory behavior as compared to station 1 is a result of the meso-scale eddying motions of the rim-current effective at the periphery of the basin.

The abundance of CIL in the initial conditions maintained for the first two years contrasts with the single event of cold intermediate water formation in 2012, and the weaker event in 2017. The reduced convection events in recent years both in

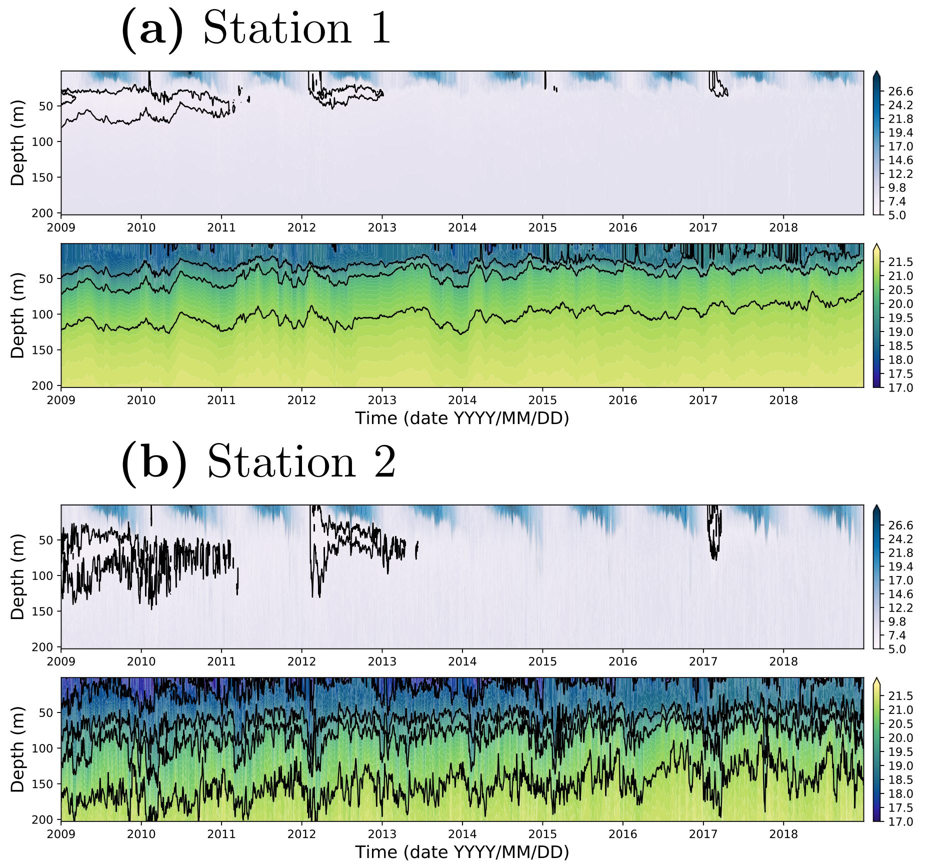

Figure 14. Time series of temperature and salinity versus depth at (a) station 1 and (b) station 2 of Figure 1.

the deeper central basin and near the coast stand as evidence that great changes are occurring in the Black Sea, much likely to be an amplified response to climate change in the isolated Black Sea basin severely limited in its communication with the Mediterranean Sea and eventually with the world ocean.

5 Conclusions

In this study, a high resolution Black Sea model was developed, with additional merits of coupling the basin hydrodynamics with exchange flows at Bosphorus Strait, with an artifical box on the Marmara side where the temperature and salinity is relaxed to climatology on a daily basis and open boundary conditions allowing a net flow in tune with the net flow across the Strait and allowing two-layer outflows and inflows of the Marmara Sea. While previous modelling studies mostly used climatological inflow/outflow water transport specified at the Strait entrance as a riverine like input over the limited number of grid points, this study includes the high frequency variations in the exchange flow while still satisfying the net water balance of the Black Sea achieved by extending the model domain to include part of the Marmara Sea and the Bosphorus Strait. The model results were rigorously evaluated by comparing them with the huge number of ARGO float profiles and available tide gauge station observations in the Black Sea.

The detailed analysis of the monthly mean circulation revealed complex and rapidly changing eddy activity in the Black Sea. Model temperature and salinity results are in good agreement with observations during the investigated period. Slight increases of salinity detected by observations in the upper water column are also evident in the model results. Ten years of simulation of temperature and salinity do not show any significant drift, which is an important feature that would allow the model to be used for long-term climate change simulations. The main feature of the Black Sea oceanography such as CIL water mass, rim current, upwelling along the southern coast are all well detected by the newly developed model. The model was also able to reproduce the SSH variability in comparison with the tide gauge observations.

Although high frequency sea level variations seem to be well reproduced by the model, there appears some mismatch between the model and observation in the SSH estimates at seasonal time scales, generally amplified in summer season. The differences in seasonal SSH pattern could be due to some deficits in water budget based on climatological river fluxes and steric effects often not considered in models.

In the future, the Marmara box domain should be extended to include the north Aegean Sea which will enable to specify the SSH and baroclinic velocities from CMEMS-Mediterranean model at the open boundaries. It is expected that this will improve performance of the model. The current model has used the linear free surface option. Since we have only defined temperature and salinity over limited part of the Marmara Sea, the non-linear free surface option was found to generate higher velocities and instabilities at Strait entrances, eventually causing the model to blow-up. Extending the model domain and with proper open boundary conditions, it is believed that the model could produce better results in non-linear free surface mode. The behaviour of the model should also be investigated by conducting long term model runs, starting with initial conditions from 1992 till present time to evaluate climate change aspects.

Data availability. The data can be made available by contacting the authors.

Code and data availability. BSEA is a regional configuration of NEMO (Nucleus for European Models of the Ocean) at version 4. stable (Madec, 2016). Model code is freely available from the NEMO website (www.nemo-ocean.eu). After registration the Fortran code is readily available using the open-source subversion software (http://subervsion.apache.org). There is only minor change over the original code. The friction was artificially increased over the Bosphorus Strait grid points.

Author contributions. MG, EO and RH set-up the NEMO model for the Black Sea. MG and EO performed the experiment. MG,EO and RH analyzed the model results. MG compare the model results with the observations. MG and EO wrote the paper with the inputs from all coauthors.

Competing interests. The authors declare that they have no conflict of interest.

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