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Effects of Energetic Particle Precipitation on the Mesosphere and Stratosphere

G.P. Stiller

IMK-ASF, Karlsruhe Institute of Technology

Outline

Ionisation of the atmosphere by EPP

- Energy spectrum
- Penetration depth
- Production of NO_x, HO_x, ions
- Ion models vs. parameterizations

Direct effects – SPEs

- Observations: MIPAS, ACE, GOMOS, HALOE, POAM, ODIN-SMR, SCIAMACHY, MLS
- NOx and ozone
- Ion (cluster) reactions: HO_x, Cl_x, HNO_3
- N_2O
- Model results: Jackman, Verronen, Winkler, Semeniuk

Indirect effects: EEPs

- Downward transport through dark mesosphere
- Dynamics vs. source strength
- Effects on stratospheric chemistry

Modeling of effects on ozone

- Short and medium term – days to winters
- Long terms – solar cycle

Sun-Earth connection

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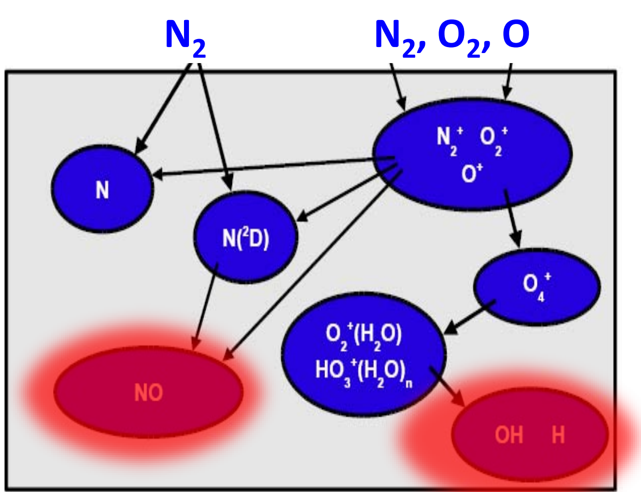
Solar particles (e, p)

Ionization, Dissociation

NO_x **HO_x**

Catalytic ozone destruction

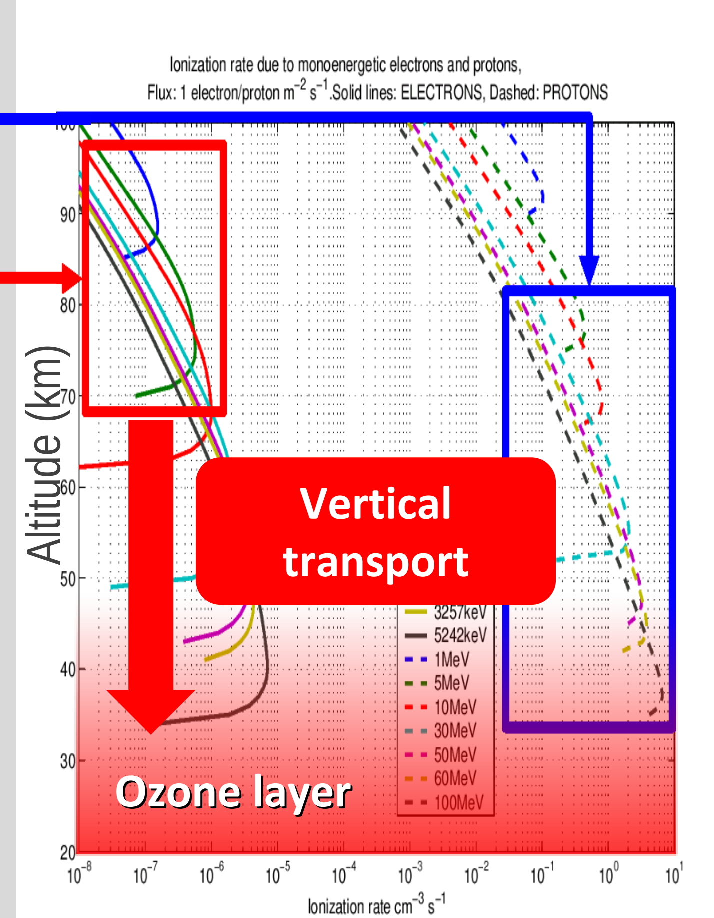
mid-/long-term short-term



Turunen et al. 2009

EEP (electrons)
Energies: 10-300 keV
Deposition: 75 – 110 km
Mesosphere, Termosphere

SPE (protons)
Energies: 10-100 MeV
Deposition: 40 – 75 km
Stratosphere, Mesosphere



Energy deposition, penetration depth

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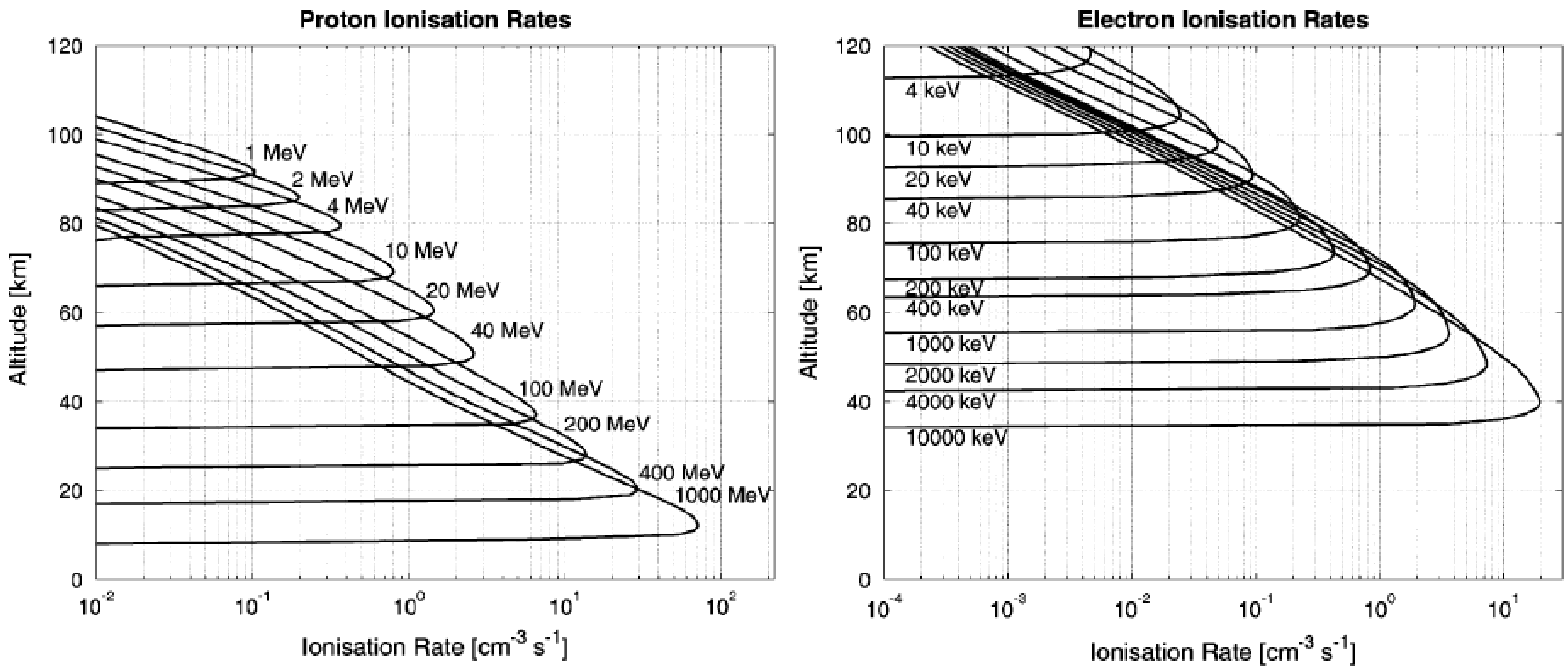
- EPPs deposit their energy at different layers of the atmosphere depending on their penetration depth
- Energy required to create one ion pair is assumed to be 35 eV (Porter et al., 1976) or 36 ev (Rees et al., 1989)
- ⇨ Ionization rates estimated from energy deposition, various approaches



Turunen et al., 2009

Formation of NO_x and HO_x from ion-electron pairs

NO_x: Dissociation of N_2 and O_2 to N_2^+, O_2^+, N^+, O^+, and NO^+; formation of exited-state $N(^2D)$ and ground-state $N(^4S)$; $2N(^2D) + O_2 \rightarrow 2NO$

HO_x: end of complex ion chemistry including protonated water cluster ions (up to 20 water molecules per proton)

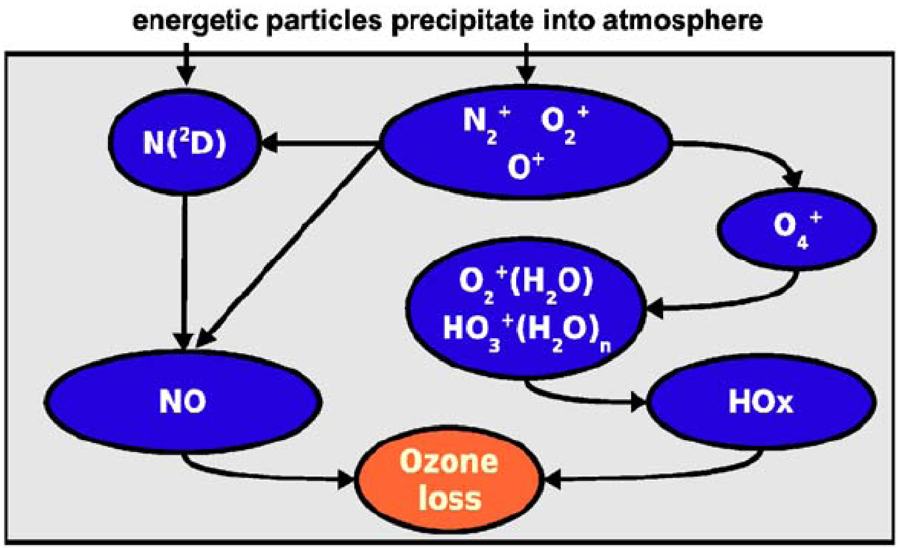
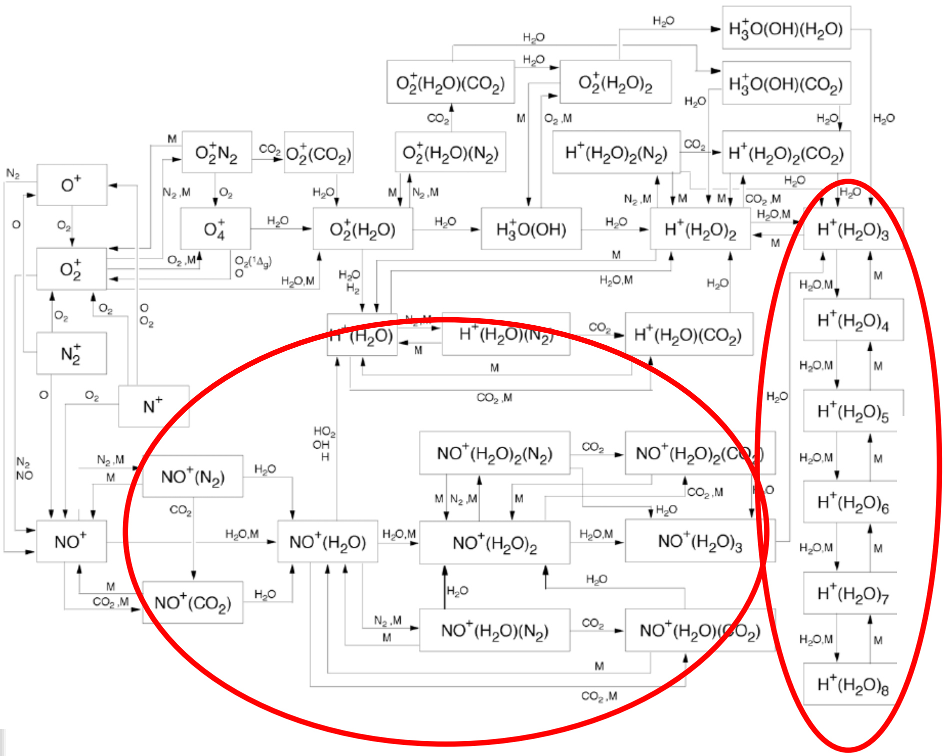


Fig. 1. Particle precipitation effects on the ion-chemistry of the atmosphere.

