Minimal impact of model biases on northern hemisphere ENSO teleconnections.

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Abstract. Correctly capturing the teleconnection between the El Niño–Southern Oscillation (ENSO) and Europe is of importance for seasonal prediction. Here we investigate how systematic model biases may affect this teleconnection. A two–step bias–correction process is applied to an atmospheric general circulation model to reduce errors in the climatology. The bias–corrections are applied to the troposphere and stratosphere separately and together to produce a range of climates.

10   ENSO type sensitivity experiments are then performed to reveal the impact of differing climatologies on ENSO–Europe teleconnections.

The bias–corrections do not affect the response of the tropical atmosphere, nor the Aleutian Low, to strong ENSO anomalies. However, the anomalous upward wave flux and the response of the northern hemisphere polar vortex differs between the climatologies. We attribute this to a reduced sensitivity of waves to the strength of the Aleutian Low. Despite the differing

15   responses of the polar vortex, the NAO response is similar between the climatologies, implying that for strong ENSO events a stratospheric response may not be necessary for the ENSO–North Atlantic teleconnection.

1 Introduction

The El Niño–Southern Oscillation (ENSO) has been shown to influence European climate via tropospheric and stratospheric teleconnections. Although ENSO is a key driver of global variability on seasonal to annual timescales it's effect on Europe is
20 less robust (Brönninman 2007), and exhibits decadal variability (Rodríguez–Fonseca et al., 2016). The large seasonal variability in the mid–latitude Northern hemisphere, and relatively low number of observed ENSO events create some difficulty in measuring the effect in observational data. The ENSO–Europe teleconnection begins with anomalous convection in the tropical Pacific, and during El Niño events this leads to increased divergence in the upper troposphere, creating a Rossby wave source (Hoskins and Karoly, 1981). The anomalous Rossby waves propagate to the Northern Pacific
25 where they strengthen the wintertime Aleutian Low. There are multiple possible connections between the North Pacific anomalies and the North Atlantic (Jiménez–Esteve and Domeisen, 2018), with a tendency for a negative North Atlantic Oscillation during El Niño event. For the stratospheric connection, as reviewed by Domeisen et al., (2019), the deepened Aleutian low can lead to upward propagating waves, particularly of wavenumber 1, which travel into the stratosphere and weaken the wintertime stratospheric polar vortex. For strong vortex weakening events, such as sudden stratospheric
30 warmings, anomalies can propagate down to the troposphere and project onto the Northern Annular Mode, and the North Atlantic Oscillation (NAO) (Butler et al., 2014). The result is also a tendency for a negative NAO during El Niño events. The opposite is approximately true for La Niña events, but the anomalous response is weaker (e.g. Jiménez–Esteve and Domeisen, 2019).

Both the tropospheric and stratospheric teleconnection pathway can be simulated with climate models of sufficient resolution
35 (Cagnazzo and Manzini, 2009, Bell et al. 2009). Models also allow for large numbers of ENSO events to be simulated, which has revealed non–linearities in teleconnections (Frauen, et al. 2014, Jiménez–Esteve and Domeisen, 2019, Garfinkel et al 2019). However, for confidence in modelling results, we need an understanding of the deficiencies of models. A fully coupled model needs to correctly represent both the complex dynamics of the ENSO ocean–atmosphere interactions to generate the convective anomalies that drive the teleconnections, and the mean climatology so the anomalies interact with
40 the base state correctly. For example, the convective response of tropical Pacific is dependent on the mean state of the Walker circulation (Bayr et al. 2018). The location and strength of the convective response is then important in controlling the location of the extratropical pressure response (Bayr et al., 2019), and can lead to non–linearities. In addition to the patterns of climatological SSTs, the state of the tropical (e.g. QBO phase) and extratropical atmosphere can influence the response of the NAO and polar vortex (Garfinkel et al., 2007).

45 The technique of flux correcting SSTs has been used to study the effect of model biases on ENSO dynamics (Spencer et al., 2007, Magnello and Huang, 2009, Domenget et al., 2014) or seasonal forecasting (Magnusson et al., 2013a, Magnusson et al., 2013b). Empirical corrections are added to the coupling between the ocean and atmosphere to push the model towards the observed climatology. It is possible to use a similar technique on the prognostic atmospheric variables of a model. This

bias–correction technique was used Kharin and Scinocca (2012), and artificially decreased biases were associated with an
50   increase in predictive skill on seasonal timescales. Simpson et al., (2013a, 2013b) used the technique to study the impact of
jet latitude bias on the Southern Annular Mode (SAM), although they did not see improvements in the persistence of the
SAM when they reduced biases in the jet. When Chang et al. (2019) used a similar bias–correction technique they found an
improvement in the North Pacific jet and North American rainfall climatology, and a modest improvement in seasonal
forecast skill. Tyrrell et al., (2020) investigated how climatological biases effect the relationship between the Eurasian snow
55   extent and the wintertime polar vortex. The strength of the vortex was found to have only a small effect on it's response to a
tropospheric forcing, however the downward propagation of stratospheric anomalies was sensitive to the tropospheric
circulation.

