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In the main body we find that one all-forcing ensemble member simulates an aging trend of mid-stratospheric air since 1988 consistent with observational constraints (labeled ALL #3 in the paper), while a second simulates freshening of air and an accelerated mid-stratospheric BDC (labeled ALL #1 in the paper). It is reasonable to ask which ensemble member is closer to reality as measured by other metrics. It is also reasonable to ask whether the difference in the wave fluxes underlying the different BDC trends leads to similar differences in temperature and zonal wind trends. We now explore these issues by comparing the trend in these two ensemble members to that in MERRA and ERAI reanalysis. As the difference in wave forcing between these ensemble members was pronounced mainly in the Southern Hemisphere, we focus on this hemisphere.

Figure 1 compares the temperature trends over the 1988 to 2014 period in each ensemble member to two reanalysis products in order to assess which integration has a trend in the thermal structure closest to observations. Consistent with the trend towards more wave convergence in ALL #1, there is a warming trends over the pole. In contrast, the trend towards less wave convergence in ALL #3 (which allows the BDC to slow down) is reflected in cooling over the pole. More relevantly, there is an equator-to-pole gradient in the trends: in ALL #3, the pole cools more than the tropics, reflecting a slowdown of the residual circulation. In contrast, in ALL #1 the tropics cools more than the pole reflecting a speedup of the residual circulation.

These trends can then be compared to those in MERRA and ERAI. First of all, it is worth noting that the two reanalysis products differ as to the magnitude of the trend, though in both there is a tripole pattern in the vertical over the pole, with cooling in the upper and lower stratosphere and warming in the mid-stratosphere. Neither model integration captures this tripole pattern. However, both reanalysis products indicate a trend towards cooling upon averaging the trends over the entire SH extratropics, and only ALL #3 captures this feature. As these experiments are all run in climate mode (no nudging), there should not be the expectation that any ensemble member agrees fully with the actual observed trends as unforced differences in the wave fluxes impact the spatial pattern of the temperature trends.

Figure 2 compares the zonal wind trends over the 1988 to 2014 period in ALL #1 and ALL #3 to two reanalysis products. Consistent with the temperature trends, there is an easterly trend in ALL #1 and a westerly trend in ALL #3 in order to maintain thermal wind balance. ALL #3 compares very favorably to the trends in ERAI, though the large differences between MERRA and ERAI preclude any meaningful quantitative comparison.

The net effect is that ALL #3 (which simulates a slowdown of the BDC from 1988 to 2014) has circulation trends that more closely resemble reanalysis than ALL #1 (which simulates a speedup of the BDC from 1988 to 2014). However, the correspondence between ALL #3 and reanalysis is not full, but it is not reasonable to expect perfect correspondence as the wave fluxes in any given realization of the atmosphere differ.

