"Sun-to-Atmosphere…Sure, Yet Still One Link Short: Results from the NSF Frontiers of Earth System Dynamics 'Sun-to-Ice' Project"

- or -

Start

How I Learned to ~~Stop~~ Worrying and ~~Love~~ Ionizing Radiation

Hate

2014 CEDAR Workshop, Seattle, WA

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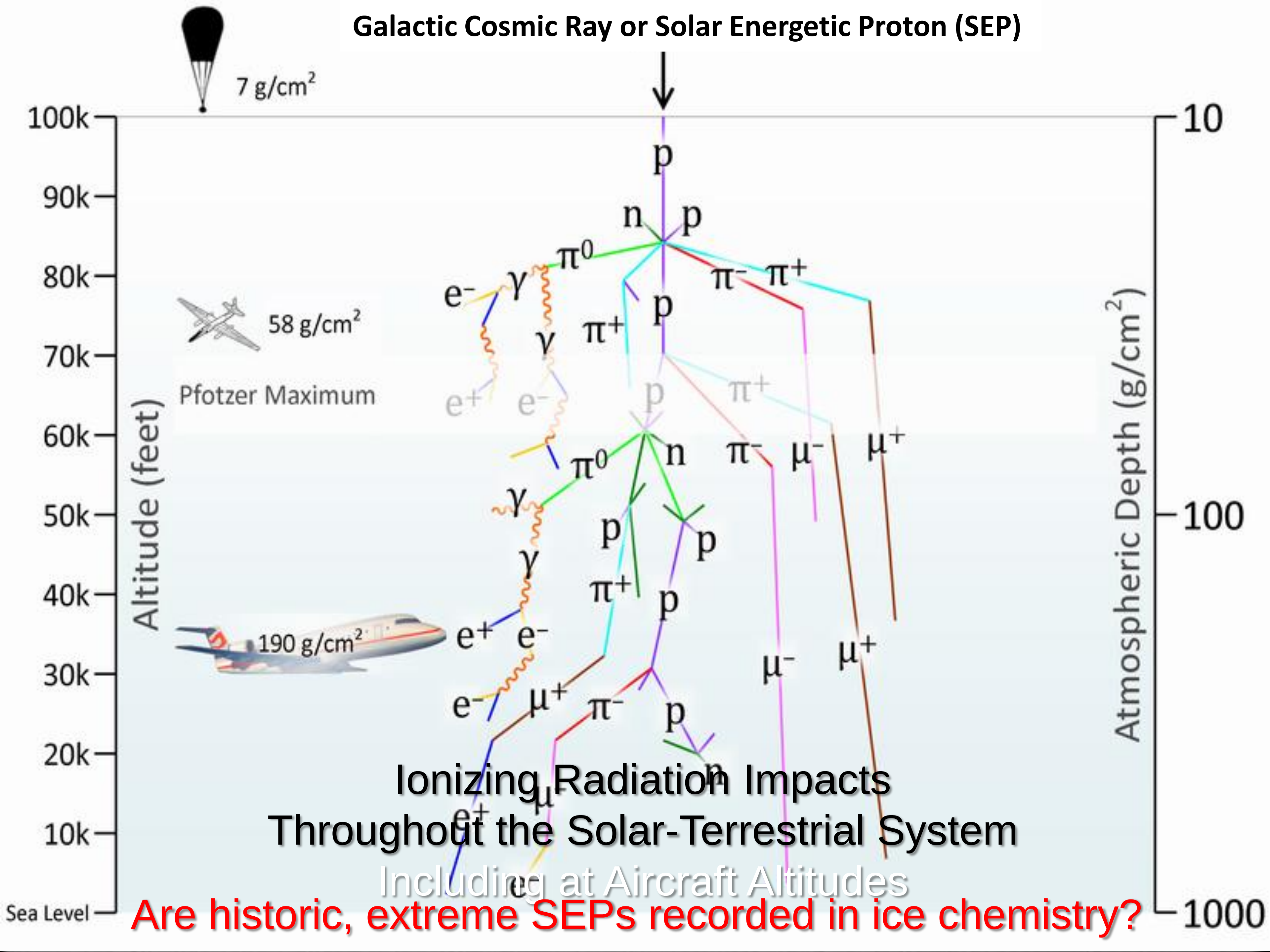
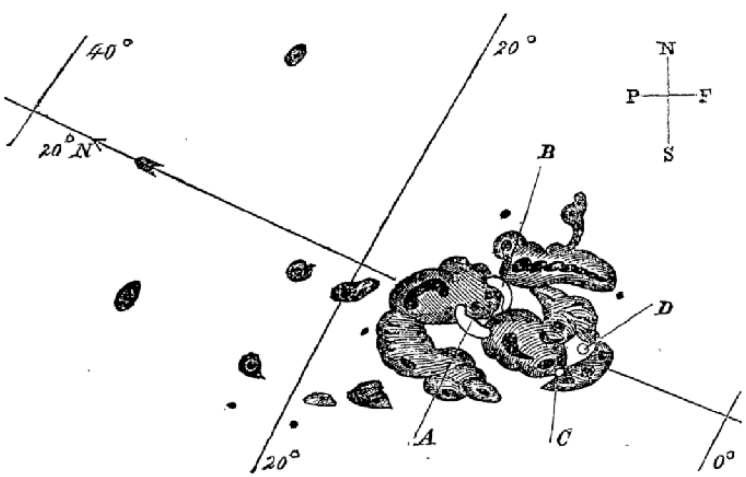
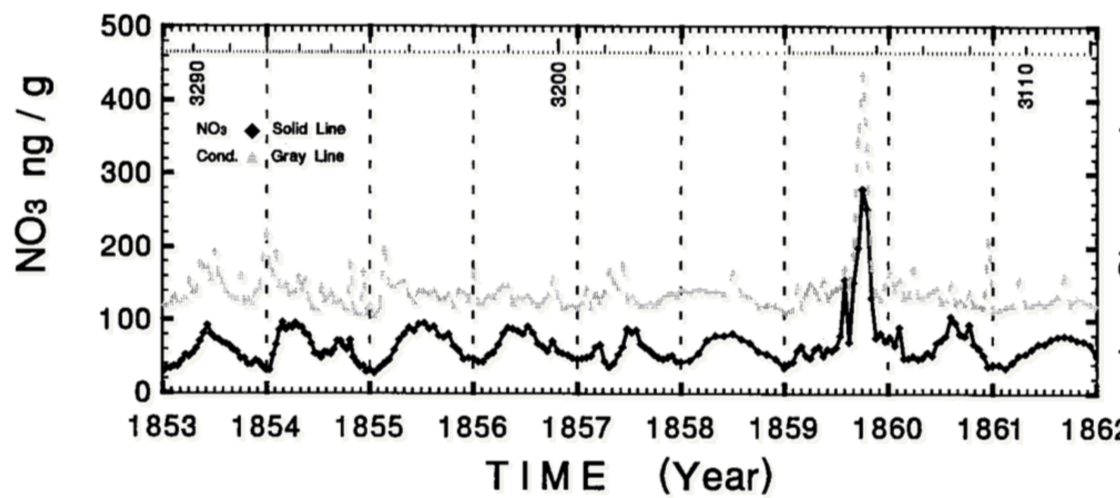

