QUALITY INFORMATION DOCUMENT

Black Sea Production Centre BLKSEA_ANALYSIS_FORECAST_BIO_007_010

Issue: 1.1

Contributors: L. Vandenbulcke, A. Capet, R. Rajagopalan, J. Rassmann, M. Grégoire

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CHANGE RECORD

When the quality of the products changes, the QuID is updated and a row is added to this table. The third column specifies which sections or sub-sections have been updated. The fourth column should mention the version of the product to which the change applies.

Issue	Date	§	Description of Change	Author	Validated By
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I EXECUTIVE SUMMARY

The V201907 release of the Black Sea biogeochemical analysis-forecast is a major upgrade with respect to previous versions. The physical model is changed from GHER to NEMO, being now aligned with BS-PHYS, and the BAMHBI biogeochemical model has been extended to incorporate a carbonate module describing the dynamics of Dissolved Inorganic Carbon (DIC), pH, Total Alkalinity (TA), air-sea flux of CO2. NEMO is online-coupled with BAMHBI.

I.1 Products covered by this document

BS_ANALYSIS_FORECAST_BIO_007_010 is the biogeochemical part of the Black Sea analysis-forecast system implemented by the Black Sea Marine Forecasting Centre (BS-MFC). The online-coupled model is run with a horizontal resolution of ~3 km resolution, 31 vertical levels, and comprises the 5 following datasets:

- NUTR: phosphorus and nitrate;
- PFTC: chlorophyll and phytoplankton biomass;
- BIOL: dissolved oxygen (O_2) concentrations and net primary production;
- CARB: pH, dissolved inorganic carbon (DIC), Total Alkalinity (TA)
- CO2F: Surface partial CO_2 pressure, surface CO_2 flux

The BIOL dataset also includes the bottom dissolved oxygen concentration on the North-Western Black Sea shelf, saved as a separate 2D variable.

II SUMMARY OF THE RESULTS

The Black Sea biogeochemical Near Real Time product (NRT) has been validated using satellite chlorophyll time series, in situ data from vessels and BG-ARGO (chlorophyll and oxygen) data collected during the period 2016-2019. The other variables cannot be validated in NRT due to the absence of NRT data. They are validated in the reanalysis model and additionally, their consistence with historical data is qualitatively checked here for inorganic nutrients, DIC, pH, pCO2, TA.

Physics: The new model version V201907 (NEMO-BAMHBI) is compared to the previous version (GHER-BAMHBI); and is able to simulate the mixed layer depth and cold intermediate water, which are key physical processes governing the distribution of biogeochemical variables, water column stability and ventilation mechanisms.

Chlorophyll: Over the whole basin, compared to satellite observations, the model accurately simulates the range of surface chlorophyll concentrations and its temporal variability. Bias is relatively low (0.15-0.50 mg.m^{-3} depending on the region) and very strongly reduced compared to the previous product version.

Oxygen: The comparison of model and BG-ARGO data reveals a bias of 18 mmol/m^3 and a Pearson correlation coefficient of 0.90. The Nash-Sutcliffe number is in the same class as the previous model version V4: “excellent”.

Carbonate system: DIC, TA, pH, pCO_2 and CO_2 air-sea flux are compared to climatologic values, and are all within the range of accepted values.

II.1 Estimated Accuracy Numbers

Table 1: Selected Estimated Accuracy Numbers (EANs). We use different statistics in order to assess the performances of the model on different aspects (e.g. variability, accuracy).

Variables	Metrics	Units	Value
Oxygen (in situ)	bias σ_r Nash-Sutcliffe Pearson correlation	mmol m^{-3} / / /	18.2 0.85 0.69 0.90
Oxygen profile maximum (in situ)	bias	mmol m^{-3}	17.7
Chlorophyll (satellite) for different regions	bias	mg/m^3	0.13 to 0.40
Depth of maximum Chlorophyll (in situ)	bias RMS	m m	29.3 32.8

III PRODUCTION SYSTEM DESCRIPTION

III.1 Production centre details

a) Production centre name: BS-MFC

b) Production subsystem name: BS-MFC-Biogeochemistry

c) Production Unit: ULiège (MAST)

d) Production centre description for the version covered by this document

The biogeochemical hindcasts and forecasts for the Black Sea are produced by the MAST / ULiège Production Unit by means of the NEMO v3.6 circulation model online coupled with the BAMHBI biogeochemical model. The nominal production runs at the Cenaero (Belgium) Tier-1 supercomputing centre called Zenobe, and at backup production runs at the ULiège/CECI "nic4" supercomputing facility.

III.2 Description of the production system

Description of the Black Sea BIO operational system.
The Black sea biogeochemical model (BS-Biogeochemistry) is the Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI, Gregoire et al., 2008; Grégoire and Soetaert, 2010; Capet et al., 2016b). It describes the foodweb from bacteria to gelatinous carnivores through 24 state variables including three groups of phytoplankton: diatoms, small phototrophic flagellates and dinoflagellates, two zooplankton groups: micro- and mesozooplankton, two groups of gelatinous zooplankton: the omnivorous and carnivorous forms, an explicit representation of the bacterial loop: bacteria, labile and semi-labile dissolved organic matter, particulate organic matter. The model simulates oxygen, nitrogen, silicate and carbon cycling. In addition, an innovation of this model is that it explicitly represents processes in the anoxic layer.
Biogeochemical processes in anaerobic conditions have been represented using an approach similar to that used in the modelling of diagenetic processes in the sediments lumping together all the reduced substances in one state variable. In this way, processes in the upper oxygenated layer are fully coupled with anaerobic processes in the deep waters, allowing performing long term simulations. This fully coupling between aerobic, suboxic and anoxic processes is absolutely necessary for performing the long term reanalysis. Processes typical of low oxygen environments like denitrification, anaerobic ammonium oxidation (ANAMMOX), reduced decomposition efficiency have been explicitly represented (Gregoire et al., 2008). Moreover, the model includes a representation of diagenetic processes (Capet et al., 2016) using an efficient and economic representation as proposed by Soetaert et al. (2000). The incorporation of a benthic module allows to represent the impact of sediment processes on important biogeochemical processes such as sediment oxygen consumption (that is responsible for the generation of hypoxic conditions in summer), the active degradation of organic matter that determines the vigour of the shelf ecosystem (~30 % of the primary production produced in shelf waters is degraded in the sediment) and the intense consumption of nitrate by benthic

denitrification that filters a substantial part (~50 %) of the nitrogen brought by the north-western shelf rivers (the Danube being the most important
one) and modulates primary production in the deep basin. In addition to a representation of diagenesis, the biogeochemical model represents the transport of sediments by waves. This is an important feature that is necessary in order to sustain the primary production of the deep basin.
At V201907, BAMHBI has been extended with a module describing the carbonate dynamics. As in Soetaert et al. (2007), the models solves for DIC and the Excess Negative charge from which is computed TA (considering the contribution of sulphide), pH, the speciation of DIC ($[HCO_3]^-$, $[CO_3]^{2-}$. $[CO_2]$), CO_2 air-sea flux.

Description of the Production chain

At V201907, the BS-Biogeochemistry model is online-coupled with the NEMO v3.6 ocean model (version aligned with PU-PHYS) and is run with a horizontal resolution of ~3 km and 31 vertical levels using z-layer vertical coordinates. This Black Sea implementation is based on the BS-physics NEMO implementation at V4 (e.g. same vertical and horizontal resolution), and uses NEMO version 3.6.
NEMO 3.6 has been fine-tuned physical processes that are known critical for simulating Black Sea biogeochemistry. This includes the open boundary condition at the Bosporus (as in the GHER and based on Stanev et al, 1997; Stanev and Beckers, 1999), a new package to ensure strict conservation of the biogeochemical tracer budgets, a refined light penetration scheme. There is currently no feedback from the biology to the light absorption in the physical model. BS-BIO NRT system runs each day one day of analysis and 10 days of forecasts.

The physical model run in the BS-BIO NRT system is not the same as in the BS-BIO RAN system (product (BLKSEA_REANALYSIS_BIO_007_005), the former uses NEMO while the latter uses the GHER 3D hydrodynamical model. Comparison of NEMO and GHER performances as concerns the simulation of NRT physics is briefly given in section V.1 as requested by MOi.

