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Vertical structure of anthropogenic zonal-mean atmospheric circulation change

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[1] The atmospheric circulation changes predicted by climate models are often described using sea level pressure, which generally shows a strengthening of the mid-latitude westerlies. Recent observed variability is dominated by the Northern Annular Mode (NAM) which is equivalent barotropic, so that wind variations of the same sign are seen at all levels. However, in model predictions of the response to anthropogenic forcing, there is a well-known enhanced warming at low levels over the northern polar cap in winter. This means that there is a strong baroclinic component to the response. The projection of the response onto a NAM-like zonal index varies with height. While at the surface most models project positively onto the zonal index, throughout most of the depth of the troposphere many of the models give negative projections. The response to anthropogenic forcing therefore has a distinctive baroclinic signature which is very different to the NAM. **Citation:** Woollings, T. (2008), Vertical structure of anthropogenic zonal-mean atmospheric circulation change, *Geophys. Res. Lett.*, *35*, L19702, doi:10.1029/2008GL034883.

1. Introduction

[2] There has been considerable interest in the possibility that anthropogenic atmospheric circulation change may project onto patterns of natural atmospheric variability [e.g., *Palmer*, 1999]. Particular attention has been paid to the leading pattern of Northern Hemisphere variability. This is known either as the North Atlantic Oscillation (NAO) or the Northern Annular Mode (NAM) [*Thompson and Wallace*, 2000]. Since a zonal mean approach is taken here, it will be referred to as the NAM throughout. Several studies have projected the output of General Circulation Model (GCM) climate change experiments onto various indices of the NAO or NAM [e.g., *Miller et al.*, 2006, and references therein]. These studies generally agree that the models are predicting a weak positive increase in the NAM index in the future, although there is considerable spread between models. This emerging consensus is reflected in the IPCC Fourth Assessment Report [*Meehl et al.*, 2007]. As noted by *Fyfe et al.* [1999] and *Osborn* [2004], the models are not predicting a strong response of the NAM, merely a pattern of mean change which has a non-zero projection onto the NAM pattern.

[3] Almost all previous studies have used a surface definition of the NAM. The NAM has an equivalent barotropic structure, in that variations in wind or geopotential height have the same sign at all levels. This means that in the analysis of the observed variability it is often sufficient to study one level only. However, it is not clear that this is true in the context of model predictions of future anthropogenic changes, especially if the mean change projects only weakly onto the NAM. As noted by *Brandefelt* [2006], there is a significant baroclinic component to the response. In this paper we demonstrate this by using a simple zonal index to infer the projection of predicted mean flow changes onto the NAM pattern at all levels.

2. Zonal-Mean Changes

[4] Firstly we show the zonal-mean circulation pattern associated with the NAM using data from the ERA-40 reanalysis [*Uppala et al.*, 2005]. December to February (DJF) months from all years are used, with the seasonal cycle removed by subtracting the mean of the respective month. The NAM is defined as the first EOF of the monthly mean sea level pressure, as is conventional. The circulation pattern is shown at all levels in Figure 1a by regressing the zonal-mean geopotential height onto the principal component time series. This pattern shows an equivalent barotropic dipole as expected. The monthly mean flow is close to being in geostrophic balance, and outside the tropics the geostrophic zonal wind associated with this can be found by differentiating the height field in the meridional direction. This is shown in Figure 1b and is very similar to that of *Thompson and Wallace* [2000].

[5] These patterns are now contrasted with the responses in GCM predictions of anthropogenic climate change. These are shown in Figure 2 as multi-model means. This uses data from the models contributing to the IPCC Fourth Assessment Report, which was obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set. The response to anthropogenic forcing is summarised as the difference between a pre-industrial control simulation and the years 2080–2099 of the SRES A1B scenario. All the distinct models for which the necessary data was available were used. These are listed in the legend of Figure 4 and are described by *Randall et al.* [2007, and references therein]. When more than one run was available for a given model, up to three ensemble members were averaged and this ensemble mean used as that model's contribution. The number of ensemble members used is also given in Figure 4. The length of the control period varies from model to model depending on data availability, but in all cases was at least 40 years. Many of the modelling centres have provided extrapolated data at low levels in regions of high topography, but some have not. In these cases no extrapolation is attempted here, and these regions are treated as missing data.

