

An analysis of trends in the boreal winter mean tropospheric circulation during the second half of the 20th century

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[1] A relaxation technique applied to the ECMWF model is used to analyse 11, 21 and 31 year trends in the boreal winter mean 500 hPa North Atlantic Oscillation (NAO), Pacific North America pattern (PNA) and Southern Annular Mode (SAM) indices. For the PNA, the results indicate a strong influence from the tropics on all time scales, whereas for the NAO, the stratosphere is important on time scales of 11 and 21 but with an indication of feedback from extratropical sea surface temperature and sea-ice (SSTSI) anomalies on the 11 year time scale. For the SAM, the tropics emerge as the most important influence. We find an influence from the stratosphere consistent with expectations based on ozone depletion, although no clear role for stratospheric forcing of the SAM is found in these experiments. **Citation:** Greatbatch, R. J., G. Gollan, and T. Jung (2012), An analysis of trends in the boreal winter mean tropospheric circulation during the second half of the 20th century, *Geophys. Res. Lett.*, 39, L13809, doi:10.1029/2012GL052243.

1. Introduction

[2] During the 20th century, the northern hemisphere winter mean circulation was marked by strong multidecadal variability in the winter North Atlantic Oscillation (NAO) index [see Greatbatch, 2000; Hurrell *et al.*, 2003], as well as the multidecadal variability of the Pacific Decadal Oscillation [Deser *et al.*, 2004]. The most important mode of atmospheric variability in the southern hemisphere, the Southern Annular Mode (SAM), also showed strong, multidecadal trends [Visbeck, 2009]. It is of considerable interest to understand the dynamics controlling these trends, not least because anthropogenic signals can project on to preferred modes of variability such as the NAO [see Gillett *et al.*, 2003]. Indeed, the recent upward trend in the SAM has been linked to anthropogenic forcing [e.g., Gillett and Thompson, 2003; Arblaster and Meehl, 2006; Deser and Phillips, 2009; Thompson *et al.*, 2011]. Furthermore, trends in the NAO are known to have a major impact on Eurasian winter climate on decadal time scales, as pointed out by Hurrell [1996]. Nevertheless, Semenov *et al.* [2008] note that the trends in the NAO during the instrumental period agree well with those from two coupled climate model integrations and that the observed trends are broadly consistent with the

natural variability of the coupled ocean/ice/atmosphere system [see also Wunsch, 1999]. These authors also note, however, that the upward trend in the NAO between the mid-1960's and the mid-1990's was an unusual event in the context of the coupled models they examined. Here we use a series of ensemble experiments carried out using a relaxation technique [Jung *et al.*, 2010a; Hoskins *et al.*, 2012] applied to the ECMWF model to diagnose influences on trends in the 500 hPa NAO, PNA and SAM indices over a range of time scales during the 42 winter period 1960/61 to 2001/02 (corresponding roughly to the ERA-40 reanalysis period). It should be noted that using the Northern Annular Mode (NAM) [Thompson and Wallace, 2000] instead of the NAO for the analysis leads to very similar results to those presented here for the NAO.

[3] The plan of this paper is as follows. In section 2, the model set-up, the different experiments and the analysis techniques are described. Section 3 focuses on the results and finally, section 4 provides a short summary.

2. Methods

[4] We use a version of the ECMWF atmosphere model very similar to that described in Jung *et al.* [2010b]. The model has the same horizontal (T159) and vertical resolution (60 levels, about half of which are above the tropopause, extending up to 0.1 hPa) as used for the ERA-40 reanalysis. Each winter was integrated separately using 12 ensemble members for each experiment. Initial conditions for the ensemble members were taken from the ERA-40 reanalysis at 6-hourly intervals from around November 1 of the respective year. All model runs were started at 1200 UTC on November 1 and the analysis was carried out on the following boreal winter; that is December, January and February (DJF).

