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Climate of the Past Discussions

Interactive comment on "Maintenance of polar stratospheric clouds in a moist stratosphere" *by* D. B. Kirk-Davidoff and J.-F. Lamarque

D. B. Kirk-Davidoff and J.-F. Lamarque

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Reply to Anonymous Referee 1

We thank the referee for his or her careful reading and helpful comments.

1. We have expanded the discussion of the mechanisms controlling PSC and stratospheric aerosol number density, adding the following paragraphs to the Introduction:

"The factors controlling the number density of type II PSCs are poorly understood, but include both the availability of background aerosol particles, whose density varies over a wide range depending on latitude, altitude, season and volcanic activity, and on dynamical factors such as the speed of the cooling that leads to condensation and cloud formation (Peter, 1997). PSC number densities tend to be larger when clouds are formed rapidly (as in mountain wave clouds), and smaller when clouds are formed

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slowly (Toon et al. 1989). This is because, in clouds formed by slow cooling, supersaturations are relatively low, and freezing occurs preferentially among aerosols that largely consist of hydrated nitric acid (Tabazadeh et al. 2007). In rapid cooling, with high supersaturations, nearly all the stratospheric aerosol are "activated", allowing homogeneous freezing, and optical depths approaching unity, while preventing much sedimentation (due to small particle size).

The subject of how PSC number density might change in radically different climates over geological time has not been much studied. Reasons for increasing number density would include larger volcanic emissions of SO2 leading to increasing aerosol number density (at least of larger particles, observations of stratospheric condensation nuclei number density show no strong differences between volcanic and non-volcanic years (Deshler et al. 2003)) and change in role of nitric acid trihydrate (NAT): in the current climate dehydration processes are modulated by the uncertain role of NAT as a competitor with smaller water ice particles for water vapor (Drdla et al. 2003, Carslaw et al. 1997), in a moister stratosphere, NAT would play a less important role, since ice nucleation would occur at warmer temperatures, so supercooling of sulfate aerosol could be sufficient to allow nucleation at temperatures above the NAT nucleation threshold. PSC number density would then be more dependent on sulfate aerosol number density. The number density of stratospheric aerosol is controlled by nucleation and coagulation of liquid sulphate solution in the upper tropical troposphere, whence aerosol droplets are transported upwards into the stratosphere, and by conversion of OCS (carbonyl sulfide) to SO2 and H2SO4 in the upper stratosphere (SPARC Authors, 2006). Stratospheric aerosol number density varies over an order of magnitude or more depending on location and time. "Background" levels, in the absence of direct injection of SO2 by volcanic eruptions, range from 1 to 10 cm^{-3}. Daerden et al. (2007) discuss the uncertainties assumptions for aerosol size distribution, and the importance of these assumptions for models of PSC formation."

2. We've added an experiment, a figure and discussion confirming that the patchiness

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of the PSCs due to their self-heating does not preclude their exerting a warming effect. We compare the downward fluxes at the tropopause due to PSCs whose optical depth is allowed to vary as their cloud particles grow or shrink with the fluxes due to PSCs whose optical depth is fixed at values equal to the annual mean of the active PSCs, and show that the forcings are similar.

3. We've included a discussion of Korty and Emanuel's paper in the introduction.

"Korty and Emanuel (2007) have investigated the response of the stratospheric overturning circulation and temperature distribution to a dramatic change in the surface temperature gradient in a GCM with enhanced stratospheric resolution. They find no reduction in overturning strength, but do note an increase in tropical tropopause temperature, probably due to increased tropical surface temperatures (by 3 K) imposed in their model. Model results for the dependence of stratospheric overturning on surface temperature distribution vary widely among GCMs since, as discussed in Kirk-Davidoff et al. (2003) the net effect of overturning is the result of two conflicting responses to surface temperature changes: a positive dependence of baroclinic eddy amplitude on meridional temperature gradient, and a negative dependence of the ability of planetary waves to propagate upwards through the tropopause on the meridional temperature gradient. "

4. The main reason for the assumption that the isentrope leaving the surface in the tropics should intersect the tropopause at the poles is to cause the model to reduce polar static stability when the pole-to-equator temperature gradient is reduced, as regularly occurs in GCM simulations of high greenhouse gas climates. We have added some further discussion of this, including a few additional citations.

5. As we note in the text, the WACCM model produces very low optical depths in the stratosphere, because it has no explicit PSC parameterization, but rather uses the same temperature-dependent cloud particle size in the troposphere and stratosphere. This results in very large particles which quickly sediment out, so that cloud optical

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depths are tiny, even when water vapor mixing ratios are many times higher than in the present climate. The WACCM results are important to our argument, though, because they show that our very simple model for the transport of water vapor and methane in the stratosphere gives results are generally consistent with WACCM's much more sophisticated treatment of atmospheric physics and dynamics.

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We thank the reviewer for his or her thoughtful comments and criticisms.

Very sophisticated models of stratopsheric chemistry and transport exist of course, but as a rule they use very simple radiative codes and do not treat the radiative impact of stratospheric aerosol or PSCs. For instance, Bingen et al. use the radiative code of Shine, 1987, and Weisenstein et al. (2007), use the the code of Rosenfield et al. (1994), neither of which treat PSC radiative effects. As discussed in the reply to reviewer 1, much of the complexity in the formation of PSC ice particles is removed if water vapor mixing ratio is sufficiently high that nitrate formation is avoided. While our model is very simple, we believe it contains enough relevant physics to support the conclusions we draw, and we hope that publication of the present work will encourage more detailed studies using more complicated models. In particular we anticipate that future versions of NCAR's WACCM model will include a realistic treatment of the growth, sedimentation and evaporation of cloud ice in the stratosphere, rather than the simple one-to-one dependence of ice particle size on Temperature that was used in the Lamarque et al. (2006) simulations. We hope this study will provide additional motivation for that work.

The reviewer asks in which respects our work represents an advance with respect to Lamarque et al. 2006. We have added language clarifying that while our model is of course much simpler than that used in Lamarque et al. (2006), we have performed a focused experiment varying the PSC number density and shown that when number density is low, as in Lamarque et al. (2006), we get optically thin PSCs that have no

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radiative role, as was also true in Lamarque et al. (2006). However, when number density is increased to high values that are nevertheless within the range of observed clouds in some circumstances, the radiative role of the PSCs can be significant.

More specifically the review asks if we've included the effect of methane or ozone changes in the radiative calculations. We did not include either, in order to focus on changes in cloud amount, but we have done sensitivity experiments that show that the direct radiative response of stratospheric temperatures to large methane changes is small (a few degrees) in our model. Of course the impact of stratospheric methane on ozone and water can become significant, as discussed in Lamarque et al. (2006).

We have carried out additional sensitivity studies bracketing the effect of reevaporation of falling particles on psc optical depth, and show that this effect, while potentially significant, does not alter the conclusions of the paper.

We have corrected a number of typos.

Interactive comment on Clim. Past Discuss., 3, 935, 2007.