ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

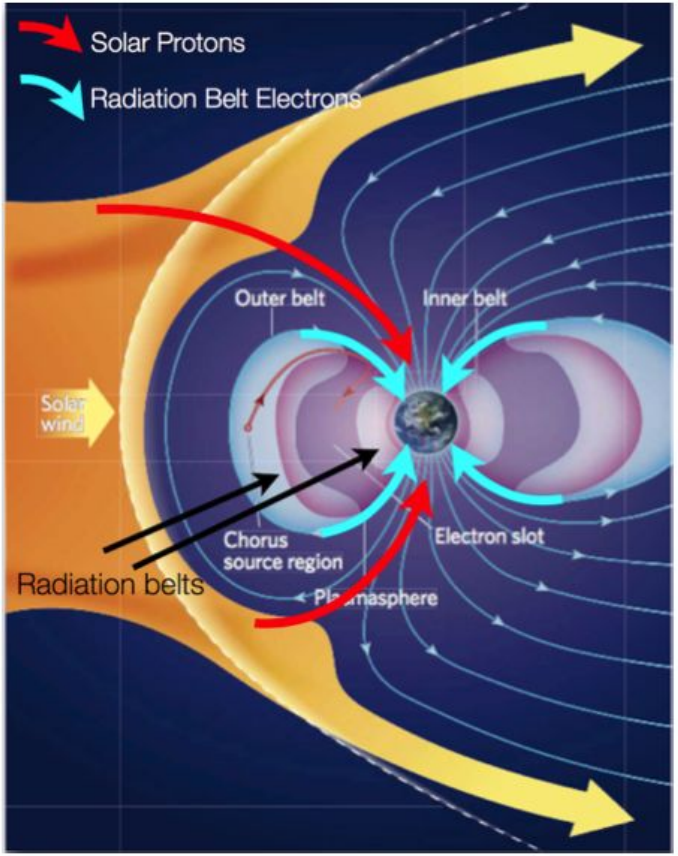
Simulating atmospheric impact of solar extreme events using the Whole Atmosphere Community Climate Model

P. T. Verronen, — University of Oulu, Finland
N. Kalakoski, M. E. Szeląg, T. Häkkilä — Finnish Meteorological Institute, Finland
D. R. Marsh, — National Center for Atmospheric Research, USA
T. Kovács, J. M. C. Plane — University of Leeds, UK

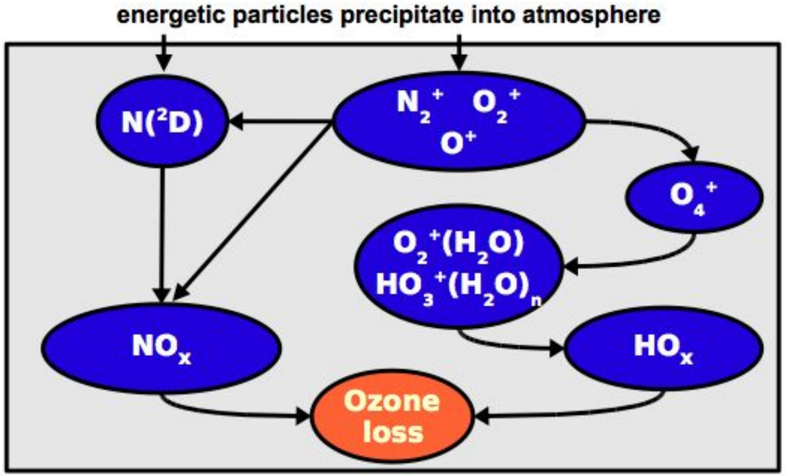
ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

