GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L04812, doi:10.1029/2006GL028328, 2007

Mesospheric dynamical changes induced by the solar proton events in October–November 2003

Charles H. Jackman,[1] Raymond G. Roble,[2] and Eric L. Fleming[1,3]

Received 29 September 2006; revised 2 January 2007; accepted 17 January 2007; published 27 February 2007.

[1] 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 solar proton events (SPEs) measured in the past 40 years. The highly energetic solar protons 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. 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. **Citation:** Jackman, C. H., R. G. Roble, and E. L. Fleming (2007), Mesospheric dynamical changes induced by the solar proton events in October–November 2003, *Geophys. Res. Lett.*, *34*, L04812, doi:10.1029/2006GL028328.

1. Introduction

[2] 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 before [e.g., *Jackman et al.*, 2005a; *Verronen 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].

[3] We are not aware of any measured atmospheric dynamical changes during these very significant atmospheric perturbations, however, past studies [*Banks*, 1979; *Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Zadorozhny et al.*, 1994; *Jackman et al.*, 1995; *Krivolutsky et al.*, 2006] have suggested that very large SPEs can lead to temperature changes through ozone depletion and/or Joule heating.

[4] In this paper, we used 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 allowed 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 and Solar Proton Caused Constituent Change

[5] The TIME-GCM was first described by *Roble and Ridley* [1994]. This model has an effective 5° latitude × 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 by *Roble* [2000].

[6] 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].

[7] 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

---

[1] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

[2] High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA.

[3] Also at Science Systems and Applications, Inc., Lanham, Maryland, USA.

0094-8276/07/2006GL028328$05.00

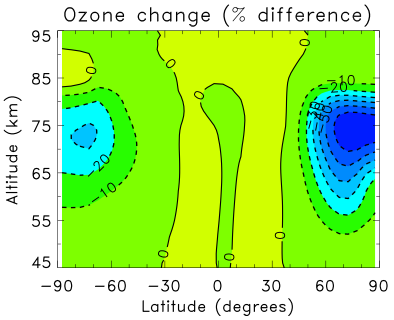

Figure 1. Predicted ozone change on 30 Oct. (Day 303), 2003 with a contour interval of 10%, near the maximum proton flux period. The largest decrease is −69% and the largest increase is +6%.

energy intervals [see *Jackman et al.*, 2005a] for the very active time period 26 October through 7 November 2003. The temporal variation of the proton flux is discussed by *Jackman et al.* [2005a] and was found to have increased by over three orders of magnitude above the background for protons >1 MeV during a large fraction of the Oct. 28–30, 2003 period.

[8] 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 by *Lummerzheim* [1992]. The protons are assumed to deposit their energy into both polar cap regions (>60° geomagnetic latitude) and ionization rates are computed assuming 35 eV/ion pair [*Porter et al.*, 1976].

[9] 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.

[10] 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].

[11] We show the predicted zonal average ozone change at a snapshot during a disturbed period at 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].

[12] Small ozone enhancements peaking at 6% are predicted near the southern polar mesopause and are driven by the changes in winds caused by the SPEs. 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.

3. Computed Heating/Cooling Rate Changes

[13] 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 below.

[14] *Banks* [1979] and *Roble et al.* [1987] showed that locally mesospheric Joule heating could be substantial (1–10 K/d) 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 Ridley*, 1987], indicate a very large thermospheric contribution and a fairly significant mesospheric contribution 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/d near 70 km, 90°N and +0.06 K/d near 75 km, 80°S (shown in Figure 2a for 0:00 UT on 30 October 2003).

[15] Ozone is a strong absorber of solar (ultraviolet, visible, and infrared) radiation, turning this light energy into heat. 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/d between 60 and 65 km (SH) and at −0.7 K/d between 57 and 63 km (NH). The computed increase between 78 and 95 km and south of 75°S in the SH is driven by an increase in atomic oxygen (O) due to an increase in downward transport as well as the HO_x enhancements produced by the solar protons. Such enhancements in O and HO_x lead to an increase in exothermic reactions involving these constituents [*Roble*, 1995] and the release of heat.

[16] The net temperature decreases in the lower and middle mesosphere (see Figure 2c and discussion in section 4) caused by the decrease in solar heating will lead to a net reduction of cooling in this region. We compute a zonal average maximum change in cooling rate of −0.6 K/d (from ~6.2 K/d to ~5.6 K/d) near 60 km, 90°S at 0:00 UT on 30 October 2003 due to the SPEs (not shown).