In this study we have used a similar bias correction technique to probe the impact of climatological biases on the
communication of ENSO anomalies from the tropical Pacific to the North Atlantic and European sector. The technical
60   details of the model and experiments are described in section 2, the results of the bias corrections and ENSO experiments are
described in section 3, and a discussion and conclusions are presented in section 3.

2 Data and Methods

We use the ECHAM6 spectral atmospheric model (Stevens et al., 2013), run with a horizontal truncation of T63 and 95
vertical levels with a model top at 0.02 hPa. The bias correction technique follows Kharin and Scinocca, 2012, and is similar
65   to that described in Tyrrell et al., 2020 (T20). It is a two–step process; first, the bias correction terms are calculated in a
nudged training stage. The model's prognostic variables – divergence, vorticity, temperature, and log of surface pressure –
are nudged towards ERA–Interim for 30 years and the nudging tendencies are recorded every 6 hours. Then the nudging
tendencies are used to create a climatology of correction terms. This climatology is then smoothed in time with a Gaussian
filter with a 25 day window, and it represents the inherent bias in the model's prognostic variables. Secondly, the
70   climatology of correction terms is added to the free running model as an additional tendency term at each time step. An
important difference between the nudged and bias corrected runs is that the bias correction terms are independent of the
current model state, so the model can respond to perturbations, whereas during the nudged run the model is tightly
constrained to the reanalysis. The technical details of the bias correction are outlined in T20, with two differences for the
current experiments. For the training step the model was nudged to ERA–Interim data from 1979–2009, whereas in T20 only
75   the years 1979–1989 was used. This did not impact the results, with the resulting bias correction terms being very similar.
The second difference to T20 was that the only bias correction terms used for this study were the divergence and
temperature, rather than the divergence, vorticity, temperature and log of surface pressure. During the training stage all the
model's prognostic variables were nudge towards ERA Interim, but it was found that using only two of the temperature,
divergence and vorticity of the bias correction terms gave the best results for reducing the biases in the winds and

80 temperature. Through testing difference combinations we found that bias correcting only the divergence and temperature lead to the biggest decreases in the climatological biases of the control run.

The bias corrections were applied on model levels between approximately 850 hPa and 2.6 hPa, and three types of bias correction runs were performed; the troposphere and stratosphere were corrected in FullBC, the stratosphere only in StratBC, and the troposphere only in TropBC (see Table 1 for details). Then ENSO SST forcing experiments were conducted with

85 each of these bias corrected climatologies. To generate the SST pattern we used a regression of the Niño3.4 timeseries and HadISST SSTs from 1979–2009. Only positive regression values between 30°S and 30°N and east of 150°E were used for the pattern, and the regression values were multiplied by 1.5 to strengthen the response, which corresponds to an El Niño or La Niña forcing of 1.5K. The pattern was then added to (El Niño), or subtracted from (La Niña) the SST climatology and the pattern was kept constant, i.e., the anomaly did not vary seasonally. Each experiment was run for 100 years.

90 To calculate the root mean square error and biases between the model and reanalysis (Fig. 1) we use ERA Interim 1979–2009, since that data was used for our bias correction scheme. However, when analysing the response to El Niño and La Niña runs, the newer ERA5 data is used (Hersbach et al., 2020), since it is a longer time series. To divide the data the NINO3.4 index was used for DJF (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). El Niño years defined as NINO3.4 above 0.9 K (8 years), La Niña years NINO3.4 below -0.9 K (8 years) and the years between

95 -0.5 K and 0.5 K were defined as neutral years (13 years). The slightly stricter threshold of +/- 0.9 K was used to define the El Niño/La Niña years to include only stronger events.

