Chemical sources and sinks in the middle atmosphere: relevance and detectability of thunderstorm-induced perturbations

E. Arnone[1], A.K. Smith[2], A. Kero[3], C-F. Enell[3], E. Castelli[1], B.M. Dinelli[1]

[1] *ISAC-CNR, Bologna, Italy*
[2] *ACP/NCAR, Boulder, CO*
[3] *SGO, Sodankylä, Finland*

Lightning and high energy processes are observed in the atmosphere above thunderstorms. These phenomena impact the Earth's atmosphere through ion-neutral chemistry reactions leading to additional chemical sources which are as yet not included in the present picture of atmospheric chemistry and climate. We study the sensitivity of the Whole Atmosphere Community Climate Model (WACCM) to sprite NOx perturbations. We compare the results to known sources and sinks in the middle atmosphere, and investigate the detectability of the atmospheric response from space-borne instruments. This model experiment allow us to evaluate the relevance of sprite perturbations and infer that of other thunderstorm-induced processes.

1. Sprites and NO_x

Since the first transient luminous events (TLEs) were discovered, their possible impact onto the atmospheric chemistry was questioned [1].

Particular emphasis has been given to sprites, with models and observations suggesting a capability of perturbing atmospheric nitrogen oxides at a local level, as it is known to occur for tropospheric lightning and laboratory air discharges. Dedicated ion-neutral chemistry modeling of sprite predict up to orders of magnitude enhancement of NO_x to be produced within individual sprite streamers at about 70 km altitude [2,3,4,5]. Satellite observations were reported of a 10% enhancement of NO_x in regions of high likelihood of sprite occurrence [6,7], although no signature of a global impact has been found [7,8].

Can then sprite chemistry be of any relevance for the atmosphere, e.g. with transport affecting our ability of observing such perturbations? With an extension of tens of kilometres, and a global rate of 3 per minute [9], the current literature point to sprites being a significant local source of atmospheric NO_x under favourable conditions, and a negligible global source. The scales and conditions under which sprites and other thunderstorm-induced perturbations are relevant remain to be investigated.

2. Sprite-NO_x in WACCM

We introduce parameterized perturbations of sprite-NO_x in the Whole Atmosphere Community Climate Model (WACCM) version 4 [10]. WACCM is a comprehensive numerical model, spanning the range of altitude from the Earth's surface to the thermosphere. As compared to earlier versions, WACCM v. 4 has an updated chemistry, inclusion of solar proton events, improved stratospheric warming frequency, gravity waves generated by convection and fronts, and also a parameterized lightning NO_x production. It therefore includes relevant processes for comparison with sprite-NO_x perturbations. In the first experiments we conducted, the model was run in a specified dynamics mode to allow a more robust comparison of control and perturbed experiments: The dynamics is controlled by nudging temperature and winds below 60 km to the specified fields based on observations, nudging strength which is reduced between 50 and 60 km and the model is free running above 60 km. Control and perturbed experiments were run starting either on 2 January 2004 or on 2 March 2011, due to a convenient available starting fields. The control experiments were run for 60 days, perturbed experiments until they converged.

The sprite-NO_x perturbations were based on the vertical profiles of the local sprite-NO_x parameterization by [2]. The global distribution of sprites was assumed as resembling the lightning climatology by [11], with a global occurrence frequency of 3 sprites/minute adopted by [9]. The atmosphere within sprite volumes was assumed to be completely filled by sprite streamers

3. Atmospheric sensitivity to sprite-NO_x

A sprite-NO_x perturbed lower mesosphere scenario was obtained applying to WACCM sprite perturbations with magnitude significantly higher than expected, adopting factors of 10x and 100x.

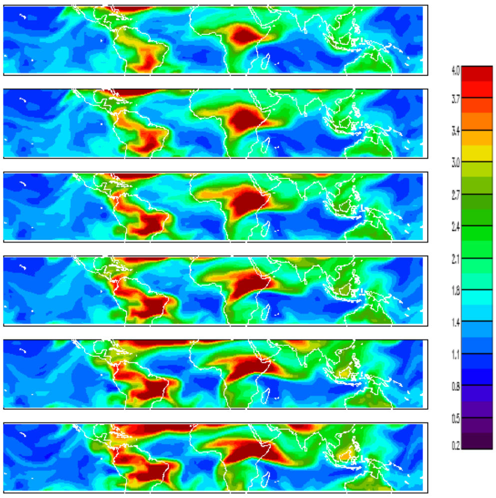

Figure 1: Distribution of WACCM NOx (ppbv) at 70 km altitude over the Tropics. Results from the sprite-NOx simulation at 0, 4, 8, 12, 16, 20 UT, day 2 (top to bottom).

The perturbed simulations show the formation of a secondary peak in NO_x at about 70 km altitude both with the 100x and 10x perturbations. Local sources are clearly identifiable above main continental lightning chimneys (see NO_x distribution on the second day of the simulation in Fig. 1). Within a few weeks, transport produces a zonally-averaged NO_x enhancement spread around the Tropics (black line, Fig. 2), and both the regional levels (colored lines) and the background zonally-averaged levels of NO_x tend to saturate.

Due to background variability and transport, enhancements above a particular region tend to oscillate and show up only under specific days. Scaling down the magnitude of the perturbation, we can expect peaks of more than 10% NO_x change at 60-85 km altitude. At this magnitude, sprite-NO_x have detectable levels, especially under favorable conditions such as above intense sprite-producing thunderstorms and with low background winds. This confirms what suggested by the analysis of satellite observations of NO_x by [6,7,8], with significant impact at local scale and negligible at global scale. On the other hand, we found that the use of partial columns of NO_x extending down to 50 km altitude as adopted by [8] is not sensitive enough to variations to sprite perturbations, since the lower atmospheric layers having the major weight in the partial columns have almost no response to sprite-NO_x.

These model results will be compared to known sources and sinks in the middle atmosphere [12]. Further investigation is ongoing to perform more realistic simulations [13].

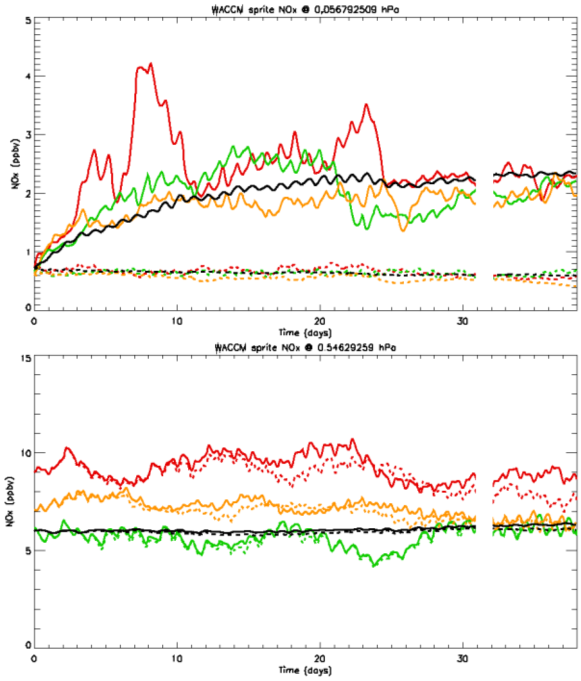

Figure 2: Evolution in time of WACCM NOx at 70 km (top) and 55 km altitude (bottom) for the 10x sprite-NOx simulation (bold lines) and reference simulation (dashed lines). Results are for target regions central Africa (red), Southern America (yellow), South East Asia (green) and the Tropics (black).

4. References

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