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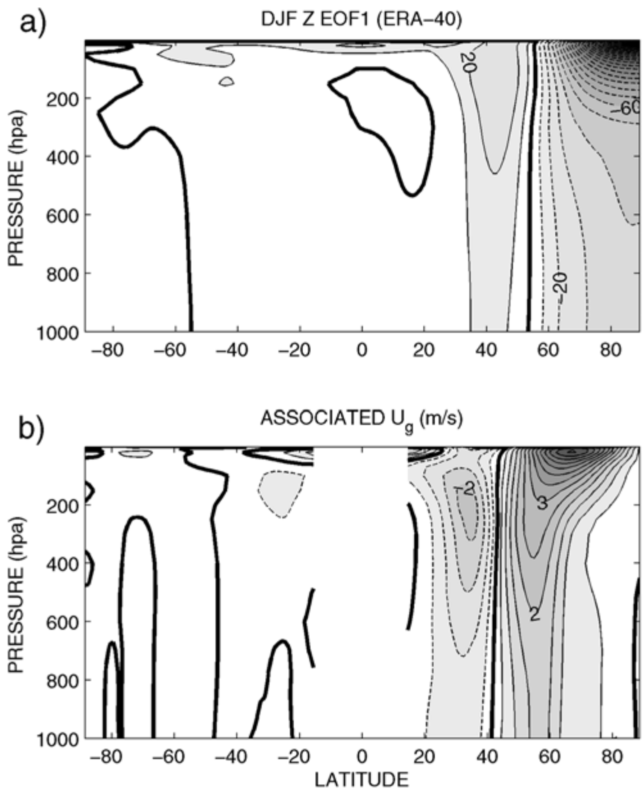

Figure 1. (a) Zonal-mean geopotential height pattern associated with the NAM in ERA-40. The contour interval is 10m per standard deviation of the time series, and in all Figures negative contours are dashed and the zero contour is in bold. (b) The geostrophic zonal wind derived from the geopotential height, with contours every 0.5 ms^{-1}.

[6] Figure 2a shows the DJF zonal-mean geopotential height change. In the Southern Hemisphere the height response over the polar cap is lower than that in the subtropics, and this is true at all levels throughout the troposphere. The response therefore projects strongly onto the Southern Annular Mode (SAM). In this season models robustly predict a positive SAM response to both greenhouse gas forcing [*Kushner et al.*, 2001] and ozone depletion [*Gillett and Thompson*, 2003]. Both of these forcings contribute to the response seen here, since several of the CMIP3 models include ozone forcing reflecting the legacy of ozone depletion during the late 20th century [*Miller et al.*, 2006].

[7] In contrast, in the Northern Hemisphere throughout much of the depth of the troposphere the geopotential height response is higher over the Arctic than it is in the subtropics, and so would be expected to project onto the negative phase of the NAM. However, the situation does change with height such that at the surface the gradient is of the opposite sign. This is consistent with previous studies showing a weak positive change in the NAM at the surface. The geostrophic wind response derived from the height pattern is shown in Figure 2b. This does have some similarities with the NAM pattern in Figure 1b, but there are also clear differences. There is a strong baroclinic component to the response, so that at many latitudes the sign of the wind response changes with height. While surface westerlies are intensified poleward of 40N, throughout most of the troposphere the response is easterly poleward of around 60N.

