Projected effects of declining anthropogenic aerosols on the southern annular mode

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Abstract
Declining emissions of anthropogenic aerosols have been shown to contribute to global warming in climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5). This study considers the response of the southern annular mode (SAM) in austral summer to declining aerosols in simulations forced by Representative Concentration Pathway 4.5 (RCP4.5) using CSIRO-Mk3.6, a CMIP5-generation model. A ten-member ensemble forced by RCP4.5 for the period 2006–2100 is compared with another experiment, which is identical except that emissions of anthropogenic aerosols are held fixed at their 2005 values.

With fixed aerosol emissions, the model simulates a negative (but statistically insignificant) ensemble-mean SAM trend in austral summer, suggesting that the effects of recovering stratospheric ozone slightly outweigh the effects of increasing long-lived greenhouse gases (GHGs). In contrast, the standard RCP4.5 experiment (including additional warming due to declining aerosols) simulates a positive ensemble-mean SAM trend, and the difference between the two trends is significant at 5%. The response of Southern Hemisphere zonal-mean atmospheric circulation and temperature to declining aerosols resembles the response to increasing GHGs; this suggests that the positive SAM trend due to declining aerosols may be driven by mechanisms that are similar to those that cause the positive SAM trend in response to increasing GHGs.

Keywords: aerosols, climate change, southern annular mode, climate projection, CMIP5

1. Introduction
The southern annular mode (SAM) is the principal source of interannual variability in the mid- to high latitudes of the Southern Hemisphere (SH). It represents a ‘flip flop’ of mass between the mid-latitudes and the high latitudes. Closely linked to the SAM are meridional shifts of the mid-latitude westerly winds; these shifts are equivalent barotropic, and extend from the surface through much of the atmosphere (e.g., Karoly 1990). Thus questions about the long-term trend in the SAM are intimately linked to the poleward shift of mid-latitude westerly winds in response to increasing long-lived greenhouse gases (GHGs) (Fyfe et al 1999, Kushner et al 2001). Note that the dynamical mechanisms that cause such a response of the SH extratropical circulation to increasing GHGs are still a topic of active research (Lorenz and DeWeaver 2007, Lu et al 2008, Kidston et al 2011, Butler et al 2011, Allen et al 2012).

During the last few decades, there has been a positive trend in the SAM, especially in austral summer and autumn (Marshall 2003, Fogt et al 2009). The positive phase of the SAM is associated with positive anomalies of sea-level...
et al. This has been driven by stratospheric ozone depletion and strong surface westerlies. Modelling studies suggest that this has been driven by stratospheric ozone depletion and increasing GHGs. In summer, ozone depletion is thought to be more important than increasing GHGs (Shindell and Schmidt 2004, Arblaster and Meehl 2006, Polvani et al. 2011, Thompson et al. 2011). Trends in the SAM have been linked to important aspects of SH climate, such as precipitation (Meneghini et al. 2007) and CO₂ uptake by the Southern Ocean (Lenton et al. 2009), so it is important to understand the drivers of such trends.

Climate projections for the 21st century suggest that future SAM trends will represent a balance between negative changes induced by the recovery of polar stratospheric ozone, and positive changes induced by increasing GHGs, but the net effect is uncertain. Arblaster et al. (2011) showed that, for a given forcing scenario, the balance of these competing effects depends on climate sensitivity. Models with larger climate sensitivity gave a stronger positive change in the SAM due to increasing GHGs; this was shown to correlate with larger global-mean warming and larger increases in the temperature gradient between the tropics and SH high latitudes. The balance of these competing effects also depends on the forcing scenario: Eyring et al. (2013) compared simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and showed that SAM trends were more positive in the stronger GHG forcing scenarios (since stratospheric ozone forcing is similar in each scenario, whereas there are large differences in GHG forcing between the low and high scenarios).