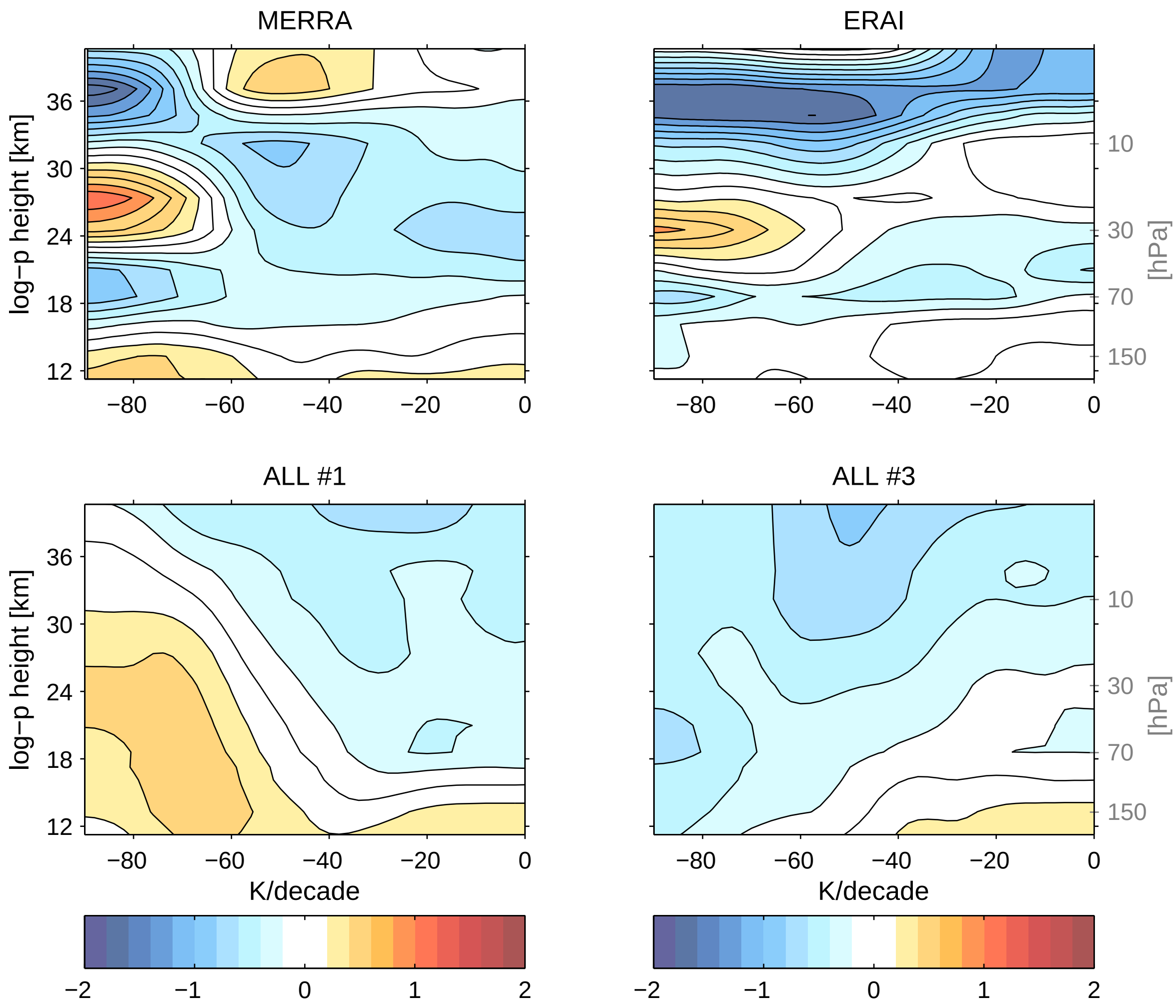

Figure 1. Trend in annual averaged temperature in the SH from 1988 to 2014 in the (a) MERRA and (b) ERAI reanalyses, and in the all forcing integrations with a trend towards a (c) accelerated BDC and (d) a decelerated BDC.

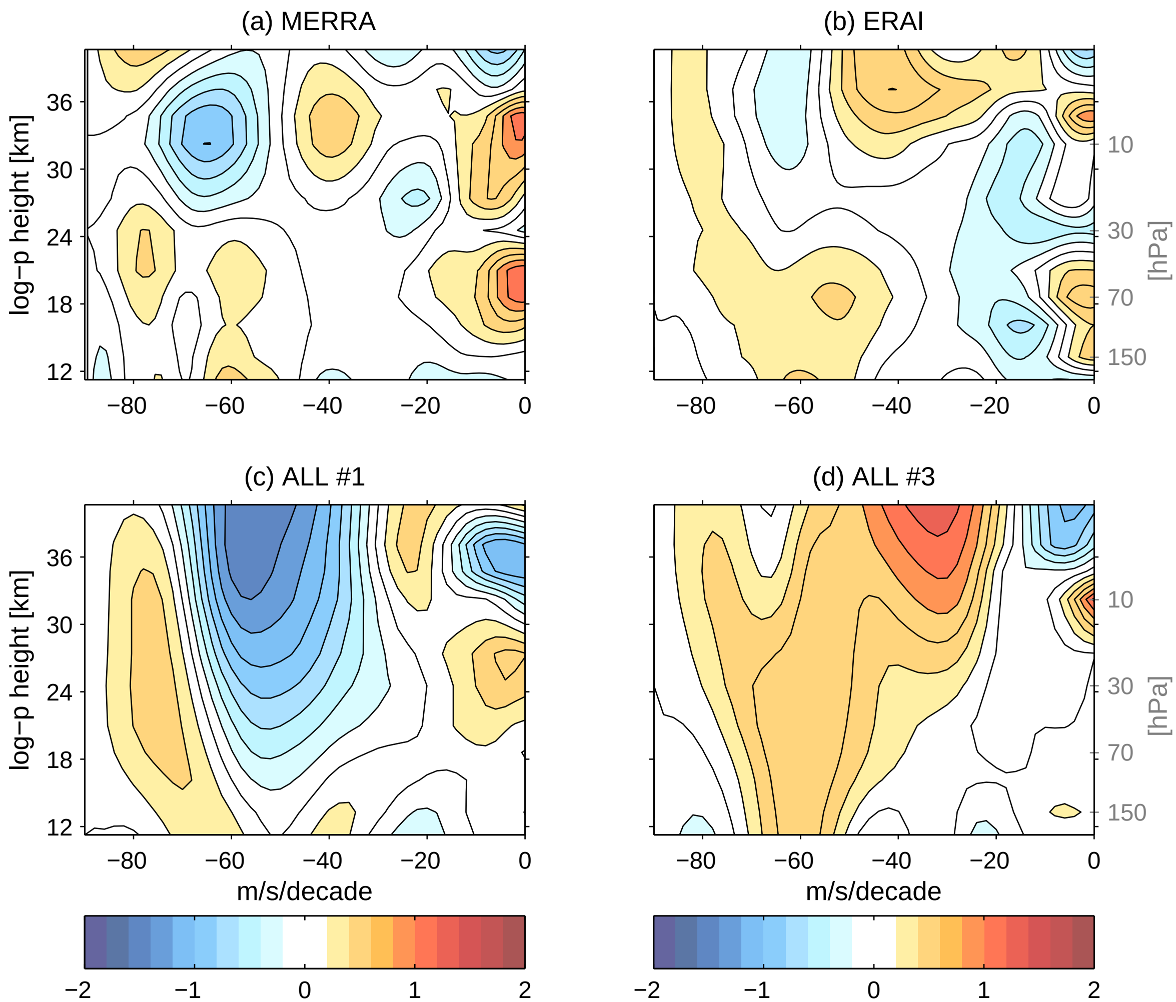

Figure 2. As in figure 1 but for zonal wind.

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References

Ray, E. A., Moore, F. L., Rosenlof, K. H., Davis, S. M., Sweeney, C., Tans, P., Wang, T., Elkins, J. W., Bönisch, H., Engel, A., et al.: Improving stratospheric transport trend analysis based on SF6 and CO2 measurements, Journal of Geophysical Research: Atmospheres, 119, 14–110, 2014.