Overview of
Energetic Particle Precipitation (EPP)
Effects on the Earth's Atmosphere

Charles Jackman
NASA Goddard Space Flight Center, Greenbelt, MD

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Acknowledgments:

Cora Randall
University of Colorado, Boulder, CO

Daniel Marsh, Francis Vitt, and Rolando Garcia
National Center for Atmospheric Research, Boulder, CO

Eric Fleming
NASA Goddard Space Flight Center, Greenbelt, MD

Shuhui Wang
JPL, California Institute of Technology, Pasadena, CA

Pekka Verronen
Finnish Meteorological Institute, Helsinki, FINLAND

Bernd Funke
Instituto de Astrofisica de Andalucia, CSIC, Granada, SPAIN
Outline

I. Introduction

II. EPP-caused $\text{HO}_x$ and Ozone Change

III. EPP-caused $\text{NO}_x$, $\text{NO}_y$, and Ozone Change

IV. Conclusions
I. Introduction

Ultimate origin of most Energetic Particles is the Sun

Galactic Cosmic Rays (GCRs) originate outside the Solar System and will not be discussed
I. Introduction

Ultimate origin of most Energetic Particles is the Sun

Stay tuned for Jón-Egill Kristjánsson’s Talk at 11:10 Tomorrow about GCR impacts
Overview of Energetic Particle Precipitation

Electrons and Protons comprise most (~90% or so) of these Particles

Higher flux of particles associated with:
1) Solar flares,
2) Coronal mass ejections (CMEs),
3) Geomagnetic storms
Animation of Coronal Mass Ejection
Electron Precipitation

Lower energy
Auroral electrons → auroral zone [~62-75° geomag. lat.]

Medium & high energy electrons
→ subauroral zone [~55-65° geom. lat.]

Each zone is ~9% of Earth area.
Protons also come via CMEs and enter through the magnetosphere near the poles and precipitate there.

"Solar Proton Event (SPE)"

Sun → Earth

GOES - Geostationary Operational Environmental Satellites
Proton Precipitation

Solar protons

Polar Caps
>~60° geomag. lat.

Very intense solar events push polar cap boundaries Equatorward

About 14% of Earth is affected during solar proton events.
Atmospheric Influences of Energetic Particle Precipitation

Most (70-80%) of the Energy Deposited creates Ion Pairs:

→ free Electron & positive Ion
Energetic Particle Precipitation

- Medium & High Energy Electrons
- Solar Protons
- Auroral Electrons
- Galactic Cosmic Rays

Ionization Rate (cm$^{-3}$ s$^{-1}$) vs. Altitude (km)
What are the dates of some large Solar Proton Events?
# Largest 15 Solar Proton Events (SPEs) in Past 50 Years

<table>
<thead>
<tr>
<th>Date of SPEs</th>
<th>Computed Rank (Total Ion Pair Production)</th>
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<tbody>
<tr>
<td>October 1989</td>
<td>1</td>
</tr>
<tr>
<td>August 1972</td>
<td>2</td>
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<tr>
<td><strong>July 2000</strong></td>
<td>3</td>
</tr>
<tr>
<td>October 28-31, 2003</td>
<td>4</td>
</tr>
<tr>
<td>November 5-7, 2001</td>
<td>5</td>
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<tr>
<td><strong>March 2012</strong></td>
<td>10</td>
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<tr>
<td>September 1966</td>
<td>11</td>
</tr>
<tr>
<td><strong>January 2012</strong></td>
<td>12</td>
</tr>
<tr>
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</tr>
<tr>
<td>Sep. 29 – Oct. 3, 1989</td>
<td>14</td>
</tr>
<tr>
<td>Jan. 28 – Feb. 1, 1967</td>
<td>15</td>
</tr>
</tbody>
</table>

Note that seven of the largest SPEs occurred in 2000-2005!

Note that two of the largest SPEs occurred in 2012!
Large SPE – GOES Proton Flux Data
(March 6-11, 2012)

Note the large (>100X) enhancement!