[5] When using relaxation, the model is drawn toward the ERA-40 reanalysis in a specific region during the course of the integration; this is achieved by adding an extra term of the form

$$-\lambda(\mathbf{x} - \mathbf{x}_{\text{ref}}) \quad (1)$$

to the ECMWF model. The model state vector is represented by \mathbf{x} and the reference field toward which the model is drawn by \mathbf{x}_{ref} . The strength of the relaxation is determined by λ , here corresponding to a time scale of 10 hours. The parameters that are relaxed are zonal velocity, u , meridional velocity, v , temperature T , and the logarithm of the surface pressure, $\ln p_s$ ($\ln p_s$ is not relaxed in stratospheric relaxation experiments).

[6] Masks were applied to localize the relaxation, care being taken to reduce adverse effects close to the relaxation boundaries by using transition zones between relaxed and

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Table 1. Correlation Between the Time Series of Running Trends, Ensemble Mean Versus Reanalysis, for the NAO, PNA and SAM Indices^a

	NAO	PNA	SAM
11 y Window			
significant levels	0.62, 0.74*	0.62, 0.73*	0.53, 0.64*
CLIM-NO	-0.30 [-0.39]	-0.18 [-0.18]	-0.52 [-0.54]
OBS-NO	0.33 [0.29]	0.44 [0.43]	0.29 [0.32]
CLIM-TROPICS	0.28 [0.20]	0.60 [0.60]	0.66* [0.72*]
OBS-TROPICS	0.65 [0.61]	0.65 [0.64]	0.73* [0.74*]
CLIM-STRAT	0.61 [0.64]	0.14 [0.10]	-0.48 [-0.65*]
21 y Window			
significant levels	0.54, 0.69*	0.88, 0.92*	0.70, 0.77*
CLIM-NO	-0.12 [-0.12]	-0.57 [-0.04]	-0.58 [-0.39]
OBS-NO	0.41 [0.41]	0.71 [0.02]	-0.20 [0.57]
CLIM-TROPICS	-0.07 [-0.06]	0.87 [0.51]	0.39 [0.70]
OBS-TROPICS	0.24 [0.26]	0.90* [0.61]	0.56 [0.73]
CLIM-STRAT	0.82* [0.88*]	0.80 [0.53]	-0.58 [-0.40]
31 y Window			
significant levels	0.87, 0.93*	0.74, 0.81*	0.63, 0.75*
CLIM-NO	0.48 [-0.06]	0.19 [0.25]	-0.18 [-0.26]
OBS-NO	0.64 [-0.12]	0.70 [0.32]	-0.37 [-0.57]
CLIM-TROPICS	0.86 [0.71]	0.84* [0.88*]	-0.15 [-0.20]
OBS-TROPICS	0.71 [-0.10]	0.93* [0.90*]	-0.09 [-0.10]
CLIM-STRAT	0.44 [0.74]	0.41 [-0.37]	-0.13 [-0.46]

^aCorrelations for detrended indices are given in brackets. Bold numbers (asterisk) mark correlations exceeding the 95% (99%) significance thresholds (also shown for each case; see section 2).

unrelaxed regions (details are given in *Jung et al.* [2010a, 2010b]). The model experiments are as follows:

[7] 1. CLIM-NO: The model sees climatological SST and sea-ice (SSTSI) at the lower boundary and no relaxation is used. Each year is distinguished only by the initial conditions.

[8] 2. OBS-NO: The model sees observed SSTSI from the ERA-40 reanalysis at the lower boundary and no relaxation is used.

[9] 3. CLIM-TROPICS: Climatological SSTSI is specified at the lower boundary and relaxation is used between 20°N and 20°S throughout the whole depth of the model atmosphere.

[10] 4. OBS-TROPICS: Observed SSTSI is specified at the lower boundary and relaxation is used between 20°N and 20°S as in CLIM-TROPICS. Since the relaxation completely overwhelms the observed SST in the tropics, this experiment tells us the additional information gained, compared to CLIM-TROPICS, by specifying the observed SSTSI in the extratropics.