3 Results

3.1 Reduced model biases

The climatological biases of the model's wind and temperature vary with latitude and height. In Fig. 1 we show the root

100 mean square error (RMSE) of the zonal mean zonal wind (UZ) for three regions; the tropics (20°S – 20°N), mid–latitudes (20°N – 50°N) and the polar region (50°N – 90°N; the polar region is extended to 50°N to capture the full extent of the stratospheric polar vortex). The RMSE is calculated relative to the 1980–2009 ERA Interim climatology. It should be noted that the control run (green dashed line) performs very well in many regions, particularly the tropics, with UZ RMSE values below 2 m s^{-1}. The errors are small in the lower troposphere, and tend to increase with height. In Fig. 1 panels d–e we show

105 the percentage change in the UZ RMSE, between the CTRL run and the three bias–corrected runs. These figures demonstrate the effectiveness of the different height–dependent bias correction experiments. For example in Fig. 1e, in the mid–latitudes the corrections in the TropBC experiment reduce the UZ RMSE by around 40% in the troposphere. Although the corrections stop at around 100 hPa their effect continues into the stratosphere, but weakens. As the tropospheric corrections weaken, the corrections in StratBC lead to around a 25% decrease in UZ RMSE in the upper stratosphere. In FullBC the UZ RMSE is

110 reduced throughout the atmosphere with reductions of over 50% in the upper troposphere–lower stratosphere region. The same is broadly true for the tropics and polar regions, although with some exceptions such as the tropical stratosphere, where

errors are increased in the FullBC and TropBC, which may be related to the QBO. The TropBC also leads to increased errors in the polar stratosphere.

The SLP bias is shown in Fig. 1 g–j. Here we see similarities between the CTRL and StratBC, with a large bias in the
115 Aleutian Low, and the FullBC and TropBC, where that Aleutian low bias is reduced. Overall the bias–correction technique is effective at reducing errors in the climatological zonal winds throughout the atmosphere, with similar results for the temperature and meridional wind fields (not shown). The reductions in biases are larger in the extra–tropics than tropics, and the vertical profile of corrections can be effectively controlled.

3.2 Teleconnection response to ENSO

120 We trace the path of ENSO anomalies from the tropical Pacific to the northern hemisphere polar regions and the North Atlantic. Following from Fig. 3 in Jiménez–Esteve and Domeisen, 2019, our Fig. 2 shows the anomalous response of indices chosen to highlight the ENSO teleconnection to the North Atlantic. The El Niño and La Niña forcing does not vary seasonally in our experiments, thus is not shown. The convective response of the tropical atmosphere to SST anomalies is represented by the meridional divergent wind at 100 hPa defined in the region 0°–20°N, 160°–220°E (Fig. 2a). As expected,
125 the positive anomalies for El Niño are greater than the negative La Niño anomalies, and we also see there is no significant difference between the experiments. This is not surprising given the small biases in the tropical atmosphere, and reasonably small improvements in the tropics between the control and bias corrected experiments. The anomalous divergence creates a Rossby wave that leads to a deepening (El Niño) or weakening (La Niña) of the Aleutian low. We measure this using an Aleutian Low Index (ALI), defined as the SLP between 35°–60°N, 180°–240°E, indicated by the green box in Fig. 1 g. The
130 response of the ALI is proportional to the tropical divergence, with the anomalous negative El Niño response being greater than the positive La Niña response. Again, there are no clear differences in the anomalous response between the different climatologies. However, in contrast to the tropical regions, the FullBC and TropBC runs have reduced Aleutian Low biases compared to the CTRL and StratBC runs (Fig. 1 g–j), implying that the response of the Aleutian Low to an ENSO signal is not dependant on model biases.

135 The next step in the teleconnection is the response of heat flux at 100 hPa, 45°–75°N (HF). The anomalous HF for both El Niño and La Niña shows a differences between the climatologies. For an El Niño forcing the CTRL and StratBC runs show an increase in HF with significant values (indicated by black dots) for the DJF and JFM three–month means, whereas the FullBC and TropBC anomalies are about half as strong and have no significant values. The results are almost opposite for the La Niña forcing, except the CTRL and TropBC anomalous HF was around half the value of the StratBC and FullBC
140 runs, and no there were no significant HF values for any of the La Niña experiments. The lack of significance could be partly due to the weaker Rossby wave source associated with a La Niña, and the high variability of the HF.

We measure the response of the stratospheric polar vortex with the zonal mean zonal wind at 60N and 10 hPa (UZ60). UZ60 is well predicted by the HF values. Namely, for the El Niño forcing the CTRL and StratBC experiments show a significant weakening, whereas the response of FullBC and TropBC only show a slight weakening of the vortex. Likewise with the La

145 Niña forcing the FullBC and StratBC show a greater strengthening than the CTRL and TropBC. As with the ALI response, the response of the polar vortex does not appear to be affected by biases, which is discussed further in the next section.

The differences in the stratospheric response are not mirrored in the response of the NAO, despite the well known connection between the vortex and the NAO and the importance of a realistic stratosphere for the ENSO–North Atlantic teleconnection (for example, as shown by Cagnazzo and Manzini, 2009 with a similar model to our study). There is a weaker

150 FullBC response in early winter UZ60 to La Nina, and correspondingly weaker NAO response in early winter. However, for the other runs the strength of the polar vortex anomaly has no clear impact on the response of the NAO. This is evident when comparing the El Niño response of the CTRL and StratBC, to FullBC and TropBC, where the latter two have a weak UZ60 response but a strong NAO response. Hence, there is weak correspondence, but overall the stratosphere plays only a minor role in the NAO response.

