Reply to J. Dykema for Climatic Impacts of Stratospheric Geoengineering with Sulfate, Black Carbon and Titania Injection

We thank Dr Dykema for the many useful comments and suggestions. As with our other replies, we address each of the comments in turn (blue/ red sentences signify added/ deleted text from the manuscript).

Specific Responses

1. In section 5, we have discussed the limitations of the aerosol scheme employed here and the requirement for detailed aerosol microphysics in order to accurately calculate radiative transfer through the atmosphere. Additionally we have referred the reader to Weisenstein et al (2015), who use a detailed microphysics scheme to assess the implications of injecting solid particles such as alumina:

   "Recent research from Heckendorn et al (2009), Pierce et al (2010), English et al (2012), and Weisenstein et al (2015) have highlighted the importance of representing aerosol growth in SAI simulations." – pp30058

   Weisenstein et al's model, AER-2D, represents important microphysical processes such as the agglomeration of solid aerosol particles to form non-spherical fractal structures, the uptake of liquid sulfuric acid onto solid aerosol surfaces, and heterogeneous ozone chemistry on aerosol surfaces. However, their model uses prescribed climatology following historical conditions, which neglects important feedback mechanisms such as changes to stratospheric wind fields induced by stratospheric heating. Additionally their model utilises a coarser grid in the zonal direction (9^o latitude increments versus 1.25^o increments here) and no meridional representation, indicating that our dynamical representation of transport is more advanced than their study. Coupling radiation to dynamics is important. Neglecting the aerosol self-lofting due to stratospheric heating will result in inaccuracies in the vertical distribution of aerosol, for example.

   We agree with Dr. Dykema that incorporating aerosol microphysics would result in a better representation of the aerosol's optical properties; this is particularly important for solid aerosols that form chain-like fractals. However, it is also important that the model's climatology is able to respond radiative changes induced by the aerosol. Our results are therefore complementary, Weisenstein et al (2015) have shown that representing aerosol microphysics is important for modelling the injection of solid particles; we have shown that representing radiative-dynamical feedback is also important. A more detailed assessment would combine our two approaches by coupling a 3D GCM with a detailed aerosol microphysics module, but such experiments over the centennial timescales of this work are currently too computationally expensive.

2. Dhomse et al (2014) reference – thanks for the comment, we have added this reference to the list

3. Precipitation – Thanks for the suggestion, we have added the model sensitivity to the text (section 4.1).

   "The precipitation sensitivity for the model is 1.32 %/^{o}C, which is close to the CMIP5 ensemble-mean [Fig. 12.7 from Collins et al, 2013]."

4. McCusker – This is an important question that deserves a detailed answer. Firstly, we don't see that our findings conflict with McCusker et al (2015). In particular, comparing the sea-ice contours from their figure 2 with our supplementary figure S5 (now S7) shows relatively close conformity between our results, i.e. limited spatial retraction of sea-ice in the geoengineering scenario. Fortuitously, we use the same criterion for determining which gridcells contain sea-ice (sea-ice fraction of >15%), which aids in the comparison. We make the point explicitly: both our results and McCusker's show that SAI can reduce Antarctic temperatures substantially (their figure 2, our figure 6) compared to RCP8.5 climate. Additionally, we both find that a similar-level of SAI can maintain the spatial extent of sea-ice at approximately historical values (their figure 2, our Fig. S5 (now S7) in the supplement).

   However, the primary finding of McCusker's paper is that SAI cannot preserve the West Antarctic Ice Sheet, in particular, the Pine Island Glacier (PIG). They show that this is ultimately due to the dynamical response of the atmosphere and ocean to tropical stratospheric warming induced by the aerosol layer. There are two obvious caveats to this finding: firstly that this result is dependent on the spatial distribution of the sulfate aerosol in the stratosphere; would polar sulfate injections produce the same tropical stratospheric warming/ dynamical response? Secondly, if a purely scattering aerosol were to be found or 'space-shields' utilised that did not produce a tropical stratospheric warming, would the same dynamical response be induced? This could be tested with a solar dimming GCM experiment such as G1 from GeoMIP. Ultimately though, our experiments here use a very similar SAI scenario to McClusker et al (2015), i.e. significant sulfate injection at the tropics, hence we expect to find the same dynamical response.