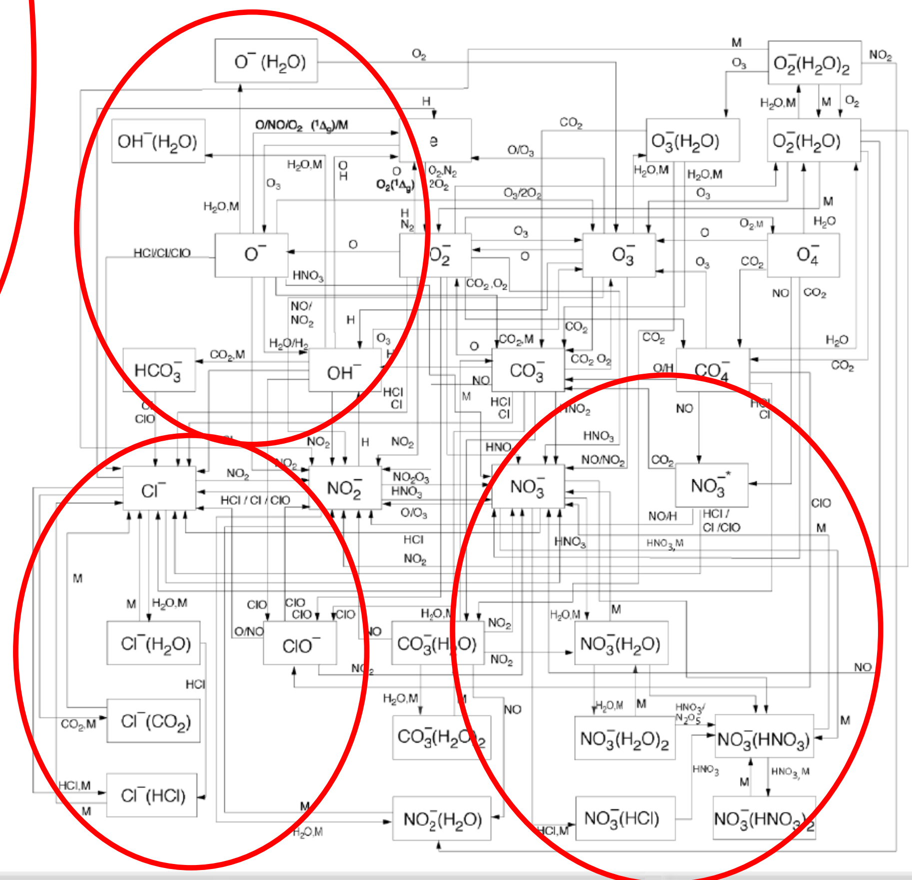
Ion chemistry models calculate produced NO_x and HO_x ab initio (for example SIC, Verronen et al., Turunen et al.)

Parameterizations are also used: 2 HO_x molecules per ion pair in the USM, <2 HO_x molecules per ion pair in the middle and upper mesosphere; 1.25 N atoms per ion pair, separated into 0.55 $N(^4S)$ and 0.7 $N(^2D)$ per ion pair (Jackman et al., 2008)

NO_x and HO_x formation (plus further ion cluster formation) are the basis for all subsequent observed chemical changes in the stratosphere and mesosphere.



Negative ion scheme of SIC



Positive ion scheme of SIC

Source: P. Verronen, PhD thesis; after Turunen

Ozone depletion – catalytic cycles

HO_x and NO_x react as catalytic substances in stratospheric ozone depletion cycles:

$OH + O_3 \rightarrow HO_2 + O_2$
$HO_2 + O \rightarrow OH + O_2$
<u>Net:</u> $O_3 + O \rightarrow 2\ O_2$

$OH + O_3 \rightarrow HO_2 + O_2$
$HO_2 + O_3 \rightarrow OH + O_2 + O_2$
<u>Net:</u> $2\ O_3 \rightarrow 3\ O_2$

$Cl + O_3 \rightarrow ClO + O_2$
$ClO + O \rightarrow Cl + O_2$
<u>Net:</u> $O_3 + O \rightarrow 2\ O_2$

Etc. etc.

$NO + O_3 \rightarrow NO_2 + O_2$
$NO_2 + O \rightarrow NO + O_2$
<u>Net:</u> $O_3 + O \rightarrow 2\ O_2$

$ZO + HO_2 \rightarrow HOZ + O_2$ (Z: Cl, Br)
$HOZ + h\nu \rightarrow OH + Z$
$OH + O_3 \rightarrow HO_2 + O_2$
$Z + O_3 \rightarrow ZO + O_2$
<u>Net:</u> $2O_3 \rightarrow 3O_2$

Ozone depletion – catalytic cycles

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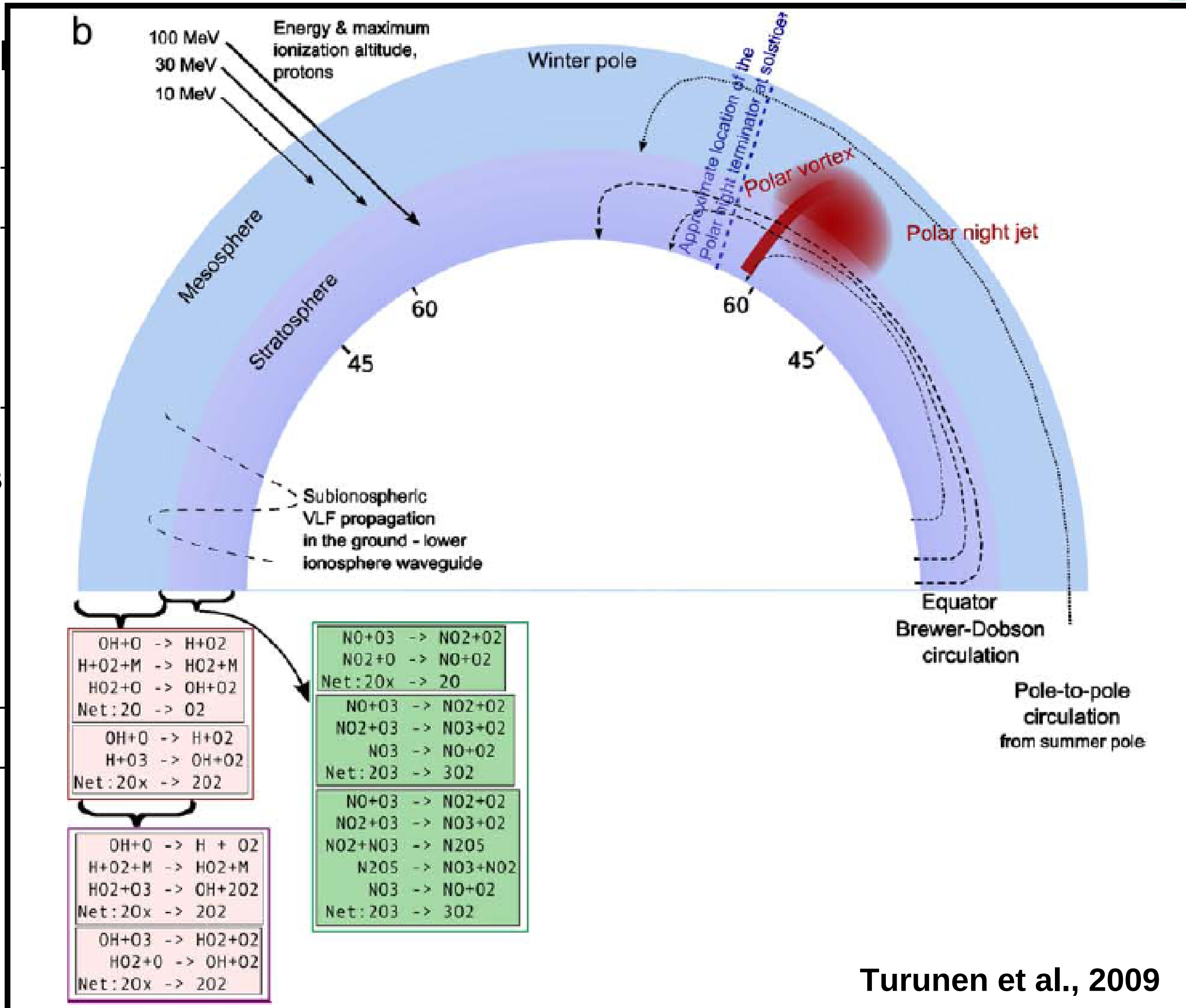
HO_x and … cycles:

$OH + O_3$ …
$HO_2 + O$ …
<u>Net:</u> O_3 + …

$OH + O_3$ … Cl, Br)
$HO_2 + O_3$ …
<u>Net:</u> $2\ O_3$ …

$Cl + O_3$ —
$ClO + O$ —
<u>Net:</u> O_3 + …

Etc. etc.



Turunen et al., 2009

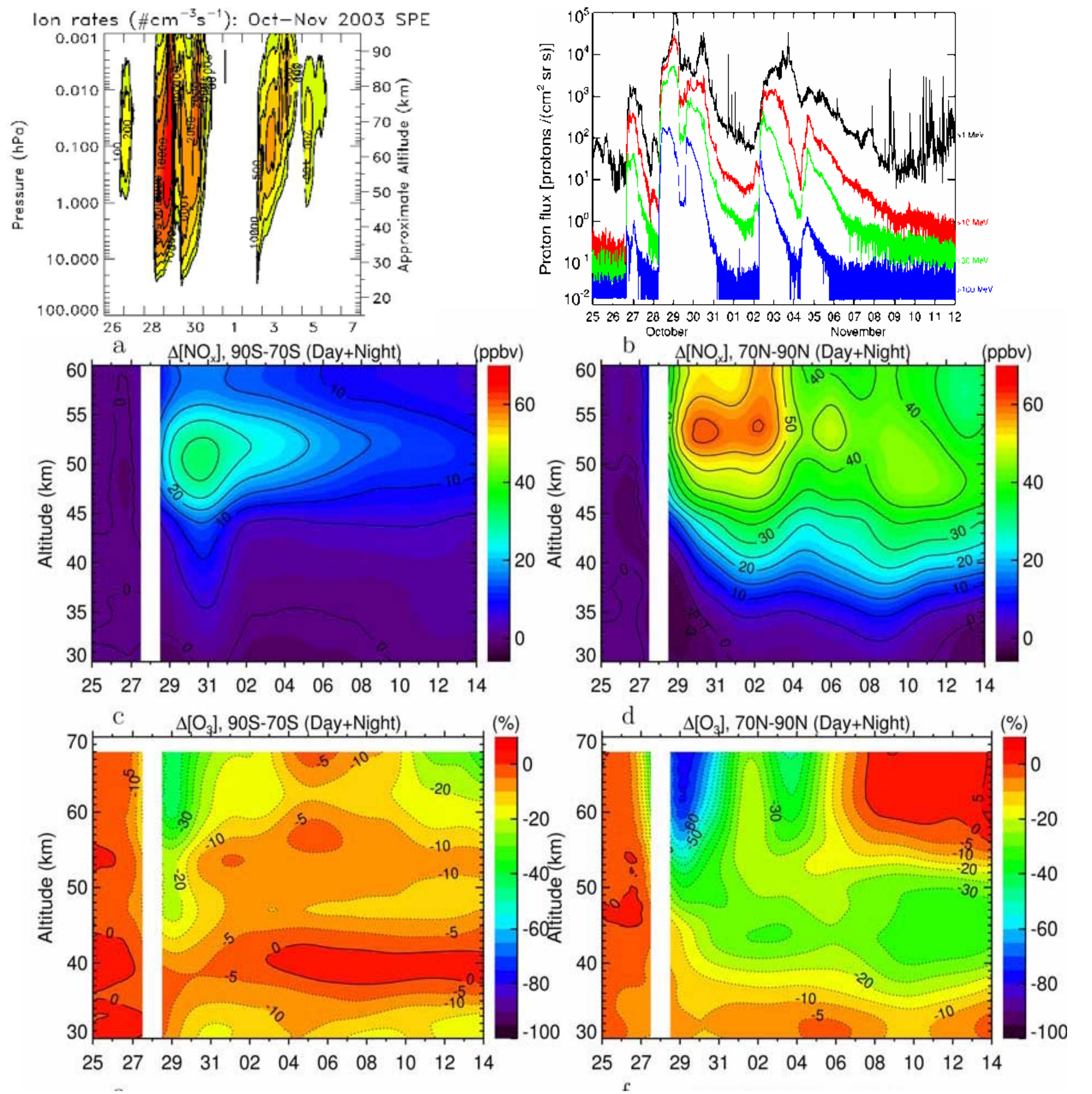
Direct effects – SPEs – NO_x and O_3

<u>Why **direct** effect?</u> Because effect is generated locally due to penetrating EPPs, without intermediate transport