[17] *Roble and Dickinson* [1970] described an induced atmospheric cooling from heating due to auroral electrons. The inverse of this effect was simulated here whereby the atmosphere can warm via adiabatic heating through com-

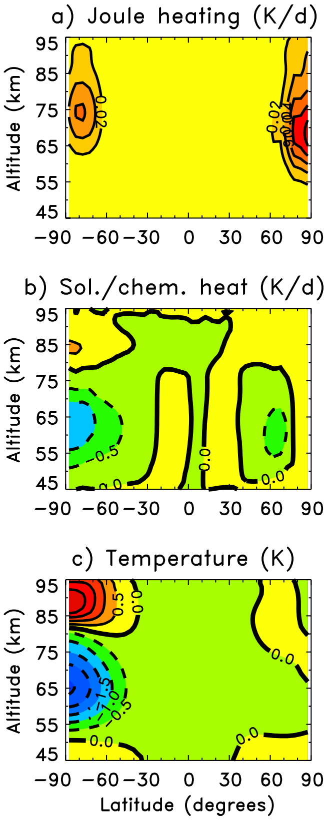

Figure 2. Predicted (a) Joule heating, (b) solar and chemical heating, and (c) temperature changes. Figures 2a–2c have contour intervals of 0.02 K/d, 0.5 K/d, and 0.5 K, respectively. All plots are for 30 Oct. (Day 303), 2003.

pression caused by enhanced downward winds (or reduced upward winds, see Figure 3a and discussion in section 4). We computed a zonal average adiabatic heating increase in the upper polar southern mesosphere with a maximum of +2.3 K/d 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 3b). 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.

[18] 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, another radiatively active gas, and more cooling. We compute a zonal average maximum increase in the cooling rate of +0.8 K/d (from ~7.5 K/d to ~8.3 K/d) near 90–95 km, 90°S at 0:00 UT on 30 October 2003 due to the SPEs (not shown). Computed cooling rate change from either ozone depletion or excited CO_2 enhancement was much smaller in the northern hemisphere.

4. Computed Dynamical Changes

[19] Dynamical (temperature and wind) changes have long been associated with SPEs. Temperature decreases of 1–10 K were computed to follow from very large SPEs in several studies [*Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Zadorozhny et al.*, 1994; *Jackman et al.*, 1995; *Krivolutsky et al.*, 2006]. Large temperature decreases of 14 K near 50 km were deduced as a result of a meteorological rocket campaign during the huge Oct. 1989 SPEs [*Zadorozhny et al.*, 1994]. *Krivolutsky et al.* [2006] derived temperature decreases of 10 K near 65 km and increases of 10 K near 80 km using UARS HALOE measurements during the very large July 2000 SPE. *Kubo et al.* [2003] deduced temperature increases near 93 km of 8 K as a result of the July 2000 SPE with the Svalbard Radar.

[20] 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 2c). Most of the middle and high latitude mesosphere was dominated by decreases in temperature. These computed temperature decreases were modest compared to those measured for other very large SPEs [*Zadorozhny et al.*, 1994; *Krivolutsky et al.*, 2006], however, they are similar to several other model computations [*Reagan et al.*, 1981; *Jackman and McPeters*, 1985; *Roble et al.*, 1987; *Reid et al.*, 1991; *Jackman et al.*, 1995].

[21] 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 2c). These computed temperature increases were smaller than those deduced from measurements during another very large SPE, the so called Bastille Day storm of July 2000 [*Kubo et al.*, 2003; *Krivolutsky et al.*, 2006].

[22] The 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.

[23] 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]. The model computed zonal, meridional, and vertical winds were all perturbed as a result of the Oct./Nov. 2003 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 (not shown). These changes were modest when compared with the background and amounted to a maximum change of about 20% in the SH, primarily opposing the prevailing easterlies at this time of year.

[24] 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.

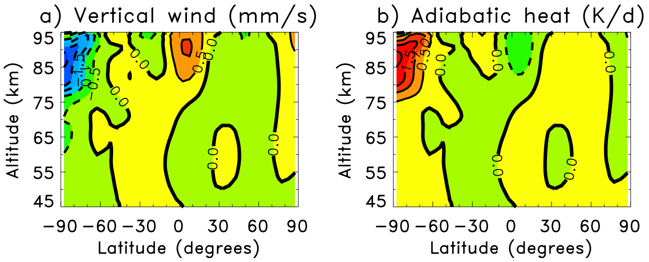

Figure 3. Predicted (a) vertical wind and (b) Adiabatic heating changes. Figures 3a and 3b have contour intervals of 0.5 mm/s and 0.5 K/d, respectively. Both plots are for 30 Oct. (Day 303), 2003. Note the strong anti-correlation between predicted vertical wind and adiabatic heating changes.

[25] 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 3a). 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 a net adiabatic heating change (see Figure 3b), which led to a heating of the upper mesosphere that was discussed in section 3.