155 **3.3 Difference in polar vortex El Niño response**

To investigate the cause of the different HF response between the experiments it is necessary to consider the effect of the bias corrections. To do that we must consider the absolute values and anomalous response together. In Fig. 3 we show the DJF ALI, HF and UZ60, for La Niña, Neutral and El Niño conditions. ERA5 is included to demonstrate the biases. Figure 3a shows the reduced bias in the ALI in the FullBC and TropBC experiments compared to the CTRL and StratBC experiments.

160 The figure also shows the deepening and weakening of the ALI for the ENSO forcing is fairly constant between the climatologies, hence, the larger biases in the CTRL and StratBC experiments do not impact the response of the AL. In Fig. 3b we again see the reduced bias in the FullBC and TropBC experiments for the HF. However, there is a smaller change between neutral and El Niño conditions for the FullBC and TropBC compared to the CTRL and StratBC. In other words, in the model the HF is less sensitive to the deepening of the AL in the climatologies where the AL is already deeper due to the

165 reduced bias. The same is not true in ERA5, although we caution against using this to dismiss the model results, due to the low number of events (around 8–9 per ENSO phase).

As shown in Fig. 2d, the response of the polar vortex is controlled by the HF response in the different climatologies. Figure 3c reiterates this, and also demonstrates that the biases in the polar vortex do not impact its response to anomalous wave forcing. In neutral conditions the UZ60 biases in the StratBC and FullBC are around 5 m s^{-1} less than the CTRL and TropBC

170 biases. However, for El Niño conditions the FullBC (less bias, stronger vortex) and TropBC (more biased, weaker vortex) have a weak response, and the StratBC (less bias, stronger vortex) and CTRL (more biased, weaker vortex) have a strong response.

We have shown that the stratospheric response to an El Niño forcing is partially dependant on model biases, and seems to be related to the sensitivity of the HF to the AL. In Fig. 4 we use regressions of HF onto SLP to show how the effectiveness of

175 wave forcing by the Aleutian low changes between neutral and El Niño conditions. Figure 4 a–d shows the regression of monthly HF onto monthly SLP for the extended winter months (November–March) in neutral ENSO conditions. The areas of SLP that are most strongly associated with HF are the Aleutian low region and Siberia, with weaker connections over

Greenland and North America. In neutral years these features are very similar between the control and the bias corrected runs, which means the deeper Aleutian low has not affected it's association with wave driving. Figure 4 e–h is the same

180 regression in years with an El Niño forcing. Rather than testing the difference between neutral and El Niño years, this is now a measure of variability during El Niño years. The connection between SLP in the Aleutian low and HF is lower in the CTRL and StratBC El Niño runs, but is now absent in the FullBC run and very weak in the TropBC runs. Therefore, for an equally large AL anomaly, there would be less wave forcing in the FullBC and TropBC. There appears to be a threshold for the depth of the Aleutian Low, below which any additional anomalies do not result in additional wave forcing. During La

185 Niña years the regression values over the AL region are slightly stronger in the FullBC and TropBC, but this did not lead to differences in the response of the HF (i.e. Figure 3 b).

4 Discussion and Conclusions

By applying a bias–correction technique to the divergence and temperature tendencies of an atmospheric model we have reduced biases in the troposphere and stratosphere to create various climatologies. With the different climatologies we have

190 performed idealized ENSO forcing experiments to test the role of biases in ENSO teleconnections. There were only small reductions in the bias in the tropics, and there was no difference in the convective response to ENSO between the experiments. Likewise, the anomalous response of the Aleutian low to El Niño and La Niña forcing was similar between the experiments, despite the reduced biases in the Northern hemisphere troposphere. Reduced biases in the Aleutian low SLP did, however, lead to differences in the anomalous upward wave flux associated with a deepened low due to an El Niño

195 forcing. A stronger polar vortex in the experiments with stratospheric bias correction did not affect the anomalous response of the vortex. Hence, we find that climatological biases do not significantly affect the response of the Aleutian low to Rossby wave forcing, or the polar vortex to upward planetary wave forcing. However, the model's ability to generate a planetary wave flux may be dependent on biases in surface pressure. Because the NAO response is not sensitive to the stratospheric representation or response, we conclude that it is dominated by tropospheric teleconnections.

