Response of the Earth's middle atmosphere to solar particle forcing

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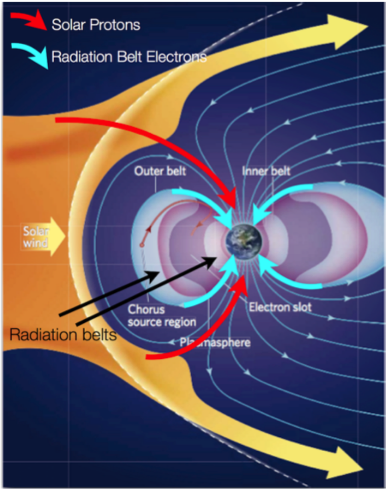
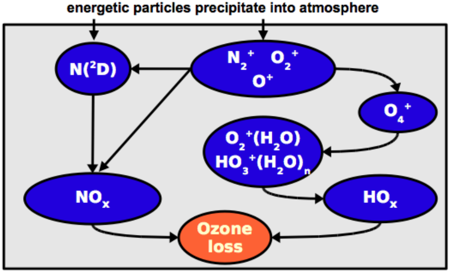
Outline

Energetic particle Precipitation (EPP) – Atmospheric Effects



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



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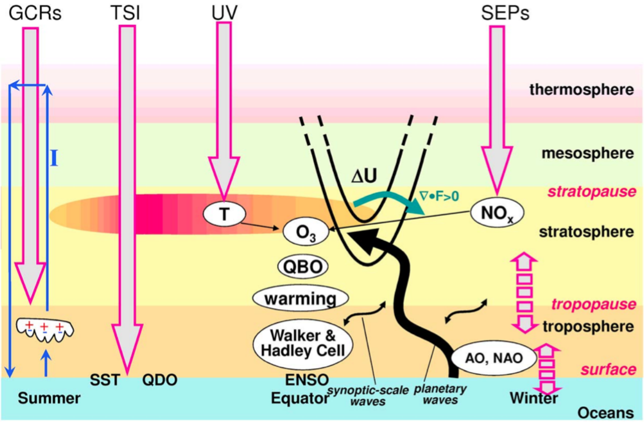
Top-Down Atmospheric Coupling

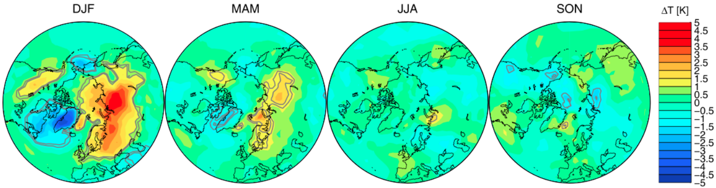
From Gray et al., *Rev. Geophys.*, 2010



Stratospheric ozone connects to winds, waves, and NAO

Proposed influence on regional climate

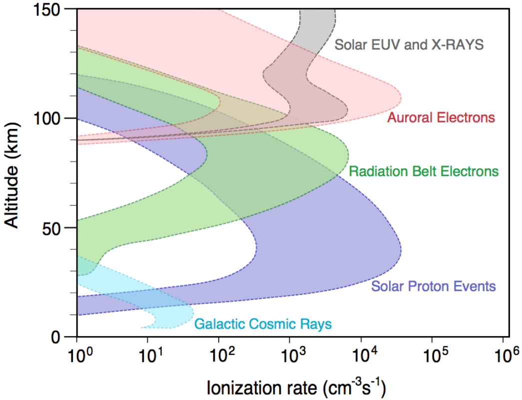
Surface Air Temperature responds to particle precipitation activity



ERA-40 data, from Seppälä et al., *J. Geophys. Res.*, 2009

- Proposed mechanism:
  – more particle precipitation and NO_x production,
  – ozone decrease leading to dynamical cooling of stratosphere,
  – effect on planetary wave propagation and the polar vortex,
  – influence on Northern Annular Mode and propagation towards the surface.

Different populations of EPP



- Different populations affect different regions of polar atmosphere
- Sporadic EPP major source of ionization at 20–90 km
- Energy of the particle determines the penetration altitude

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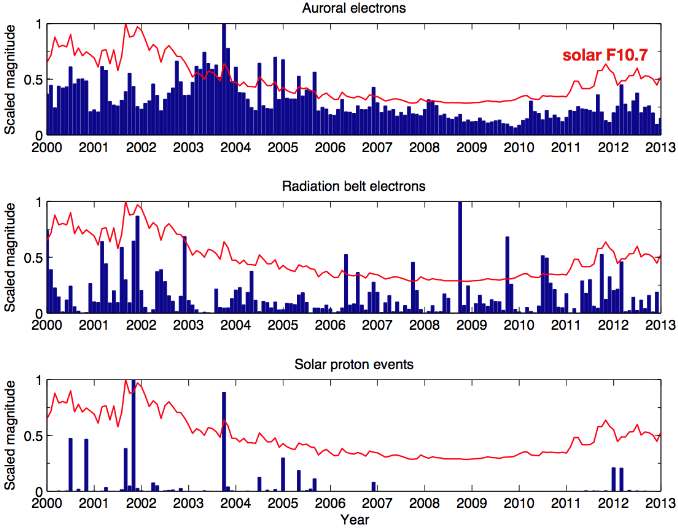
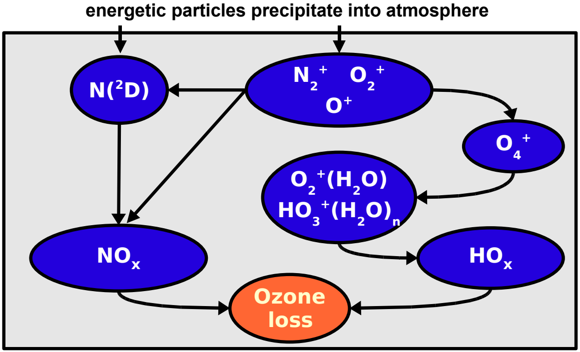
Solar cycle behaviour of EPP