   We present some additional figures on the last pages of this document which are used for reference in the following text. Firstly, our figure SF1 is comparable with McCusker's figure 2. In the RCP8.5 scenario, there is a clear strengthening and poleward shift in southern-hemisphere jet stream which extends to the surface. As McCusker et al (2015) showed, this same effect is present but less pronounced in the G3S scenario. This is caused by the preferential heating of the tropical stratosphere at ~20 km altitude increasing the zonal temperature differential. Our figure SF2 is equivalent to their figure 3. RCP8.5 produces a much stronger zonal surface stress near to the Antarctic continent than in the HIST era. The same pattern is present but to a much lesser extent in G3S. The sea-ice extent is much closer to the HIST period for G3S than RCP8.5 (the black and grey contours respectively). All the results so far concur with McCusker's findings and support our conclusions in the report.

Figure SF3 shows the ocean potential temperature differences between RCP8.5 (2090s) and HIST, and G3S (2090s) and HIST, evaluated for the SH and the PIG region. It is clear for G3S that the PIG region (~70^{o}S) warms (bottom right plot), which will exacerbate the ice melt. Our results therefore corroborate McCusker's, that Ekman pumping from the poleward shift in zonal wind causes anomalous upwelling (fig S4) of warmer water at the PIG region, which might not stop the currently destabilised ice shelf from collapsing. Therefore, this particular SAI strategy might not ameliorate the melting of the west Antarctic ice shelf.

5. Stratospheric temperatures – The correlation between stratospheric temperature adjustment and stratospheric wind perturbation follows immediately from the thermal wind relationship. Aquila et al (2014) found a similar effect – 5Tg[SO_2]/yr caused a greater QBO perturbation than 2.5Tg[SO_2]/yr. Other factors that impact stratospheric winds include ozone depletion (which would amplify the polar vortex response), and changes to wave propagation from the troposphere [e.g. Stenchikov et al, 2002]. Driscoll et al (2012) analysed CMIP5 multi-model simulations of volcanic eruptions, but found that the models were unable to replicate either the stratospheric warming signal or the dynamical feedback observed after eruption. However, the authors didn't explicitly analyse the correlation between the two fields – which would have answered the question of whether our result is replicable by other GCMs.

6. BC on snow – Thanks for the comment, BC on snow is a well established climate forcing that currently contributes ~0.04 Wm^{-2} [IPCC, 2013]. The IPCC's assessment of this forcing now includes the effects of BC deposition on sea-ice, which is also a significant contributor to the overall effect. Although we emphasized this issue with respect to BC, it is important to note that any particle that absorbs SW radiation will instil this forcing. Therefore, titania, which has a non-unitary single scattering albedo at short wavelengths, will also cause snow-grain coarsening and snow-melt by absorbing solar radiation and warming the top layer of the snow pack. A more comprehensive investigation than ours would include explicit representation of this process by incorporating the optical properties of the deposited substance. Implicit relationships between BC deposition and snow albedo modification, such as provided by Marks and King (2013), could also provide an indication of the importance of this process.

