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Impact of sea surface temperature biases on extended-range forecasts

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Abstract

The impact of sea surface temperature (SST) biases on extended-range forecast skill scores are investigated using a series of coupled forecast experiments in which the SST biases are removed by adding a correction term during the coupled integrations. The bias correction depends on the forecast lead time and on the starting calendar date, and it is estimated from a set of coupled re-forecasts. Results show that this methodology is efficient in removing the SST biases in the Extratropics but is less successful in the Tropics. Therefore additional experiments have been performed where the bias correction has been applied only to the Extratropics or to the North Atlantic. Removing the SST biases in the Extratropics results in a modest reduction of the coupled model atmospheric biases over the North Atlantic, and increased extended range forecast skill over Europe. Most of these improvements are reproduced if the bias correction is applied only over the North Atlantic region. This impact of the SST bias correction is particularly strong when there is an MJO in the initial conditions. The MJO teleconnections following an active MJO over the Western Pacific are significantly stronger when the SST bias corrections have been applied, while the teleconnections following an active phase of the MJO over the Indian Ocean are unaffected.

1 Introduction

Operational extended–range forecasts at ECMWF are currently produced from an ensemble of coupled ocean-atmosphere integration up to day 46. The ocean model used is NEMO at a ¼ degree resolution. Coupled ocean-atmosphere integrations produce more skilful and reliable extended-range forecasts than atmosphere-only integrations using damped persistence of sea surface temperature (SST), particularly in the Tropics. Several studies have shown that more than a week of predictive skill in the prediction of the Madden Julian Oscillation (MJO) can be gained by coupling the atmosphere model to an ocean model, instead of using uncoupled atmosphere model forced by persistence of SST anomalies (e.g. Woolnough *et al*. 2007). De Boisseson *et al*. (2012) go farther by showing that coupling has an advantage over the uncoupled mode in predictions of the MJO even when observed SSTs are used to force the atmosphere. This improvement is mostly due to the fact that the coupling between ocean and atmosphere favours a coherent propagating coupled mode, with the phase of SST anomalies synchronized with the phase of the deep atmospheric convection. This coherence is disrupted in uncoupled atmospheric integrations. Over the recent years, benefit of coupling the atmosphere to an ocean model has also been demonstrated for medium-range forecasts (Janssen et al, TM712). Since cycle 45r1, all the ECMWF forecasting systems, including the High-Resolution forecast, are coupled to an ocean model. In the S2S community, there is a general consensus that running coupled ocean-atmosphere system is beneficial compared to using persisted SSTs. For instance, uncoupled models (e.g. ECCC, HMCR, JMA) from the S2S database (Vitart et al. 2017) display less skill in predicting the MJO than the coupled ocean-atmosphere models (Vitart, 2017).

In spite of the benefits of ocean-atmosphere coupling for predictions of the MJO, ocean-atmosphere coupled forecasts display large systematic errors in SSTs, which can exceed a few degrees after 4 weeks (see Section 2). In regions where the atmosphere is responsive to SST values, these systematic errors in SSTs will affect the atmospheric circulation and, as a consequence, may degrade the forecast skill scores.

Several publications have documented the impact of correcting tropical SST biases on seasonal forecasts. Magnusson *et al.* (2013) found positive impact on seasonal forecast skill scores of ENSO and tropical precipitation when using momentum-flux correction, mainly because it avoids the positive Bjerkness feedback responsible for a strong cold bias in the tropical Pacific. However, the authors cautioned that this result was highly dependent on the type of systematic errors and may not hold true for other models. Vecchi *et al*. (2014) documented significantly improved simulation of tropical cyclones (TC) climatology and interannual variations in a climate model by correcting systematic ocean biases through "flux adjustment".

Mid latitude SST biases, especially those related with sharp SST fronts have also received increasing attention in recent years. Studies based on AMIP experiments (e.g. Nakamura et al., 2008, Woollings et al. 2010, Keeley et al 2012) have documented the impact of errors in the representation of the westerly currents (Kuroshio, Gulf Stream) on the position of the jet stream and storm tracks. Scaife *et al*. (2011) found that the improved the representation of SST errors over the North Atlantic Current resulting from the increased ocean resolution -from 100Km to 25 Km - led to improved Atlantic winter blocking in the MetOffice coupled climate model. More recently, Lee *et al.* (2018) ran an AMIP experiment where the SSTs over the Gulf were taken from a coupled experiment with a low-resolution ocean (~100Km grid spacing), which displayed large SST errors. Results indicated a significant impact on the position of the jet stream.

The studies above deal with fully developed SST errors that appear in multi-decadal integrations. Mid-latitude biases developing during the course of extended range or seasonal integrations are comparatively smaller. Balmaseda et al. (2010), using a previous version of the ECMWF seasonal forecasting system, showed that correcting the SST bias over the Gulf Stream area during the course of seasonal integrations, had a large impact on the climate of seasonal forecast over the North Atlantic, and modified the mid-latitude response to sea-ice anomalies of specific events. It is also known that SST errors in ocean analysis degrade the skill of medium range coupled forecast. This is the reason why the practice of "partial coupling" or "tendency coupling" has been adopted (Janssen et al 2014). This tendency coupling effectively applies a correction to the SST initial conditions, which is persisted during the first 10 days. The tendency coupling is needed even when the ocean analysis is produced with a ¼ degree ocean (Buizza et al., 2018). The correction to the initial SST is not applied during the extended range phase. Therefore, it remains an open question whether the mid-latitude SST errors impact forecast skill at extended range forecast.

The impact of the SST biases on sub-seasonal prediction has never been assessed so far, and constitutes the main goal of this article. Here we evaluate the impact of the SST errors in the ECMWF Ensemble system on the atmospheric biases and sub-seasonal forecast skill scores. Previous studies have addressed the impact of errors typical of 1 degree ocean model resolution. In this study, we report the impact of SST errors from a ¼ degree ocean model. The experimental setup is the reverse of that used by Lee et al (2018), in that we try to correct the SST errors in an imperfect ¼ of degree ocean model rather than degrade the SST from observational records. By applying the bias correction to different regions, we will be able to quantify the impact of the tropical and extratropical SST biases on the bias and skill of the extended range predictions.

After this introduction, Section 2 describes the control experiment and its SST biases. The experimental set-up of the bias corrected experiments is then described. Section 3 discusses the impact of the bias corrections on the systematic errors in the atmosphere. An evaluation of the impact of the SST bias correction on the extended-range forecast skill scores is presented in Section 4. Section 5 concludes and discusses the main results of this study.

2 SST biases and Experimental setup

A 15-member ensemble of 46-day coupled ocean-atmosphere integrations has been produced starting on the 1^{st} and 15^{th} of each month of the extended winter November to March 1989 to 2015 (270 start dates). This series of re-forecasts, which will be thereafter referred to as Control, uses the version of the Integrated Forecast System (IFS) known as Cycle 43r1. The atmospheric component is run at a resolution of Tco399 (about 25 km resolution) with 91 vertical levels. The ocean component is NEMO with a ¼ degree resolution. The atmosphere is initialized from ERA Interim (Dee et al. 2011) and the ocean is initialized from the ECMWF ocean rea-analysis known as ORAS5 (Zuo et al. 2018). This configuration is close to the configuration which was used operationally from November 2016 to July 2017, except for the atmospheric resolution (Tco639 up to day 15 and Tc319 from day 15 to 46 in operations). As in operational coupled runs, the ocean and atmosphere are freely coupled only after day 10. Before day 10, the SST tendencies computed from the ocean model are added to the SST initial conditions (partial coupling, see Janssen et al. TM712 for more details).