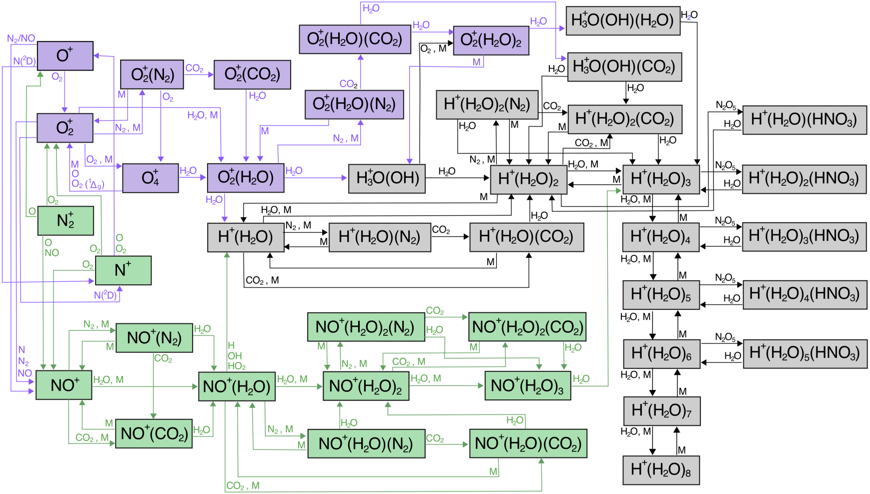
EPP and atmospheric chemistry



– Ion chemistry connects EPP to production of HO_x and NO_x
– HO_x (= H + OH + HO_2) and NO_x (N + NO + HO_2) are important to ozone chemistry
– Ozone connects to temperature and dynamics

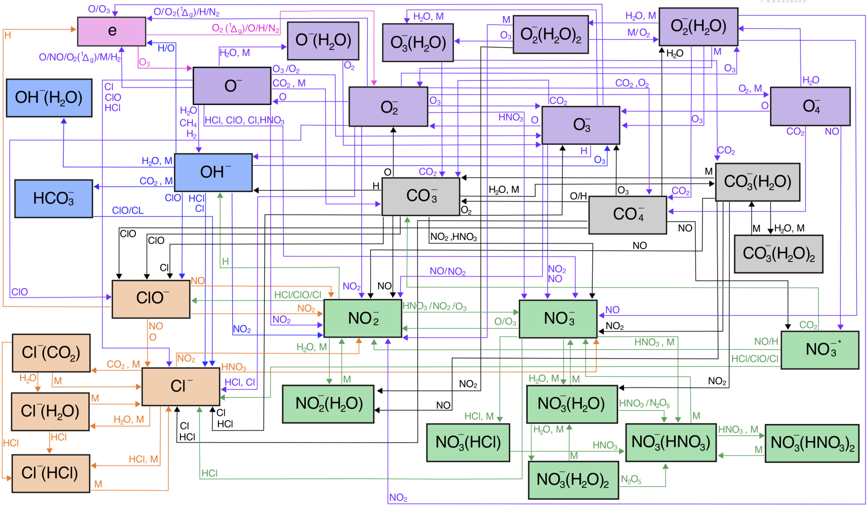
D-region ion chemistry scheme

Positive ions, from the Sodankylä Ion and Neutral Chemistry (SIC) model

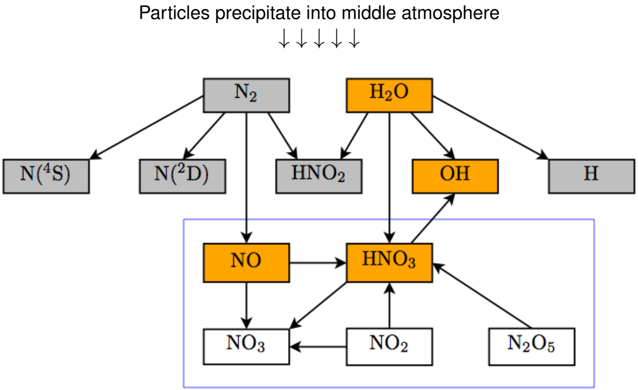


D-region ion chemistry scheme

Negative ions, from the Sodankylä Ion and Neutral Chemistry (SIC) model



Changes in hydrogen and nitrogen species due to ion chemistry



– Ion chemistry dissociates N_2 and H_2O
– Negative ion chemistry redistributes NO_y (inside the blue box)
– From Verronen and Lehmann, *Ann. Geophys.*, 2013.

