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Is the Antarctic oscillation trend during the recent decades unusual?

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Abstract: The Antarctic oscillation (AAO) has been characterized by a persistently positive trend in summer (December–January–February, DJF) during the last 50 years. Thus, the question has arisen of whether the trend is unusual. By investigating five reconstructed historical AAO time series for the past 500 years, recurrences of similar and even stronger trends have been found, indicating that the recent DJF AAO trend is not unprecedented in a historical perspective. To estimate the possible roles played by greenhouse gases or/and ozone, an analysis for DJF AAO trends during the 1969–98 period was conducted using three multiple model ensembles derived from the projects of 'The twentieth-century climate in coupled models' (20C3M) and 'Pre-industrial control experiment models' (PICTL) of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4). The results show that the ozone depletion over Antarctica and global warming may play significant roles in the strengthening trend. Combining the simulations and reconstructions we emphasize that the AAO trend related to global warming may get much stronger when enhanced by low-frequency natural variability.

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Introduction

The Antarctic oscillation (AAO), also known as the Southern Annular Mode, is the dominant mode of extratropical atmospheric circulation in the Southern Hemisphere and is characterized primarily by zonal symmetry (Gong & Wang 1999, Thompson & Wallace 2000). The annular structure is not only present in the sea level pressure (slp) field, but it also dominates the geopotential height, air temperature, and zonal wind fields through the troposphere and the lower stratosphere. The AAO not only plays an important role in climate change over Antarctica and the Southern Ocean, but also over New Zealand, Patagonia and Australia (Thompson *et al*. 2011).

Based on observation and reanalysis data, a significant positive trend of the AAO in recent decades has been reported, with the largest trends being detected in summer (December–January–February, DJF) (Fyfe *et al*. 1999, Marshall 2003). Thompson & Wallace (2000) and Kushner *et al*. (2001) have shown that the increase of greenhouse gas concentrations can lead to a positive trend of the AAO. Thompson & Solomon (2002) and Gillett & Thompson (2003) proposed that the strengthening of the AAO could be attributed to Antarctic stratospheric ozone depletion caused by anthropogenic halogens. Using an atmosphere–ocean general circulation model, Shindell & Schmidt (2004) showed that the combined effect of greenhouse gas increases and ozone depletion over Antarctica led to significant positive trends in the AAO. They further indicated that the combined effects of ozone recovery and greenhouse gas increases would result in no obvious AAO trend because the two would effectively balance each other out.

These attribution studies paid much attention to the anthropogenic forcings. Some studies have also indicated that the interannual variability, or even trend, of the AAO may be teleconnected to the tropical ocean sea surface temperature (Zhou & Yu 2004, Grassi *et al*. 2005, Ding *et al*. 2012, Greatbatch *et al*. 2012). Moreover, other natural factors (e.g. solar activity or volcanic eruptions) may also influence the variability of the AAO (Kuroda & Kodera 2005). To make a more reliable projection of future AAO, and to better understand whether the recent AAO trend is unusual or not, the natural variability should be assessed. The main purpose of this study is to evaluate the AAO trends in the context of historical reconstructions of AAO time series. Here we are concerned with a key issue: are there occurrences of strong AAO trends in historical periods which are comparable to the trend in recent decades?

Data and methods

Several summer AAO indices (DJF AAO) derived from observation and reanalysis data are used in the study, including a station-based Marshall-AAO index observed from 1958 (Marshall 2003), an NCEP/NCAR-AAO index derived from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) reanalysis data records beginning in 1949 (Kalnay *et al.* 1996), an ERA40/Interim-AAO index derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) and ERA-Interim reanalysis data covering the period from 1958–2011 (Uppala *et al.* 2005, Dee *et al.* 2011), and a HadSLP-AAO index derived from the Hadley Centre HadSLP dataset covering the period from 1851–2004 (Allan & Ansell 2004). Although HadSLP data was updated to 2011 in HadSLP2r, the variance in the latter product is greater than that of the former, thus, the slp data after 2004 were not used to avoid discontinuity in the AAO series. Note that for all grid datasets (e.g. reanalyses, HadSLP and models) the time series corresponding to the first eigenvector from the empirical orthogonal function (EOF) analysis of the area-weighted mean sea level pressure (mslp) were defined as the AAO indices. When performing