Solar proton event Oct/Nov 2003: one of the largest events observed, many observations from a suite of satellite instruments available: MIPAS, SCIAMACHY, GOMOS, ODIN-SMR

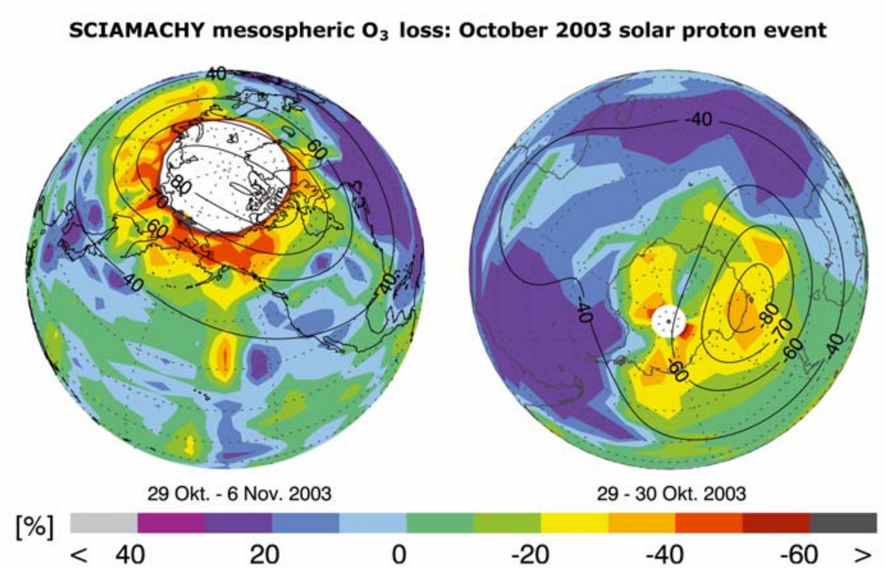
Aftermath of the event in Arctic winter 2003/04: additional observations by ACE-FTS, HALOE, POAM

Solar proton event Jan 2005: observed by MIPAS, MLS, ACE-FTS, ODIN-SMR,…



López-Puertas et al., 2005

Other observations - SPE 2003 / 2005 – NO_x and O_3



http://atmos.caf.dlr.de/projects/scops/sciamachy_book/ sciamachy_book_figures/chapter_10/fig_10_32.jpg

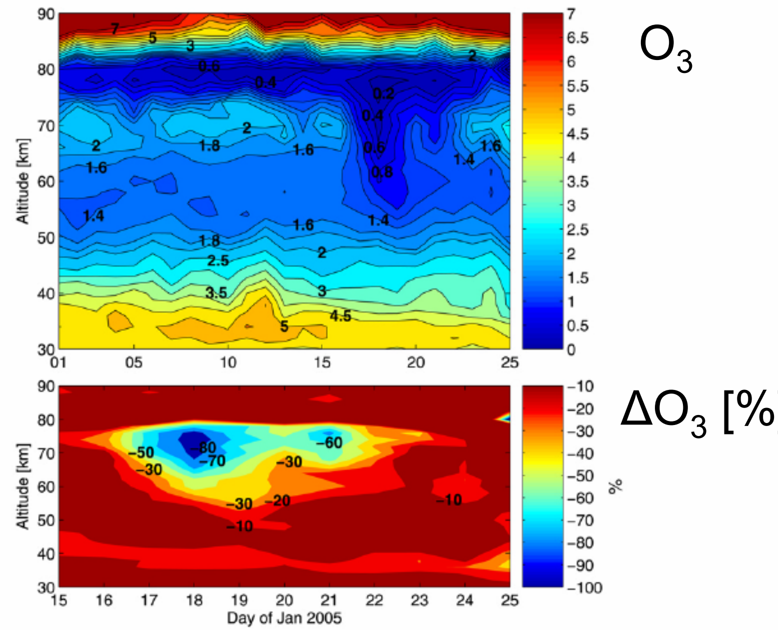
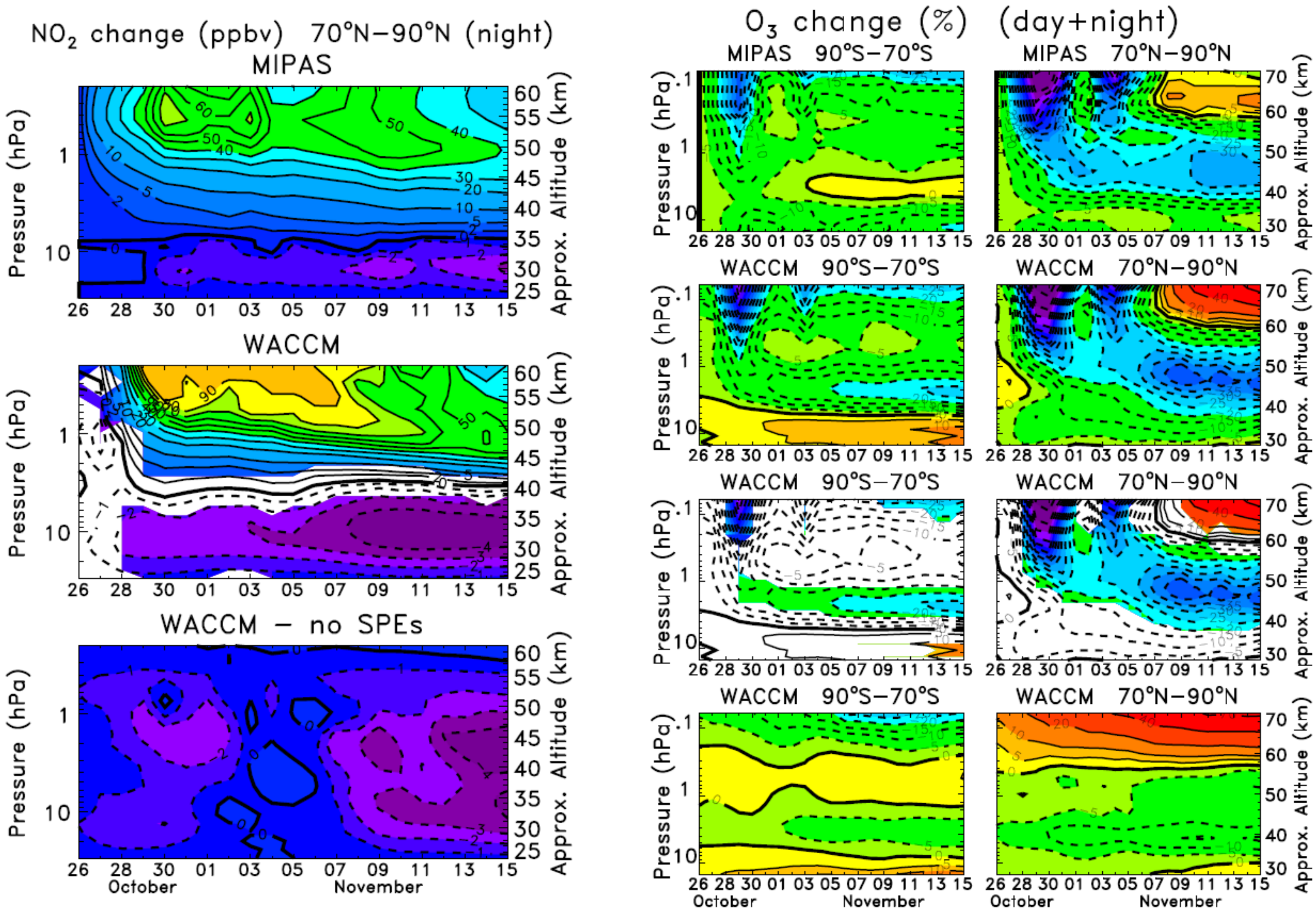


Figure 4. (top) GOMOS daily (January 1–24, 2005) zonal mean night-time ozone mixing ratio [ppmv] at latitudes 65°N–75°N. Note the destruction of the tertiary ozone maximum at 72 km altitude following the SPE on January 17, 2005. Contour lines as in Figure 3. (bottom) Ozone %-change (January 15–24) from the average of January 10–14. The contour lines are (−80, −70, −60, −50, −40, −30, −20, −10%). X-axis is the same as for the model results in Figure 2. Note the different x-axis in the two panels.

