Atmospheric Coupling via Energetic Particle Precipitation (EPP)

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ACE Science Team

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Vertical Coupling

- Troposphere to thermosphere
- In the polar region
- Mainly in winter

Outline

- Intro to Mechanism
- Historical Evidence
- Recent Anomalies
- Model Results
Energetic Particle Precipitation

Adapted from Lean, 1994
Low-energy particles precipitate in thermosphere

High-energy particles precipitate in mesosphere and stratosphere

Energetic Particle Precipitation (EPP)

NO transported downward and/or produced locally

NO catalytically destroys ozone

Strong horizontal winds prevent transport to lower latitudes

NO\textsubscript{x} and HO\textsubscript{x} Destroy Ozone
EPP Effects on the Stratosphere

**DIRECT EFFECT (DE):** NO\(_x\) produced in stratosphere.

- Requires highly energetic particles
  - Stratosphere: > 300 keV electrons
  - > 30 MeV protons
- Sporadic production

**INDIRECT EFFECT (IE):** NO\(_x\) produced in mesosphere or thermosphere and descends to stratosphere

- Requires only medium or low energy particles
- Routine production
EPP Indirect Effect

NO produced in mesosphere or thermosphere and descends to stratosphere

Routine production, but MLT NO$_x$ has lifetime of days, so stratospheric effects require efficient downward transport

- Polar night
- Strong descent in MLT
- Confinement in Polar Vortex

NO$_x$ in stratosphere destroys ozone
First satellite observations of EPP Indirect Effect from LIMS in NH, 1978-1979

EPP is the ONLY source of mesospheric NO$_x$ in the polar winter!

Based on Russell et al., 1984
Satellite observations of EPP-NO$_x$ were sparse from 1979 to 2003.

EPP Investigations mainly used solar occultation data from SAGE, HALOE, and POAM

- Sparse geographic coverage
- SAGE & POAM only measure NO$_2$, not NO
- No polar night

In 2003 more data became available

e.g., GOMOS, MIPAS, SCIAMACHY, ACE-FTS
(Still cannot measure polar night NO in MLT)
EPP-NO$_x$ enhancements accompanied by ozone reductions

MIPAS NO$_x$
From Randall et al., 1998

MIPAS O$_3$
Lopez-Puertas et al., 2005

POAM ozone: 1994 vs. 1996
35%: ~30 km

From Randall et al., 2001

POAM ozone: 1999 vs. 2000
45%: ~32 km

Randall et al., 2005

Randall et al., 2005
EPP-NO$_x$ entering the Southern Hemisphere Stratosphere

How significant is this?

Up to 10% of total SH NO$_y$ (rest from N$_2$O oxidation)

Up to 40% of polar NO$_y$

What determines the interannual variability?
Strong correlation with Ap (and auroral & MEE power, and thermospheric NO) but not F10.7

Variability in SH stratospheric NO$_x$ from EPP controlled by variation in EPP-NO$_x$ production: Stable Dynamics!
In NH, correlations with Ap index & F10.7 are poor. Both dynamical variability and EPP play critical roles in controlling the NH variability.

2001-2002: SPE  
2003-2004: SPE+Met  
2005-2006: Met
NORTH ACE NO$_x$ 2004 – 2009

Less than average EPP!

Less than average EPP!

Randall et al., 2009
Elevated Arctic stratopause in 2004, 2006, & 2009

Slightly different temperature color scales; range from ~170K-270K (blue-red).
Ratio of observed $\text{NO}_x$ in 2004, 2006, & 2009 to average $\text{NO}_x$ in 2005, 2007, & 2008

$\text{NO}_x$ enhancements coincide with elevated stratopause
Elevated stratopause indicative of enhanced descent in (normal) mesosphere region (adiabatic compression).

Enhanced descent brings down more EPP-NO$_x$.

More efficient transport leads to large stratospheric EPP IE even when EPP itself is well below average.

What is the mechanism?

Begins with extraordinary sudden stratospheric warming (strong and persistent; Manney et al., 2005; 2008; 2009)
1. Stratospheric Warming: Equator-to-pole T gradient reverses → Zonal wind reverses direction

2. Planetary waves cannot propagate upward so upper stratosphere & lower mesosphere cool

3. Causes reformation of very strong upper vortex and westerly winds

4. Gravity waves with westward phase speed preferentially propagate to the mesosphere

5. Mesospheric westerly zonal wind slows → induces poleward meridional wind to balance pressure gradient & Coriolis

6. Leads to enhanced descent in the polar mesosphere
   - Brings down more NO$_x$
   - Adiabatic compression results in elevated stratopause

[Hauchecorne et al., 2007; Siskind et al., 2007; Sahishkumar & Sridharan, 2009; Winick et al., 2009]
Why did we get such impressive stratospheric warmings and recovery in 2004, 2006, & 2009? We don’t know.

Maybe climate change, but still speculative

- Although 2004, 2006, and 2009 were highly unusual, the frequency of SSW seems to be increasing (~1 per year since 1999, twice as frequent as in previous half-century)
- Models predict more variability with climate change, so extremes might occur more often
- Models inconclusive with regard to frequency & strength of SSWs
The EPP IE Story from Observations

- EPP-NO$_x$ is produced continually and can contribute up to 40% of polar stratospheric NO$_x$ budget even in years with low geomagnetic activity.

- Ozone is depleted by EPP-NO$_x$ by 35% or more.