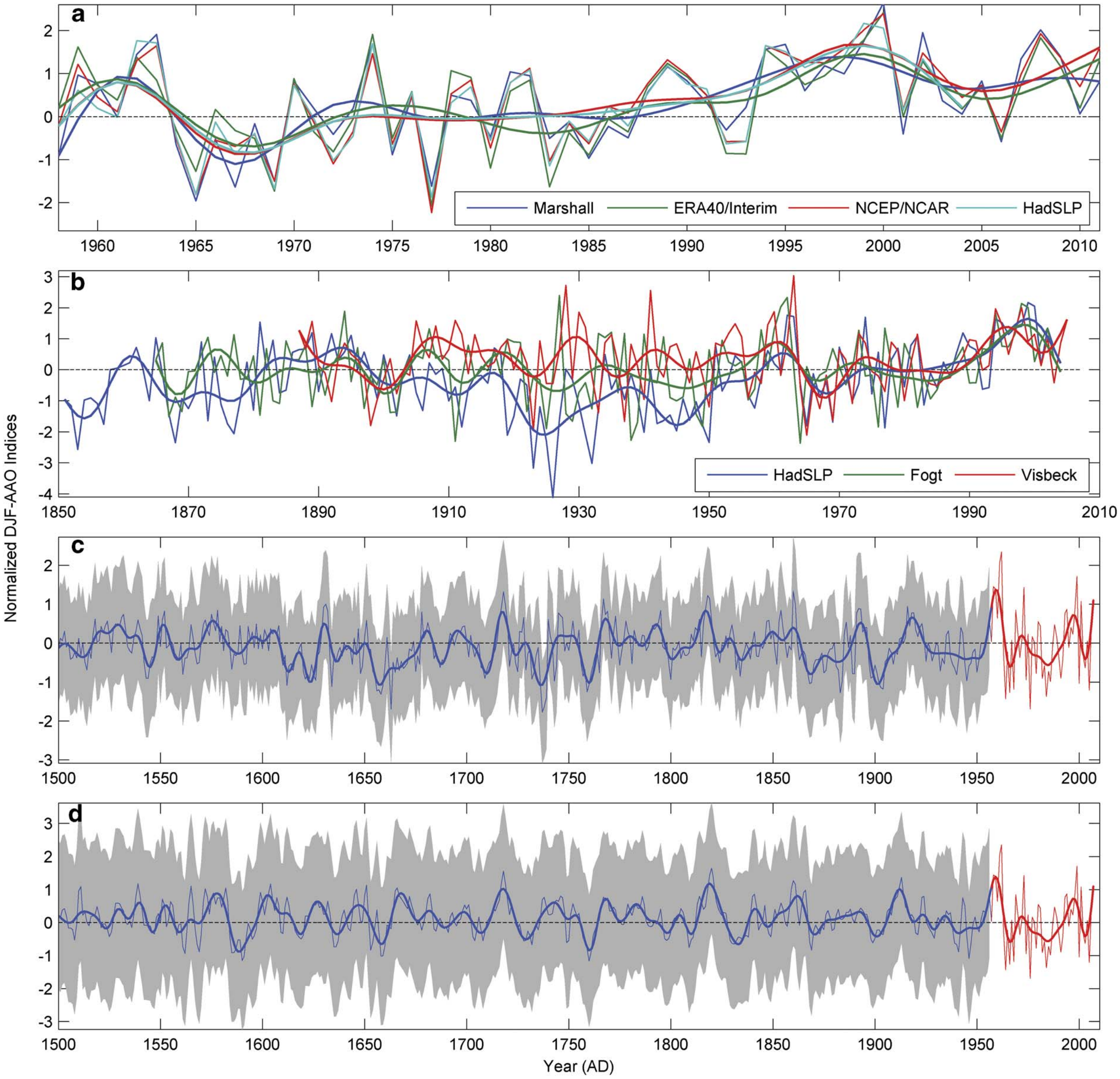

Fig. 1. a. Observed December–January–February Antarctic oscillation (DJF AAO) indices since 1958. **b.** Sea level pressure (slp)-based DJF AAO indices since 1850s. **c.** Principal component reconstruction method (PCR-recon) DJF AAO indices since 1500. **d.** Composite plus scale reconstruction method (CPS-recon) DJF AAO indices since 1500. All the series are normalized with respect to the period 1961–90. The smoothed lines denote low-frequency (> 10 years) variations from a Butterworth filter. Shading indicates the range of ± 2 x standard error derived from the unresolved variance in the calibration period in c. and d. DJF in 1958 denotes December 1957, January 1958 and February 1958.

Table I. Linear trends of December–January–February Antarctic oscillation (DJF AAO) indices in different periods (unit is σ 10 years^{-1}, all the series are normalized with respect to the period 1961–90).