III.3 Upstream data and boundary condition of the NEMO-BAMHBI model

The CMEMS–BS-MFC-Biogeochemistry analysis and forecast system uses the following upstream data:

1. Atmospheric files of air temperature, air dew temperature, total precipitation, cloud coverage, wind velocity and mean sea level pressure produced by ECMWF analysis and forecast fields (i.e. at 1/8° spatial resolution with 3hr and 6hr temporal resolution) are used to force NEMO physics and for the wind, to compute the air-sea exchanges of O_2 and CO_2.
2. Atmospheric deposition of inorganic nitrogen delivered by Kanakidou et al. (2012) that have a similar order of magnitude than river inputs and are needed to sustain primary production in the deep basin.
3. Due to the absence of NRT data, BS-BIO NRT system uses climatological averages of river flows, inorganic nutrients and organic materials inputs computed from the long time series of data provided by Ludwig et al., (2009) in the frame of the EU SESAME and PERSEUS projects. In its current configuration, BS-BIO system involves the river inputs from 6 main rivers: the Danube (split into three branches), Dniepr, Dniestr, Rioni, Sakarya and Kizilirmak. These river loads consist in annual loads modulated by repeated seasonal distribution.
4. The Bosporus Strait is considered as an open boundary as in Stanev et al, 1997; Stanev and Beckers, 1999. The velocity and salinity are determined in such a way that total sea-water and salt are conserved in the Black Sea domain. Temperature use a zero-gradient boundary condition. Biogeochemical variables use zero-gradient (“Neumann”) or fixed value (“specified”) boundary conditions.

IV VALIDATION FRAMEWORK

The quality assessment of the V201907 analysis-forecast BS-MFC-Biogeochemistry system (described in the previous section) has been done by comparing a simulation that covers the period 2016-2018 with available NRT observations. The product quality activities used both quantitative metrics and qualitative assessment approaches. The metrics used for the quantitative validation are reported in Table 2. These error statistics are computed for oxygen and chlorophyll for which we have NRT data thanks to satellite and BG-ARGO. Some variables could not be validated in NRT, such as nutrients (nitrate and phosphate), phytoplankton biomass, primary production, carbonate system due to the lack of NRT data for such variables. These variables are however validated for the reanalysis (see CMEMS-BS-QUID-007-005-V2.0) and as concern the carbonate variables, they have been compared with historical data that have been considered with high enough quality (e.g. Sesame, KNORR). We also compare the density profiles of inorganic variables (e.g. NO_3, O_2, DIC, Alkalinity, pH, ODU, NH_4, PO_4, SiO_2) with data aggregated profiles found in the literature.

NRT Datasets

The datasets used to validate the product are the following:

1) In situ ARGO observations are available from the CMEMS in-situ TAC (product: INSITU_BS_NRT_OBSERVATIONS_013_034); they can also be obtained from the Coriolis (Brest, France) website, see http://www.coriolis.eu.org/. They are used for the validation of physical variables (temperature, salinity, and derived quantities such as mixed layer depth (MLD), Cold Intermediate Water (CIL) Cold Content (CCC)) and biogeochemical variables (oxygen))
2) Chlorophyll provided from BGC Argo fluorescence using a correction adapted for the Black Sea (high content of CDOM, anoxia) as described in Ricour et al. (2019).
3) BLKSEA_ANALYSIS_FORECAST_BIO_007_009 (the previous version of this product)
4) CMEMS satellite Level-3 observations for the Black Sea were downloaded from the CMEMS OC-TAC (product: OCEANCOLOUR_BS_CHL_L3_NRT_OBSERVATIONS_009_044).

Error Metrics

The quality assessment of model results is done using different errors statistics that allow to quantify model-data mismatches on different aspects. Table 2 presents these statistics (more details can be found in Allen et al., 2007). For the definition of the metrics, “O” represents the observations and “P” is the model output. In additional to these global statistics we assess the ability of the model to simulate the monthly vertical profiles of oxygen and its maximum value.

For chlorophyll, the model – observation comparison has been performed by splitting the basin in 11 sub-regions as done by Kopelevich et al. (2003). This partitioning is essentially based on the depth: regions shallower than 50 m, between 50 and 200 m, and deeper than 200 m. Furthermore, these regions are divided in eastern / western zones. The obtained map of regions is shown in Figure 1, white dots indicate the location of in situ BG-ARGO measurements.

Table 2: List of metrics -- used to assess the model performance.

Definition	Meaning	Interpretation
The percentage bias (no units) $PB = \frac{P-O}{O} * 100$	Compares the mean values of *O* and *P*, and expresses the average bias as a percentage value of the *O* average	PB>0: global overestimation PB<0: global underestimation |PB|<10%: excellent skill, 10-20: very good, 20-40: good, > 40 poor (Maréchal, 2004)
Standard deviation ratio (no units) $r_\sigma = \frac{\sigma_O}{\sigma_P}$	Compares the distribution of *O* and *P* around their respective average	>1: larger variability in the observations <1: larger variability in the model
Nash-Sutcliffe efficiency (no units) $N-S = 1 - \frac{\sum(O-P)^2}{\sum(O-\bar{O})^2}$	Relates the model errors to the variability in the observations.	>0.65: excellent >0.5: very good >0.2: good <0.2: poor (Maréchal, 2004)
Pearson correlation coefficient (no units) ρ	Indicates how the variations of *O* and *P* around their respective mean are related	Significant correlations can be concluded for values of ρ above threshold values according to the amount of available data
Chi-squared statistic (no units) $\chi^2 = \frac{1}{n\,\sigma_O^2}\sum(P-O)^2$	Is an estimation of the model cost	The lowest χ^2, the better. This statistic is useful for comparing different versions of the model (model evolution)