[26] A simulation was completed for the period 26 Oct. through 11 Dec. 2003 to study the longevity of the dynamical influence. We found that the perturbation to the atmosphere was fairly quickly damped such that over 90% of the impact of the Oct./Nov. 2003 SPEs was gone by 11 Dec. 2003. The majority of the mesospheric dynamical effects from SPEs diminish 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.

[27] Could these computed changes in winds due to SPEs have significantly influenced the transport of constituents in Oct.–Dec. of 2003? This is an especially important question when focusing on the downward transport of NO_y created during SPEs, which has been shown to be an important factor in prolonging their influence [e.g., *Jackman et al.*, 2005a]. Although the vertical winds were computed to have been altered by the Oct./Nov. 2003 SPEs, the change did not significantly impact the downward transport of NO_y. The vertical winds were only changed by a maximum of about 20% and these changes diminished rapidly in the next few weeks.

5. Sensitivity Studies and Uncertainties

[28] We investigated the sensitivity of these results to the seasonal timing of the SPE and also the magnitude. The July 2000 (Bastille Day storm) SPE was similar in magnitude to the Oct./Nov. 2003 SPE. The computed dynamical changes for the July 2000 SPE 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.

[29] 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.

[30] There are a large number of uncertainties in the model simulations including: 1) the magnitude of the input ionization rates for the protons; 2) possible latitudinal and longitudinal variations in the ionization rates, which are assumed to be uniform over the polar caps; 3) a relatively coarse 5 degree latitude-longitude and two grid point per scale height model, which will not simulate small scale structures; 4) uncertainties in the input photochemical reaction rates; and 5) uncertainties in the input of physical mechanisms (e.g., gravity waves). The TIME-GCM is continually being tested against measurements [e.g., *Roble*, 2000] and has been shown to represent the large-scale features of the mesosphere fairly well.

[31] **Acknowledgments.** We thank NASA Headquarters Living With a Star Targeted Research and Technology Program for support during the time that this manuscript was written. We also thank the NOAA GOES team for providing the solar proton flux data over the Internet. We thank two anonymous reviewers whose comments and suggestions have led to an improved manuscript.

References

Banks, P. M. (1979), Joule heating in the high-latitude mesosphere, *J. Geophys. Res.*, *84*, 6709–6712.

Crutzen, P. J., et al. (1975), Solar proton events: Stratospheric sources of nitric oxide, *Science*, *189*, 457–458.

Jackman, C. H., and R. D. McPeters (1985), The response of ozone to solar proton events during solar cycle 21: A theoretical interpretation, *J. Geophys. Res.*, *90*, 7955–7966.

Jackman, C. H., M. C. Cerniglia, J. E. Nielsen, D. J. Allen, J. M. Zawodny, R. D. McPeters, A. R. Douglass, J. E. Rosenfield, and R. B. Rood (1995), Two-dimensional and three-dimensional model simulations, measurements, and interpretation of the influence of the October 1989 solar proton events on the middle atmosphere, *J. Geophys. Res.*, *100*, 11,641–11,660.

Jackman, C. H., M. T. DeLand, G. J. Labow, E. L. Fleming, D. K. Weisenstein, M. K. W. Ko, M. Sinnhuber, and J. M. Russell (2005a), Neutral atmospheric influences of the solar proton events in October–November 2003, *J. Geophys. Res.*, *110*, A09S27, doi:10.1029/2004JA010888.

Jackman, C. H., et al. (2005b), The influence of the several very large solar proton events in years 2000–2003 on the neutral middle atmosphere, *Adv. Space Res.*, *35*, 445–450.

Johnson, R. M., and J. G. Luhmann (1993), Poker Flat MST radar observations of high latitude neutral winds at the mesopause during and after solar proton events, *J. Atmos. Terr. Phys.*, *55*, 1203–1218.

Krivolutsky, A. A., et al. (2006), Dynamical response of the middle atmosphere to solar proton event of July 2000: Three-dimensional model simulations, *Adv. Space Res.*, *37*, 1602–1613.

Kubo, K., et al. (2003), Upper mesosphere temperature changes observed in PMSE and by incoherent scatter radar during a strong polar cap absorption event, paper presented at 10th MST Radar Workshop, Inst. Geofis. del Peru, Lima.

Liu, H. L., and R. G. Roble (2005), Dynamical coupling of the stratosphere and mesosphere in the 2002 Southern Hemisphere major stratospheric sudden warming, *Geophys. Res. Lett.*, *32*, L13804, doi:10.1029/2005GL022939.

Lummerzheim, D. (1992), Comparison of energy dissipation functions for high energy auroral electron and ion precipitation, *Rep. UAG-R-318*, Geophys. Inst., Univ. of Alaska-Fairbanks, Fairbanks.

