Response to Anonymous Referee #1

Manuscript "Interannual response of global ocean hindcasts to a satellite-based correction of precipitation fluxes" by A. Storto et al.

First of all we would like to thank the reviewers for the careful reading and the valuable comments that led us to a much improved and readable version of the manuscript.
Below we address the concerns that Anonymous Referee #1 (hereafter AR1) stated in its review, and provide, for each point, the modifications that were made in the revised version of the manuscript.
Please note that since many points are in common between the Comments of AR1 and those of Anonymous Referee #2 (hereafter AR2), the two Responses should be considered simultaneously.
Further to addressing the Referees comments, we have also corrected a few typo errors in the revised manuscript, and redone all the figures with lon-lat maps to include polar areas that were cut off in the original manuscript.

MAJOR POINTS

1) ***"Corrected values of Precipitation seems still far from observation estimates"***
We have recomputed the values and find some errors in the previous estimation. We have indeed recomputed offline the corrected precipitation as daily fields (previously, they were deduced from the E-R-EMP – where EMP is hereafter defined as the net upward freshwater flux E-P-R – computation on monthly means as the model output does not include the precipitation, also using the actual masks used within the ocean model). Now corrected values are in very good agreement with the original PMWC data. Below (within Specific Points) we report the new values and comment them.

2) Impact of EMP redistribution
For a detail explanation why the correction is justified and required, please refer to the Response to the Referee #2 who questions why we have adopted it. Given the different values of the EMP balance (in the new Table 1), it is clear that this will have an effect and we discuss it and quantify it within the next MAJOR POINT and the Specific Points of this response.

3) Impact of the correction in the Southern Ocean
This point is the one we found very crucial to assess and discuss and crucial as well for improving the quality, the readability and the validity of our work. Its investigation allowed us to better deepen the mechanisms that the correction involves.

It was not clearly stated in the manuscript that the correction at high latitudes is negligible.
This was actually imposed by construction, since the corrective coefficient north of 65N and south of 65S is imposed equal to 0, and smoothed in the two latitudinal bands 55N-65N and 60S-50S. This was decided for two basic reasons: i) do not change too much the freshwater income where the interaction between the sea-ice and the ocean is relevant; ii) do not change the freshwater income in areas where the availability of PMWC data is intermittent, due to the fact that the precipitation on ice-covered areas cannot be sensed.
We found that the impact in the ACC is due in most extent to the EMP redistribution and is therefore somehow only indirectly due to the correction itself.

We try to quantify the impact in the ACC (that we define as the portion of Ocean south of 35S). The mean difference in the net freshwater flux in the ACC between the two experiments ECMWF+PMWC

minus ECMWF is equal to -0.74-(-0.30) = -0.44 Sv, ie the correction leads to larger positive freshwater income in the ACC, which is mostly due to the EMP redistribution. Indeed, by looking at the different time-mean terms in the ACC and by spreading on the ACC area the two different EMP imbalance (see Table 1 where the net global imbalance difference is ~ 0.9-(-0.255), whose 25.7% goes over the ACC area) we found that EMP imbalance accounts for the 72.1% (0.3 Sv) of the EMP variation in the ACC, while the variations in the evaporation, precipitation and ice volume loss are respectively equal to 15.6%, 9.9% and 2.5% (0.06, 0.04 and 0.01 Sv) in the same area.
Clearly, going southwards within the ACC where the variations in precipitation tend to vanish, the EMP redistribution has an even larger impact.
It is therefore clear that the most important mechanism in the ACC region (and, symmetrical, in the Arctic region north of 60N) is the EMP redistribution.
Just to have a rough idea, by repeating a similar diagnosis in the Tropical Ocean (20S-20N), we found that there:

DIFFERENCE BETWEEN THE TWO EXPERIMENTS (ERAINT/PMWC - ERAINT)
NET EMP DIFFERENCE = 1.01 Sv
REDISTRIBUTION DIFFERENCE = 0.38 Sv
EVAPORATION DIFFERENCE = -0.01
PRECIPITATION DIFFERENCE = -1.40 Sv
Thus, the redistribution is about 26% of the precipitation variation, and it is then much less important than in the ACC.

AR1 also asks to remove the EMP effect from the analysis of the results. We have done it within the discussion on the different contributors to the SSH variations. In particular, in formulating Equation (5) and (6), now the contribution of the EMP redistribution is explicitly taken into account, and consequently also in the following discussion. It is actually quite difficult (and imprecise) its quantification for other parameters, unless to rerun the very expensive simulations. We want to emphasize once again (see Response to AR2) that, although it might appear artificial, the EMP redistribution is a constraint that contributes to the model equations as any other forcing term and it is needed to avoid unrealistic model drifts.

We provide also a motivation ***why the EMP redistribution has such a positive effect in the ACC.***
The starting point is the fact that (from Table1, new) a weakness of all the simulations is the overestimation of the evaporation fluxes, which is also found in the ERA-Interim dataset and mentioned by Troccoli and Kallberg (2004).
PMWC data of evaporation are found in agreement with other estimates. By comparing the two experiments with observed data of evaporation from PMWC (Figure 1 of this Response for the ERAINT experiment, no significant difference was found in the comparison against the experiment with corrected precipitation), it is clear that the overestimation is important at high latitudes.
Therefore, the global overestimation of the evaporation flux is mostly due to the overestimation at high latitudes. Possible reasons for this problem might be 1) inaccuracy of wind fields from ERA-Interim, also because of the absence of scatterometer data at high latitudes; 2) inaccuracy of near-surface air temperature and humidity fields, also because of a poor observing network 3) systematic errors in the heat and water exchanges between the sea-ice and the ocean, 4) inaccuracy of the transfer coefficients (bulk parametrization) that are known to have been extensively validated in the Tropical regions.
Without the application of the correction, the EMP imbalance is equal to -0.255 (precipitation exceeds evaporation, due to the fact that the precipitation overestimation is greater than the evaporation overestimation), and the EMP redistribution uniformly increases the evaporation. In areas like the ACC, where the evaporation is already too large, the EMP redistribution increases the evaporation even