200 Although one motivation behind artificially bias–correcting the model was to investigate how the response to various forcings might improve if the biases were reduced, it should be noted that the ECHAM atmospheric model has already been shown to have a realistic response to an ENSO forcing (Manzini et al. 2006, Cagnazzo and Manzini, 2009). The ENSO teleconnection, and the Siberian snow–polar vortex connection investigated in Tyrrell et al. (2020), are both relevant to seasonal forecasting, but the bias correction technique is unlikely to be used for operational forecasting. Hence, for these

205 experiments the bias corrections are a tool that is used not to improve the response relative to observations, but rather to explore the sensitivity of the response to climatological biases.

It was interesting to find that response of the Aleutian low and the stratospheric polar vortex was not affected by climatological biases. These two features are important in the ENSO–to–Europe teleconnection and had large reductions in bias due to the corrections. These features are also both forced by planetary waves; horizontally propagating waves from

210   anomalous convection in the tropical Pacific, or vertically propagating waves from the northern hemisphere troposphere to the stratosphere. Hence, model biases in the depth of the Aleutian low, or the magnitude of the polar vortex winds, do not appear to strongly affect their response to wave forcing.

The control and bias corrected runs differed in the magnitude of wave forcing caused by the deepening Aleutian low due to the El Niño forcing. We theorize that this was due to the relationship between the depth of the Aleutian low and it's

215   effectiveness at wave forcing. The two experiments with bias corrections in the troposphere both had a deeper Aleutian low, which was closer observations. Although the magnitude of ALI anomaly was the same, the runs with a deeper Aleutian low had reduced wave forcing for El Niño conditions. Regressions between SLP and HF showed that lower Aleutian low SLP was associated with a decreasing correlation between Aleutian low SLP and HF. Therefore, we speculate that the reduced wave forcing when the troposphere was bias corrected, was due to the lower climatological SLP values in the Aleutian low

220   area. It appears that at some threshold of low values of SLP, further anomalies in the Aleutian low do not result in anomalous upward waves. The opposite was not true for the La Niña conditions, since there appears to be no maximum values where the relationship between HF and Aleutian low SLP changes. Additionally, the non–linearity in the El Niño/La Niña atmospheric response (e.g. Frauen et al., 2014) means that the La Niña response is smaller, making it more difficult to distinguish robust differences between the climatologies. By artificially bias correcting an atmospheric model, we have

225   shown that some aspects of ENSO teleconnections are very robust to model biases, while more subtle interactions of anomalies with the basic state can impact the overall response. A deeper understanding of the influence of inherent model biases on teleconnections can guide future model development, and also aid in the physical understanding of these important teleconnections.

Data availability

230   The climatological means of all model experiments, for the variables used in this paper are available at: https://figshare.com/articles/dataset/ECHAM6_Bias_Correction_ENSO/13311623. The full timeseries is available upon request to Nicholas Tyrrell. ERA-Interim and ERA5 data Copernicus Climate Change Service Climate Data Store (CDS, https://climate.copernicus.eu/climate-reanalysis). The ECHAM6 model is available to the scientific community under a version of the MPI-M license http://www.mpimet.mpg.de/en/science/models/license/. The HadISST SST and sea ice data are

235   available from the U.K. Met Office https://www.metoffice.gov.uk/hadobs/hadisst/.

Author contributions

NLT conducted the model runs, analysis, and wrote the first draft. AYK contributed to the interpretation of the results, and improving the final manuscript.

Competing interests

240 The authors declare that they have no conflict of interest.

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Table 1. Experiment details and run names.

Bias corrections	ENSO Neutral	El Niño	La Niña
None	CTRL	CTRL_EN	CTRL_LN
850 hPa to 2.6 hPa	FullBC	FullBC_EN	FullBC_LN
100 hPa to 2.6 hPa	StratBC	StratBC_EN	StratBC_LN
850 hPa to 100 hPa	TropBC	TropBC_EN	TropBC_LN

