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HO_2 enhancements due to sprite discharges - observations and model simulations

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Introduction

Sprites are large scale electrical discharges in the mesosphere occurring above active thunderstorm clouds. During the last years, several model simulations of the chemical processes in sprites have been presented. However, until recently there were no direct measurements of the chemical impact of sprites.

Yamada et al. (2020) have presented measurements from the SMILES (Superconducting Submillimeter-Wave Limb Emission Sounder) satellite instrument in combination with sprite observations from ISUAL (Imager of Sprites and Upper Atmospheric Lightnings) which indicate an increase of mesospheric HO_2 due to sprites. These are the first direct observations of chemical sprite effects, and provide a unique opportunity to test our understanding of the chemical processes in sprites.

Here we give a brief summary of the results of Yamada et al (2020), and present preliminary model results corresponding to the satellite observations.

Measurements

Yamada et al. (2020) have presented there cases of ISUAL sprite observations followed by SMILES measurements in spatial-temporal coincidence with the sprite detection.

ΔHO_2 is the total HO_2 enhancement along the line-of-sight of SMILES, Δt is the time difference between ISUAL sprite observation and SMILES measurement, LT is the local time of the SMILES measurement, TH is the tangent height of the SMILES measurement, and ΔR is the shortest distances between the line-of-sight of the SMILES measurement and the estimated sprite location.

Event	Date	ΔHO_2 [molecules]	Δt [hour]	Sprite location	LT	TH [km]	ΔR [km]
A	14 Nov. 2009	$8.9 \pm 2.5 \times 10^{24}$	2.4	159.7°W/20.8°N	01:15:38	75	<10
B	18 Nov. 2009	$16 \pm 2 \times 10^{24}$	1.5	78.9°W/6.7°N	00:34:06	77	110
C	9 Mar. 2010	$17 \pm 2 \times 10^{24}$	4.4	19.4°E/1.9°N	03:23:52	80	<10

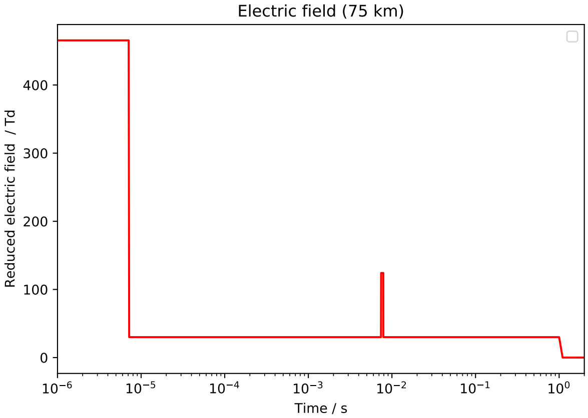
Model description

A one-dimensional atmospheric chemistry and transport model has been used for this study.
Altitude range: 40–120 km, vertical resolution: 1 km.
The chemistry routines are based on the model of Winkler and Notholt (2015). Modelled species:

Negative species
e, O^-, O_2^-, O_3^-, O_4^-, NO^-, NO_2^-, NO_3^-, CO_3^-, CO_4^-, $O^-(H_2O)$, $O_2^-(H_2O)$, $O_3^-(H_2O)$, OH^-, HCO_3^-, Cl^-, ClO^-
Positive species
N^+, N_2^+, N_3^+, N_4^+, O^+, O_2^+, O_4^+, NO^+, NO_2^+, N_2O^+, $N_2O_2^+$, $NO^+(N_2)$, $NO^+(O_2)$, H_2O^+, OH^+, $H^+(H_2O)_{n=1-7}$, $H^+(H_2O)(OH)$, $H^+(H_2O)(CO_2)$, $H^+(H_2O)_2(CO_2)$, $H^+(H_2O)(N_2)$, $H^+(H_2O)_2(N_2)$, $O_2^+(H_2O)$, $NO^+(H_2O)_{n=1-3}$, $NO^+(CO_2)$, $NO^+(H_2O)(CO_2)$, $NO^+(H_2O)_2(CO_2)$, $NO^+(H_2O)(N_2)$, $NO^+(H_2O)_2(N_2)$
Neutrals
N, $N(^2D)$, $N(^2P)$, O, $O(^1D)$, $O(^1S)$, O_3, NO, NO_2, NO_3, N_2O, N_2O_5, HNO_3, HNO_2, HNO, H_2O_2, N_2, O_2, H_2, CO_2, $N_2(A^3\Sigma_u^+)$, $N_2(B^3\Pi_g)$, $N_2(C^3\Pi_u)$, $N_2(a^1\Pi_g)$, $N_2(a'^1\Sigma_u^-)$, $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g)$, H_2O, HO_2, OH, H, HCl, Cl, ClO
New: CH_4, CH_3, CH_3O, CH_3O_2, CH_3OOH, CH_2O, HCO, CO, HOCl, $ClONO_2$, OClO

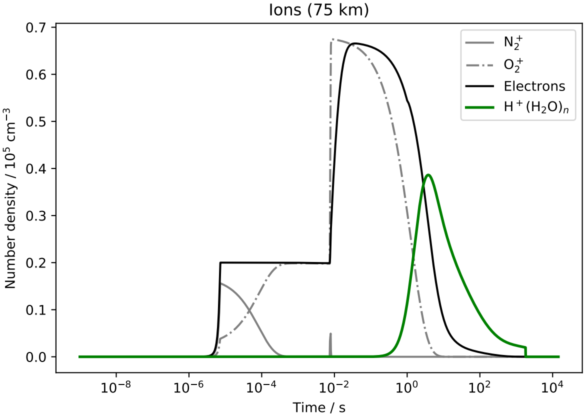
Sprite parameters

The sprite is modelled as a streamer discharge in the altitude range 70–80 km. The streamer parameters are estimated from the simulation results of Luque and Ebert (2010). The streamer head electric field is modelled as a boxcar pulse followed by a second pulse in the trailing column.



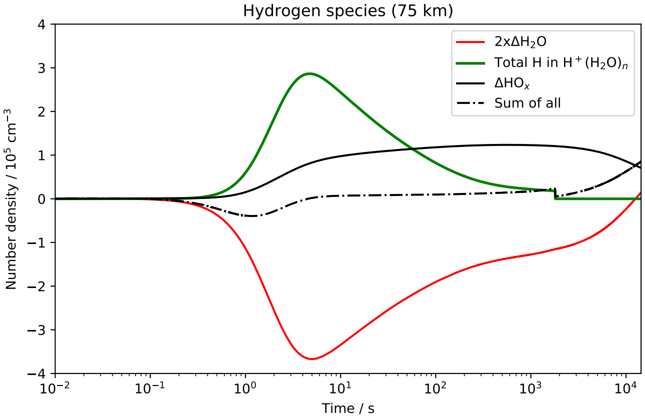
Results

The plot shows selected charged species at an altitude of 75 km. Electron and ion densities significantly increase at the streamer tip and subsequentely in the trailing column. After $\sim$1 s the most abundant ions are proton hydrates (PHs), $H(H_2O)_n^+$.



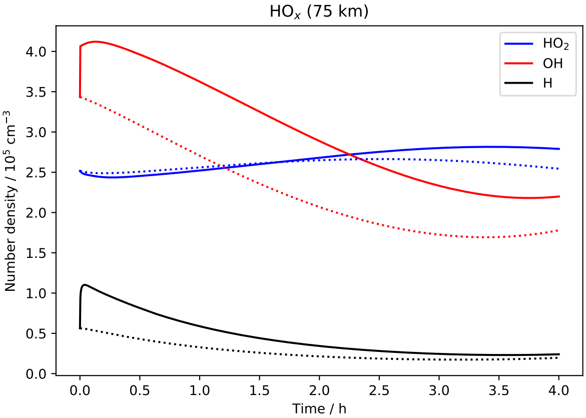
Results

PHs are formed from water molecules. Recombination reactions of PHs lead to a release of hydrogen radicals. The net effect is $H_2O \rightarrow H + OH$.