Galactic Cosmic Ray or Solar Energetic Proton (SEP)
7 g/cm²
58 g/cm²
Pfotzer Maximum
190 g/cm²
100k
90k
80k
70k
60k
50k
40k
30k
20k
10k
Sea Level
Altitude (feet)
10
100
1000
Atmospheric Depth (g/cm²)
p
n
π0
π−
π+
γ
e−
e+
μ−
μ+
Ionizing Radiation Impacts
Throughout the Solar-Terrestrial System
Including at Aircraft Altitudes
Are historic, extreme SEPs recorded in ice chemistry?

Initial Background and Motivation

- Initial work associated solar energetic proton (SEP) events with impulsive nitrate spikes in polar ice (Dreschhoff and Zeller, *Solar Phys., 127*, 333, 1990)
- Largest nitrate spikes aligned with known solar flares and with various historic large solar particle events
- **Others (e.g., McCracken et al., 2001) propose SEPs penetrate to low atmospheric altitudes, converting O_3 into NO(y), subsequent downward transport, NO(y) snows out, and is entrained in polar ice**

Is Carrington flare of 1859 observed in Greenland Summit ice core nitrate record?





The Association Accelerates

- Palmer et al. (GRL, 28, 1953, 2001), performed a statistical analysis of the frequency of NO(y) increases found in ice cores from Law Dome (66° S, 112° E; at an altitude of about 1300 meters but in a high precipitation area near the ocean)

- They compared average annual nitrate cycle as with annual nitrate cycles containing documented significant solar particles events

- They found that there may be a statistical significant association suggesting that there may be a solar contribution to the nitrate in polar ice → **additional evidence for a causal relationship between SEPs and nitrate spikes in arctic ice**

The Debate Develops

- Wolff et al.'s (Atmos. Chem. Phys., 8, 5627, 2008) systematic analysis of daily nitrate deposition in precipitation during 2004 and 2005 at a coastal site (Halley Bay, 75° S, 333° E)

- They found no association of nitrate deposition with solar events
    - One solar proton event noted by Wolff et al. occurred in July and August 2004; it had a total integrated omni- directional >30 MeV proton fluence of 6.5×10^6 cm^{-2} - far below the notional established NO(y) detection threshold of 1.0×10^9 cm^{-2} (McCracken et al., 2001)
    - A GLE on 20 January 2005 had a >30 MeV omni-directional fluence of 1.0×10^9 cm^{-2}, but Wolff et al. did not observe a time-associated NO(y) increase.

