TOR
"Thunderstorm Observations and Research"

a sensor package on the ISS for investigations of thunderstorm coronas
and their perturbation to greenhouse gas concentrations

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Abstract

TOR is a sensor package proposed for the International Space Station (ISS) to measure electric coronas at the upper levels of thunderstorm clouds, recently identified by the Atmosphere-Space Interactions Monitor (ASIM) on the ISS. The activity represents a new pathway of atmospheric greenhouse gas perturbations by thunderstorms, adding to such studied processes as water vapor and aerosol transport[1], NOx perturbations by lightning[2], and wrapping of air across the tropopause[3]. TOR will observe the three-dimensional structure of thunderstorm clouds and their electrical activity in optical and UV bands with unprecedented temporal and spatial resolution, that allow for improved estimates of greenhouse gas perturbations by thunderstorms and their trend in a changing climate[4,5,6]. TOR observations will complement those of the Lightning Imager Sensor (LIS) payload on the ISS and of the French micro-satellite TARANIS, with synergistic benefits for the research objectives of the three missions. In addition, TOR will pave the way for the scientific and operational use of EUMETSAT's Meteosat Third Generation Satellite (MTG) that, for the first time, carries a lightning imager to geostationary orbit in the European sector. The TOR mission will

provide data that allow for improved parametrization of thunderstorm perturbations to the atmosphere. The parametrisation will be implemented in models driven by MTG cloud and lightning measurements, and tested by measurements of greenhouse gas perturbations by MTG and instruments on other platforms. The TOR investigation will allow for improved parametrisation in climate models of thunderstorm effects in a changing climate, reducing the uncertainties of the models.

1. Scientific objectives

1.1. *Corona emissions in thunderstorms*

ASIM is an experiment on an external platform of ESA's Columbus module, installed in April 2018. The instruments measure thunderstorm electrical activity in the clouds and above in the stratosphere, mesosphere and lower ionosphere, the so-called transient luminous events (TLEs) and terrestrial gamma-ray flashes (TGFs)[7].

With ASIM we have discovered copious electrical corona activity in the upper regions of thunderstorm clouds and above[8,9,10]. Coronas are streamer discharges, the ionization waves that normally are emitted during lightning leader propagation from the leader tips. They are observed in a narrow band at 337 nm of N_2, with no, or small intensities observed at 777.4 nm, a line emission of atomic oxygen used by lightning imagers to detect lightning. It means that the coronas have largely gone undetected before ASIM

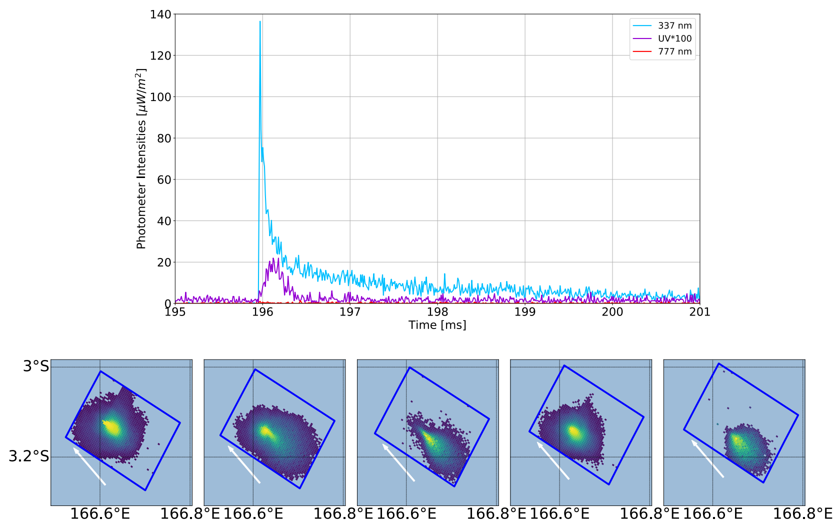

Figure 1. Corona discharges from cloud tops observed towards nadir by ASIM[8]. **Top**: photometer measurements of a corona flash observed in a UV band and at 337 nm at 100.000 samples per second. Emissions in the band of normal lightning leaders (777 nm) are absent. **Bottom**: A corona jet extending to ~50 km altitude observed by the nadir-viewing camera at 337 nm. Five consecutive frames at 12 frames per second. The arrow point in the direction towards the ISS. In the nadir-viewing geometry, the jet appears extended away from the observer, when view at some angle from the optical axis.

