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Interactive comment on "How essential are Argo observations to constrain a global ocean data assimilation system?" *by* V. Turpin et al.

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I would like to first thank the referee for its attentive reading and the detailed comments that help us to improve the article.

Anonymous Referee #1

The manuscript describes observing system experiments (OSEs) carried out with the Mercator-Ocean assimilation and forecasting system to demonstrate the impact of the Argo array on analyses and forecasts. A number of one-year experiments are carried out with all data assimilated, all data except Argo, and all data except half the Argo floats, as well as a free run. The demonstration of the impact of Argo data is important for funders of the observing system, and can also be beneficial to improve understand-

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ing of the data assimilation and forecasting system. There are two major areas which should be addressed before the paper is published, as described below, followed by some more minor comments. Major comments 1. The main assessment strategy in the paper is to compare with Argo data. Presumably that will over-estimate the impact of Argo data. Some assessment using independent data, or data which are assimilated in all the assimilative runs would give a clearer picture of the impact. There needs to be at least some discussion of whether this assessment strategy is objective/fair. Only impact on temperature and salinity is shown – what is the impact of Argo on other variables? Also, in parts of section 3, the analysis is compared to observations, and some of the experiments are assimilating Argo data - the observations could in principle be bad, we could fit them closely and we would see a positive impact on the analyses, but that wouldn't necessarily be a good thing.

We first present in this article the analyzed fields from the different OSEs and compare them between each others and with the Argo data in order to qualify the 3D T/S model analysis field realism. It is true that we focused on in situ observation misfit and did not keep any fully independent data set. We wanted to stay as close as possible to the real time system conditions. We will add forecast error estimates using the other assimilated data sets. This will give some indication on the impact of Argo data assimilation on other variables and will help verify that the forecast error reduction on T/S fields do not lead to unphysical corrections on the other model variable. To properly assess the impact of the Argo floats in a forecasting system, one need to do it with the forecasts. That's what we do in the second part of the article by using the innovations statistics. That will allow us to estimate if the differences seen in the analyzed fields correspond to improvement of the forecast in term of in situ error misfit. We will explain more clearly our choice and indicate the limitation of them.

2. The description of the system used in the experiments is not very clear in section 2. Some things are repeated a few times (observations assimilated), and other important details are not described clearly. Aspects of the data assimilation, which are obviously

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crucial to the impact of the Argo data, are not clear from the description. For instance, it would be useful to have an idea of the effective length-scales, and to know how the temperature/salinity data affect other variables. What is the time window of the data assimilation? Crucially for interpretation of the results, is there any relaxation to climatology, and if so does it vary with depth? For the observations which are assimilated, are they the "real-time" version of the Argo data or have they undergone delayed-mode quality control? What about the other data-sets (e.g. SLA) – are they real-time versions of the data?

We did not give many details on the assimilation system. We will add in the text information that are important for the interpretation of the results and remove the duplicate information on assimilated data. Here are few precisions, they will be added in the text with others suggested by the second reviewer. The correlation scales are about 100 km for most of the globe and reach 400 km at the equator for the zonal scales. The maps of the spatial and temporal length scales can be found in Lellouche et al. 2013. The increment on T and S, computed during the analysis step from the in situ profile innovations, is projected on the barotropic height and U, V fields thanks to the multivariate properties of the model covariance matrix. The covariances are static over the assimilation window of 7 days and vary "climatologically" over the year. They are estimated from an ensemble of anomalies computed from a multi-year forced simulation. There is no climatology or reference field relaxation in the system. The only external reference field used in the system is the MDT from CLS/CNES used to assimilate the SLA data. The data sets used for those experiments are the real time along track sea level anomalies from AVISO, the real time in situ data base from Coriolis data center. Real time automated QC was applied, later data are included but the QC procedures are still the real time ones.

Minor comments Abstract "half of Ago data sets" should be "half of the Argo data"

This will be corrected in the text.

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“reducing observation-model forecast error” should be “reducing model forecast error” or “reducing observation-model forecast differences”

We will correct that.

Lines 16-17: There also seems to be a large impact in the Gulf Stream region.

Yes, we will add the Gulf Stream in the list of impacted regions.