	Marshall	ERA40/Interim	NCEP/NCAR	HadSLP	Fogt	Visbeck
1958–2011[#]	0.24 ± 0.008**	0.18 ± 0.008*	0.28 ± 0.008**	0.28 ± 0.010**	0.12 ± 0.012	0.18 ± 0.010*
1980–2011	0.34 ± 0.016*	0.45 ± 0.017**	0.42 ± 0.015**	0.57 ± 0.022**	0.58 ± 0.021**	0.54 ± 0.018**
1970–2000	0.46 ± 0.017**	0.45 ± 0.021**	0.60 ± 0.018**	0.56 ± 0.018**	0.47 ± 0.017*	0.38 ± 0.015**

**Significant at 0.01 level, *significant at 0.05 level, based on a two-tailed student's t-test. ± standard error. [#] The HadSLP-AAO, Fogt-AAO and Visbeck-AAO end in 2004, 2004 and 2005, respectively.

EOF analysis all available data are utilized for the observational datasets (including the reanalyses and HadSLP data). For the model datasets, the EOF analysis period is confined to 1900–98. Several reconstructed AAO indices were also used here including a Fogt-AAO index covering 1865–2004 (Fogt *et al*. 2009), a Visbeck-AAO index covering 1887–2005 (Visbeck 2009) and two other multiple-proxy based AAO indices which focused on interannual to interdecadal variability (< 50 years) and extended back to 1500 AD (Zhang 2010, Zhang *et al*. 2010). To facilitate understanding the process of the multiple-proxy based reconstructions, a compressed file is given in Appendix A (which can be found at http://dx.doi.org/10.1017/S0954102013000734). All the AAO series were normalized with respect to the base period of 1961–90. In addition, a Monte Carlo test was performed by randomly sampling proxies in reconstructions to evaluate the uncertainty in the reconstructed AAO trend estimation.

To compare the historical AAO variability with the trend caused by anthropogenic forcing (mainly greenhouse gases and ozone), we analysed the simulation outputs from 24 global-coupled general circulation models (GCMs). These model experiments were designed for the projects of 'The twentieth-century climate in coupled models' (20C3M) and 'Pre-industrial control experiment models' (PICTL) of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4) (Solomon *et al*. 2007). Details about the models are given in Appendix B, including the list of models and three group ensembles (http://dx.doi.org/10.1017/S0954102013000734).

Results

Observed Antarctic oscillation trends

Several DJF AAO indices derived from observed data and reanalysis slp data are displayed in Fig. 1a. Generally speaking, these AAO indices from different sources show consistent year-to-year variability over the entire period. Their similarities are evident as suggested by the co-variations in the overlapping periods. For example, a low point that occurred in 1977 appears in most of the AAO indices and a high event that occurred in 2000 is manifest in these time series. Generally, there are more positive AAO events after the 1980s.

The smoothed lines in Fig. 1a denote the interdecadal variations (> 10 years) of each AAO index during the last 50 years. There is an obvious positive phase in the early 1960s which is consistent with the series in Jones & Widmann (2004), and another significant positive phase occurred in the mid-1990s. From the mid-1960s to 2000s, the station-based Marshall-AAO shows a positive trend. The persistent increasing trends are also evident for the other three AAO model-based records (Fig. 1a). The linear trends of each DJF AAO index over different periods are estimated and shown in Table I. It is clear that the summer AAO has undergone a strengthening since the 1960s, and the most intense enhancement occurred from the mid-1980s to the end of the 1990s. Although the linear trend varies from a minimum 0.34 σ 10 years^{-1} to a maximum of 0.58 σ 10 years^{-1} during the period 1980–2011, the trends for six different AAO series are all significant at the 0.05 level. Similar conditions can also be found for the period 1970–2000. The positive increasing trends described here are basically consistent with several previous studies.

Trends and interdecadal variations of the December–January–February Antarctic oscillation in reconstructions