Relatively little attention has been paid to the possible role of anthropogenic aerosols (AAs) as a driver of long-term trends in the SAM. Arblaster and Meehl (2006) found a weak negative (but statistically insignificant) annual-mean SAM trend during 1958–1999 in response to AA forcing. However, their model only treated direct aerosol effects, so the forcing was presumably weaker than in models that also include indirect aerosol effects; see discussion below. In an attribution study of extratropical SH summer precipitation, Fyle et al. (2012) found that the observed pattern of precipitation and sea-level pressure changes during 1957 to 2010 were substantially forced by increasing GHGs and decreasing ozone, with an opposing influence from increasing AAs in CanESM2, a CMIP5-generation model. Their sea-level pressure index implied a negative SAM-like response to forcing from AAs. In another CMIP5-generation model (CSIRO-Mk3.6, the model used in this study), Collier et al. (2013) found that increasing AAs during 1951–2010 caused a weakening of annual-mean zonal wind stress at sub-Antarctic latitudes (implying a negative AA-induced SAM trend). In an attribution study of sea-level pressure trends, Gillett et al. (2013) found a negative SAM trend during 1951–2011 in summer and winter due to forcing from AAs in three CMIP5 models; trends in autumn and spring were not statistically significant. Recently, Xie et al. (2013) compared aspects of the response of three CMIP5 models to historical forcing from GHGs and AAs individually; the ensemble-mean response to increasing AAs included a reduction of annual-mean wind speed at sub-Antarctic latitudes, suggesting a negative change in the SAM.

The studies cited in the previous paragraph generally suggest that the response of the SAM to increasing AAs is negative. A different view was presented by Cai and Cowan (2007), who compared historical simulations with and without increasing AAs in a low-resolution climate model. They identified changes in ocean circulation and a positive air–sea feedback that contributed to a positive annual-mean trend in the SAM due to increasing AAs.

Aerosol effects tend to be weaker in the SH than the Northern Hemisphere (NH), so it may seem counter-intuitive that AA changes can affect the SAM. However, the literature suggests some reasons why this might occur. There is evidence that a more positive SAM in response to increasing GHGs is associated with an increased meridional temperature gradient, both at the surface (Kushner et al. 2001, Cai et al. 2003) and near the tropopause (Lu et al. 2008, Wilcox et al. 2012). Aerosol radiative forcing is weak over the higher latitudes of the SH (Shindell et al. 2013), and this may contribute to changes in the meridional temperature gradient. Studies have also shown that models that project larger increases in global-mean surface temperature give more positive trends in the SAM (Arblaster et al. 2011, Wang and Cai 2013). This could be related to trends in the meridional temperature gradient, or increased static stability of the mid-latitude troposphere in a warmer climate (Frierson 2006, Lu et al. 2008). As noted above, the detailed dynamical mechanisms that link increasing GHGs to positive trends in the SAM are still uncertain.

In CMIP5, climate projections are forced by four different representative concentration pathways (RCPs). Of interest for the present study is that the decline in aerosol emissions in the RCPs is larger than assumed in earlier scenarios (Van Vuuren et al. 2011). Declining aerosols in the RCPs are expected to accelerate projected global-mean warming, with a tendency towards larger effects in models that have stronger (more negative) aerosol forcing in the present climate (Rotstayn et al. 2013a).

Another potentially important aspect of CMIP5 is an increase in the number of models that treat indirect aerosol effects relative to earlier intercomparisons. Since indirect effects substantially increase the magnitude of negative AA forcing in the present climate, this is likely to increase positive AA forcing in 21st century climate projections. Levy et al. (2013) found that in the GFDL-CM3 model, declining AAs caused about 1 °C of extra warming by 2100 in RCP4.5, and this was mostly caused by indirect aerosol effects. Indirect effects also have important effects on the simulation of historical climate change; for example, Wilcox et al. (2013) found that CMIP5 models that treat indirect aerosol effects better reproduce inter-decadal variability in historical global-mean near-surface temperatures and inter-hemispheric temperature difference, compared to models that treat direct effects only.