Figure 1 shows the SST biases at the time range day 26-32 for the period November to March 1989 to 2016. Compared to the SST from ERA Interim, the coupled model develops large scale biases, which have the potential for influencing the large scale atmospheric circulation. The figure shows that the SST biases result in increased meridional SST gradients (warmer tropics and colder Extratropics); there are strong warm biases appear over stratocumulus areas off the American and African coast, and over the Southern Ocean; there are also large scale warm biases over the Indian Ocean, with possible consequence for the atmospheric convection. Aside from these large-scale biases, narrower but strong biases (larger than 2 degrees C) are visible over the sharp SST fronts and Western boundary currents such as the Gulf Stream and Kuroshio. The latter are common to most coupled general circulation models (GCMs), and are related with the insufficient resolution of the ocean; it is estimated that resolutions finer than 1/12 of degree are needed to realistically represent the Gulf Stream separation (Hewitt et al 2016)

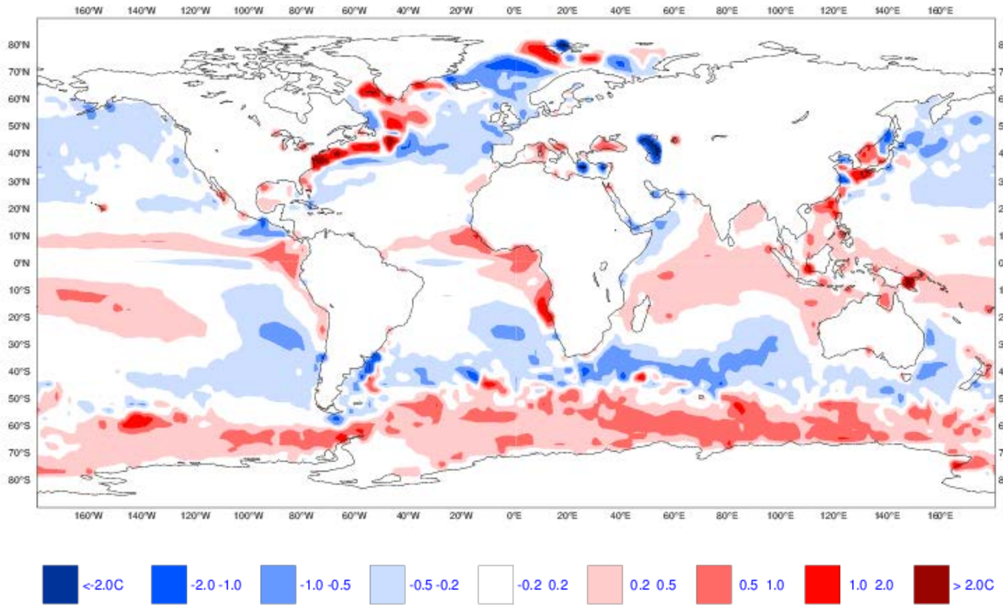

Figure 1: SST biases (relative to ERA-Interim) at the time range day 26-32 for the period NDJFM 1989-2016.

In order to assess the impact of these SST biases on the extended-range forecasts, a series of experiments has been set up where the ocean sees the atmospheric fluxes as in the control experiment, but the SSTs from the ocean model are bias corrected before they are passed to the atmosphere, as shown in Figure 2. The correction consists on removing the SST biases estimated from the Control experiment, which depend on the forecast lead-time and calendar starting date.

Figure 2: Schematic of the bias corrected experiments. The SST produced by the ocean are corrected by a small term BC which is the opposite of the SST bias and which is dependent on the initial time (t0), lead time (t), latitude (x) and longitude (y).

Three experiments have been run with bias correction applied to different regions. In the first experiment, the bias correction has been applied globally (BC_GL). In a second set of experiments it has been applied only over the Extratropics (North of 30N and South of 30S). This experiment will thereafter be referred to as BC_ET. In a third experiment, the bias correction has been applied only over the North Atlantic (BC_AT). Figure 3 shows the domains where the bias correction has been applied in the 3 bias correction experiments.

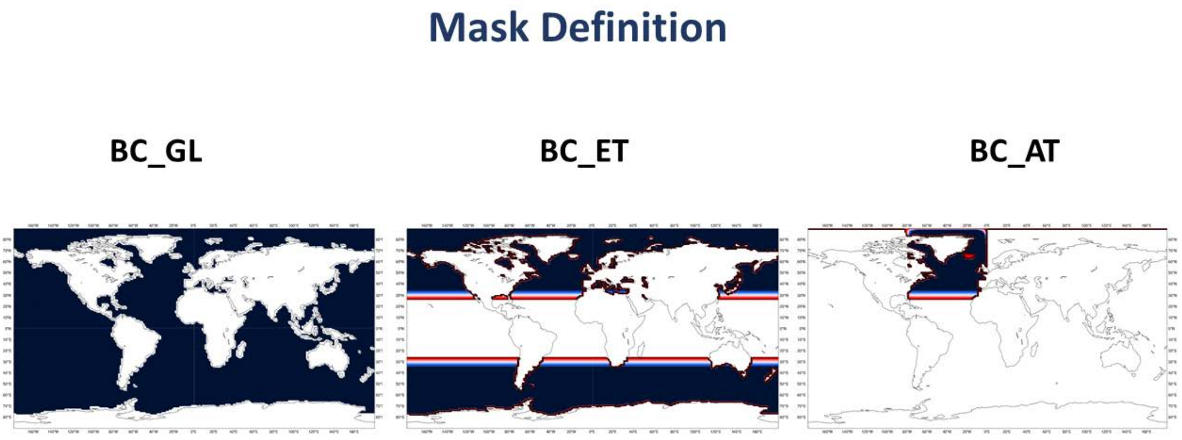

Figure 3: Mask applied to the three bias corrected experiments. The dark blue color represents the areas where the bias correction has been applied.

3 SST and atmospheric biases

This section will discuss the impact of the bias correction applied in different regions on the SST biases, but also on the atmospheric biases.

3.1 Impact on the SST biases

The SST biases relative to ERA Interim have been computed for the four experiments. Figure 4 shows the SST biases at day 26-32 for the period November to March. According to Figure 4, the biases in the Extratropics are significantly reduced when applying the bias correction method globally (BC_GL). This suggests that this bias correction methodology efficiently removes the strong biases in the western boundary currents at least for the extended time range. This is also the case for the pronounced biases in the Southern Ocean. Therefore, the bias correction does not seem to create unwanted feedbacks on the ocean field which would degrade the SST model climate. Interestingly, the bias correction in the Tropics is less effective. In some regions (Tropical Atlantic, Maritime Continent) there is a clear reduction of warm biases when applying the bias correction, but over the tropical central Pacific, there is a clear degradation in the bias corrected experiment, which develops a cold SST bias. Over the Indian Ocean, the bias correction methodology fails to correct the warm bias, which suggests that the bias is likely to originate from atmospheric fluxes rather than from ocean model errors. These results indicate that the impact of the bias correction methodology depends on the region and support the idea of applying it only in the extratropical regions. Indeed, BC_ET displays similar biases in the Tropical regions than Control, but the biases are overall successfully reduced in the extratropics. BC_AT shows very similar biases to Control everywhere except over the North Atlantic, where the strong bias over the Gulf Stream has been corrected. Overall it appears that the bias correction method works as expected, except in the Tropical Pacific where it can create negative feedbacks and deteriorate the SST biases, and over the Indian Ocean, where the biases remain constant.

