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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Middle atmosphere response to the solar cycle in irradiance and ionizing particle precipitation" *by* K. Semeniuk et al.

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Response to Referee # 4

General Comments

We address the concerns of the referee in detail in the Specific Comments section. The relevance of NO_x above 100 km to the middle atmosphere is overstated. There is no simple transport conduit linking the mesosphere to the thermosphere in winter. The Antarctic ozone hole has not significantly changed the dynamical behaviour of the SH polar vortex. There was a dynamical "hole" that predates the chemical ozone hole. It is the strength of the SH polar vortex that shapes the response of the middle atmosphere to EPP so our experimental setup is justified. As stated in our paper the tropospheric ozone in CMAM is reasonable (deGrandpré et al., 1997) so it is not likely that including surface and lightning NO_x emissions would lead to a significantly different response pattern. There would be an issue if the CMAM tropospheric ozone deviated significantly from observations.

Specific Comments

p24856, l29: By not including medium energy electron fluxes they missed a significant amount of NO_x production in the MLT region, which has a higher chance of surviving transport to the stratopause region and the stratosphere. One of the features of aurora is that it is not intermittent like SPEs. So as long as CCMs produce the correct transport features (such as major sudden warmings with the right frequency) they will do a good enough job capturing the effects. For SPEs the weather state is much more important, if one happens to coincide with a SSW. Chemical uncertainties are important as well. We have modified the text to note some of these issues.

p24857, l12: We have changed the wording (see highlighted manuscript in the included supplement).

p24858, l25: Conversion into chlorine nitrate would not be of importance outside the PSC zone, which does not typically extend above 25 km. Gas phase catalytic destruction would still be active above this level and at times of the year other than early spring when chlorine activated by PSCs destroys ozone, namely, late fall and winter. In the SH, the auroral NO_x supply is active as long as there is a vortex and during its final break up. At times of the year when auroral NO_x is not transported into the stratosphere, there is still GCR induced ozone loss between 20 and 30 km. So there is no

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reason to expect that annual mean ozone would increase in the SH in the presence of EPP.

The ozone hole will not remove the positive ozone anomaly seen in the solar cycle CMAM ensemble in the SH polar region. The vortex evolution depends on periods when there is no ozone hole in late fall and early winter. EPP plays the important role of offsetting the gain in ozone during solar maxima at high latitudes in the SH. This effect will not disappear or change sign in the presence of a fully developed ozone hole.

We have added some text about the formation of $ClONO_2$ and HOCl and a reference to Vogel et al. (2008) in section 2.

p24857, l21: We prefer to retain the label auroral since the electrons are originating from the same source and are deposited in an auroral oval (only the highest energy channel which has relativistic electrons deviates from this, but its contribution to the energy deposition profile is small). The low energy auroral electron channel is less important below 90 km as now discussed in more detail in section 2. The definition of SPEs has been removed.

p24861, l19: This effect was not taken into account for HO_x production. It does not change our results pertaining to dynamics since the auroral HO_x does not survive transport into the stratosphere or even lower mesosphere. This is now noted explicitly in section 2.2.

p24863, l1 and l8-12: ACE FTS data that tells us that the values of NO_x at 90 km are lower than 10 ppmv at polar latitudes (e.g. Fig. 1, Randall et al., 2009). From this figure it is clear that even major SSW events are not associated with descent of NO_x values larger than 10 ppmv from above 90 km. In both the SH and NH winter there is a zonal wind reversal in a layer between 80 and 100 km (e.g. McLandress

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et al., 2006; Liu et al., 2010). In this layer the meridional wind is equatorward and there is no descent or even weak upwelling at polar latitudes, which acts as a barrier to downward transport. The wave diffusivity is large at these altitudes so some NO_x will be transported downgradient in this region.

Observations of the winter polar MLT region of both hemispheres show the presence of an eastward traveling zonal wave number two wave with significant amplitude (Sandford et al., 2008); Tunbridge and Mitchell, 2009). These waves are able to produce meridional air parcel displacements of over 10 degrees latitude. There are other types of planetary waves in the polar MLT regions as well including the 16 day wave (see Fig. 12 in Pancheva et al., 2008). The amplitude of these waves increases during major SSW events and this would reduce the survival of high altitude NO_x at the same time as downward transport through the ~90 km surface improves.