Whereas the elve signatures are clear in ASIM data because of their strong UV signal, it is still unknown how to identify the other types of TLEs because of lack of altitude resolution. Analysis procedures are emerging to identify them, but confirmation of the procedures await simultaneous ground observations that inherently have altitude resolution. The occurrence of blue 337 nm corona emission, however, are well identified in the data, but their extent in altitude is only confirmed in the case shown in Figure 1.

1.2. *Perturbations of the atmosphere by corona emissions*

It is well established that lightning is a source of chemical perturbations in the Earth's atmosphere. Of particular interest is the production of nitrogen radicals (NOx), and its subsequent impact on the atmospheric chemistry, including effects on hydrogen species and ozone. Although several model- and measurement studies on lightning NOx (LNOx) have been published in recent years, there are still considerable uncertainties regarding LNOx production rates[2]. Even less well investigated are the effects of discharges in the lower stratosphere such as blue jets, blue starters and coronas near the top of thunderstorm clouds, where only a few studies have been published[11,12,13]. However, any release of reactive species in the stratosphere is of interest as it potentially affects the ozone layer. The proposed TOR instrument will provide valuable data on the electrical activity in thunderstorm clouds, and help to improve estimates on production of NOx and other constituents. These data will be used as input for chemistry and transport models (CTMs) in order to simulate chemical effects from local to global scales, for instance Lagrangian dispersion models to simulate the mixing of a cloud of reactive species with the ambient atmospheric gas. Such models can bridge the gap between the local scales of electrical discharges and the grid scales of global CTMs or climate chemistry models.

1.3. *Scientific objectives*

The microphysics of corona emissions must be understood and modelled accurately with plasma chemical models to quantify their effects on the atmosphere. This requires observations that resolve the coronas in altitude and place them in the context of the cloud structure where they are generated. Observations are further needed of the cloud development phase and other cloud parameters that characterize corona-active clouds which will give insights into their generation, and thereby the microphysics, and will allow for models of the global impact on thunderstorm coronas on the atmospheric composition in the upper troposphere and lower stratosphere.

The scientific objectives of the TOR mission are then summarized as:

1. To provide unequivocal measurements of corona discharges that allow us to understand their micro physics and the properties of the clouds that generate them, and to develop of plasma chemical models of perturbations to atmospheric composition.
2. To develop plasma chemical models of the perturbations to greenhouse gases thunderstorm coronas, and models of the global impact on greenhouse gas perturbations that can be based on data from geostationary weather satellites on clouds and lightning.

2. TOR measurement concept

ASIM views towards the nadir with limited capability to resolve the altitude of the coronas and of the three-dimensional structure of the clouds in which they are produced. These are important measurements when aiming to quantify their effects on the atmosphere. To address this challenge, we propose for a UV- and optical sensor package, TOR that will view thunderstorms at a slanted angle from the vantage point of the ISS, characterizing cloud electrical activity and cloud structure in three dimensions. An example illustrating the power of such measurements is shown in Figure 2. The image is taken from the ISS and shows a thunderstorm with two main clouds, one in the process of collapsing (right) and one growing mushroom cloud (left). Corona emission are generated in the growing cloud.

The TOR module will have identical sensors as the UV- and optical module of ASIM, the Modular Multi-spectral Imaging Array (MMIA) (Table 1). The ISS is an ideal platform for the investigation because it is the lowest available orbit and covers the major thunderstorms regions of the Earth. The measurements will characterise, day and night, thunderstorm clouds and thereby their development phase. During the day, clouds are observed when illuminated by sunlight and by night, as they are illuminated by lightning, revealing their inner structure. In addition, the measurements will identify clouds that penetrate into the lower stratosphere, affecting the concentration of important greenhouse gasses such as water vapour and ozone. Electrical activity is observed during night only because sun illumination is too bright relative to lightning illumination.