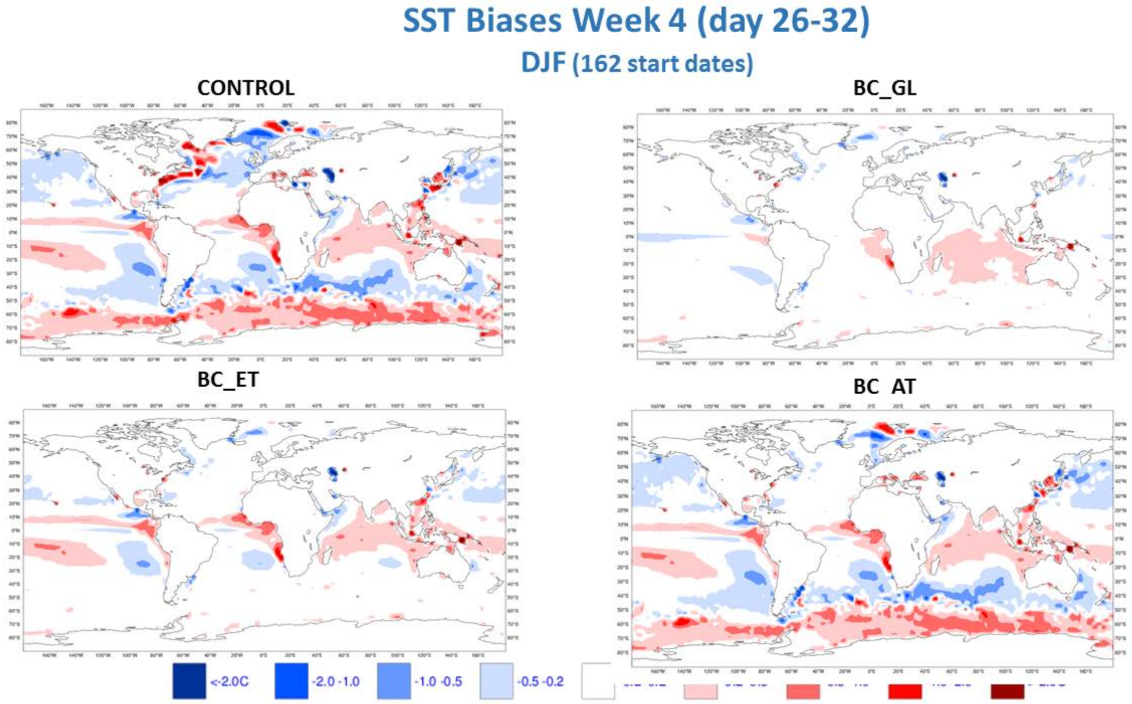

Figure 4: SST biases (relative to ERA-Interim) at the time range day 26-32 for the period NDJFM 1989-2016 for the four experiments (Control, BC_GL, BC_ET and BC_AT).

3.2 Impact on atmospheric biases

In this section, we show if the impact of the SST biases discussed in the previous section on the atmospheric biases. Figure 5 shows the precipitation biases in the different experiments. There is a reduction of precipitation biases in the tropical Atlantic in BC_GL, but a clear and statistically significant degradation in the tropical Pacific, which is likely a consequence of the increased SST biases in the Tropical central and eastern Pacific (cold SST bias in Figure 3). The tropical biases of precipitation in BC_ET and BC_AT, which have no SST bias corrections in the Tropics, are identical to the biases in Control.

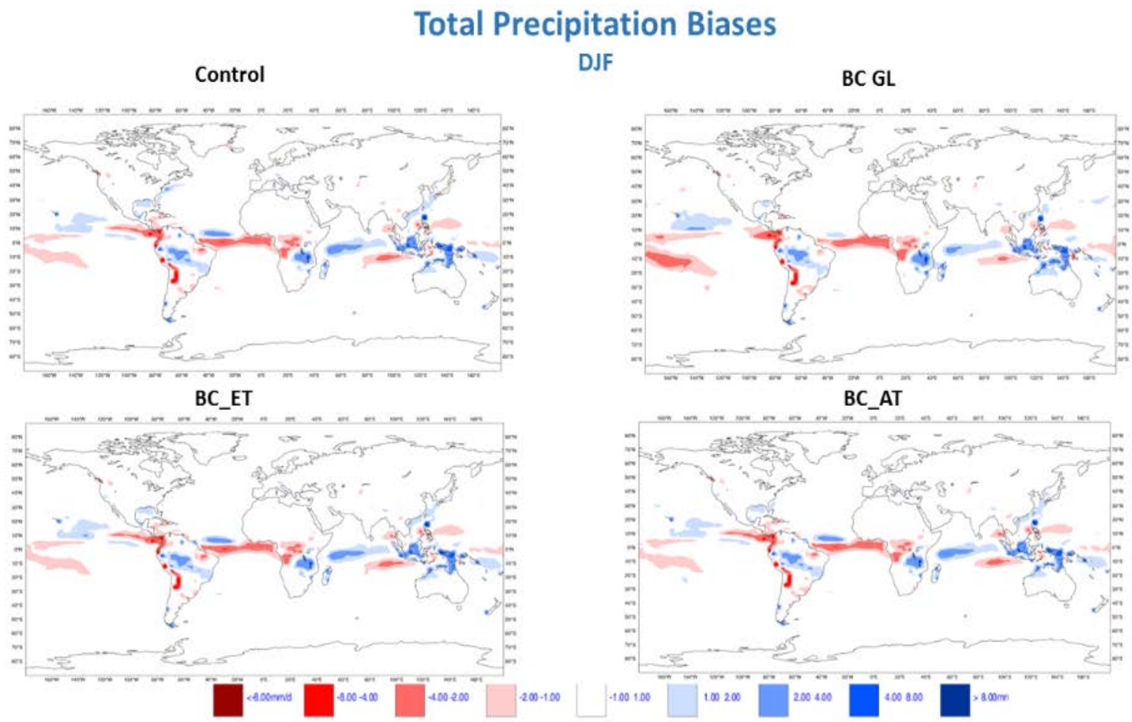

Figure 5: Precipitation bias (relative to ERA Interim) at the time range day 26-32 for the period NDJFM 1989-2016 for the four experiments (Control, BC_GL, BC_ET and BC_AT).