[11] 5. CLIM-STRAT: Climatological SSTSI is specified at the lower boundary and relaxation is used in the stratosphere (globally, including the tropics). A concern regarding CLIM-STRAT is the quality of the ERA-40 reanalysis prior to the satellite era. We note, however, that the reanalysis provides a dynamically consistent representation of the stratosphere using a model that is very similar to the model used here. We think, therefore, that influences from the stratosphere reported in section 3 are, at least, consistent with the ECMWF model dynamics. Also, comparison of the SAM index for DJF derived from the ERA-40 reanalysis with the

station-based index of *Visbeck* [2009] and also the NCEP reanalysis shows good agreement, especially after 1970.

[12] Throughout this paper “anomalies” for a particular experiment refer to departures of the ensemble mean or individual ensemble members from the mean winter state of the same experiment, the winter mean being the average over all ensemble members and all years comprising the experiment.

2.1. Definitions used for the NAO, SAM and PNA

[13] We define the NAO as the first Empirical Orthogonal Function (EOF) of the winter mean Z500 anomalies taken from the ERA-40 data applied to the region 30°N–80°N and 90°W–40°E. This is similar to the definition given in *Hurrell et al.* [2003] but using only the region north of 30°N to avoid intersecting the relaxation zone used in the tropical relaxation experiments. The NAO index is then the principal component time series of this EOF and one unit of the index refers to one standard deviation departure from 0 (positive index corresponding to enhanced westerly winds over the northern North Atlantic). To obtain NAO indices from the model results, winter mean anomalies from the model are projected on to the spatial pattern associated with the NAO in the ERA-40 data and normalised by the standard deviation of the index derived from the reanalysis. The SAM indices are derived in the same way, with the SAM defined as the first EOF of austral summer (DJF) mean Z500 anomalies over the region 90°S–30°S. For the PNA index, we use minus the area-weighted average of winter mean Z500 anomalies in the North Pacific sector (the region 30°N–65°N and 160°E–140°W, following *Trenberth and Hurrell* [1994]) normalised by the standard deviation of the time series (positive index corresponding to a deepened Aleutian low). The PNA index for the model experiments is defined in the same way, except that the time series is normalised by the standard deviation of the index from the reanalysis.

2.2. Statistical analysis

[14] We illustrate the method for the case of the NAO index (same procedure for the other indices). We first compute the time series of the ensemble mean NAO index from each model experiment. We then compute running trends in the ensemble mean index on a range of different time scales focusing here, for illustrative purposes, on time scales of 11, 21 and 31 years (we also considered intermediate time scales; these results are mentioned as appropriate in what follows). We then compare the time series of these running trends with the time series of the same running trends in the NAO index from the reanalysis by computing the correlation between the two time series, ensemble mean versus reanalysis.

[15] To test the significance of the correlation for a particular model experiment, we choose 12 artificial time series for the NAO index by randomly selecting (without replacement) 42 values (one representing each year) 12 times from the $12 \times 42 = 504$ values available from all model runs comprising the model experiment. An ensemble mean NAO index is then computed from the 12 selected values corresponding to each year and the running trends are computed from this index. The time series of running trends is then correlated with the time series of running trends from the reanalysis index. The process is repeated a large (typically 10,000) number of times and a histogram of the correlation values is computed to produce the probability density