Current and planned missions view lightning, clouds and other atmospheric parameters towards the nadir. When observed by weather satellites, the structure of the clouds is inferred from sunlight scattering during the daytime and from imaging sounding day and night. Cloud altitudes are then estimated from the temperature of cloud tops with balloon soundings of atmospheric temperatures or atmospheric models. Clouds illuminated from within by lightning, however, and the close proximity from the ISS relative to geostationary orbit, give a much more detailed view of their structure and of the cloud layers from where the emissions originate. With TOR, the altitude can be determined by triangulation of a sequence of images as the ISS passes over a storm.

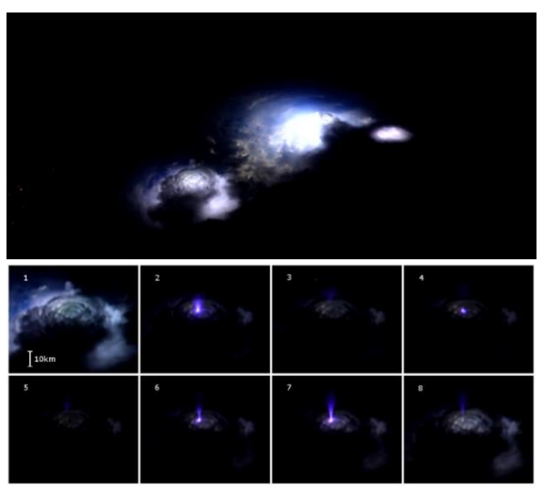

Figure 2: The thunderstorm viewed in the slanted perspective of TOR. The clouds (top) are ~20-30 km across and reach the tropopause at ~16 km altitude. The corona emissions (bottom) are of a blue jet reaching ~35 km altitude. Corona emissions are expected to be more prolific within the top regions of the clouds, but may on occasion extend well into the stratosphere[10] (Photo by A. Mogensen from the ISS, 2015).

The combination of flash detection of electrical activity and detailed cloud structure measurements provided by TOR are the necessary ingredients for characterizing thunderstorm corona activity and its impact on the atmosphere on a global scale. The analysis of TOR data will include important data from other sources such as lightning detection systems, cloud radars and other satellite measurements, as described below.

3. International context

3.1. *Lightning detection from space missions*

The timeline of the missions with optical lightning detection is shown in Figure 3. The monitoring missions are weather satellites in geostationary orbit. The two GOES satellites carry the Global Lightning Mapper (GLM) and cover the western and eastern sectors of the Americas, and the MTG is the Meteosat Third Generation Satellite that, for the first time, will measure lightning with the Lightning Imager (LI). The research satellites are in low earth orbit. All satellites carry as their lightning detection, cameras that measure in a narrow band around the 777.4 nm line of atomic oxygen. The research missions, TARANIS and ASIM, carry additional sensors.

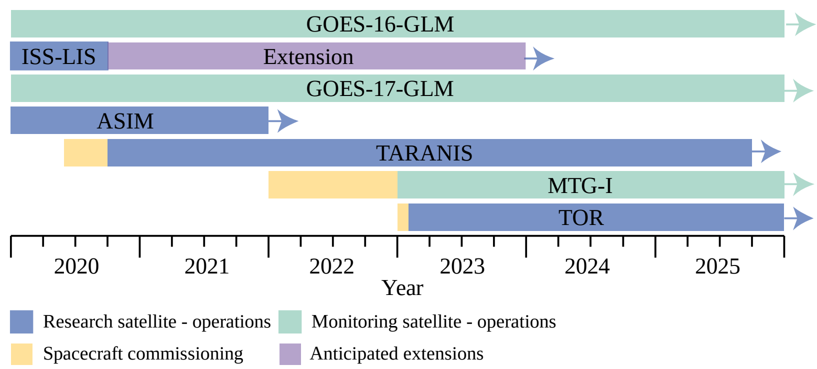

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Figure 3: Space missions with lightning detection instruments. The monitoring missions are in geostationary orbit. All missions carry lightning imagers in the same band at 777.4 nm. The satellite extensions are under discussion.