Line 19: “even with a 1/4° model resolution”. Not sure what is implied by this statement.

“Even” was related to the spatial resolution, meaning “even in an eddy permitting model”. We first thought that in a $\frac{1}{4}^{\circ}$ spatial resolution system keeping only half of Argo observations will be “sufficient” to constrain the resolved model time scales. Our result shows that assimilating all of the Argo floats compared to half of them clearly improve the analysis and forecasts in an eddy-permitting model. We will reformulate more explicitly this fact.

Line 20: This last sentence seems to be making a general statement for all global data assimilation systems, but the study is only about the Mercator-Ocean one.

This is true. We will change the sentence so systems will become Mercator Ocean system.

Page 1146, Line 26: on first reading I thought you meant that the Argo was array is measuring T & S mainly for operational oceanography, but I think you mean it is reporting in real time mainly for operational oceanography. More generally the first paragraph of the introduction doesn’t read very well.

We will modify the first paragraph to make it clearer. We mean, in fact like you said, real time reporting which is crucial for operational oceanography.

Page 1147, Line 11: “optimizing the design” seems a bit strong here. Maybe “improving the design” would be better.

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Yes, “optimizing” is not correct, we will change this to “improving”.

Page 1147, para starting on line 22. Two papers by Oke et al, 2015, in the Journal of Operational Oceanography provide a good overview of recent efforts on OSEs and should be included in the introduction.

Yes, we will cite them in the introduction when mentioning the GODAE project.

Page 1148, line 9. The impact of Argo data on T and S only are assessed. What is the impact on e.g. SSH?

This is linked to one of the major comment. We will briefly present the impact of Argo data on SSH and SST in the experiments with and without Argo. In fact, when looking at innovation global statistics they do not differ significantly (Figure 1,2 3 and 4 in this comment). A more complete analysis will be part of a future work where the complementarity of the in situ and altimetry observation will be assessed.

Page 1148, Line 13. “conclusions are”.

We will correct that.

It is worth highlighting in the introduction that the results obtained from this study on the impact of Argo are specific to the Mercator-Ocean system, and that they can be put into the context of other similar studies.

We will put more emphasis on the limitations of our approach and the fact the results are dependent of the system used for the experiments and can’t be generalize to other system without an extensive system intercomparison.

Page 1148, Line 18. SLA should be Sea Level Anomaly. Also, this list of in situ data is repeated later in section 2.2.

We will correct both point in the text.

Page 1149, line 3. “Momentum and sea surface fluxes”. Do you mean “Momentum,

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heat and freshwater fluxes"?

Yes, we will correct that.

Page 1149, line 6. It should be made clear that the error covariances are static.

As we will give more details on the assimilation system, this specificity of the covariance matrix will be added.

Page 1149, line 10. Many readers will not know IAU, so it is worth giving a little bit more detail and referring to a paper on it.

We will add a short explanation and the reference for the Incremental Analysis Update.

Page 1149, paragraph 2. There is no way to understand from this how the MDT was modified.

That's right. Mean SLA residuals computed over a multi year simulation with assimilation (the Glorys2 reanalysis) are used to "correct" the CLS/CNES MDT.

Table 1 doesn't add much as it is full of acronyms which aren't all described in the text (e.g. SAM). Perhaps the table could be removed?

We will remove it and keep the important point in the text.

Paragraph starting on line 19, page 1149. This seems more like an acknowledgement so should go at the end of the paper.

The paragraph will be removed from this section.

Page 1150, line 3. "important" should be changed to "numerous". An assessment of their importance is the focus of the paper.

Yes, we will change this adjective.

Page 1150. Line 14. There are other regions where the marine mammals also provide useful information such as the Kerguelen region.

We will change the sentence to be more general.

Page 1150, line 16. Perhaps it would be worth mentioning that there is some coordination of gliders through EGO?

We will mention this initiative in the text.

Page 1150, line 22-23. This approach is similar to that used by Fujii et al 2015 – "Evaluating the impacts of the tropical Pacific observing system on the ocean analysis fields in the global ocean data assimilation system for operational seasonal forecasts in JMA".

We used the WMO platform ID to select a part of the floats.