Energetic particle precipitation (EPP) - Atmospheric effects

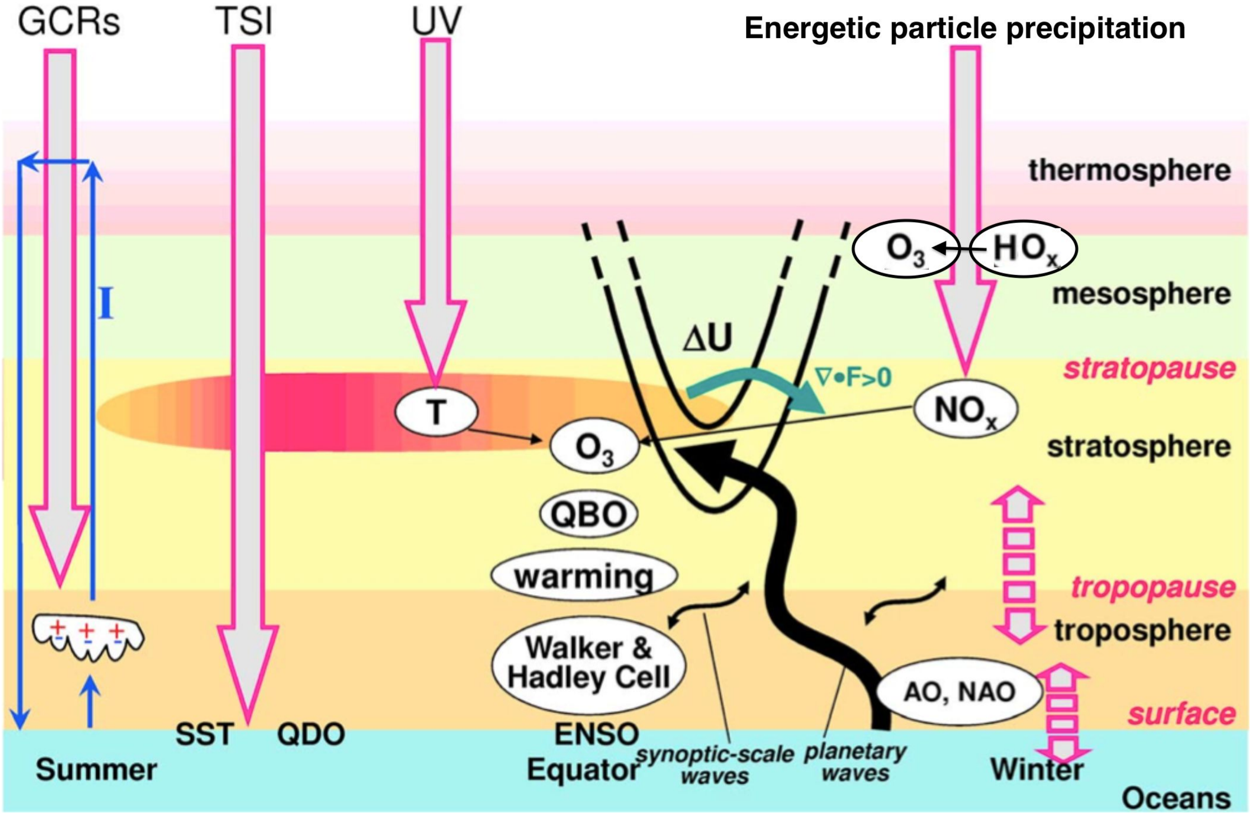


The concept: particles ionize middle atmosphere, leading to an ozone response.



ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE
UNIVERSITY OF OULU

Top-down atmospheric coupling - role of EPP



Connection between

- solar influence
- ozone and temperature
- winds and waves

For EPP, action takes place

- in polar regions
- during winter months.

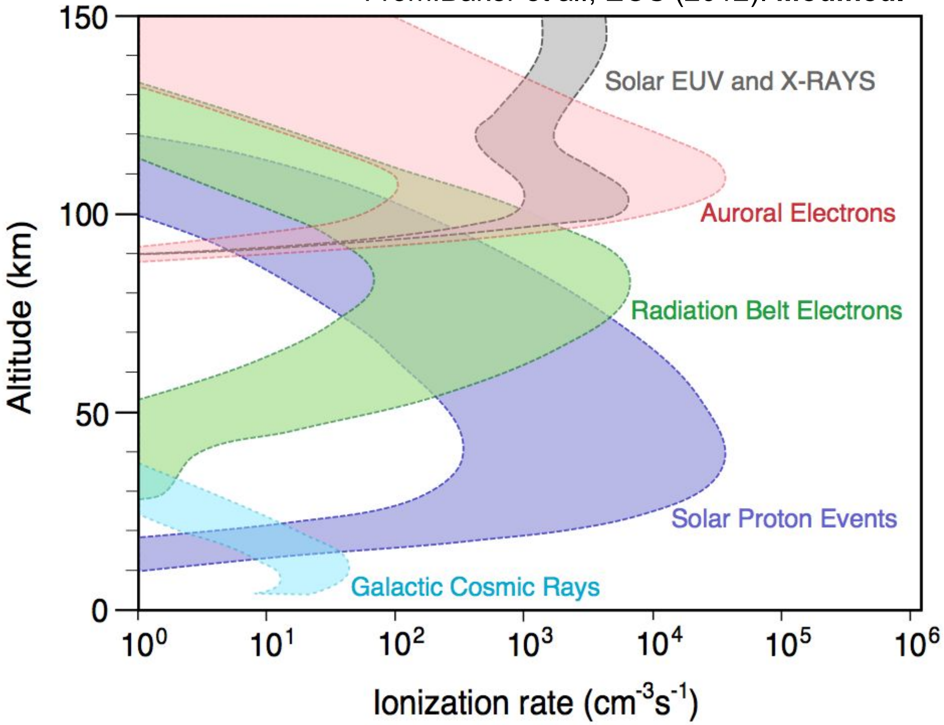
From: Gray et al.,
Rev. Geophys. (2010). **Modified.**

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

Solar proton events (SPEs) - Extreme impact on polar ozone

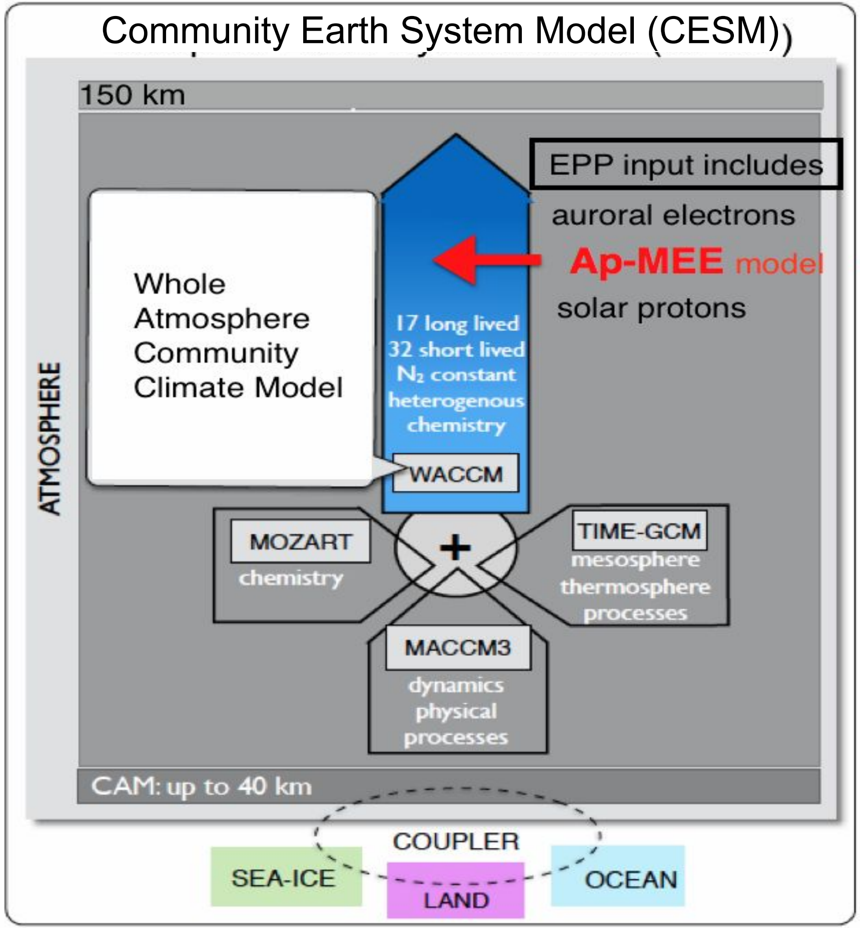
From:Baker et al., EOS (2012). **Modified.**