[8] Aspects of the circulation response can be understood by considering the temperature response. In the long-term mean the atmosphere is very close to being in hydrostatic balance, so the temperature response can be calculated by differentiating the height response according to the hydrostatic equation. This response (shown in Figure 2c) is well known, with enhanced warming near the surface over the Arctic due to snow and ice feedback, and enhanced warming at upper levels in the tropics due to latent heating. The response is clearly baroclinic, featuring horizontal temperature gradients which are associated with vertical wind shear. Near the surface between 60 and 80N there is a strong positive meridional temperature gradient in the response. This is associated with a negative vertical wind shear as seen in the wind response. The polar circulation response (negative geopotential response at the surface with

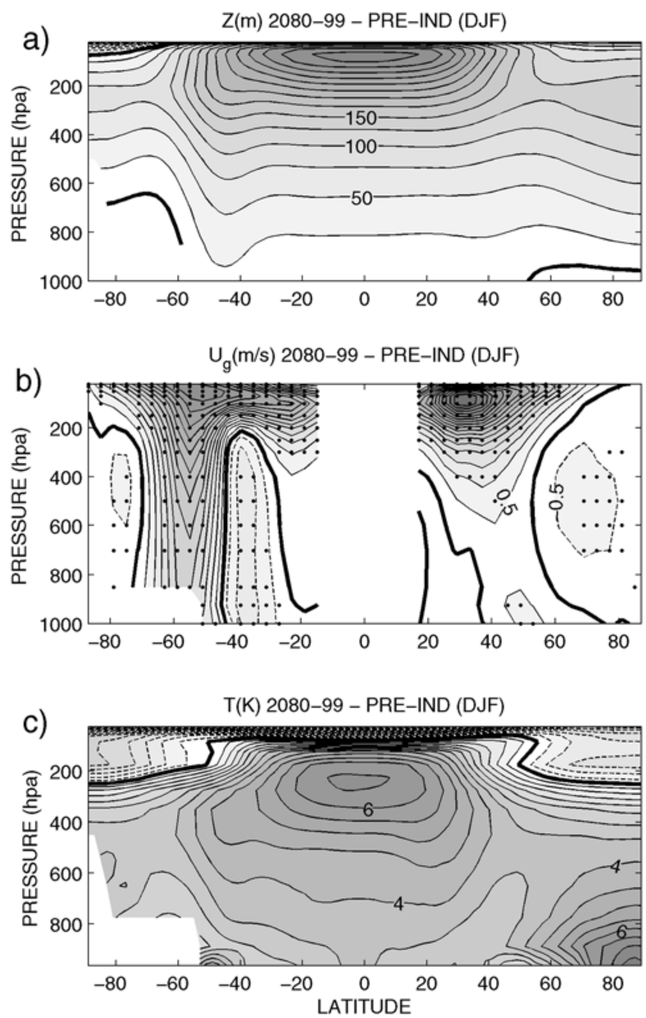

Figure 2. (a) The multi-model mean zonal-mean DJF geopotential height response, contoured every 25m. (b) The geostrophic zonal wind response derived from the height, with contours every $0.5ms^{-1}$. Dots mark points at which at least 19 out of the 22 models agree on the sign of the wind response. (c) The temperature response derived from the height, with contours every 0.5K.

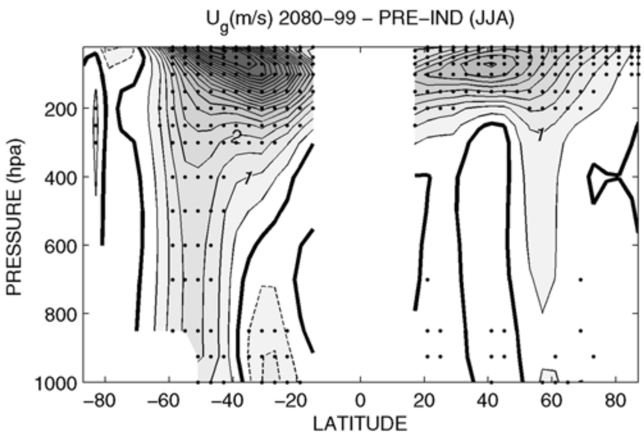

Figure 3. Same as Figure 2b but for JJA.

a positive geopotential response aloft) resembles the linear response to surface heating in quasi-geostrophic theory.