SIC model: example of HNO_3 production paths

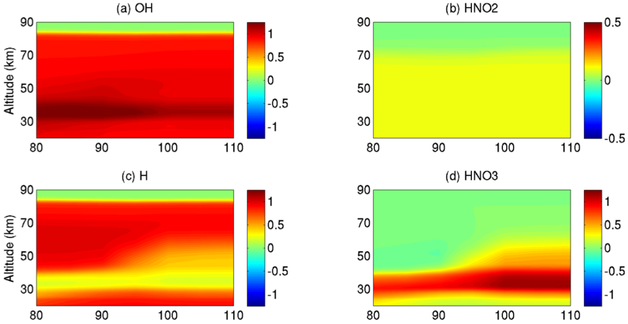
$$
\begin{aligned}
N_2 + p^+(E) &\rightarrow N_2^+ + e^- + p^+(E - \Delta E) \\
O_2 + O_2 + e^- &\rightarrow O_2^- + O_2 \\
O_2^- + O_3 &\rightarrow O_3^- + O_2 \\
O_3^- + CO_2 &\rightarrow CO_3^- + O_2 \\
CO_3^- + NO_2 &\rightarrow NO_3^- + CO_2 \\
NO_3^- + H_2O + M &\rightarrow NO_3^-(H_2O) + M \\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

SIC model: example of HO_x production paths

$$
\begin{aligned}
N_2 + p^+(E) &\rightarrow N_2^+ + e^- + p^+(E - \Delta E) \\
N_2^+ + O_2 &\rightarrow O_2^+ + N_2 \\
O_2^+ + O_2 + M &\rightarrow O_4^+ + M \\
O_4^+ + H_2O &\rightarrow O_2^+(H_2O) + O_2 \\
\ldots & \\
O_2^+(H_2O)_2 + H_2O &\rightarrow H_3O^+(OH)H_2O + O_2 \\
H_3O^+(OH)H_2O + \mathbf{H_2O} &\rightarrow H^+(H_2O)_3 + \mathbf{OH} \\
H^+(H_2O)_3 + H_2O + M &\rightarrow \mathbf{H^+(H_2O)_4} + M \\
\mathbf{H^+(H_2O)_4} + e^- &\rightarrow H + 4H_2O \\
--- & \quad --- \\
\mathbf{Net} : \mathbf{H_2O} &\rightarrow \mathbf{OH} + H
\end{aligned}
$$

P/Q: relative production/loss rates from SIC

P/Q = (ionic production - ionic loss) / ionization rate

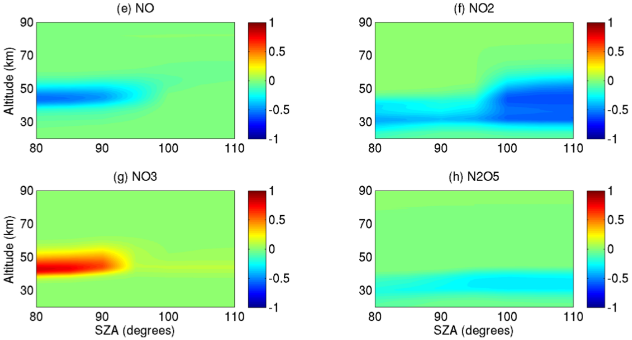


– H_2O becomes the limiting factor at upper altitudes

– At night: more negative ions, more HNO_3 production, less H production

P/Q: relative production/loss rates from SIC

P/Q = (ionic production - ionic loss) / ionization rate

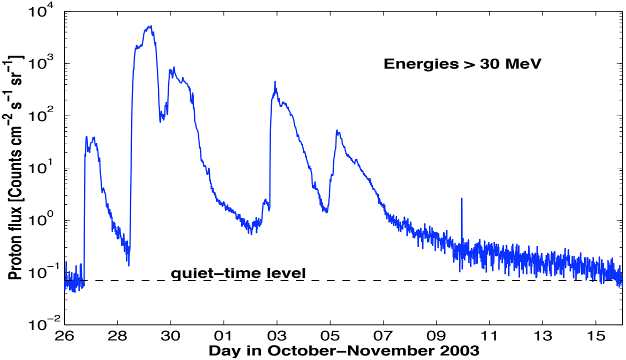


– Note: Zero net change of NO_y (incl. HNO_3) by negative ion chemistry

– Note: net production of NO_x is by positive ion chemistry ($\approx 1.25Q$, not included here)

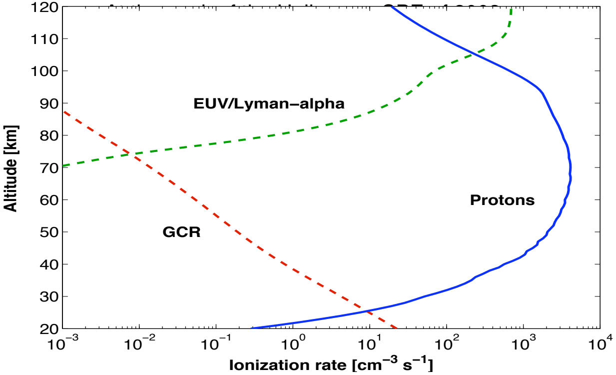
SPE: Proton flux observations (GOES-11)

The Halloween storm



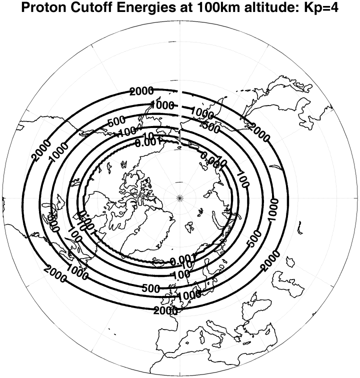
Large SPEs are infrequent, but they are
extreme examples of solar forcing on the middle atmosphere

Ionization due to protons



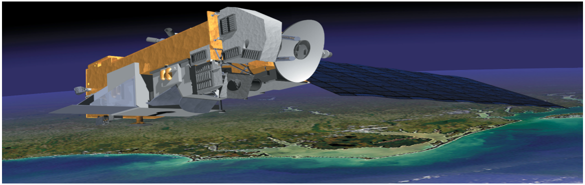
SPEs typically have largest impact in the upper stratosphere and mesosphere

