Solar magnetic flux influences on the dynamics of the winter middle atmosphere

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Abstract. A number of observational studies have reported a connection between various lower atmospheric parameters and a range of geomagnetic and solar coronal indices. The bulk of the Sun’s magnetised plasma energy is absorbed in the high-latitude upper atmosphere, far removed from the troposphere and the stratosphere, so a physical mechanism which accounts for these correlations has proved elusive. In this paper, a mechanistic three-dimensional model of the atmosphere between 10 and 130 km has been developed to demonstrate that high energy particles from the solar wind can perturb the winter stratosphere significantly. Planetary waves provide an effective means of coupling solar-induced changes in the thermosphere down to the stratosphere. A qualitatively similar response to forcing by increasing solar ultraviolet radiation was obtained even though there was no in situ forcing in the stratosphere.

Introduction

Chapman and Ferraro [1931] were the first to postulate the existence of a stream of ionized particles, ejected from the Sun and interacting with the Earth’s atmosphere, to explain the occurrence of aurorae and other related disturbances. Most of the plasma that enters the Earth’s magnetosphere is directed along magnetic field lines into the polar regions where it is deposited in the ionosphere and subsequently the thermosphere (for a review refer to Cowley [1996]). There is evidence to suggest that the atmosphere below 90 km responds to solar coronal activity. For example, an examination of over one hundred crossings of the polar cap by the Earth by Wilcox et al. [1973] produced significant reductions in the area of winter time troughs at 500 mb. Pudovkin and Veretenenko [1995] and Svensmark and Friis-Christensen [1997] have noted a change in the cloud cover that is related to the solar wind. They proposed a modulation of incoming galactic cosmic ray flux to bring about the requisite atmospheric changes. Tinsley and Heeis [1993] have suggested that solar wind induced changes in the global atmosphere-ionosphere circuit would affect the rate of initial ice nucleation via electro-scavenging. Variations in the cloud cover would then affect the radiation budget and latent heat release with implications for the general circulation.

Evidence for dynamic processes enhancing the atmospheric response to solar irradiance variability was presented by Labitzke and Van Loon [1988]. They pointed out that the combination of the Quasi-Biennial Oscillation and irradiance changes resulted in an enhanced response in the winter stratosphere. Kodera et al. [1991] modeled this successfully, albeit using exaggerated levels of ultraviolet heating. Bochtíček et al. [1999] used 40 years of global surface parameters to detect a significant QBO/geomagnetic activity dependence. In contrast to ultraviolet heating, the in situ forcing of the lower atmosphere by solar particles is negligible. Additional amplification could be obtained through ozone feedback (Haigh [1994] and Balachandran et al. [1995]) and through coupling with the upper mesosphere and thermosphere (Arnold and Robinson [1998]).

To assess the contribution from dynamic activity via planetary wave coupling with the upper atmosphere a number of numerical simulations were carried out using a model of the middle atmosphere and lower thermosphere under a range of geomagnetic conditions. The impact on the winter stratosphere was examined.

Description of the coupled middle and upper atmosphere model and the experimental procedures

Planetary scale Rossby waves play an important role in maintaining the winter stratospheric circulation (for a review see for example Geller [1993]). To investigate the dynamical coupling with the thermosphere, an extended version of the UK Meteorological Office Stratosphere Mesosphere Model has been developed (Arnold and Robinson [1998, 2000]). The version used in this paper has sixty five vertical levels at a resolution of four per scale height.

To avoid the difficulties associated with simulating the complex processes in the upper atmosphere, such as non-Local Thermodynamic Equilibrium and heating from particle precipitation, linear relaxation to the empirical MSIS-90E temperature model (Hedin [1991]) was adopted. Detailed infra-red radiative transfer calculations were carried out between 10 and 70 km at eight equally spaced longitudes every three hours using the scheme developed by Shine [1987]. In the Northern Hemisphere winter, large amplitude planetary waves regularly displace the eastward motion of the circulation, resulting in significant errors if zonally averaged temperatures are used.