further, and this in turn increases the salinity and seawater density and lowers the SSH (see Figure 3a and 6 of the manuscript, respectively).
With the application of the correction, the global value for the precipitation is very well captured. Since changes in the evaporation are very small, the EMP imbalance turns to positive (the evaporation exceeds the precipitaion by 0.9 Sv). The EMP redistribution then uniformly increases the freshwater income to overcome this imbalance. This latter procedure proves of benefit for the ACC, where, the evaporation overestimation is mitigated by the EMP redistribution, the salty bias is reduced and the sea-level rises. In practice, in our second experiment, the EMP redistribution simply overcomes the evaporation overestimation by decreasing it uniformly, while in our control experiment the EMP redistribution further deteriorates the freshwater flux.
Future strategies for the EMP constraint might be based on the “a priori” knowledge of the evaporation overestimation in polar areas, by for instance decreasing the evaporation flux only north of 60N and south of 50S, and this will certainly be considered in our future applications.

It is now clear that the corrected precipitation at global scale along with the EMP redistribution lead to an improved representation of SSH and near-surface salinity in the ACC.

Now, to simply diagnose and quantify the effect of the correction on the ACC transport, we assume for simplicity that the ACC region dynamics can be approximated to a geostrophic flow with no interaction with the region north of its northern boundary.
This is in accordance with many studies (see for instance Gnanadesikan and Hallberg, 2000; Bi et al., 2002; Borowski et al., 2002; Hattermann and Levermann, 2010 and many other authors).
The geostrophic formulation of the zonal momentum may be further decomposed in a barotropic contribution (surface displacement) and in a baroclinic contribution (internal density distribution).
Assuming that the correction may therefore induce in the ACC a geostrophic adjustment, we can quantify the variations from the control experiment to the experiment with corrected precipitation, taking for simplicity as “steady state” the 1989-2009 climatology of the two experiments.

From the geostrophic balance, integrating across the ACC and assuming the Boussinesq approximation and a constant Coriolis parameter (f_0 =-1.1 10^{-4} s^{-1}), the zonal volume transport can be diagnosed as:

$$M=\int\left[\frac{-g}{\rho_0 f_0}\int_{-H}^{0}\rho_0\frac{d\eta}{dy}dz+\int_{-H}^{0}\left(\int_{z}^{0}\rho(z')\,dz'\right)dz\right]dy=M^{BT}+M^{BC}$$

where ρ_0 is a reference density (1025 Kg/m3), g is the gravitational acceleration (9.8 m/s2), ρ is the spatially varying 1989-2009 time-mean density and η is the sea-surface height. The outer integral in dy extends across the ACC.
For clarity, the barotropic and baroclinc effects have been separated into M^{BT} and M^{BC} , respectively. As explained before, correcting the precipitation decreases the evaporation towards the Antarctic, which has the double effect of increasing the SSH and decreasing the density southwards across the ACC. These two effects contrast each other. This is shown in Figure 2 of this Response, where the zonal means of the differences of SSH and 0-2000 m density between the climatology of the two experiments (ERA-Interim+PMWC minus ERA-Interim) are plotted. From such a Figure, we already see that the variations in the density are less relevant than those in SSH, as, according to Bi et al. (2002), an increase in 21 Sv in the mean zonal volume transport across the ACC requires a variation of

about 100 g/m3 in the 0-2000 m density contrast across the ACC (density at ACC southern boundary minus density at ACC northern boundary), while the variation in the density contrast between our two experiments is of the order of 20 g/m3.
Diagnosing the variation between the transports of the experiments provides these results:

Mean zonal transports from 70S to 35S

M^{BT}(ERA-INT) – M^{BT}(ERA-INT+PMWC) = 42.7 Sv
M^{BC}(ERA-INT) – M^{BC}(ERA-INT+PMWC) = -19.5 Sv
M(ERA-INT) – M(ERA-INT+PMWC) = 23.2 Sv

Despite the numerous approximation adopted with respect to the OGCM physics (perfect geostrophy of the ACC, calculated from the climatology), all these values are in quite good agreement with those reported in the Table 2 of the manuscript, demonstrating that in first approximation the precipitation correction and the EMP redistribution induces a geostrophic adjustment in the ACC caused by the evaporation diminution, with a barotropic decrease of the zonal volume transport that exceeds the baroclinic response, leading to a mean volume transport that is about 20 Sv smaller.

To summarize, the revised version focuses more on the direct effects of the correction, for instance the fresh bias reduction in the Tropics that was the major problem that induced us to conceive the correction. While we shortly quantify and comment the effect in the ACC from the text previously reported (need for zeroing the EMP, evaporation overestimation at high-latitudes, effectiveness of EMP redistribution when the precipitation is well-specified), its reference in the Abstract and Conclusions is shortened, since it represents a (positive) indirect effect of the correction. A quantification of the effect of the EMP is also provided, along with the mechanism leading to an improved dynamics in the ACC. Note however that considering the EMP redistribution as a constrain in our Surface Boundary Conditions, the improvement in the ACC follows the fact that if precipitation is well calibrated, the EMP redistribution is able to mitigate the evaporation surplus.