- Contribution of all EPP should included for the assessment of decadal effects
- Major part of direct D-region comes from SPEs and RBE
- **SPEs**

  (a) cause direct ozone effect in the mesosphere and stratosphere
  (b) impact the whole polar cap
  (c) are strong and event-type

CESM / WACCM model



Whole Atmosphere Community Climate Model (WACCM)

- Global, 3-D chemistry-climate model
- Range of altitude 0 - 140 km
- Fully interactive chemistry, radiation, and dynamics
- Horizontal resolution is 1.9° latitude by 2.5° longitude.
- Vertical resolution: 1-2 km below stratopause, 3.5 km above
- The chemical time step is 30 minutes.
- Ionization sources include
  - EUV and soft X-ray photons,
  - photoelectron impact, EPP
  - D-region ion chemistry

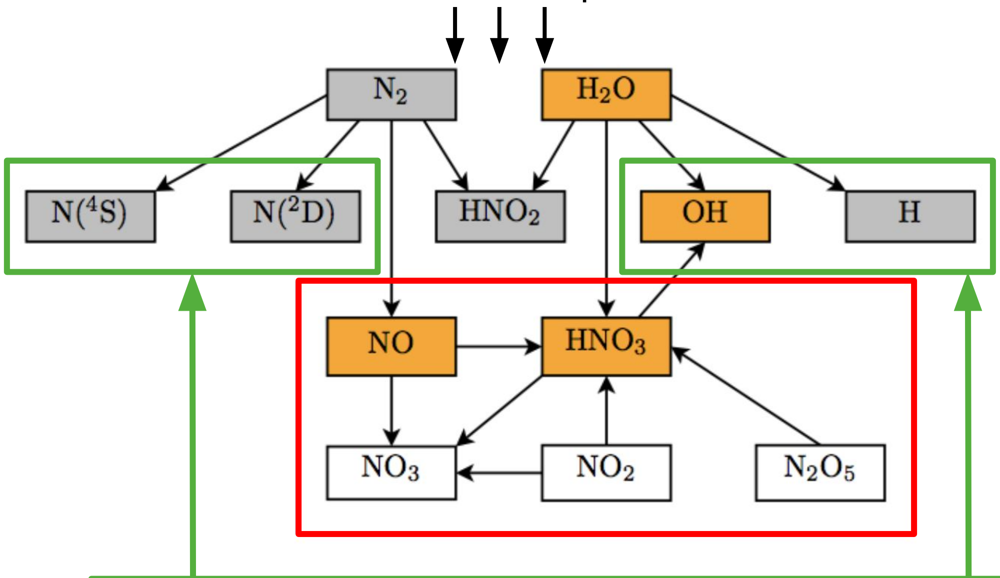
- CESM/WACCM simulations require a supercomputer, e.g. Cray XC30 at Finnish Meteorological Institute.

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

Adding lower ionospheric chemistry - impact

EPP into atmosphere



HOx and NOx production are included in the standard parameterization

$$
\begin{aligned}
N_2 + p^+(E) &\rightarrow N_2^+ + e^- + p^+(E - \Delta E)\\
O_2 + O_2 + e^- &\rightarrow O_2^- + O_2\\
O_2^- + O_3 &\rightarrow O_3^- + O_2\\
O_3^- + CO_2 &\rightarrow CO_3^- + O_2\\
CO_3^- + NO_2 &\rightarrow NO_3^- + CO_2\\
NO_3^- + H_2O + M &\rightarrow NO_3^-(H_2O) + M\\
NO_3^-(H_2O) + HNO_3 &\rightarrow NO_3^-(HNO_3) + H_2O\\
NO_3^-(HNO_3) + \mathbf{H^+(H_2O)_4} &\rightarrow \mathbf{HNO_3} + HNO_3 + 4H_2O\\
--- &\quad ---\\
\mathbf{Net:}\ \mathbf{H_2O} + O_3 + NO_2 &\rightarrow \mathbf{OH} + \mathbf{HNO_3} + O_2
\end{aligned}
$$

- ion chemistry is reasonably well known
- but parameterizations are not using our full knowledge

From: Verronen and Lehmann, Ann. Geophys., http://doi.org/10.5194/angeo-31-909-2013, 2013

