Anonymous Referee #2

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General comments

The authors present the last release of the ECMWF reanalysis and real-time analysis system, e.g. the OCEAN5 system. They describe both the reanalysis part, ORAS5, and the OCEAN5-Real Time systems. Description is focused on upgrades of all the different OCEAN5's components compared to the previous reanalysis ORA5. This paper gives a detailed and full comprehensive description including initial conditions set up, assimilation, models choices, different observations data sets used along the historical period and ensemble generation. Numerous experiments have been performed to assess the choice of the SST and SIC in the assimilation framework, to perform twin experiments with in situ datasets, to update the quality control of in situ data, to generate and assess the off-line bias correction ensemble estimation, to produce OSEs with in-situ network and to measure the impact of different sources of data sets. This valuable paper, likely to become the reference publication for the OCEAN5 system, is well written and this manuscript contains material that deserves to be published with minor revisions listed below.

We would like to thank the reviewer for his/her very constructive and useful comments. Please see our responses for all specific comments below.

Specific comments

1 – Introduction
P.2 L. 3: The primary purpose of ORAs also could be initialization/verification of long term prediction such as decadal or climatic projection.

Thank you. Sentence has been rewritten to "The primary purpose of ORAs includes climate monitoring, initialization/verification of both seasonal forecasts and long term prediction such as decadal or climatic projection."

P2. L.23-24: Funding item should be put in acknowledgement to my point of view; or mention the support in the text as well.

Thank you. Funding support from C3S for ORAS5 production has already been included in the Acknowledgement, so we removed this sentence from Introduction.

2 - The ORAS5 system
2.1 - Ocean-sea ice model and data assimilation
P.3 L.11 : Bernard et al. 2006 should be cited as Barnier et al. 2006

Thank you and corrected.

P.4 Table 1 : - What is the + TKE mixing in partial ice cover meaning? - ERA-Interim is replaced by IFS in 2015, for sake of continuity is there any plans to re-run ORAS with ERA-Interim on 2016-2018 time slots? Is the small increase in RMSE in Figure 16 could also be related to this transition?

1. Given that the wave field is not defined under sea-ice, the wave impact in the Turbulent Kinetic Energy (TKE) scheme is not used under sea-ice. Instead of using the TKE flux from the waves, a constant value of 20 is used under sea-ice as coefficient of the surface input of TKE in ORAS5. This information has been added in Section 2.1.

2. Re-run of ORAS5 using ERA-Interim forcing and reprocessed observation like EN4 has just been finished for the 2015-2017 period. This re-processed ORAS5 data will be distributed by CMEMS in the future.
We have added this information in Section 2.2 as below

"Readers, however, should note that ORAS5 will be re-processed with ERA-Interim forcing and reprocessed observation data set (e.g. EN4) from 2015 onwards. This re-processed ORAS5 product will be extended annually with consistent forcing and observation data set whenever possible. This should produce consistent time series that are suitable for climate monitoring applications. The reprocessed ORAS5 will be available as part of the ensemble of global reanalyses distributed by the Copernicus Marine Environmental Monitoring Services (CMEMS)"

3.The small rise of ORAS5 temperature and salinity RMSEs in Fig. 16 is mainly associated with the switch over from re-processed EN4 to the NRT GTS data stream. But switching to NWP forcing may have an impact as well.

2.2 Model initialization and forcing fields
Figure 2: it would be highly valuable to add the spread in the salt content.

Thank you for the suggestion. The ORAS5 salt content spread information will be included in a separate manuscript (Zuo et al., in preparation). It has also been investigated by Jackson et al (JGR-Ocean, submitted). Considering that there are already more than 20 figures in this manuscript, we prefer not to include more plots and only focus on primary variable as ocean heat content here.

P.6 Table 2: "Sali. Capping" refers to salinity bias correction? It should be mentioned in the caption or in the text.

Thank you. We have replaced "Sali. Capping" by "Bias capping" in Table 2, and added following text in Table 2 to clarify this term.

"*Bias capping is a switch to cap the minimum value of salinity bias correction term to prevent static instability, see Section.2.3.3.*"

2.2.2 - Forcing, SST and SIC
P7 L.12-13: is the value of SSS relaxation term has then the same representative time scale of 12 days?