The Stratospheric Sounding Unit, (Müller et al. [1980]), provided observations to derive realistic, vertically propagating planetary waves at a lower boundary of 314 mb between 1st December 1992 and 28th February 1993. The appropriate solar minimum flux rates for this time of year were selected for both sets of experiments described in this paper. The initial conditions were obtained from MSIS and the Horizontal Wind Model (Hedin et al. [1993]). The model was stepped forward in time at 90 second intervals for 90 days.
The contribution of transient planetary waves to the output on time scales of less than a week was reduced by computing 10-day averaged quantities. To generate an ensemble of runs, the time series of Ap values were multiplied by scaling factors between geomagnetically quiet and active conditions. Least squares fitting of each atmospheric parameter and Ap provided a quantitative estimate of the response to external forcing and the level of internal variability.

**Results from the steady geomagnetic forcing experiment**

Within MSIS, the atmospheric response to magnetic flux changes above 90 km can be prescribed via the Ap index. In the first series of ten simulations, a range of constant Ap values evenly spaced between 1 and 60 was chosen with the former representing extremely quiet conditions whilst the latter was applicable to strongly disturbed conditions. This experiment most closely resembles the study by Arnold and Robinson [2000] where constant F10.7 cm fluxes between solar minimum and solar maximum levels were employed.

An Ap index sustained at 60 is greater than that observed in practice but allows the model to be tested over a wide range of conditions.

After 75 days, changes to the heating of the thermosphere associated with enhanced geomagnetic activity had made a significant impact on the winter stratospheric circulation (figure 1). Transport processes contribute a significant fraction of the heating in this region as levels of direct solar irradiance are low. The cooling of the winter polar stratosphere indicated that meridional transport was being inhibited by increased forcing in the lower thermosphere. In the summer hemisphere, planetary waves tend to be prevented from propagating from the troposphere into the stratosphere against a background of westward flow conditions (Charney and Drazin [1961]). Without planetary wave forcing, the coupling between the stratosphere and the lower thermosphere is very weak (Arnold and Robinson [1998]).

Holton [1994] had postulated that the combination of the Quasi-Biennial Oscillation and the modulating influence of solar heating by ultraviolet radiation in the middle atmosphere might induce a change of the circulation in the win-

**Figure 1.** 10 day mean zonally averaged temperature differences (°K) after 75 model days derived from the best fit to 10 constant Ap experiments ranging in value from 1 to 61.

**Figure 3.** Daily indices of Ap between August and October 1992.

**Figure 2.** Best fit 10 day mean zonally averaged zonal wind differences after 75 model days.

**Figure 4.** As figure 1, but using time varying Ap. The 10 simulations were generated by scaling the Ap by between 0 and 150% of the observed values.
The polar vortex in the winter stratosphere provides a mechanism for positive feedback between radiative and dynamical processes. Any stratospheric cooling results in the intensification of the latitudinal thermal gradient that in turn enhances the upper air jets. Stronger jets reduce the ability of planetary waves to mix mid- and high-latitude air masses (see for example McIntyre [1987]) and so the sunlight-poor vortex cools further. Arnold and Robinson [1998] demonstrated that planetary waves from the troposphere could be redirected by changes in the thermosphere and the response of the stratosphere amplified by this effect.

The high latitude Northern Hemisphere jet experienced significant acceleration when the geomagnetic activity was enhanced. The zonal mean zonal wind increase approached 7 ms\(^{-1}\) at close to 40 °N (figure 2). This represented a significant fraction of the upper atmosphere jet strength whose peak was typically 60-80 ms\(^{-1}\). The close proximity of the wind enhancement in the Northern Hemisphere to the direct forcing region provided an indication that the latter was influencing the wave-mean flow interactions in the mesosphere that ultimately propagated down into the stratosphere. A lesser deceleration of the mean flow was generated at equatorial latitudes to conserve angular momentum. When the appropriate Quasi-Biennial Oscillation forcing is active, it is conceivable that the process can either be amplified or a reversal of the flow pattern sustained (see for example, Kodera et al. [1991]).

