Energetic Particle Precipitation Effects on the Energy Balance of the Thermosphere and Ionosphere

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Outline

• Introduction
  – TIMED Mission, SABER Experiment
  – Energy Balance and Radiative Cooling concepts
  – Derivation of radiative cooling from SABER data *in thermosphere*

• Effects of Particle Precipitation: Short-Term
  – Short-term periodicities from a long-term record
  – 9-day, other periods in NO, CO$_2$ cooling
  – Evaluation of a high-speed solar wind event

• Effects of Particle Precipitation: Long-Term
  – NO cooling and large-scale dynamics of thermosphere

• Summary, Future Work
  – Generation of climate data records for GCMs
Thermospheric Energy Balance

Solar EUV, UV
Solar Particles e.g., CMEs

Thermosphere
$T, \rho, q$
100 – 200 km

Infrared Cooling
NO, CO$_2$, O
Airglow
O$^{(1)D}$, O$_2^{(1)\Delta}$, etc.

Tides, Waves
Conduction, Transport
TIMED

Thermosphere • Ionosphere • Mesosphere • Energetics • Dynamics

Launched December 2001
74.1 Degree Inclination
625 km Circular Orbit
Routine Operations ~ 8 Years
Ongoing to 2013!
SABER Experiment Limb Viewing Geometry

\[ N(H_o) \approx \int \int J_v(x) \frac{d\tau(v,q,T,P)}{dx} \, dx \, dv \]

TANGENT POINT \( H_o \)

RAY PATH TO SATELLITE

\( N(H_o) \)
## SABER Channels and Data Products

*Almost Eight Years and Counting!!*

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength</th>
<th>Data Products</th>
<th>Altitude Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>15.2 μm</td>
<td>Temperature, pressure, cooling rates</td>
<td>15-100 km</td>
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<tr>
<td>CO₂</td>
<td>14.8 μm</td>
<td>Temperature, pressure, cooling rates</td>
<td>15-100 km</td>
</tr>
<tr>
<td>O₃</td>
<td>9.6 μm</td>
<td>Day and Night Ozone, cooling rates</td>
<td>15 - 95 km</td>
</tr>
<tr>
<td>H₂O</td>
<td>6.3 μm</td>
<td>Water vapor, cooling rates</td>
<td>15-80 km</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.3 μm</td>
<td>Carbon dioxide, dynamical tracer</td>
<td>90-160 km</td>
</tr>
<tr>
<td>NO</td>
<td>5.3 μm</td>
<td>Thermospheric cooling</td>
<td>100 - 300 km</td>
</tr>
<tr>
<td>O₂(¹Δ)</td>
<td>1.27 μm</td>
<td>Day O₃, solar heating; Night O</td>
<td>50-100 km</td>
</tr>
<tr>
<td>OH(υ)</td>
<td>2.0 μm</td>
<td>Chemical Heating, photochemistry</td>
<td>80-100 km</td>
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</tbody>
</table>

Over 30 data products including T, CO₂, O₃, VER, O, H, ∂T/∂t
Thermospheric Radiative Cooling Mechanisms

- figure is to scale in energy -

Energy ↑

ν = 1

NO

ν = 0

5.3 μm

1876 cm⁻¹

CO₂(ν₂)

ν = 1

ν = 0

15 μm

667 cm⁻¹

ν = 0

O

3p₁

3p₂

63 μm, 158 cm⁻¹

Energy →

ν = 0

15 μm

667 cm⁻¹

ν = 1

CO₂(ν₂)

ν = 0

5.3 μm

1876 cm⁻¹

ν = 1

O

3p₁

3p₂

63 μm, 158 cm⁻¹

4
Radiative Cooling Derivation from SABER Radiances

• **NO cooling: Three parameters**

  – Cooling Rates \((W m^{-3})\)
    • Abel inversion of limb radiance: \(W m^{-2} sr^{-1} \rightarrow W m^{-3}\)

  – Radiant Fluxes \((W m^{-2})\)
    • Vertically integrated cooling rates: \(W m^{-3} \rightarrow W m^{-2}\)

  – Radiant Power \((W)\)
    • Zonally integrate fluxes w/r/t Area: \(W m^{-2} \rightarrow W\)

  – Meridional Integration to obtain Daily Global Power
Radiative Cooling Derivation from SABER Radiances

• **CO₂ cooling: Three Parameters**

  - Cooling rates $Q \ (W \ m^{-3})$
    - Invert radiances to $T_K$ and “regular” cooling rates (K/day)
    - $W \ m^{-2} \ sr^{-1} \rightarrow T_K$ and $\partial T_K/\partial t$

$$Q = \frac{p}{RT_K} C_p \left( \frac{\partial T_K}{\partial t} \right)$$

  - Radiant Fluxes ($W \ m^{-2}$)
    - Vertically integrated cooling rates: $W \ m^{-3} \rightarrow W \ m^{-2}$

  - Radiant Power ($W$)
    - Zonally integrate fluxes w/r/t Area: $W \ m^{-2} \rightarrow W$

  - Meridional Integration to obtain Daily Global Power
Example: NO Radiance → Cooling Rate → Flux → Power

SABER NO(5.3 μm) Limb Radiance

Cooling Rate W m⁻³

Radiated Flux W m⁻²

Daily Radiated Power (W)
Effects of Particles: Short-Term

- Examine Time Series of Global Radiated Power for NO and Geomagnetic Indices

- Annual Basis: 2002 to 2009 (7.5 years)