SPECIFIC POINTS

Introduction

AR1 argues that since evaporation fluxes are not used, the fact that PMWC data are chosen also because they aim at closing the hydrological cycle is not a good point. We agree that the sentence is not clear, we meant that PMWC data, with respect for instance to GPCP, is constructed in order to have closed freshwater fluxes, which can be of advantage for ocean applications. However, since the sentence might be not clear and we cannot provide any evidence of this advantage, we have drop the sentence. **The motivation about the higher resolution of PMWC data holds and the sentence has been reformulated accordingly.**

We have added the proper references for ERA-Interim suggested by AR1.

Correction of precipitation

AR1 suggests checking the change in the daily variability, with respect to the native ERA-Interim fields, due to the linear interpolation of the correction between monthly values.
Figure 3 (of this Response) depicts the zonal averages of the precipitation daily variability (standard deviation of daily means) for the simulation periods before and after the correction.

The correction with daily corrective coefficients linearly interpolated from monthly values does not have any impact on the day-to-day variability out of the Tropical region. In the Tropics, where the variability is acknowledged to peak, the correction slightly decreases the daily variability. The difference between the two daily variability is maximum at around 7S, with a decrease of about 3.5 E-6 Kg/m2/s from the standard deviation value of 63.0 E-6 Kg/m2/s (about 5% decrease) for the uncorrected value. However, this variations in the daily variability seems negligible and not important for these interannual ocean applications. We have shortly mentioned this note on the day-to-day variability in the revised version.

We agree that the sentence about potential applicability in operational framework is rather naive and it has been drop off. We agree that it is hard to justify that modifications in the atmospheric model (e.g. increase of resolution, change of observing network, change of physical parameterizations) do not change the "precipitation systematical errors". We actually meant in the manuscript that such atmospheric model modifications are upgraded not so often, thus allowing the re-calibration of the corrective coefficients; however, we prefer to cut the entire sentence since we cannot provide any proof of applicability in an operational framework.

The comment to Figure 2 has been reformulated, we agree that referring to Arctic/antarctic was wrong (please read "mid latitudes" instead); furthermore, it is important to clearly state that the corrective coefficient has no significant impact at high latitudes.

Ocean Model Description

NSIDC actually does not have information on sea-ice thickness. In facts, only the sea-ice cover was taken from NSIDC, and, in particular, for the initialization of the sea-ice parameters we followed the same strategy of Mercator-Ocean (G. Garric, Mercator-Ocean, personal communication):

1) The lead fraction is issued from mean NSIDC (Bootstrap algorithm) sea ice cover for January 1989.
2) The sea ice thickness is rebuild from a mean GLORYS1V1 January 2002-2008 sea ice fraction. A relationship (hyperbolic or 3rd order polynomial regression) is built between them and the regressive coefficients are applied on the sea ice cover observations.
3) Snow thickness, sea ice surface temperature, sea surface salinity and sea surface temperature are from the mean GLORYS1V1 January 2002-2008.
4) The internal sea ice temperatures have been fixed to the the melting point of sea water for sea ice temperature with a reference salinity of 34 psu and a freezing temperature of sea water of 273.15.

GLORYS1V1 is the release 1 of the Mercator-Ocean ¼ degree resolution reanalysis, covering the Argo era (reference added in the revision).

We have corrected the text by referring to NSIDC for the sea-ice cover only and referring to Mercator-Ocean for the other parameters, without going into details since the initialization strategy for sea-ice does not seem crucial for the impact of the precipitation correction (it is the same for the two experiments).

The reference on the model physics has been added.

Freshwater budget

AR1 noted how the corrected P does not lead to globally averaged values close to those indicated by Lagerloef et al. (2010). While Lagerloef et al. (2010) actually reports value from Schanze et al. (2010), which consist in a combination of many precipitation dataset and not necessarily should provide values comparable to those from PMWC, the correction seems however to fail in reducing the global surplus of P from ERA-Interim. Following this evidence and thanks to the AR1 suggestions, we have built the standalone dataset of corrected precipitation (ERA-Interim blended with PMWC, as described in

Section 2 of the manuscript). This was not done before, as the routine for the correction was inserted within the NEMO model and the global averages of the precipitation fluxes were deduced “a posteriori” indirectly from EMP, R and E, which are monthly mean model outputs. This procedure was found wrong when cross-checked with the direct EMP computation, due to an inconsistency between the masks and the fact that the EMP redistribution contribution in the a posteriori estimation of P was wrongly performed. We have recomputed all the diagnostics, used the same land-sea mask and finally found quite different results that show that the corrected precipitation agrees with the original PMWC data more than in the original Table 1.
We report here (and in the revised version) the new Table, along with the PMWC estimates and with also values of evaporation from PMWC and evaporation from ERA-Interim. Also estimates from Schanze et al. (2010) are inserted in the Table. Furthermore, the new Table also reports values of EMP before and after its zeroing, which allows further discussion as requested by AR1 and as done in the MAJOR POINT.

Here we want to briefly report a few comments that have been ingested in the revised version:

1) The correction leads to global values of P very close to the original PMWC data. This represents a self-consistency proof for the correction that was missing within the previous computation, and that was also questioned by AR2.
2) One major problem is the overestimation of the evaporation term (discussed in this Response and in that to AR2).
3) The EMP imbalance turns to positive. The discussion about the reduction of the imbalance in the old manuscript is obsolete and superseded with that from the replies to the MAJOR POINTS.
4) EMP imbalance estimations are however in the range estimated by Schanze et al. (2010).

Note also that the standalone computation that has been performed ad hoc for this Response allows data distribution to potentially interested users.

