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Ground level events and consequences for stratospheric chemistry

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Abstract. The precipitation of energetic particles into the polar atmosphere modifies the mesospheric and stratospheric chemistry. We compare particle fluxes of a wide range of energies in different solar energetic particle events, in particular their spectral evolution. The resulting changes in NO_x and HO_x and consequently in ozone are compared. Our calculations and comparisons with observations show that for a significant atmospheric response rogue events rather than ground level events are required.

1 Introduction

The influence of precipitating solar energetic particles (SEPs) on high latitude ozone first has been observed in the large August 1972 flare (e.g. Heath et al., 1977) and has led to the discovery of the influence of NO_x on stratospheric and in particular on ozone chemistry (Crutzen et al., 1975).

The strongest modifications sofar have been observed during the August 1972 and October 1989 events (Vitt et al., 2000; Jackman et al., 2000), an event comparable in size and consequences was in July 2000 (Jackman et al., 2001).

In this paper, we will expand analysis in two ways: (a) for the numerical analysis, also precipitating particles with energies above a few hundred MeV will be considered, and (b) the analysis will also include the recent strong ground level event (GLE) on 15 April 2001. The aim is to understand the influence of the higher energetic particles and to define the properties of particle events that are relevant in modifying the mesospheric and stratospheric chemistry.

2 The Model

The numerical analysis is performed with a model consisting of two parts dealing with (a) the interaction of precipitating particles with the atmosphere and (b) the resulting modifications in atmospheric chemistry.

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2.1 Particle precipitation: ionization profiles

Interaction of precipitating energetic particles is treated as Coulomb interaction. The Bethe-Bloch equation then is solved numerically for an atmosphere consisting of 78% N_2, 21% O_2 and 1% Ar. Minor species are not considered since we are only interested in ionization rates. The mean binding energies required to calculate energy losses are taken from the Fermi-Thomas model to be 95 eV. Density and temperature height profiles are adjusted to the chemistry model (see below). Energy loss rates from Bethe-Bloch then are converted to ionization rates assuming the typical average ionization energy for air of about 35 eV. This number is smaller than the one in the Fermi-Thomas model because the average energy loss can lead to more than one ionization: the electron resulting from the primary interaction might have enough energy to cause secondary ionizations.

2.2 Atmospheric chemistry: model description

We use a two-dimensional chemical and transport model running on a 9.5 degree to 3 km latitude versus altitude grid. The model extends from 90 S to 90 N, and from 0 to 100 km altitude. It consists of two individual modules to calculate dynamical and chemical parameters, respectively. The dynamical module is based on J. Kinnersleys THIN AIR model (e.g. Kinnersley, 1996) and calculates temperature, pressure, horizontal and vertical transport. It also includes planetary waves and a gravity wave scheme. The chemistry module is the TOMCAT model (Chipperfield 1996), the same as used in the well-known 3 D CTM SLIMCAT. It uses 57 species, considering 181 chemical reactions and 37 photolysis reactions. Gas-phase as well as heterogeneous reactions are considered, and stratospheric particles are formed by state-of-the art formation mechanisms. NO_x, HO_x and O_x families are calculated in photochemical equilibrium, which reduces the reliability of the chemical code to altitudes below 70 km. The production of NO_x and NO_x due to ion pair production is calculated according to Porter et al. (1976), the produc-