Air parcels in the CMAM MLT experience extreme vertical and horizontal motion over short periods of time due to resolved waves (gravity or Rossby or mixed waves). This is in spite of the fact that there is a non-zonal sponge layer damping all spectral components from zonal wave number 1 and higher.

"Sources of auroral NO_x (aurora here referring to NO_x produced in the aurora between 100 and 130 km) and their variability over the solar cycle have been modeled by HAMMONIA and WACCM and shown to affect NO concentrations into the mesosphere."

The more recent version of WACCM includes the Fang et al. (2008) medium energy electron parametrization but still underestimates NO_x by a factor of two (http://www.agci.org/dB/PPTs/10S1_0614_CRandall.pdf; http://www.acd.ucar.edu/Events/Meetings/HEPPA/pdf_files/Indirect_Effects_Coupling/Fang.pdf). The previous version of WACCM used the Roble and Ridley (1987) parametrization and we cannot find any comparison of the differences using WACCM. The study of Codrescu et al. (1997) is the only one we are aware of that makes any comparison of the effect on medium

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energy electrons on a model using the Roble and Ridley scheme. They find NO_x increases by around 500% at 80 km in the polar regions under perpetual equinox conditions with the TIME-GCM. This difference is likely to be much smaller under transient transport conditions but indicates that medium energy electrons are not a secondary source for MLT NO_x.

We are unable to find a publication comparing EEP NO_x to observations in HAMMONIA. It is not clear to us that the Huang et al. (1998) parametrization is exclusively low energy.

The included Figure 1 compares the 2006 ACE-FTS observed NO_x descent in the NH to our model results chosen based on a similar major SSW event from another year (the meteorology is not constrained to observations). The values of NO_x between 80 and 90 km in our model are quite similar to observations and the amounts transported to the stratopause level are in very good agreement as well. We do not see where the NO_x source above 100 km is an issue for our simulations. The case that very high values of NO_x migrate from around 120 km to 80 km is overstated and as we note above does not conform to the transport characteristics of the winter polar MLT.

We have changed the text to remove reference to gravity waves and tides and added discussion of the planetary wave transport aspect. Since the low energy electron ionization is not a dominant source of EPP NO_x for the middle atmosphere we do not feel it needs to be raised in the abstract.

p24864, l20: The phrase "between 25° and 45° away from the geomagnetic poles" means that the SPEs disc is zero when the distance to the geomagnetic pole exceeds 45°. There is no SPEs energy deposition at 25° in either geomagnetic or geometric cooridinates. The peak SPEs energy deposition is in a disc with a diameter of 50° centered on the geomagnetic pole. The Jackman papers use a disc with a diameter of 60°.

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p24866, l18: The key is that all EPP types deplete ozone in the 20 to 30 km layer around 60°S to a similar degree. Our speculation is that this modifies the evolution of the SH polar vortex in such a way as to make it weaker. However, there are structural differences in the response. This is raised in section 4.4.

p24867, l2: The text has been changed to refer to EP-flux divergence changes, which are not shown in the paper but which have been computed for all the runs. The change in EP flux divergence is shown in the included Figures 2 and 3. The drag change is complicated but consistent with the streamfunction. It should be noted that below 40 km the bulk of the wave drag change in middle and high latitudes is negative in JJA, indicating more easterly drag. We believe the wave drag increase is due to the weakening of the SH polar vortex in late fall and early winter due to ozone loss in the polar and subpolar region. To prove this requires a level of analysis which is beyond the scope of this paper and which requires mechanistic model experiments.

p24867, l20: We have added a discussion of DJF and included another figure giving a better flow.

p24869, l14: At these altitudes the photochemical lifetime of NO_y is long enough for it to survive for six months. Orsolini (2001) discusses fossil tracer remnants in more detail. This aspect is now discussed in this section but earlier.

Orsolini, Y. J.: Long-lived tracer patterns in the summer polar stratosphere, Geophys. Res. Lett., 28, 3855–3858, doi:10.1029/2001GL013103, 2001.

p24870, l1: Yes. We touch on this issue already. We have conducted analysis, not included in the paper, to evaluate the impact of a 15% increase in ozone, which is rather well mixed, on the dynamics and find it to be very small. The tropopause height does not change except in the SH pole. This now noted in section 4.3.