Seppälä et al., 2005

Model results – SPE 2003 – NO_x and O_3

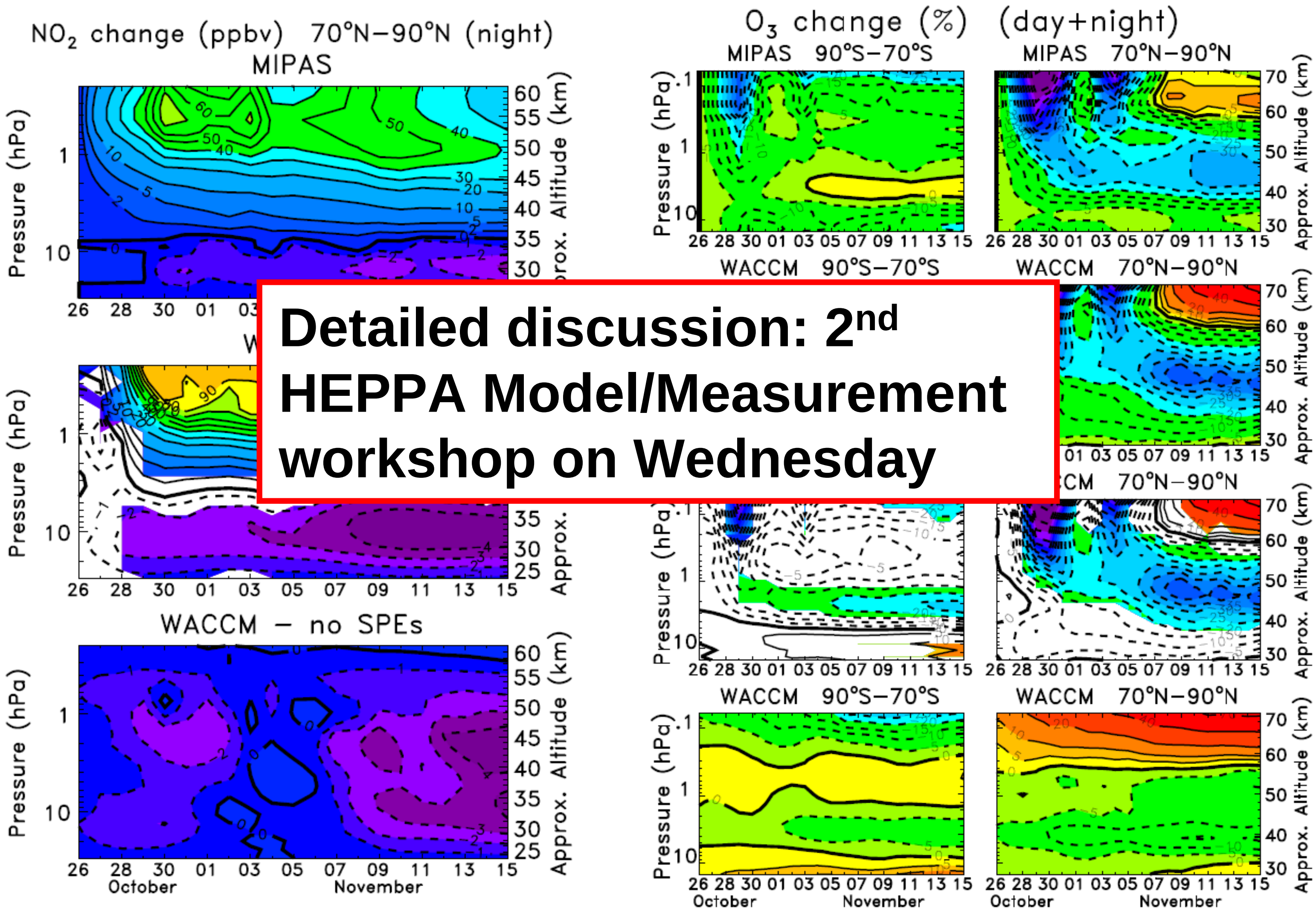


2σ significance

Seasonal change

Jackman et al., 2008

Model results – SPE 2003 – NO_x and O_3



Detailed discussion: 2nd HEPPA Model/Measurement workshop on Wednesday

2σ significance

Seasonal change

Jackman et al., 2008

Direct effects – SPEs – nitrogen, chlorine and hydrogen compounds

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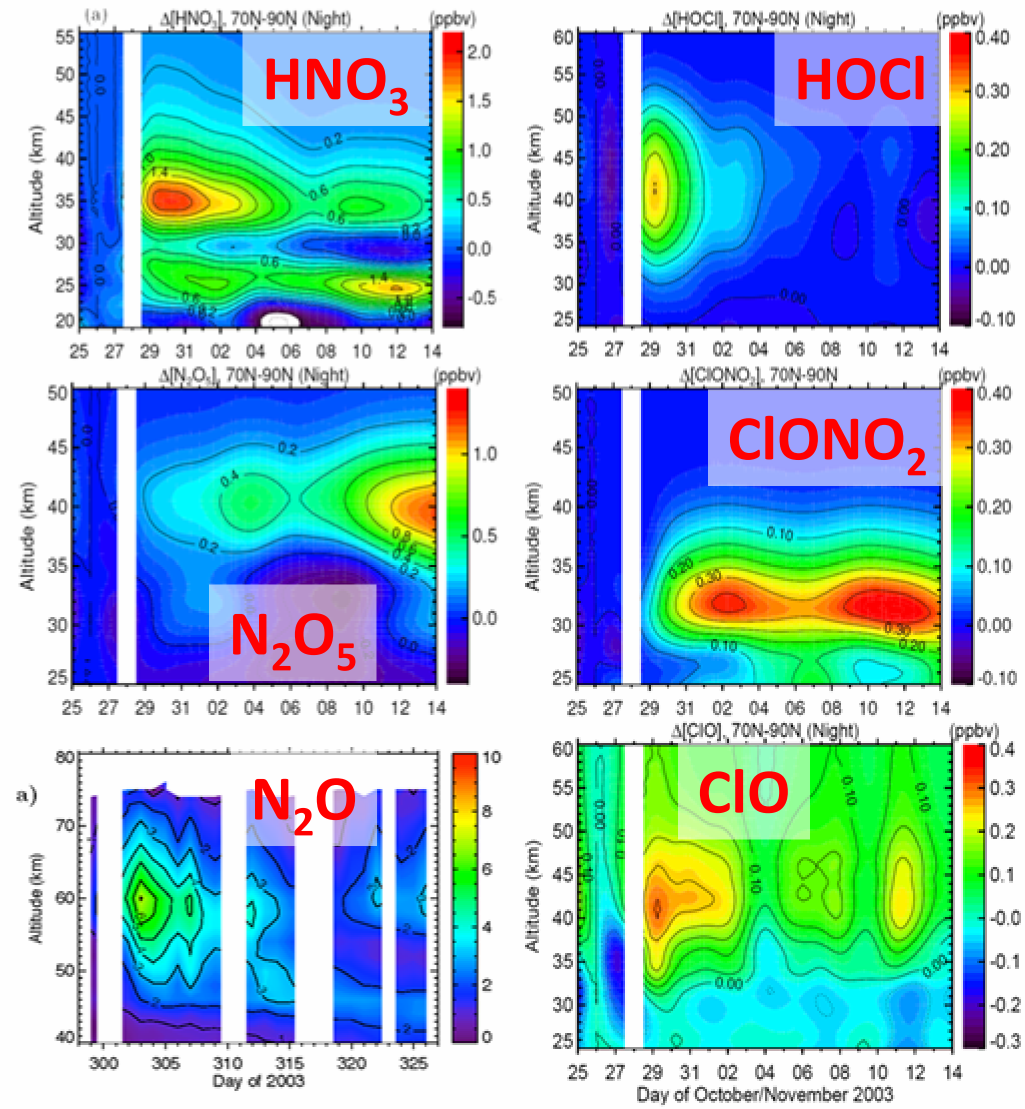
MIPAS observations during SPE Oct/Nov 2003

Further parameters from MIPAS available: Temperature, HNO_4, CH_4, H_2O, CO, $BrONO_2$ (⇨ poster Höpfner et al.), H_2O_2 (⇨ poster Versick et al.).

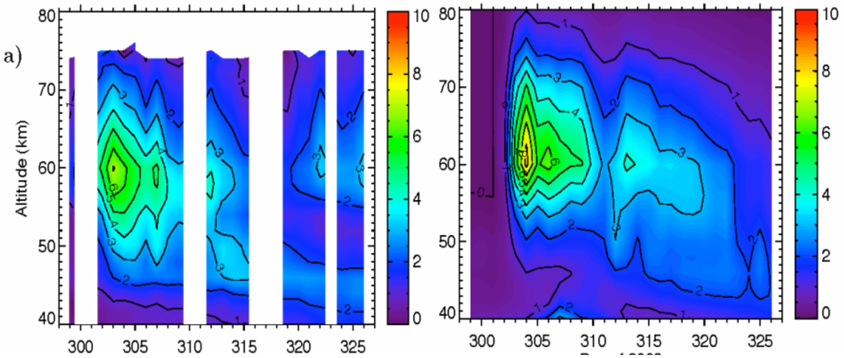
MLS observations during SPE Jan 2005: OH and HO_2 (⇨ talk and poster Verronen et al.; poster Versick et al.)

HALOE observations during SPE July 2000: HCl (⇨ poster Winkler et al.)



Model results – SPE 2000/ 2003 – nitrogen and chlorine compounds

MIPAS N_2O CMAM model



N_2O enhancements can be explained by $NO_2 + N \rightarrow N_2O + O$.

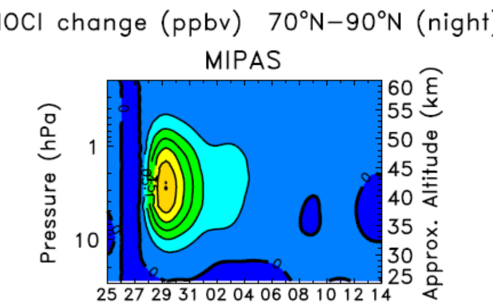
Funke et al., 2008

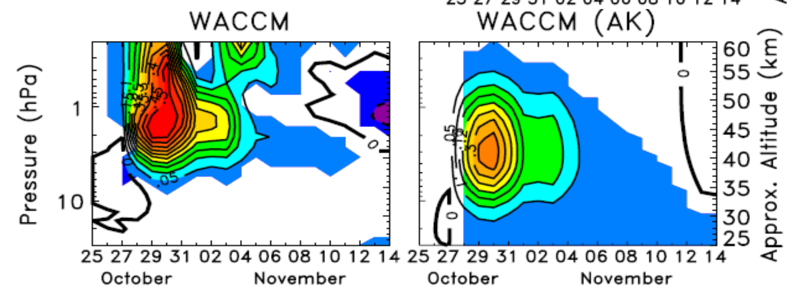
HOCl change

$$OH + HCl \rightarrow H_2O + Cl$$

$$Cl + O_3 \rightarrow ClO + O_2$$

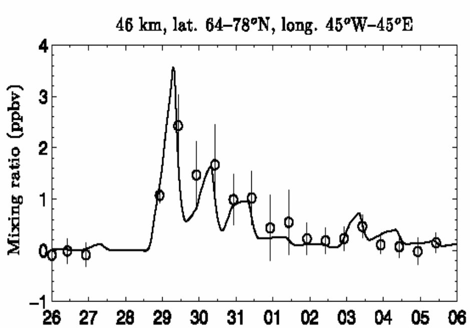
$$ClO + HO_2 \rightarrow HOCl + O_2.$$

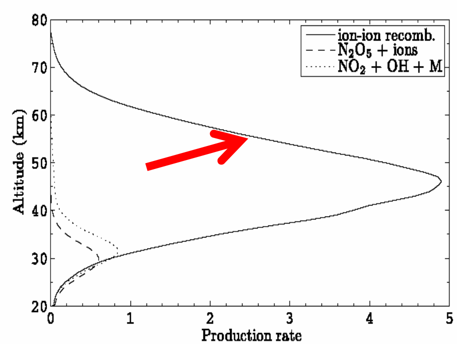




Jackman et al., 2008

HNO_3 (46 km) Production rates

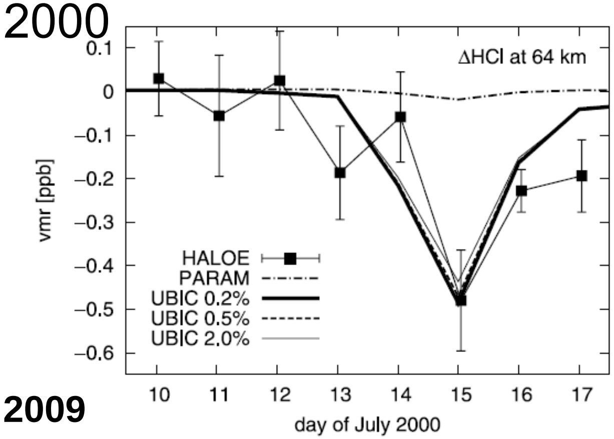




HNO_3 enhancements can be reproduced by inclusion of **ion-ion recombination** between NO_3^- and H^+ cluster ions. **Verronen et al., 2008**

HALOE Jul 2000

Reactions with **negative chlorine ions**



Winkler et al., 2009

Model results – SPE 2000/ 2003 – nitrogen and chlorine compounds

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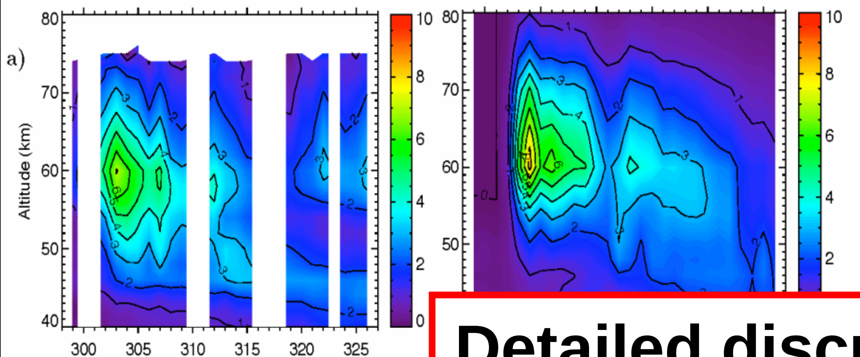
MIPAS N_2O CMAM model



N_2O enhancements by $NO_2 + N \rightarrow N_2O$

HOCl change

$OH + HCl \rightarrow H_2O + Cl$

$Cl + O_3 \rightarrow ClO + O_2$

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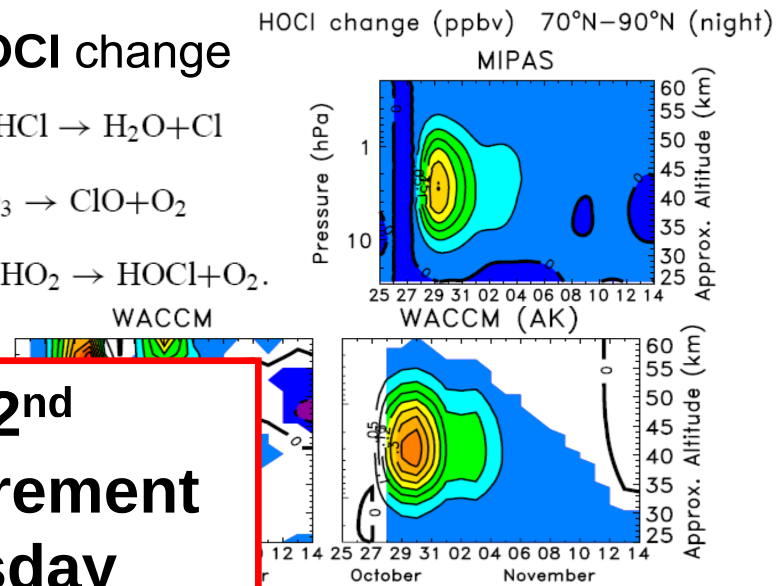
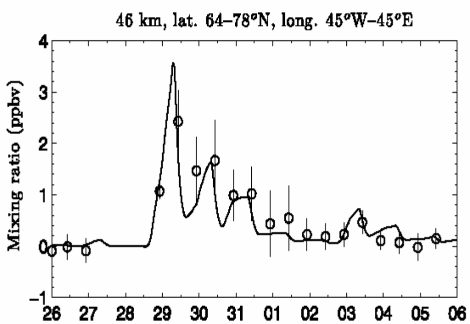