We have therefore rewritten the Section about the freshwater balance with these comments and those from point 2) and 3) of Major points and also from the discussion contained in the Response to AR2.

Salinity and Temperature
The sentence “the correction...constantly moves the salinity bias closer to zero” was unclear and has been reformulated. We meant that the difference between the two experiments is rather constant (after approximately 1 year of “precipitation correction spinup”). Note also that this refers to the TAO/RAMA/PIRATA statistics, therefore involving only a few locations at or in close proximity to the Equator.

Sea-level
In light of the previous discussions, we added a more detailed explanation about the effect of the EMP redistribution to the linear trends of SSH. In practice, the EMP redistribution differs from the two experiments. Its effect on the trend is horizontally uniform and equal to 100.8 mm/y, in terms of difference of trends between the two experiments as shown in the panels of Figure 8 of the Manuscript (see Figures 4 of this Response). This allows to appreciate how the EMP redistribution impacts the barotropic contribution of the correction to sea-level variations.

Unfortunately, the bottom panel of Figure 5 was by mistake taken from the middle panel. We attach here (Figure 3) and, consequently, in the revised version the new panels that allow the relative discussion.

AR1 asks to better clarify the impact of SSH skill scores against AVISO in the ACC (Figure 6). This was already explained in details within the MAJOR POINTS (overestimation of evaporation due to the better EMP redistribution → mitigated lowering of the SSH in the ACC) and explicated in the text.

Figure 8: panel f) was by mistake the same as e). An additional panel g) is added, with the barotropic contribution of the correction net of the EMP redistribution. This panel eases the understanding of the sole effect of the precipitation correction without the EMP redistribution as asked by AR1. In particular, the impact in the high-latitudes areas are much smaller as previously explained, while elsewhere the precipitation correction is not significantly affected by the EMP redistribution.

Circulation and Transport

AR1 notes an inconsistency between Figure 9 (increase of near-surface current speed) and Figure 10 (decrease of current speed), but Figure 9, as indicated in the corresponding caption, shows the bias between observed current speed minus model values for both experiments, namely an increase of the bias in Figure 9 (bias = obs minus model) corresponds to a decrease of model current speed (if observations are steady). Therefore, Figure 9 and 10 are consistent.
From Figure 9 for instance (and it is consistent with Figure 10 and Table 2), the current speed in the ACC is overestimated (value too negative), and with the precipitation correction this overestimation still holds but is significantly mitigated thanks to mechanism mentioned in MAJOR POINT 3).
However, since the definition of bias as observation minus model might be misleading, and since Figure 9 has been redone taking into account different areas (see below), in the new Figure 9 the bias is defined as model minus observations.

Decrease of surface speed in the ACC:
See the discussion contained in MAJOR POINT 3), where the effect of the precipitation correction and the consequent different EMP redistribution is detailed for the ACC region.

Significance of reduction of current speed RMSE.
AR1 asked to better understand and specify the near-surface skill scores against the OSCAR dataset. We have recomputed the statistics, now separating the results into 3 regions: Southern Extra-Tropics, Tropics and Northern Extra-Tropics (Figure 7 of this response, which substitutes Figure 9 of the manuscript). The computation allows us to understand that the correction significantly improves the current speed only in the Southern Extra-Tropics, and this is clearly stated in the revised version of the manuscript.

Figure 10 has been redone with increased arrows and reported arrow scale.

Table 2: The reviewer questions about the significance of the variation in the volume transport in the Fram and Bering Straits due to the precipitation correction, given the larger variability of the transport in this region. Figure 6 shows the timeseries of the transport monthly means for these two straits and (for comparison) for the Drake Passage. The two straits as noted by AR1 exhibit a seasonality (in the Table 2 as standard deviations of the monthly means) that is more pronounced than the effect of the correction itself. This is quite evident for the Bering Strait. Nevertheless, the difference in the transport through the Fram Strait, even though dominated by the seasonal signal, is appreciable and grows with time. Based on these evidences, we have reformulated the comments by stating that the impact in the Bering Strait is not significant with respect to the volume transport variability, while it is still appreciable in the Fram Strait.

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Schanze, J.J.; Schmitt, R.W.; Yu, L.L. (2010). The global oceanic freshwater cycle: A state-of-the-art quantification. Journal of Marine Research, Volume 68, Numbers 3-4, pp. 569-595(27).

Table 1: Mean (M, Sverdrups), interannual (T, linear trend, Sverdrups/year) and seasonal amplitude (A.A.: annual amplitude; S.-A. A.: semi-annual amplitude, both in Sverdrups) for the precipitation, the runoff, the evaporation and the net upward freshwater fluxes (EMP) for ERA-Interim atmospheric reanalysis, PMWC data and the two ocean simulations without and with the correction to the precipitation fluxes. Values in brackets for the EMP estimation within the ocean simulations refer to the values after the EMP redistribution. In all EMP estimations, the river runoff is from Dai and Trenberth (2003). For comparison, the Table also reports mean values of the freshwater flux components from Schanze et al. (2010).