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p24875, l3-15: The text has been modified to mention EP-flux divergence analysis. See the included Figures 2 and 3.

p24876, l25: There is nothing specific to the ozone hole in the Polvani and Kushner mechanism. It pertains to the coupling between the stratospheric polar vortex and tropospheric circulation.

p24879, l11: We prefer to keep it for clarity.

p24881, l22: The text changes suggested by the referee have been made.

The EESC term has been added to the regression analysis when comparing with observations. It removes most of the long term variation in global ozone from halogen loading changes. The included Figure 4 shows the 1979 average zonal mean total column ozone from the solar variability only ensemble and the Fioletov ground based data. There is a "dynamical ozone hole" in 1979 in the model that is deeper than the observations. This is the result of the strong SH polar vortex and the late breakdown of the model vortex in spring compared to observations. This feature shows little interannual variability. For the JJA period the observations reach the model total column ozone value in the SH polar region only by 1994. We believe the model basic state without EPP for the 1979 to 2006 period is not that far from the observed state as to render a comparison with observations pointless. The key feature is the strength of the SH polar vortex, which is not fundamentally changed by the development of the ozone hole. It is the strength of the SH polar vortex which results in the significantly different response of the SH to the solar cycle compared to the NH.

p24885, l13: See the included Figures 5 and 6 showing the regression analysis of the EP flux divergence and streamfunction for the solar variability only and combined EPP and solar variability ensembles. In the presence of EPP the EP flux divergence

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experiences an intensification at high SH latitudes between 20 and 30 km during solar minima (Fig. 6). In the tropical tropopause region there is an intensification of easterly drag during solar minima as well (Fig. 6). This contributes to upwelling through the TTL and affects the cold point temperature.

In contrast, the solar variability only ensemble response (Fig. 5) lacks the tropical wave drag change and has the opposite behaviour in the SH. At high latitudes between 20 and 30 km there is a weakening during solar minima. In the upper and middle SH stratosphere there is also a reverse response with weakening during solar minima. Given the behaviour of the zonal wind, this suggests that the wave drag is responding to differences in the zonal wind structure rather than driving the it. The main difference between the two ensembles is the ozone build-up in the SH pole region which is removed by EPP. Figure 18 in the paper has been split into two parts to show the EP flux divergence regression, which is also discussed in section 5.2.1.

The suggested reference has been included in addition to a change in the regression model to include EESC. Figures 21, 22 and 23 have been changed accordingly.

References:

Codrescu, M. V., Fuller-Rowell, T. J., Roble, R. G., and Evans, D. S.: Medium energy particle precipitation influences on the mesosphere and lower thermosphere, J. Geophys. Res., 102, 19,977–19,987, 1997.

Liu, H.-L. et al.: Thermosphere extension of the Whole Atmosphere Community Climate Model, J. Geophys. Res., 115, A12302, doi:10.1029/2010JA015586, 2010.

McLandress, C., Ward, W. E., Fomichev, V. I., Semeniuk, K., Beagley, S. R., McFarlane, N. A., and Shepherd, T. G.: Large-scale dynamics of the mesosphere and lower thermosphere: An analysis using the extended Canadian Middle Atmosphere Model, J. Geophys. Res., 111, D17111, doi:10.1029/2005JD006776, 2006.

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Portnyagin, Y. I., et al.: Monthly mean climatology of the prevailing winds and tides in the Arctic mesosphere/lower thermosphere, Ann. Geophys., 22, 3395–3410, 2004.

Randall, C. E., Harvey, V. L., Siskind, D. E., France, J., Bernath, P. F., Boone, C. D, and Walker, K. A.: NO_x descent in the Arctic moddle atmosphere in early 2009, Geophys. Res. Lett., 36, L18811, doi:10.1029/2009GL039706, 2009.

Sandford, D. J., Schwartz, M. J., and Mitchell, N. J.: The wintertime two-day wave in the polar stratosphere, mesosphere and lower thermosphere, Atmos. Chem. Phys., 8, 749-755, doi:10.5194/acp-8-749-2008, 2008.