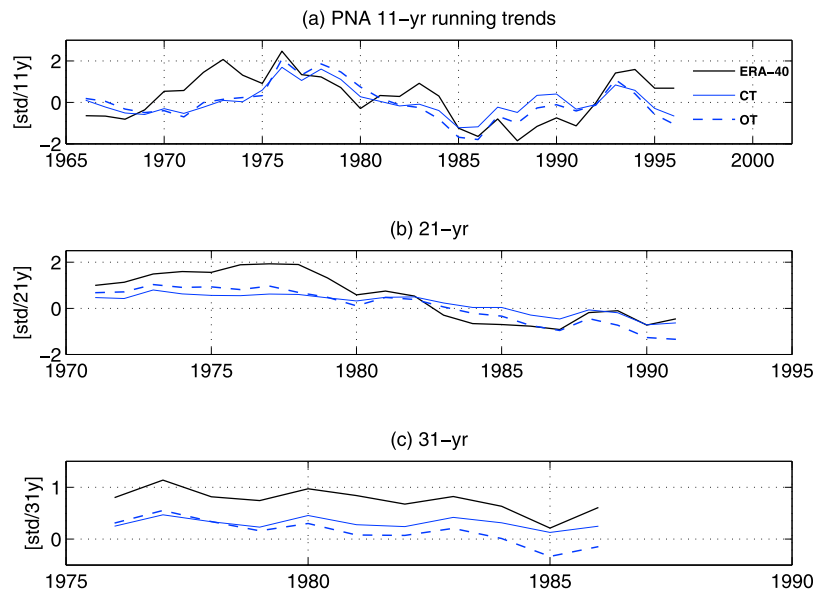


Figure 1. Time series of selected (a) 11, (b) 21 and (c) 31 year running trends for the PNA index plotted against the centre year of each trend period. The time series derived from the reanalysis is shown in black (ERA-40), from the ensemble means of CLIM-TROPICS in blue (CT) and OBS-TROPICS as blue-dashed (OT).

function (PDF) of the correlation values. The resulting PDF is centred around zero correlation and significance levels can be derived by calculating the correlation ranges corresponding to percentiles. For example, the 95% range is defined so that 95% of all values sit within this range centred on the median value. The significance of the correlation between the time series of the running trends in the real ensemble mean NAO index and the time series of running trends in the reanalysis index can then be assessed by noting into which percentile the correlation falls. In the following, when we say that a correlation is significantly different from zero at the 95% level we mean that the correlation is found outside the 95% range (likewise for 99%). Since we shuffle the years in the above analysis, there is an assumption that autocorrelation is weak in the starting time series we use to create the running trends. It follows that serial correlation associated with memory from one year to the next, although not of serious concern for the NAO, PNA or the SAM, will raise the significance thresholds slightly and should be born in mind when interpreting the correlations listed in Table 1.

3. Results

[16] We begin with the PNA index. Figure 1 shows time series of running trends (time scales of 11, 21 and 31 years) derived from those ensemble mean time series that are the most highly correlated with the time series of running trends in the reanalysis index (see Table 1 where the correlations for all model runs and all the indices are given). Consistent with previous studies [e.g., Trenberth and Hurrell, 1994; Trenberth et al., 1998], a strong influence from the tropics is found over a wide range of time scales. On the 11 year time scale, the running trends in both CLIM-TROPICS and OBS-TROPICS have similar amplitude to those of the reanalysis time series (despite being for the ensemble mean indices) and also show similar variability, indicating the strong

tropical influence on the PNA (see also *Greatbatch et al.* [2012]). For 21 and 31 year running trends, the amplitude of the trends in the model is lower than in the reanalysis. Nevertheless, the tropics remains influential even on the 31 year time scale. Overall, these results for the PNA are consistent with expectations and provide reassurance that our analysis technique is robust.

[17] For the NAO (Figure 2), the amplitude of the trends from the ensemble mean indices is noticeably reduced compared to those in the reanalysis index indicating a reduced influence from the imposed forcing compared to that we see in Figure 1 for the PNA. Previous studies have suggested an important influence from the stratosphere [*Scaife et al.*, 2005; *Douville*, 2009], as can be seen here on the 11 and especially 21 year time scale running trends. Running trends in OBS-TROPICS are also significantly correlated with the observed running trends on 11 year time scales (also on 15 year running trends, not shown). Since the same does not hold for CLIM-TROPICS, we can conclude that there is a significant influence from extratropical SSTSI on trends in the NAO on the 11 year time scale in the model. Since SSTSI is itself forced by the NAO on interannual time scales [e.g., *Cayan*, 1992; *Greatbatch*, 2000; *Visbeck et al.*, 2003] these results suggest a positive feedback from the extratropical oceans on 11 year trends in the NAO, an influence that is not significant on 21 year trends or, indeed on longer time scale trends. The lack of influences (e.g., from the tropics), other than from the stratosphere and extratropical SSTSI, is consistent with trends on 11 and 21 year time scales in the NAO being largely associated with internal atmospheric variability. On the 31 year time scale, no case is found to give results that are statistically significant above the 95% level, although the ensemble mean trends from CLIM-TROPICS are almost significant at the 95% level (see Table 1), suggestive of influence from the tropics. Indeed, *Greatbatch et al.* [2012] previously noted the importance of tropical forcing on the NAO trend over