Page 1150, line 26. Be more specific about which regions are more densely sampled by the No Argo platforms.

We will give more details in the text on the inhomogeneous geographical distribution of the "No Argo" in situ observations.

Page 1151 line 1. The time distribution is described as fairly regular yet fig 2 seems to show variations in terms of global observation numbers through the time period. What are these due to? The last 6 months is chosen throughout the results sections. There doesn't seem to be much justification other than saying that there is a "spin-up" of the impact. It would be interesting to know how long the spin-up really takes.

Figure 2 shows the number of all the in situ data available for assimilation and validation Argo. The "horizontal"maxima appearing at depth are the signature of moored instruments, mainly the tropical moorings. The "vertical" maxima correspond probably to field campaign. The global time coverage is "fairly" regular compared to a long term reanalysis or regional coverage. The "spin-up" period will be discussed briefly in the text by showing the 1-year evolution of the innovation statistics (figure 5 and 6 here) in a experiment where Argo data are not assimilated. It is an important point to rise when doing OSE as the ocean "time" response depend on the region and the depth and the results found could have been different on a longer simulation. We think that analyzing the last 6-month of the experiment is already quite representative and not so large changes will appear on a longer simulation. We will mention that as a limitation of the study.

Page 1151. The term “Other No Argo in situ data” seems quite convoluted. How about “non-Argo in situ data”?

We will reformulate as you suggest the sentence.

Page 1152, line 25. Why are the model’s western boundary currents warmer than observations?

This is probably due to the too weak currents in this configuration with local recirculation. The heat export is then too weak.

Page 1152, line 27. The model’s tropical Pacific is also warmer in the east which could imply an error in the slope of the thermocline. Some discussion of why that might occur would be useful to have. In fig 3 the tropical differences appear quite large given that the moored buoys are assimilated in those regions. Is there an explanation for that?

The tilt of the thermocline is too strong or too weak depending on the ENSO index. The assimilation of the tropical moored observations is not sufficient to constrain the thermocline slope variability in our system. We know that our system do not optimally “used” the tropical mooring information.

In this article, concerning the impact of Argo at global scale, we made the choice to not present any exhaustive “physical” analysis of the changes as it will be too long. This would be possible for a regional model.

Page 1154, line 19. Fig 5 is shown for one date in December. Would we see larger impacts in the southern hemisphere rather than northern hemisphere if we looked in June?

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The largest impact on temperature at 100 m of Argo data assimilation are found in the mixed layer of the northern hemisphere in winter and southern hemisphere in summer, but the Kuroshio and Gulf Stream regions still show large differences. The impact at depth, under the thermocline shows much smaller seasonal variability. This is still difficult to conclude from a 1-year only experiment with the “spin-down” effect of removing one part of the observations. Page 1155. Line 4-7. It seems strange not to show any results from the 300-700m depth range.

The figures for this layer are presented in this response (figure 5 and 6). It appears as a “transition layer” between the surface and the deep ocean. We chose to not show it, but we will add a short comment on the text.

Page 1155, lines 20-23. I got confused in this discussion about which layer you are commenting on.

It is still a comment on the 700-2000m layer. We will change the text so there is no ambiguity.

Page 1156. Line 26. Are the differences smaller in the 0-300m layer because SST data are assimilated?

It is our guess, but as we do not have an OSE without SST assimilated this difficult to tell.

Page 1157. Line 6. Heat Content anomaly is only reduced in the 700-2000m layer.

Yes. We will correct the text.

Page 1157, Line 26. There do appear to be significant differences in parts of the South Atlantic.

We will add in the text “except in the Southern Pacific and Indian Oceans”.

Page 1158, line 13. It could be worth mentioning here whether the large differences are due to issues with the modelling of the Mediterranean outflow.

Yes, we will explain the error source: the Mediterranean outflow in forced the model is too shallow. This is largely corrected with the assimilation of Argo profiles.

It is quite difficult to compare Figs 4 and 11 when they are quite far apart in the paper. Could you show the ratio of the differences shown in fig 11 to fig 4 to show the improvement more clearly?

We did this exercice for SLA observation but the resulting map is difficult to read and too Âń patchy Âż. We did not do it for in situ observations. It is true that the figures are far apart as we did separate the innovation and residual analysis in different sections.