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Vogel, B., Konopka, P., Grooß, J.-U., Müller, Funke, B., López-Puertas, M., Reddmann, T., Stiller, G., von Clarmann, T., and Riese, M.: Model simulations of stratospheric ozone loss caused by enhanced mesospheric NO_x during Arctic winter 2003/2004, Atmos. Chem. Phys., 8, 5279–5293, 10.5194/acp-8-5279-2008, 2008.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/10/C13084/2011/acpd-10-C13084-2011-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 10, 24853, 2010.

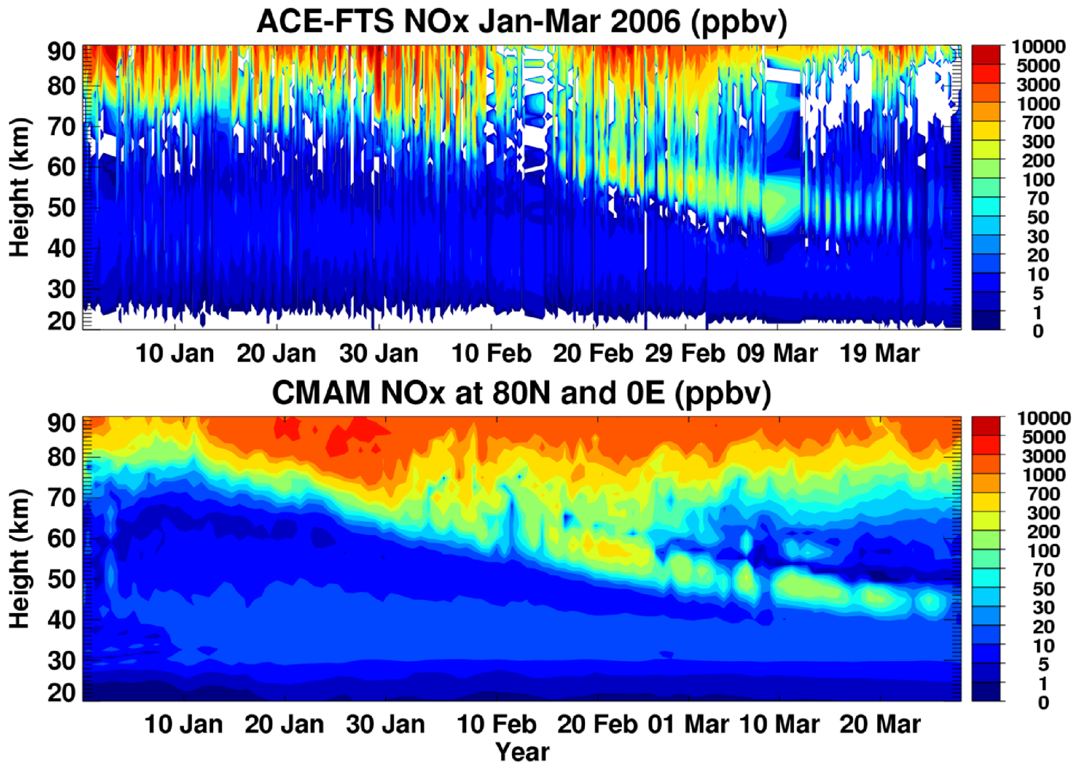

Fig. 1. NH high latitude NO$_x$ observed in 2006 (top) compared to CMAM simulations for a year with a comparable major SSW (bottom).