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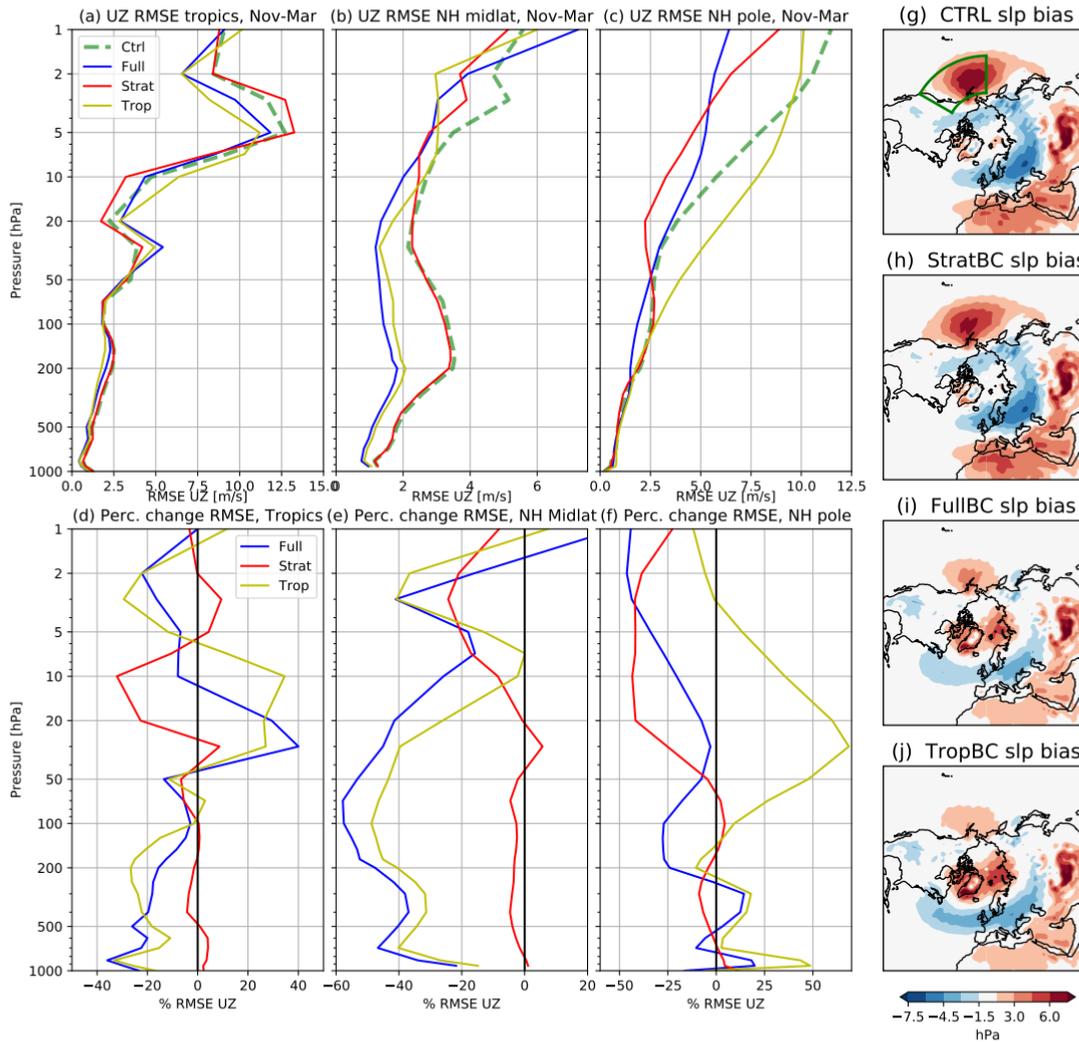
Figure 1: Panels a–c shows RMSE of UZ in the four experiment, in the tropics (20°S to 20°N), the mid–latitudes (20°N to 50°N) and the pole (50°N to 90°N). RMSE calculated using difference between model and ERA Interim climatology. Panels d–f are the percentage change of UZ RMSE between the control run and the three bias–corrected runs, with negative values showing improvement in the climatology of the bias corrected runs. Panels g–j show the bias in the control and bias corrected experiments, calculated as the experiment minus ERA interim. The green box in (g) shows area of the Aleutian Low Index.