The model used in this study (CSIRO-Mk3.6) treats indirect aerosol effects, and has substantial AA forcing of...
−1.4 W m$^{-2}$ in the year 2000; of this, −0.3 W m$^{-2}$ is due to direct radiative effects, and the remainder can be attributed to indirect effects (Rotstayn et al. 2012). Strongly relative AA forcing can be attributed to the fact that the model treats both the first indirect (‘cloud albedo’) effect and the second indirect (‘cloud-lifetime’) effect; in general, models that include both of these effects tend to have stronger AA forcing (Rotstayn et al. 2013a).

The focus of this study is on the medium–low RCP4.5 scenario and austral summer (December to February, DJF). This is the season when the response of SH extratropical circulation to global warming projects most strongly onto the SAM (Kushner et al. 2001). It is also the season when the inter-model correlation of simulated SAM trends with trends in global-mean surface temperature is strongest (Arblaster et al. 2011). Further, since insolation is largest in the SH in DJF, aerosol effects in the SH are expected to be substantial in this season. CSIRO-Mk3.6 treats indirect aerosol effects, and has a substantial AA forcing; this suggests that there may be a significant response of the SAM to projected declines of AAs in this model.

A projection forced by RCP4.5 for the period 2006–2100 is compared with a modified RCP4.5, which is identical except that emissions of AAs and their precursors are held fixed at their 2005 values. The difference between the two projections gives the effect of declining AAs, which are found to induce a positive trend in the SAM and changes in zonal-mean atmospheric circulation and temperature in the SH that resemble the effects of increasing GHGs.

2. Model, experiments and radiative forcing

The following analysis uses coupled atmosphere–ocean simulations carried out for CMIP5 using CSIRO-Mk3.6 (Rotstayn et al. 2012, Jeffrey et al. 2013). CSIRO-Mk3.6 is similar to the earlier Mk3.5 version (Gordon et al. 2010), except that it includes an interactive aerosol treatment, a new radiation scheme, and an updated boundary-layer scheme. The model treats the direct radiative effects of sulfate, organic aerosol, black carbon, dust and sea salt and the first and second indirect effects of sulfate, sea salt and carbonaceous aerosol on liquid-water clouds. Further details of the aerosol treatments are given by Rotstayn et al. (2012).

The analysis of coupled atmosphere–ocean simulations is based on the following experiments, all of which are ten-member ensembles.

- **RCP45**: projection for 2006 to 2100 forced by the medium–low RCP4.5 pathway (Thomson et al. 2011). Anthropogenic forcing in this experiment is based on time-varying prescribed concentrations of GHGs and ozone and emissions of AAs and their precursors (sulfur dioxide, organic aerosol and black carbon).
- **RCP45A2005**: identical to RCP45, except that emissions of AAs and their precursors are held fixed at 2005 values. (Note that AAs include aerosols from biomass burning.)
- **Historical**: standard historical experiment (1850–2005) with ‘all forcings’, namely GHGs, ozone, AAs, volcanic and solar forcing.
- **HistoricalGHG**: historical experiment forced only by changes in GHGs.

RCP45 and RCP45A2005 are described and compared in more detail by Rotstayn et al. (2013a); they show that in RCP45, AAs decline to 19th century levels by 2100. The effects of declining AAs are diagnosed from RCP45 minus RCP45A2005, though it should be noted that the response may be non-linear, so an experiment forced only by declining AAs after 2005 may give significantly different results. Non-linear aerosol effects have been found in earlier studies using slab ocean models (Feichter et al. 2004, Ming and Ramaswamy 2009), but the issue has not been systematically addressed using coupled atmosphere–ocean models. In section 3.3, it is shown that linearity appears to be a reasonable assumption for the case considered here.

Comparison with the historicalGHG experiment is useful because it shows the response of the model solely to increasing GHGs; trends are calculated for the 95-yr period 1911–2005 (to match the length of the projections).