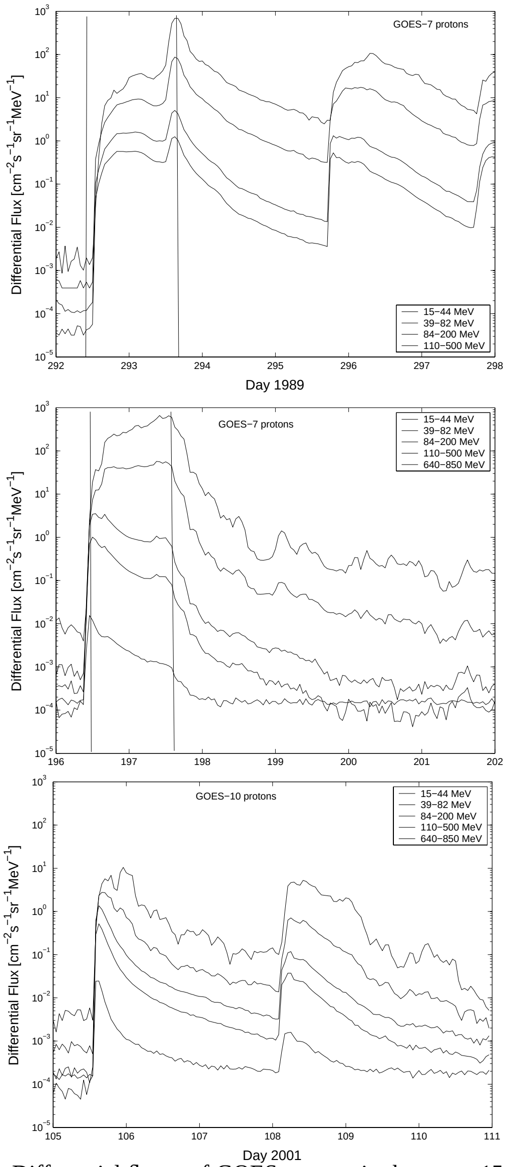

Fig. 1. Differential fluxes of GOES protons in the range 15 to 850 MeV, cf. text

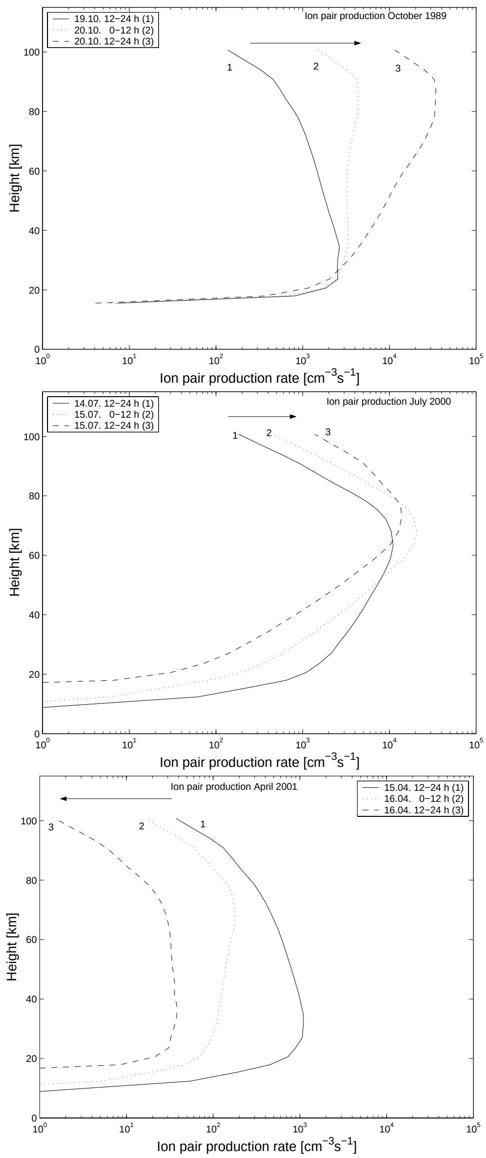

Fig. 2. Time development of ionization rates during the three events, cf. text.

tion of HO_x according to Solomon et al. (1981). For further information see Jackman et al. (1990).

3 Results

We focus on the GLEs October 1989, July 2000, and April 2001. The former two are rogue events (Kallenrode and Cliver, 2001) with unusually large particle fluences at hundreds of MeV, the latter shows an unusual large increase in neutron monitor counting rates.

3.1 Properties of the particle events

Figure 1 shows the fluxes of energetic protons between 15 and 850 MeV observed by GOES for the three selected events. Vertical lines mark the arrival of interplanetary shocks. In the upper two events, the criteria of a rogue event obviously are fulfilled: long-lasting high intensities even in a few hundred MeV with the particles stored between shocks. The third event is different: although it extends to high energies (the maximum intensity in the highest energy channel in Fig. 1 is comparable to that in the October 1989 event and at neutron monitor energies shows even larger fluxes), fluences and intensities in the lower energy channels are markedly smaller.