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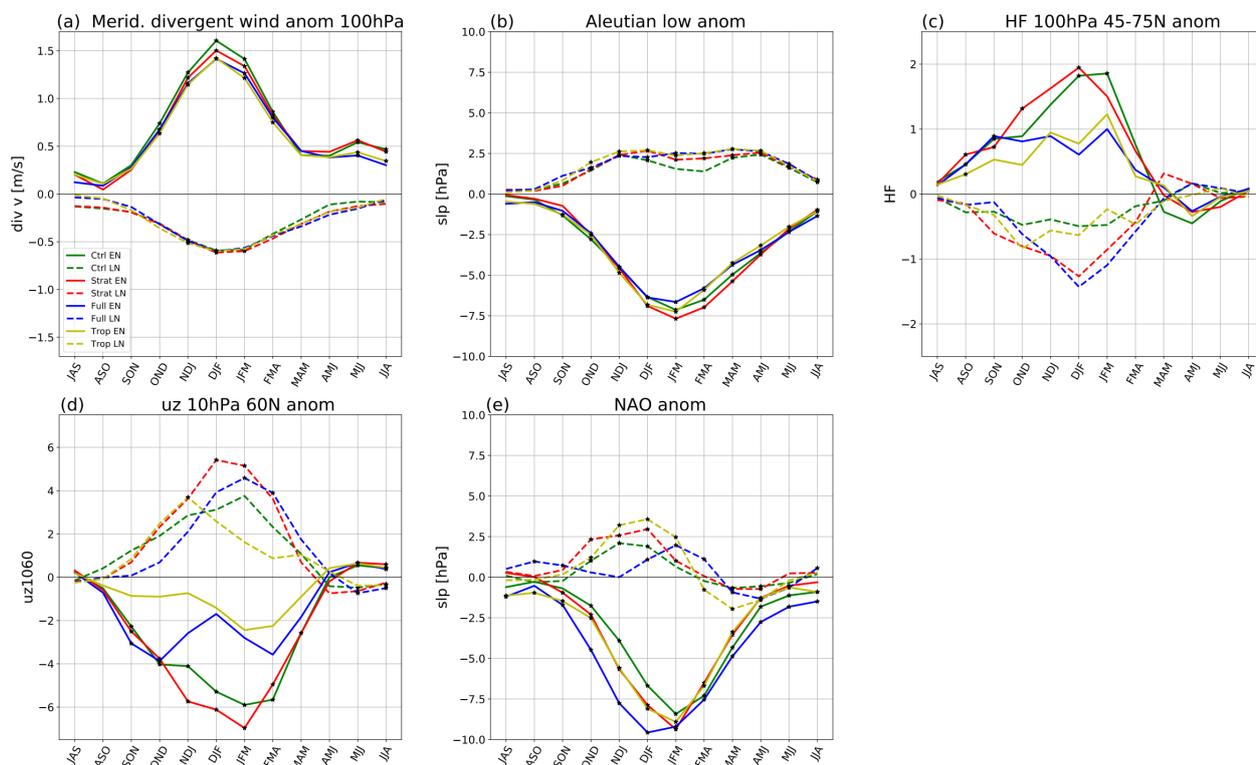
Figure 2. Progression of anomalies from the ENSO region to the stratospheric polar vortex and NAO. Timeseries uses three–month means, and black dots indicate significance at p < 0.05. Solid lines show 100 years of the El Niño run minus 100 years neutral run, dashed lines show 100 years of the La Niña run minus 100 years neutral run.

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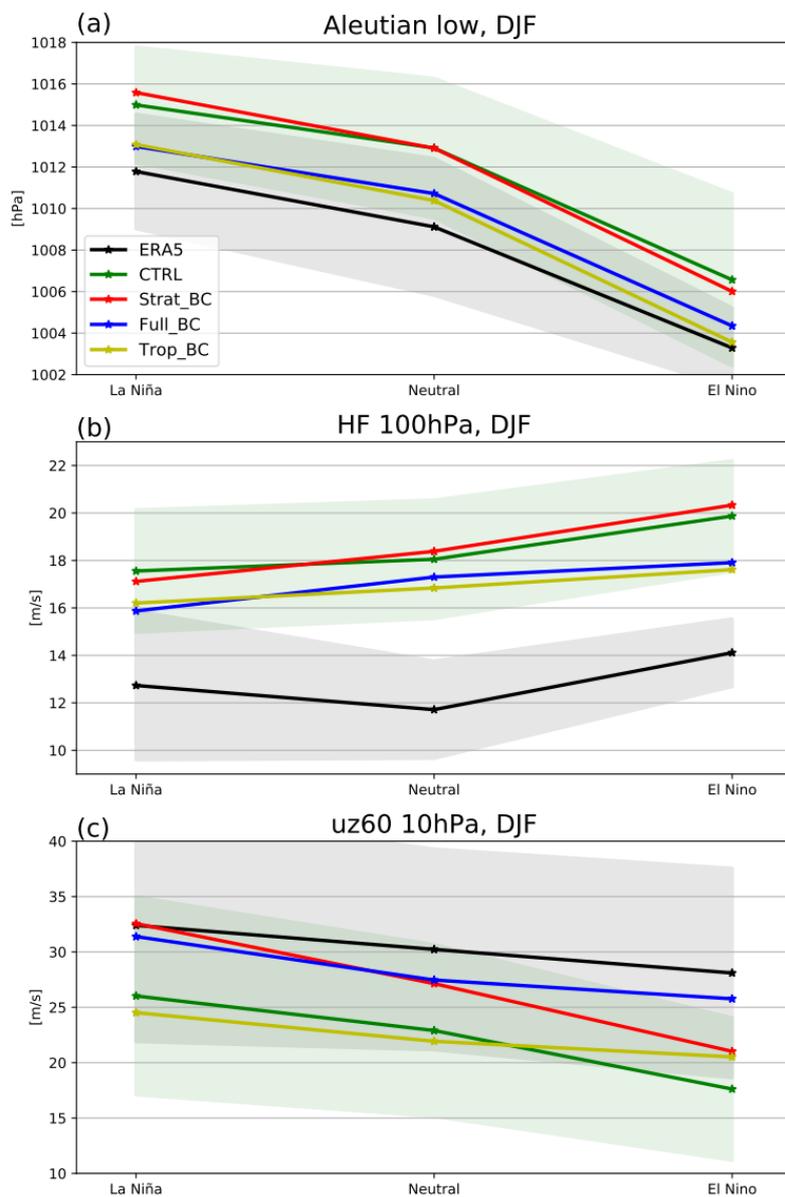
Figure 3. DJF values of (a) Aleutian Low Index, (b) heat flux between 45N–75N at 100 hPa and (c) UZ60 for La Niña, neutral and El Niño years. Shading is the standard deviation for the CTRL run (green) and ERA5 (grey).