- Look for occurrence of short-term periodicities in the long-term record

- Lomb Normalized Periodograms are tool of choice
Solar, Geomagnetic & Thermospheric Data

7.5 Years

Short-Term Variability In Solar Wind, $K_p$

Long-Term Variability In F10.7

Short, Long Term Variability in Radiative Cooling
Global Radiated Power (W)
NO and CO$_2$: 2002 through 2008

GLOBAL NO and CO2 POWER, 100–200 km, from SABER V1.07

Power ($10^4$ W)

Time

2003 2004 2005 2006 2007 2008 2009
Global NO Power (W): 2002 to 2009

GLOBAL NO POWER, 100–250 km, from SABER V1.07
Lomb Normalized Periodograms

$K_p$ and NO - 2002

60-day period corresponds to the TIMED satellite yaw period
Lomb Normalized Periodigrams
$K_p$ and NO - 2003
Lomb Normalized Periodograms
$K_p$ and NO - 2004

Kp Index 2004

Global NO Power 100-200 km 2004
Lomb Normalized Periodograms

$K_p$ and NO - 2005
Lomb Normalized Periodigrams
$K_p$ and NO - 2006

Kp Index 2006

Global NO Power 100-200 km 2006
Lomb Normalized Periodograms

$K_p$ and NO - 2007

![Graphs showing periodicity in Kp Index and Global NO Power in 2007.](image-url)
Lomb Normalized Periodograms
$K_p$ and NO - 2008
Short-Term Effects: Summary

- Time series of global cooling in radiated infrared power reveals many short-term periodicities 27 days and shorter
- Most common are 27-day, 13.5-day, and 9-day
- The periodicities in all cases occur in the $K_p$ index as well
- In 2006 a 6.75-day period ($27/4$) occurred in NO and Kp
- Higher order harmonics ($27/5$, $27/6$, $27/7$) in NO are often seen but are not statistically significant
- Results imply continuous geomagnetic coupling but with variable temporal effects
- Short-term effects are then tied to particle deposition – solar UV output is not variable on these shorter timescales
Case Study: Response to High Speed Solar Wind Stream Event

- October 10 to 22, 2003

- **Approach**
  - Plot global NO, CO\textsubscript{2} power vs. solar wind speed and particle density

- **General Results**
  - NO, CO\textsubscript{2} power (hence thermospheric cooling) track the solar wind variations almost directly

  - Even on these short timescales (few days) the infrared cooling responds (thermostat effect)
Infrared Cooling, Solar Wind Parameters, October HSS Event
October 05 – 27 2003

“Movie” of Radiative cooling

Zonal averages in 11 deg latitude bins

Evolution of radiative cooling by NO

100 to 200 km

5 October to 27 October 2003

High Speed Event 10 to 22 October

Substantial increase in cooling observed during high speed event, especially October 14-22

Event influences entire thermosphere
Study Period
October 10 – 22 2003
October 05 2003
October 06 2003
October 07 2003
October 08 2003
October 10 2003
October 11 2003
October 12 2003
October 13 2003
October 14 2003

![Chart showing NO cooling rate with altitude and latitude ranges.]
October 16 2003
October 18 2003
October 19 2003
October 20 2003
October 21 2003
October 22 2003
October 23 2003
October 24 2003
October 25 2003
October 26 2003
October 27 2003

End of study period
High Speed Event Summary

- Both NO and CO$_2$ cooling increase with onset of HSS event
- Both emissions track changes in solar wind speed during the events
- NO cooling response greatest at high latitudes
- Effects present throughout entire thermosphere below 200 km altitude
Effects of Particles: Long-Term

- Cooling data offer unique look at effects of solar cycle on radiative cooling of the atmosphere

- Examine Cooling Rates (W m⁻³) and over the 7 complete years to date

- Results show NO cooling dominates the changes over this time

- Largest changes in cooling are in polar regions where particle precipitation dominates

- Suggests strong link between solar wind, chemistry of NO, and large-scale dynamics of thermosphere
Nitric Oxide Radiative Cooling 2002 – 2008

Annual Averages
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
Zonally Averaged Annual NO Cooling Rate W m$^{-3}$
Summary

- Infrared cooling measurements from SABER offer unique insight into solar-terrestrial coupling on time scales from a few days to 11-year solar cycle

- The “natural thermostat” effect of NO is highly efficient in removing energy deposited from solar wind particle events

- Short-term periodic features in radiative cooling are observed and shown to have geomagnetic origins

- Long-term changes in radiative cooling have both geomagnetic and solar – ultraviolet causes

- Results imply a strong coupling between both particles and photons from the Sun and long-term changes in thermospheric neutral dynamics
Future Work

• The SABER NO and CO$_2$ data constitute the first long-term climate data record of cooling rates, fluxes, and power in the thermosphere

• These data are the fundamental for validating the basic energetics in all upper atmosphere general circulation models

• These data are available – just ask!

Reference:
Observations of infrared radiative cooling in the thermosphere on daily to multiyear timescales from the TIMED/SABER instrument, M. Mlynczak et al., *JGR-Space*, almost accepted, 2009.
Thank You from 500 hPa!
Marty Mlynczak

Cerro Toco, Chile, @ 17,500 Feet
Site of the RHUBC-II/FORGE Campaign