- Contribution of EPP-NO$_x$ to the stratosphere does not correlate well with the solar (F10.7) cycle.

- Understanding wave mean flow interactions is required to elucidate mechanisms controlling interannual variability.

- Improved picture of EPP effects requires continuous nighttime observations of NO$_x$ throughout the MLT.
Aside #1

Does EPP affect surface air temperature?

CCM MODEL

EEP minus NoEEP

Rozanov et al., 2005. Model results for DJF surface air temperature differences (NH).

From Annika Seppälä, FMI
Is there empirical evidence that EPP-NO\textsubscript{x} affects climate?

Seppälä et al., JGR 2009:
- Analysis of ERA-40 temperatures yields statistically significant surface air temperature differences between years with high and low EPP.
- Can rule out correlation with solar flux, QBO, ENSO, SAM
- Possible correlation with NAM or random variations in SST
Aside #2

What about EPP effects on clouds/aerosols?

POAM III aerosol surface area increased significantly (>2σ) after January 2005 SEPs.

- Dynamical cause ruled out.
- No other such increase in 8-year record.
- No information from POAM at lower altitudes

Mirinova et al., in preparation
Whole Atmosphere Community Climate Model
A 3D coupled chemistry climate model

- 0 to ~145 km
- Comprehensive chemistry incl. heterogeneous rx
- Interactive Chemistry or Specified Meteorology
- 1-1.5 km vertical resolution in stratosphere
- 1.9° x 2.5° or 4 x 5° horizontal resolution
- Ref: Garcia et al., 2007

(Adapted from Rolando Garcia)
WACCM Parameterization of Precipitation Effects

**Aurora**
- Input = Kp
- Distribution = Auroral Oval
- Roble and Ridley, 1987

**Medium Energy Electrons**
(30 keV – 2.5 MeV)
- Input = MEPED activity level (or hemispheric power)
- Distribution = Statistical patterns [Codrescu et al., JGR, 1997]
- Fang et al., 2008

(Adapted from Rolando Garcia)
WACCM Runs (free-running coupled climate-chemistry model):

- Seasonally varying (but annually invariant) SSTs
- Constant F10.7 = 210
- 1995 greenhouse gas and halogen concentrations

Daily (repetitive) forcing with 3 cases of EPP:

**Case 1:** ~Zero particle precipitation, Kp=2/3 (Ap=3)
80 years (after spin-up) = 80-member ensemble

**Case 2:** Moderate auroral electrons, Kp=4 (Ap=27)
50 years (after spin-up) = 50-member ensemble

**Case 3:** Moderate auroral electrons plus >30 keV electrons (level 1; occurs 40% of the time)
50 years (after spin-up) = 50-member ensemble
WACCM simulation similar to MIPAS

- 70-90° S Latitude
- Case 3 (realistic simulation of 2003 geomagnetic activity)

But WACCM underestimates EPP-NO\(_x\) by about a factor of 2.
Change in NO$_x$ due to EPP: Annual Averages

Aurora Effect
Case 2 minus Case 1

MEE Effect
Case 3 minus Case 2

Regions without cross-hatching significant at 95% level

Cora Randall, Aspen Global Change Institute, 14 June 2010
Change in NO$_x$ and O$_3$ due to EPP
Annual Averages: Aurora + MEE (Case 3 minus Case 1)

Regions without cross-hatching significant at 95% level
Auroral Effect Time Series (Case 2 minus Case 1)
Monthly average ozone depletion of up to 15% at high southern latitudes, 30-40 km

\[ \Delta O_3 \ (\%) \]

Corresponds to catalytic NO\(_x\) destruction
Randall et al., 1998

POAM Data 1994 1996

Cora Randall, Aspen Global Change Institute, 14 June 2010
Up to 2 K monthly average temperature changes due to Aurora + MEE.

Are these changes consistent with ozone?

Is heating due to less radiative cooling by O3 in polar night upper stratosphere?
Are temperature effects valid?

Still trying to understand statistical significance:

Statistically significant differences found between two sets of 80-member ensembles, both with same forcing.
Summary of WACCM Model Results

- Free-running WACCM-EEP compares well qualitatively to observations for typical (i.e., low) EEP conditions
  - Clear descent of EPP-NO$_x$
  - Corresponding ozone depletion

- Descending NO$_x$ underestimated by factor of ~2 even for standard meteorological conditions

- Concerns about T statistics in polar stratosphere

- Specified SSTs, so cannot probe tropospheric effects

- Never see elevated stratopause as in 2004, 2006, 2009
SD-WACCM vs. MLS Temperatures, 2006

If WACCM is nudged to Met assimilation (e.g., GEOS-5) temperature & winds in stratosphere, elevated stratopause is captured.

Still must modify SD-WACCM for MEE.

Figures courtesy of Dan Marsh, NCAR
Conclusions & Outstanding Questions

EPP DE (Jackman talk) and IE significantly affect polar stratospheric NO$_y$ and Ozone.

Temperature effects not yet quantified.

WACCM underestimates EEP effects for baseline conditions.

Some Questions

What is NO$_x$ really doing in the polar night?

What are the detailed dynamical mechanisms that link EPP to atmospheric change?

Does EPP affect surface level temperatures?

Are coupling mechanisms from the surface to the MLT changing (more favorable for enhanced EPP-NO$_x$ descent)?

Is there feedback between EPP and the coupling?
Thanks very much!