No, The SSS relaxation term is -33.3 mm/day. We have added the following text for SSS relaxation.

"*The SSS relaxation term is -33.3 mm/day. This is equivalent to a restoration time-scale of about 1 year for a well-mixed upper 10 m water with a mean model surface salinity of 35 psu.*"

P8 L10: We would read ": : : prior to 2008 comes from HadlSST2.1 : : :"
Thanks and corrected.

P9: The choice of SST products is truly justified in terms of temporal consistencies, what about the spatial patterns, where are the main differences prior 2018 between OSTIA and HadlSSTv2?

We assume that by "prior 2018", the reviewer actually means "prior 2008" here. ORAS5 switched from HadISSTv2 to OSTIA SST since 2008. We have demonstrated in Fig. 4 that global mean OSTIA SST is colder than HadISST2 SST. And map of SST differences between OSTIA and HadISSTv2 prior 2008 can be derived from Fig. 20-a) and c). It shows that OSTIA is colder than HadISSTv2 almost everywhere in the global ocean, except in the Gulf Stream extension, near Japan and in the Brazil-Malvinas Confluence region.

P.9 L12-P.10 L1-4: It is difficult to understand that changing the source of sea ice concentration data in the assimilation has such a big impact on sea ice thickness. Either the source of the impact is coming from the Hadley SIC itself; either the control of the ice volume through the assimilation of SIC has changed between experiments. Further explanations are needed.

The SIC in the HadISSTv2 data is higher than in the OSTIA and Reynolds products. This has been discussed in the manuscript at P8 L11-17, and in Titchner and Rayner (2014). Large differences in sea-ice thickness between ASM-HadI (Fig.5-b) and the other two experiments (Fig. 5-a,c) are result of assimilating different sea-ice concentration products. There is no change in data assimilation method when carrying out these three experiments. In fact, assimilation of HadISSTv2 SIC during 1979-1984 implies strong positive sea-ice volume increments in the Arctic domain. Compared to sea-ice volume increments from assimilation of ERA40/Reynolds SIC, which are much more neutral, assimilation of HadISSTv2 SIC adds approximately 3 m of sea-ice thickness per year in most of the Arctic basin for the first 5 years (see Figure 1). To help readers to better understand this difference, we have added the following content in Section 2.2.2.

"*This is mainly due to assimilation of HadISST2 SIC that is in general higher than those of Reynolds/OSTIA data. In fact, assimilation of HadISST2 SIC during 1979-1984 implies strong positive sea-ice volume increments with respect to ERA40/Reynolds data, which are equivalent to adding approximately 3 meters of SIT per year in most of the Arctic basin during this period (not shown). This effect has also been discussed by Tietsche et a., (2013) in their sea-ice assimilation experiments.*"

