Mesospheric Dynamical Changes Induced by the Solar Proton Events in October-November 2003

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Brief, Popular Summary of the Paper:

Large-scale explosions on the Sun near solar maximum lead to emissions of charged particles (mainly protons and electrons). Occasionally the Earth is positioned in its orbit such that these solar particles interact with the Earth's magnetosphere and rain down on the polar regions. "Solar proton events" have been used to describe these phenomena since the protons associated with these solar events sometimes create a significant atmospheric disturbance.

The very large solar proton events in October-November 2003 caused very distinctive polar changes in a layer of the atmosphere known as the mesosphere, which is located between about 50 and 90 km (~30 to 55 miles) above the Earth's surface. The solar protons created hydrogen- and nitrogen- containing compounds, which led to the mesospheric ozone destruction. A general circulation model with a bottom at 30 km and a top at 500 km was used to study the atmospheric influences. The model showed ozone decreases of 10-70% during a very intense period of the solar proton events. The polar ozone depletion led to a cooling of a few degrees in the lower mesosphere and a heating of a few degrees in the upper mesosphere during the events. The associated polar mesospheric wind changes amounted to 20-25% of the background winds. These solar proton-induced mesospheric modifications gradually diminished over a period of 4-6 weeks. Although solar proton events appear to have no long-term mesospheric impact, they do play a significant role in short-term polar mesospheric variability.

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Abstract: The very large solar storms in October-November 2003 caused solar proton events (SPEs) at the Earth that impacted the upper atmospheric polar cap regions. The Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIME-GCM) was used to study the atmospheric dynamical influence of the solar protons that occurred in Oct-Nov 2003, the fourth largest period of SPEs measured in the past 40 years. The highly energetic solar protons caused ionization, as well as dissociation processes, and ultimately produced odd hydrogen (HO_x) and odd nitrogen (NO_y). Significant short-lived ozone decreases (10-70%) followed these enhancements of HO_x and NO_y and led to a cooling of most of the lower mesosphere. This cooling caused an atmospheric circulation change that led to adiabatic heating of the upper mesosphere. Temperature changes up to +/- 2.6 K were computed as well as wind (zonal, meridional, vertical) perturbations up to 20-25% of the background winds as a result of the solar protons. The solar proton-induced mesospheric temperature and wind perturbations

diminished over a period of 4-6 weeks after the SPEs. The Joule heating in the mesosphere, induced by the solar protons, was computed to be relatively insignificant for these solar storms with most of the temperature and circulation perturbations caused by ozone depletion in the sunlit hemisphere.

1. Introduction

Several very large solar eruptive events in late October and early November 2003 resulted in huge fluxes of charged particles at the Earth [Mewaldt et al. 2005]. Much of the energy was carried by solar protons, which impacted the middle atmosphere (stratosphere and mesosphere) leading to ionizations, dissociations, dissociative ionizations, and excitations. The proton-induced atmospheric interactions resulted in the production of odd hydrogen, HO_x (H, OH, HO_2), and odd nitrogen, NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, HONO, $ClONO_2$, $ClNO_2$, $BrONO_2$) constituents either directly or through a photochemical sequence [e.g., Swider and Keneshea, 1973; Crutzen et al., 1975]. There were a few periods from 26 Oct. – 7 Nov., 2003, when the proton fluxes increased dramatically beyond background levels for 1-3 days. These periods are known as solar proton events (SPEs) and some of the middle atmospheric constituent influences during these SPEs have been discussed in Degenstein et al. [2005], Orsolini et al. [2005], Jackman et al. [2005a], Rohen et al. [2005], Lopez-Puertas et al. [2005a,b], Verronen et al. [2005], and von Clarmann et al. [2005]. These Oct./Nov. 2003 SPEs were very intense and were computed to be the fourth largest SPE period in the past 40 years [Jackman et al. 2005b].

