Tropical/Extratropical forcing of the AO/NAO: A corrigendum

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Abstract.
In two of our previous papers, we described the separate influence of tropical and extratropical forcing on the North Atlantic (NAO) and the Arctic (AO) Oscillations. Here, we point out a problem with the way the split between tropical and extratropical forcing was carried out. In the corrected model results, we find that extratropical forcing dominates tropical forcing in accounting for interannual variance in both the observed NAO and AO indices. We find that the recent upward trend in the NAO index is driven from the tropics, whereas for the AO index, we now find that extratropical forcing also contributes to the upward trend in the model. It follows that our corrected model results do not support a strong link between tropical forcing and the interannual variability of the wintertime AO, as claimed previously.

1. Introduction

In two recent papers, *Peterson et al* [2002] and *Lin et al* [2002], we described results from ensembles of experiments carried out using a simple, dry dynamical model of the atmosphere with linear damping and driven by forcing computed from the NCAR/NCEP reanalysis data (*Kistler et al* [2001]). The two papers focussed on the North Atlantic Oscillation (NAO - see *Hurrell* [1995] and Arctic Oscillation (AO - see *Thompson et al* [1998]), respectively, and the relative importance of tropical versus extratropical forcing for driving the variability of these modes. The model forcing was computed separately for each winter from 1949 to 1999 using the method described in *Hall* [2000] and is the average over each winter of the model time tendency when the daily mean states from the reanalysis are substituted into the unforced model equations. For future reference, we refer to the average of the forcing over all 51 winters as the climatological forcing, and the departure of each winter's forcing from the climatological forcing as the anomalous forcing. An ensemble of 30 model runs was carried out separately for each winter, each ensemble member being initialised using a different, randomly selected daily realisation from the NCAR/NCEP reanalysis. Since the model is nonlinear, the model computes its own eddy fluxes as part of the model integration, and these eddy fluxes must be realistic in their effect on the model mean state for the model to be useful, as is the case in all the model runs described here. In fact, the model has skill, in the ensemble mean, at reproducing aspects of the observed mean state in each winter. For example, *Peterson et al* [2002] found that the time series of the ensemble mean North Atlantic Oscillation (NAO) index for each winter correlates with the observed NAO index at 0.8. Likewise, *Lin et al* [2002] found that the Arctic Oscillation (AO) index computed from the ensemble mean sea level pressure for each winter correlates with the observed AO index at 0.6. Both correlations are significally different from zero at the 1% level. In order to unscramble the influence of the tropics from that of the extratropics, we considered model results obtained with the full model forcing applied only between 30^oN and 30^oS (the tropical forcing case), or outside of 30^oN and 30^oS (the extratropical forcing case), the forcing being specified to be the climatological forcing in the remaining part of the domain. We found that a significant part of the interannual variance of the NAO was accounted for by the extratropical forcing case, while the recent upward trend in the NAO index was related to tropical forcing. In the case of the AO, a very different conclusion was obtained. In particular, the extratropical forcing case showed no significant correlation between the model-computed AO index and the observed AO index, while the tropical forcing case accounted for almost as much variance as the global forcing case. This led us to conclude that the influence of diabatic forcing on the AO comes from the tropics alone, and gave us a simple way to distinguish the hemispheric AO from the more regionally focused NAO (e.g. *Wallace* [2000]; *Ambaum et al* [2001]).

Since these papers were published, we discovered a problem with the way the tropical/extratropical forcing split was done in the model. In this note, we briefly describe the problem, and correct our previous results. Our previous conclusions regarding the NAO are not greatly changed; extratropical forcing is found to be important for the interannual variability of the NAO, and the recent upward trend is related to tropical forcing. For the AO, on the other hand, we now find similar behaviour to that for the NAO, with extratropical forcing playing a significant role on all time scales.