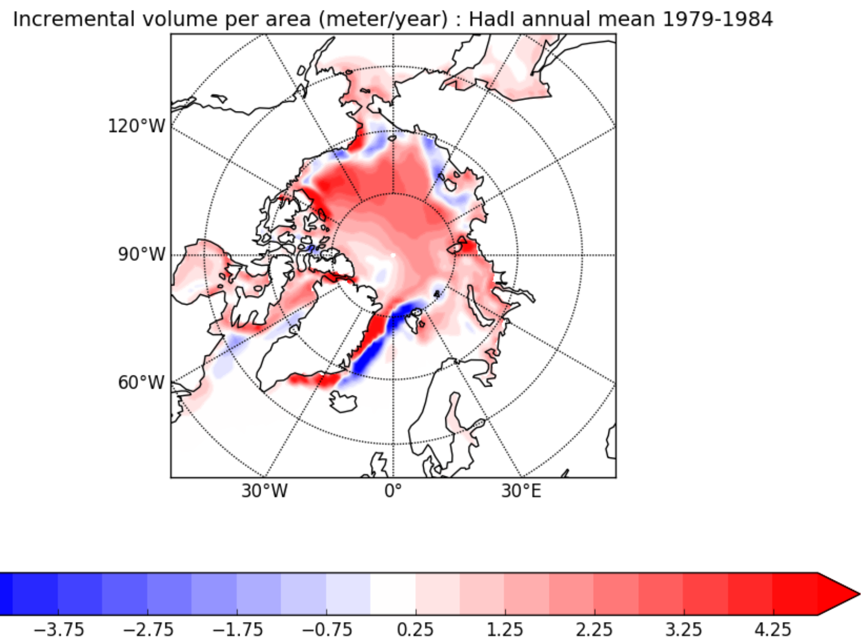

Figure 1. Differences in sea-ice volume increments (in m/year) as ASM-HadI minus ASM-HadI-OST, averaged over the 1979-1984 period. Sea-ice volume increments are computed as SIC increments times the mean model sea-ice thickness, shown as volume per area.

2.2 Assimilation of in-situ observations

2.3.2 – Quality control of in-situ data

The improvement with pair-check verification looks pretty weak, how much? and from Figure 7 hardly noticeable. A zoom in the Northern Atlantic with changes in the color bar will be appreciated or this Figure can be withdrawn. How many isolated salinity profiles has been rejected? Are these profiles located in key areas?

We would like to thank the reviewer for this very useful comment.

The implementation of pair-check for in-situ observation was designed to avoid introducing spurious vertical convection when assimilating salinity observation alone, and to tackle large reanalysis error in the North Atlantic following the Mediterranean outflow waters. Therefore, we agree that we should focus on the North Atlantic alone. Fig.7 has been replotted for the N.Atlantic region, and with the same colour bar for all panels.

We have also added following context in this section
"*… This was improved in PC-ON as shown in Figures 7c,d with a small compensating temperature difference (~0.3 K) defined as PC-ON minus PC-OFF, which also leads to reduced RMSE in PC-ON (not shown) between 1000–2000 m. This new pair-check mostly affected the North Atlantic Ocean between 1000–2000 m and rejected ~3% of salinity observations in this region.*"

2.3.3 – Bias correction scheme
Figs8 and 9: It is surprising that an ensemble mean (set up of ORAS5) give larger biases than a single realization (set up in ORAP5). Part 2.3.1 also showed that model bias is reduced with EN.4 compared to EN.3. Is it then possible that these systematic larger biases come from different periods used to estimate these biases correction?

We would like to thank the reviewer for the comments.

I assume that in his/her second sentence, by "Part 2.3.1" the reviewer refers to Fig. 6 and Section2.3.1. This figure only suggests that by assimilating EN4 instead of EN3 data set, model analysis exhibits a reduced bias in the Barent Sea in 2009. This is verified against independent CTD observations and is mainly associated with an increased number of observations in EN4 data set. However, this cannot be translated into a reduced model bias, which is determined by model and forcing errors but is also affected by the bias estimation method, e.g. both sampling periods and spatial coverage will affect the bias estimation result. Compared to ORAP5, the a-priori bias in ORAS5 has been estimated in a slightly later period during the Argo era, and against the EN4 in-situ observation data set. As a result, this means that the sampling space is improved with better spatial and temporal coverages when estimating ORAS5 bias. We believe that the sampling space is the reason why the ORAS5 bias estimate differs from ORAP5. However, it is not easy to anticipate what would be the effect on the amplitude of the bias. In fact, Fig 8 shows that the bias estimate in ORAS5 is larger in the upper ocean and reduced in the mid/abyssal depths. These larger values in the upper ocean come mainly from the high latitudes. In areas where the observation coverage is more stationary (Gulf Stream, Tropics), the ORAS5 bias is indeed weaker than the one in ORAP5.

P14 L4-7 now reads as
"*… This bias term is the systematic model/forcing errors estimated using in-situ observations, therefore the result is subject to the temporal and spatial coverage of global ocean observing system. The differences between ORAS5 and ORAP5 as seen in Fig. 8 and Fig. 9 are results from (a) improved temporal and spatial coverage in the new EN4 data set with increased vertical resolution; (b) a different climatological period used for ORAS5 bias estimation; and (c) the ensemble bias estimation method used in ORAS5.*"

2.4 – Assimilation of satellite altimeter sea-level anomalies
P.16 L.2-3: Is cutting the assimilation of the SLA at 50_ latitude doesn't bring others issues such as artificial and abrupt changes in the circulations? Is there any ramp to smooth this cut off for instance? Is the MDT still assimilated in these shelves and polar areas?