We are not aware of any measured atmospheric dynamical changes during these very significant atmospheric perturbations, however, past studies [Banks, 1979; Reagan et al., 1982; Jackman and McPeters, 1985; Roble et al., 1987; Reid et al., 1991; and Jackman et al., 1995] have suggested that very large SPEs can lead to modest temperature changes through ozone depletion and/or Joule heating. To the best of our knowledge past studies have used two types of models to study the dynamical influence of SPEs on the atmosphere: 1) those with ozone photochemistry which calculated temperature decreases caused by reduced solar heating from decreased ozone; and 2) those with Joule heating which computed temperature increases via enhanced heating from the proton flux and electric field changes during the SPEs. We will use the latest version of the TIME-GCM (Thermosphere Ionosphere Mesosphere Electrodynamics – General Circulation Model) [Roble, 2000], which contains both ozone photochemistry and auroral particle and Joule heating, to study the influence of the very large proton fluxes during Oct./Nov. 2003 on the temperature and winds of the middle atmosphere. The TIME-GCM allows us the opportunity to compare and contrast the different atmospheric perturbations during SPEs that lead to temperature and wind changes. We will focus on a snap-shot output from the model for one day, 30 October 2003, at 0:00 UT near a period of maximum solar proton flux to investigate these effects.

2. Model Description

The TIME-GCM was first described in Roble and Ridley [1994]. This model has an effective 5° latitude x 5° longitude grid with 45 constant pressure surfaces in the vertical between approximately 30 and 500 km altitude with a vertical resolution of 2 grid points per scale height and a model time step of 5 minutes. The TIME-GCM has a comprehensive set of physical, chemical, and dynamical processes included to simulate the upper atmosphere and ionosphere. A detailed description of the model and its components is given in Roble [2000].

The model is forced at its lower boundary of 10 hPa by global geopotential height and temperature distributions from NCEP (National Centers of Environmental Prediction) analysis.

This feature provides the ability to simulate particular periods of interest, such as 27 October through 11 December 2003 for this specific study [e.g., Liu and Roble, 2005].

3. Solar Proton Caused Constituent Changes

We use the proton flux data provided by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) for the NOAA Geostationary Operational Environmental Satellites (GOES) (see http://sec.noaa.gov/Data/goes.html). The GOES 11 data are considered to be the most reliable of the current GOES datasets for the proton fluxes depositing energy into polar latitudes and were used as the source of protons in several energy intervals [see Jackman et al. 2005a] for the very active time period 26 October through 7 November 2003.

The protons are fit using an isotropic Maxwellian type input spectra, similar to what was used by Roble and Ridley [1987] for electrons. The energy deposition of the proton fluxes into the atmosphere is computed using a fitting technique described in Lummerzheim [1992], which agrees well with other energy deposition techniques [e.g., Reid, 1961; Jackman et al., 1980]. Ionization rates are computed assuming 35 eV/ion pair.

3.1. HO_x and NO_y Enhancments

Solar protons and their associated secondary electrons produce both odd hydrogen and odd nitrogen as well as ion pairs. Odd hydrogen is produced via complicated ion chemistry that takes place after the initial formation of ion pairs [Swider and Keneshea, 1973]. Odd nitrogen (NO_y) is produced when the energetic charged particles collide with and dissociate N_2 [Porter et al., 1976]. We follow the methodology of Jackman et al. [2005a] in the production of NO_y and Solomon et al. [1981] in the production of HO_x via solar protons.

3.2. Ozone Depletion

Both HO_x and NO_y can lead to the destruction of ozone in the middle atmosphere via catalytic cycles. However, the HO_x constituents are the primary cause of ozone depletion in the mesosphere and upper stratosphere during SPEs. Due to the relatively short lifetime of HO_x species (~hours), the HO_x impact on ozone is also short-lived [e.g., Solomon et al., 1981].

The most intense proton fluxes were recorded 28-30 October 2003 [Mewaldt et al. 2005]. We show the predicted zonal average ozone change at a snapshot during this time period (0:00 UT on 30 October 2003) in Figure 1. The largest decreases are at the poles with about 70% predicted in the northern and about 30% in the southern middle mesosphere (70-75 km). Ozone depletions over 10% extended over most of the lower and middle mesosphere between about 50° and 90° in both hemispheres. The SPE-caused ozone depletion has a strong solar zenith angle dependence such that larger (smaller) depletions are observed at larger (smaller) solar zenith angles [Solomon et al., 1983].

Small ozone enhancements of just over 5% are predicted near the southern polar mesopause and are driven by the changes in winds caused by the SPEs (see section 5.1.2). The vertical winds in the upper mesosphere were modified such that more atomic oxygen was transported to this region leading to an increase in ozone.

4. Computed Heating/Cooling Rate Changes

Any dynamical (temperature and winds) changes due to SPEs are likely to be driven by heating and/or cooling rate variations. The Joule, solar, and chemical heating rate changes as well as cooling rate changes are discussed in the following subsections.