DATASET or EXPERIMENT		Schanze et al. (2010)	ERA-Int	PMWC	NEMO (ERA-Interim)	NEMO (ERA-INTERIM+PMWC)
Precipitation	M	12.2±1.2	13.547	12.295	13.547	12.286
	T		-0.028	0.023	-0.028	-0.026
	AA		0.033	0.327	0.033	0.066
	SAA		0.198	0.095	0.198	0.200
Evaporation	M	13.0±1.3	14.643	13.923	14.602	14.499
	T		0.029	0.022	0.014	0.011
	AA		0.093	0.083	0.144	0.141
	SAA		0.087	0.267	0.271	0.278
Runoff*	M	1.25±0.1	1.310			
	T		-			
	AA		0.300			
	SAA		0.083			
EMP	M	0.5±1.8	-0.214	0.313	-0.255(-0.008)	0.902(-0.009)
	T		0.058	-0.002	0.042(-6.6E-5)	0.037(-5.9E-5)
	AA		0.298	0.060	0.432(0.003)	0.387(0.003)
	SAA		0.324	0.134	0.235(0.001)	0.233(0.001)

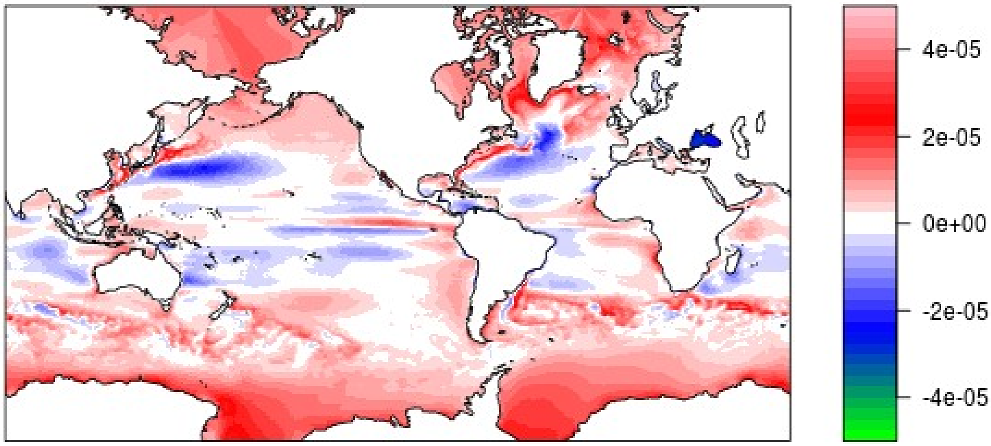

Figure 1. Mean difference between NEMO (ERA-Int experiment) and PMWC upward evaporation flux within the period 1989-2009. Unit is Kg/m2/s.

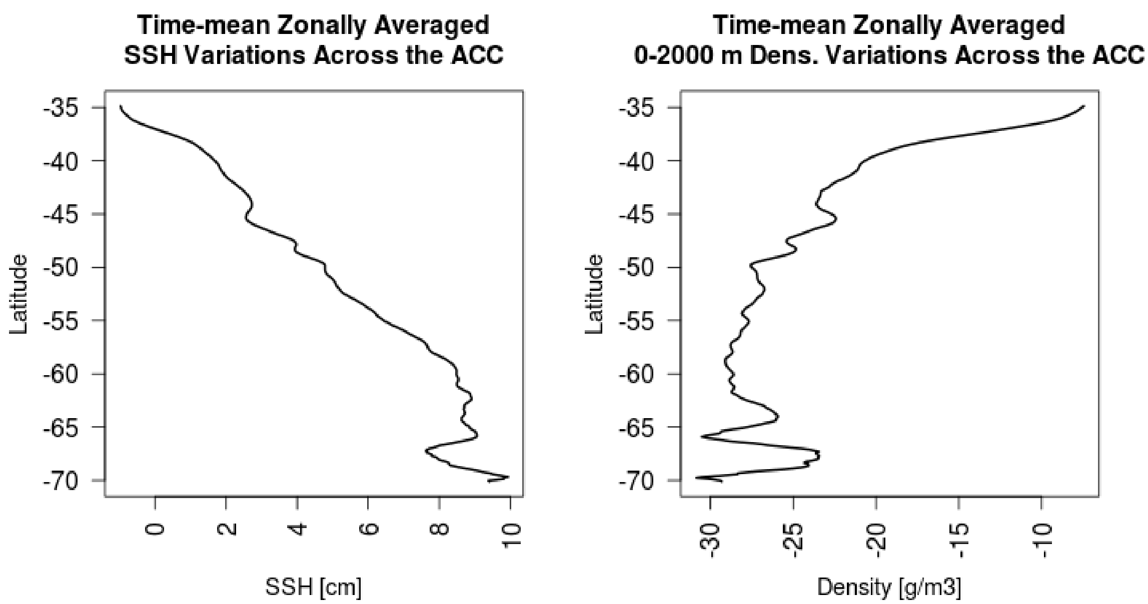

Figure 2. Zonally averaged difference of SSH (left) and 0-2000m density (righ) between the two experiments (EI+PMWC – EI) derived from the 1989-2009 climatology.