We are in a unique time for thunderstorm research, with almost global coverage of lightning (China also has a weather satellite with a lightning imager) and at the same time with several high-resolution lightning measurements taken from low-earth orbit. The specifications of the UV- and optical sensors of the missions are shown in Table 1. The relationship between the observations of the missions go through observations in the 777.4 nm band, allowing for cross calibrations and data analysis across platforms. However, all missions are nadir-viewing over the tropical regions of the most thunderstorm activity. *TOR will have the only sensors that directly resolve the cloud structure and electrical activity in altitude – and with relatively high spatial resolution compared to the other missions*.

4.1. *TOR with TARANIS*

The study of corona emissions will be supported by the French "Tool for the Analysis of RAdiations from lightNIngs and Sprites" (TARANIS) satellite, planned for launch in June 2020. The spacecraft carries similar optical sensors as ASIM/TOR in a nadir-viewing geometry, with the addition of electromagnetic measurements over a wide frequency band. It is expected that TARANIS and TOR at times will monitor the same thunderstorms. The number of common storms for analysis with TOR/TARANIS will be larger than with ASIM/TARANIS because the TOR slant viewing sensors will view further ahead in the ram direction of the ISS. Likewise, the expected time differences between overpasses of TOR/TARANIS will in general be shorter. As the electromagnetic measurements from TARANIS will be important for TOR-studies of corona microphysics, the slant-viewing geometry of TOR will be of immense value for the analysis of the TARANIS optical and UV data.

Table 1: Optical sensors for lightning detection.

Mission	Orbit	Observ. Periods	Sensor	Band/ Bwidth (nm)	Spatial Resolution (km)	Temporal Resolution (ms)
TARANIS/MCP	Polar	Night	Photometer	180-260	500	0.05
			Photometer	337/10	500	0.05
			Photometer	762/10	500	0.05
			Photometer	600-900	700	0.05
			Camera	762/10	1	100
			Camera	777/10	1	100
ASIM and TOR*	51.6^{o}/400 km	Night*	Photometer	180-260	400	0.01
			Photometer	337/5	400	0.01
			Photometer	777/3	400	0.01
			Camera	337/5	0.4	83
			Camera	777/3	0.4	83
ISS-LIS/LIS	51.6^{o}/400 km	Day/night	Camera	777/5	10	2
GOES/GLM	Geostation.	Day/night	Camera	777/5	8	2
MTG/LI	Geostation.	Day/night	Camera	777/5	4.5	2

*TOR also measures clouds during day and night

4.2. *TOR with MTG/LI*

Europe will launch MTG-I into geostationary orbit in 2022. The MTG will give unprecedented observations of thunderstorm clouds, humidity and chemical perturbations with IRS and FCI instruments that sample several thousand spectral channels. A third instrument is the Lightning Imager that for the first time will provide lightning measurements in the European sector. Together, the instruments open for new opportunities to study convection and electrification, and the effects of these processes on the atmospheric chemistry.

The LI data are to be distributed to partners of EUMETSAT for weather forecasts and predictions of severe weather conditions. Considerable effort goes into calibration and validation of data, by analysing ground observations of lightning and storm cloud conditions by radars with past data of the LIS on TRMM, and analysing current data from ISS-LIS and the GLM. The is collaboration with the US counterparts of the GLM for this purpose.

Lightning imaging is inherently more sensitive to in-cloud lightning than the ground based systems that are more sensitive to cloud-to ground lightning, which is a greater cause of lightning damage. However, in-cloud lightning activity has proven a powerful tool for predicting the onset of severe weather conditions and allows for following and predicting the development of convective storms.

Clouds may obscure optical emissions or may reflect emission from distant and lower cloud tops, thereby reducing the detection efficiency and the accuracy of lightning location. A TOR sensor package on the ISS will have more than 10 times higher spatial accuracy of data on lightning activity and cloud structure than LI, both with altitude resolution. TOR observations will then allow for quantifications of LI data product accuracies and possibly for improvement of the data products.