D-region positive ion chemistry in WACCM-D

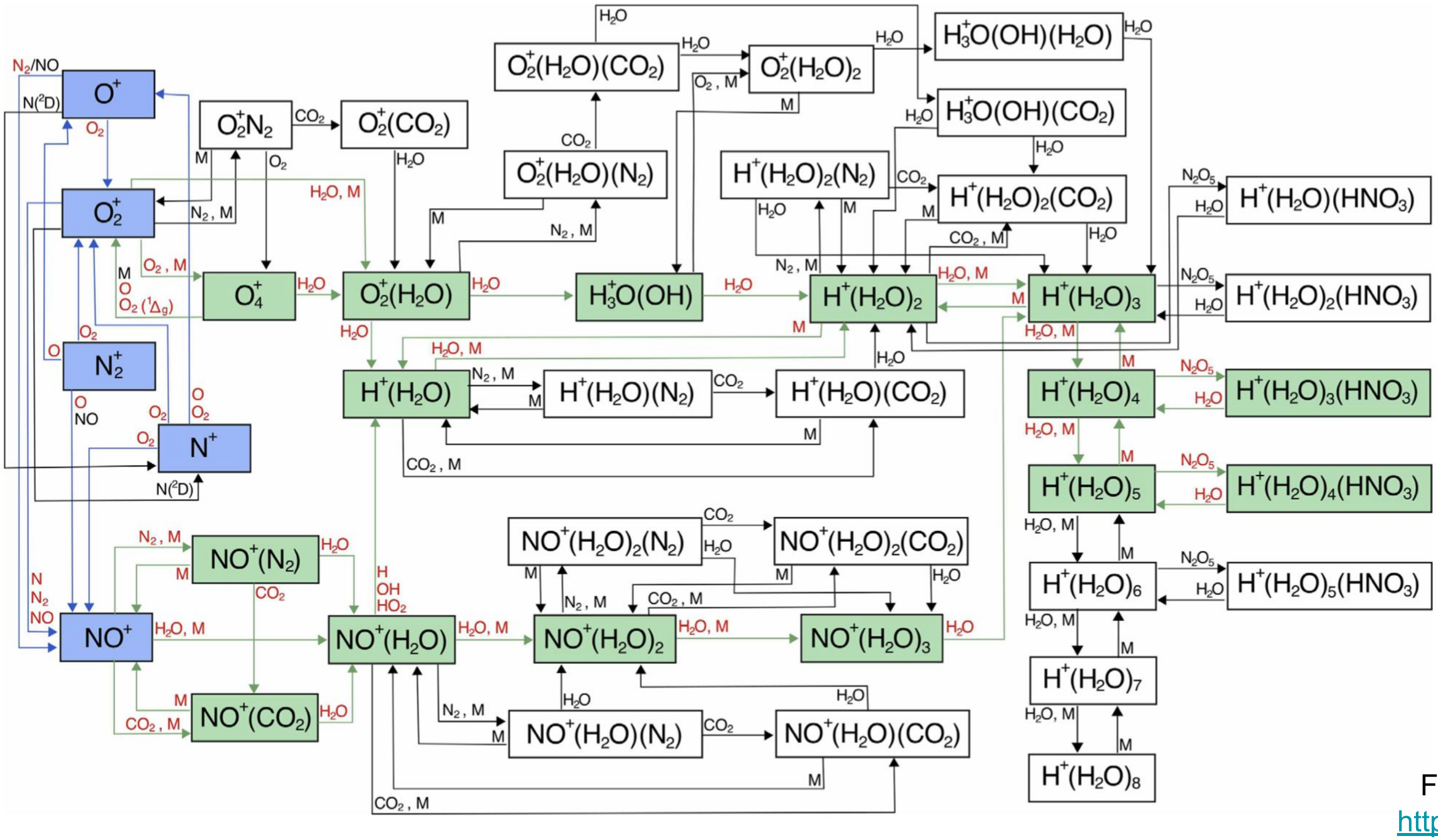


Figure 1. Positive ion reaction scheme of the SIC model. The colors indicate the subsets included in WACCM (blue) and WACCM-D (blue and green).

- 307 reactions of
- 20 positive ions and
- 21 negative ions

- Allows for a representation of ionosphere below 90 km

- WACCM ions in blue, WACCM-D has also green ions

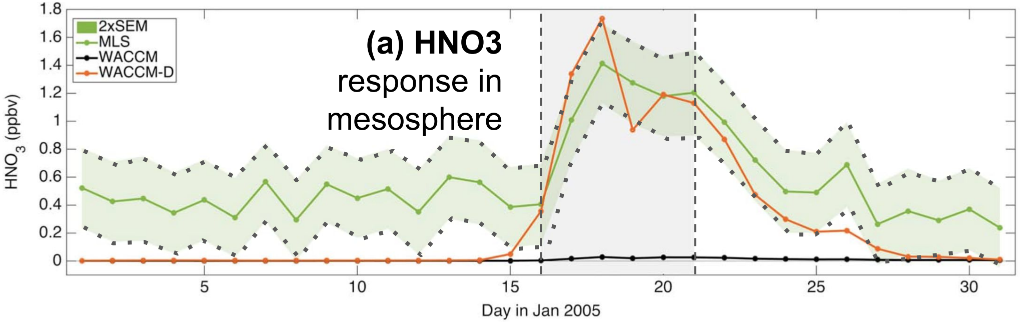
From: Verronen et al., JGR (Atmos.), http://doi.org/10.1002/2015MS000592, 2016

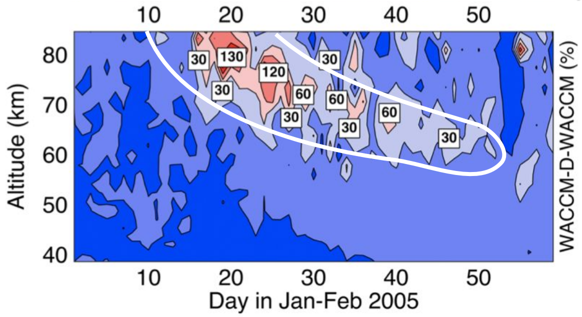
ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

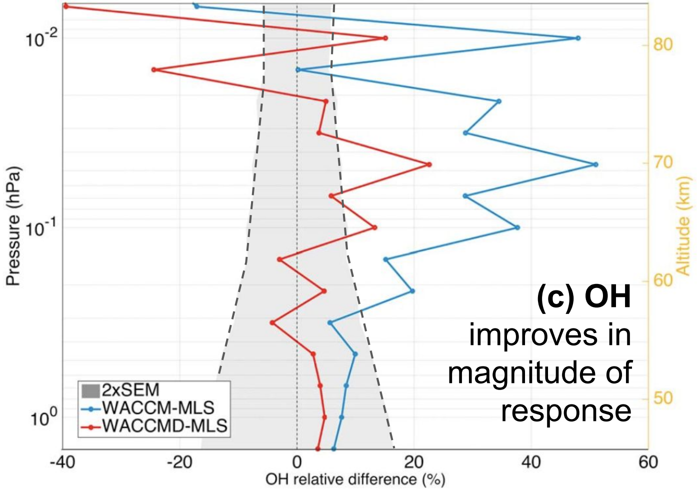
WACCM improvements from D-region ion chemistry