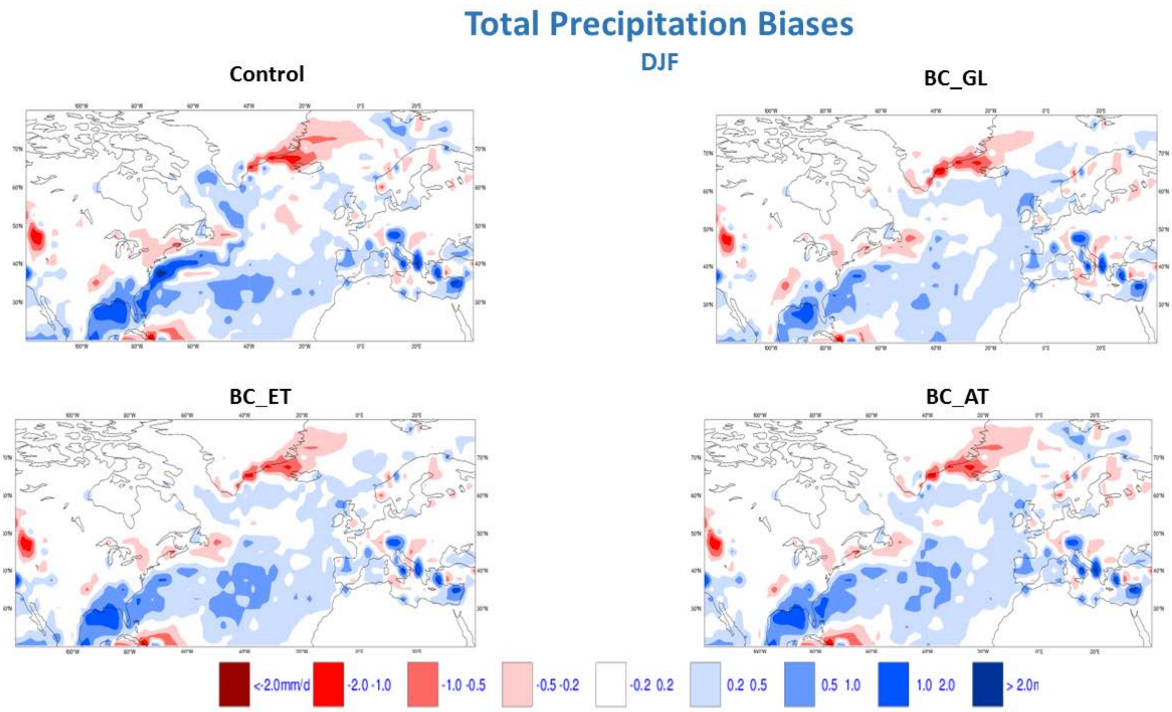

Figure 6: Same as Figure 5 but for the North Atlantic region and a different scale.

Over the North Atlantic, the precipitation biases are similar in all three bias correction experiments (BC_GL, BC_ET and BC_AT). All display reduced precipitation biases over the Gulf Stream. Elsewhere in the extra-tropics, the differences in precipitation biases are not significant.

Two-metre temperature biases are not significantly changed in the bias corrected experiments (Fig. 7) while Z500 biases are reduced by up to 10 metres, with similar patterns over the North Atlantic in all three bias correction experiments compared to Control. However, the difference is not statistically significant. BC_GL displays a degradation of Z500 biases over the Tropics and North Pacific which is likely to be a consequence of the negative impact of the bias correction in the tropical eastern Pacific. Wind biases at 850 hPa are significantly improved in BC_ET, as well as in the other two experiments (not shown) compared to Control (Figure 9) over the Euro-Atlantic sector. Zonal wind biases at 200 hPa are also slightly reduced over the North Atlantic in the three bias corrected experiments (not shown).