Day in March 2012

Particles cm⁻² s⁻¹ sr⁻¹

10⁻¹

10⁻²

10⁻³

10⁻⁴

> 10 MeV

> 50 MeV

> 100 MeV
Ionization Rates (#cm\(^{-3}\) s\(^{-1}\)) – March 6-11, 2012

Contour levels: 100, 200, 500, 1000, & 2000 (#cm\(^{-3}\) s\(^{-1}\))

Protons from 1-300 MeV included
Energetic Particles also Produce $\text{HO}_x (\text{H,OH,HO}_2)$ & $\text{NO}_x (\text{N,NO,NO}_2)$

Both of which can destroy Ozone
II. EPP-caused $\text{HO}_x$ and Ozone Change
EPPs Enhance $\text{HO}_x$ (H, OH, HO$_2$)

- $\text{HO}_x$ constituents are produced through water cluster ion formation & neutralization
  - Primarily short-term effects as $\text{HO}_x$ lifetime is short (~hours) in the atmosphere

- $\text{HO}_x$ production by EPPs to be shown here:
  - For Solar Proton Event in March 2012
  - For Electron Precipitation in April 2006
Solar Proton
HO$_x$ Production
Ionization Rates (top) & 
$\text{HO}_x$ Production Rates (bottom)

for March 6-11, 2012

Contour levels: 100, 200, 500, 1000, 2000, & 5000 ($\text{cm}^{-3}\text{s}^{-1}$)
Aura MLS
(Microwave Limb Sounder)
measures HO$_2$ and Ozone
HO$_2$(ppbv) change for 60-82.5°N Latitude Band

HO$_2$ average for Feb.14-Mar.5 (3 weeks) is subtracted from Mar. 6-11 values

Top: MLS Data
Bottom: Computed HO$_x$ Production
Ozone Impact
– March 2012 SPE

Aura MLS observations
Ozone & HO$_2$ change for 60-82.5°N Lat. Band

Average for Feb.14-Mar.5 (3 weeks) is subtracted from Mar. 6-11 values

Top: MLS Ozone Data

Bottom: MLS HO$_2$ Data
OH Production
– Precipitating Electrons in April 2006

Aura MLS - OH observations

Adapted from Verronen et al. [2011]
Aura MLS OH Measurements (71-78 km) vs.
Medium Energy Electron Flux (100-300 keV)
for geomagnetic latitudes 55-65°N

Larger OH correlated with Higher Electron Flux

Adapted from Verronen et al. [2011]
III. EPP-caused NO$_x$, NO$_y$, and Ozone Change
EPPs Enhance
\( \text{NO}_x \) (N, NO, NO\(_2\))

- \( \text{NO}_x \) constituents are produced by primary electrons and protons and associated secondary electrons dissociating \( \text{N}_2 \)
  - Short- and long-term effects as \( \text{NO}_x \) constituents can last for weeks

- **SCISAT-1 ACE** (Atmospheric Chemistry Experiment) measures \( \text{NO}_x \) (NO+NO\(_2\)) constituents

Adapted from Randall et al. [2006]
NO$_x$ in the Northern Hemisphere (50-85°N) → Use ACE – started Feb. 18, 2004

Year 2004:
- **Significant EPP (electrons) in 2004**
- Also, Unusual Meteorology
  - Sudden Stratospheric Warming (SSW) in January
  - Enhanced descent

Adapted from Randall et al. [2006]
NO$_x$ in the Northern Hemisphere (50-85°N)
→ Use ACE – started Feb. 18, 2004

→ Downward transport of NO$_x$
from the Mesosphere to the Upper Stratosphere

Year 2004:
- Significant EPP (electrons) in 2004
- Also, Unusual Meteorology
  - Sudden Stratospheric Warming (SSW) in January
  - Enhanced descent

Adapted from Randall et al. [2006]
NO$_x$ descent in Northern Hem.
$\rightarrow$ Use ACE (50-85°N)

Years 2004, 2006, 2009:
- Unusual Meteorology $\rightarrow$ descent

Adapted from Randall et al. [2009]
Also, note that:

Years 2004, 2006, 2009:
- Unusual Meteorology → descent

However: Yrs 2006 and 2009 did not show much NO\textsubscript{x} descent to stratosphere

Adapted from Randall et al. [2009]
Now back to Year 2004:

How did the electron-produced NO\textsubscript{x} impact Ozone?

→ Use data from POAM (Polar Ozone and Aerosol Measurement) instruments

Adapted from Randall et al. (2005)
POAM II & III obs. (54-71°N)

NO$_2$ at 40 km

Ozone at 40 km

Column Ozone (35-50 km) -1.5 to 3 D.U. (~0.5-1%)

Adapted from Randall et al. (2005)
Year 2004 appears to be very exceptional for EPP (electron) NO\textsubscript{x} transport to the Stratosphere.