The global, annual-mean AA effective radiative forcing (including indirect effects and rapid adjustments) in CSIRO-Mk3.6 is −1.4 W m$^{-2}$ in the year 2000 (Rotstayn et al. 2013a); this estimate was obtained from the difference in net radiation at the top of the atmosphere between two 30-yr runs with prescribed sea-surface temperatures (SSTs) and sea ice, following the CMIP5 experimental design (Taylor et al. 2012). Rotstayn et al. (2013a) also presented results from a series of analogous fixed-SST runs, which were designed to calculate the effective radiative forcing due to declining AAs in RCP4.5 and compare the AA forcing with that due to increasing GHGs. For the present study, one further run was carried out to obtain the GHG effective radiative forcing for 1910, since the GHG forcing between 1910 and 2005 is useful to put the historicalGHG results in the context of RCP4.5.

GHG forcing between 2005 and 2100 in RCP4.5 is 1.5 W m$^{-2}$, compared to 1.8 W m$^{-2}$ between 1910 and 2005. This implies that if GHGs in RCP4.5 were considered in isolation, trends in the SAM during 2006–2100 would likely be somewhat smaller than in historicalGHG during 1911–2005. For comparison, global, annual-mean AA forcing between 2005 and 2100 in RCP4.5 is 1.5 W m$^{-2}$, which is similar to GHG forcing in RCP4.5. Consistent with the aerosol distribution, AA forcing is smaller in the SH than the NH, but in DJF the AA forcing between 2005 and 2100 is 0.9 W m$^{-2}$, which is still substantial.

Stratospheric ozone forcing is essentially the same in all the RCPs in CSIRO-Mk3.6, since the simulations used prescribed ozone from Cionni et al. (2011), who used a single scenario to generate future stratospheric ozone fields; see Cionni et al. (2011) and Eyiring et al. (2013) for further details.

The definition of the SAM index follows Gong and Wang (1999) that is, the difference between the normalized, zonally averaged sea-level pressure between 40°S and 65°S. Trends for DJF are calculated using ordinary least squares. Statistical significance of ensemble means is assessed using a two-sided t-test, taking the ten individual trend values as independent data points. For the difference of two ensemble means at each grid point (RCP45 minus RCP45A2005), a two-sample t-test for the difference of the mean of two populations is used.
3. Results and discussion

3.1. Trends in the SAM and circulation

Projected changes in the SAM are expected to represent a balance between positive changes induced by the warming effects of increasing GHGs, and negative changes induced by the recovery of Antarctic ozone depletion (Arblaster et al. 2011, Eyring et al. 2013). The global-mean surface warming trend in RCP45 is 2.4 K/century, and is almost twice as large as in RCP45A2005, which omits the effects of declining AAs (Rotstayn et al. 2013a). This suggests that trends in the SAM may be quite different in RCP45 and RCP45A2005.

Figure 1 shows time series of the ensemble-mean SAM index from experiments RCP45, RCP45A2005 and the difference. There is a positive trend of 0.54 units/century in RCP45, and a negative trend of −0.34 units/century in RCP45A2005 (though the latter is not statistically significant at 5%). This implies that in RCP45, the combined effect of increasing GHGs and declining AAs on the SAM outweighs that of recovering ozone. The effect of declining AAs (RCP45 minus RCP45A2005) is a significant positive trend of 0.88 units/century (p = 0.014).

These trends are fairly modest compared to the large positive trends of the last few decades, when stratospheric ozone depletion and increasing GHGs have been acting in the same direction. Over the period December 1957 to February 2005, the observed DJF trend (extended from Marshall 2003) is 4.3 units/century. The corresponding ensemble-mean trend in the CSIRO-Mk3.6 historical experiment is 2.8 units/century, with ensemble members ranging from 0.0 to 5.4 units/century, so the model is in reasonable agreement with the observations. Over the entire historical period, trends are weaker, e.g. CSIRO-Mk3.6 gives 0.72 units/century in DJF during 1850–2005.