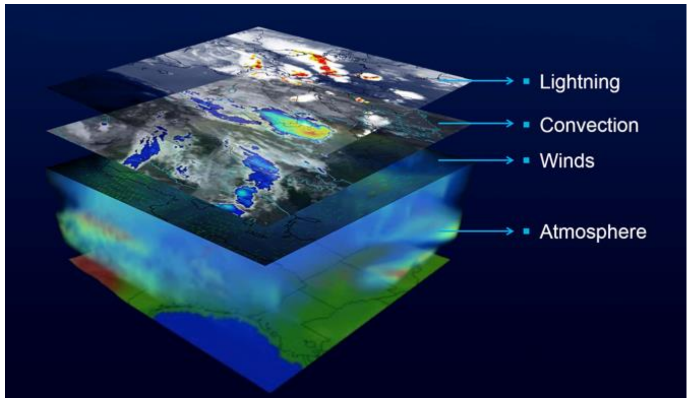

Figure 4: EUMETSAT illustration of the combined observations of the MTG spacecraft.

4.3. *Scientific collaborations*

Extensive international collaborations in the ASIM project and several European-wide networks have been ongoing during the past several years. The international team includes experts in corona and lightning discharge physics, space- and ground observations of thunderstorm activity, the plasma chemistry of discharges, thunderstorm effects on the atmosphere, and in climate modelling.

4.4. *National and international strategic goals*

The objective of the TOR mission is to secure data and to develop algorithms that allow for a reduction of the uncertainties in climate models that are related to the contributions of thunderstorms to greenhouse gas concentrations. Reduced uncertainties will improve climate change forecasts and reduce the costs of adaption measures.

- United Nations 2030 Agenda for Sustainable Development Goal 13: Take urgent action to combat climate change and its impacts 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (A/RES/70/1).
- Danish goals for space research: Green change from Space, January 2020, Status report from cross-ministerial Space Board: Climate research and adjustment[1].

5. Accommodation on the ISS

5.1. *Scenario one: TOR on CEPA*

The Columbus External Payload Adapter (CEPA) is designed to be mounted on the platform structures of the Columbus module. Columbus is in the ram direction of the ISS and ASIM is

[1] Grøn Omstilling fra Rummet, Januar 2020, Status rapport for det tværministerielle Rumudvalg: Klima forskning og tilpasning

mounted on the CEPA on the lower structure facing starboard (Figure 4). TOR on the CEPA is shown in Figures 4 and 5, with TOR on the upper platform structure in the same configuration as MMIA. The optical table is part of the ASIM configuration and allows MMIA an unobstructed view towards the nadir even if a larger payload is mounted on the nadir-pointing platform structure. It is not needed for TOR, but could be reused if it saves cost. The only change is the MMIA optics to accommodate larger viewing distances (smaller field of view) and possibly design changes of radiators for thermal control.

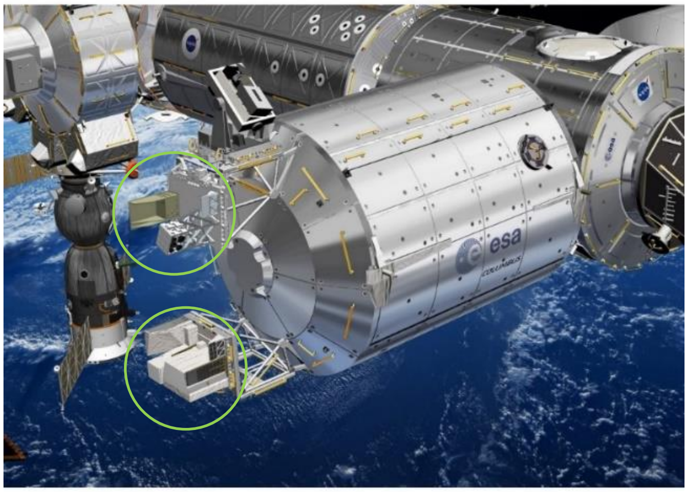

Figure 4: The TOR module is on the upper platform viewing in the ram direction and at an angle down towards the earth. ASIM is on the lower platform viewing towards the nadir.