Mewaldt, R. A., C. M. S. Cohen, A. W. Labrador, R. A. Leske, G. M. Mason, M. I. Desai, M. D. Looper, J. E. Mazur, R. S. Selesnick, and D. K. Haggerty (2005), Proton, helium, and electron spectra during the large solar particle events of October–November 2003, *J. Geophys. Res.*, *110*, A09S18, doi:10.1029/2005JA011038.

Porter, H. S., et al. (1976), Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air, *J. Chem. Phys.*, *65*, 154–167.

Reagan, J. B., R. E. Meyerott, R. W. Nightingale, R. C. Gunton, R. G. Johnson, J. E. Evans, W. L. Imhof, D. F. Heath, and A. J. Krueger (1981), Effects of the August 1972 solar particle events on stratospheric ozone, *J. Geophys. Res.*, *86*, 1473–1494.

Reid, G. C., S. Solomon, and R. R. Garcia (1991), Response of the middle atmosphere to the solar proton events of August–December 1989, *Geophys. Res. Lett.*, *18*, 1019–1022.

Roble, R. G. (1995), Energetics of the mesosphere and thermosphere, *in The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory*, *Geophys. Monogr. Ser.*, vol. 87, edited by R. M. Johnson and T. L. Killeen, pp. 1–21, AGU, Washington, D. C.

Roble, R. G. (2000), On the feasibility of developing a global atmospheric model extending from the ground to the exosphere, in *Atmospheric Science Across the Stratosphere*, *Geophys. Monogr. Ser.*, vol. 123, edited by D. E. Siskind, S. D. Eckermann, and M. E. Summers, pp. 53–67, AGU, Washington, D. C.

Roble, R. G., and R. E. Dickinson (1970), Atmospheric response to heating within a stable auroral red arc, *Planet. Space Sci.*, *18*, 1489–1498.

Roble, R. G., and E. C. Ridley (1987), An auroral model for the NCAR thermospheric general circulation model (TGCM), *Ann. Geophys.*, *5A*, 369–382.

Roble, R. G., and E. C. Ridley (1994), A thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (time-GCM): Equinox solar cycle minimum simulations (30–500 km), *Geophys. Res. Lett.*, *21*, 417–420.

Roble, R. G., B. A. Emery, R. R. Garcia, T. L. Killeen, P. B. Hays, G. C. Reid, S. Solomon, D. S. Evans, N. W. Spencer, and L. H. Brace (1987), Joule heating in the mesosphere and thermosphere during the July 13, 1982, solar proton event, *J. Geophys. Res.*, *92*, 6083–6090.

Rottger, J. (1992), Solar proton events: A source for long-period gravity waves in the polar mesosphere?, in *Solar-Terrestrial Energy Program: The Initial Results From STEP Facilities and Theory Campaigns*, edited by D. N. Baker, V. O. Papitashvili, and M. J. Teague, p. 473, Elsevier, New York.

Solomon, S., et al. (1981), The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere: 2. Odd hydrogen, *Planet. Space Sci.*, *29*, 885–892.

Solomon, S., G. D. Reid, D. W. Rusch, and R. J. Thomas (1983), Mesospheric ozone depletion during the solar proton event of July 13, 1982: 2. Comparison between theory and measurements, *Geophys. Res. Lett.*, *10*, 257–260.

Swider, W., and T. J. Keneshea (1973), Decrease of ozone and atomic oxygen in the lower mesosphere during a PCA event, *Planet. Space Sci.*, *21*, 1969–1973.

Verronen, P. T., A. Seppälä, M. A. Clilverd, C. J. Rodger, E. Kyrölä, C.-F. Enell, T. Ulich, and E. Turunen (2005), Diurnal variation of ozone depletion during the October–November 2003 solar proton events, *J. Geophys. Res.*, *110*, A09S32, doi:10.1029/2004JA010932.

Zadorozhny, A. M., V. N. Kikhtenko, G. A. Kokin, G. A. Tuchkov, A. A. Tyutin, A. F. Chizhov, and O. V. Shtirkov (1994), Middle atmosphere response to the solar proton events of October 1989 using the results of rocket measurements, *J. Geophys. Res.*, *99*, 21,059–21,069.

Zhang, X. X., C. Wang, T. Chen, Y. L. Wang, A. Tan, T. S. Wu, G. A. Germany, and W. Wang (2005), Global patterns of Joule heating in the high-latitude ionosphere, *J. Geophys. Res.*, *110*, A12208, doi:10.1029/2005JA011222.

E. Fleming and C. Jackman, NASA Goddard Space Flight Center, Code 613.3, Greenbelt, MD 20771, USA. (fleming@kahuna.gsfc.nasa.gov; charles.h.jackman@nasa.gov)

R. Roble, High Altitude Observatory, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307-3000, USA. (roble@hao.ucar.edu)