Column Ozone (35-50 km) -1.5 to 3 D.U. (~0.5-1%)

POAM II & III obs. (54-71°N)

\(\text{NO}_2\) at 40 km

Adapted from Randall et al. (2005)
Does the electron-caused Ozone change impact Climate?

Stay tuned for Annika Seppälä’s Talk at 16:30 Today for more information.
### Largest 15 Solar Proton Events (SPEs) in Past 50 Years

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<td>“Halloween” SPE of Oct. 2003 was Very Large</td>
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In memory of:
ESA Envisat
(1 March, 2002 – 8 April, 2012)
→ Over 10 years of Earth observations

MIPAS, SCIAMACHY, & GOMOS
Instruments provided great measurements of EPP impact on the Atmosphere
MIPAS provided measurements of most NO$_y$ constituents:

NO, NO$_2$, N$_2$O$_5$, HNO$_3$, HO$_2$NO$_2$, ClONO$_2$

Only missing N, NO$_3$, BrONO$_2$, which are minuscule in the middle atmosphere.

→ NO$_y$ lifetime can be long (~months)
MIPAS NO\textsubscript{y} \ (NO+NO\textsubscript{2}+2N\textsubscript{2}O\textsubscript{5}+HNO\textsubscript{3}+ClONO\textsubscript{2}+HNO\textsubscript{4})
observations (40-90°N) in 2003

Changes with respect to October 26, 2003

Adapted from Funke et al. (2011)
Model

• Whole Atmosphere Community Climate Model (WACCM) – NCAR Model
  - Domain [90°S – 90°N, 0 - 145 km]
  - Atmospheric physics & photochemistry
  - Specified dynamics from measurements for 2003

• Perturbed: Simulation ‘With’ SPEs

D. Marsh et al.
NO$_y$ (40-90°N) in 2003

Changes with respect to October 26, 2003

Adapted from Funke et al. (2011)
More WACCM Simulations

→ Interactive dynamics

- Perturbed (1963-2004): Four realizations ‘With’ SPEs
- Base (1963-2004): Four realizations ‘Without’ SPEs
- Difference mean of Perturbed and Base results to compute SPE-caused change

Look at Average for Years 2000-2004
Perturbed – Base (2000-2004 average)

Very Large SPEs in 2000, 2001, & 2003

From Jackman et al. (2009)
Colored Regions are Statistically Significant to 95% (Student’s t-test)
Perturbed – Base (2000-2004 average)

Large stratospheric area with statistically significant NO\textsubscript{y} increase

Some stratospheric area with statistically significant Ozone decrease (mainly NH)

\[ \rightarrow \text{more NO\textsubscript{y}-induced O}_3 \text{ loss} \]

\[ \rightarrow \text{Ozone increase} \]

\[ \rightarrow \text{Interference of NO\textsubscript{y} with Cl/Br O}_3 \text{ loss} \]

Colored Regions are Statistically Significant to 95% (Student’s t-test)
Do Solar Proton Events impact Total Ozone?
Predicted Impact (GSFC 2D Model) of Solar Protons on Total Ozone (%) from Jackman et al. (2008)
Predicted Impact (GSFC 2D Model) of Solar Protons on Total Ozone (%)

Larger decreases in NH caused by 1989, 2001, & 2003 SPEs

Larger decreases in SH caused by 1972, 1989, & 2000 SPEs

From Jackman et al. (2008)
Predicted Impact (GSFC 2D Model) of Solar Protons on Total Ozone (%)

Computed Total Ozone decreases from SPEs are <3%.

These can be compared with measured interannual variability of up to ~10%, thus are not observable.

From Jackman et al. (2008)
IV. Conclusions

• Both electrons & protons influence the polar mesosphere/stratosphere – mainly in certain years
  → e.g., near solar max, large Ap, unusual meteorology

• EPP produces \( \text{HO}_x \), which is short-lived
  → Mesospheric Ozone depletion can be large (>20%)

• EPP produces long-lived \( \text{NO}_y \) (1972, ’89, 2000, ‘01, ‘03,’04, ‘06?)
  → Stratospheric Ozone impacts can last for months
  → Computed total ozone changes are small (<3%)
Addendum:
EPP also impacts other constituents
(e.g., HNO$_3$, N$_2$O$_5$, HO$_2$NO$_2$, N$_2$O, ClONO$_2$, ClO, HOCl, HCl, CO, H$_2$O$_2$) & T

Thank you for your attention!