4.1. Heating Rate Changes

4.1.1 Joule Heating Changes

Large fluxes of energetic solar protons can lead to enhancements of the Pederson conductivity of the mesosphere. These conductivity enhancements coupled with increases in electric fields associated with concurrent ionospheric disturbances can result in Joule dissipation or heating. Banks [1979] and Roble et al. [1987] showed that locally mesospheric Joule heating could be substantial (1-10 K/day) for certain large SPEs (August 1972 and July 1982) at particular locations and times. However, not much information is available to determine the global Joule heating impact because of the complex electric field distribution over the polar cap during storms [e.g., Zhang et al., 2005].

Our computations of Joule heating during Oct./Nov. 2003, which is derived using an empirical ion convection model with a time varying cross-polar cap potential drag specified by the 3-hr Kp index [Roble and Rodley, 1987], indicate a very large thermospheric contribution and fairly significant mesospheric contributions at certain times and locations within the polar cap regions (>60° geomagnetic latitude). However, the net zonal average contribution of SPE-induced Joule heating to total mesospheric heating appears to be small in the two hemispheres with a maximum input of +0.1 K/day near 70 km, 90°N and +0.05 K/day near 75 km, 80°S (shown in Figure 2a for 0:00 UT on 30 October 2003).

4.1.1 Solar and Chemical Heating Changes

Ozone is a strong absorber of solar (ultraviolet, visible, and infrared) radiation, turning this light energy into heat [Brasseur and Solomon, 2005]. Therefore, any decrease in ozone will ultimately lead to a decrease in solar heating. Changes in chemical heating will also result in the SPE-perturbed atmosphere. The influence of the SPEs due to the combined solar and chemical heating rate changes at 0:00 UT on 30 October 2003 are shown in zonal average form in Figure 2b.

The depleted ozone leads to less heating in the sunlit atmosphere below about 77 km (Southern Hemisphere, SH) and 80 km (Northern Hemisphere, NH) peaking at -1.5 K/day between 60 and 65 km (SH) and at -0.7 K/day between 57 and 63 km (NH). The computed increase near 85 km and south of 75°S in the SH is driven by the HO_x enhancements produced by the solar protons as well as an increase in atomic oxygen (O) due to an increase in downward transport (see section 5.1.2). Such enhancements in HO_x and O lead to an increase in exothermic reactions involving these constituents [Roble, 1995] and the release of heat.

4.1.3 Adiabatic Heating

The atmosphere can warm via adiabatic heating through compression caused by enhanced downward winds (or reduced upward winds). We computed a zonal average adiabatic heating increase in the upper polar southern mesosphere with a maximum of +2.3 K/day near 85-90 km at 0:00 UT on 30 October 2003 due to circulation changes driven by the SPE-caused ozone reductions below 80 km (see Figure 2c). Other computed adiabatic heating changes were smaller at lower southern and all northern latitudes. The Equatorial cooling above 85 km was caused by enhanced upwelling.

4.2. Cooling Rate Changes

Ozone is a radiatively active gas which absorbs and re-radiates infrared light. A loss of ozone in the tenuous mesosphere will thus lead to a decrease in this process and cause a net reduction in cooling, especially in the lower and middle mesosphere. We compute a zonal average maximum decrease in cooling rate of -0.6 K/day near 60 km, 90°S at 0:00 UT on 30 October 2003 due to the SPE-caused ozone reductions (not shown).

Other cooling rate changes from SPEs involve impacts on carbon dioxide (CO_2), another radiatively active gas. SPE-caused enhancements in atomic oxygen in the southern polar upper mesosphere will lead to more O-CO_2 collisions which will result in more excited CO_2 molecules and more cooling. We compute a zonal average maximum increase in cooling rate of +0.8 K/day near 90-95 km, 90°S at 0:00 UT on 30 October 2003 due to the SPEs (not shown).

Computed cooling rate changes from either ozone depletions or excited CO_2 enhancements tended to be much smaller in the northern hemisphere.