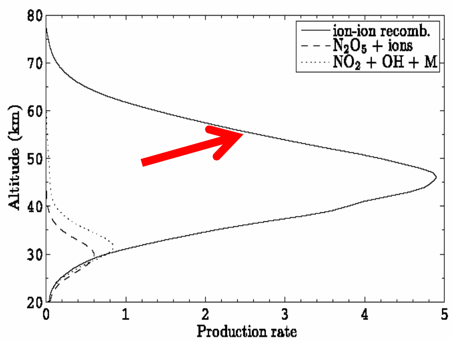
Detailed discussion: 2nd HEPPA Model/Measurement workshop on Wednesday

Jackman et al., 2008

HNO_3 (46 km)



Production rates



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HALOE Jul 2000

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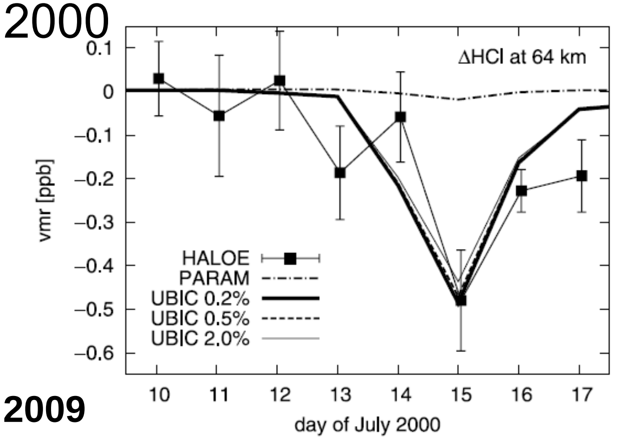

Winkler et al., 2009

Model results – SPE 2003 / 2005 – hydrogen compounds

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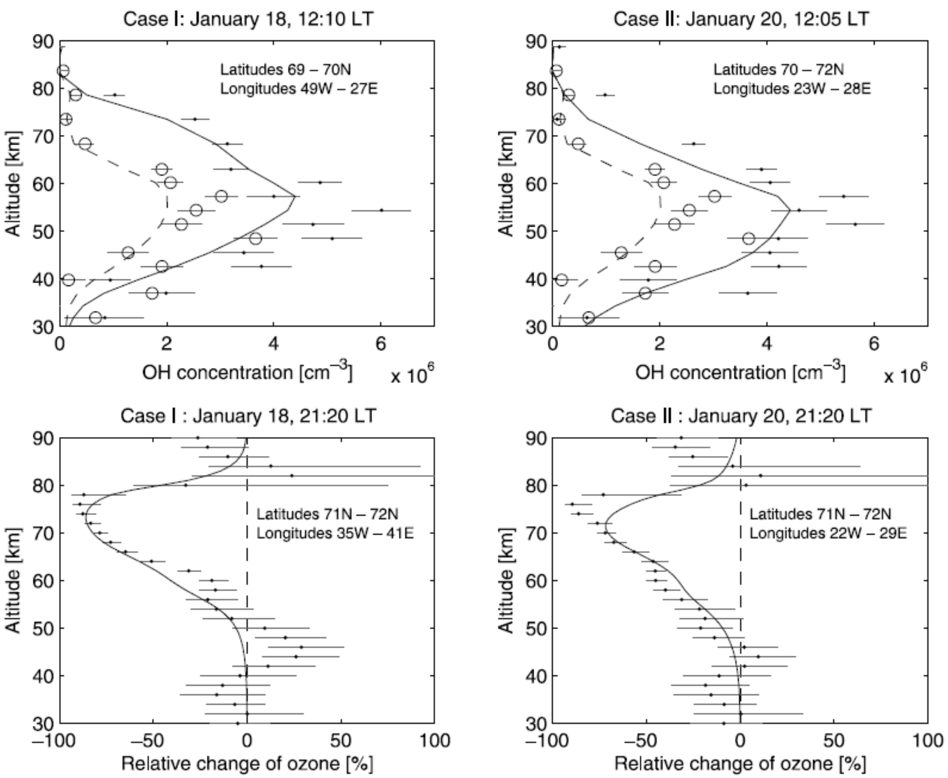
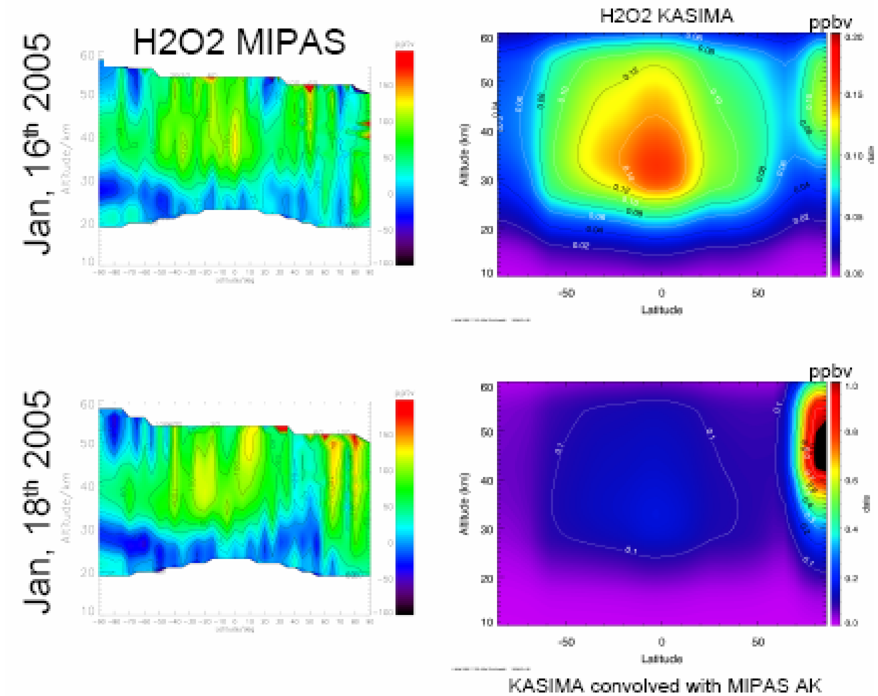
OH during SPE Jan 2005



O_3 during SPE Jan 2005

MLS observations, SIC (full ion chemistry) 1-D modelling

Verronen et al., 2006



H_2O_2 during SPE Jan 2005

MIPAS observations, KASIMA 3D-CTM modelling

Versick et al., Poster session

Summary direct (SPE) impact of EPP:

- High energetic protons penetrate deeply into the mesosphere and stratosphere and deposit their energy there
- ~ 35 eV produce one ion-electron pair
- Ions generate - via more or less complicated ion (cluster) chemistry – NO_x (mainly in the stratosphere) and HO_x (mainly in the mesosphere)
- NO_x and HO_x are involved in catalytic ozone destruction cycles ⇨ immediate ozone depletion observed and modeled
- Further perturbation of stratospheric/mesospheric chemistry is observed: HNO_3, N_2O_5, $BrONO_2$, HNO_4, N_2O, CO, $ClONO_2$, HCl, ClO, $ClONO_2$, OH, HO_2, H_2O_2,…
- Some of the chemical reactions can be modeled (by direct gas-phase or ion (cluster) chemistry), some are not yet understood.

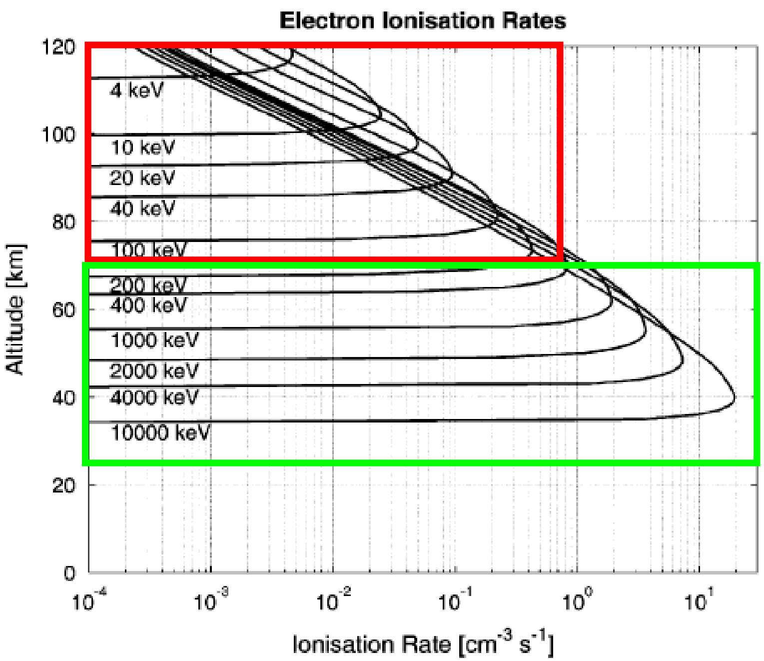
Further topics to be discussed:

- Impact of (secondary) electrons vs. protons
- Effects on temperature and dynamics (e.g. via ozone depletion)
- …

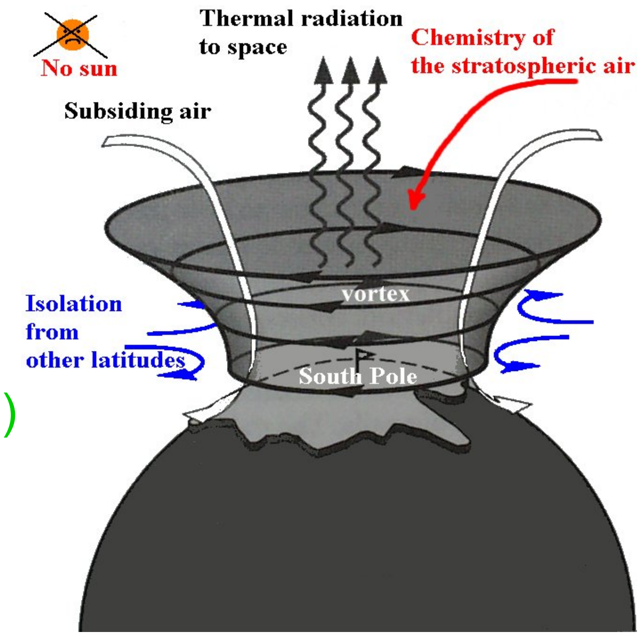
Indirect EPP effects

What are indirect EPP effects?

NO_x, HO_x or other species (ions) are affected at higher altitudes by EPP.
Changed atmospheric composition is transported downwards into the mesosphere/ upper stratosphere and affects chemical composition there.

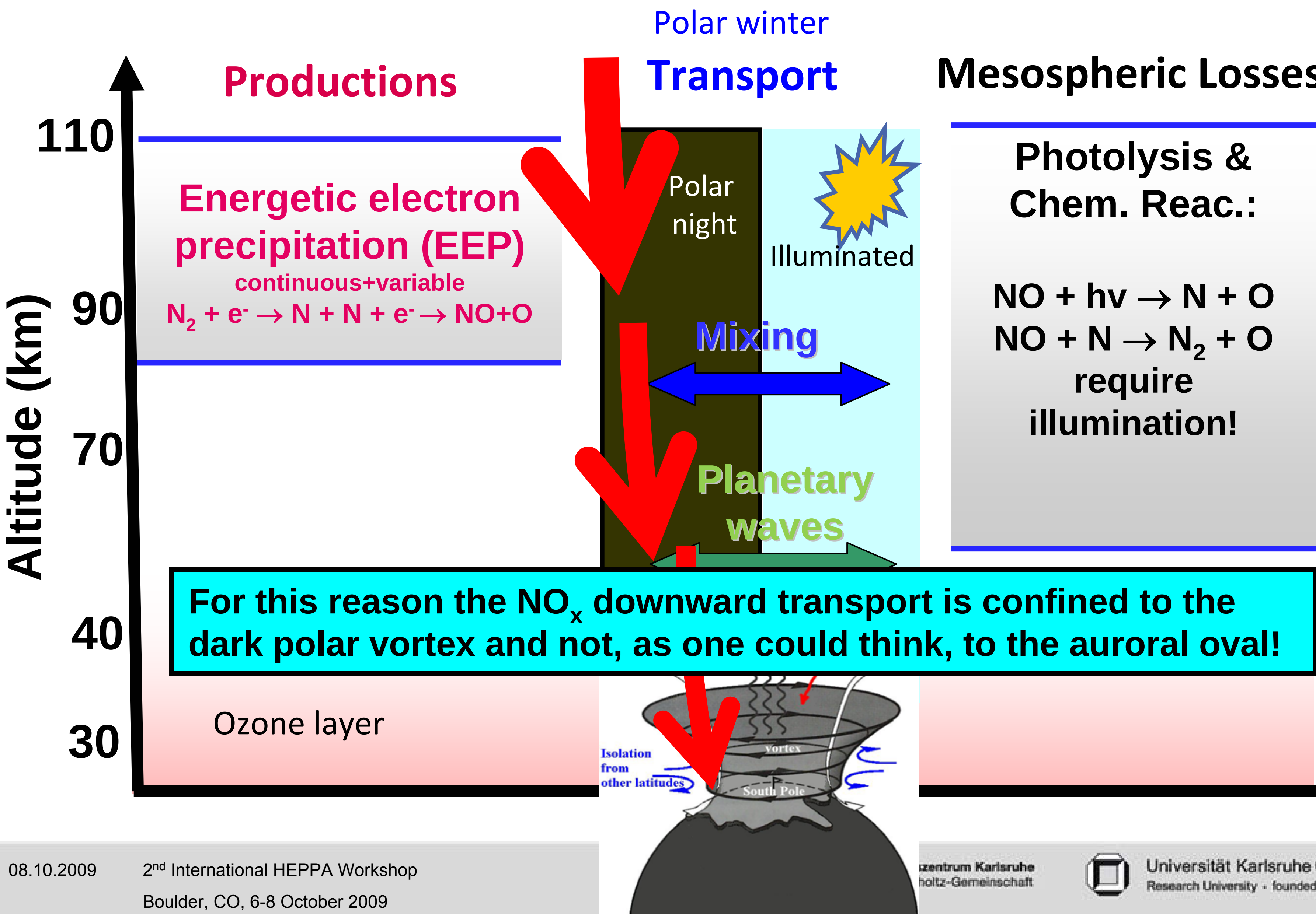


⇨talk by Esa Turunen (?)