As mentioned in the previous section, the DJF AAO during the last 50 years is characterized by significant positive trends, especially in the 1980–2000 period. We wish to assess whether the trend over the last several decades is unusual from a long-term perspective. We show five reconstructed DJF AAO indices in Fig. 1b–d, including Visbeck-AAO, Fogt-AAO, HadSLP-AAO, and two optimal reconstructions of AAO conducted by Zhang (2010) and Zhang *et al*. (2010). These are labelled as PCR-recon (by using the principal component reconstruction method) and CPS-recon (by using the composite plus scale reconstruction method). The latter two optimal reconstructions were based on multiple proxies distributed widely in the Southern Hemisphere (including tree rings, corals and ice cores) and extend back to 1500 AD. Both the PCR-recon and CPS-recon AAO time series focused only on the interannual to interdecadal components (< 50 years). In historical periods, there are apparent differences among these reconstructed AAO indices on both interannual and interdecadal time scales (see Appendix A, http://dx.doi.org/10.1017/S0954102013000734). The AAO time series inevitably contains uncertainty, whether the AAO is based on multiple proxies or slp (Jones *et al*. 2009, Visbeck 2009, Zhang 2010). However, the statistics for the multiple-proxy optimal reconstruction indicate that more skilful proxies used in reconstruction would be helpful to reduce the uncertainty or error. For example, with the available proxy increases from 41 in the period of 1500–1518 to 263 in the period of 1894–1956, the standard error (s.e.) of the CPS-recon (shading in Fig. 1c) decreases from 1.14 to 0.97, respectively. For the PCR-recon (shading in Fig. 1d) the s.e. decreases from 0.79 to 0.50. Generally, the multiple-proxy based DJF AAO indices since 1500 AD