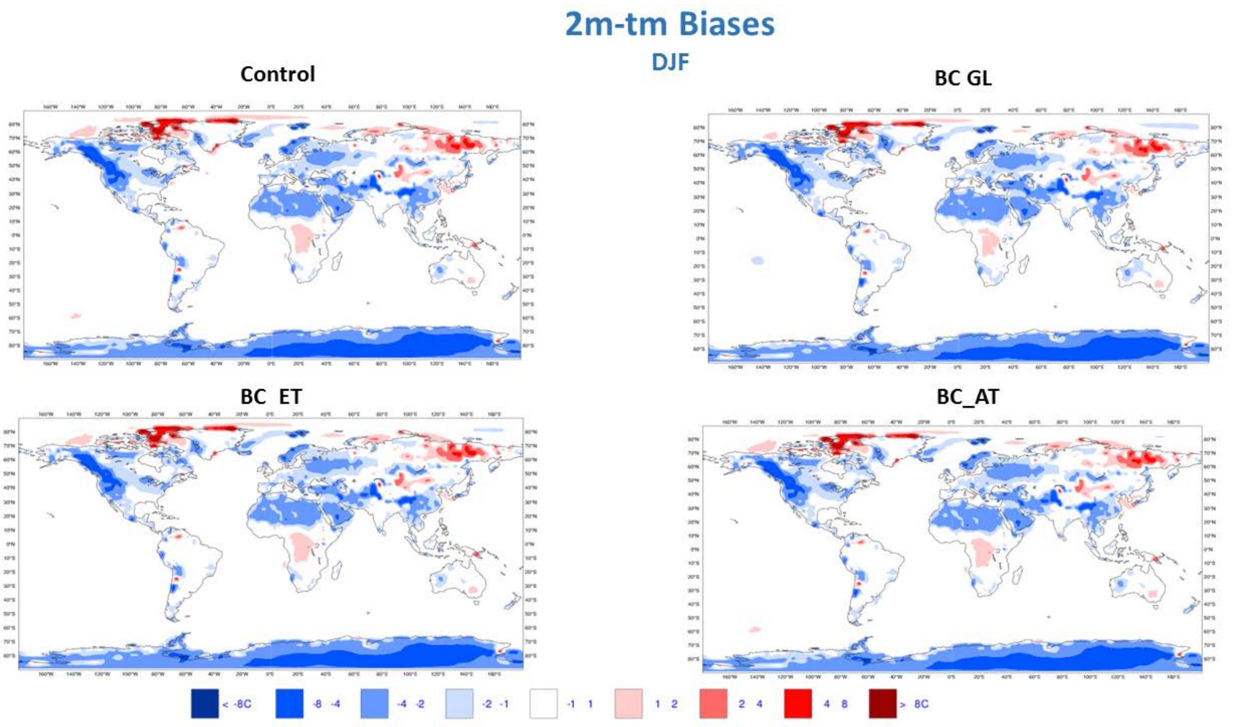

Figure 7: Same as Figure 5 but for 2-metre temperature

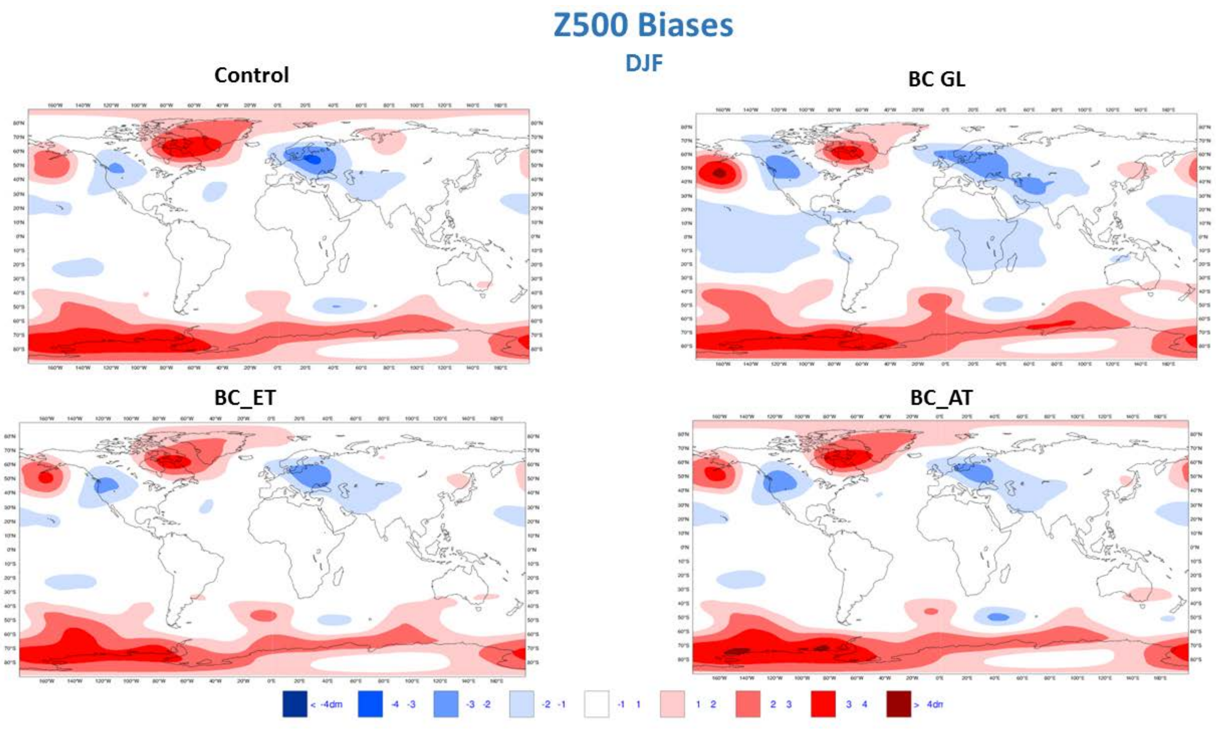

Figure 8: Same as Figure 5 but for 500 hPa geopotential height. Units are decametres

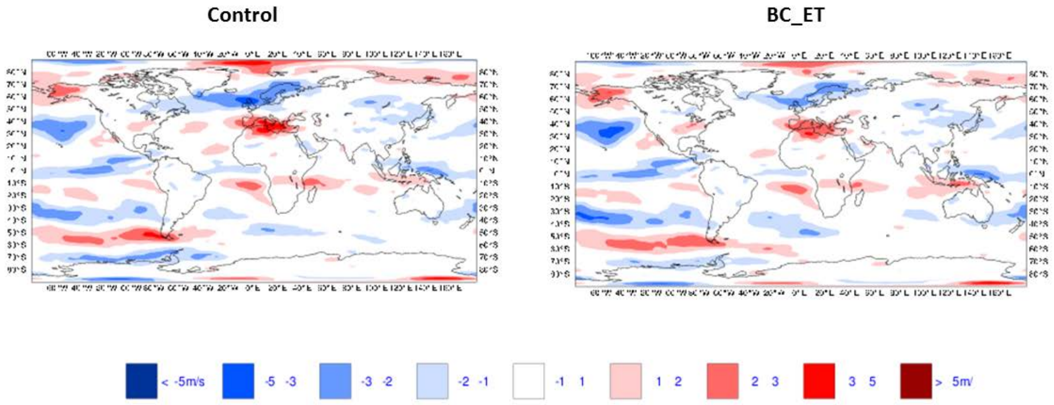

Figure 9: 850 hPa wind biases (relative to ERA Interim) at the time range day 26-32 for the period NDJFM 1989-2016 for Control and BC_ET.

4 Impact of SST biases on Extended-range forecast skill scores

The series of re-forecasts have been scored against ERA Interim. This section will discuss the results obtained with the Continuous Ranked Probability Skill Score (CRPSS) which has been applied to the re-forecast anomalies. This probabilistic skill score has been computed over several regions. Figure 10 shows the scorecard of BC_GL compared to Control over the northern Extratropics. The blue (red) colors indicates that BC_GL (Control) outperforms Control (BC_GL).

According to Figure 10, the bias correction globally has a positive impact over the northern Extratropics in week 4, but a negative impact on tropical skill scores, which is consistent with the deterioration of biases mentioned in the above section. This confirms that applying this bias correction methodology globally is not always beneficial and supports the idea of applying the SST bias correction only in the Extratropics, as it has recently been introduced in Cy45r1 for the tendency coupling in the ENS (Buizza et al., 2018). Figure 11 shows the scorecard for BC_ET, confirming the benefit impact over the northern Extratropics without the degradation in the Tropics. This is also the case with BC_AT (not shown). These results indicate that the impact of the SST bias correction on the northern extratropical skill scores is very small during the first 3 weeks, followed by a slight, but sometimes statistically significant, improvement in week 4. However, the impact of the SST bias correction is higher over Europe than over the northern Extratropics (Figs 12 and 13), where the scores show statistically significant positive impact in weeks 3 and 4. The three SST bias correction experiments display very similar scorecards over Europe (Fig. 12) which suggests that most of the impact comes from the correction of SST error in the North Atlantic, most likely from the errors in the representation of the Gulf Stream. This would be consistent with recent work from Lee et al. (2018) who performed a similar experiment in AMIP mode. In Lee at al. (2018), the AMIP forcing was degraded to include the systematic SST errors from the Met Office coupled models over the Atlantic. The authors found a significant impact on the location of the jet stream and atmospheric circulation over the Euro-Atlantic sector.

4.1 Impact on MJO-NAO teleconnections.

A main source of sub-seasonal to seasonal predictability is the Madden Julian Oscillation (MJO). However, all S2S models underestimate strongly the intensity of the MJO teleconnections over the Euro-Atlantic sector, and most especially the impact of the MJO on the North Atlantic Oscillation (NAO) (Vitart, 2017). An inter-comparison of MJO teleconnections in the S2S database (Vitart et al. 2017) showed that two S2S models (ECCC and JMA) displayed better MJO teleconnections following an MJO in Phase 7 than all the other models. These two models, which are atmosphere-only models forced by persisted SSTs, produced much stronger negative NAO following an active phase of the MJO over the western pacific than all the coupled models. This result suggested that the SST biases in the western boundary currents could play a role in the MJO teleconnection through their impact on the jet stream. The SST bias correction experiments described in this paper may help to address this question.

The MJO teleconnections have been diagnosed in the four experiments by computing the composites of 500 hPa geopotential height 11 to 15 days after an active phase of the MJO over the Indian Ocean (Phase 3), or over the western Pacific (Phase 7). The amplitude of these teleconnections in the Control experiment is significantly weaker than in ERA Interim with only 50% of the amplitude after an MJO in Phase 3 and 30% after an MJO in Phase 7. The amplitude of the teleconnections after an MJO in Phase 3 is about the same in the three SST bias corrections experiments as in Control (Figure 14, left panel). This suggests that the SST biases do not affect the impact of the MJO on positive phase of the NAO. However, the amplitude of the MJO Phase 7 teleconnections increases from 30% in control to about 45% (relative to ERA Interim) in the three SST bias correction experiments, which all show remarkably similar statistics (Fig. 14, right panel). This difference between the SST bias correction experiments and Control is statistically significant. Since the teleconnections after an MJO in Phase 7 project into a negative NAO, this result indicates that the SST biases over the North Atlantic impact the probability of negative NAO associated to the Madden Julian Oscillation. This is consistent with the more realistic teleconnections in the JMA and ECCC uncoupled models after an MJO in Phase 7, but not after an MJO in Phase 3 (Vitart, 2017). This impact of the SST biases on the MJO teleconnections is likely to affect the European skill scores when there an active MJO in the initial conditions. Indeed, Figure 15 shows that the European skill scores are significantly improved when using SST bias correction in weeks 2, 3 and 4 when there is a strong MJO in the initial conditions. On the other hand, the SST bias corrections do not impact significantly the European skill scores when there is no MJO in the initial conditions (Fig. 15, right panel). Figure 16 confirms that the SST bias corrected experiment BC_AT displays higher NAO skill scores in the extended range than the Control experiment, although the difference is statistically significant only after 28 days. The two other SST bias corrected experiment also display similar improvement (not shown).