Page 1159, line 1."operational" PSY3 – presumably here you mean the Run-ref experiment analyses?

Yes. We will change the text.

Page 1161, top paragraph. It would be helpful to the reader if you put these percentage improvements into some sort of context. For example, how much improvement would you expect from a normal upgrade to the model or data assimilation?

The time series of T and S innovations were computed on a same time period for 3 successive version of the global $\frac{1}{4}^{\circ}$ system. The latter one is the one used in this study. The improvement made from initial version to the first one was the same order as adding half of the Argo array (15%). The latter system update lead to much smaller changes (less than 5%). As the systems become mature, improvements tend to be smaller.

Page 1162. Line 6. It sounds from this that the experiments were carried out in real time, so perhaps leave out the “real time” part.

Yes, this is ambiguous, we will remove real time.

Page 1163, final paragraph. I don’t quite understand what you mean by “our statements ..... can be generalized to include other systems”.

We will remove this part of the conclusion as we did not conduct systematic system intercomparison.

Table 2. At the moment, the table uses “x” to denote that an observing system is assimilated and a blank to denote that is isn’t assimilated. It might be clearer to use a tick and a cross.

We will change the symbol in the table 2 to give a clearer view of the assimilated data sets.

It is often very difficult to read text on the figures, particularly the color scales.

We will improve the color scales so they will be more readable.

Figure 1. It isn’t clear from the caption what the terms “odd” and “even” mean.

We will change the legend to Argo profiles to odd and even WMO platform numbers.

Figure 3 and subsequent figures. The time period of these comparisons should be included in the caption.

Yes, we will add this information in the legends.

Figures 8 and 12. The light and dark blue lines are difficult to distinguish – perhaps use a different color. Also, in the caption the sub-plot letters follow the description for that sub-plot whereas in the other plots they precede the description. “South Ocean” should be “Southern Ocean”.

We will homogenize the legend and change the light blue color on the plots.

Figures 13 and 15. The figures are very small. Perhaps split them onto two rows.

We will split them in two rows.

Figures 14 and 16. The green and yellow lines are difficult to distinguish. Also the “normalized RMS of innovations” statement is not very precise. In the bottom axis of plot (b) it has “(% of performance)” but presumably this is not a percentage.

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We will change the color of the green line to make it mode distinguishable to the others. We will also correct the legend as what we show is not a percentage.

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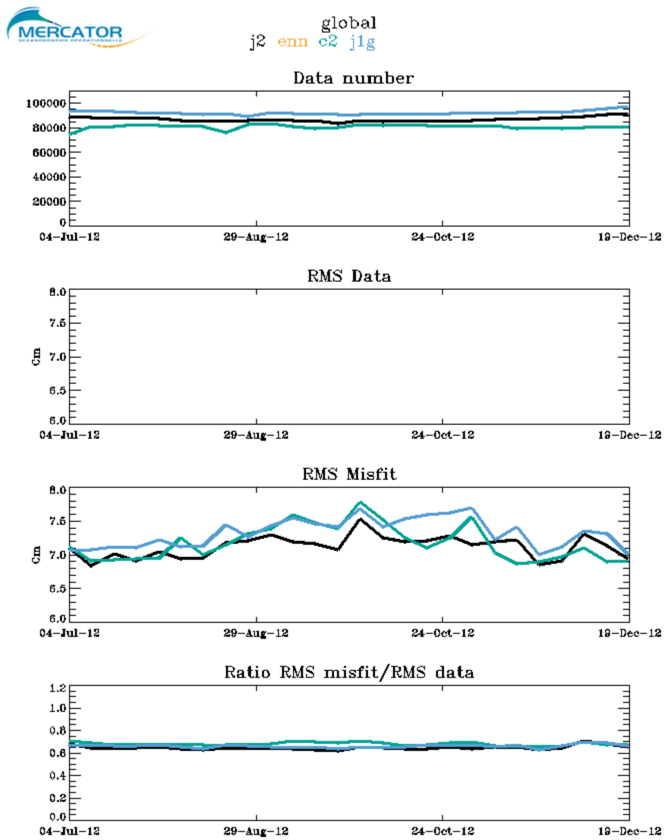

Fig. 1. SSH innovation statistics when All Argo floats are assimilated.