Figures

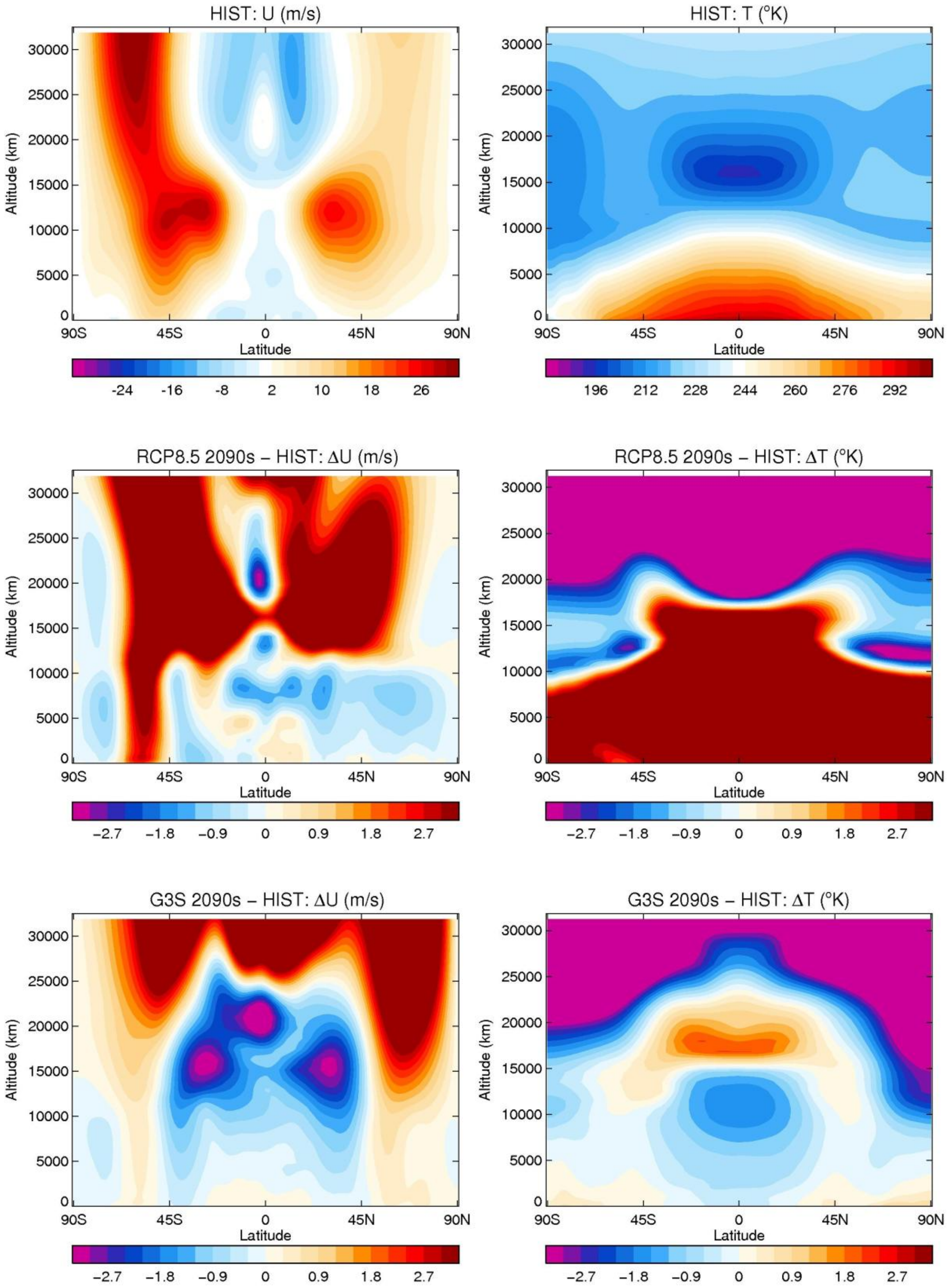

Figure SF1. Zonal-mean, annual-mean zonal-wind (left) and atmospheric temperature (right) for HIST period (top), RCP8.5 (2090s) minus HIST (middle), and G3S (2090s) minus HIST (bottom)