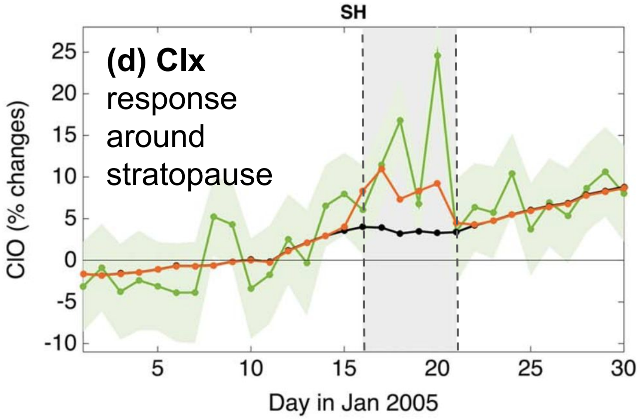
January 2005 SPE, comparison against MLS/Aura observations, NH polar cap averages





(b) NOx increase in mesosphere compared to standard WACCM





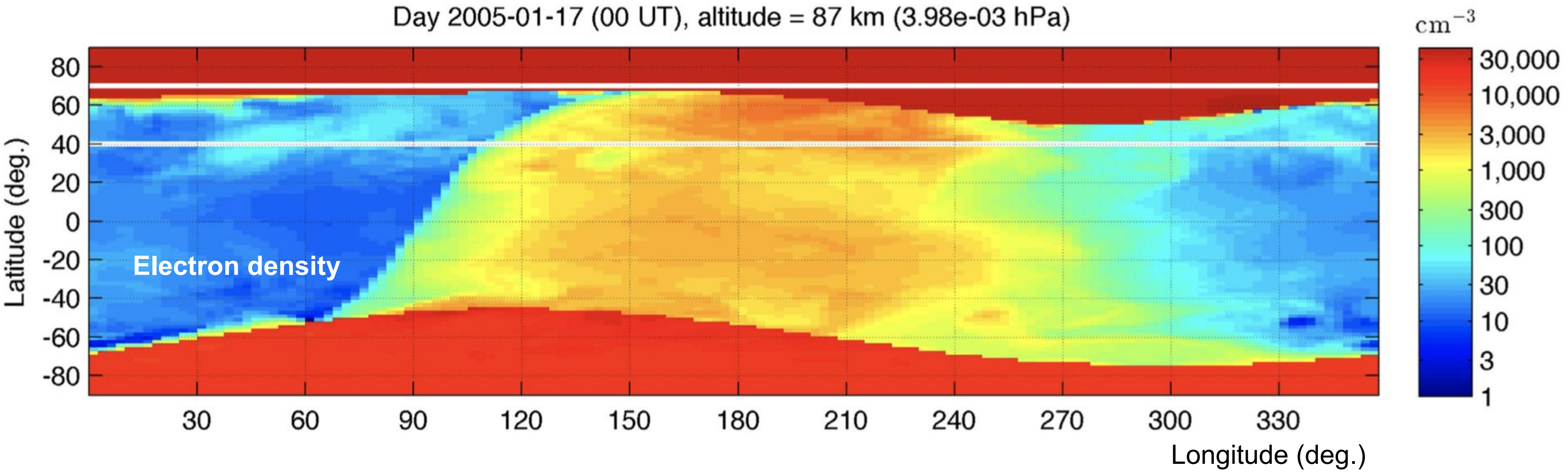
- (a) **HNO3**
- (b) **NOx**
- (c) **OH**
- (d) **Clx**

From: Andersson et al., JGR (Atmos.), http://doi.org/10.1002/2015JD024173, 2016

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

WACCM-D: global electron density maps (17 Jan 2005 SPE)



- Global view of the highly dynamic MLT region
- Putting the regional observations into larger context
- Note the effect of dynamics at sunset (around 270 deg.)

From: Verronen et al., JGR (Atmos.), http://doi.org/10.1002/2015MS000592, 2016

JGR Space Physics

RESEARCH ARTICLE
10.1029/2018JA026192

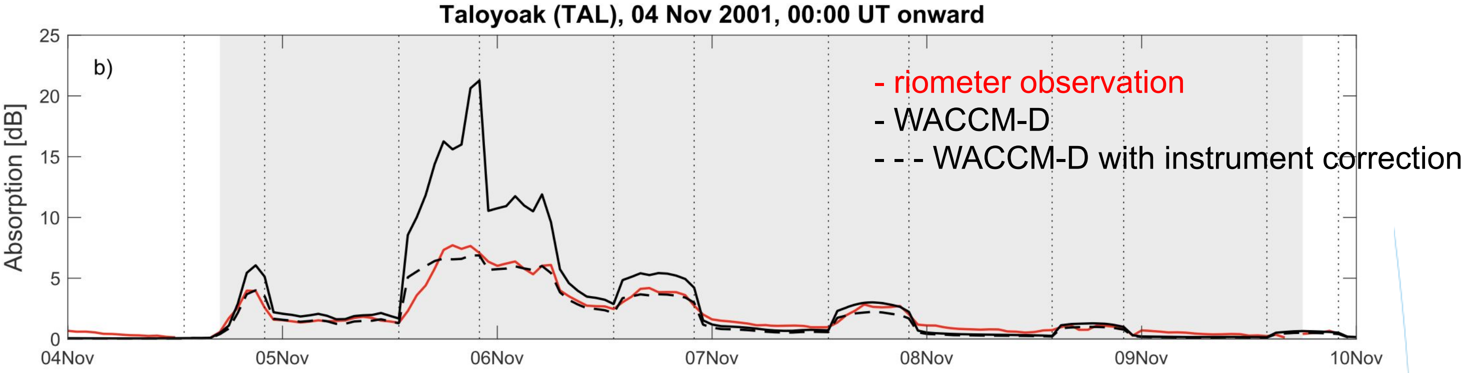
Cosmic Noise Absorption During Solar Proton Events in WACCM-D and Riometer Observations

Erkka Heino[1,2], Pekka T. Verronen[3], Antti Kero[4], Niilo Kalakoski[3], and Noora Partamies[1,5]