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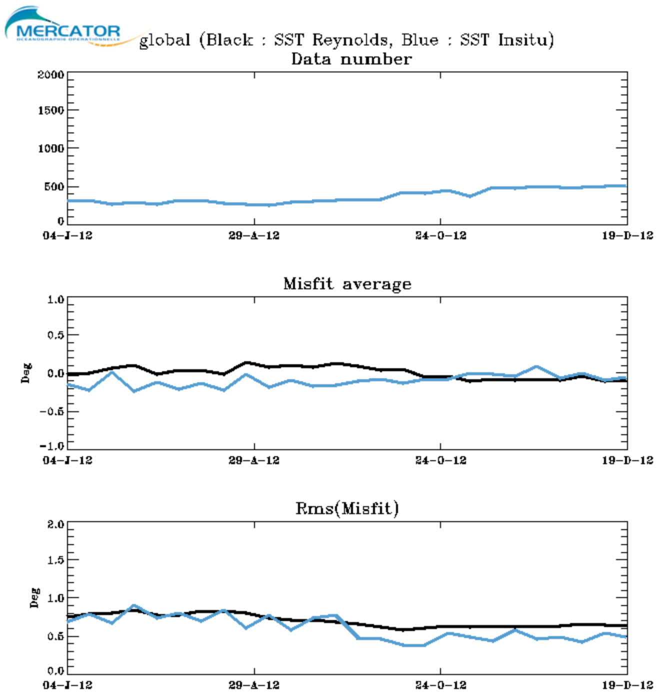

Fig. 2. SST innovation statistics when All Argo floats are assimilated.

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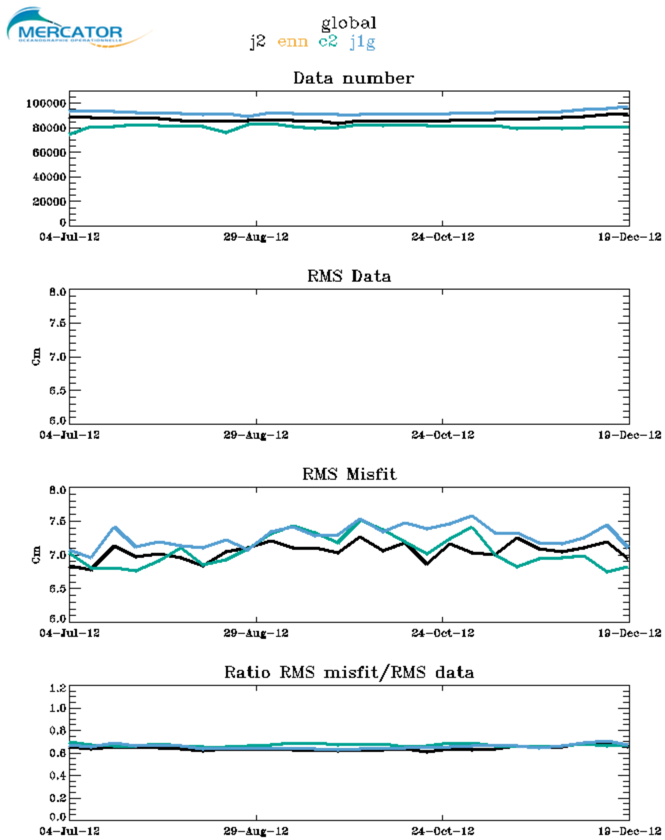

Fig. 3. SSH innovation statistics when No Argo floats are assimilated.