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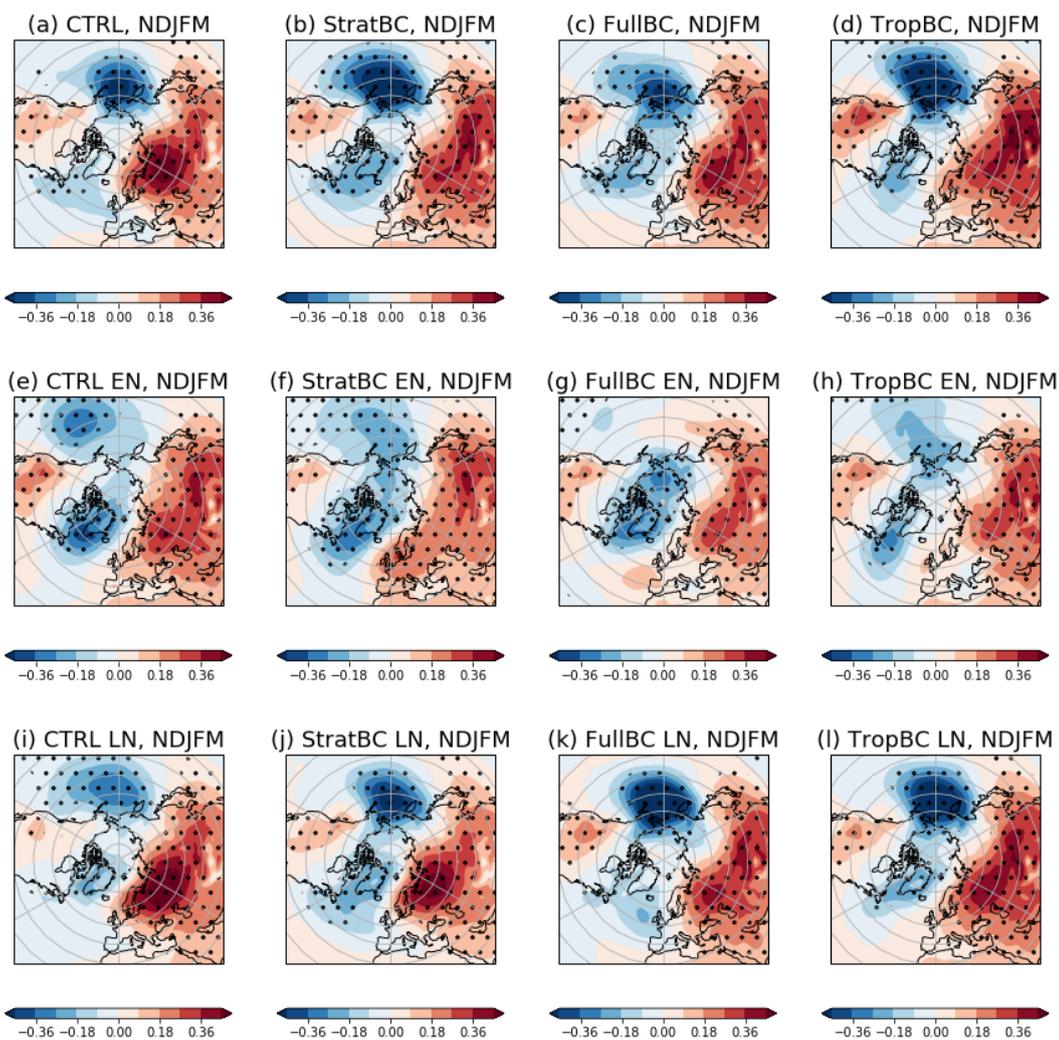
Figure 4. Regression of monthly HF and monthly sea level pressure for extended winter months (Nov–Mar). Top row is neutral years, middle row is El Niño years, bottom row is La Niña years. Stippling indicates significance at p < 0.05.