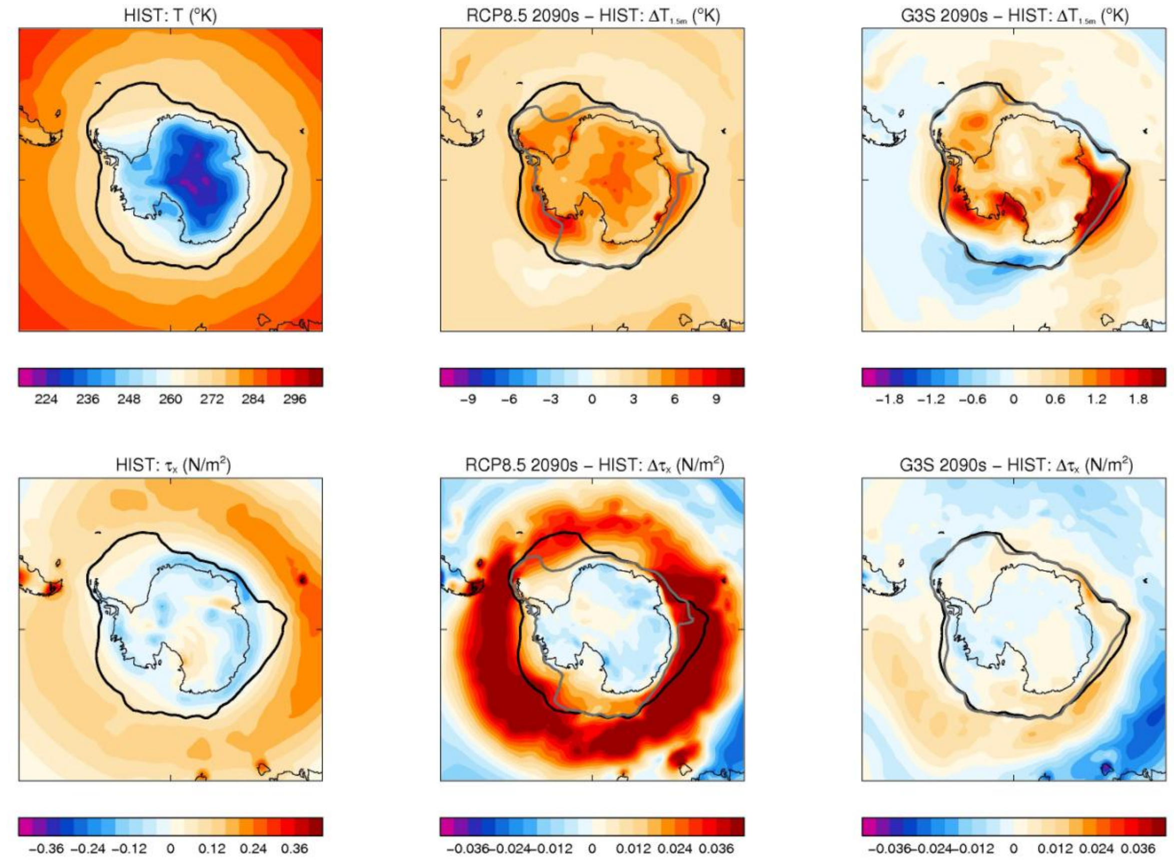

Figure SF2. Antarctic annual-mean temperature (top) and zonal surface wind stress (bottom) for the HIST period (left), RCP8.5 (2090s) minus HIST (middle), and G3S (2090s) minus HIST (right). Black contours show the HIST annual-mean sea-ice extent and grey contours show the 2090s extents