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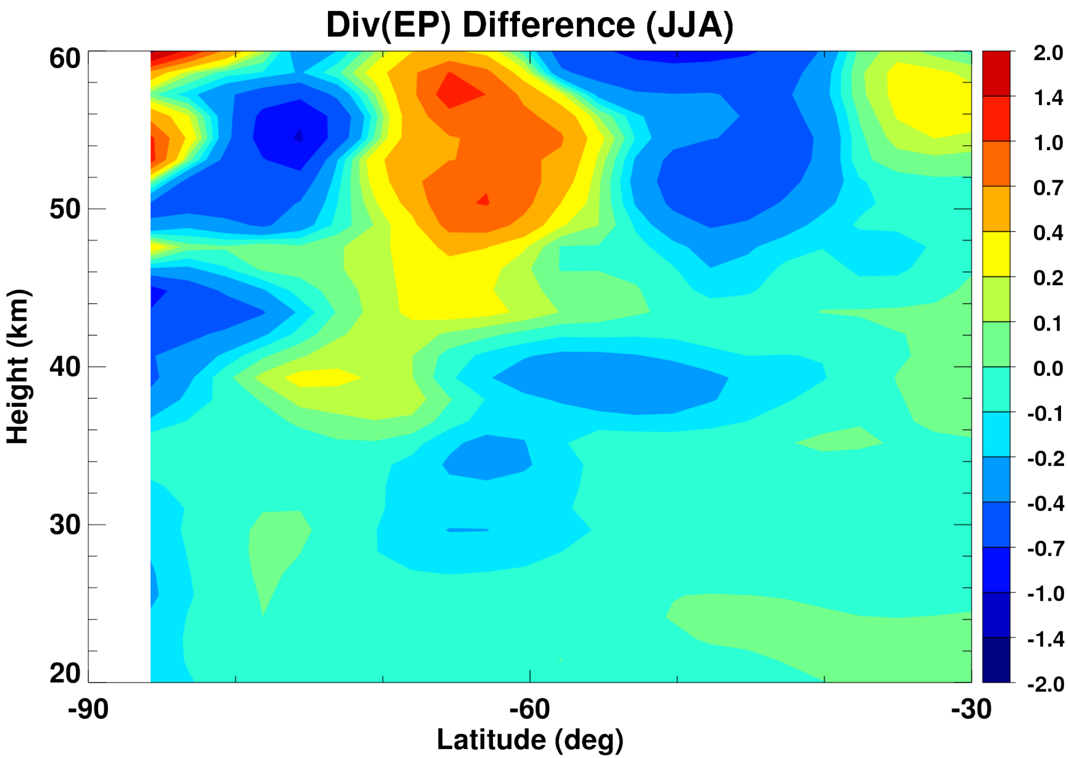

Fig. 2. JJA change in the Eliassen-Palm Flux divergence for the Aurora run from the Reference run.

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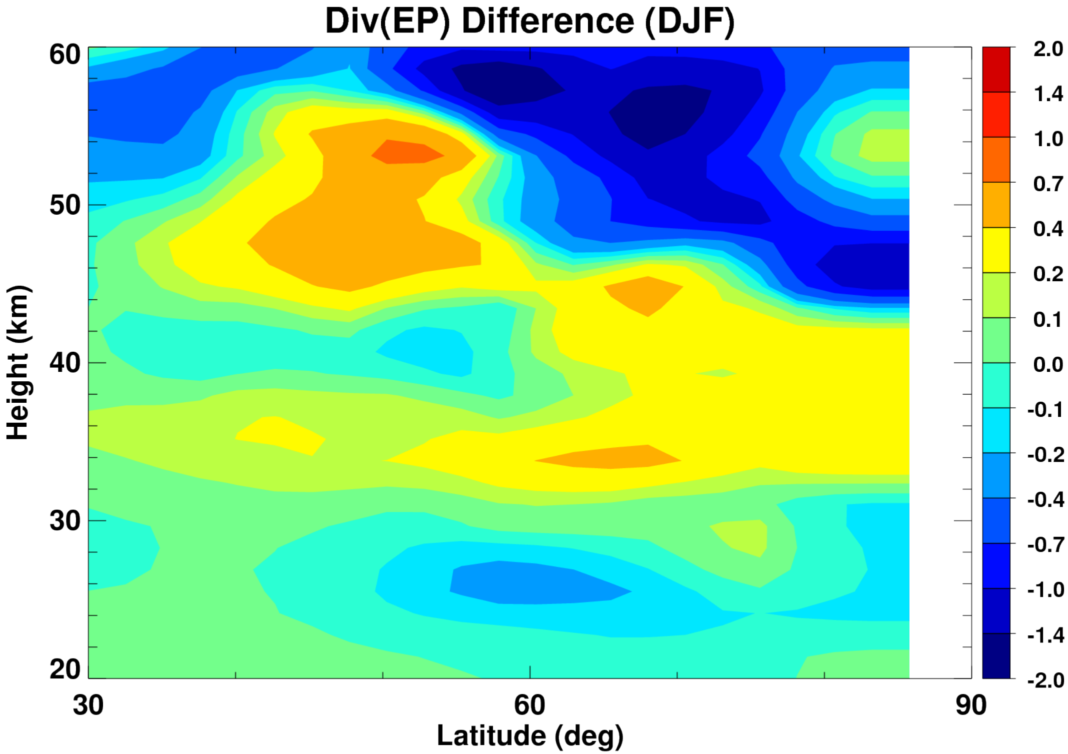