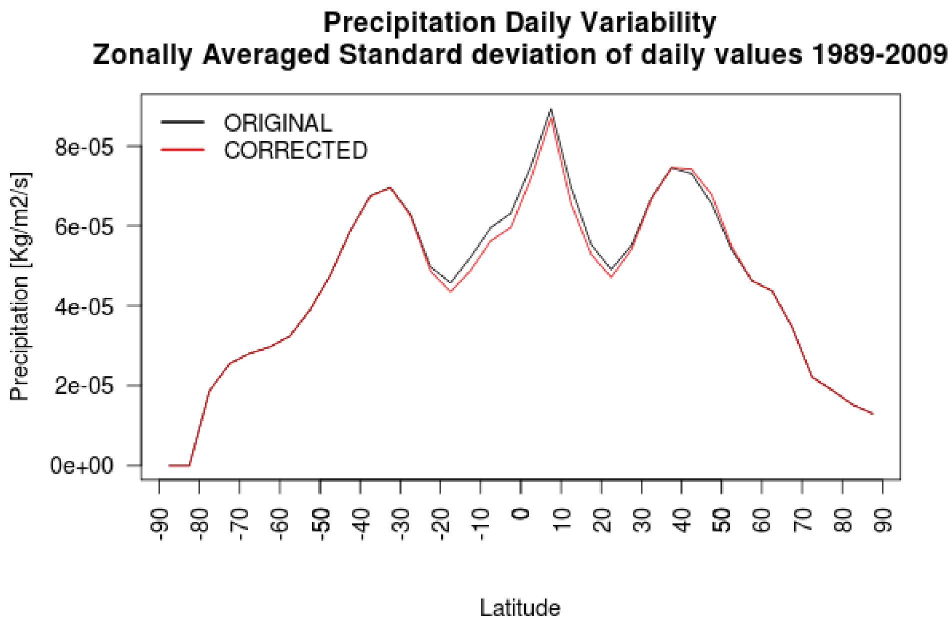

Figure 3. Zonal averages of the standard deviation of daily means precipitation values before and after the precipitation correction for the experimental period.

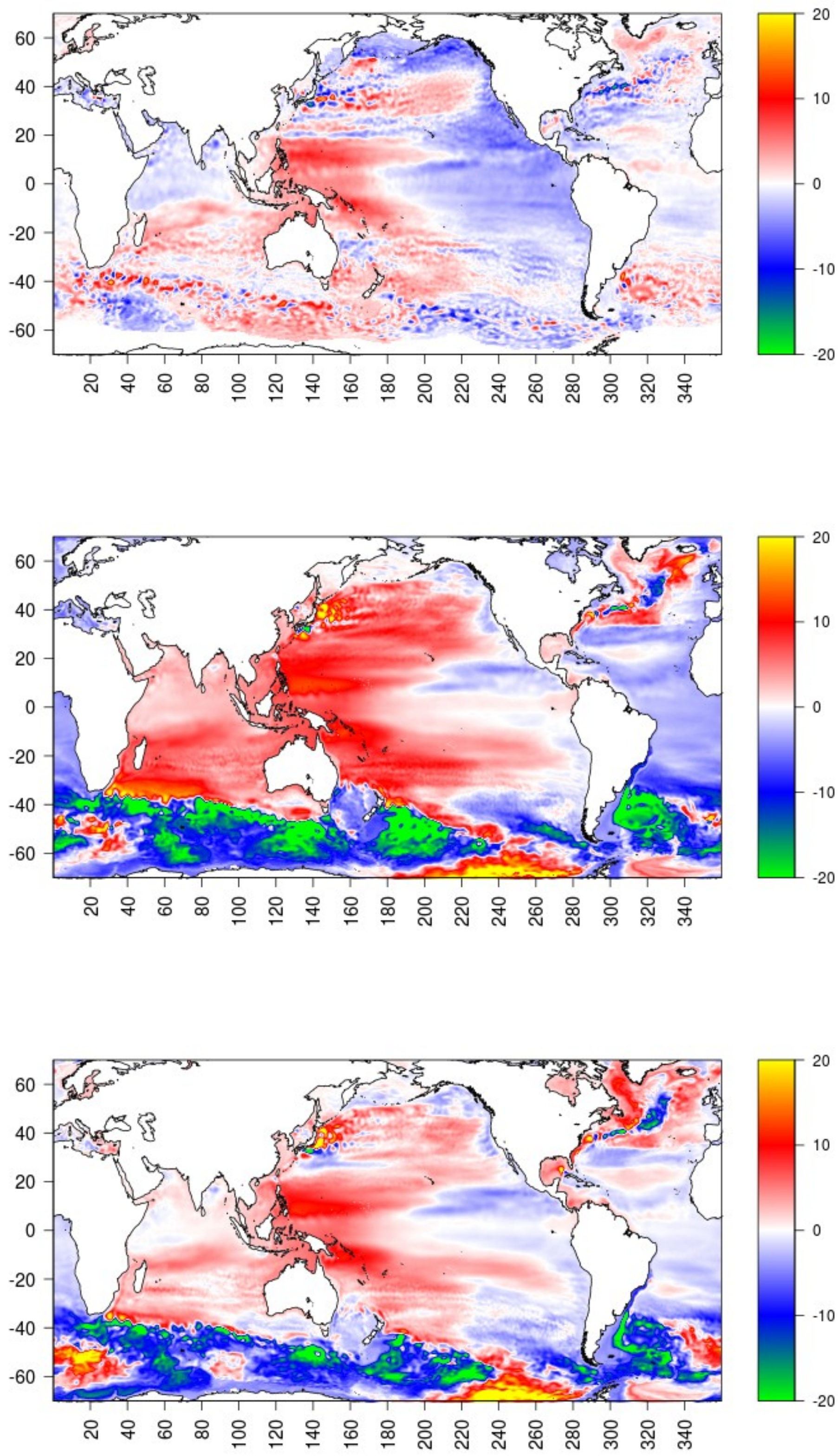

Figure 4: Sea level linear trend (mmy−1) for the period 1993–2009. Top: from altimetric observations (monthly gridded merged products from CLS/AVISO); middle: without the precipitation correction; bottom: with the precipitation correction.