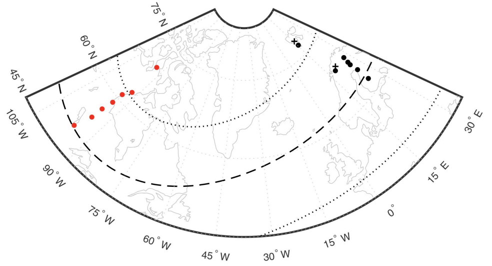
Key Points:
- CNA during 62 SPEs was studied with WACCM-D and riometer observations
- CNA is modeled well on average and in individual events with a nonlinearity correction for high levels of CNA
- The fixed proton cutoff latitude in WACCM-D at 60 degrees leads to overestimation of the extent of the CNA, especially in small to moderate SPEs

Correspondence to:
E. Heino,
erkkah@unis.no

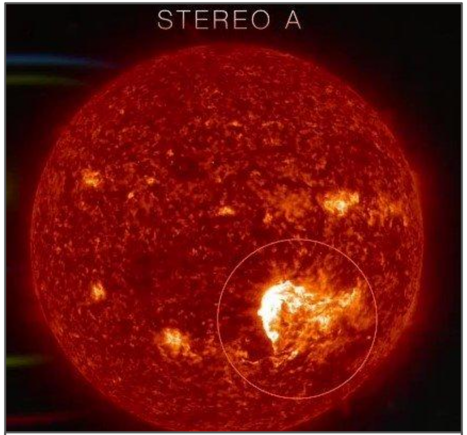
Citation:
Heino, E., Verronen, P. T., Kero, A., Kalakoski, N., & Partamies, N. (2019). Cosmic noise absorption during solar proton events in WACCM-D and riometer observations. *Journal of Geophysical Research: Space Physics*, *124*, 1361–1376. https://doi.org/10.1029/2018JA026192

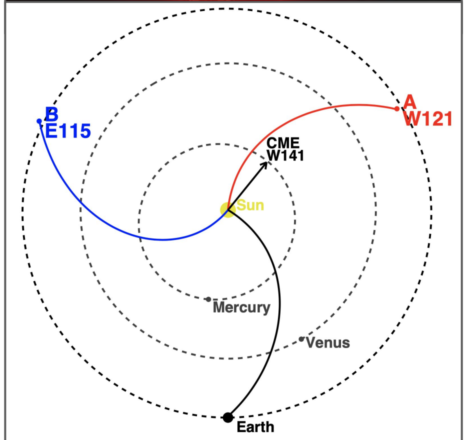


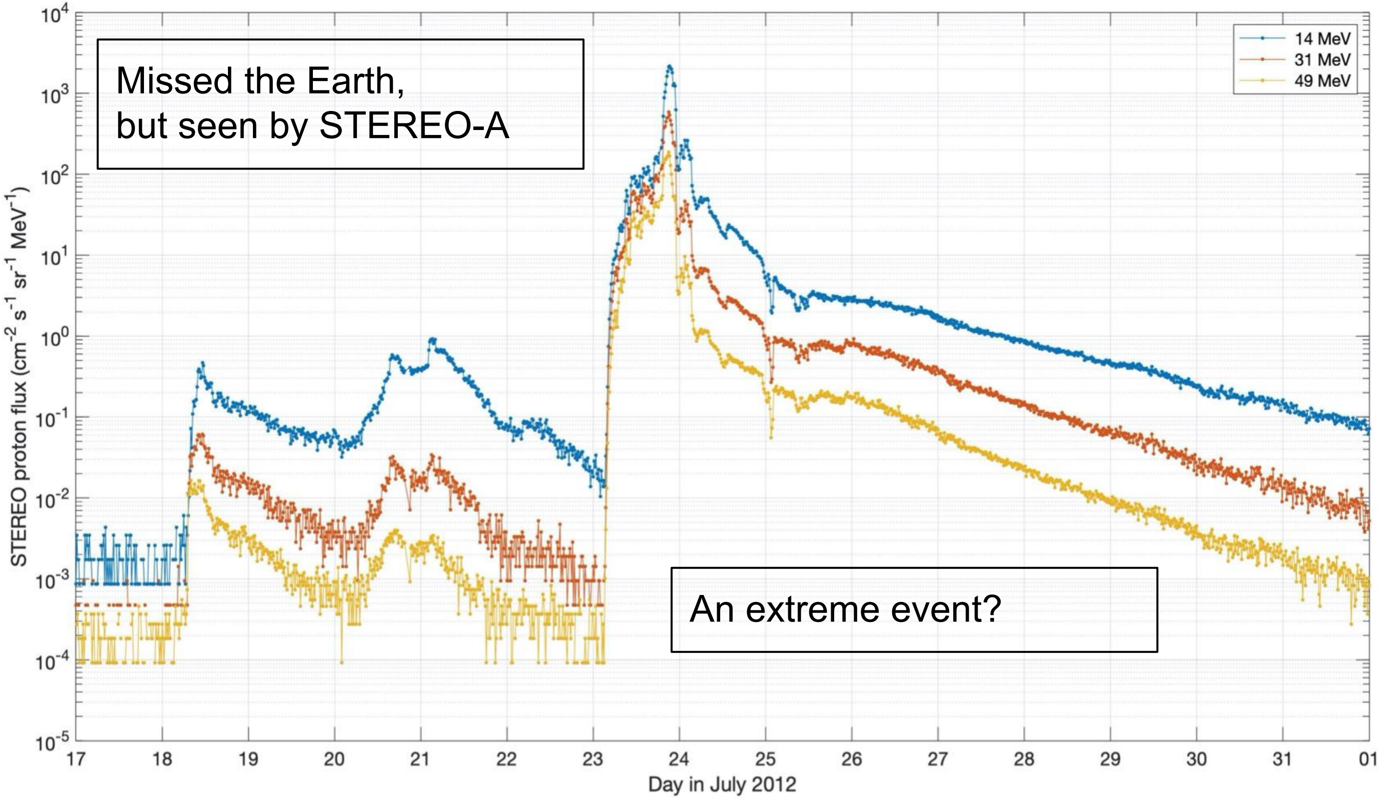
Example of modeled and observed CNA at 70°N during a solar proton event (Nov 2001).