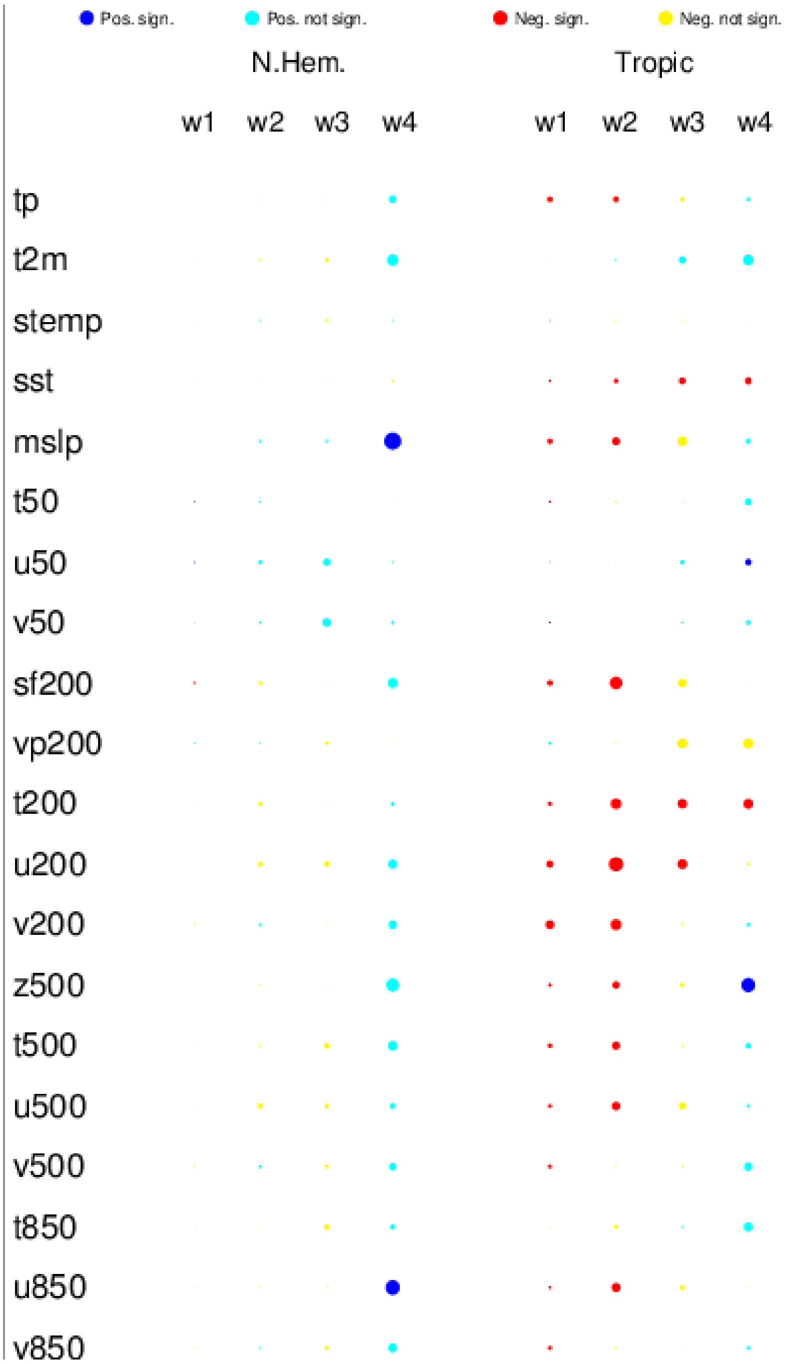

Figure 10: Scorecard of BC_GL CRPSS compared to Control RPSS over the Northern Extratropics. Blue colors indicate positive impact and yellow/red colors indicate degradation.