5. Computed Dynamical Changes

Dynamical (temperature and wind) changes have long been associated with SPEs. Temperature decreases of 1-3 K were computed to follow from very large SPEs in several studies [Reagan et al., 1982; Jackman and McPeters; Roble et al., 1987; Reid et al., 1991; and Jackman et al., 1995], although such SPE-driven temperature decreases have not yet been observed. Other dynamical changes including variations in mesospheric winds have been observed associated with SPEs in 1982, 1984, and 1989 [Rottger, 1992; Johnson and Luhmann, 1993]. Our calculations of the resultant dynamical changes during and after the Oct./Nov. 2003 SPEs as well as some sensitivity studies investigating the seasonal variations and saturation of the impact will be discussed in this section.

5.1. 30 October 2003

We continue with our presentation of results from the TIME-GCM for 30 October 2003, a very active period of the Oct./Nov. 2003 SPEs.

5.1.1 Temperature Changes

The heating and cooling rate changes ultimately led to calculated temperature variations as a result of the Oct./Nov. 2003 SPEs. The largest temperature changes in the lower to middle mesosphere were driven by the ozone decreases, which forced both heating and cooling rate changes. The heating rate reductions dominated the effect and resulted in temperature decreases of a zonal average maximum of -2.6 K on 30 Oct. 2003 near 65 km, 90°S (see Figure 3a). Most of the mesosphere was dominated by decreases in temperature.

Net heating rate increases due to adiabatic heating and cooling rate increases caused by enhanced CO_2 excitation were of significance in the upper mesosphere. The adiabatic heating change dominated and resulted in predicted temperature increases of a zonal maximum of +2.5 K on 30 Oct. 2003 near 90 km, 90°S (see Figure 3a). These predicted temperature changes are mainly concentrated in the sunlit southern hemisphere and were very small in the northern hemisphere. The maximum temperature changes are about a 1-2% variation compared with the background temperature distribution.

5.1.2. Wind Changes

The zonal, meridional, and vertical winds were all perturbed as a result of the SPEs. The zonal wind was forced to be more westerly by the SPEs resulting in a zonal average maximum speed change of 2.4 m/s on 30 Oct. 2003 near 80 km, 65°S (see Figure 3b). These changes were modest when compared with the background and amounted to a maximum of about a 20% change in the SH, primarily opposing the prevailing easterlies at this time of year.

The meridional wind was forced to be generally more southerly in the SH resulting in a zonal average maximum speed change of -0.8 m/s on 30 Oct. 2003 near 95 km, 65°S (not shown). These changes were modest compared with the background and amounted to about a

20-25% change near the SH mesopause, primarily opposing the general northerly flow at this time of year.

The vertical wind was forced to be more downward in the SH with a maximum change of -0.3 mm/s on 30 Oct. 2003 near 88 km, 90°S (see Figure 3c). These changes were again modest compared with the background and amounted to about a 20% change in the upper polar SH mesosphere, primarily opposing the general upward motion at this time of year. The reduced upward motion thus resulted in some adiabatic heating change leading to a heating of the upper mesosphere that was discussed in section 4.1.3.

5.2. Temporal Changes: 26 Oct. - 11 Dec. 2003

A simulation was completed for the period 26 Oct. through 11 Dec. 2003 to study the longevity of the dynamical influence. Some of the temperature predictions from this simulation are presented in Figure 4. One location in the TIME-GCM (82.5°S at 0°W) is given in the plot. The perturbation to the atmosphere is fairly quickly damped such that over 90% of the impact of the Oct./Nov. 2003 SPEs is gone by 11 Dec. 2003. The majority of the mesospheric dynamical effects from SPEs thus appear to diminish over a period of 4-6 weeks after the events. A similar outcome occurs at all SH locations. The NH SPE-caused perturbations are much smaller than in the SH and they also dissipate over a period of 4-6 weeks after the events. The maximum dynamical impacts appear to be confined to about 10 days near the big events.

5.3. Sensitivity Studies

We have also simulated the 14-15 July 2000 (Bastille Day storm) SPE, the third largest SPE period in the past 40 years [Jackman et al. 2001, 2005b]. The computed dynamical changes were very similar to those reported here for the Oct./Nov. 2003 SPEs, however, the majority of the response was in the NH, the sunlit hemisphere. The bulk of the impact from SPEs is apparent in the sunlit hemisphere because of the very substantial impact on atmospheric heating/cooling from the ozone decreases.