[9] The response in June-August (JJA) is summarised in Figure 3 by the geostrophic zonal wind. The Northern Hemisphere response is weak but clearly less baroclinic, as the polar surface warming is weaker. In the Southern Hemisphere the response is more baroclinic than in DJF, as seen by *Kushner et al.* [2001]. The ozone forcing is absent in this season, so the SAM response is weaker [*Miller et al.*, 2006], but the multi-model response does still project onto the positive phase of the SAM.

3. A Zonal Index

[10] We now use a simple zonal index to characterise the projection of each model response onto the NAM at all levels. The zonal index at a given level is defined as the geopotential height area-averaged over 20–50N minus the geopotential height area-averaged over 60–90N (the results do not change qualitatively with reasonable changes in the latitude bands used). This definition is chosen to reflect the projection onto the zonal-mean NAM pattern, and is indicative of the mean zonal wind in the mid-latitudes. It is clear from Figure 2b that this is not the optimal index to represent the actual circulation change in the model predictions.

[11] Figure 4 shows vertical sections of the zonal index response for each of the models. At the surface almost all the model responses project onto positive values of the zonal index, in agreement with previous studies. However, the positive meridional temperature gradient near the surface implies negative vertical wind shear, so that many of the models show negative zonal index responses throughout much of the troposphere. To be precise, 14 out of the 22 models have a negative zonal index response in the mid-troposphere, while only one model has a clearly negative zonal index response at the surface. Conversely, in the upper troposphere the negative meridional temperature gradient implies positive vertical wind shear. Although there is a significant barotropic component in some model responses, they all exhibit these same vertical gradients in zonal index.

[12] The zonal index responses are summarised in Figure 5 for both hemispheres and both seasons, showing that it is only in the Northern Hemisphere in winter that such a strong baroclinic response is seen. For comparison, Figure 5a also shows the zonal index changes associated with the NAM in ERA-40. In the troposphere this is much more uniform in the vertical, confirming that the recent variability has been dominated by this nearly barotropic structure which is very different in character to the model responses. The NAM structure has also dominated the trend when measured over the reanalysis period, though this is sensitive to the exact period chosen due to the decrease in the NAM index since the mid 1990s [*Cohen and Barlow*, 2005]. There is an interesting contrast between the tropo-