3.2 Ionization rates

To determine ionization rates, the time profiles shown in Fig. 1 are averaged over 12 h intervals. Under consideration of the lower energies (down to 4 MeV, not shown in Fig. 1) power law spectra in energy, $I = I_o \cdot (E/E_o)^{-\gamma}$ are obtained. Depending on relative intensities, the spectrum has been divided

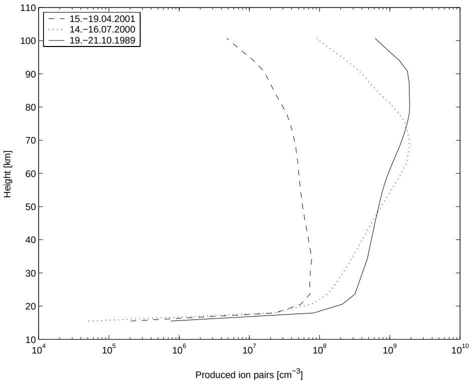

Fig. 3. Comparison of total ionization (up to energies of 500 MeV) during the three particle events.

in up to three separate power-laws. The spectrum extends to about 800 MeV while in previous studies the energy range normally was limited to up to 300 MeV. Higher energies are not considered here: although the events are ground level events and particles have been accelerated up to several GeV, the intensity increase in these high energies is only very short and thus almost vanishes in the background if averaged over a 12 h interval. To use a conservative approach we therefore omitted the highest energies from our analysis.

These energy spectra are used to determine ionization rates as described above. The resulting temporal evolution in ionization rates is shown for the first three 12 h bins for all three events in Fig. 2. The October 1989 event initially leads to a strong ionization in the lower stratosphere while the ionization in the mesosphere is about an order of magnitude smaller. As time increases, the ionization in the lower stratosphere does not change (since high energy particle intensities are roughly constant) while the mesospheric ionization increases significantly as intensities in the low energies continue to rise. The temporal development of ionization rates in the July 2000 event is more complex: initial ionization in the lower stratosphere is comparable to that in October 1989 while ionization in the middle mesosphere is larger and in the upper mesosphere is lower. Since particle intensities in the higher energies start to decrease rather early, ionization rates in the stratosphere decrease, too, as the event evolves. Only upper mesospheric ionization rates increase with time. In the GLE of April 2001, initial ionization profiles are comparable to that in the October 1989 event in shape although numbers are smaller by about a factor of 2 to 3. However, ionization decreases with increasing time at all heights.

Consequently, the total ionization as shown in Fig. 3 is significantly larger in the two rogue events compared to the GLE.

3.3 Chemical Consequences

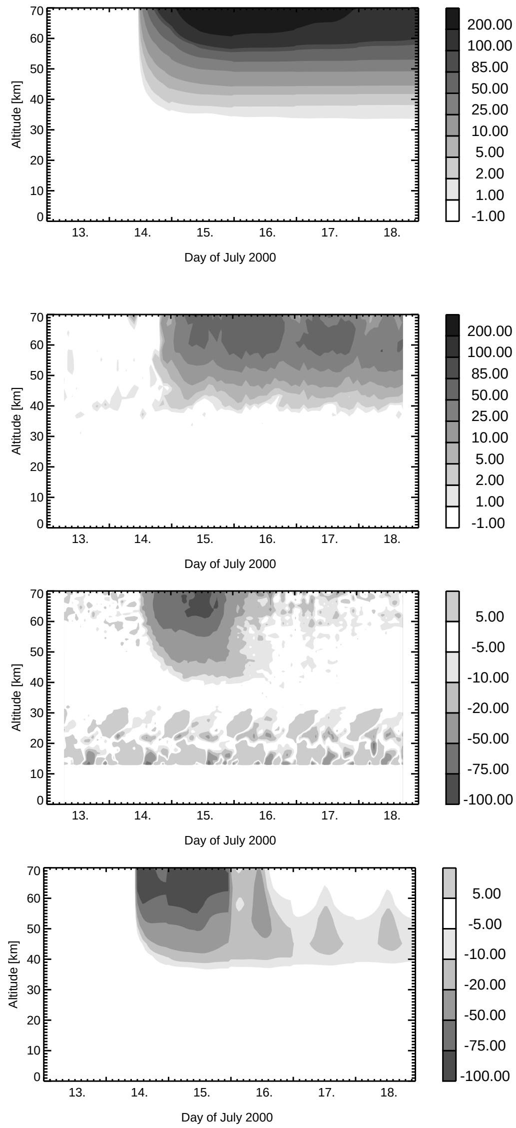

Fig. 4. Variations compared to background level in NO_x in ppb (1st panel modeled, 2nd observed by HALOE) and O_3 in % (3rd observed, 4th modeled).