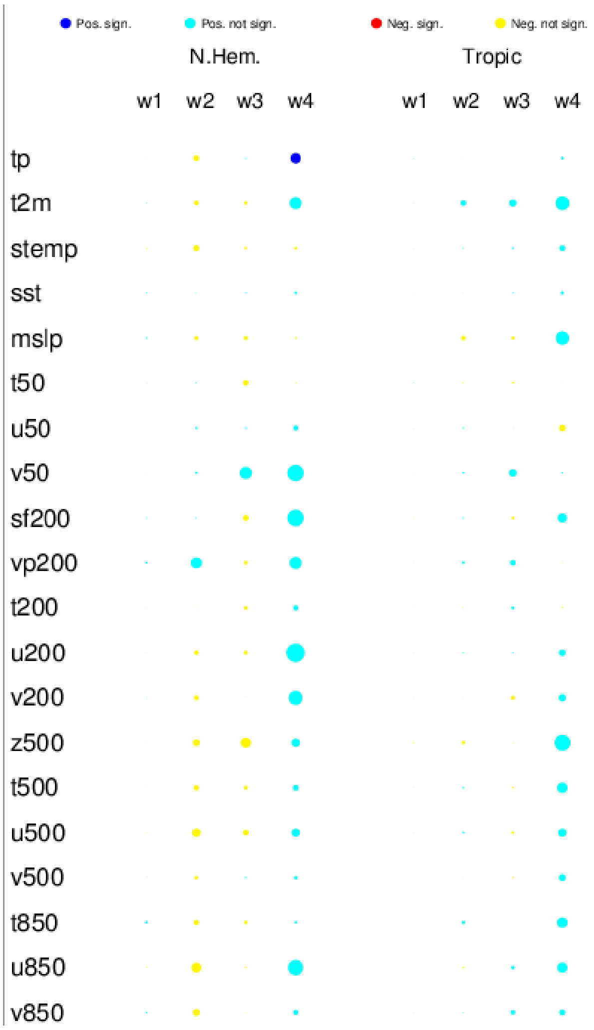

Figure 11: Same as Figure 10 but for BC_ET

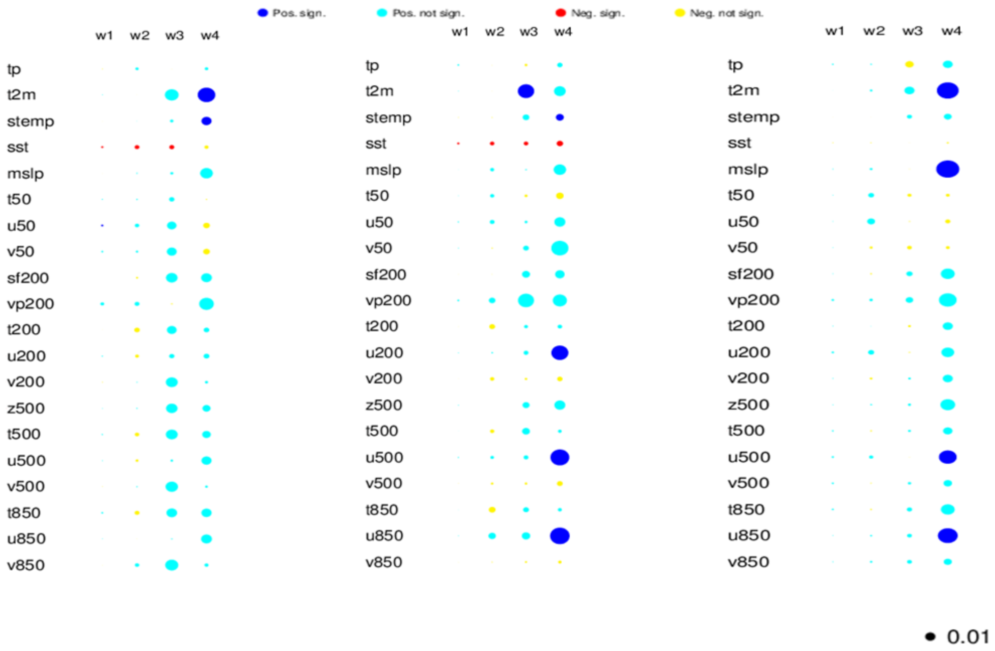

Figure 12: CRPSS Scorecard of BC_GL (Left panel), BC_ET (middle panel) and BC_AT (right panel) compared to Control CRPSS Europe. Blue colors indicate positive impact and yellow/red colors indicate degradation.

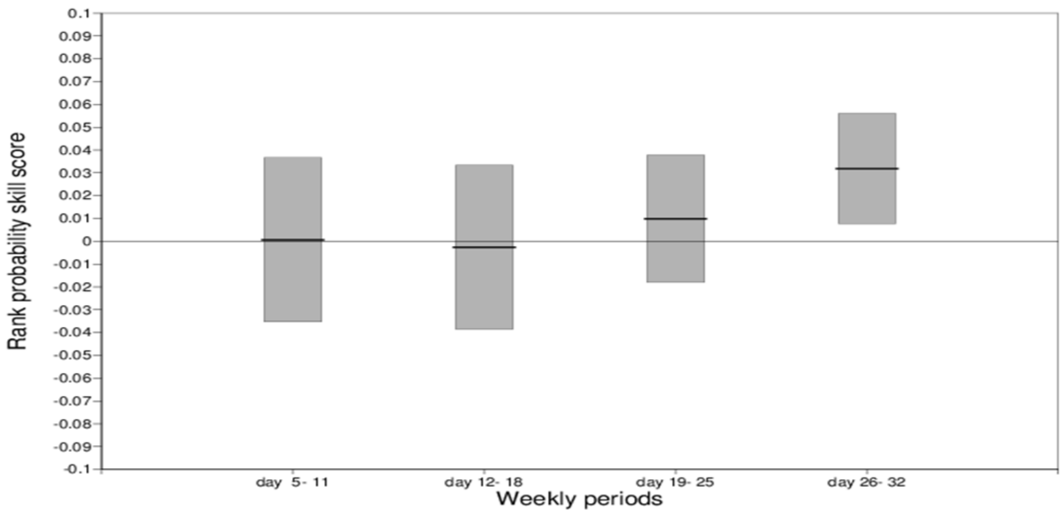

Figure 13: Difference of CRPSS of 200 hPa zonal wind between BC_ET and Control for week 1 to 4 over Europe. Positive (negative) differences indicate that BC_ET outperforms (underperforms) Control.

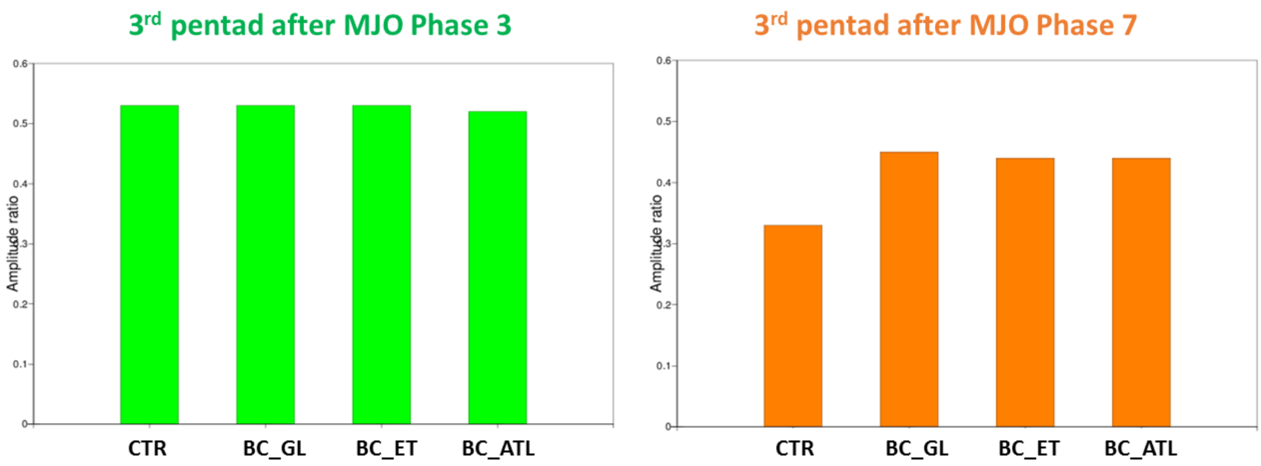

Figure 14: MJO teleconnection amplitude ratio compared to ERA Interim. The absolute values of composites of geopotential height anomalies 11 to 15 days after an MJO in Phase 3 (left panel) or after an MJO in Phase 7 (right panel) have been averaged over all the grid points North of 60N for each experiment (CONTROL, BC_GL, BC_ET and BC_AT).

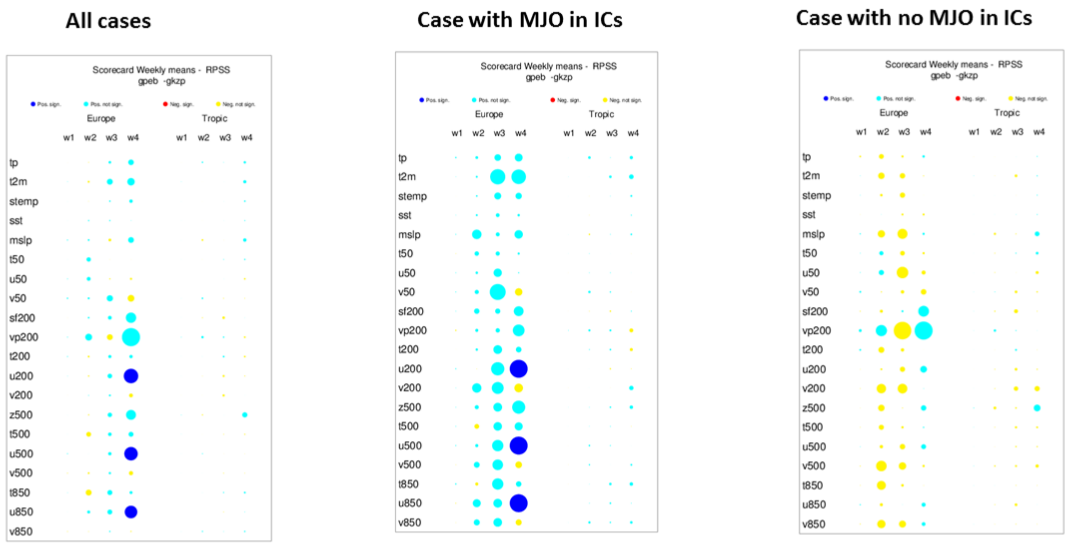

Figure 15: Scorecards of BC_ET CRPSS over Europe relative to Control when all the forecasts are included (left panel), only cases with a strong MJO in the initial conditions (middle panel) and when there is no MJO in the initial conditions (right panel).