Fig. 3. DJF change in the Eliassen-Palm Flux divergence for the Aurora run from the Reference run.

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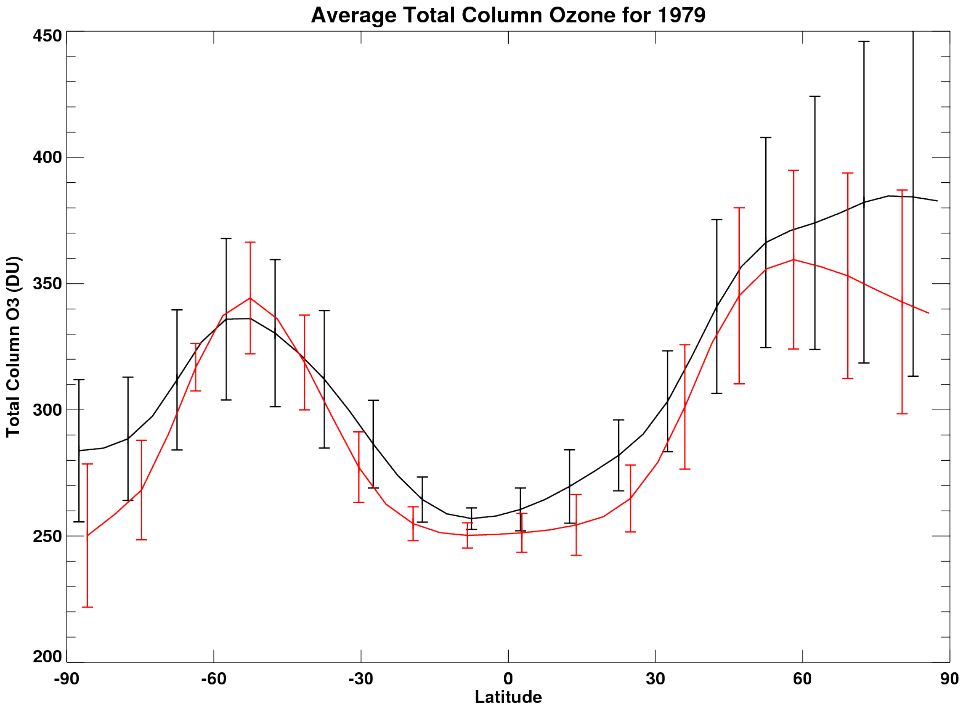

Fig. 4. The zonal mean total column ozone average for 1979 in Dobson units. Solar variability only ensemble (red) and ground based observations (black) are shown. The error bars are variance for 1979.