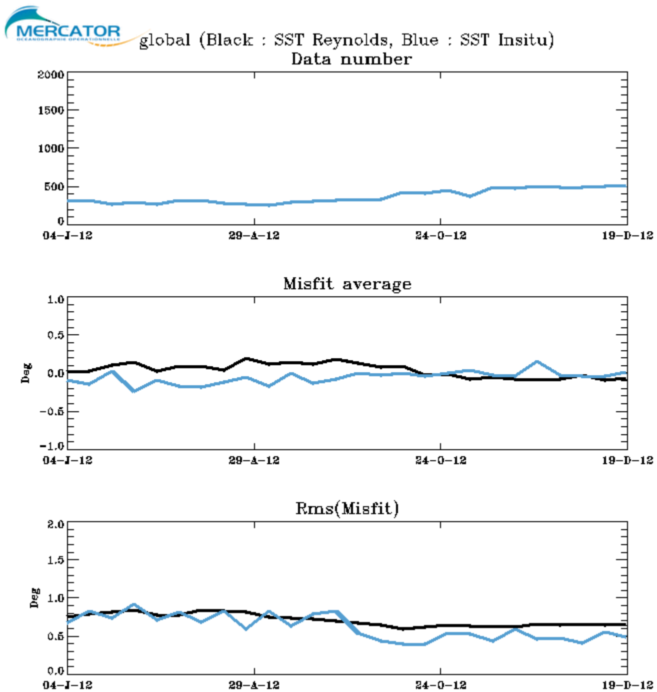

Fig. 4. SST innovation statistics when No Argo floats are assimilated.

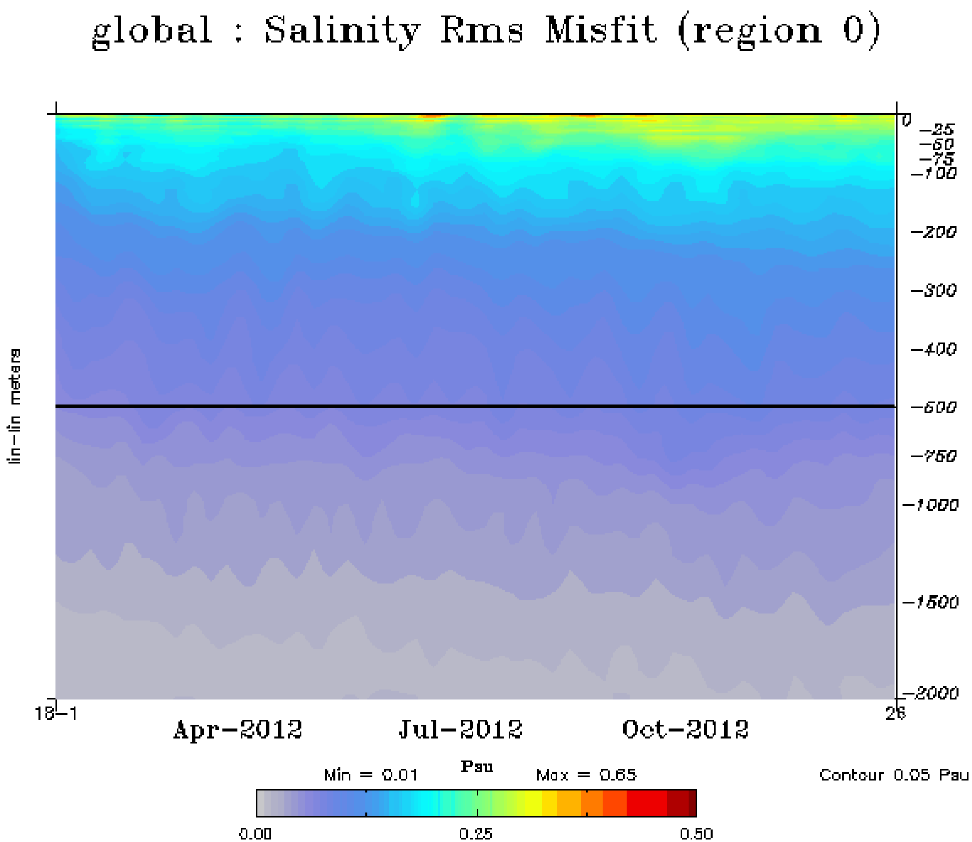

Fig. 5. RMS of the In Situ salinity innovations when No Argo floats are assimilated.

