Numerical prediction of changes in atmospheric chemical composition by precipitation of solar energetic particles at Mars

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Introduction:

Solar energetic particles (SEPs) are high-energetic particles that consist mainly of electrons and protons with energies from a few tens of keV to GeV ejected from the Sun associated with solar flares and coronal mass ejections. SEPs that precipitate into planetary atmospheres cause ionization, excitation and dissociation of atmospheric molecules, leading to changes in atmospheric chemical composition via chemical network (e.g. Solomon et al., 1981; Adams et al., 2021). The effects of SEPs on the atmospheric chemical composition on Earth has been intensively studied. For instance, during the enormous solar flare that occurred in late October 2003, NOx (NO + NO_2) and HOx (OH + HO_2) concentrations were enhanced and ozone concentration was depleted by 40% at the polar lower mesosphere (e.g. Jackman et al., 2005). Recently, the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has discovered global diffuse aurora on the nightside of Mars during SEP events (Schneider et al., 2015), which has been shown to be generated mainly by SEP protons (Nakamura et al., 2022). However, changes in the neutral chemical composition of the Martian atmosphere during SEP events have not yet been estimated. By coupling a Monte Carlo model, Particle TRansport In Planetary atmospheres (PTRIP) (Nakamura et al., 2022) and a newly developed 1-dimensional photochemical model, we investigated the effects of SEPs on the atmospheric composition at Mars.

Models:

In this study, we used PTRIP to calculate production rate of CO_2^+ and N_2^+ in the Martian atmosphere under a SEP proton flux taken from a SEP event that occurred on 28 October 2003 at Earth (Mewaldt et al., 2005). Production rates of N and N(^{2}D), which are important drivers for NOx chemistry, were estimated assuming a ratio N_2^+:N:N(^{2}D) = 1:0.84:1 (Krasnopolsky, 2009). Ionization rate by cosmic rays as an ionization source at low altitudes were taken from Haider et al. (2009). In the 1-dimensional photochemical model, we implemented 486 chemical reactions consisting of HOx chemistry (Chaffin et al., 2017), NOx chemistry (Nair et al., 1994), ionospheric chemistry (Fox and Sung, 2001) and water cluster ion chemistry (Molina-Cuberos et al., 2001; Verronen et al., 2016) to fully describe chemical network during SEP events.

Results:

We first ran the photochemical model only for neutral species to obtain the steady state neutral composition. After that we ran the model for 10 days including ion species with solar extreme ultraviolet flux and cosmic ray as ionization sources to obtain the quasi-steady state solution for ion profiles. Then we ran the model with additional ionization source of SEP protons for 1 day to examine the changes in ion and neutral compositions during SEP events.

The calculated ion profiles before SEP event and after 1 day of SEP event onset is shown in Figure 1. Ion and electron densities were enhanced below 100 km altitude and densities of water cations were enhanced below 70 km altitude. The results indicate that ionization by SEP protons is more effective than ionization by cosmic rays, producing large amount of water cations below 70 km altitude, which agree well with the previous modeling study by Sheel et al. (2012).

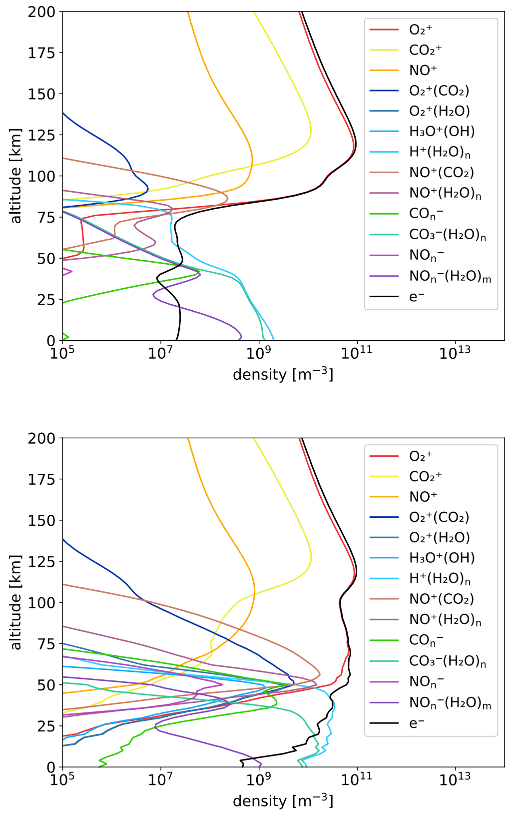

Figure 1. (upper) Calculated ion profile before SEP event and (bottom) after 1 day of SEP event onset.

The change in neutral chemical composition was investigated. The calculated density profiles of ozone, HOx and NOx before SEP event, 1day after SEP event onset, 1 day after SEP event termination and 10days after SEP event termination are shown in Figure 2. Enhancement of HOx and decrease of ozone by a factor of 10 occurred in the altitude range of 20-60 km and enhancement of NOx by a factor of more than 100 occurred in the altitude range of 20-100 km 1 day after SEP event onset. After the end of the SEP event, ozone and HOx densities were almost recovered 1 day after the end of SEP event, however, NOx density was not recovered even 10 days after the end of SEP event, due to the different loss time scales between HOx and NOx. These results indicate that, as on Earth, similar effects on ozone, HOx and NOx concentrations are expected even in the case of the CO_2-dominated Mars atmosphere.

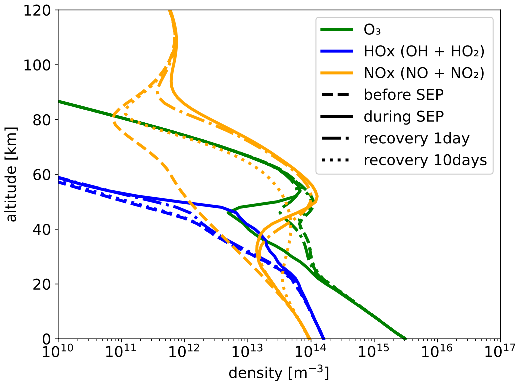

Figure 2. Calculated density profiles of ozone, HOx (OH + HO_2) and NOx (NO + NO_2) before SEP event, 1 day after SEP event onset (represented as "during SEP"), 1 day after SEP event termination (represented as "recovery 1 day") and 10 days after SEP event termination (represented as "recovery 10 day").

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