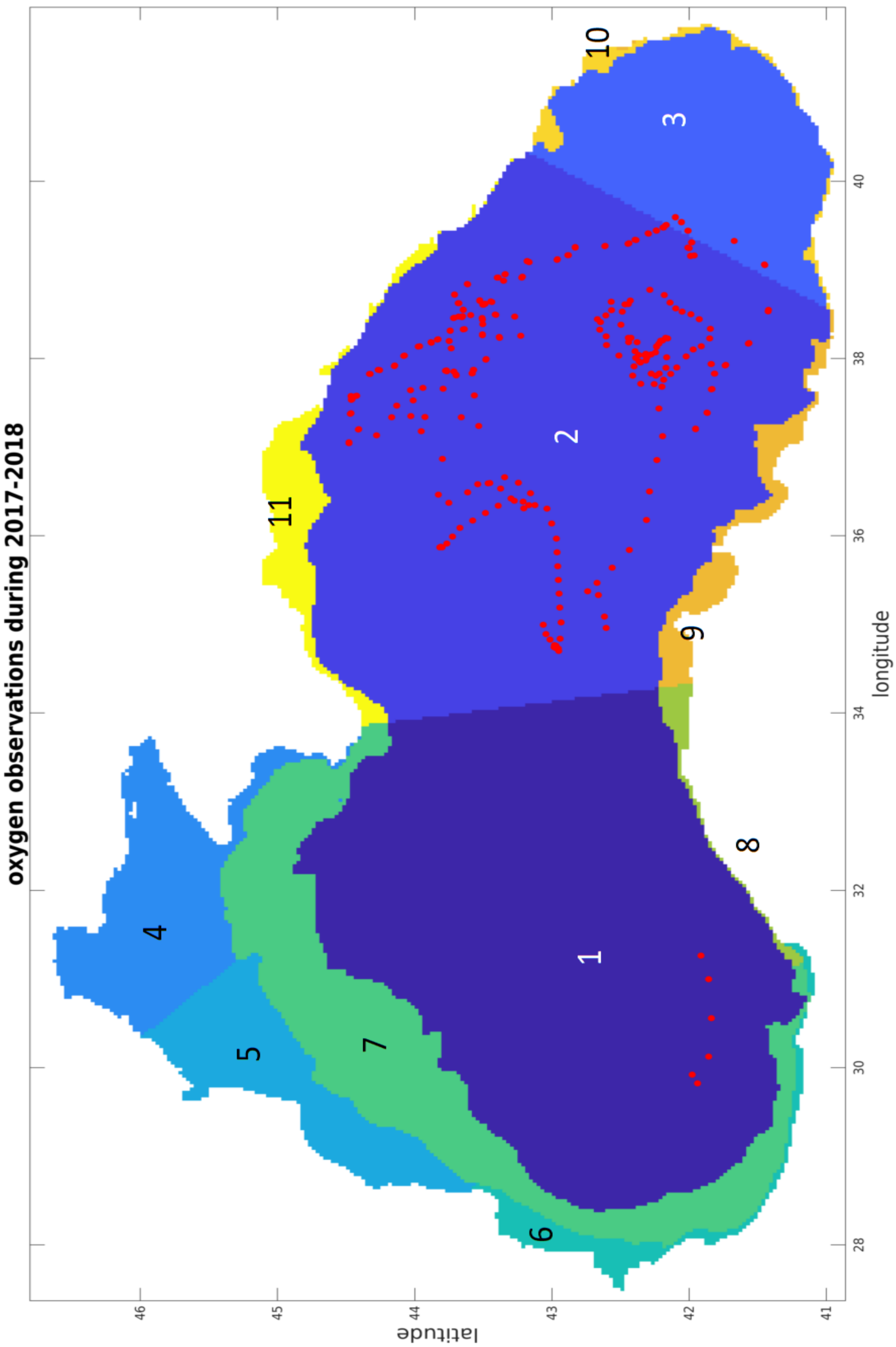


Figure 1: Sub-Regions (based on Kopelevich et al., 2003) used for computing the error statistics for chlorophyll. The red dots represent the position of the oxygen profiles obtained during the 2017-2018 period. The numbers indicate the regions of the Black Sea. Regions 1-3 are the “open sea”, regions 4-5 is the North-Western Shelf and region 7 is a transition region.

V VALIDATION RESULTS

In the following we first compare the performances of the physical model used for running BLKSEA_ANALYSIS_FORECAST_BIO_007_009 (V4 system) and BLKSEA_ANALYSIS_FORECAST_BIO_007_010 (V201907, current system) with a focus on physical variables that are known to act as primary control on biogeochemistry (e.g. mixed layer depth, ventilation). Next, for biogeochemical variables we will mainly focus on the validation of oxygen and chlorophyll because there the only variables available in NRT. For oxygen, we will assess the global statistics of the model (computed over the whole model domain and period of simulations), its ability to represent the monthly oxygen vertical profiles and value of the maximum concentration. For chlorophyll, we will compare model results with satellite product for the different regions identified in Figure 1; we will also compare with the chlorophyll retrieved from fluorescence data provided by BG-ARGO. Finally, we qualitatively compare the carbonate system to climatology.

V.1 Physical variables

The Black Sea presents an oxygen-rich surface layer on top of an anoxic water mass. Basin ventilation is mainly governed by the formation each year of cold oxygen-rich waters that accumulate at depth to form the Black Sea Cold intermediate Layer (CIL). The ventilation mechanism is limited by a permanent halocline. In this section, we assess the capacity of the BS-BIO physical model (NEMO 3.6) to simulate the formation of the CIL and mixing processes by comparison with observations and the BLKSEA_ANALYSIS_FORECAST_BIO_007_009 (V4 system) (GHER model)

V.1.1 Mixed Layer Depth (MLD)

In the Black Sea, the general criterion for the MLD is usually a density gradient above 0.125 kg m^{-3} referenced at 3 m (Kara et al., 2009). However, the use of the definition is compromised by the lack of high quality data close to the surface (<10 m depth). Hence, the model MLD is computed at each point as the depth where the density is 0.125 kg/m^3 larger than the density at 10 m depth, and then spatially averaged over the basin. The basin averaged model MLD is compared with punctual Argo derived MLD. Results over 2017-2018 are shown in Figure 2.

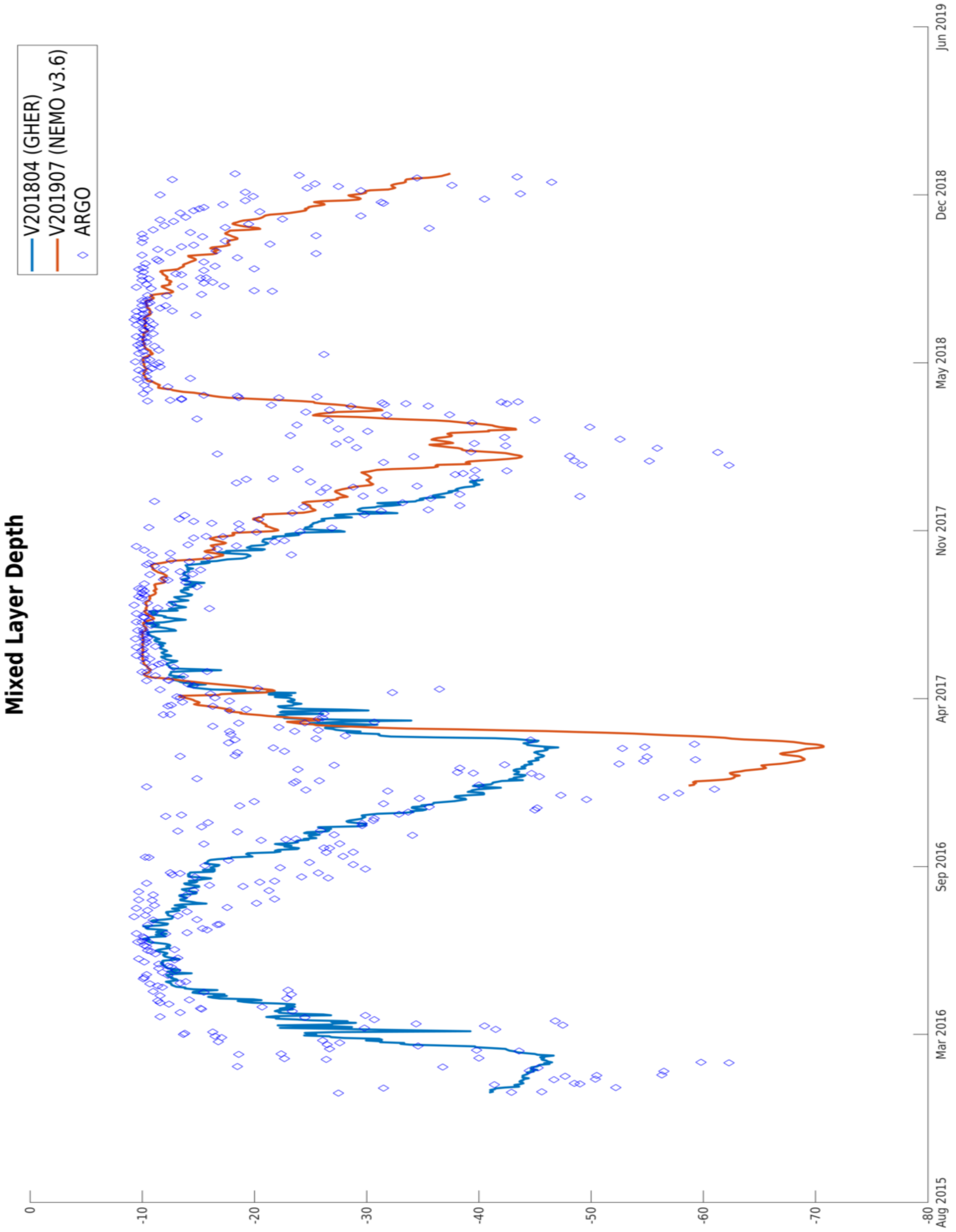


Figure 2. Mixed layer depth computed from V201804 (GHER), V201907 (NEMO) and T,S profiles from ARGO floats.

GHER and NEMO models are able to reproduce the typical seasonal MLD cycle (Figure 2). In winter 2017 NEMO simulates an averaged MLD ~25 m deeper than that simulated by GHER and is in the higher range of Argo estimates while in summer NEMO quite well matches Argo observations with a MLD shallower than 10 m. It should be noted that GHER and NEMO use different vertical resolutions: the current NEMO configuration has only 2 levels up to 10 m depth, whereas the GHER model has many more levels; the double sigma-levels depend on the bathymetry, but there are always more than 2 levels in the first 10 meter.

V.1.2 Cold Intermediate Layer

The Black Sea CIL is characterized by temperature lower than 8.35°C, and density larger than 1014 kg m^{-3}. This water mass is abundantly described in the literature. The amount of “CIL cold content” (CCC) can be estimated from temperature and density values as the deficit of heat in the CIL compared to a 8.35°C-layer. The figure below shows the CCC estimated by the GHER model, the NEMO model, and ARGO profiles (yearly means). For this exercise, we assess the performance of NEMO over multiple years of simulations in order to check the capacity of the model to generate and maintain each year the CIL.