2. The Tropical/Extratropical Split

The method of computing the forcing is described in detail in *Hall* [2000]. The forcing mimics processes not explicitly included in the model code, most importantly the diabatic forcing of the atmosphere due to incoming solar radiation, latent and sensible heat release associated with

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deep convection and the midlatitude storm track (*Hoskins et al* [1990]), and, since the model has a flat bottom, the effect of the missing orography. It is important to appreciate that all the prognostic equations of the model are forced and, in addition to temperature, there are prognostic equations for absolute vorticity, divergence and surface pressure (the basic model code is described in *Hoskins et al* [1975]). Furthermore, the forcing applied to these other equations is an essential aspect of the model; if we neglect this forcing, keeping only the forcing for the temperature equation, we are unable to reproduce our model results. This is also true of the case considered by *Hall* [2000]. Of particular concern is the forcing applied to the vorticity and divergence equations, since special care is required in the treatment of these equations when splitting the anomalous forcing between the tropics and extratropics. To obtain the results shown in *Peterson et al* [2002] and *Lin et al* [2002], the global forcing for the vorticity and divergence equations was first transformed to the equivalent forcing for the momentum equations. To split the anomalous forcing between the tropics and the extratropics, the anomalous forcing for the momentum equations was zeroed out poleward (equatorward) of $30^o N$ and $30^o S$ in the tropical (extratropical) forcing case, and the new forcing transformed back to a forcing for the vorticity and divergence equations. Since the last process involves taking derivatives of the momentum forcing with respect to the horizontal coordinates (see *Bourke* [1974]), the effect of this procedure is to introduce spurious "spikes" to the forcing for the vorticity and divergence equations along $30^o N$ and $30^o S$. These "spikes" impact on at least some of our previous model results.

The correct procedure for carrying out the tropical/extratropical split is to zero out the anomalous forcing for the divergence and vorticity equations directly, without recourse to the corresponding momentum equations. However, care is required when doing this because it is a requirement of the forcing for the divergence and vorticity equations that its global integral be zero on each vertical level (this is because the forcing is derived from the equivalent forcing for the momentum equations by taking the curl and divergence of those equations; see *Bourke* [1974]). It is therefore important, when splitting the forcing into tropical and extratropical parts, that the lines of latitude demarking tropical from extratropical are chosen in such a way that the area integrals of the anomalous forcing for divergence and vorticity within the tropical region (and hence by default also for the extratropical region) are both close to zero. To illustrate this, Figure 1 shows the result of averaging the anomalous forcing for the divergence and vorticity equations over the area contained within a latitude band centered on the equator. The plot shows this integral on each of the 5 model levels as a function of the outer, bounding latitude, and averaged over all 51 winters. In each case, the average is expressed as a percentage of the standard deviation of the forcing over the global domain. It is clear that the most significant departure from zero occurs on the top model level (nominally $100mb$) for the anomalous forcing of the divergence equation (Figure 1a), and that the value of the integral is significantly reduced if the tropical/extratropical forcing split is carried out at $36^o N$ and $36^o S$ rather than at $30^o N$ and $30^o S$. For this reason, all the new results that follow make the split along $36^o N$ and $36^o S$. It should be noted that the residual, arising from not having an exactly zero average within either the tropical or extratropical part of the domain, is compensated by means of a globally uniform correction on each model level. In the tropically forced case, the magnitude of this correction is smaller than the percentage shown in Figure 1 by a factor that is the ratio of the area within the tropical latitude band to the area of the globe, and so is, at most, a few percent when the split is carried out at $36^o N$ and $36^o S$.

3. New Results

Figure 2 and Figure 3 show the new model results for the NAO and the AO with the tropical/extratropical split carried out along $36^o N$ and $36^o S$, and applied directly to the forcing for the vorticity and divergence equations, as described above. Comparing Figure 2 with Figure 1 in *Peterson et al* [2002], we see that the new results for the NAO are similar to our previous results, except that in the new results, the extratropical forcing case is now accounting for almost as much variance in the observed NAO index as the global forcing case, and there is a reduced role for tropical forcing. Indeed, for detrended time series, the correlation between the NAO index in the tropically forced case and the observed NAO index is only 0.05, indicating no role for tropical forcing in accounting for the interannual variability of the observed NAO index. Nevertheless, the upward trend in the NAO index is seen to originate almost entirely from the tropics, as in our previous results, and consistent with *Hoerling et al* [2001].