Another view of the SAM is presented in figure 2, which shows trends in zonal-mean zonal winds in the SH. RCP45 (panel (a)) shows a strengthening of the mid-latitude jet on its poleward flank, consistent with a positive trend in the SAM, whereas the trends in RCP45A2005 (panel (b)) are consistent with a relatively weak negative trend in the SAM. The positive SAM-like dipole pattern is more pronounced in response to declining AAs (panel (c)).

For comparison with the response of CSIRO-Mk3.6 to pure forcing from GHGs, figure 2(d) shows 1911–2005 zonal wind speed trends from the historicalGHG experiment. The responses to declining AAs and increasing GHGs are qualitatively similar, with a clear positive SAM-like dipole pattern (more pronounced in historicalGHG); this suggests that, to first order, declining AAs in RCP45 have an effect on the SAM that resembles that of increasing GHGs. Both also show an eastward acceleration of tropical winds in the mid- to upper troposphere. Consistent with the stronger SAM-like zonal wind dipole pattern in historicalGHG, the 1911–2005 SAM trend in historicalGHG is also stronger (1.3 units/century, almost 50% larger than the 2006–2100 trend in RCP45 minus RCP45A2005). As discussed in section 2, the SAM trend in RCP4.5 due solely to increasing GHGs is likely to be somewhat smaller than the trend in historicalGHG.

The impression that the effects of declining AAs and increasing GHGs are similar is reinforced by trends in vertical velocity (figure 3). In both historicalGHG (panel (a)) and RCP45 minus RCP45A2005 (panel (b)) the area of strong ascent in the tropics moves north. The strongest subsidence in the subtropics weakens, but the region of subsidence expands southward into the mid-latitudes. This poleward expansion of the southern edge of the Hadley cell is consistent with other simulations of the effects of increasing GHGs, and in SH summer it has been found that the edge of the Hadley cell is consistent with other simulations of the effects of increasing GHGs, and in SH summer it has been found that the edge of the Hadley cell and the eddy-driven jet move in the same direction (Lu et al. 2008, Kang and Polvani 2011, Kidston et al. 2013), which is also consistent with the present simulations. At sub-polar latitudes there is increasing ascent on the southern flank of the enhanced mid-latitude jet; together with the subsidence trend in mid-latitudes, this forms an anomalous meridional circulation, with the westward Coriolis torque on the anomalous northward flow in the upper troposphere being balanced by the convergence of eddy momentum flux [e.g., Thompson and Wallace 2000].

3.2. Associated temperature changes

It was shown in section 3.1 that simulated circulation trends due to declining AAs and increasing GHGs have a similar
Figure 2. 95-yr zonal-mean DJF zonal wind trends (shaded) in the SH (m s$^{-1}$/century) from (a) RCP45 (2006–2100), (b) RCP45A2005 (2006–2100), (c) RCP45 minus RCP45A2005 (2006–2100), (d) historicalGHG (1911–2005). The mean 1986–2005 field from the historical experiment is contoured, and stippling denotes trends significant at 5%.

Figure 3. 95-yr zonal-mean DJF vertical velocity trends (shaded) in the SH (hPa d$^{-1}$/century) from (a) historicalGHG (1911–2005), (b) RCP45 minus RCP45A2005 (2006–2100). The mean 1986–2005 field from the historical experiment is contoured, and stippling denotes trends significant at 5%. Positive values denote downward motion.

The similar simulated temperature responses to declining AAs and increasing GHGs in the SH occur despite the distinct spatial structure of radiative forcing due to declining AAs. Figure 5(a) (red curve) shows DJF zonal-mean AA effective radiative forcing for 2100 relative to 2005. There is a peak due to strong indirect effects near 30$^\circ$S, where aerosols interact with subtropical marine layer clouds, and a secondary peak near 55$^\circ$S, where there are deep clouds associated with the storm track. South of 55$^\circ$S, AA effective radiative forcing weakens sharply, and over Antarctica it is close to zero, due to low AA concentrations and the large albedo of the underlying surface.