July 2012 event from Solar TErrestrial RElations Observatory

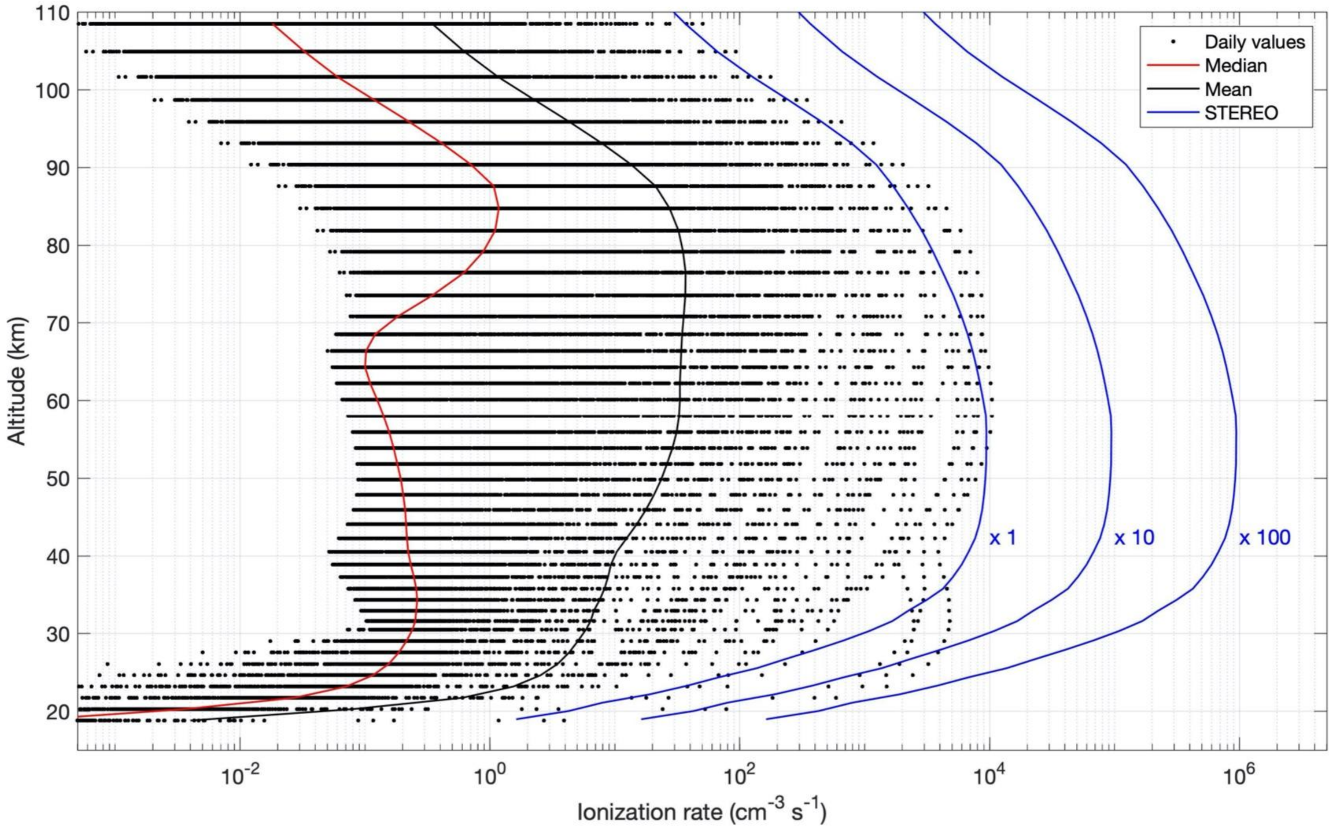






ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE
UNIVERSITY OF OULU

July 2012/STEREO compared to SPEs in 2000-2005



Comparison to GOES-based daily ionization reveals that the **July 2012 event would have been among the largest but not extreme**.

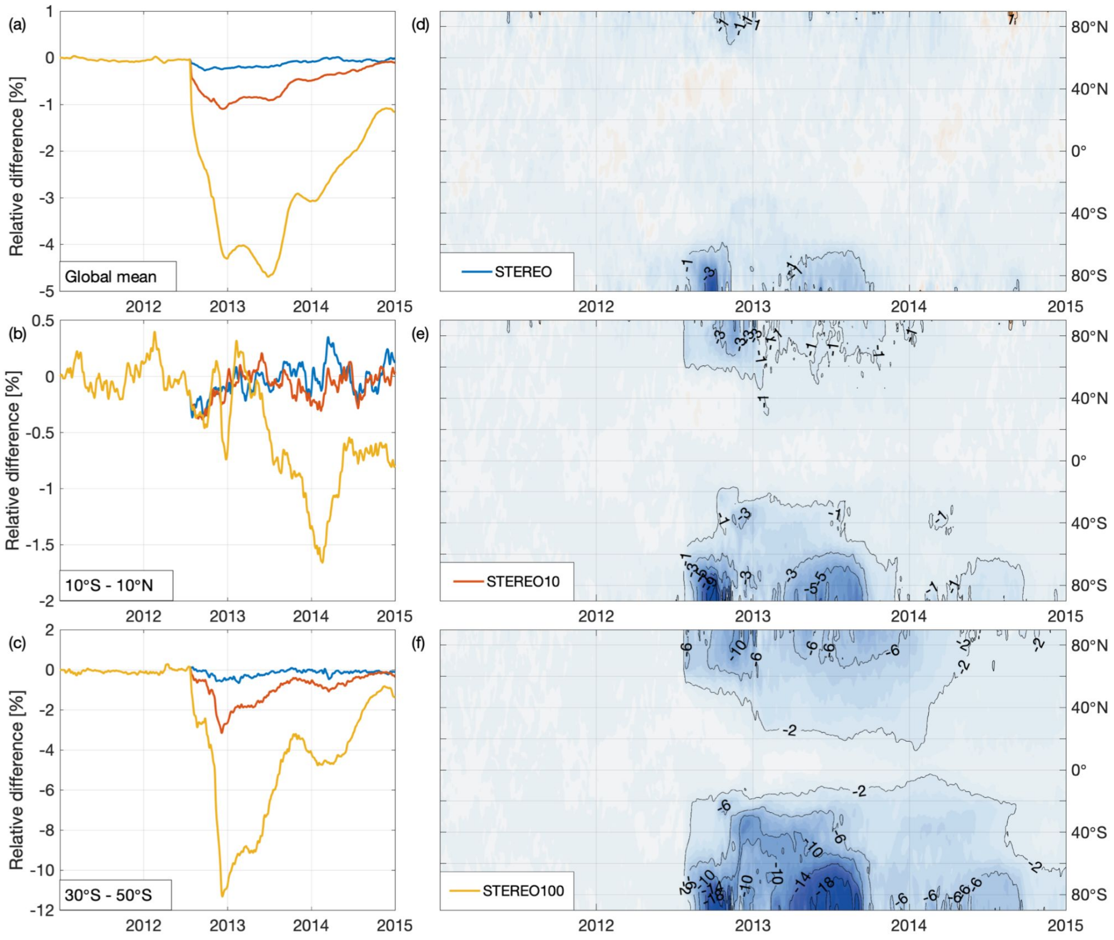
But how about making it extreme e.g. multiplying by 10 or 100?