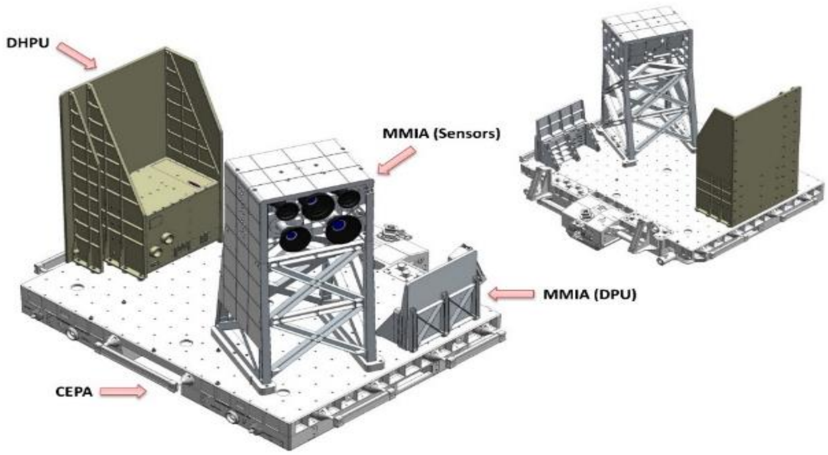

Figure 5: TOR includes the ASIM MMIA optical module, the MMIA instrument computer, DPU (Data Processing Unit), the platform interface computer to the ISS, the DHPU (Data Handling and Processing Unit), and the mechanical structures.

5.2. *Scenario two: TOR on the Bartolomeo platform*

A new platform, Bartolomeo, has been developed by Airbus and is scheduled for launch in March 2020. Bartolomeo is a platform for Columbus that will have a simpler power and data interface to Columbus. It allows for a more elegant solution than the DHPU of ASIM, but requires a redesign of this unit.

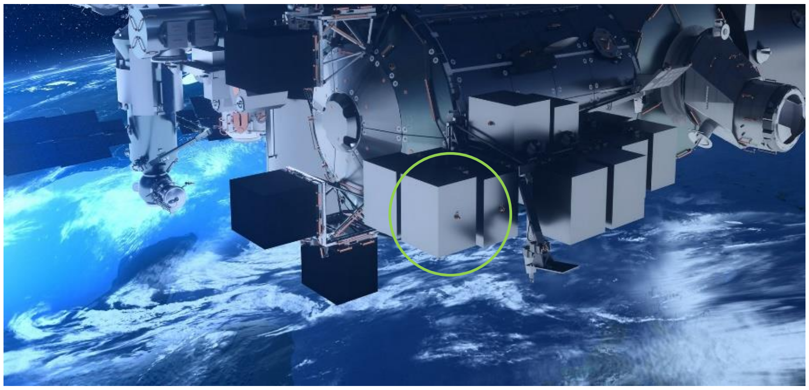

Figure 6: TOR on the Bartolomeo platform. The boxes indicate the envelope of instruments that can be accommodated.

6. Programmatics

ASIM includes a gamma-ray sensor (MXGS) and an UV- and optical module (MMIA), both viewing towards the nadir. When ASIM was first proposed to ESA and accepted in the ELIPS research programme, it also included a limb-viewing MMIA that was de-scoped because of limitations in the funding. Some of the climate related science was dependent of the limb module, since it allows characterization of the altitude of observed emissions, which is essential for assessing the climate impact of thunderstorms. We propose to recover the MMIA limb module, to regain the configuration accepted into the ELIPS programme, and to recover the climate science of the original project.

7. Timeline

We propose that the TOR sensor module is a reuse of MMIA developed for ASIM, with redesign of the optics to accommodate larger viewing distances, and possibly a modified interface to Columbus. The instrument computer, cameras and photometers are otherwise identical, including the software on the instrument computer. The high degree of reuse, and the high technological readiness level, lead to a timeline for instrument manufacture and tests that is comparatively short, relative to other space missions, and of the order of 3 years, once the go ahead is given. The timeline for identification of the suitable platform on the ISS, launch opportunity, and the establishment of the consortium and funding, must be assessed.

8. Costs

Instrument cost is according to reuse of flight proven hardware and is estimated to ~7M€. Costs of launch, ISS interface, etc. must be assessed.