Overall, both models are in agreement (Figure 3), and also in agreement with ARGO estimates. The winter formation of CIL is comparable in both models, for years with relatively cold winters and large CIL formation (e.g. 2012, 2017) as well as for years with hot winters and almost no CIL formation (e.g. 2013, 2014). The summer destruction of CIL happens a little faster in NEMO than in GHER.

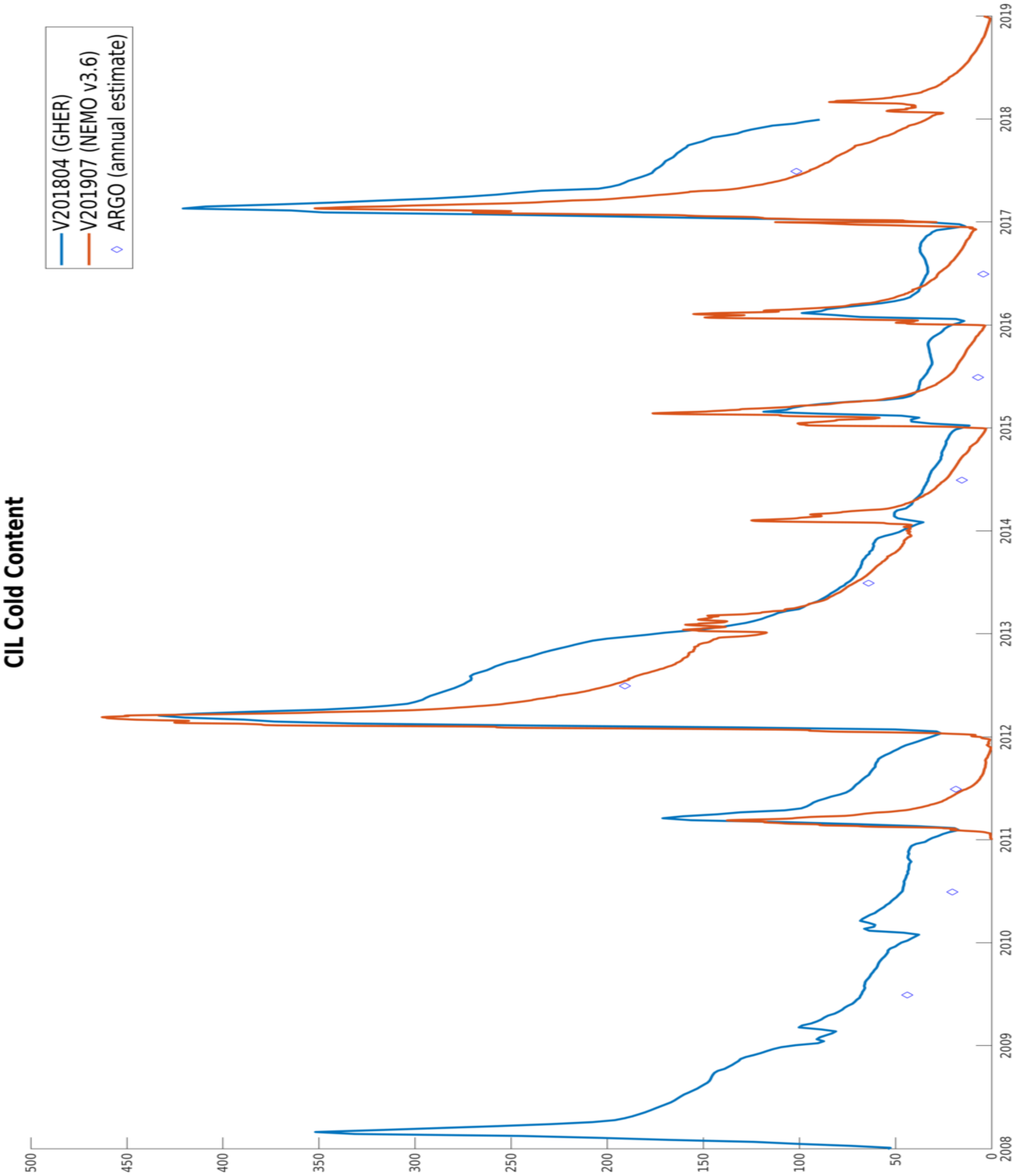


Figure 3. CCC from V201804 (GHER), V201907 (NEMO) and ARGO

V.2 Oxygen

The simulated oxycline is slightly deeper in the model than that obtained from ARGOs (Table 3). This is related to an imperfect initialization of the oxygen field in the model for this period of time using climatological relationships that do not perfectly represent the shoaling of the oxycline acknowledged in Capet et al. (2016).

Table 3: Model skill statistics obtained when considering all ship data and BG-ARGO (see the position of the sites in Figure 1) model-observation predictions pairs for oxygen. Error metrics are defined in Table 2.

Oxygen	**Value at V201907**
Bias (mmol m^{-3})	**18.2**
Rms (mmol m^{-3})	**49.2**
Standard deviation ratio (no unit)	**0.85**
Nash-Sutcliffe (no unit)	**0.69**
Pearson coefficient (no unit)	**0.90**

During 2017-2018, there were 282 vertical profiles with oxygen data (at least 20 per month). All of them are in the deep sea.

Figure 4 compares all the modelled and BG-ARGO observed oxygen points, arranged by month.

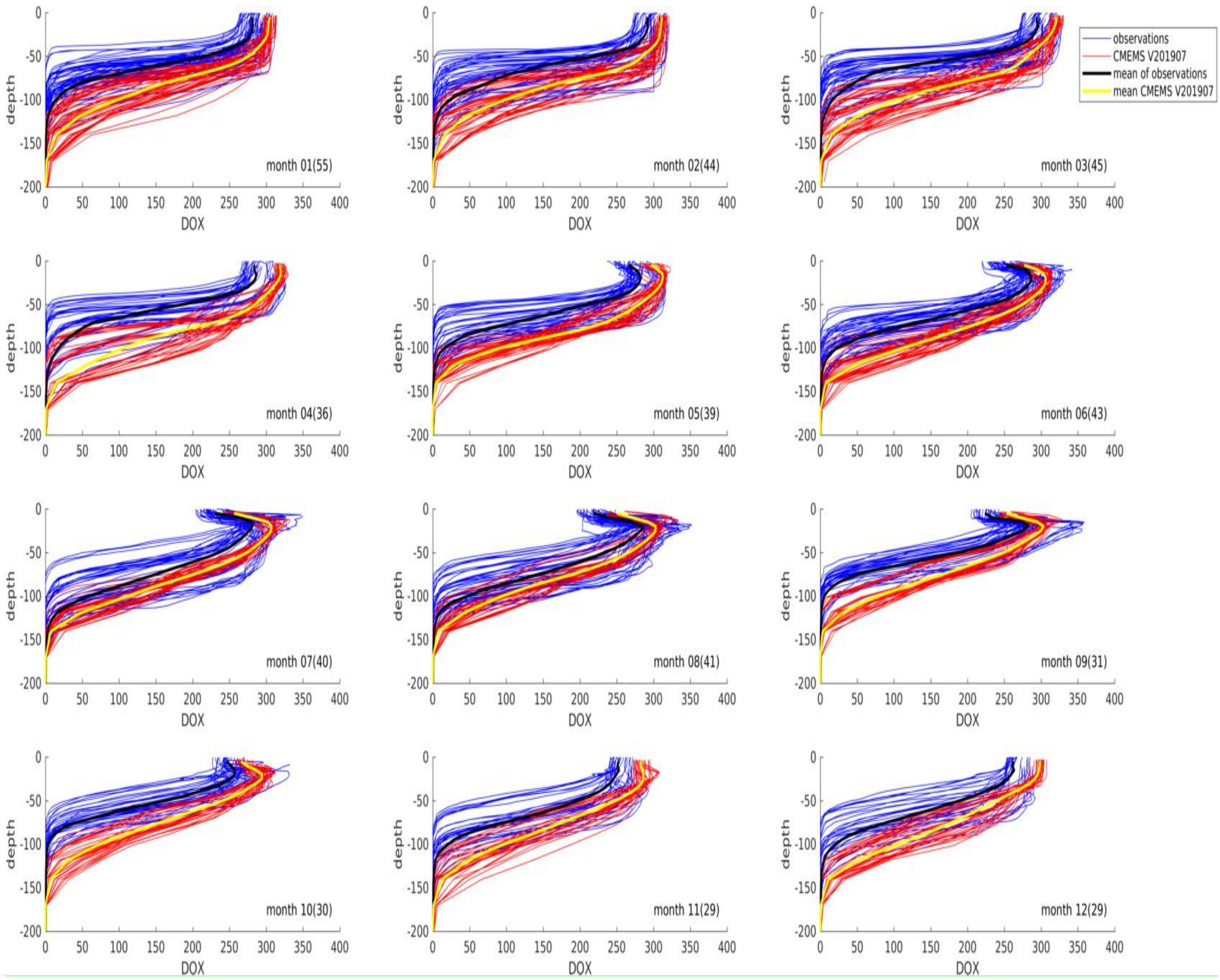


Figure 4: Monthly oxygen profiles during 2017-2018 (model in red, in situ observations in blue; the model and observed monthly mean profiles are respectively in yellow and black)

The oxygen maximum is well simulated by the model, with a mean bias of 17.7 mmol.m^{-3}, corresponding to a percentage bias of 6.1%. Figure 5 shows the comparison of the profile maximum value in the model and observations.