Results from variable geomagnetic forcing experiments

Transient, non-linear and non-conservative phenomena play an important role in driving the underlying circulation of the middle atmosphere (Andrews and McIntyre [1978]). Therefore, rapidly varying thermospheric conditions associated with geomagnetic activity can have a significance greater than that from the seasonally averaged activity levels. Once the middle atmosphere has been modified, further internal coupling between the circulation and the waves can amplify the process as discussed in the previous section and irreversibly alter the evolution of the atmosphere.

Episodes of intense fluctuations in Ap can occur on a time scale of just of few days, usually associated with geomagnetic storms. As the winter of 1992/3 was geomagnetically eventful, an adjacent three month interval starting on August 1st, 1992 was selected instead for a series of daily values to be fed into the MSIS reference field (figure 3). A series of intense geomagnetic storms would now occur in the same month as winter stratospheric warming events in the Northern Hemisphere. The model simulation used the same lower boundary forcing data and seasonal irradiance levels as the previous experiments.

The variable geomagnetic forcing scenario generated perturbations in the winter polar stratosphere temperature (figure 4) whose amplitude was comparable to that of the previous experiment, even though the time averaged Ap was considerably lower (=18.3). The morphological similarity between the results from this and the previous experiment indicated that the precise details of the original thermospheric forcing mechanism were of only secondary importance. One possible explanation for this is that transport time scales in the thermosphere are much shorter than those associated with planetary waves.

An assessment of the correlation coefficients generated for each zonally averaged temperature within the model confirmed the dominance of the direct forcing above 80 km and a complex response pattern at lower altitudes. A significance above the 95 % threshold was achieved in the lower stratosphere between 30 °N and 60 °S, although the heating involved was barely discernible. The cooling region in the winter stratosphere was both significant and of large amplitude.

Zonally averaged quantities are not always the best indicators of changes in the circulation. Constant pressure cross-sections of the best-fit temperature differences revealed considerable planetary wave structure in the geomagnetically induced perturbations in the winter stratosphere. As the winter stratospheric vortex was often disturbed and displaced from the pole by planetary waves, the extent of the external forcing was partially obscured using zonally averaged output. The difference fields themselves exhibited wave-like structures highlighting the contribution being made by planetary waves to the winter climatology. There was a warmer region during this ten day period over Southern Europe during active geomagnetic conditions indicating that the global response to external forcing need not be uniform.

Conclusion

Corpuscular emissions from the Sun are able to enter the Earth's upper atmosphere, especially at high latitudes and can bring about significant heating of the lower thermosphere. In addition, strong ionospheric convection currents are generated that accelerate the neutral atmosphere through friction. The resulting changes to the climatology of the lower thermosphere modify the propagation of waves travelling upwards from the lower atmosphere. In the current paper, we have investigated the role that planetary waves play in coupling the middle and upper atmospheric response to geomagnetic activity related changes.

Using physically plausible levels of solar and planetary wave activity sustained over the Northern Hemisphere winter period, the extent of the stratospheric response was found to be comparable to that achieved in an earlier study that considered ultraviolet flux variations between solar minimum and solar maximum conditions. In the latter case, significant amounts of energy were being input directly into the stratosphere, whereas in the case of geomagnetic activity changes, the in situ contribution was negligible. Two ensembles of experiments were performed to enhance the statistical robustness of the results. The global lower thermosphere adjusted rapidly to relatively localised forcing near the magnetic poles, compared to the time scales of the planetary wave disturbances. Therefore, the stratospheric response was qualitatively similar to that obtained by ultraviolet radiation, even though the latter heating occurred in a different region of the atmosphere.

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