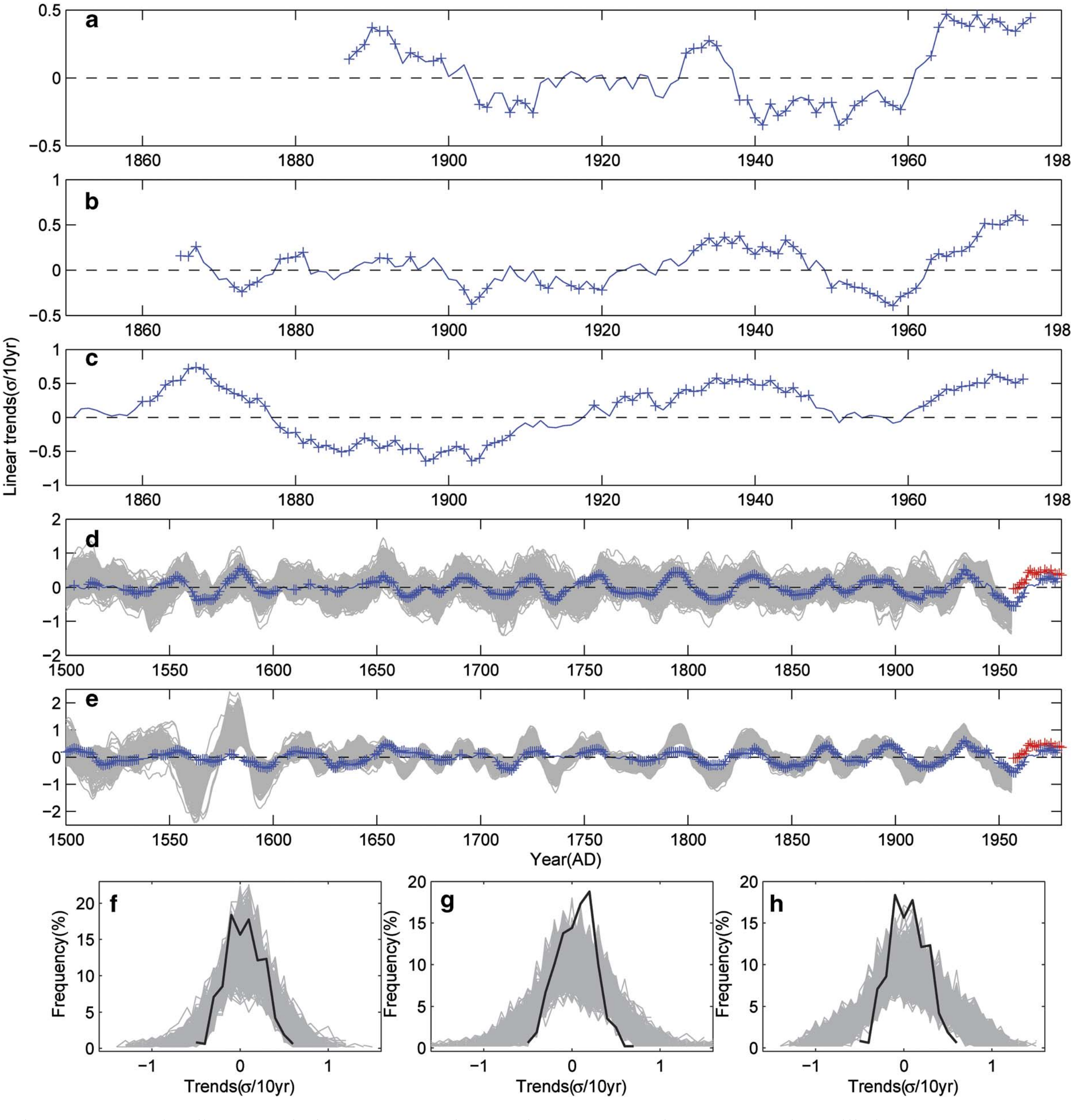

Fig. 2. The 30-year running linear trends for reconstructed December–January–February Antarctic oscillation (DJF AAO) series. **a.** Visbeck-AAO. **b.** Fogt-AAO. **c.** HadSLP-AAO. **d.** Principal component reconstruction method (PCR-recon). **e.** Composite plus scale reconstruction method (CPS-recon). The red lines in d. and e. denote the 30-year running trends derived from the raw (not filtered) AAO series. Trends significant at the 0.05 level are marked by the cross for all trend lines. The frequency of 30-year trends for 1000 Monte Carlo reconstructions. **f.** For PCR from randomly sampling proxies. **g.** For CPS from randomly sampling proxies. **h.** For PCR from randomly sampling time coefficients of the principal component analysis (PCs). The black lines in f.–h. denote the corresponding trends from the optimal reconstructions.

are skilful and reliable according to the s.e., reduction of error and other statistics (see Appendix A, http://dx.doi.org/10.1017/S0954102013000734).

Figure 2 presents the 30-year running linear trends of the five reconstructed DJF AAO indices. The Visbeck-AAO, Fogt-AAO and HadSLP-AAO indices have experienced persistent positive trends since the 1960s, and exhibited negative trends in the 1950s, though the evolutions of the three curves are not consistent before the 1920s. Moreover, the positive trends of the Visbeck-AAO index (Fig. 2a) in the 1890s are close to the trends found since the 1960s. The positive trends of the HadSLP-AAO index (Fig. 2c) in the 1870s and from 1930 to the 1940s are close to or higher than the trends in the period since the 1970s. Taking the PCR-recon (Fig. 2d) and CPS-recon (Fig. 2e) DJF AAO series over last 500 years into account, it is clear that, under the half-century timescale (< 50 years), all of the positive trends of PCR-recon in the 1650s, 1870s, 1890s and 1940s, and of CPS-recon in the 1580s, 1650s, 1750s, 1790s, 1830s and 1940s are greater than the trends during 1970–2000, which are near or exceed $0.4\ \sigma\ 10\ \text{years}^{-1}$. Moreover, comparing the trends derived from the raw Marshall-AAO series (not filtered, the red crosses in Fig. 2d & e) with PCR-recon and CPS-recon, we find that, even though the trends of the raw AAO series are slightly larger than filtered values, the highest value is still not beyond the maxima of the optimal reconstruction trend. Thus, it can be concluded that the intense positive trends of the DJF AAO