SPE: example of geomagnetic cutoff



Rodger et al., Journal of Geophysical Research (2006)

MLS/Aura observations



- Microwave Limb Sounder, measures emissions at mm and sub-mm wavelengths
- Launched in July 2004 into a near-polar orbit, observations cover latitudes between 82°S – 82°N, day and night
- Can be used to monitor temperature and more than 15 trace gases, including O_3, OH, and HNO_3
- First satellite instrument providing continuous observations of mesospheric OH and HO_2

Nitric acid: comparisons

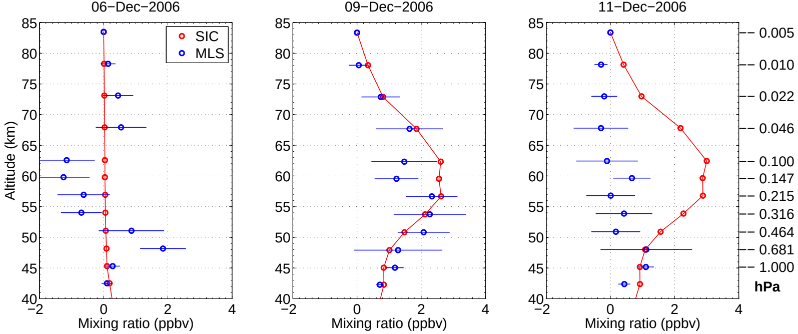
Modeling: Sodankylä Ion and Neutral Chemistry

- Uses MLS temperatures, neutral density, and water vapor.
- 80°N/December–January, no diurnal variations.
- Results reduced to MLS altitude resolution using averaging kernels.

Observations: data version 3.30, SZA $>$ 100° (night-time)

- Data are daily means, uncertainty is standard error of the mean.
- Useful range up to 1.5 hPa ($\approx$50 km) in normal conditions,
  but can be extended into mesosphere when high amounts are observed.
- Mesospheric HNO_3 data have not been validated.
- Comparison is made with the highest amount of HNO_3 observed after the peak of SPE forcing, assuming that it is least affected by dynamics.

SIC vs. MLS: nitric acid, December 2006 SPE



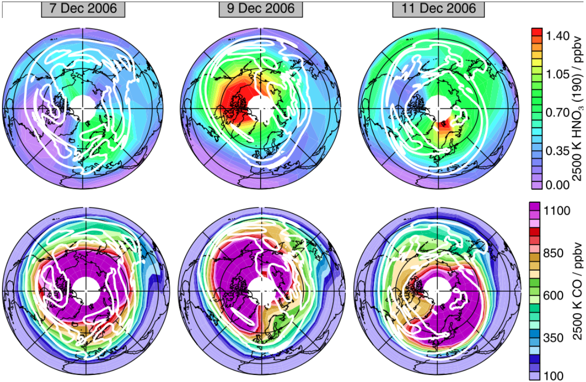
– The model overestimates the HNO_3 increase on Dec 9 at 60–65 km.

– 1-D SIC does not capture the recovery on Dec 11.

– For more details, see Verronen et al., *J. Geophys. Res.*, 2011.

MLS: HNO_3 (top) and CO (bottom)

Daily avarages at approx. 60 km



– Polar vortex dynamics strongly affects HNO_3 distribution over the pole.

Odd hydrogen: comparisons

Modeling: Sodankylä Ion and Neutral Chemistry

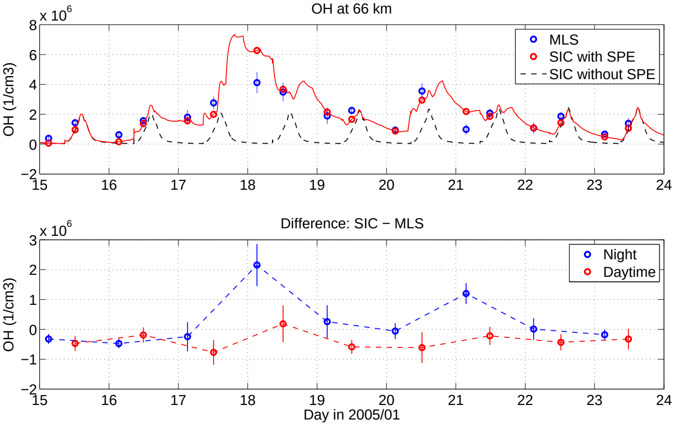
- Uses MLS temperatures, neutral density, and water vapor.
- Latitudes $>60^{\circ}$N, solar proton events of January 2005.

OH observations: data version 3.30

- Useful range up to 0.0032 hPa ($\approx$90 km).
- Mesospheric data have been validated by Pickett et al., JGR, 2008.
- Data are averaged at 65–75°N, for day and night separately.

MLS was the first instrument that provided continuous and global observations of mesospheric HO_x.

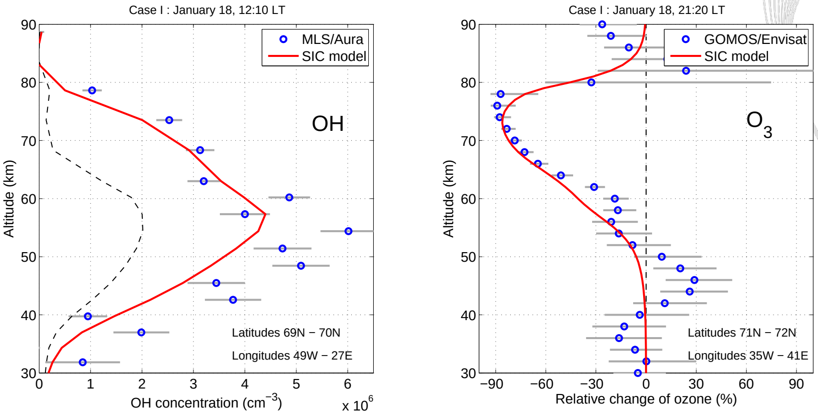
SIC vs. MLS: hydroxyl, January 2005



– A good agreement in general.