Since the dynamical effects of the Oct./Nov. 2003 SPEs were relatively modest, we performed a sensitivity study in which the proton flux was enhanced by a factor of 10. The purpose of this simulation was to determine the response of the atmosphere in a more perturbed state. We found that the temperature and wind effects were almost a factor of two larger in this **very perturbed** simulation implying that the SPE-induced mesospheric impact saturates. Since the majority of the mesospheric dynamical response is driven by the ozone depletion, the mesospheric effect is limited by the amount of ozone destruction, which is computed to be over 50% in the SH mesosphere.

6. Conclusions

Significant short-lived ozone decreases (10-70%) accompanied the Oct./Nov. 2003 SPEs and led to a cooling of most of the mesosphere. This cooling induced circulation changes that led to adiabatic heating of the upper polar mesosphere above ~80 km. Temperature changes up to +/- 2.6 K were computed as well as resultant wind (zonal, meridional, vertical) perturbations up to 20-25% as a result of the solar protons. The solar proton-induced mesospheric temperature and wind perturbations diminished over a period of 4-6 weeks past the SPEs. The Joule heating in the mesosphere, induced by the solar protons, was computed to be relatively insignificant for these solar storms.

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Figure 1. Predicted ozone change on 30 Oct. (Day 303), 2003 with a contour interval of 5%, near the maximum proton flux period. The largest decrease is -69% and the largest increase is +6%.

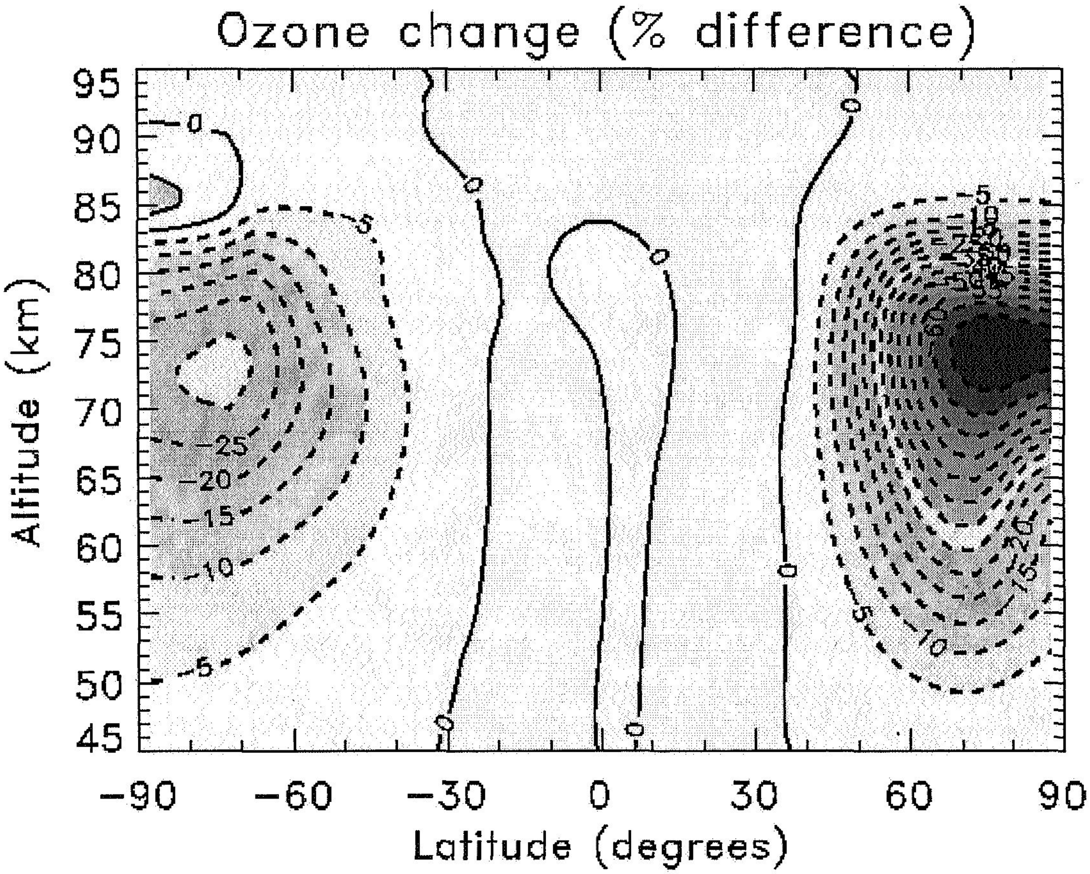

Figure 2. Predicted heating rate changes in K/day on 30 Oct. (Day 303), 2003 in three groups: a) Joule heating; b) Solar and chemical heating; and c) Adiabatic heating. Plot a) has a contour interval of 0.02K/day and plots b) and c) have contour intervals of 0.2K/day.