Results

Solid lines depict the streamer simulation, and dashed lines depict a control run without electric fields applied.



Results

The HO_2 increase at 75 km is $\sim 3\times10^4 \mathrm{cm}^{-3}$.
Estimated streamer volume in the SMILES pencil beam: $\sim 1.5\times10^{15}\,\mathrm{cm}^3$.
$\Rightarrow 4.5\times10^{19}$ molecules per streamer.
The observed $\sim 10^{25}$ molecules would require $> 200,000$ streamers.

As ΔHO_2 can be stable for several hours, there is a chance of an accumulation of HO_2 produced by different sprites over the observed thunderstorm systems.

Questions: How many sprites occurred? How many streamers per sprite?

Transport

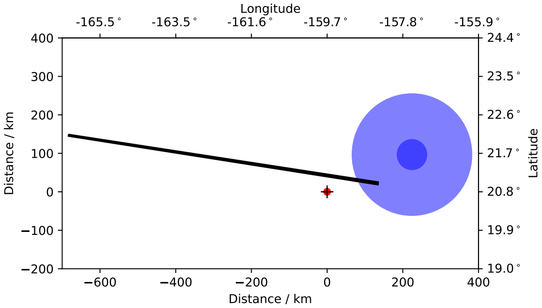
There are time differences between the ISUAL sprite detection and the SMILES HO_2 measurements of 1.5–4.5 h. On such time-scales, horizontal transport processes might be relevant.
We have performed transport and dispersion simulations of the sprite cross section. Advection is calculated using wind fields from the LIMA model (Berger, 2008), dispersion is calculated using atmospheric eddy diffusion coefficients from the literature.

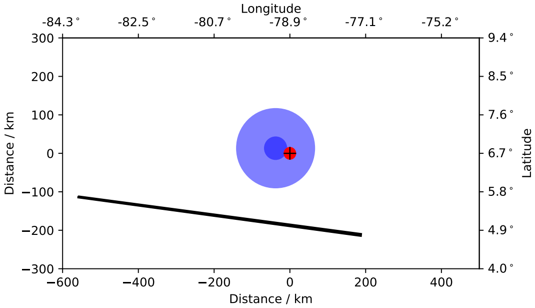
Events A and B

Red circle: Initial sprite cross section (ISUAL).

Blue circles: Sprite cross section at time of SMILES measurement. Large/small circels correspond to large/small eddy diffusivity.

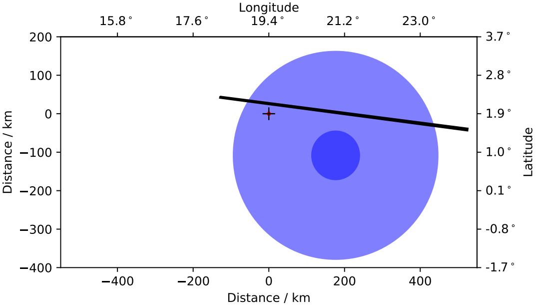
Black area: SMILES field of view at $\pm$ 1 km sprite altitude.





Event C

Only in this case and only for a large dispersion rate, there is a significant overlap of SMILES field of view and the expanded sprite.



Conclusions

Chemistry model: Mesospheric HO_2 enhancements mainly due to ion-chemical conversion of water molecules into HO_x. However, the observed $\sim 10^{25}$ molecules in each event are very large numbers compared to the model prediction of HO_2 increase per streamer.

Transport model: In event A and B no overlap of SMILES field of view and the sprite body are expected. Therefore, the observed HO_2 enhancement cannot be directely caused by these sprites.

Speculation: Additional sprites may have occurred.

References

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