In Fig. 4, modeled and measured variations of NO_x (N + NO + NO_2) and ozone due to particle precipitation are shown for the July 2000 event. Both measurements and model show a similar temporal and vertical distribution. Significant changes in NO_x start on 14 July 2000 at altitudes above 40 km. As NO_x is very long-lived in the upper stratosphere, the NO_x formed during the event decreases only very slowly after particle precipitation has stopped, and enhanced values of NO_x last in the stratosphere for weeks or months (see e.g. Jackman et al., 2000). This may lead to significant ozone decrease in the lower stratosphere when NO_x from particle events is transported downward during polar winter. While this behavior is well represented in both model and measurements, the amount of NO_x formed in the model is more than a factor of two larger than the observed one. Ozone destruction in the upper stratosphere and lower mesosphere is mainly due to catalytic cycles of HO_x (H + OH + HO_2). Like NO_x, HO_x is supposed to increase considerably during particle events. Measurements of HO_x in this altitude region are extremely sparse, but as ozone destruction in this altitude is mainly

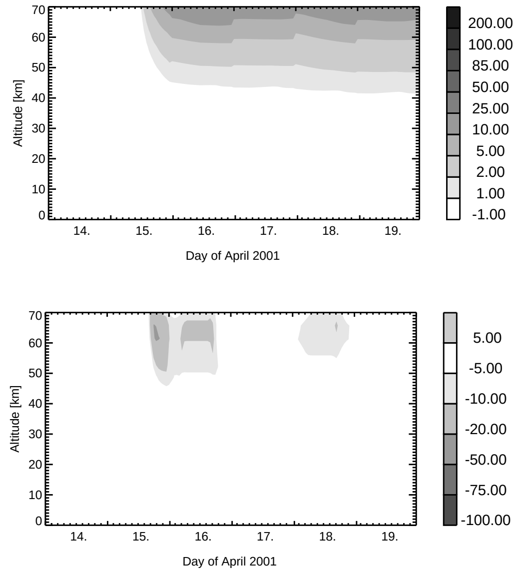

Fig. 5. Modeled variation in NO_x (upper) and O_3 mixing ratio (lower panel) during the ground level event on April 14.

caused by HO_x, comparison of ozone measurements to modeled O_3 can be used as an indicator of the validity of HO_x production during the event. As HO_x is extremely short-lived in the upper stratosphere and lower mesosphere, HO_x will decrease to background level as soon as the particle fluxes decrease. Equally, ozone depletion due to HO_x will last only as long as the event lasts. Again, measurement and model show similar temporal and vertical behavior, but the amount of ozone loss is overestimated in the model.

The model produces almost the same results if the particle spectrum extends up to 500 MeV or 800 MeV: although ionization curves are markedly different because higher energies can penetrate down into the lower stratosphere or even the troposphere, modifications caused by them vanish since atmospheric density is too large. Thus changes of atmospheric chemistry due to solar energetic particles seem to be limited to altitudes of above about 35–40 km; even in the October 1989 event despite much larger particle fluences variations in NO_x and O_3 cannot be found below 30–35 km.

Figure 5 shows similar calculations for the GLE on 14 April 2001. Compared to Fig. 4 the total variation is much smaller (about a factor of 20 in the NO_x maximum in the mesosphere in agreement with the lower ionization rates in Fig. 3). In addition, NO_x variations with respect to the undisturbed atmosphere by more than 5% are observed at altitudes above about 58 km. Because HO_x and NO_x production are correlated, reduction in O_3 consequently is much smaller and limited to greater heights.

4 Conclusions

The comparison of different solar energetic particle events and their consequences on terrestrial chemistry shows that for significant atmospheric consequences a particle event must have very high fluences at particle energies of some tens to a few hundred MeV. These particles are absorbed in the upper stratosphere and mesosphere. Ionization caused by higher energetic particles from solar events does not lead to modelable or observable consequences because (a) particle numbers are small even in largest events and (b) atmospheric density at the stopping height is too large. Thus for terrestrial consequences a rogue event is required rather than a ground level event. It should be kept in mind that particles with very high energies have an influence on atmospheric chemistry if fluences are sufficiently high, as is the case for galactic cosmic rays.

The model presented here allows a fair reproduction of observed temporal and spatial variations in NO_x and O_3, however, modeled effects tend to be larger than observed ones. Here some fine tuning in both parts of the model, the calculation of ionization profiles as well as the subsequent chemical model, is required.

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