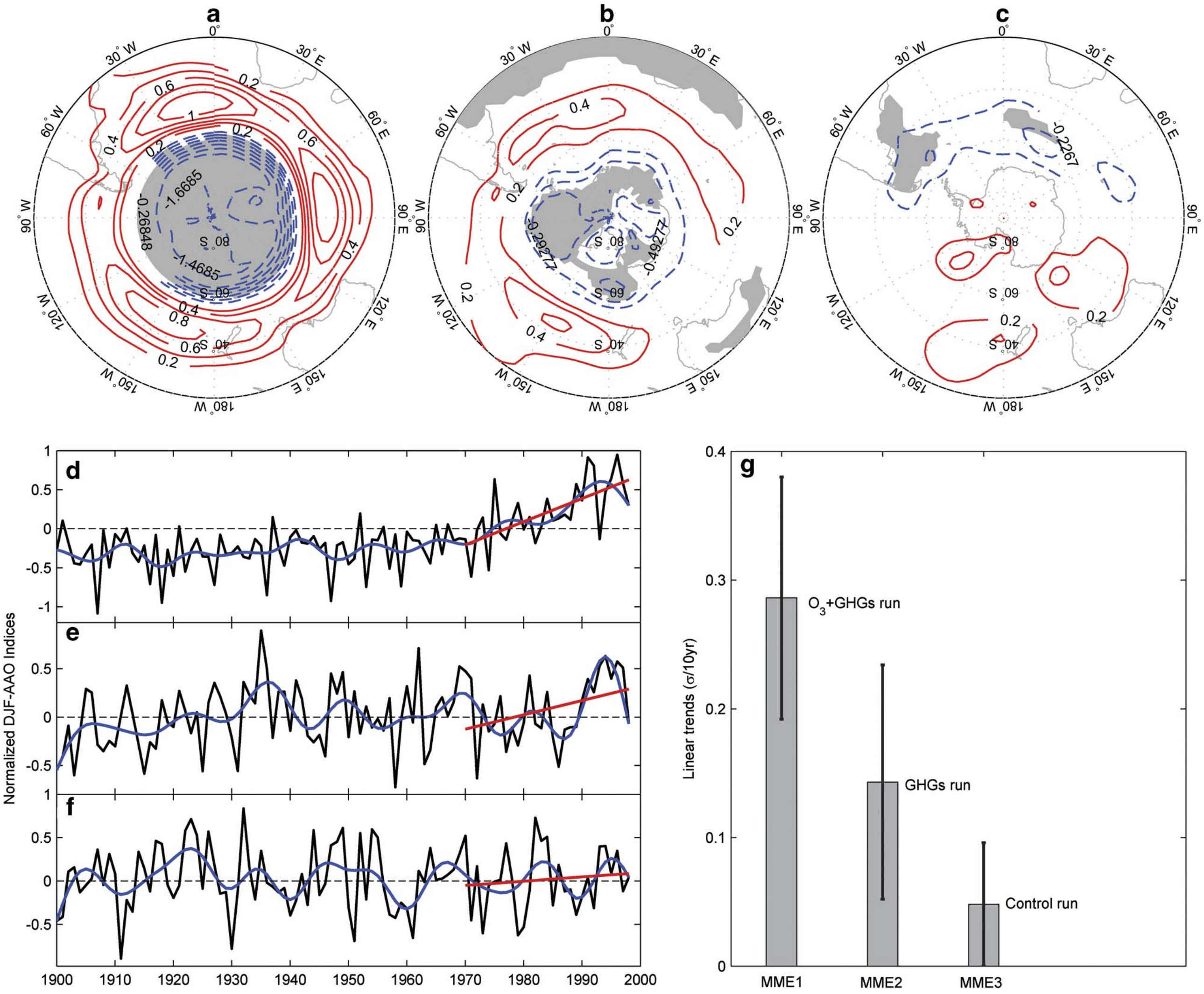

Fig. 3. The differences of sea level pressure (slp) (1969–98 minus 1901–30). **a.** Multi-model ensemble 1 (MME1). **b.** MME2. **c.** MME3. Areas significant at the 0.05 level are shaded. The corresponding time series of AAO. **d.** MME1. **e.** MME2. **f.** MME3. Time series are normalized with respect to the base period of 1961–90, the smoothed lines denote low-frequency (> 10 years) variations from a Butterworth filter, and the red lines indicate linear trends during 1969–98. **g.** The means of the linear trends plus the error bars (one standard error) for 1969–98.

on the 30-year timescale have occurred not only in the past 150 years but also occurred in the past 500 years. This implies that the persistent positive trend of the DJF AAO since the 1970s is unlikely to be unprecedented from a historical perspective.

The uncertainty of the reconstructions may exaggerate or bias the trend estimations. We investigated this issue and performed multiple AAO reconstructions through Monte Carlo simulation. Here we take into account two kinds of data sampling. One is proxy data sampling and the other is PC (time coefficients of the principal component analysis, PCA) sampling. The proxy sampling test was performed for both PCR and CPS. In these multi-reconstructions, we firstly re-sample the original proxy data by 1000 times. To harness as much information as possible, we confine the number of proxy candidates to being the maximum (i.e. varying between 236 and 262). Based on each set of re-sampling data, the PCR reconstruction and CPS reconstruction are conducted respectively. Then the 30-year running linear trends of each AAO series were examined and plotted as the frequency distribution in Fig. 2f & g. As expected, the AAO series from Monte Carlo simulations show larger variability than the optimal PCR-recon and CPS-recon. The maximum increasing trends of DJF AAO index from Monte Carlo simulation are generally greater than the optimal PCR-recon. There are only 23 simulations showing smaller maximum linear trends than the optimal reconstruction. For the Monte Carlo CPS simulations, all maximum linear trends are larger than the maximum trend of the corresponding optimal AAO. Additionally, we repeated PCR but re-sampling the PCs. According to the proxy data availability, we divided the whole reconstruction period into 150 segments. Given a segment, all available proxies were utilized for PCA analysis. Then the Monte Carlo simulation was performed by randomly selecting PCs. As we did in the optimal reconstruction, only the significant PCs are considered. Note that in the early period the number of proxy is lower, to successfully re-sample 1000 times we intently selected more PC candidates which meet a slightly lower significance level than the later periods. The running trends are shown in Fig. 2h. The probability distribution is similar to that derived from proxy re-sampling simulations. There are much broader tails on both the positive and negative sides of the distribution than for the optimal reconstructions. This implies that the possibility of the maximum trends in our optimal AAO reconstructions exceeding the maximum trends of the re-sampling reconstructions is very low.