Also shown in figure 5(a) are zonal-mean simulated trends in surface air temperature due to increasing GHGs (1911–2005, blue curve) and declining AAs (2006–2100, green curve). Between the equator and about 55$^\circ$S, the response to declining AAs resembles a slightly weaker version of the response to increasing GHGs; the weaker temperature response for declining AAs is broadly consistent with weaker effective radiative forcing, as discussed in section 2. However, the trend in the meridional temperature gradient is similar, except at high latitudes. Both curves show enhanced warming in the tropics, and a minimum at the lower troposphere over the Southern Ocean, and stratospheric cooling. These are robust aspects of the simulated response to increasing GHGs (Lorenz and DeWeaver 2007, Xie et al 2013). In RCP45A2005 (panel (b)) the pattern is mostly similar, but there is warming in the lower stratosphere over Antarctica, due to the recovery of stratospheric ozone. The main features of the temperature response to declining AAs (panel (c)) are remarkably similar to those of increasing GHGs (panel (a)).
the case being considered, feedbacks are more important to declining AAs and increasing GHGs suggest that, for shifted slightly south relative to that for increasing GHGs. Further south. Note that for declining AAs, the pattern is westerly winds (figures 2 and 3), whereas the converse occurs to anomalous subsidence to the north of the strengthening ◦ of about 60 variation with latitude; in both cases, enhanced warming north at 500 hPa. At 250 hPa, the response to both forcing agents shows relatively little temperature response to declining AAs and increasing GHGs, than declining AAs. (where AA forcing changes sign), there is a much stronger latitudes do the two curves diverge markedly; over Antarctica (where AA forcing changes sign), there is a much stronger temperature response to increasing GHGs than declining AAs.

To reinforce the point about the similar patterns of the temperature response to declining AAs and increasing GHGs, figure 5(b) shows zonal-mean temperature trends at 250 and 500 hPa. At 250 hPa, the response to both forcing agents shows enhanced upper-tropospheric warming in the tropics, and a similar trend in the meridional temperature gradient. At 500 hPa, the temperature responses show relatively little variation with latitude; in both cases, enhanced warming north of about 60°S may be related to adiabatic warming due to anomalous subsidence to the north of the strengthening westerly winds (figures 2 and 3), whereas the converse occurs further south. Note that for declining AAs, the pattern is shifted slightly south relative to that for increasing GHGs.

The similar patterns of zonal-mean temperature response to declining AAs and increasing GHGs suggest that, for the case being considered, feedbacks are more important drivers of temperature change than the spatial details of the forcing. Tropospheric aspects of the temperature response to declining AAs can be explained (to first order) by analogy with the effects of increasing GHGs, which are relatively well understood. Enhanced warming in the tropical upper troposphere occurs because tropical convection tends to adjust the troposphere towards a moist adiabat (Wilson and Mitchell 1987). At the surface in the SH, large ocean heat uptake tends to suppress warming (Kuhlbrodt and Gregory 2012), and poleward of about 50°S enhanced westerly winds further suppress warming due to a combination of increased latent and sensible heat fluxes and Ekman-induced upwelling (Sen Gupta and England 2006).

The stratospheric cooling induced by declining AAs is interesting. It is essentially the inverse of the effect seen in the multi-model ensemble mean of historical simulations forced only by increasing AAs (Xie et al 2013, their figure S4). Considering the effect of increasing AAs, possible mechanisms for stratospheric warming include radiative heating by carbonaceous aerosols injected into the stratosphere, and increased reflection of shortwave radiation by tropospheric sulfate, which would tend to increase stratospheric heating rates. Also, decreasing stratospheric water vapour (which is seen in CSIRO-Mk3.6 in response to increasing AAs) would decrease stratospheric longwave cooling (Maycock et al 2011).