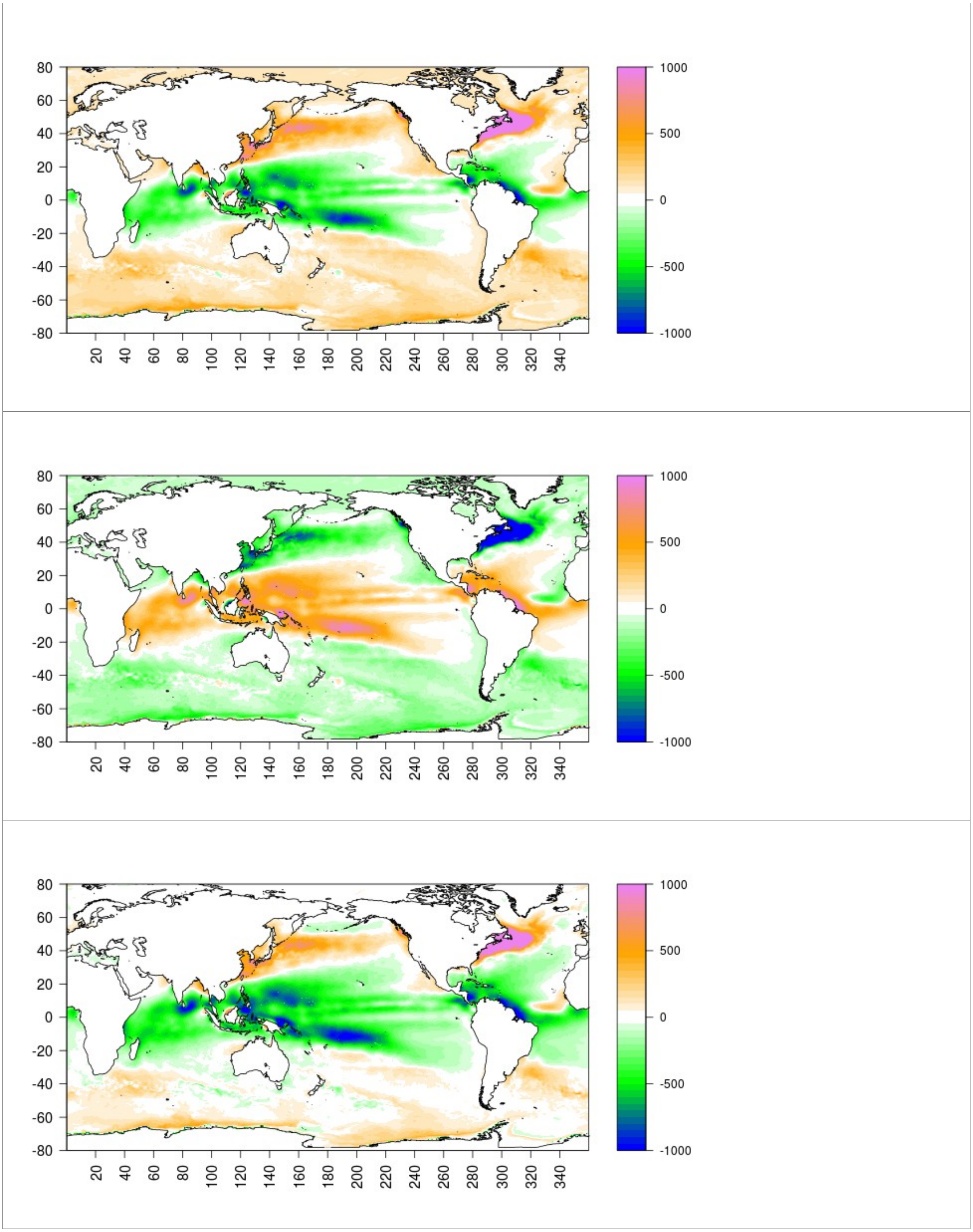

Figure 5: Panels of Figure 8 of the manuscript that were unclear. Top: barotropic effect of EMP as difference in SSH (mm/y), middle: response of the vertically integrated divergence; bottom: as the top panel, but prior of the EMP redistribution.