Trends and interdecadal variations of the December–January–February Antarctic oscillation in modelling

To investigate the possible contributions of anthropogenic forcings to the positive trend of the DJF AAO over the past several decades, three group multi-model ensemble (MME1, MME2, MME3) mslp fields obtained from the 20C3M and PICTL simulations were developed. Only the first runs of each model were used, and an ensemble denotes the average of a group of models. MME1 is an ensemble of 14 models from the 20C3M scenario, in which the experiments were run with the time-varying greenhouse gases (GHGs) and ozone (O_3) concentration as observed during the twentieth century (denoted as O_3+GHGs run). MME2 is an ensemble of ten model runs forced by only time-varying greenhouse gases (GHGs run). MME3 is an ensemble of eight models from the PICTL runs forced with constant pre-industrial levels of greenhouse gases and ozone (control run).

The differences of mslp climatology in the late nineteenth century (1969–98) and early twentieth century (1901–30) for summer are shown in Fig. 3. The slp difference in each case can be regarded as the results of the greenhouse gas or ozone and greenhouse gas increment. In Fig. 3a & b, the increment of greenhouse gases for MME1 and MME2 is the same between the two analysis periods; the only forcing difference between Fig. 3a & b is the ozone increment. Similarly, the difference between Fig. 3b & c should be related to the greenhouse gases increment. Therefore, their slp differences are suggestive of ozone and greenhouse gas forcings. In the GHGs run, the positive and negative mslp anomalies dominate in the mid-latitudes and high latitudes, respectively. This pattern of pressure indicates that GHGs play a role in strengthening AAO over the twentieth century. In the O_3+GHGs run, the spatial feature is similar but with much larger values, suggesting that ozone and greenhouse gases are both effective at enhancing the positive AAO trend. The control run (Fig. 3c) does not show an obvious AAO feature suggesting that AAO trends cannot be simulated without varying greenhouse gases or/and ozone concentration.

The normalized DJF AAO indices derived from the three group simulation ensembles are shown in Fig. 3d–f. There are distinct interdecadal variations in all three MME AAO series. The linear trends are evident for the GHGs and O_3+GHGs runs, especially during the last several decades. During 1969–98 the linear trends of MME1 and MME2 are 0.29 σ 10 years^{-1} and 0.14 σ 10 years^{-1}, respectively. In contrast, MME3 shows no evident trend (only a value near zero). We note that the ozone and greenhouse gas forced trend in the IPCC AR4 simulations is approximately 63% and 85% of the trend of station-based Marshall Index for 1970–2000 and for 1980–2011, respectively. This suggests that the anthropogenic forcing may dominate AAO trends in recent decades, although natural forcings, such as solar activity, may also play a role (Kuroda & Shibata 2006).

Conclusion

By comparing various AAO indices, the present study verified the robustness of the strengthening trend of the

DJF AAO in the last 50 years, especially in the last three decades of the twentieth century. However, the reconstructed AAO series based on slp records and multi-proxies demonstrate that similar or stronger positive trends have likely occurred in the last 500 years. Thus, we conclude that the strong AAO trend observed during the recent decades is unlikely to be unprecedented from a long-term perspective. Moreover, an analysis for model simulation of 20C3M and PICTL shows that the anthropogenic forcing of greenhouse gases and ozone could result in positive AAO trends, which are as strong as 63–85% of the observed magnitude. Within the context of global warming, it is possible that the trend of DJF AAO will become stronger in the future when the AAO trend is enhanced by low-frequency natural variations of the AAO. Combining the simulations and reconstructions, we warn that there is a risk that the AAO might become much higher when natural trends add to the anthropogenic trends.

Supplemental material

Supplemental material will be found at http://dx.doi.org/575 10.1017/S0954102013000734

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References

Allan, R. & Ansell, T. 2004. A new globally complete monthly historical gridded mean sea level pressure data set (HadSLP2): 1850–2004. *Journal of Climate*, **19**, 5816–5842.