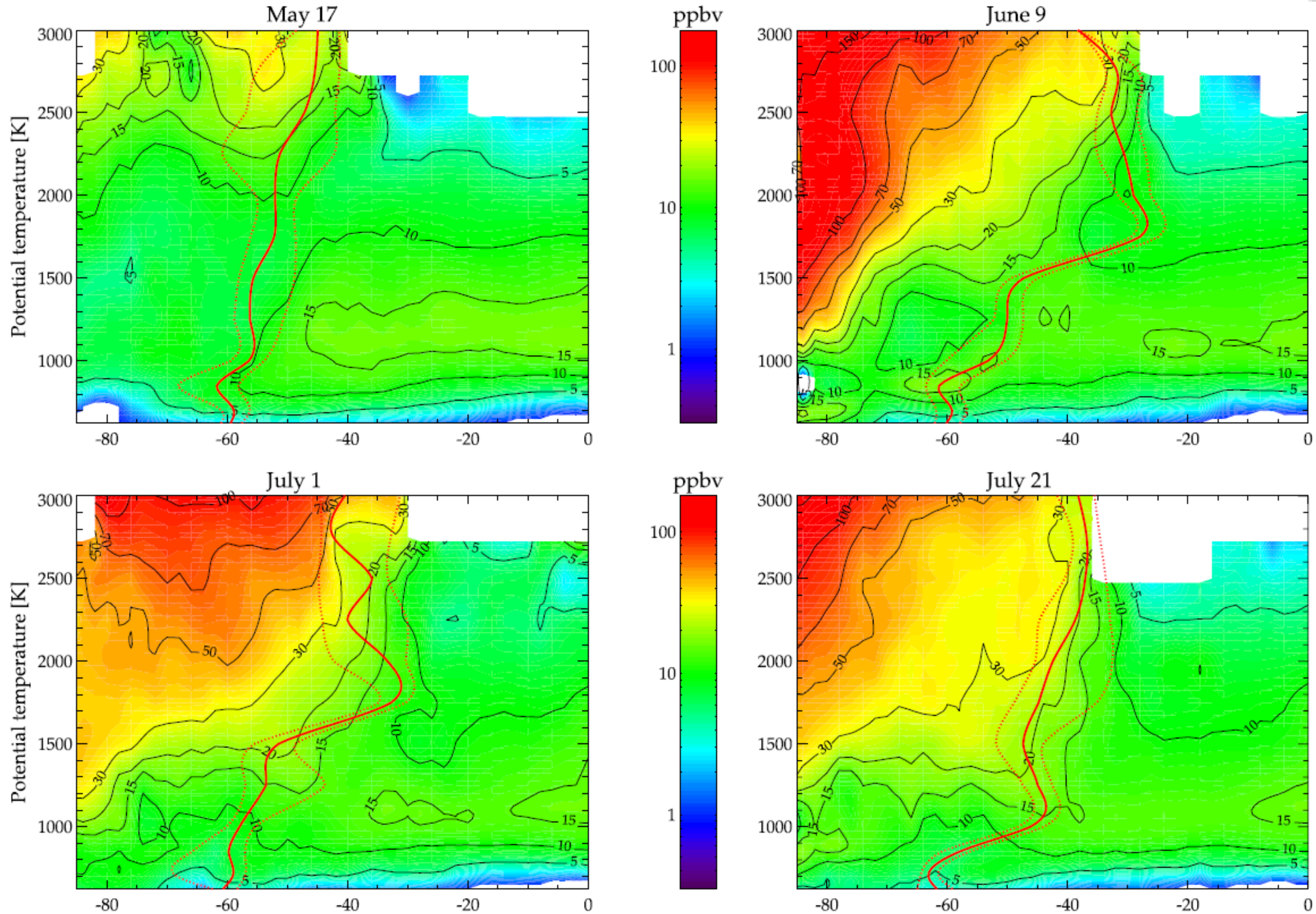


Auroral to high energetic electrons produce NO_x and HO_x in the upper mesosphere/lower thermosphere region (80 – 120 km).
The polar winter vortex acts as a “bathtub sink” where air is sucked down during polar winter.
But: The lifetime of HO_x is much too short to survive downward transport.
Only relevant species is NO_x. NO is produced in the MLT and can survive transport through the mesosphere in darkness only. Why?

NOx polar winter descent



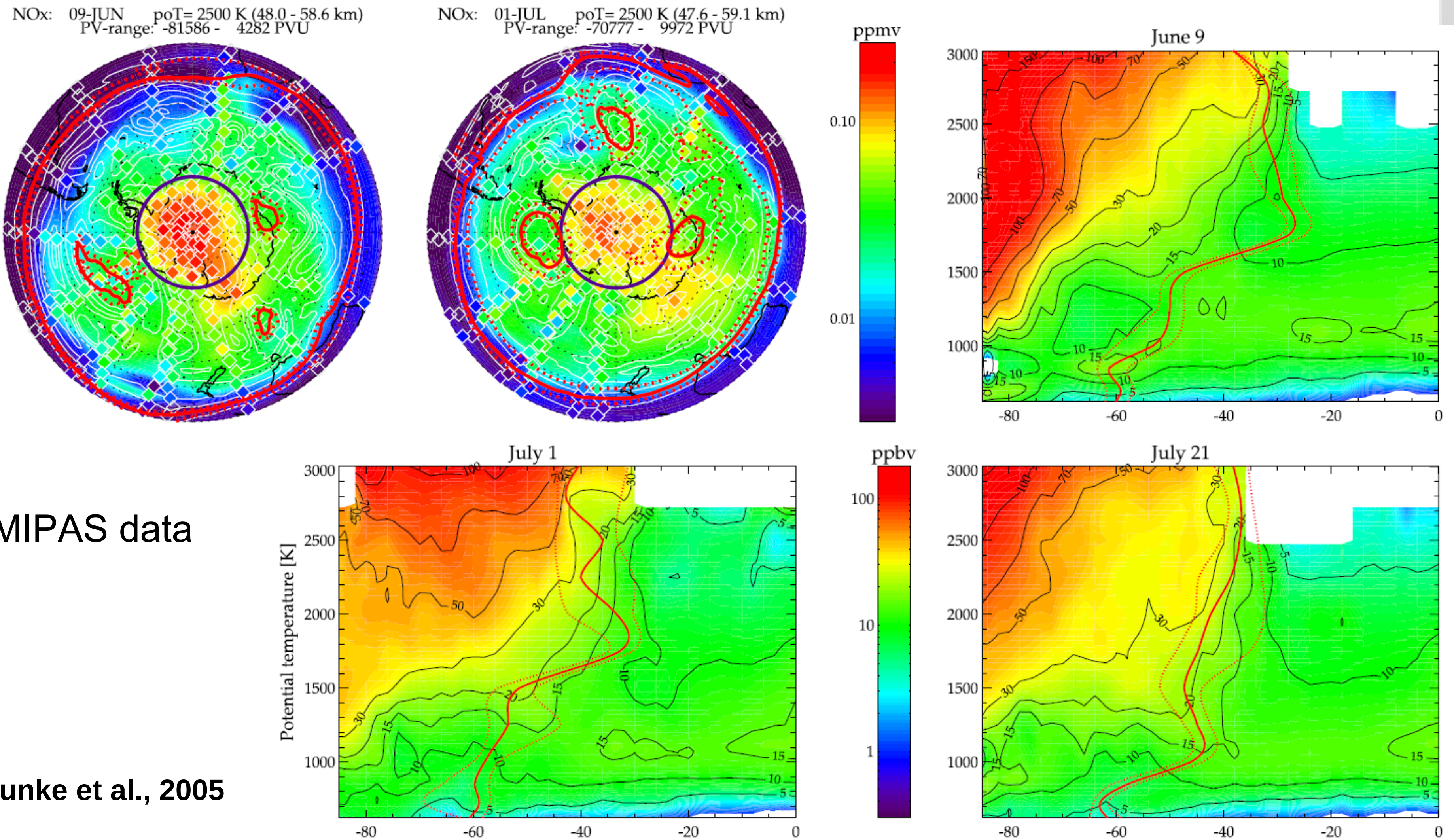
NO_x in Antarctic polar winter 2003: confinement to the dark vortex



MIPAS data

Funke et al., 2005

NO_x in Antarctic polar winter 2003: confinement to the dark vortex



MIPAS data

Funke et al., 2005

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D08308, doi:10.1029/2006JD007696, 2007

HALOE observations

Year-to-year variability of NO_x Subsidence in SH

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Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992–2005

C. E. Randall,[1,2] V. L. Harvey,[1] C. S. Singleton,[1] S. M. Bailey,[3] P. F. Bernath,[4] M. Codrescu,[5] H. Nakajima,[6] and J. M. Russell III[7]

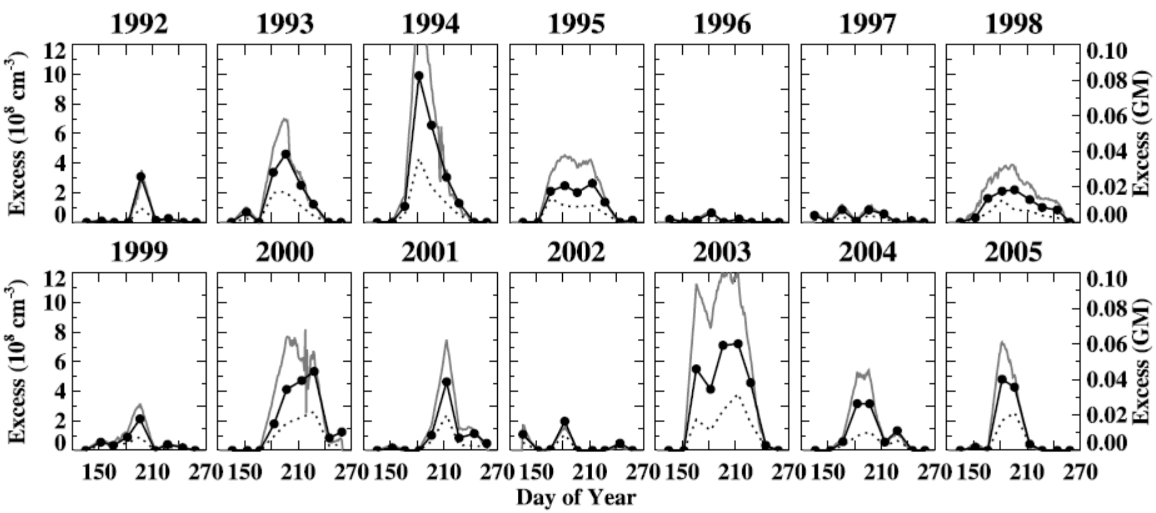


Figure 7. Maximum (black, solid) and average (dotted) excess NO_x densities in 2-week time periods from 15 May through 15 September, calculated as described in the text and Figure 6. Gray solid lines denote the number of molecules derived from the maximum excess densities (right axis, gigamoles). For clarity, the number of molecules in year 1994 has been allowed to run off-scale; numbers peak at 0.2 GM.