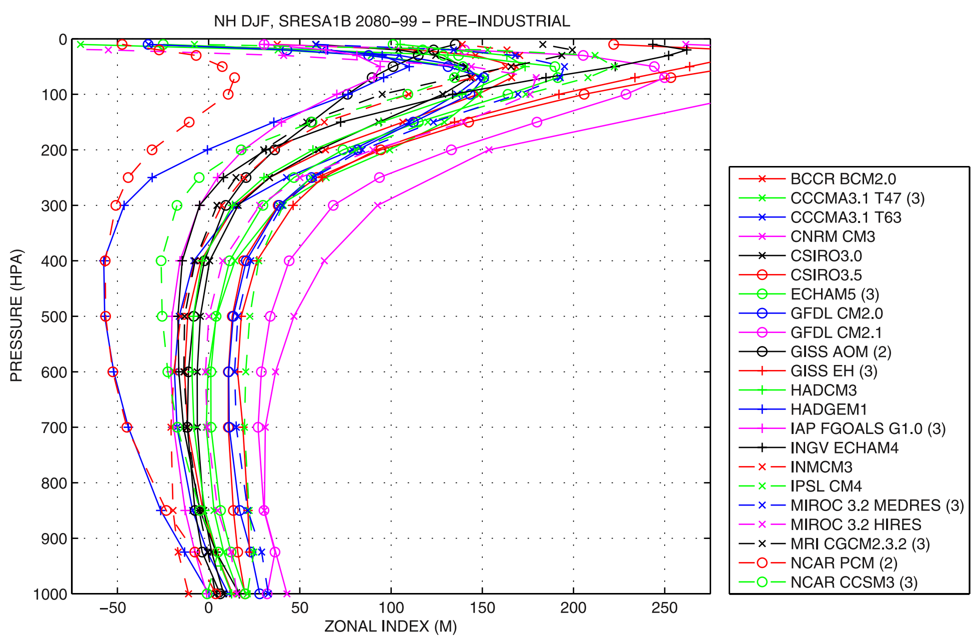

Figure 4. Vertical structure of the Northern Hemisphere DJF zonal index response for each of the models. The number of ensemble members used for each model is given in parentheses in the legend whenever this is greater than one.

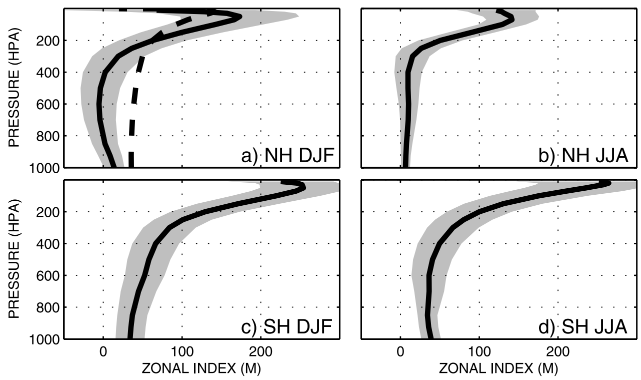

Figure 5. A summary of the zonal index response in both hemispheres and both seasons. In each case the solid line marks the multi-model ensemble mean and the shaded region is the ±1 standard deviation range. In Figure 5a the dashed line is the zonal index change associated with a one standard deviation variation of the NAM in ERA-40.

spheric and stratospheric responses. In the model responses the ratio of the stratospheric change to the tropospheric change is much larger than it is in the NAM structure.

[13] In Figure 4 there is considerable disagreement between the models over the magnitude of the index, and there are some models which show an increased zonal index at all levels. This suggests that there is a significant barotropic component of the response, which may indicate a real NAM response in these models. However, for most of the models it is the baroclinic component which determines the sign of the wintertime zonal wind response in the mid-troposphere at mid-latitudes. The disagreement between models may result from differences between the models in the size of the enhanced warming at the northern polar surface and in the tropical upper troposphere [*Rind et al.*, 2005].

4. Conclusions

[14] The main conclusion of this paper is that the zonal-mean response to anthropogenic forcing has a distinctive baroclinic signature which is very different to the NAM. This is evident from a comparison of the zonal wind response in Figure 2b to the pattern associated with the NAM (Figure 1b). The baroclinic nature of the response means that in many places the zonal index changes sign with height, in marked contrast to recent observed trends. Most studies projecting model responses onto the NAM have used surface data, since the equivalent barotropic component of the response is clearest at the surface [*Thompson and Wallace*, 1998]. This is because the vertically-integrated, time- and zonal-mean eddy momentum flux convergence must be balanced by the surface wind stress, so that changes in the surface winds are expected to mirror changes in the eddy-driven jet [*Kushner et al.*, 2001]. Almost all of the models show a weak positive zonal index response at the surface, suggesting that the transient eddies in the models may be responding consistently, as described by *Yin* [2005]. Away from the surface, however, it is the baroclinic, rather than the NAM-like eddy-driven component of the response which determines the sign of the zonal wind response. Note that while the Southern Hemisphere response is more barotropic, *Shindell and Schmidt* [2004] also saw an analogous decoupling of the warming and SAM signatures there.

[15] Since the long-term mean state is in hydrostatic balance, any model prediction featuring amplified low-level polar warming will also feature the baroclinic circulation structure described here. However, there remains considerable doubt over the ability of current models to represent variations in circulation [e.g., *Gillett*, 2005]. The models are not predicting a circulation response dramatic enough to dominate over the polar warming signature, but this does not mean that such a response is not possible.

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