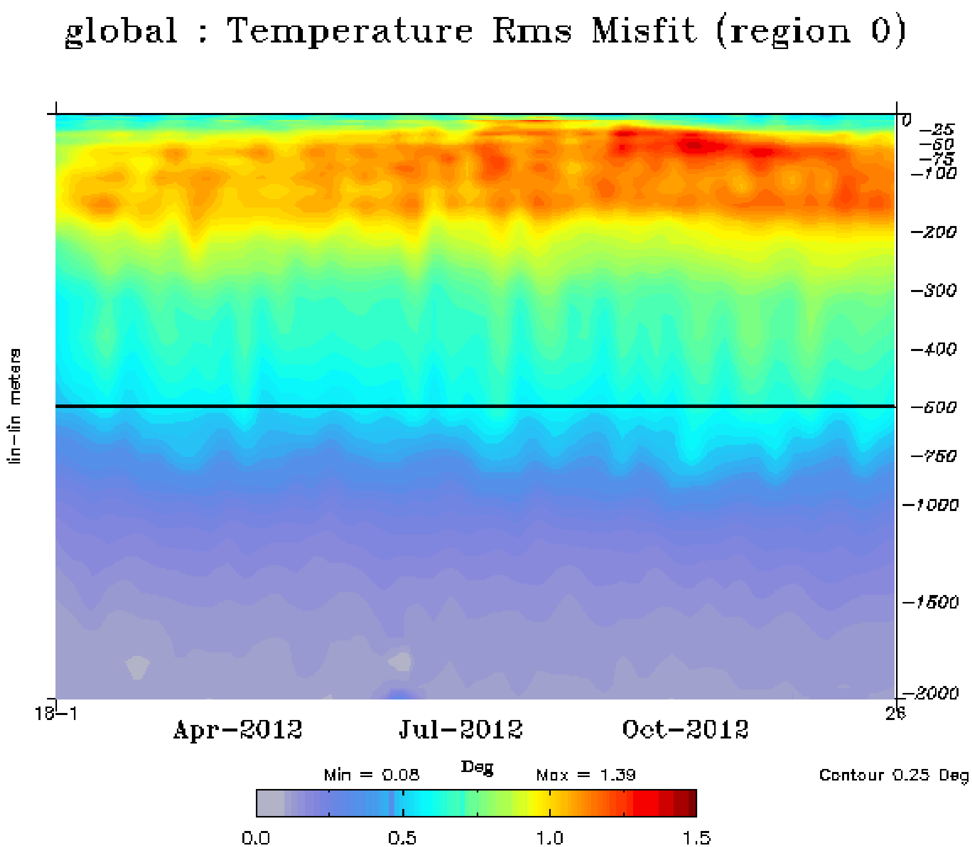

Fig. 6. RMS of the In Situ temperature innovations when No Argo floats are assimilated.

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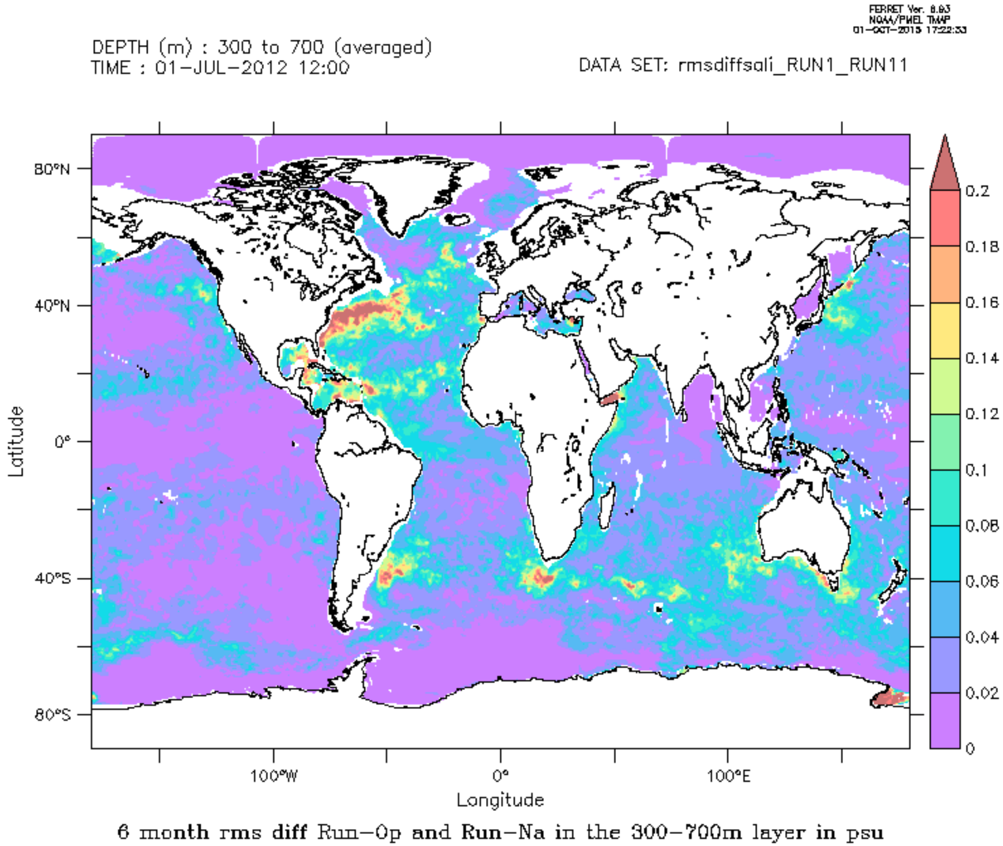