– Model overestimation at night during most intense forcing.

SIC vs. MLS: OH



– Ozone response is well modelled.
– From Verronen et al., *Geophys. Res. Lett.*, 2006

SPE summary

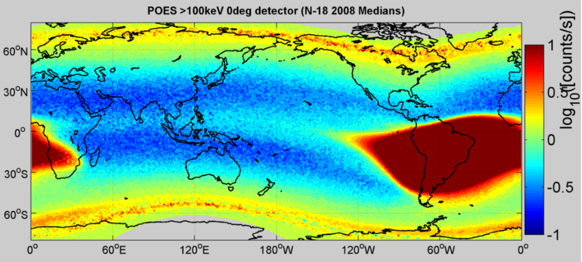
– SPEs cause substantial changes in the middle atmosphere.

– Effects cover the whole polar cap, and are easy to detect from satellites.

– Large SPEs are infrequent, most like occuring during solar maximum.

– SPE effects can be well modelled, when D-region ion chemistry is considered.

Role of electron precipitation below 80 km



- Compared to solar proton events, electron precipitation typically has smaller fluxes, more temporal variability, and it affects more restricted latitude regions.
- Electron flux observations are not always straight forward to use in atmospheric modeling.
  $\Longrightarrow$ It is not clear how big the direct effect of electron precipitation is.

Mesospheric odd hydrogen: indicator of EPP

- nighttime HO_x (= H + OH + HO_2) concentration is relatively low.
  $\Longrightarrow$ It can be enhanced by moderate EPP forcing.
- HO_x has a relatively short chemical lifetime (hours) below $\approx$ 80 km.
  $\Longrightarrow$ Returns quickly to normal values after EPP forcing stops.

Odd hydrogen follows closely
increases and decreases of EPP forcing

- In the case of major solar proton events, HO_x increases are relatively easy to detect due to the large fluxes and polar cap coverage of the forcing.

How to study the electron impact in the mesosphere?

- Find the connection between precipitating electrons (measured in the radiation belts by MEPED/POES) and mesospheric OH observed by MLS/Aura.
- Look for
  1) OH increases in high-precipitation cases, e.g. March 2005.
  2) signatures of electron precipitation in OH during years 2004–2009.
- Ask
  1) is electron precipitation causing measurable changes in OH?
  2) how often is OH affected by electron precipitation?
  3) can we model OH and ozone changes caused by electrons?

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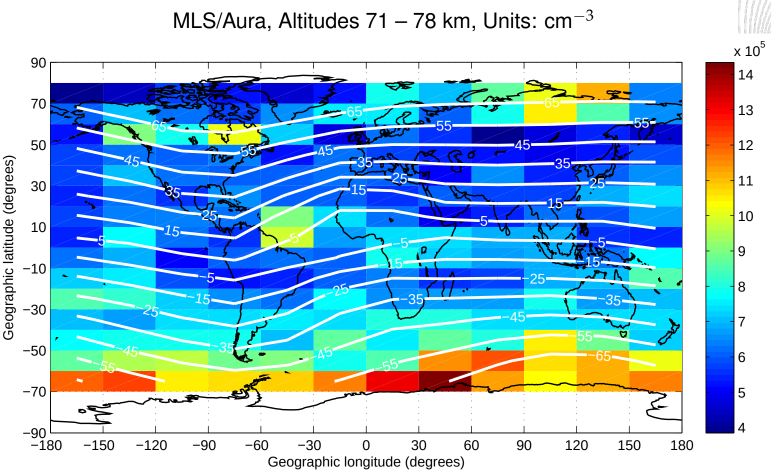
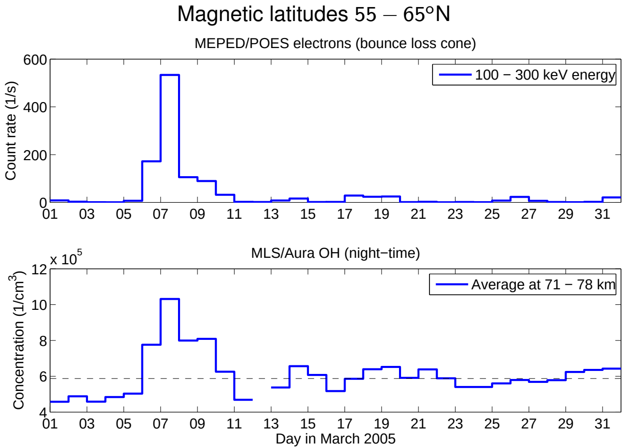
Mean nighttime OH, March 5–10, 2005

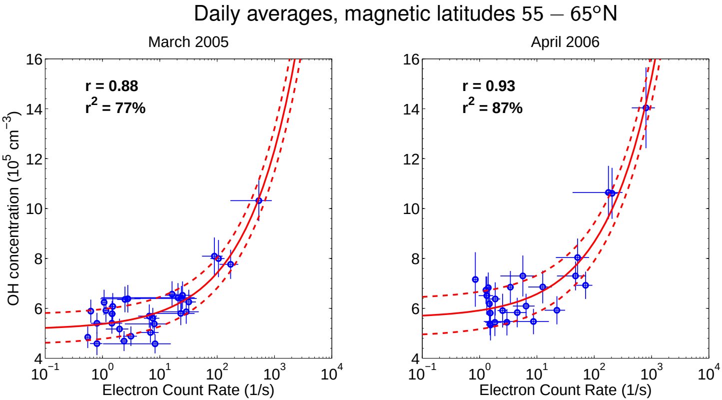


– Radiation belt EPP signature at magnetic latitudes 55 – 72°

Electron precipitation and OH in March 2005



Electron count rate vs. OH concentration



High electron count rates correspond to high OH concentrations!