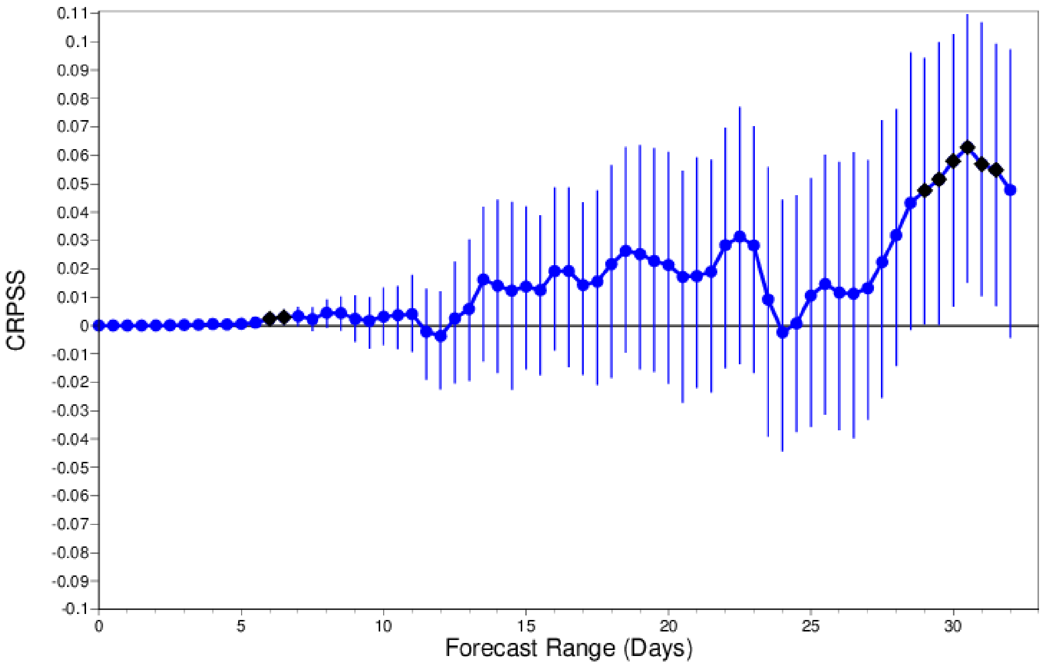

Figure 16: Difference of Continuous Ranked probability Skill Score (CRPSS) of the North Atlantic Oscillation Index (NAO) (computed by projecting 500 hPa geopotential height anomaly patterns onto pre-defined EOF patterns associated to the NAO) between BC_AT and Control as a function of the forecast lead time. Positive (negative) values indicate higher (lower) skill scores when using SST bias correction over the North Atlantic. Black diamonds indicate when the difference is statistically significant.

5 Conclusions

The main goal of this study was to assess the impact of the SST biases on sub-seasonal forecast biases and skill scores. This was done by artificially correcting the SST passed to the atmospheric model. This methodology suggests that there is no feedback from the impact of this correction on the atmospheric circulation into the ocean. Results suggest that this correction works fine in the Extratropics, but not in the tropical regions. Over the Indian Ocean, the SST biases seen by the atmosphere remain roughly the same and SST biases in the eastern tropical Pacific are degraded and generate larger biases over the North Pacific and a degradation in the forecast skill scores in the Tropics. However, applying the bias correction to the Extratropical regions alone leads to an almost complete reduction of the extratropical SST biases without negative impact. The impact on the atmospheric biases is relatively small and the improvement is mostly visible over the boundary current regions (for example reduction of precipitation biases over the Gulf Stream). The impact of forecast skill scores over the northern Extratropics is also relatively small, and mostly visible in week 4, although it is rarely statistically significant. However, the skill scores are significantly improved over Europe in weeks 3 and 4. The impact is particularly important and statistically significant for the tropospheric zonal winds. Similar improvements are obtained in all the three bias corrected experiments which provides additional confidence that these results are robust. This impact is sensitive to the presence or not of an MJO in the initial conditions. Cases with a strong MJO in the initial conditions display a statistically significant forecast improvement in week 4 whereas the cases with a weak MJO in the initial conditions do not display any impact. This suggests that the improvement may be linked to more realistic MJO teleconnections due to the impact of mid latitude SST biases on the position of the jet stream. A diagnostic of MJO teleconnections shows that the amplitude of the teleconnections after an MJO in Phase 7 is higher and therefore more realistic in the three biases correction experiments than in the Control experiment.

Overall these experiments suggest that most of the impact of the SST biases comes from the North Atlantic and therefore most likely from the errors in the position of the Gulf Stream. Further experimentation and diagnostic work is needed to fully prove this fact in the ECMWF forecasting system. Although the impact of the Gulf Stream SST biases has not been strictly isolated in these experiments, the results presented here are consistent with previous findings in seasonal and climate models at other time-scales, which show that correcting the Gulf Stream errors impact the European winter blocking frequency (Scaife et al 2011, Keeley et al 2012…),

The impact of the biases on overall forecast skill is not huge, but it is large enough to make the correction of these systematic error an important contribution to improved extended range forecasts. The best solution would be to reduce the SST biases in the coupled model. However, if the relevant SST errors are related with the position of the Gulf Stream, there are not immediate prospects for reducing them. The errors tend to improve with higher oceanic resolution, but there has been so far no evidence that they will be fixed in a higher horizontal resolution ocean mode (e.g. 1/12 degree). Even if this is the case, it is very unlikely that such resolution will become operational before 5 years. Another option would be to artificially fix this problem as in this study, by correcting the SSTs used by the atmospheric model, along the same lines as the SST partial coupling fix used for the medium-range. The bias correction investigated in this study operates only at the surface, which although simple is not ideal. Besides, it would be cumbersome to use operationally, since it needs to run a re-forecast dataset beforehand to estimate the systematic errors followed by a second set of re-forecasts with bias corrected SSTs. There are other reasons against the use of surface flux correction in coupled models, especially in the context of non-initialized integrations: in the long term, it can slow progress in model development, since it masks issues and interfere with coupled feedbacks. On the other hand, from the perspective of initialized forecast, it would allow ECMWF to produce more reliable and skilful extended range forecasts over Europe. It may be possible to find a consistent framework for treatment of model error by making use of assimilation terms, which will provide a continuous transition from assimilation to forecast mode.

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