A cut-off latitude at 50N/S for SLA assimilation was initially introduced to prevent introducing undesirable barotropic/baroclinic adjustments from the balanced SSH increment in the high latitude regions, where the ocean state is normally less stratified with respect to that in the Tropics. This should not introduce artificial or abrupt changes in the circulation.

However the main filter operating for the SSH assimilation is a check on stratification, which provides a flow-dependent ramping of SLA assimilation. The MDT is only needed to compute the observation equivalent model background field when assimilating SLA, therefore information in MDT is only assimilated whenever SLA is assimilated.

P.18 L14-15: then how the steric component in the GMSL is estimated prior 1993?

Prior to 1993, only the mass variations of GMSL are constrained using a climatology of the GRACE-derived bottom-pressure data. The steric height in ORAS5 is still estimated as an area average of the vertical integral of the model density. This is the same as in ORAP5 (Zuo et al., 2015) and allows for inter-annual variations of the total GMSL.

Now it reads as
"*Prior to 1993, mass variation that contributes to the change of Global Mean Sea Level (GMSL) in ORAS5 was constrained using the GRACE-derived climatology. The total GMSL was then constrained by assimilating altimeter-derived GMSL after 1993. This is the same as in ORAP5 (Zuo et al., 2015).* "

Figure 12: BGE acronym should be informed in the text before figure's citation.

Thank you. This acronym has now been introduced in Section 2.5.

Figure 13: We should read : : : : The specified BGE standard deviation: : :

Thank you. Corrected.

2.5 – Ensemble generation
P.19 L14-15: net precipitation refers to what?

Here net precipitation refers to total precipitation minus evaporation. This has been clarified in the text.

P.19 L.23: From Figure 12 : : : The salinity and temperature are under-dispersive : : : to my point of view

This sentence has been rewritten as below
"*… Here, the ORAS5 temperature ensemble spread (Fig. 12-a) shows a spatial pattern that is very similar to the diagnosed value using the Desroziers method (Fig. 12-e), except its amplitude is weaker, especially in the Tropics.* "

3 - The OCEAN5 Real-time analysis system
P.22 : YMD should be informed in the text.

This information has been added in Section 3.

4 – Assessment of ORAS5
4.1 – OSE

Clear and informative part which regionally characterizes the importance of in situ network.

Thank you!

4.2 – Sensitivity experiments
Table 5: It is not clear from the Table 5 in which sensitivities experiments the assimilation of in situ data set is activated. From the text, we understand that this assimilation is switched on in the O5-NoAlt and O5-NoBias experiments but it should be specified in the text, idem for the assimilation of SIC.

Thank you for this comment which we completely agree. Table 5 has been remade with additional information about assimilation of SIC and in-situ observations.

4.3 – Verification in observation space
Figure 16: It is surprising to notice that the impact (improvement) of the SST nudging is increasing from the year 2008, is it likely due to the change from HadlSST to OSTIA but why?

The impact from SST nudging is shown in Fig. 16 as RMSE departures between CTL-HadIS and CTL-NoSST. This is sampled in observation space of EN4 in-situ data. The temporal evolution of this RMSE departure is associated with a) model/forcing error changes; b) characteristics of SST observation that model nudging to; and c) observation space changes. Improvement from SST nudging has gradually increased since 2000, which is more likely due to improvement in ocean observation coverage with Argo floats.

4.4 – Verification of ocean essential climate variables
4..4.1 – SST Figure 19: remove the 'sosstsst' title.

Done.

4..4.2 – Sea level
P.32 L.24: ": : :reasonably well: : :" Figure 22 b): We understand the same color bar is used for the Figure 21 but contours are hardly noticeable in this ratio.

Thank you for the comment.

The AVISO DT2014 and SL_cci2 SLA are very similar in the context of regional sea-level variance, resulting in a ratio value close to 1 (the near-white color) in Fig. 22-b. As the reviewer already pointed out, we chose to use the same color bar from Fig. 21 here to facilitate inter-comparison between these two figures. Therefore we prefer not to change it.