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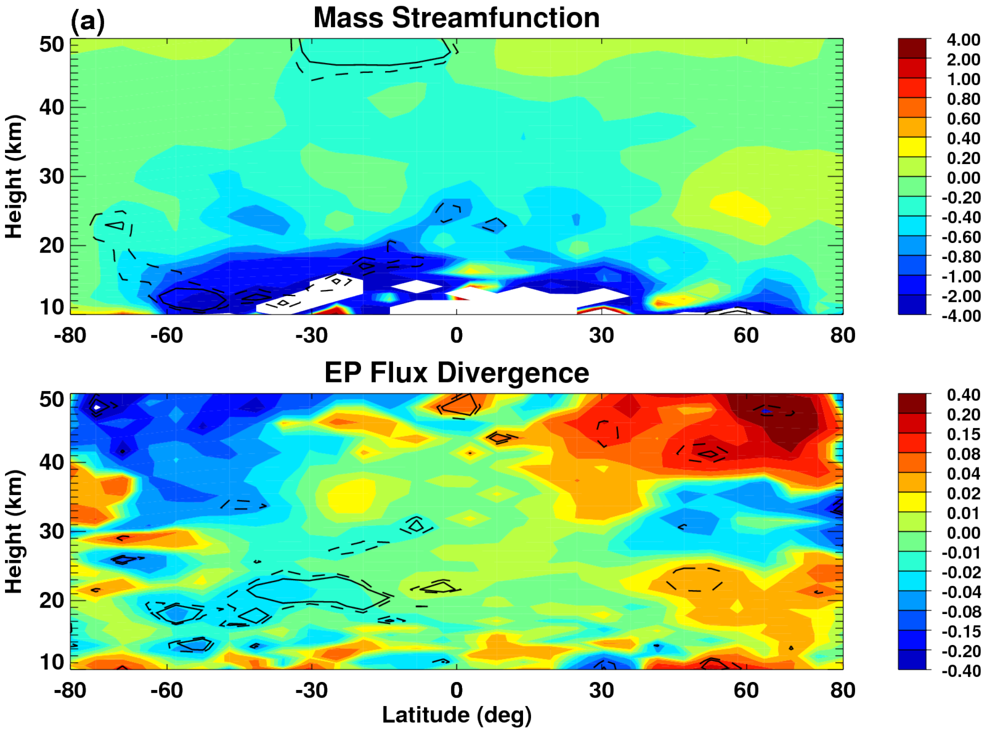

Fig. 5. F10.7 regression coefficient for the solar variability only ensemble.

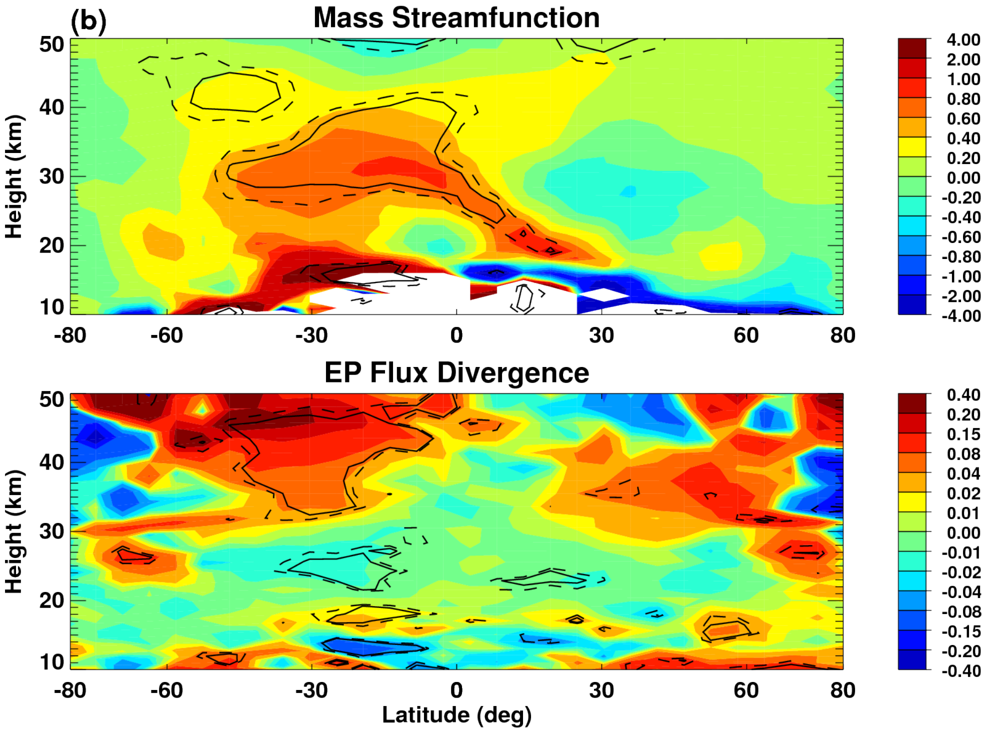

Fig. 6. F10.7 regression coefficient for the combined EPP and solar variability only ensemble.

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