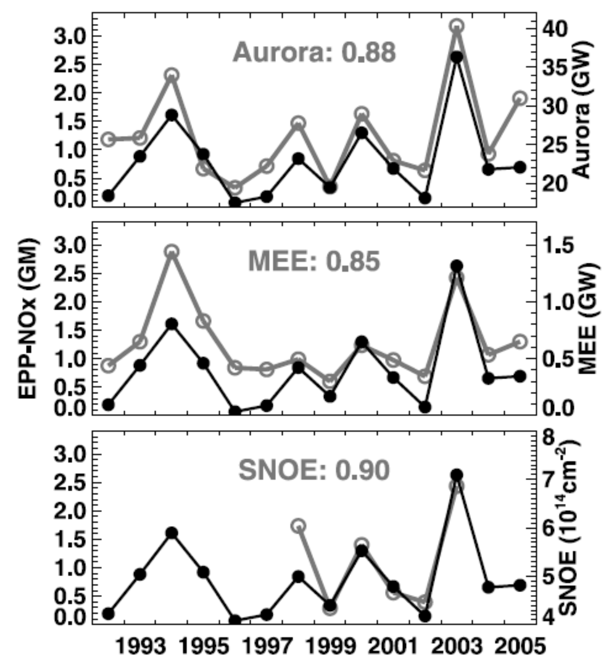
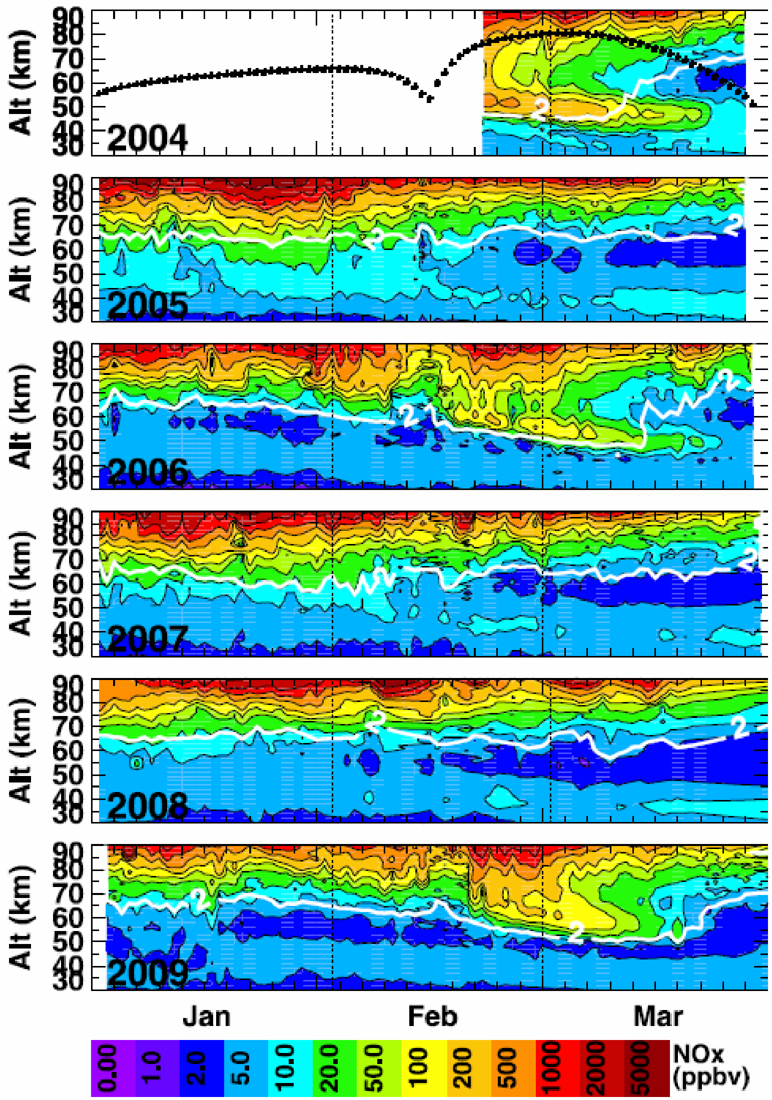


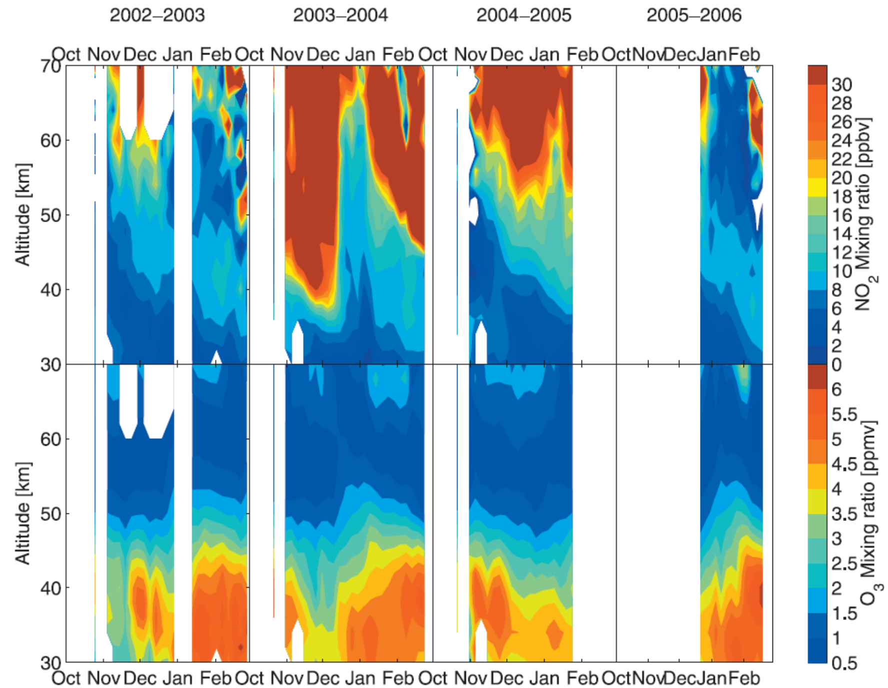
Figure 10. EPP-NO_x calculated from the maximum NO_x residuals as in Figure 9 (dots, solid line, left axis) compared to auroral hemispheric power (top), medium energy electron hemispheric power (middle), and SNOE column NO from 97 to 150 km averaged over the sunlit region poleward of 60°S (bottom). Energetic particle and SNOE data (gray) are averaged over the months of May-July and are referenced to the right vertical axes. Correlation coefficients are given in each panel.

SH: Deposited NO_x in stratosphere reveals high inter-annual variability and correlates well with auroral activity and NO produced in the thermosphere

High variability in NH



Randall et al., 2009 ACE-FTS data



GOMOS data **Seppälä et al., 2007**

High variability observed

High NO_x although geomagnetic activity was low: 2006, 2009

Unusually strong descent in 2004, 2006, 2009

NH stratospheric excess NO_x amounts seem to be ruled more by dynamics than by production

See also talks by Randall and Funke

Vivid discussion: Arctic winter 2003 - 2004

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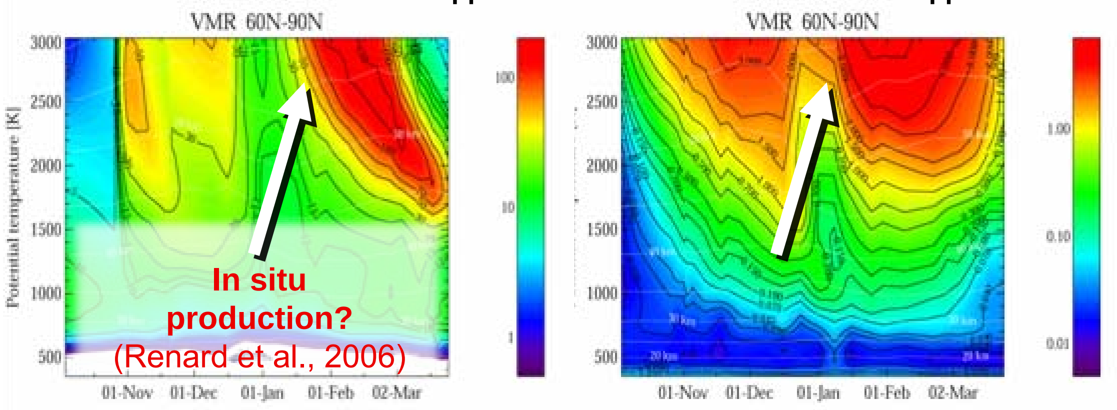


Funke et al., 2007

Dynamic origin or in situ production?

- Correlation with dynamic tracers confirm downward transport of NO_x produced in the thermosphere (e.g. Funke et al., 2007; Hauchecorne et al., 2007)
- Semeniuk et al. (2005) found that SPE-generated thermospheric NO_x is not sufficient to explain amounts ⇨ additional production by auroral electrons
- Seppälä et al. (2007) found indication for contributions from aurorally generated NO_x

$>$10 MeV protons
K_p index

Ionization levels (radio wave index)

GOMOS ngt. NO2

POAM day NO2

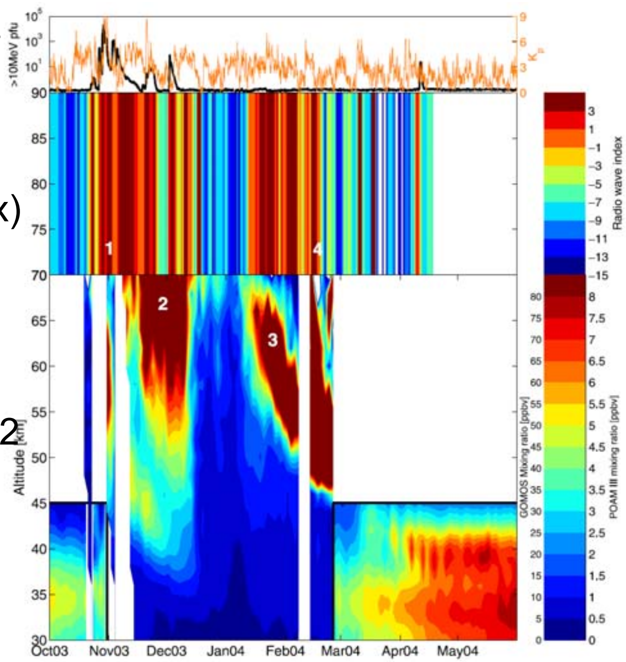
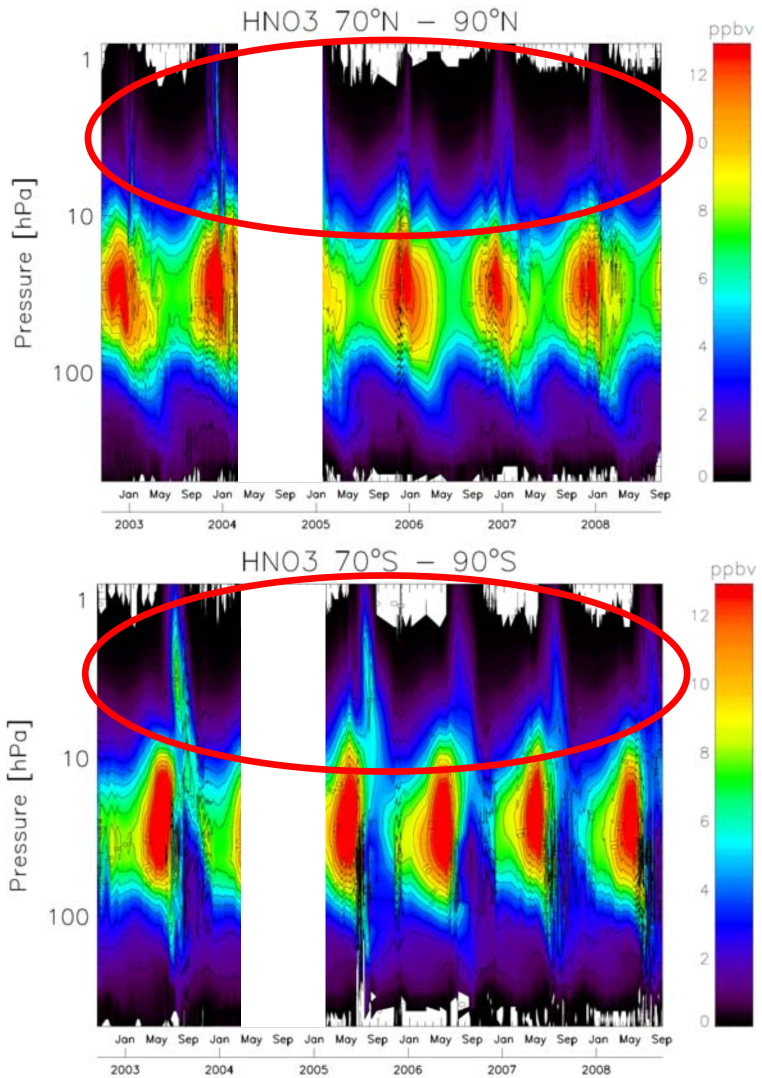


Figure 1. Combined observations of NO_2 during the Northern Hemisphere winter 2003–2004, showing (top) the >10 MeV proton flux (heavy line) and K_p index (light line), (middle) high-altitude ionization levels determined from the subionospheric radio wave index, and (bottom) GOMOS nighttime and POAM III daytime NO_2 mixing ratios, with the POAM data shown inside heavy boxes. Both data sets have been zonally averaged over 2 d. Note the differing color scales for the two satellite data sets. These observations show the generation and descent of NO_x into the upper stratosphere.