Other studies do not present a simple picture of possible effects of AAs on stratospheric temperature. Wu et al (2012) considered the direct effects of increasing AAs and found that both sulfate and carbonaceous aerosols caused stratospheric warming in their global climate model, though they noted that the mechanisms were complex. In an observational study, Baumgardner et al (2004) demonstrated a significant contribution to radiative heating rates by black carbon in the Arctic stratosphere. Simulations by Koch and Hansen (2005) suggest that the principal sources of black carbon in the Arctic stratosphere are long-range transport from South Asia and low-latitude biomass burning. Similar studies in the SH are lacking, but observations following the eruption of Mount Pinatubo indicate that stratospheric aerosol is transported from the tropics to higher latitudes by the Brewer–Dobson circulation (McCormick et al 1995). Preliminary analysis of CMIP5 historical simulations forced only by increasing AAs (a larger set than considered by Xie et al 2013) reveals that several models show stratospheric warming over Antarctica in DJF, similar to that in CSIRO-Mk3.6, whereas other models show small temperature trends or even cooling (figure not shown). CSIRO-Mk3.6 does not treat longwave effects of AAs, but calculations for potential stratospheric geoengineering aerosols indicate that for larger aerosol sizes, longwave absorption and emission can be significant (Ferraro et al 2011). This is an intriguing topic that merits further investigation.

3.3. Further discussion

As mentioned in section 2, there is a question regarding the linearity of the results. This cannot be addressed directly without access to an experiment forced only by
declining AAs after 2005. However, for the historical period there are published ten-member ensembles with CSIRO-Mk3.6 driven by ‘all forcings’ (historical), by increasing AAs only (historicalAA) and by all forcings except AAs (historicalNoAA). DJF SAM trends for 1911–2005 are $-0.73 \pm 0.43$ units/century for historicalAA and $-0.94 \pm 0.45$ units/century for historical minus historicalNoAA, where the uncertainty ranges are 5–95% confidence intervals. The SAM trends are not significantly different using the two methods, which suggests that linearity is a reasonable assumption in the present study.

Is there likely to also be a substantial effect on the SAM due to declining AAs in other CMIP5 models? Rotstayn et al (2013a) found that the present-day aerosol forcing (including indirect effects) in CSIRO-Mk3.6 has larger magnitude than the average of CMIP5 models for which data were available. The global-mean anthropogenic aerosol forcing at the top of the atmosphere in CSIRO-Mk3.6 was $-1.4 \text{ W m}^{-2}$, compared to a range of $-0.8$ to $-1.6 \text{ W m}^{-2}$ and a mean value of $-1.21 \text{ W m}^{-2}$ for 11 models that included at least the first indirect aerosol effect. For DJF in the SH, the corresponding forcing in CSIRO-Mk3.6 is $-0.7 \text{ W m}^{-2}$; the range for models that include indirect effects is $-0.2$ to $-1.0 \text{ W m}^{-2}$, with a mean value of $-0.56 \text{ W m}^{-2}$.

These numbers suggest that, although CSIRO-Mk3.6 is not an outlier, the average effect of declining AAs across the CMIP5 models may be smaller than that found in our simulations. However, this statement is somewhat speculative. The best way to isolate the effects of changes in aerosols (or other forcing agents) in climate projections is to perform runs similar to ours. Note that at least two other modelling groups have recently carried out modified experiments based on RCP4.5 with fixed AA emissions (Levy et al 2013, Gillett and Von Salzen 2013), although these studies did not consider SH circulation.

The results from CSIRO-Mk3.6 suggest that in the low and medium RCPs, declining AAs may exert substantial effects on the SAM. In RCP8.5, AAs are also projected to decline sharply, but the large magnitude of GHG forcing in RCP8.5 means that the effects of AAs are relatively less important. Gillett and Fyfe (2013) showed that in the ensemble mean of 37 CMIP5 models, the SAM index is roughly constant in DJF in RCP4.5, due to an approximate balance between the effects of increasing GHGs and recovering ozone. If declining AAs in RCP4.5 enhance projected global warming in RCP4.5, especially in models with strong AA forcing, then they may substantially contribute to the spread of projected SAM trends around a small mean value.