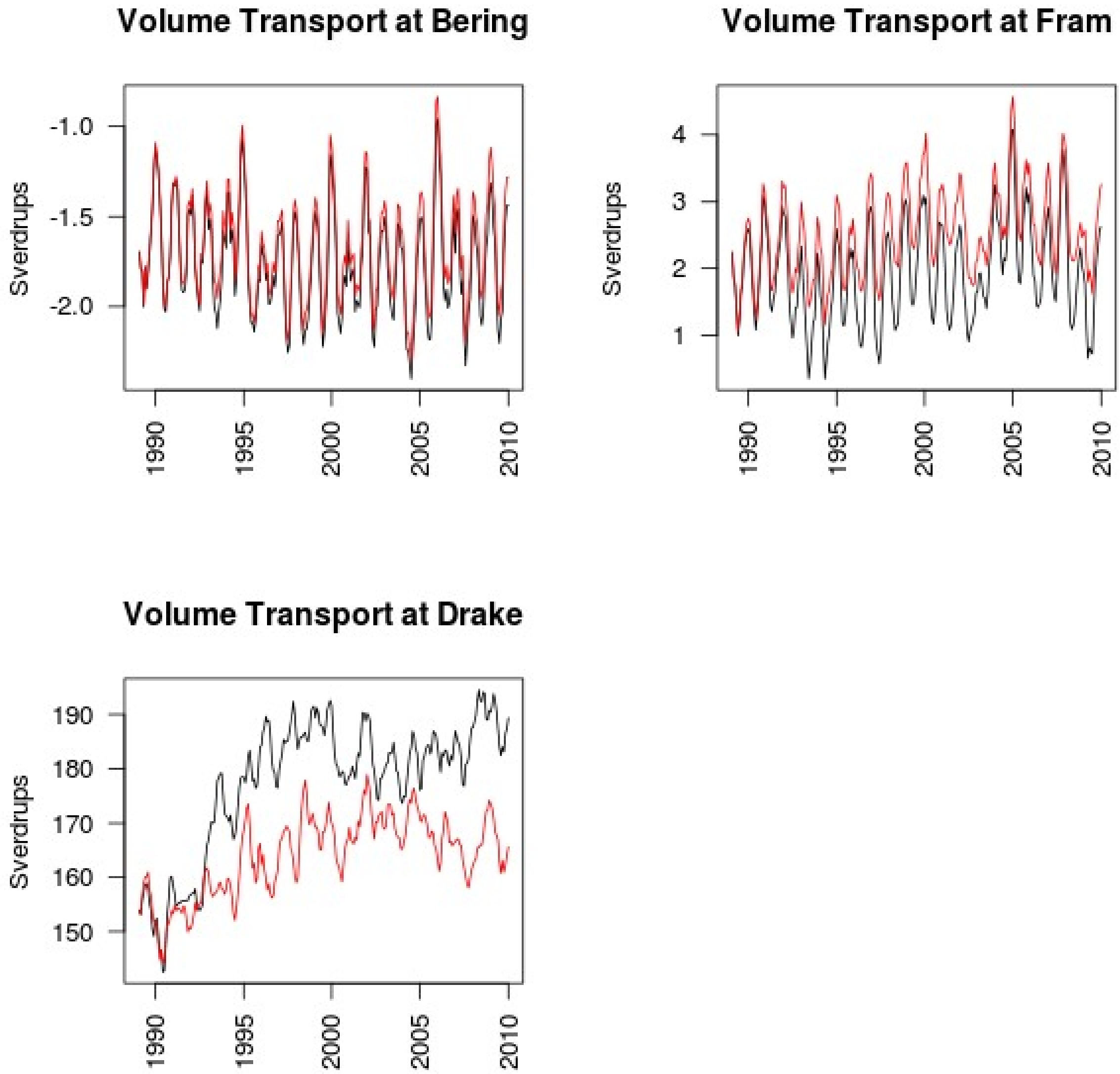

Figure 6: Volume Transport monthly means for the Beiring and Fram Straits and for the Drake Passage: black lines show the ERA-Interim experiment while the red lines the ERA-Interim+PMWC experiment.

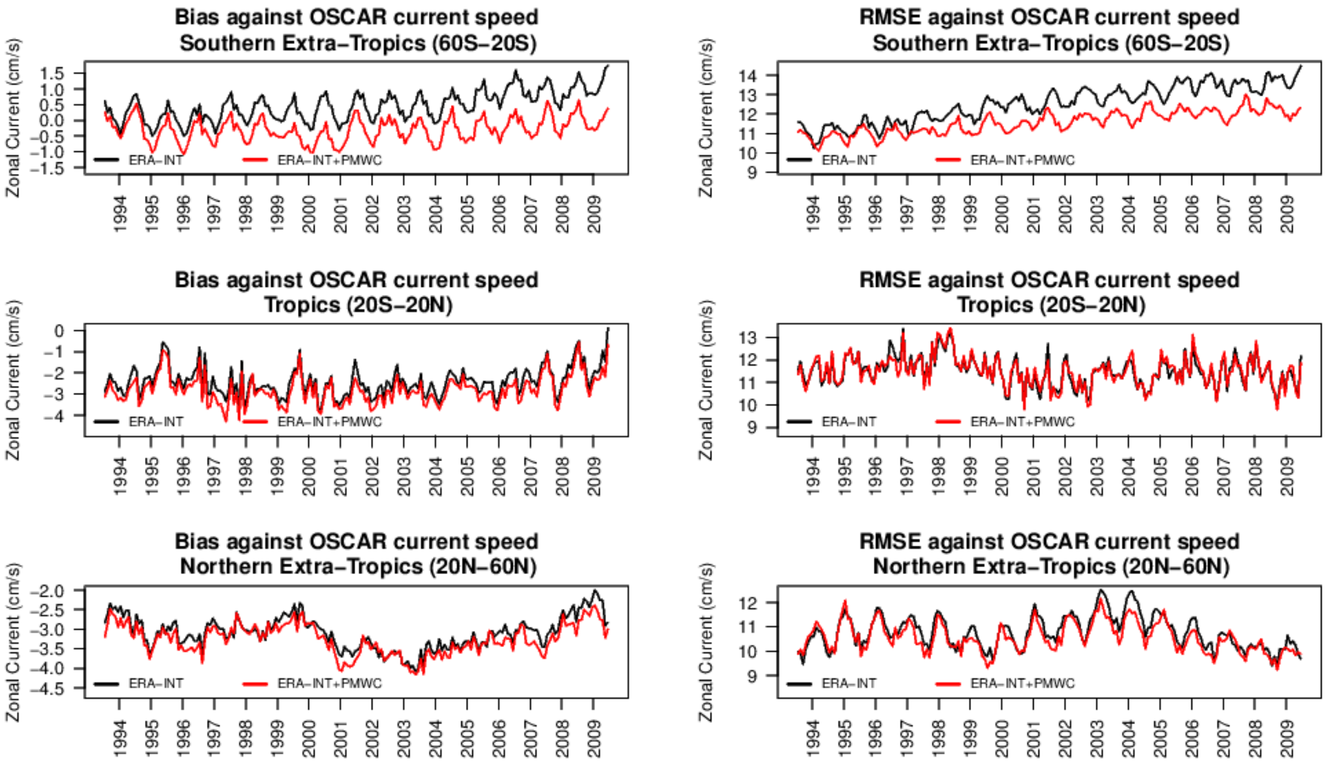

Figure 7: Near-surface current speed bias and RMSE against the OSCAR dataset for Southern Extra-Tropics, the Tropics and the Northern Extra-Tropics. Bias has to be intended as model minus observed values.