Comparing Figure 3 with Figure 1 in *Lin et al* [2002], we find that for the AO index, our new results are somewhat different from our previous results. Whereas before, the extratropical forcing case was unable to account for significant variance in the observed AO index, here the story is much more like that of the NAO, with the extratropical forcing case accounting for as much variance as the global forcing case. The correlation between the AO index for the ensemble mean and the observed AO index is 0.66 in both cases and is significantly different from zero at the 1% level. We also find that the tropically forced case now accounts for only 13% of the observed variance, compared to 29% before. Nevertheless, for the tropically forced case, the correlation with the observed AO index (0.37) is still significantly different from zero at the 5% level, although for detrended time series, the correlation drops to 0.28 and is only marginally significant at the 5% level (the significance level drops even further if account is taken of serial correlation). It follows that while some of the tropically-driven signal is associated with the upward trend, there may still be enough interannual variance that is accounted for by tropical forcing to be useful for predicting the AO index one season ahead. Indeed, studies using the same model as used here show that there is some predictability of the winter AO-index contained in the model forcing for the previous November although it remains to be established if the predictability originates from the tropics. It is also possible that tropical forcing might influence both the AO and the NAO indirectly; that is, in a way that does not project onto the AO or NAO indices directly, but rather through the influence of the atmospheric response to tropical forcing on diabatic heating in the extratropics, and hence on the extratropical forcing seen by our model. This is an issue for future investigation. Concerning the upward trend, we note that the model overestimates the trend in the both the observed NAO and AO indices. Whereas almost all the upward trend in the NAO index in the model is accounted for by tropical forcing, in the case of the AO index both tropical and extratropical forcing contribute about equally.

4. Summary

We have pointed out a problem with the way the tropical/extratropical forcing split was carried out in our previous papers (*Peterson et al* [2002]; *Lin et al* [2002]). Correcting this problem, we find that our previous conclusions regarding the NAO appear robust, with a significant role played by extratropical forcing on interannual time scales, and with the upward trend between 1949-1999 being driven from the tropics, consistent with *Hoerling et al* [2001]. For the AO, on the other hand, we now find an important role for extratropical forcing on all time scales, in contrast to our previous results. Indeed, extratropical forcing accounts for as much of the variance of the observed AO index as global forcing, and both tropical and extratropical forcing are found to be important for the upward trend of the AO index in the model. Overall, it is difficult, on the basis of our new results, to make a clear distinction between the NAO and the AO in terms of the relative importance of tropical and/or extratropical forcing in accounting for the variance of their respective indices.

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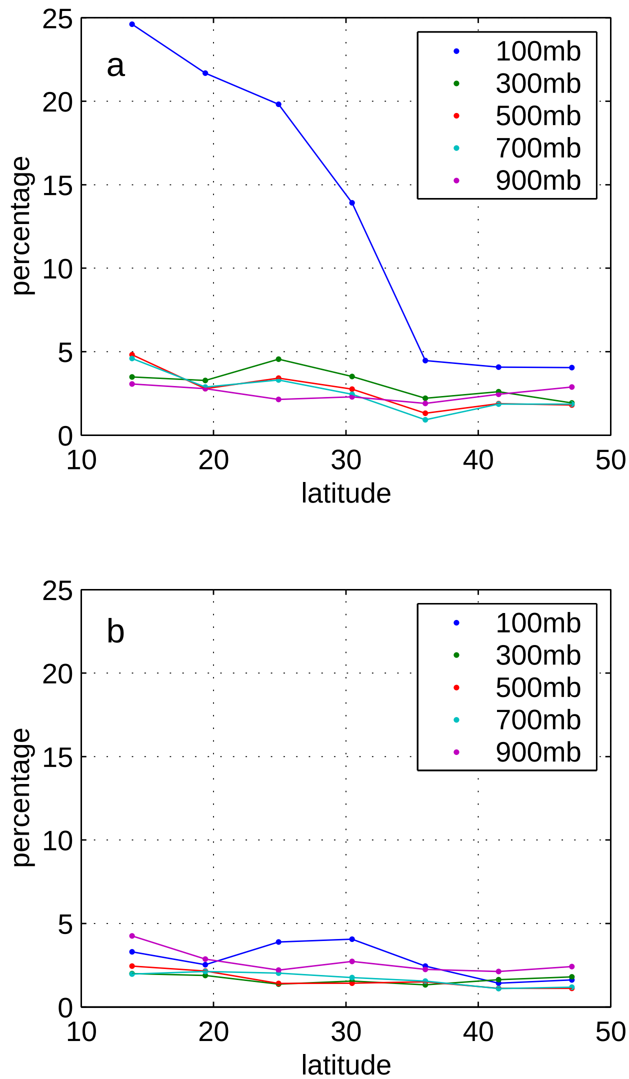