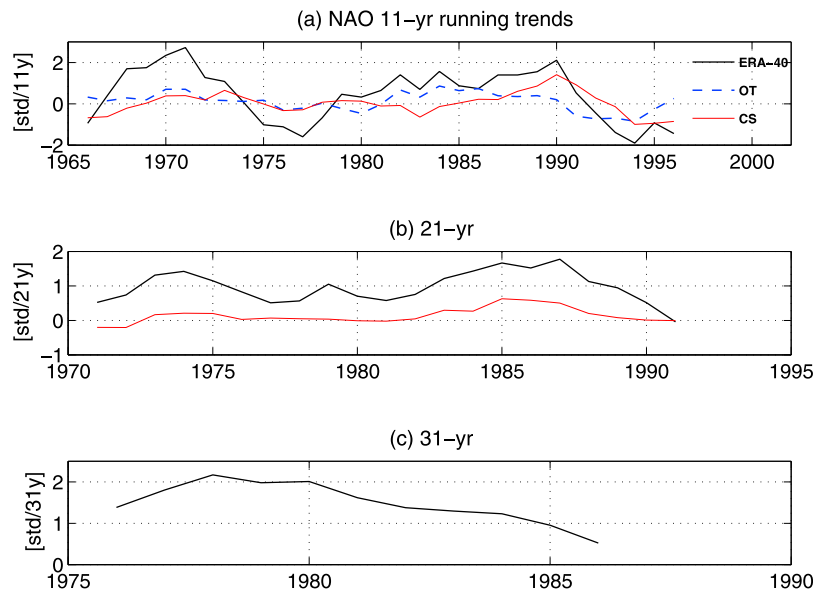


Figure 2. As Figure 1 but for the NAO. The time series for CLIM-STRAT are shown in red (CS).

both the full 42 year period, 1960/61–2001/02, and the 31 year subperiod 1964/65 to 1994/95, although the stratosphere was also found to play a role on the trend over the subperiod 1964/65–1994/95, consistent with *Scaife et al.* [2005] and *Douville* [2009], be it with reduced amplitude compared to those studies.

[18] Figure 3 shows time series of selected running trends for the SAM index. While the amplitude of trends

in the model are generally smaller than in the reanalysis time series, the difference is less striking than is the case for the NAO, indicating the importance of the imposed forcing. Striking is the different character of the time series before and after 1980, possibly related to the introduction of satellite data. Nevertheless, what is new here is the clear influence from the tropics (as seen in experiments CLIM-TROPICS and OBS-TROPICS) on 11 and 21 year