9. Danish partners

Partners include Copenhagen University, Ice and Climate Section, and Danish Meteorological Institute. Terma will lead the Instrument consortium as they did for ASIM.

10. International partners

An extensive network of international groups with a history of collaboration will back the mission. The core team are co-proposers of the TOR project with expertise in discharge physics, thunderstorm physics, plasma and thunderstorm chemistry and climate modelling.

11. References

1 Contributions of stratospheric water vapor to decadal changes in the rate of global warming, Solomon S, Rosenlof KH, Portmann RW, Daniel JS, Davis SM, Sanford TJ, Plattner GK, *Science* 327.5970 (2010): 1219-1223.

2 Schumann, U., and H. Huntrieser, The global lightning-induced nitrogen oxides source, *Atm. Chem. Phys. 7*.14, 3823-3907, https://doi.org/10.5194/acp-7-3823-2007, 2007.

3 Pan, L., et al. Thunderstorms enhance tropospheric ozone by wrap-ping and shedding stratospheric air, *Geophys. Res. Lett*., 41.22 (2014): 7785-7790.

4 Declan L. Finney, Ruth M. Doherty, Oliver Wild, David S. Stevenson, Ian A. MacKenzie and Alan M. Blyth, A projected decrease in lightning under climate change, Nature Climate Change, **212,** 8 210–213, www.nature.com/natureclimatechange, 2018.

5 David M. Romps, Jacob T. Seeley, David Vollaro and John Molinari, Projected increase in lightning strikes in the United States due to global warming, DOI: 10.1126/science.1259100, *Science* 346 (6211), 851-854.

6 Banerjee, A. et al., Lightning NO_X, a key chemistry–climate interaction: impacts of future climate change and consequences for tropospheric oxidising capacity, *Atmos. Chem. Phys., 14*, 9871-9881(2014).

7 Neubert, T., N. Østgaard, V. Reglero, E. Blanc, O. Chanrion, C. A. Oxborrow, A. Orr, M. Tacconi, O. Hartnack, D. D. V. Bhanderi, The ASIM mission on the International Space Station, *Space Sci. Rev*., 215:26 https://doi.org/10.1007/s11214-019-0592-z, 2019.

8 Neubert, T., O. Chanrion, K. Dimitriadou, M. Heumesser, I. Lundgaard Rasmussen, Lasse, V. Reglero and N. Østgaard, The genesis of blue lightning into the stratosphere, submitted, 2020.

9 Soler, S., F. J. Pérez-Invernón, F. J. Gordillo-Vázquez, A. Luque, D. Li, A. Malagón-Romero, T. Neubert, O. Chanrion, V. Reglero, J. Navarro-González 3, G. Lu, H. Zhang, A. Huang, Blue optical observations of narrow bipolar events by ASIM confirm streamer activity in thunderstorms, *J. Geophys. Res. Atm.*, submitted, 2020.

10 Chanrion, O., T. Neubert, A. Mogensen, Y. Yair, M. Stendel, N. Larsen and R. Singh, Profuse activity of blue electrical discharges at the tops of thunderstorms, *Geophys. Res. Lett., 44*, doi: 10.1002/2016GL071311, 2017.

11 Winkler, H., and J. Notholt, A model study of the plasma chemistry of stratospheric Blue Jets, *J. Atm. Sol.-Terr. Phys.*, *122*, 75, doi:10.1016/j.jastp.2014.10.015, 2015.

12 Gordillo-Vazquez, F. J., Smith, A. K., Arnone, E., & Winkler, H.. Global occurrence and chemical impact of stratospheric Blue Jets modeled with WACCM4, *J. Geophys. Res. Atm.*, *124*. https://doi.org/10.1029/2018JD029593, 2019

13 Gordillo-Vazquez, F. J., Pérez-Invernón, F. J., Huntrieser, H., & Smith, A. K., Comparison of six lightning parameterizations in CAM5 and the impact on global atmospheric chemistry, *Earth and Space Science*, *6*, 2317-2346, https://doi.org/10.1029/2019EA000873, 2019.