Seppälä et al., 2007

Impact of EEP-generated NO_x on stratospheric chemical budget: NO_y

1. Formation of upper stratospheric HNO_3



☜ MIPAS observations (Stiller et al., 2005)

- Every-year occurrence of upper strat. HNO_3 maximum confirmed by ODIN-SMR observations (Orsolini et al., 2009)
- Mechanism proposed by de Zafra and Smyshlyaev (2001):

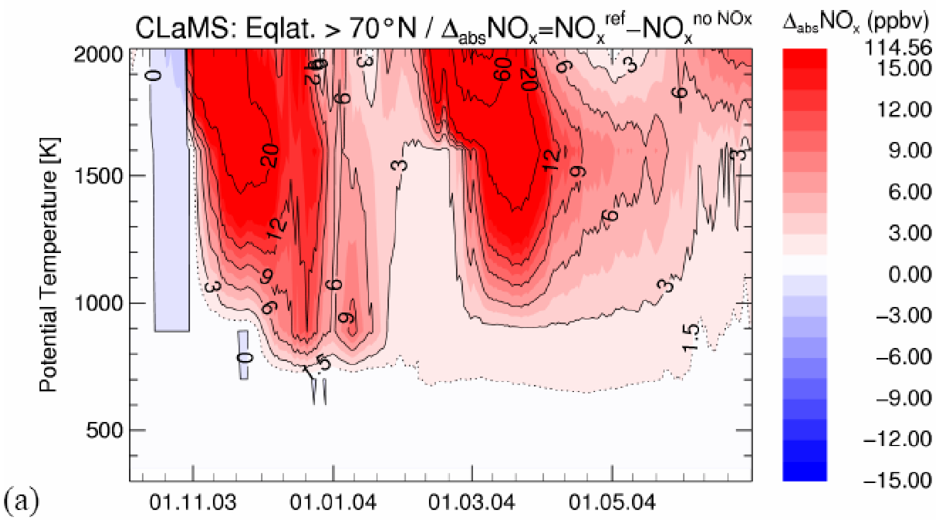
$N_2O_5 + H^+(H_2O)_n \rightarrow H^+(H_2O)_{n-1} + 2HNO_3$

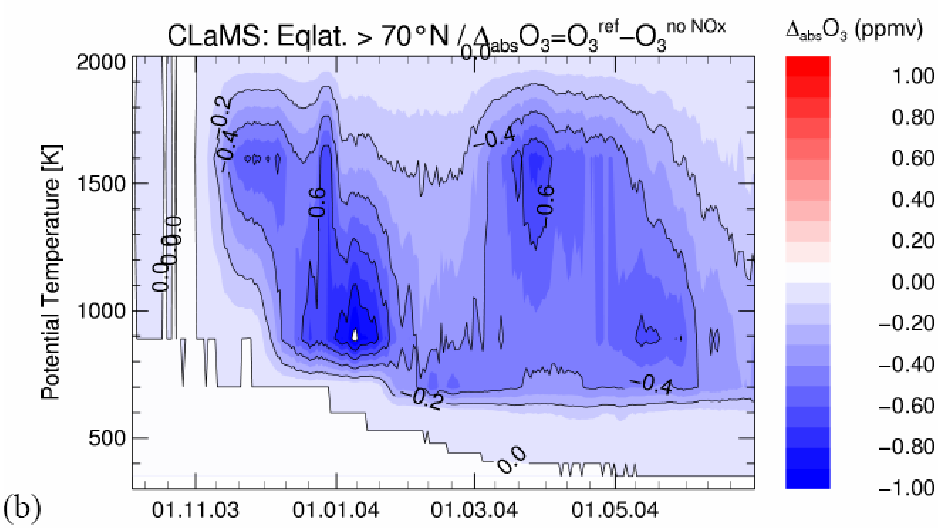
(only for z > 40km)

- N_2O_5 is formed immediately from NO_x under dark conditions
- Note: this is a different ion cluster reaction than during/after SPE!
- Mechanism confirmed by KASIMA model calculations (see Poster Reddmann et al.)

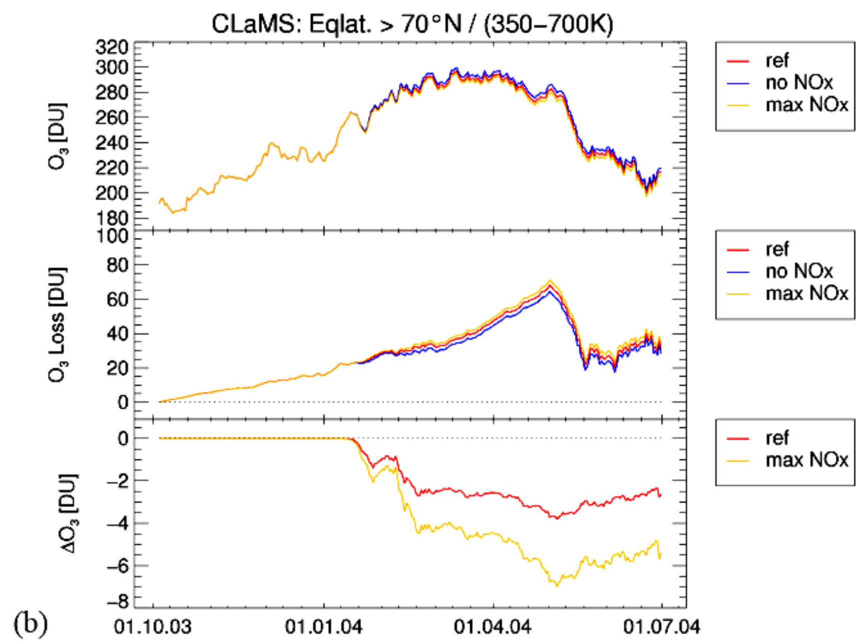
2. NO_x has impact on further NO_y species (e.g. $BrONO_2$, ⇨ poster Höpfner et al.)

Impact of EPP-generated NO_x on stratospheric chemical budget: O_3



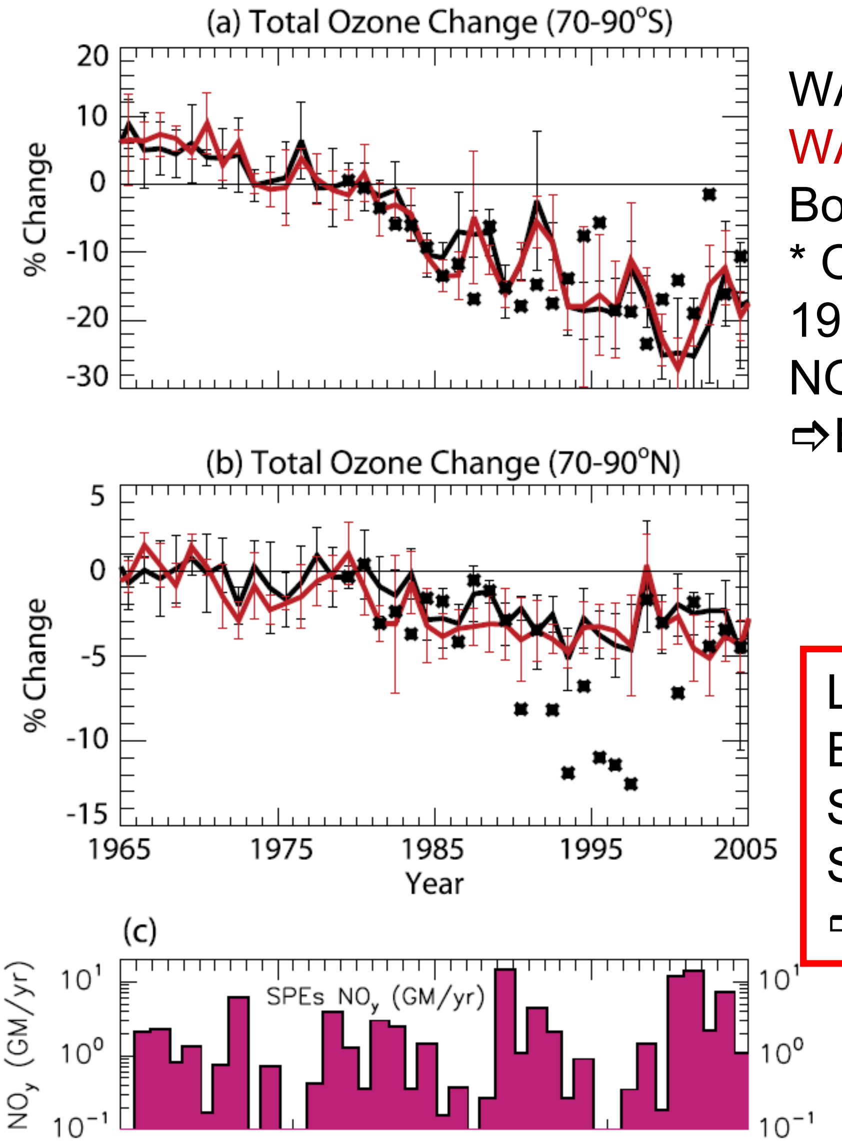


- Both SPE-generated NO_x (and HO_x) and EEP-generated and descended NO_x lead to additional ozone depletion.
- Short-term (days to winters) and long-term (solar cycle) effects.



Vogel et al., 2008

Impact of EPP-generated NO_x on stratospheric chemical budget: Long-term O_3



WACCM3 without SPEs

WACCM3 with SPEs

Both mean value minus average 1979-1980

* Observed ozone minus the observed average 1979-1980

NO_y production by SPEs

⇨Effect is very small

Long-term (decadal and longer) impact of EEP produced and descended NO_x?
Should be larger and more regular than by SPE-produced NO_x!
⇨ Callis et al., 1998 covered 1979-1988

Summary: Indirect impact of EPP:

- NO_x and HO_x produced by auroral and high energetic electrons in the upper mesosphere and lower thermosphere
- Only NO_x is long-lived enough to be transported into the stratosphere by polar winter descent
- Transport through mesosphere possible only in darkness due to NO photolysis ⇨ confinement to dark polar winter vortex
- Import of NO_x during Antarctic winter highly variable and well correlated with geomagnetic activity ⇨ ruled by source strength
- Typical import amounts: 1 to 3 GMoles N per winter, this is about 5 to 15 % of the N_2O source.
- Arctic winters: extremely variable with exceptional winters 2004, 2006, 2009. High amounts also for years with low geomagnetic activity ⇨dynamical variability more important
- Winter 2003/2004: Discussion about descent vs. local production, contribution of SPE vs. EEP-generated NO_x
- Excess NO_x has impact on NO_y partitioning (upper stratospheric HNO_3 maximum produced by N_2O_5 conversion on protonated water ion clusters), $BrONO_2$, $ClONO_2$, …
- Excess NO_x (and HO_x in the mesosphere) leads to short-term and medium-term (few months) ozone depletion
- Long-term ozone depletion by SPEs not significant
- Long-term ozone depletion by EEPs?

Certainly I have mentioned by far not all work regarding EPP impacts.

My apologies if any relevant observations, analyses, and modeling work are missing.

Thank you for your attention!