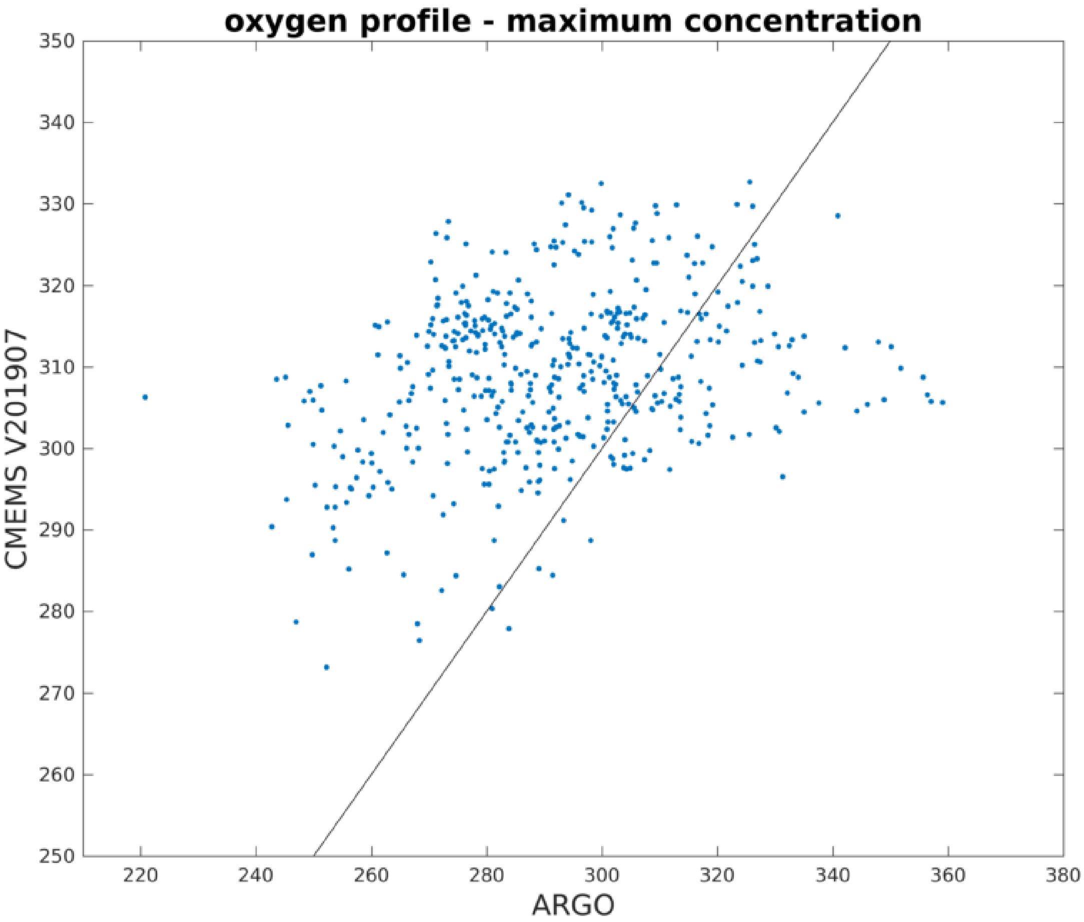


Figure 5. Oxygen maximum (1 point per profile)

V.3 Chlorophyll

In this section, chlorophyll concentration obtained from the model, from satellite L3 chlorophyll concentration and from ARGO floats are compared for the period 2017-2018.

V.3.1 Satellite data

The regional time-series are computed by averaging, every day, all available points in each sub-region shown in Figure 1. For satellite products, if the image over a region presents many clouds and does not have at least 100 pixels, the result for that particular day and region is not computed and the time-series presents a gap.

The satellite observations used in the comparison are taken from the April 2019 version of the CMEMS OCEANCOLOUR_BS_CHL_L3_NRT_OBSERVATIONS_009_044 (NRT product based on multi-satellite composites). They are obtained by a new algorithm based on a neural network.

The time-series shown in the left column of Figure 6 concern the first 3 regions in the open sea. Compared to previous model versions, the model and satellite values are in much better agreement. The range of values is similar in model and observations, but presents temporal shifts which will degrade error statistics. In regions 2 and 3 (further away from the North-Western Shelf (NWS) and the main rivers), the model predicts too low chlorophyll contents (with a bias of 0.13 and 0.22 mg m^{-3} respectively). On average in the 3 regions, the ratio of model and observation standard deviations is close to one.

The right panels of Figure 6 shows the time-series is the NWS regions. Region 4 is influenced by the Dnestr and Dnepr, whereas region 5 is directly in front of the Danube. Hence, for these regions, the river discharge (flow) as well as river water nutrient concentration is critical. In the current version V201907, these values are obtained from a monthly climatology. Region 6 is also a shelf region, located to the South of the NWS, and is less sensitive to rivers. The bias is positive (0.40 mg m^{-3}) especially in the winter season. Region 7 is the transition region between the NWS and the open sea, and here also, the model and observations are very close (bias = 0.22 mg m^{-3}).