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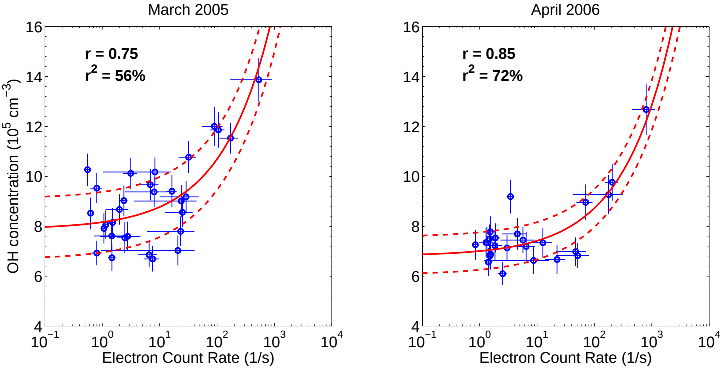
Electron count rate vs. OH concentration

Daily averages, magnetic latitudes 55 – 65°S



Higher background OH, higher electron flux threshold

Modelling approach

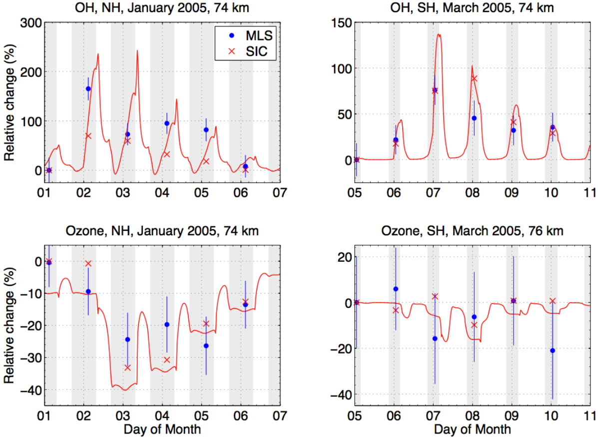
- Consider months with high electron fluxes were considered: January 2005, March 2005.
- Model input:
  daily zonal mean electron fluxes calculated using data from three MEPED instruments.
  Data correction applied (e.g. proton contamination).
  Form of energy-flux spectrum needs to be assumed.
- Model runs:
  two runs, one with daily electron forcing (EEP), one with constant quiet-time electron background (CTR).

– Using daily mean data improves the signal-to-noise ratio, and compensates differences between MEPED and MLS data sampling.

– Does the model can produce anything similar to the observations?

Comparison of relative OH and ozone changes

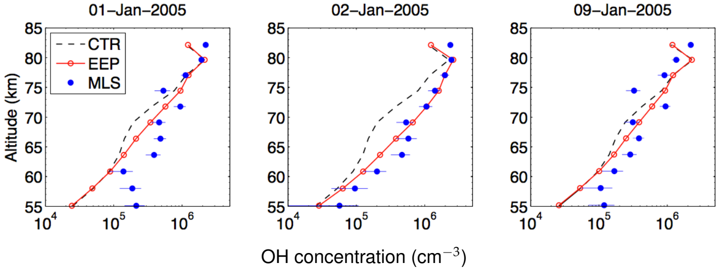
Magnetic latitudes 59 – 65°



Overall behavior is captured by the model.

Comparison of OH altitude profiles

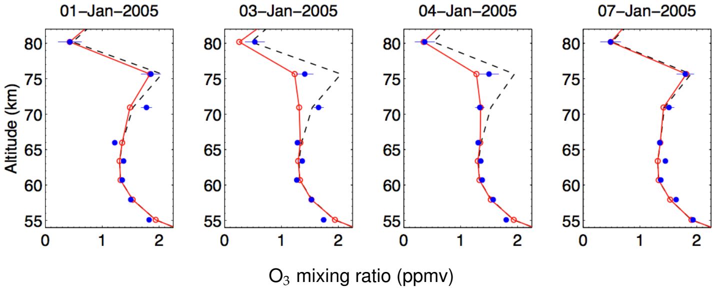
Magnetic latitudes 59 – 65°N



- OH increases between 60 and 80 km.
- SIC generally underestimates OH below 70 km, electron flux/spectrum needs adjustment?
- However, the differences are relatively small (log scale!) and there are other possible reasons.

Comparison of ozone altitude profiles

Magnetic latitudes 59 – 65°N



- Ozone decreases above 65 km.
- SIC and MLS are in reasonable agreement.
- Again, no need for substantial flux corrections above 70 km (E $<$ 300 keV)

Summary

- Energetic electron precipitation (EEP) is significantly affecting mesospheric odd hydrogen at the magnetic latitudes connected to the outer radiation belt.
- In March 2005 and April 2006, EEP causes factor-of-two increases in daily average OH at 71–78 km altitude and can explain 56–87% of OH day-to-day variability.
- No electron signature is found in stratospheric OH. This indicates that $>$3 MeV electron fluxes are relatively small.
- Comparisons between Sodankylä Ion and Neutral Chemistry model and MLS/Aura observations indicate that EEP-caused ozone changes can be tens of percent at 70–80 km.