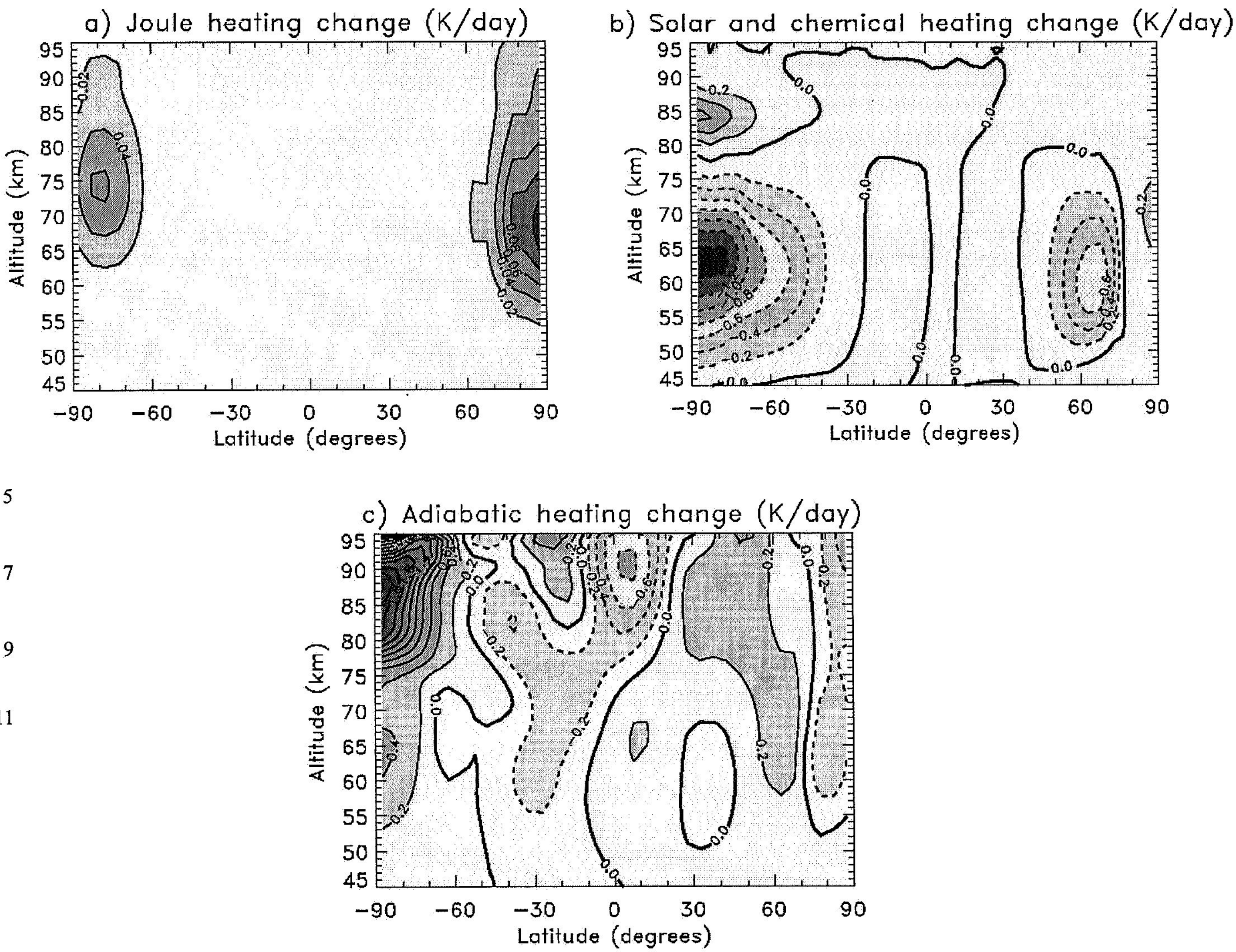

Figure 3. Predicted dynamical changes on 30 Oct. (Day 303), 2003 in three groups: a) Neutral temperature (K) with contour interval 0.25; b) Neutral zonal wind (m/s) with contour interval 0.25; and c) Neutral vertical wind (mm/s) with contour interval 0.25.