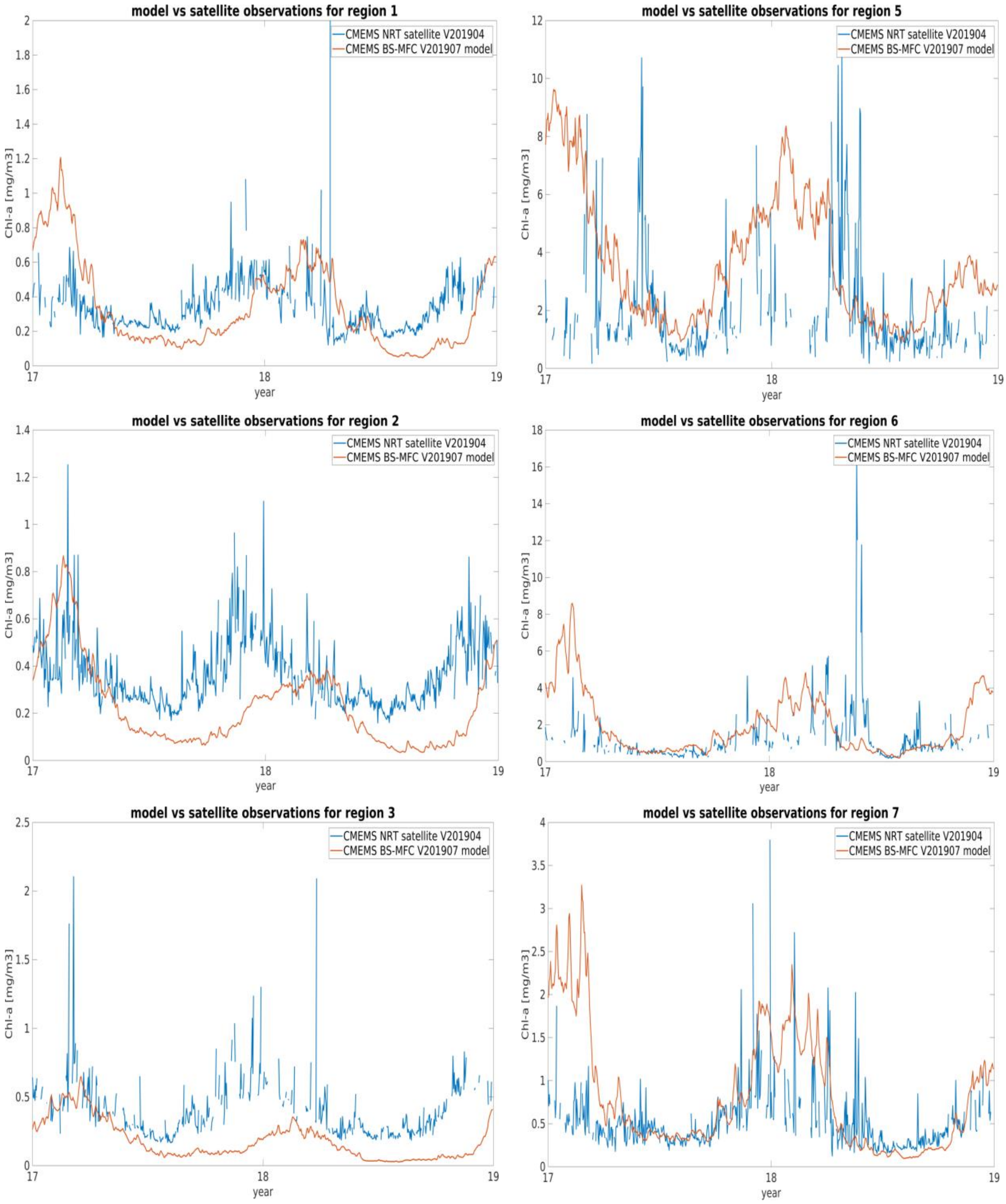


Figure 6: Time series of satellite (in blue) and model (in red) chlorophyll spatial averages computed for (left column) open sea sub-regions 1, 2 and 3, and (right column) NWS regions 5, 6 and 7. The regions are shown in Figure 1.

Table 4 shows the bias between the model and observations, expressed in $\log_{10}$ of the difference [mg. m^{-3}].

Table 4: bias_log10 statistic for chlorophyll obtained for V201907 when considering the observation-model prediction pairs, for the different regions (1 to 11). The bias error metric has been defined in Table 2. Data are the V201904 near real-time (NRT) CMEMS satellite observations.

EAN \ Region	1	2	3	4	5	6	7	8	9	10	11
$\overline{log10(model) - log10(obs)}$	-0.13	-0.31	-0.48	0.64	0.26	0.11	0.05	0.08	0.04	-0.21	-0.50

Compared to V201804, the error statistics are obtained over another period, (2017-2018 rather than 2016-2017), and using a new version of the satellite observations dataset. In any case, the model change from V201804 to V201907 leads to a strong improvement of the surface chlorophyll.

V.3.2 In situ data

There are 4 BGC-ARGO in the Black Sea that collect oxygen and chlorophyll, all of them being in the central basin and never on the North-Western shelf. However, the estimation of the chlorophyll concentration from the fluorescence data provided by the BG-ARGO cannot be made using a generic algorithm. Indeed, due to the presence of anoxic conditions it seems that the chlorophyll pigments are not efficiently degraded and this makes that fluorescence is increasing with depth in the Black Sea. If generic algorithms are used this means that the chlorophyll concentrations will also increase with depth, reaching approx. 0.3 mg/m^{-3} at 1000 m depth. Therefore, a specific correction (on the model of Xing et al., 2017) was applied to the deep chlorophyll which essentially sets it to zero. The corrected data from Argo floats are stored at ULiege and will be the subject of a publication (Ricour et al., 2019).

The comparison of the depth of the chlorophyll maximum in the in situ observations and model shows that the model chlorophyll maximum is too deep, at least some of the months. Error statistics are shown in Table 5.

Table 5: Model error statistics obtained when considering all the vessel and BG-ARGO (see the position of the sites in Figure 1) observation - model predictions pairs for chlorophyll. Error metrics are defined in Table 2.

Depth of chlorophyll maximum	**Value at V201907**
Bias (m) RMS (m)	**29.3** **32.8**

V.4 Carbonate sub-system

The validation of the carbonate system is not possible in NRT. Besides, even for the past the quality of carbonate data (e.g. pH) is sometimes not optimal. Also, for assessing the consistency of the simulated carbonate components, we used KNORR 88 observations described in Goyet et al. (1990), Knorr (2001) data and Sesame 2008 data (Borges, personal communication). In addition, we compared with typical profiles collected on a density scale and presented in Moiseenko et al. (2011). When comparing model values to climatologic measurements, the comparison is best performed as a function of the density anomaly, σ_t [kg.m^{-3}], instead of depth because it is well know that in the Black sea most of biogeochemical variables present particular characteristics at specific density levels. At the surface, σ_t is around 11; it increases to 14-16 in the oxycline zone, and rises up to 16.2 at the starting of the anoxic layer and to 17-17.5 at the bottom.

V.4.1 Oxygen and Nitrate

Figure 7 shows the simulated oxygen on a density scale. Oxygen was already compared to observations in section V.2. The model is able to simulate the disappearance of oxygen at a density of 15.8-16 in agreement with data profiles. In Figure 8, the nitracline is clearly visible around σ_t=15.2kg m^{-3} with a maximum nitrate concentration between 4 and 5 mmol.m^{-3}. Surface values are highly time- and space-dependent. In particular, on the NWS, very high values can be found close to river mouths (on the NWS shelf, blue points in the plot).

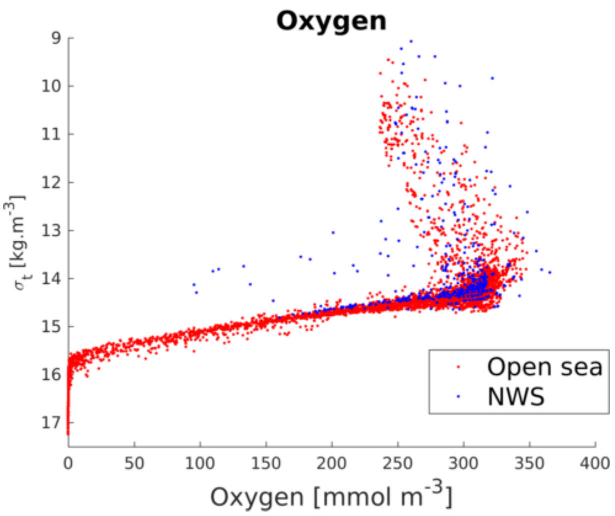


Figure 7. Oxygen as a function of the density anomaly. Vertical profiles are selected randomly in space, and throughout the simulation period (2017-2018)

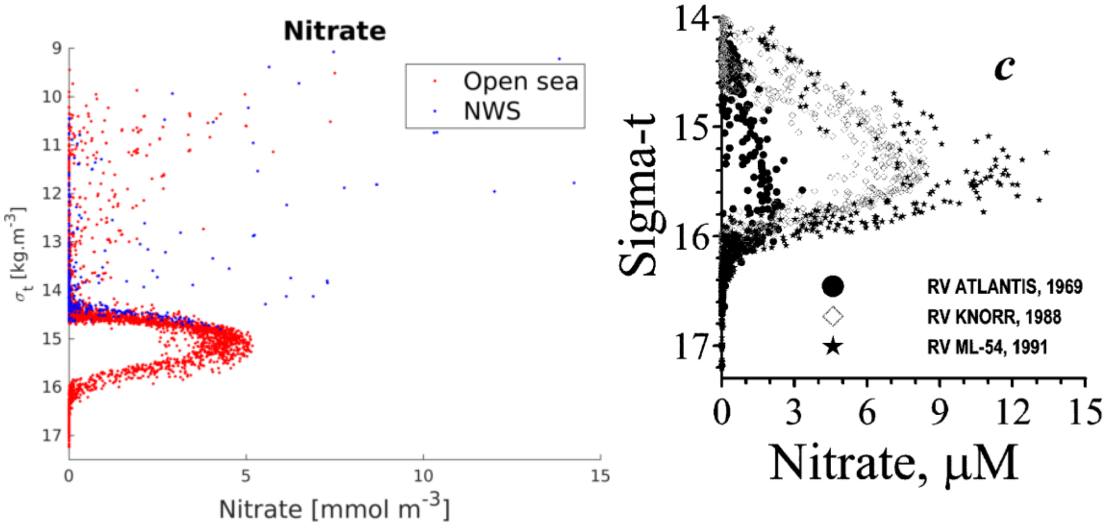


Figure 8. Nitrate as a function of the density anomaly. Left panel: CMEMS BS-MFC V201907 model (2017-2018). Right panel : reprinted from Konovalov and Murray, 2001. It should be noted that compared to the eutrophication period 1988-1992, it is acknowledged that the value of the nitrate peak has decreased to ~4-6 µM (Borges, 2008, unpublished Sesame data in the deep basin) which is in perfect greement with the order of magntude simulated by the model.