EPP and atmospheric ozone – solar cycle variability

Indirect NO_x effect vs. direct HO_x effect

Indirect NO_x (= N + NO + NO_2):

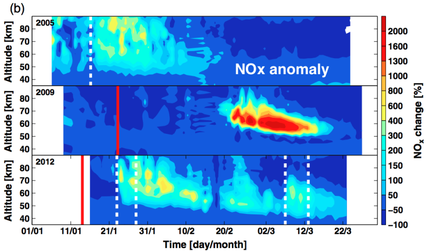
– NO_x is produced in the MLT region where it cannot directly affect ozone
– NO_x must be transported to stratosphere where ozone can be depleted
– Transport takes place during winter time when polar vortex is in place
– mechanisms depends on NO_x production and atmospheric dynamics
– most of the production by auroral electrons above 90 km

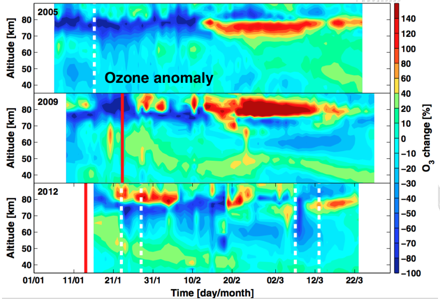
Direct HO_x (= H + OH + HO_2):

– HO_x produced in the mesosphere and affects ozone in-situ
– mechanism depends on HO_x production only
– so-called medium-energy electrons are needed from, e.g. radiation belts

Indirect effect from ACE-FTS observations

Päivärinta et al., *J. Geophys. Res.*, 2013

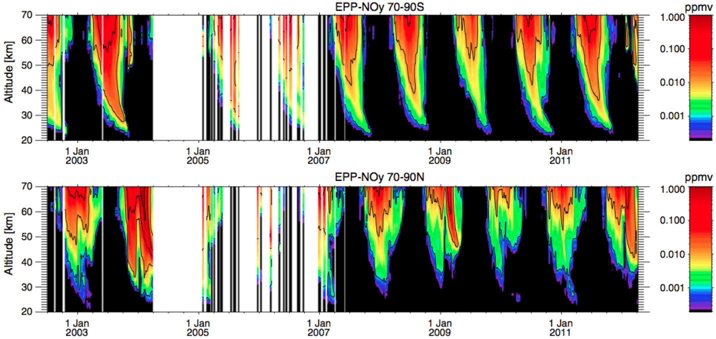




– Wintertime NO_x descend is easy to observe, until stratopause
– Yearly variability depends on both NO_x production and descent
– Effect on stratospheric ozone remains unclear, because there is large variability in general

Indirect effect from MIPAS observations

Funke et al., *J. Geophys. Res.*, 2014



– Descent better assessed by NO_y observations and tracer correlations
– Extra NO_y descends down to 30–20 km every year, also in the NH
– A lot of year-to-year varibility, especially in the NH
– Effect on stratospheric ozone still unclear

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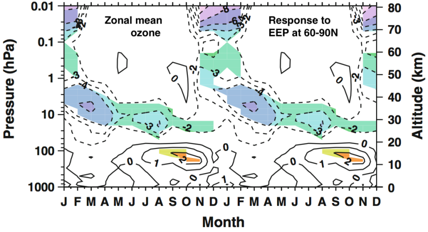
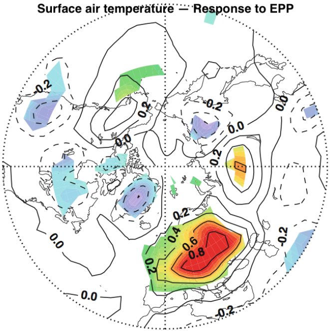
Indirect effect from SOCOL model

Rozanov et al., *Surv. Geophys.*, 2012

– SPE + auroral effect on ozone from model ↓
– Significant effects in mesosphere/upper stratosphere
– Leads to NAM-like temperature patterns at surface





– But the magnitude is smaller than what is observed
– Mesospheric forcing by radiation belt electrons is missing

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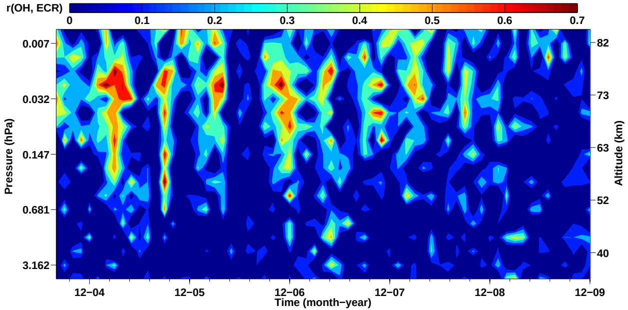
Direct effect from odd hydrogen observations

From Andersson et al., *J. Geophys. Res.*, 2012

Correlation r(OH,ECR) in 2004–2009, magnetic latitudes $55-65°$N

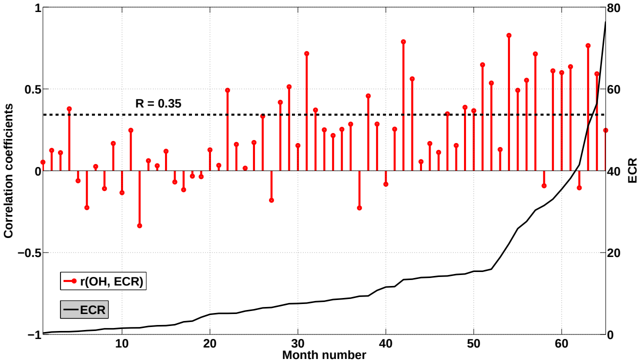


– ECR = observed count rate of 100–300 keV radiation belt electrons
– Correlation is related to strong precipitation events
– Declining solar activity, declining correlation
– No stratospheric correlation, no effect by $>$3 MeV electrons