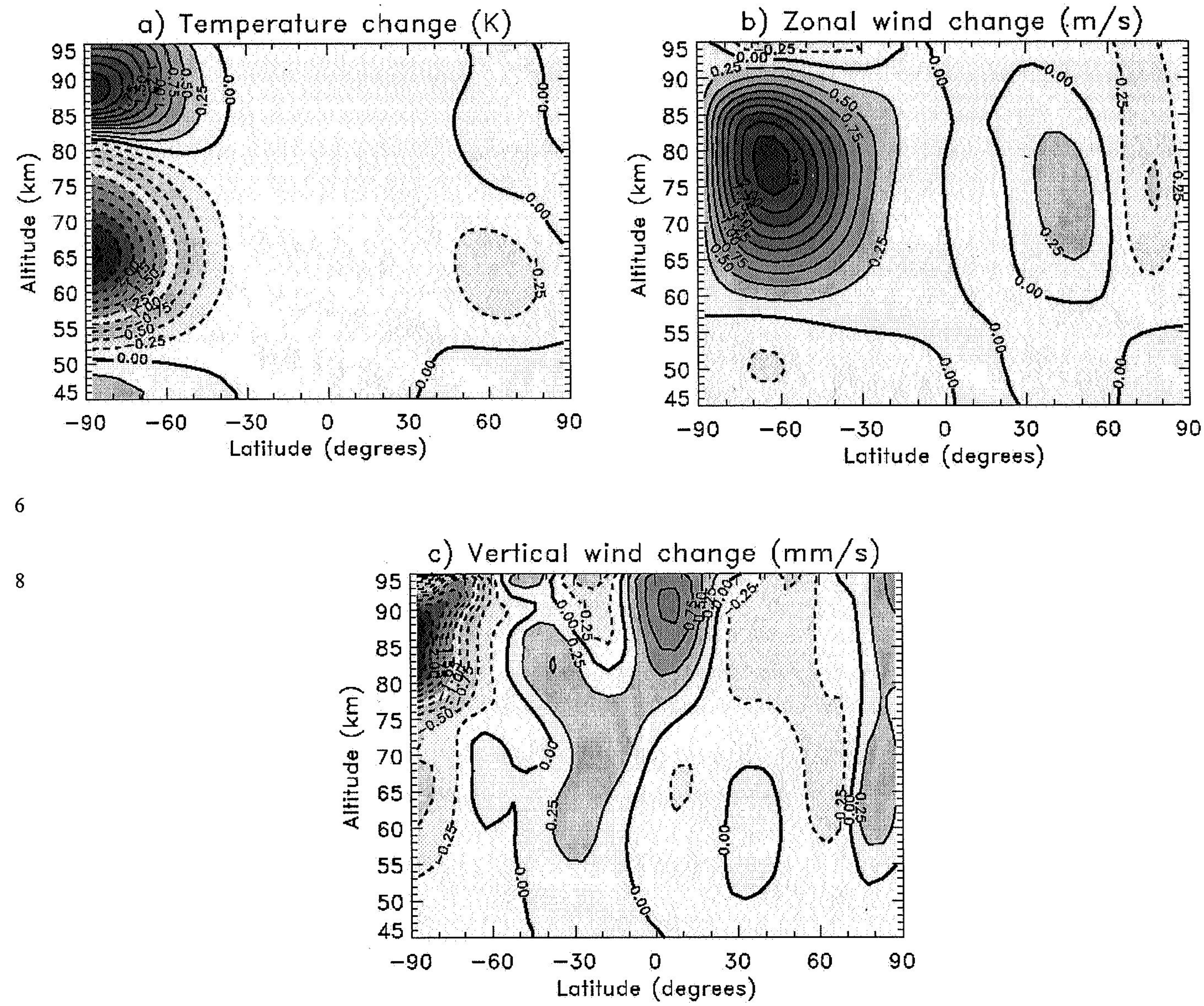

Figure 4. Predicted temporal changes in temperature (K) between 26 Oct. (Day 299) and 11 Dec. (Day 345), 2003 Latitude 82.5°S, Longitude 0°W. Contour intervals are -2.5, -2, -1.5, -1, -0.75, -0.5, -0.25, 0.0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, and 3.5.