V.4.2 Dissolved Inorganic Carbon

For the considered period (2017-2018), there are no available measurements of Dissolved Inorganic Carbon (DIC), pH, Total Alkalinity, surface pC02 and air-sea CO2 flux. However, the literature presents some estimates and it is possible to qualitatively check if the modeled values are in the correct range, as a function of density. Results are presented for the different variables in Figures 9 to 12.

Concerning DIC, it can be seen that the modelled values and the ones from the literature indeed correspond very well (Figure 9).

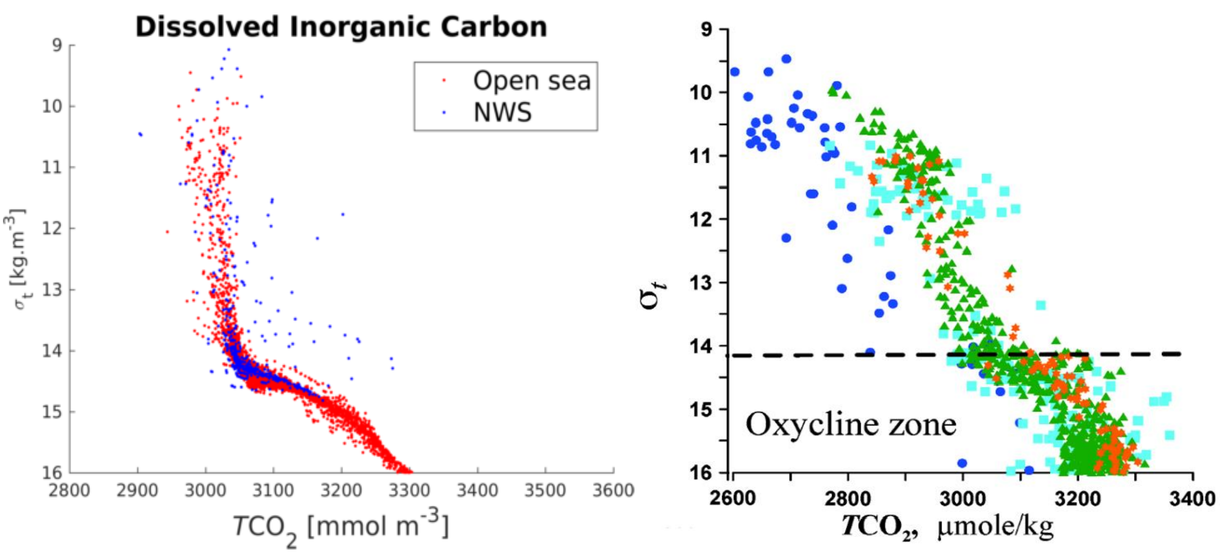


Figure 9. Dissolved Inorganic Carbon as a function of the density anomaly.Left panel: CMEMS BS-MFC V201907 model (2017-2018). Right panel: reprinted from Moiseenko et al, 2011

V.4.3 pH and Total Alkalinity

As for DIC, values for pH and alkalinity, from the model and from the literature, are compared qualitatively. Figure 10 shows that the shape of the profiles in function of density, as well as magnitudes of the variables, correspond very well.

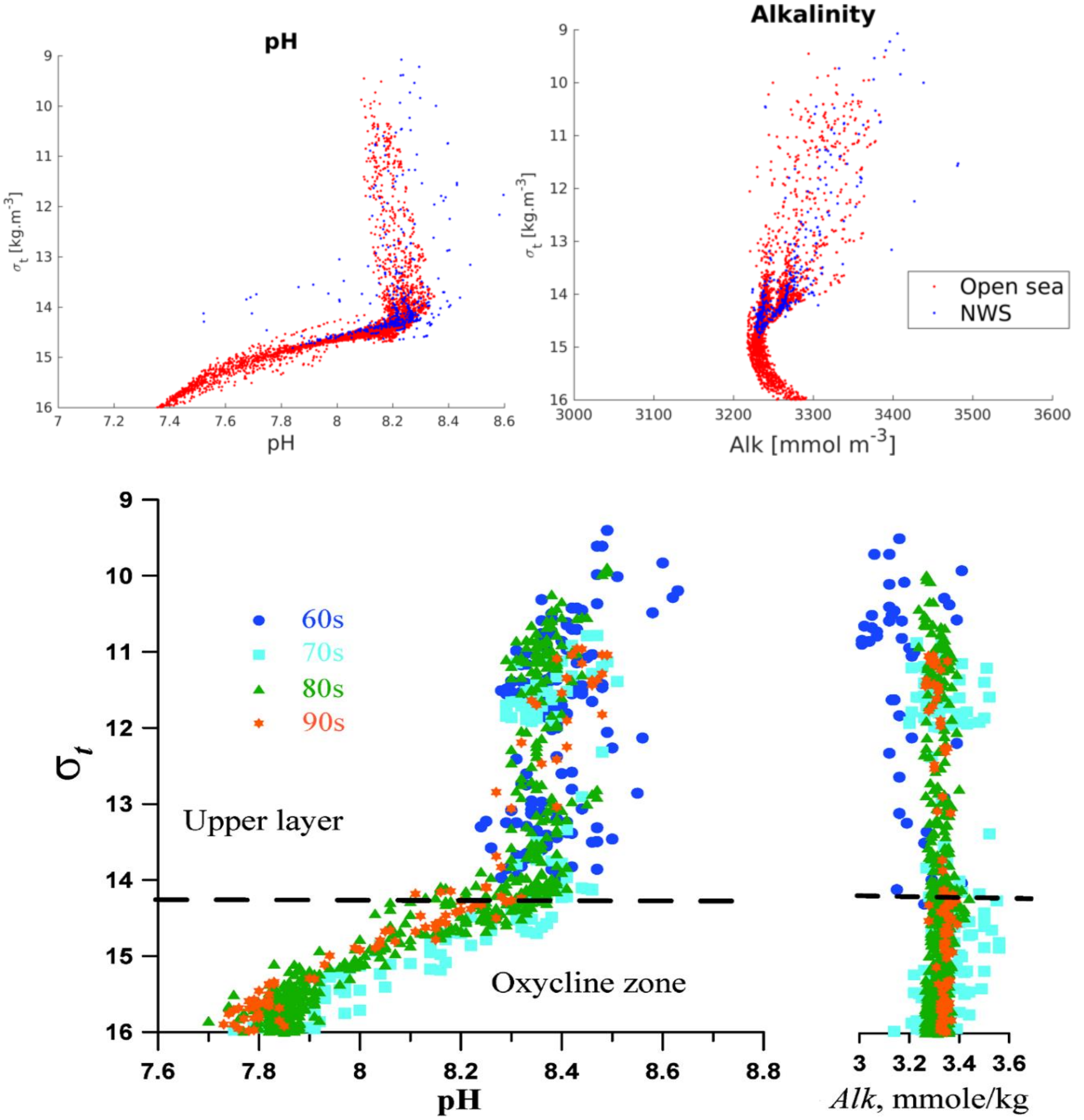


Figure 10. Comparison of model and observations of pH (left) and Alkalinity (right) as a function of the density anomaly. Top panels: CMEMS BS-MFC V201907 model (2017-2018). Lower panels: reprinted from Moiseenko et al. (2011).

V.4.4 pC02

For the pCO2 variable, one can again see qualitatively from Figure 11 that model and literature are in good agreement. The right panel shows a tendency of increasing values during the recent decades, and the modeled values (left panel) is indeed in the upper range.