Correlation r(OH,ECR) in 2004–2009 at 75 km

From Andersson et al., *J. Geophys. Res.*, 2012

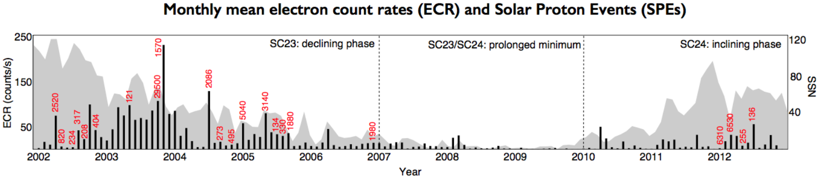
Magnetic latitudes 55 – 65°N

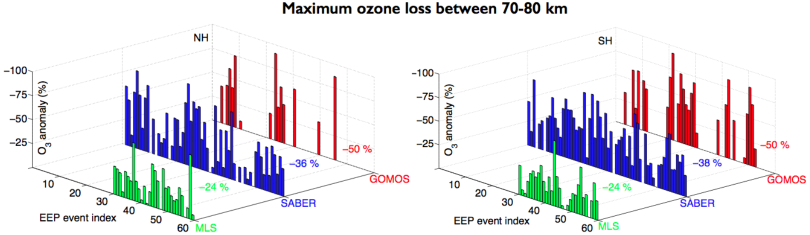


35% of months show electron impact in the mesosphere ($r > 0.35$)

Direct effect from ozone observations

Andersson et al., *Nature Commun.*, 2014



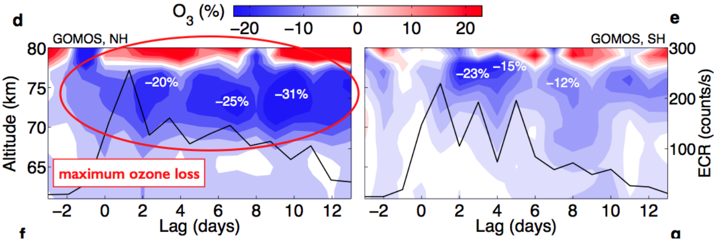


Events are frequent and strong enough for solar cycle effects

Direct ozone effect from observations

Andersson et al., *Nature Commun.*, 2014

Superposed epoch analysis of 60 events in 2002–2012

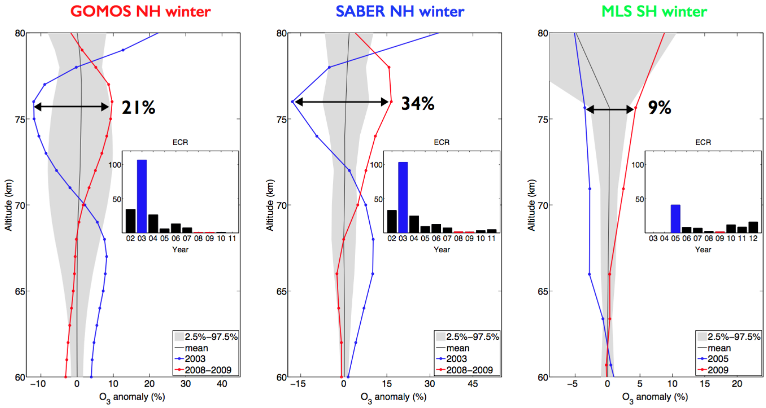


– Tens of percent reduction of ozone in middle mesosphere
– One event affects ozone up to 10 days
– Difference between poles, distribution of events, winter/summer

Direct solar-cycle effect from observations

Andersson et al., *Nature Commun.*, 2014

Ozone yearly anomaly for high and low electron forcing



– Effects on heating/cooling and dynamics need to be studied

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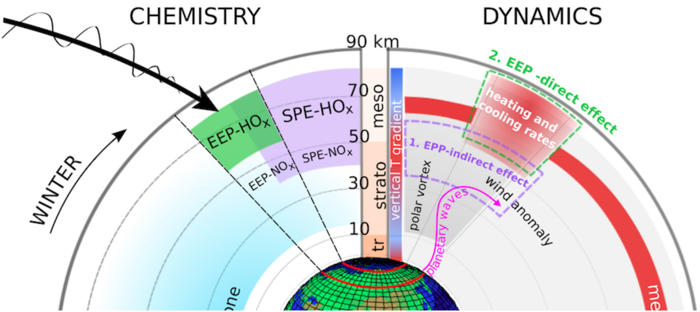
Complete EPP forcing for full effect modelling



– All particle inputs have to be included for a complete picture
– Solar protons, OK, satellite observations readily usable
– Auroral electrons, OK, magnetic A_p index can be used as proxy
– Radiation belt electrons, not OK, suffer from satellite data issues

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Missing driver in the Sun–Earth connection from energetic electron precipitation impacts mesospheric ozone

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Summary

- Hypothesis: EPP modulates ground-level regional climate on solar cycle time scales through the top-down mechanism
- First we have to understand the atmospheric ozone varibility caused by EPP.
- Indirect NO_x effect on stratospheric ozone has been modeled but not observed.
- Direct HO_x effect of radiation belt electrons on mesospheric ozone has been observed and needs to be modelled.

More information

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