Dee, D.P., Uppala, S.M., Simmons, A.J., *et al*. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137**, 553–597.

Ding, Q.H., Steig, E.J., Battisti, D.S. & Wallace, J.M. 2012. Influence of the tropics on the Southern Annular Mode. *Journal of Climate*, **25**, 6330–6348.

Fogt, R.L., Perlwitz, J., Monaghan, A.J., Bromwich, D.H., Jones, J.M. & Marshall, G.J. 2009. Historical SAM variability. Part II: twentieth-century variability and trends from reconstructions, observations, and the IPCC AR4 models. *Journal of Climate*, **22**, 5346–5365.

Fyfe, J.C., Boer, G. & Flato, G. 1999. The Arctic and Antarctic oscillations and their projected changes under global warming. *Geophysical Research Letters*, **26**, 1601–1604.

Gillett, N.P. & Thompson, D.W.J. 2003. Simulation of recent Southern Hemisphere climate change. *Science*, **302**, 273–275.

Gong, D.Y. & Wang, S.W. 1999. Definition of Antarctic oscillation index. *Geophysical Research Letters*, **26**, 459–462.

Grassi, B., Redaelli, G. & Visconti, G. 2005. Simulation of polar Antarctic trends: influence of tropical SST. *Geophysical Research Letters*, **32**, 10.1029/2005GL023804.

Greatbatch, R.J., Gollan, G. & Jung, T. 2012. An analysis of trends in the boreal winter mean tropospheric circulation during the second half of the 20th century. *Geophysical Research Letters*, **39**, 10.1029/2012GL052243.

Jones, J.M., Fogt, R.L., Widmann, M., Marshall, G.J., Jones, P.D. & Visbeck, M. 2009. Historical SAM variability. Part I: century-length seasonal reconstructions. *Journal of Climate*, **22**, 5319–5345.

Jones, J.M. & Widmann, M. 2004. Atmospheric science: early peak in Antarctic oscillation index. *Nature*, **432**, 290–291.

Kalnay, E., Kanamitsu, M., Kistler, R., *et al*. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**, 437–471.

Kuroda, Y. & Kodera, K. 2005. Solar cycle modulation of the Southern Annular Mode. *Geophysical Research Letters*, **32**, 10.1029/2005GL022516.

Kuroda, Y. & Shibata, K. 2006. Simulation of solar-cycle modulation of the southern annular mode using a chemistry-climate model. *Geophysical Research Letters*, **33**, 10.1029/2005GL025095.

Kushner, P.J., Held, I.M. & Delworth, T.L. 2001. Southern Hemisphere atmospheric circulation response to global warming. *Journal of Climate*, **14**, 2238–2249.

Marshall, G.J. 2003. Trends in the southern annular mode from observations and reanalyses. *Journal of Climate*, **16**, 4134–4143.

Shindell, D.T. & Schmidt, G.A. 2004. Southern Hemisphere climate response to ozone changes and greenhouse gas increases. *Geophysical Research Letters*, **31**, 10.1029/2004GL020724.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. 2007. *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 996 pp.

Thompson, D.W.J. & Solomon, S. 2002. Interpretation of recent Southern Hemisphere climate change. *Science*, **296**, 895–899.

Thompson, D.W.J. & Wallace, J.M. 2000. Annular modes in the extratropical circulation. Part I: month-to-month variability. *Journal of Climate*, **13**, 1000–1016.

Thompson, D.W.J., Solomon, S., Kushner, P.J., England, M.H., Grise, K.M. & Karoly, D.J. 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, **4**, 741–749.

Uppala, S.M., Kallberg, P.W., Simmons, A.J., *et al*. 2005. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, **131**, 2961–3012.

Visbeck, M. 2009. A station-based southern annular mode index from 1884 to 2005. *Journal of Climate*, **22**, 940–950.

Zhang, Z.Y. 2010. *The variability of Antarctic Oscillation and its relation to climate change during the last 500 years*. PhD thesis, Beijing Normal University, 183 pp. [Unpublished].

Zhang, Z.Y., Gong, D.Y., He, X.Z., Lei, Y.N. & Feng, S.H. 2010. Statistical reconstruction of the Antarctic Oscillation index based on multiple proxies. *Atmospheric and Oceanic Science Letters*, **3**, 283–287.

Zhou, T.J. & Yu, R.C. 2004. Sea-surface temperature induced variability of the Southern Annular Mode in an atmospheric general circulation model. *Geophysical Research Letters*, **31**, 10.1029/2004GL021473.