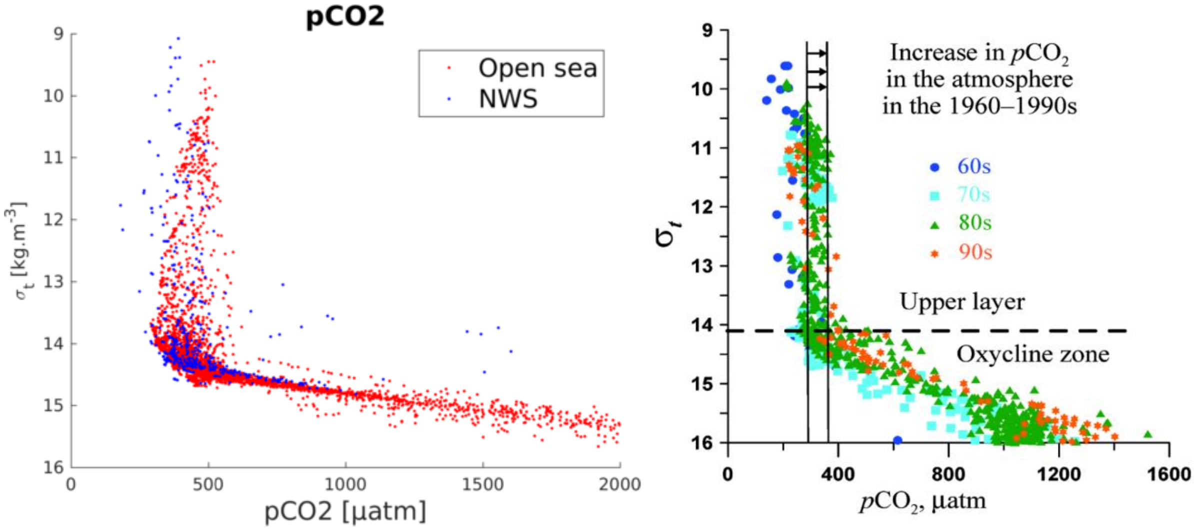
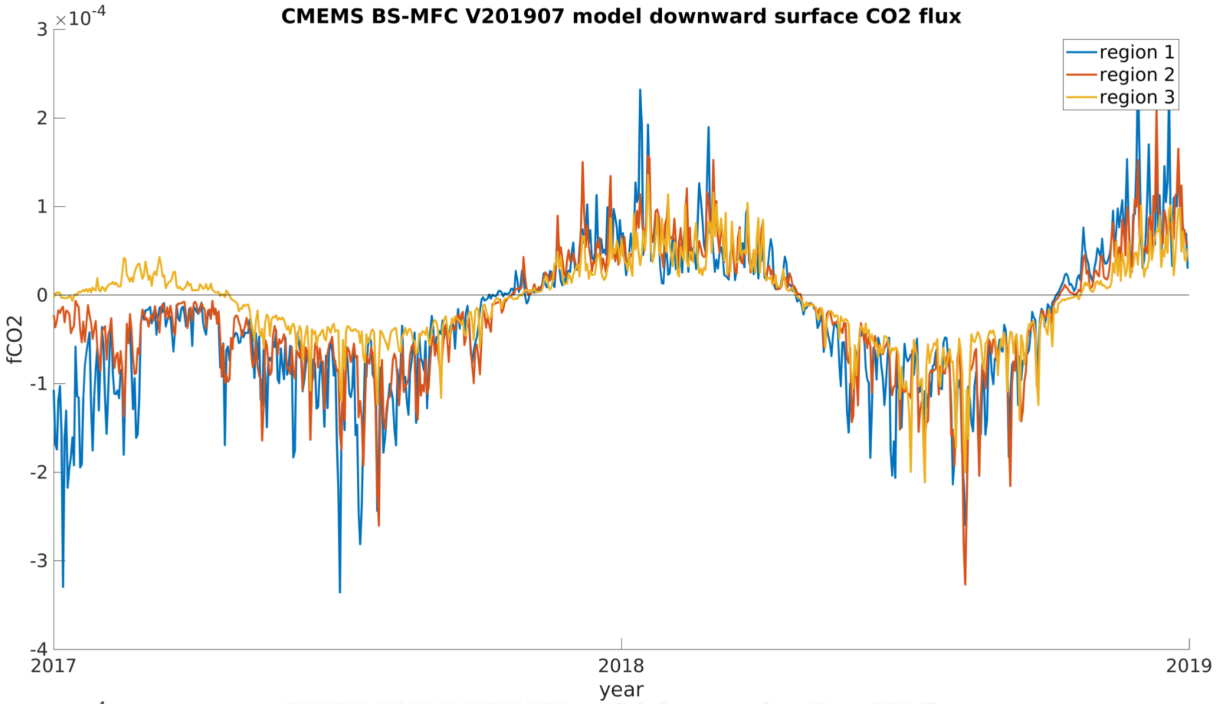


Figure 11. Comparison of model and observations of pCO2 as a function of the density anomaly.Left panel: CMEMS BS-MFC V201907 model (2017-2018). Right panel: reprinted from Moiseenko et al. (2011).

V.5 Air-Sea CO2 Flux

Figure 12 shows time-serie of spatially integrated (for each region) air-sea CO2 flux. There are no available measurements of air-sea CO2 flux over the Black Sea open sea area for the validation period. Regarding the coastal areas, however, the modelled values in region 4 can be compared to the literature (Khoruzhiy, 2018) presenting values for 2011-2014. The modelled values are in a similar range as in Khoruzhiy (2018), and furthermore, they present a realistic seasonal variability.



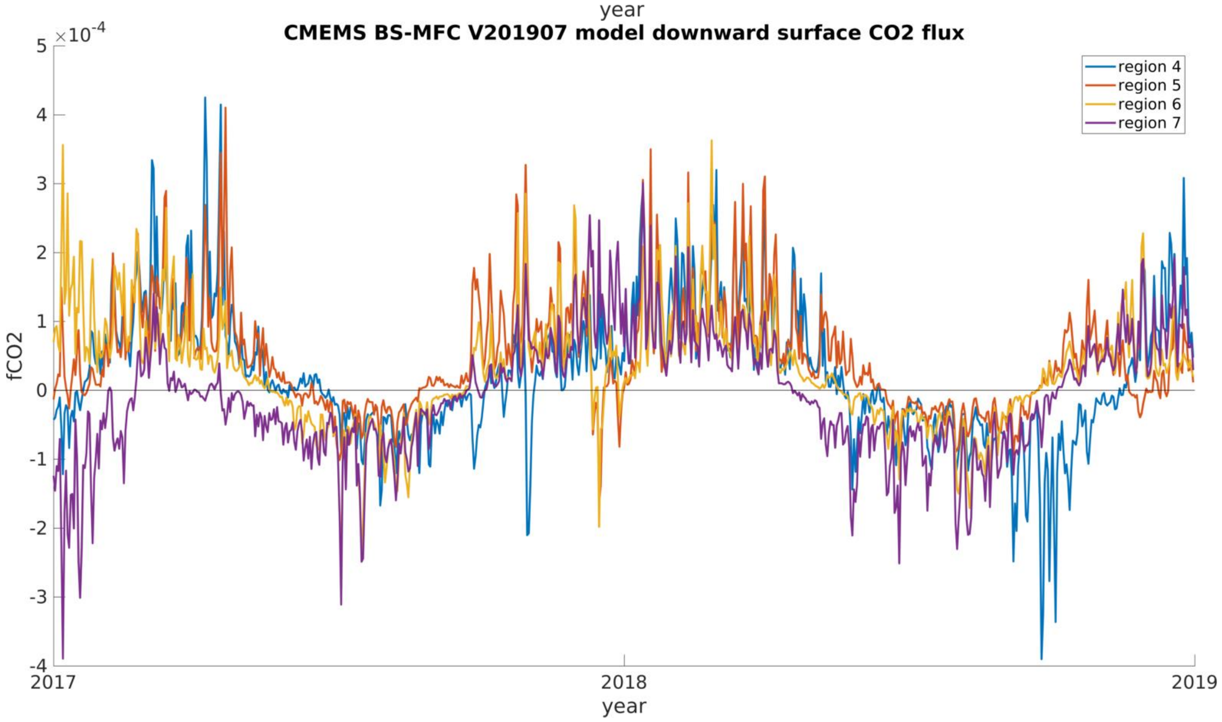


Figure 12. Time-series of modelled air-sea CO2 flux over the open sea regions (upper panel) and NWS regions (lower panel). The fluxes are positive downward, and are given in mmolC.$m^{-2}.s^{-1}$.

VI SYSTEM'S NOTICEABLE EVENTS, OUTAGES OR CHANGES

N/A

VII QUALITY CHANGES SINCE PREVIOUS VERSION

The system at V201907 did undergo 2 major changes:

- The switch from the GHER to the NEMO v3.6 physical forcing model. The NEMO implementation is based on the BS-MFC-Physics model at V4, modified to better suit the biogeochemical forecasts.
- The addition of an alkalinity module.

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