Figure 1. The average of the anomalous forcing for (a) the divergence and (b) the vorticity equations on each model level and within a latitude band centered on the equator, plotted as a function of the outer bounding latitude, averaged over all 51 winters, and expressed as a percentage of the area-weighted standard deviation of the forcing over the globe on each level.

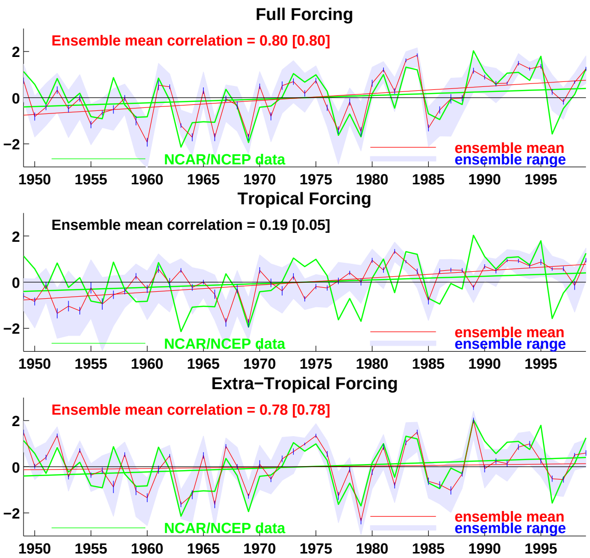

Figure 2. Time series of the NAO index for three different forcing scenarios. The green line is the observed NAO index computed from the NCAR/NCEP data, and the red line is the NAO index computed from the ensemble mean sea level pressure (SLP) field produced by the model. In each case, the NAO index is computed exactly as in *Peterson et al* [2002]. The shading indicates the spread in the individual ensemble members. The straight lines indicate the trend. Also shown are the correlations between the NAO index computed from the ensemble mean SLP field and the observed NAO index. Correlations for the detrended time series are shown in brackets.

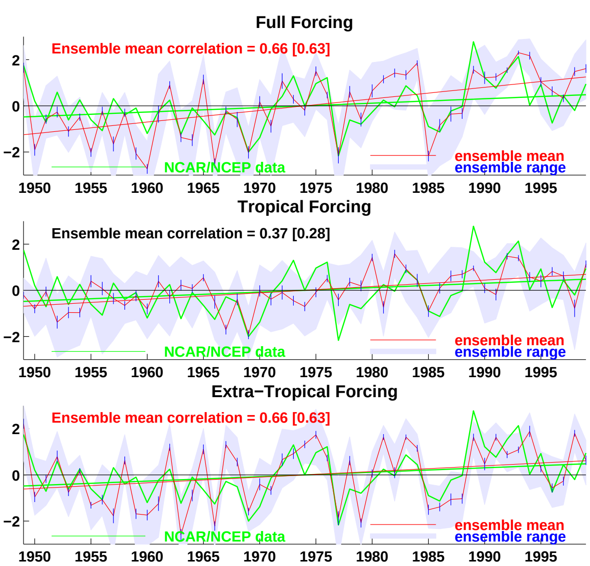

Figure 3. As Figure 2, but for the AO. In each case, the AO index is computed exactly as in *Lin et al* [2002].