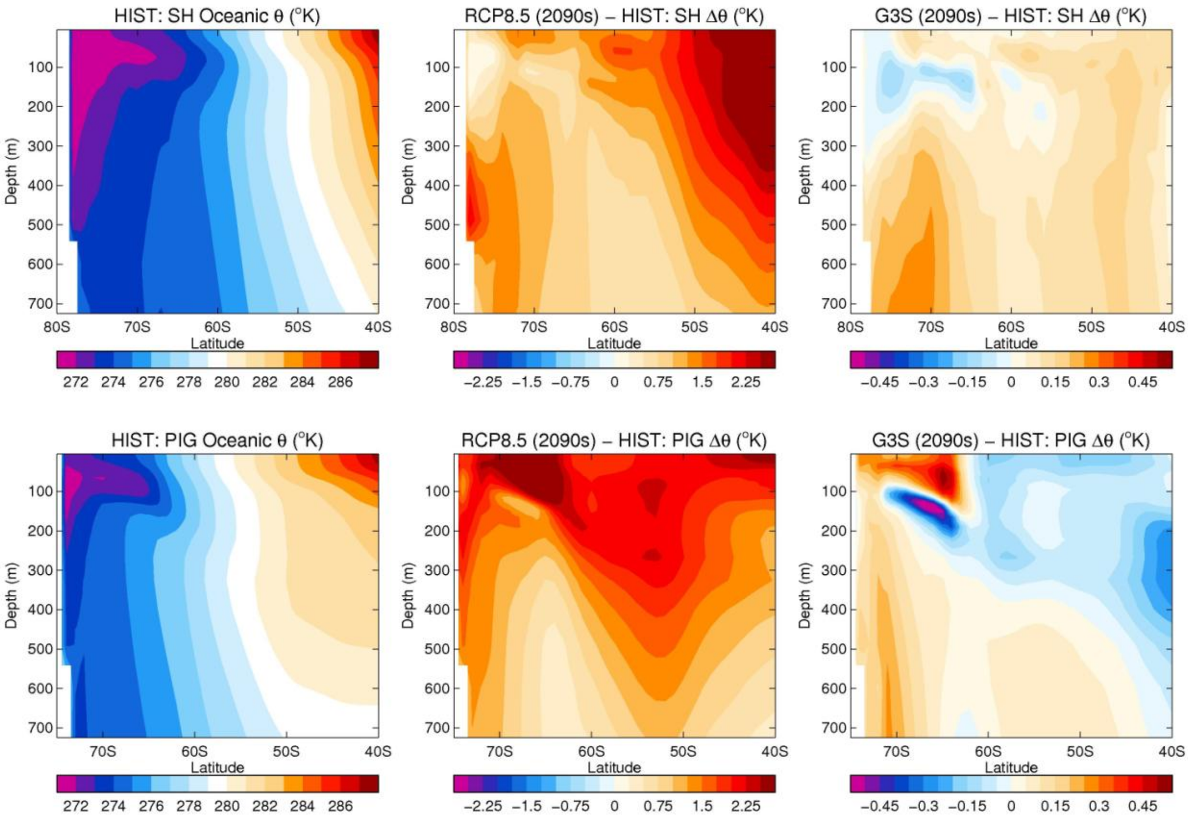

Figure SF3. Ocean potential temperature for SH zonal-mean and annual-mean (top) and PIG region (80°W-120°W) zonal-mean (bottom) for HIST period (left), RCP8.5 (2090s) minus HIST (middle), and G3S (2090s) minus HIST (left)

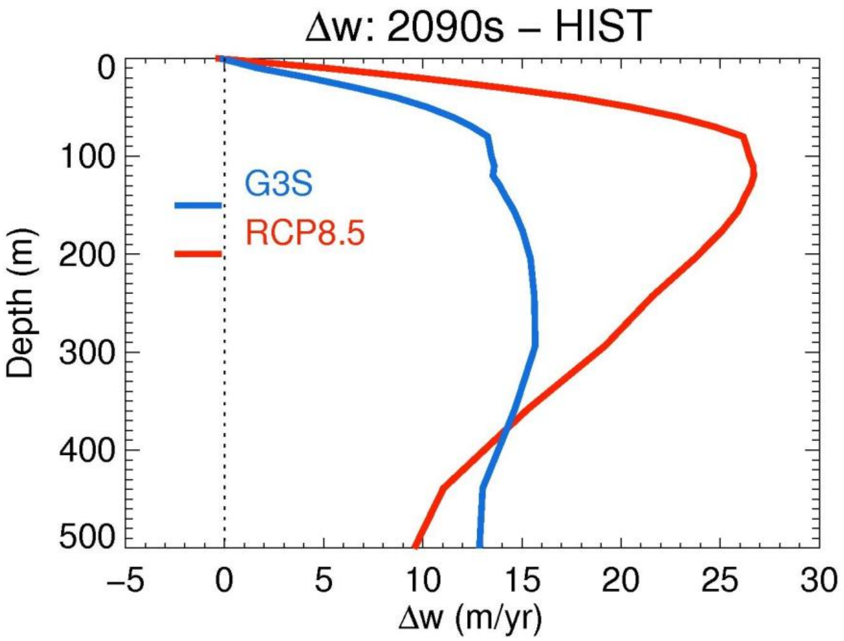

Figure SF4. Oceanic vertical velocity anomaly (m/s) in the PIG region (80°W-120°W and 65°S-74°S) for RCP8.5 (red) and G3S.