Can we see a response in **total, global ozone** when the **forcing covers the polar cap only**?

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

UNIVERSITY OF OULU

Zonal mean ozone anomalies from WACCM



- Specified dynamics
- Years 2011-2014
- July 2012 added to SPE forcing based on STEREO-A observations.

Increase in forcing is reflected in response

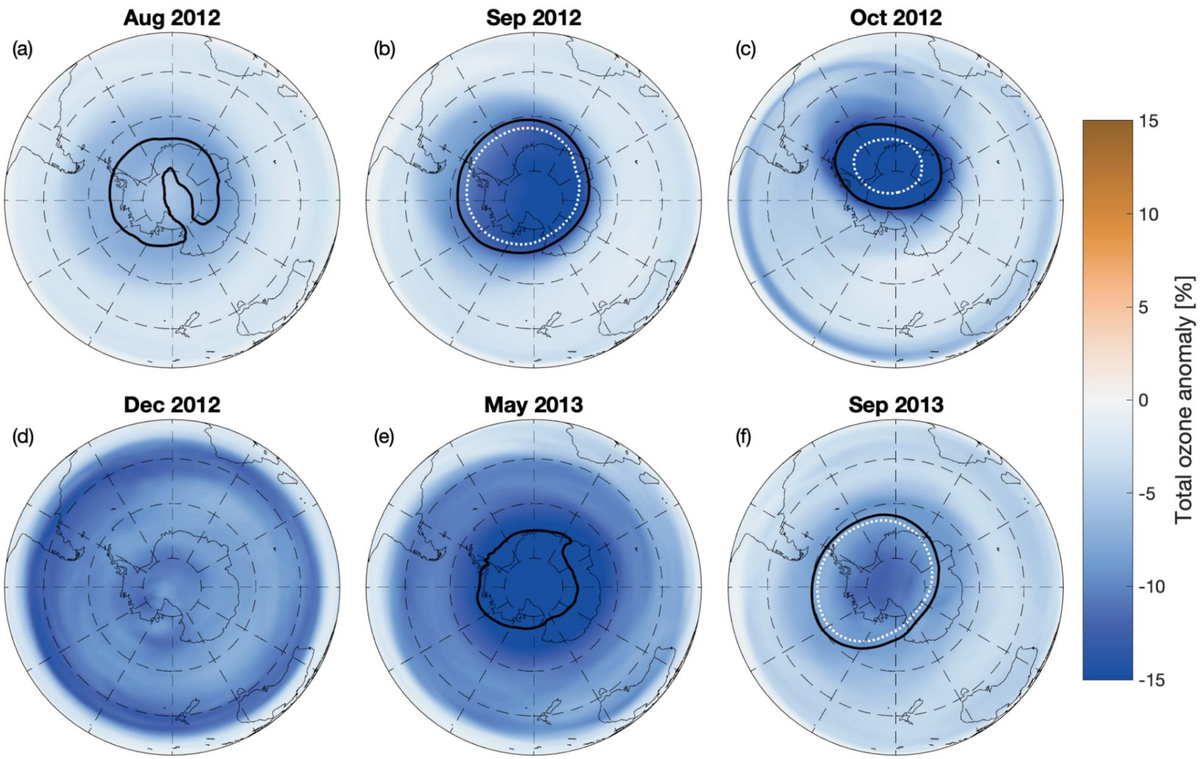
- magnitude
- latitudinal extent
- duration

For the “STEREO x 100” event, response

- is clear globally
- lasts up to two years

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE
UNIVERSITY OF OULU

Impact on SH ozone hole



Early formation of in Aug 2012

Larger and deeper in Sep-Oct 2012.

After the break-up of the polar vortex, ozone anomaly spreads to mid-latitudes, reaching 10-15% at around 40°S.

Ozone hole threshold (220 DU) is reached earlier in winter 2013

Black line: ozone hole with STEREO x 100
White line: ozone hole with STEREO x 0

Summary

WACCM is a powerful tool for extreme EPP event studies

- covers atmosphere up to lower thermosphere
- includes required ion-neutral chemistry
- allows for dynamical impact and coupling to climate
- can be used for short-term and long-term studies

WACCM-D allows for detailed study of atmospheric effects of any ionization source affecting D-region

The **July 2012 event** observed by STEREO:

- Large but not extreme
- Ozone response typical of SPEs, i.e. short-term in polar regions

Global, long-term impact on total ozone requires a "STEREO x 100" event

Such event would also affect ozone hole characteristic over several years

Impact would be comparable to those of major volcanic eruptions, regional scale nuclear conflict, or long-term stratospheric geoengineering

But is "STEREO x 100" realistic?