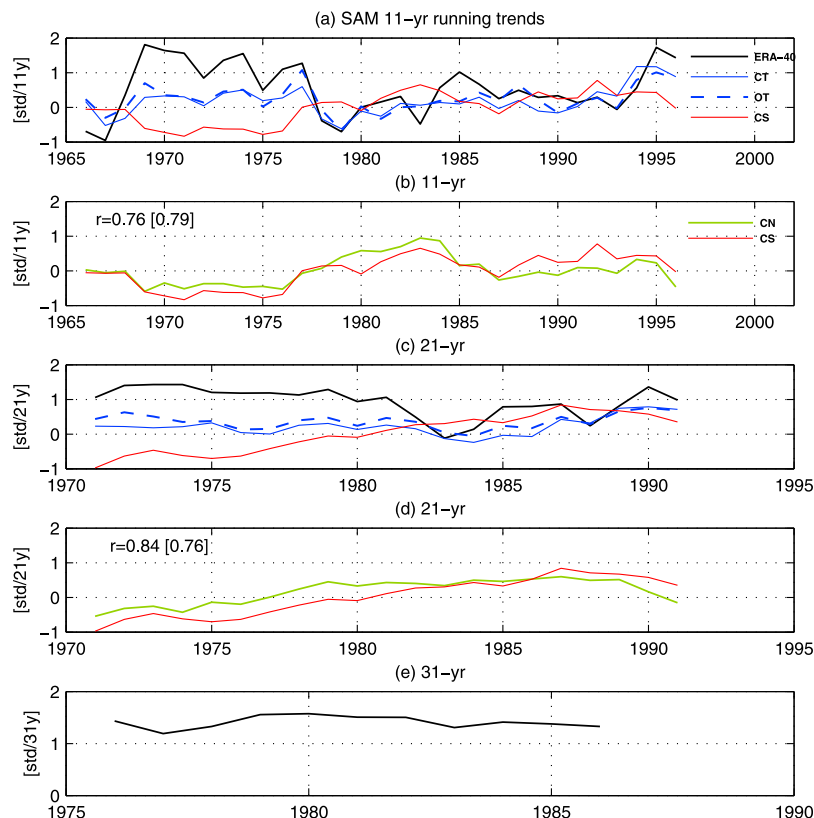


Figure 3. (a–e) As Figure 1 but for the SAM. In Figures 3b and 3d, the time series from CLIM-NO is shown in green (CN) and from CLIM-STRAT in red (CS) together with the correlation between the two time series (detrended in brackets).

trends. Influence from the tropics on the SAM on inter-annual time scales has been noted before by *L'Heureux and Thompson* [2006], among others, and is consistent with our results. Influence from the stratosphere, on the other hand, is somewhat ambiguous in our model experiments. The ensemble mean from CLIM-STRAT has time series of trends that are negatively correlated with those from the reanalysis (Table 1). For the 11 year time scale, this is particularly evident before 1980, as can be seen in Figure 3a, and for 21 year trends the negative correlation can be seen visually in Figure 3c. It is not clear whether the negative correlation indicates a dynamical influence from the stratosphere or whether it is spurious; for certain, the negative correlation reduces markedly after 1980 when there is an impact from satellite data on the reanalysis, suggesting that the negative correlation over the whole study period might not be robust. Interestingly, the time series of the 11 and 21 year running trends from CLIM-STRAT are highly correlated with those from CLIM-NO (Figures 3b and 3d) and both show positive trends after 1980, especially for 21 year trends. The high correlation results from the long memory in the stratosphere in summer [see *Simpson et al.*, 2011, Figure 2a] and note that in CLIM-NO the memory is of the stratospheric initial conditions from the previous November, the only information that distinguishes one summer from the next). The agreement between the results for CLIM-NO, in which no relaxation is used, and CLIM-STRAT (both before and after 1980) provides confidence that CLIM-STRAT correctly represents the influence of the stratosphere on the tropospheric SAM in the model. The switch to positive trends in both CLIM-STRAT and CLIM-NO after 1980 is consistent with expectations based on forcing from ozone depletion [e.g., *Thompson et al.*, 2011]. It is clear, however, that other factors, notably forcing from the tropics, are influential on the reanalysis trends, even after 1980. For 31 year trends, no case considered here is found to have a significant correlation with the observed trends (Table 1). When looking separately at the trend over the full 42 year period, only forcing from the tropics is found to be important (not shown here) and when looking at the trend from 1980 to the end of the record, all model experiments exhibit a trend that projects strongly on the positive SAM (again not shown).

4. Summary

[19] We have used a novel statistical technique to analyse trends in the boreal winter mean atmospheric circulation in ensemble experiments carried out using the ECMWF model. For the PNA, the tropics emerges as the most important influence, consistent with expectations and providing reassurance that our analysis technique is robust. We also find that forcing from the tropics is influential on trends in the SAM, while the role of the stratosphere is somewhat ambiguous despite consistency between our results and the commonly held view that recent trends in the austral summer SAM are a consequence of stratospheric ozone depletion during the southern hemisphere spring [e.g., *Thompson et al.*, 2011]. For the NAO, the stratosphere is found to be important for trends on time scales of 11 and especially 21 years and there is also evidence of a positive feedback from the extratropical SSTSI on 11 year trends for the NAO. We argue that these results are consistent with NAO trends on 11 and 21 year time scales being largely the result of internal

atmospheric variability. For longer time scale trends in the NAO, we argue that there is influence from the tropics.

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