As yet there is no clear consensus on the effect of AAs on the SAM. My finding of a positive SAM trend due to declining AAs in austral summer is qualitatively consistent with the results of several studies cited in section 1. On the other hand, annual-mean results from a coarse-resolution version of the CSIRO climate model indicated a positive SAM trend due to historical changes in AAs over the period 1941–2000 (Cai and Cowan 2007). The authors argued that the trend was caused a positive air–sea feedback, which was initiated by anomalous northward cross-equatorial ocean heat transport, which in turn was a response to the inter-hemispheric imbalance in AA forcing.

The present results for DJF are not directly comparable with the annual-mean results of Cai and Cowan (2007), but the annual-mean SAM trend in RCP4.5 minus RCP45A2005 is $+0.91$ units/century, which is of similar magnitude to the trend in DJF. Preliminary analysis of CMIP5 historical simulations forced only by changes in AAs (figure not shown) reveals negative SAM trends in the majority of models. In this study, the SAM is discussed as an intrinsically atmospheric phenomenon, which is consistent with the

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**Figure 5.** (a) 95-yr zonal-mean DJF surface air temperature (SAT) trends from historicalGHG (1911–2005) and RCP45 minus RCP45A2005 (2006–2100); also shown is DJF aerosol effective radiative forcing (including indirect effects) for 2100 relative to 2005. (b) 95-yr zonal-mean DJF tropospheric temperature trends from historicalGHG (1911–2005) and RCP45 minus RCP45A2005 (2006–2100) at 250 and 500 hPa.
prevailing view (e.g., Lorenz and Hartmann 2001). The atmospheric perspective suggests that the SAM ‘should’ have a positive response to decreasing AAs in austral summer, by analogy with the effects of increasing GHGs. However, some other authors have also found evidence for a feedback from the ocean to the atmosphere, which contributes to variability in the SAM (e.g., Sen Gupta and England 2007). While it is possible that the low resolution of the model used by Cai and Cowan (2007) exaggerates the magnitude of the air–sea feedback (and the associated positive SAM trend due to increasing AAs), their hypothesis is interesting and merits further study.

This letter has only considered austral summer. In winter, projected aerosol effects in the SH may be driven by different dynamical processes, because the winter Hadley cell ‘connects’ the SH to the ascending branch of the Hadley circulation, which is collocated with strong aerosol forcing and convective latent heating in the NH (Rotstayn et al. 2013b). The seasonality of the response is an interesting topic for further research.

4. Conclusions

In CSIRO-Mk3.6, declining anthropogenic aerosols in RCP45 induce a positive trend in the SAM in austral summer. Associated changes in atmospheric circulation include a poleward shift of the mid-latitude westerly winds and poleward expansion of the southern edge of the Hadley cell, similar to the effects of increasing GHGs. Trends in the simulated atmospheric temperature structure in the SH are also similar for declining aerosols and increasing GHGs. These results suggest that the positive SAM trend due to declining aerosols may be driven by mechanisms that are similar to those that cause the positive SAM trend in response to increasing GHGs; as noted above, these mechanisms are still a topic of active research. The similarity of the dynamic response to declining aerosols and increasing GHGs is consistent with the findings of Xie et al. (2013).

These findings suggest that in the medium–low RCP4.5 scenario, assumptions about aerosols may contribute substantially to inter-model variability in projected SAM trends in the 21st century. Aerosol forcing is highly uncertain, and this causes uncertainty in most aspects of climate projections, even in the relatively pristine SH. The effect of declining aerosols may be smaller than the individual effects of increasing GHGs or recovering stratospheric ozone in DJF. However, increasing GHGs and stratospheric ozone recovery exert opposing effects on the SAM, and this causes the DJF multi-model-mean SAM trend to be small in RCP4.5 (Gillett and Fyfe 2013).

This study has revealed significant trends in SH mid-latitude circulation due to projected declines in anthropogenic aerosols in one model. This suggests that corresponding effects on mid-latitude circulation in the NH, where aerosol concentrations are larger, are likely to be a fruitful topic for research. Until now, single-forcing transient simulations have mostly been used as a way to understand and attribute historical climate change; they are likely to also be valuable for improving our understanding of projected climate change.

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