Fig. 7. RMS salinity differences 300m-700m between the run with All and No Argo floats assimilated.

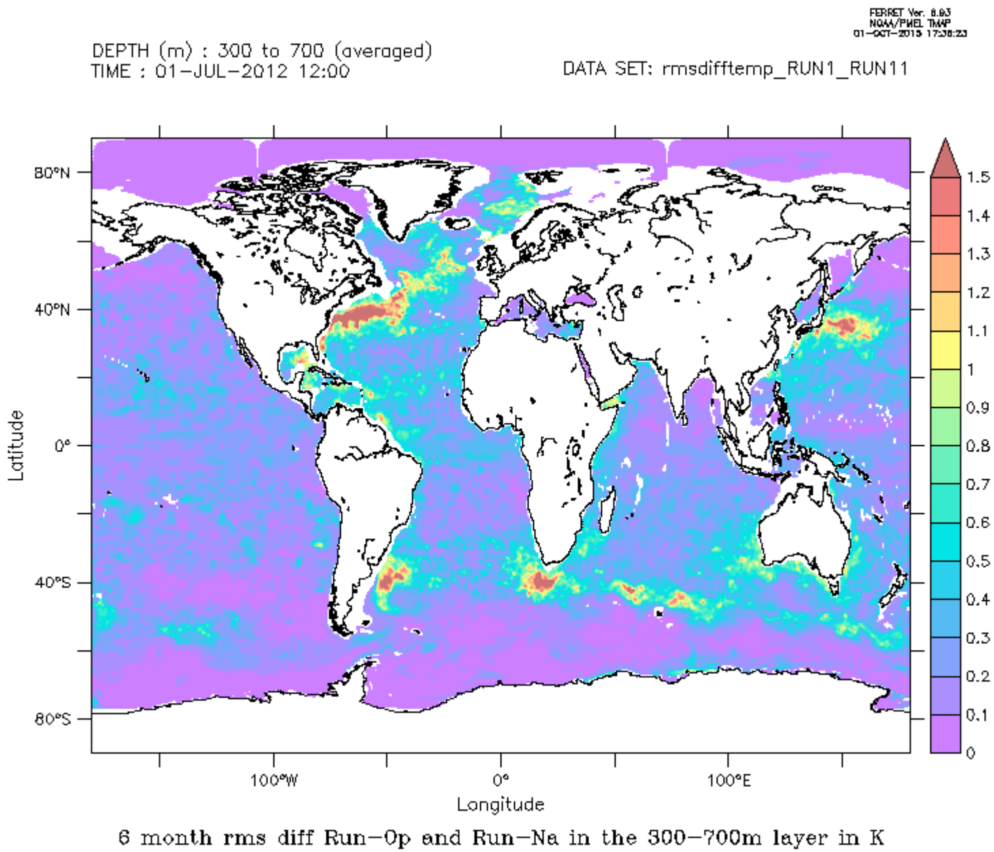

Fig. 8. RMS salinity differences 300m-700m between the run with All and No Argo floats assimilated.