- **Evidence against a causal relationship between SEPs and nitrate spikes in arctic ice → theoretical arguments about why not, as well**

The Controversy Continues

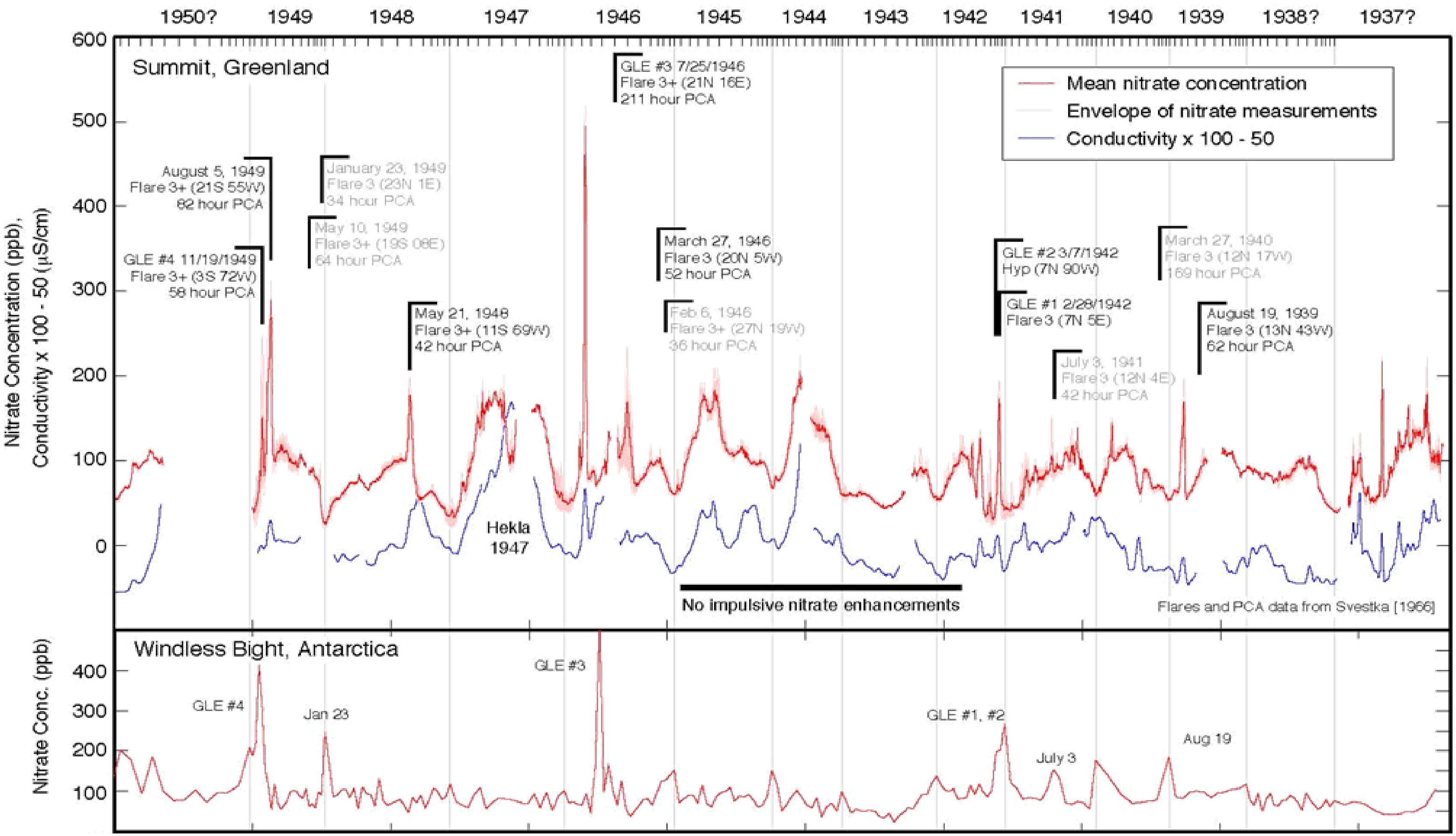
- Kepko et al. (JASTP, 71, 1840, 2009) analyzed an independent "shallow core" from Summit, Greenland, expressly trying to assess initial association of nitrate spikes with SEPs

- They used continuous flow technique resulting in ~400 samples per year, as opposed to the ~10 samples per year in many earlier studies

- **Well-resolved impulsive NO(y) increases for each of the large solar cosmic ray ground- level events in the 1940-1950 decade**

- Spikes robust (seen in multiple core samples at same depth) and well resolved in time/depth; evidence for concurrent nitrate spikes in Antarctic ice cores (Windless Bight)

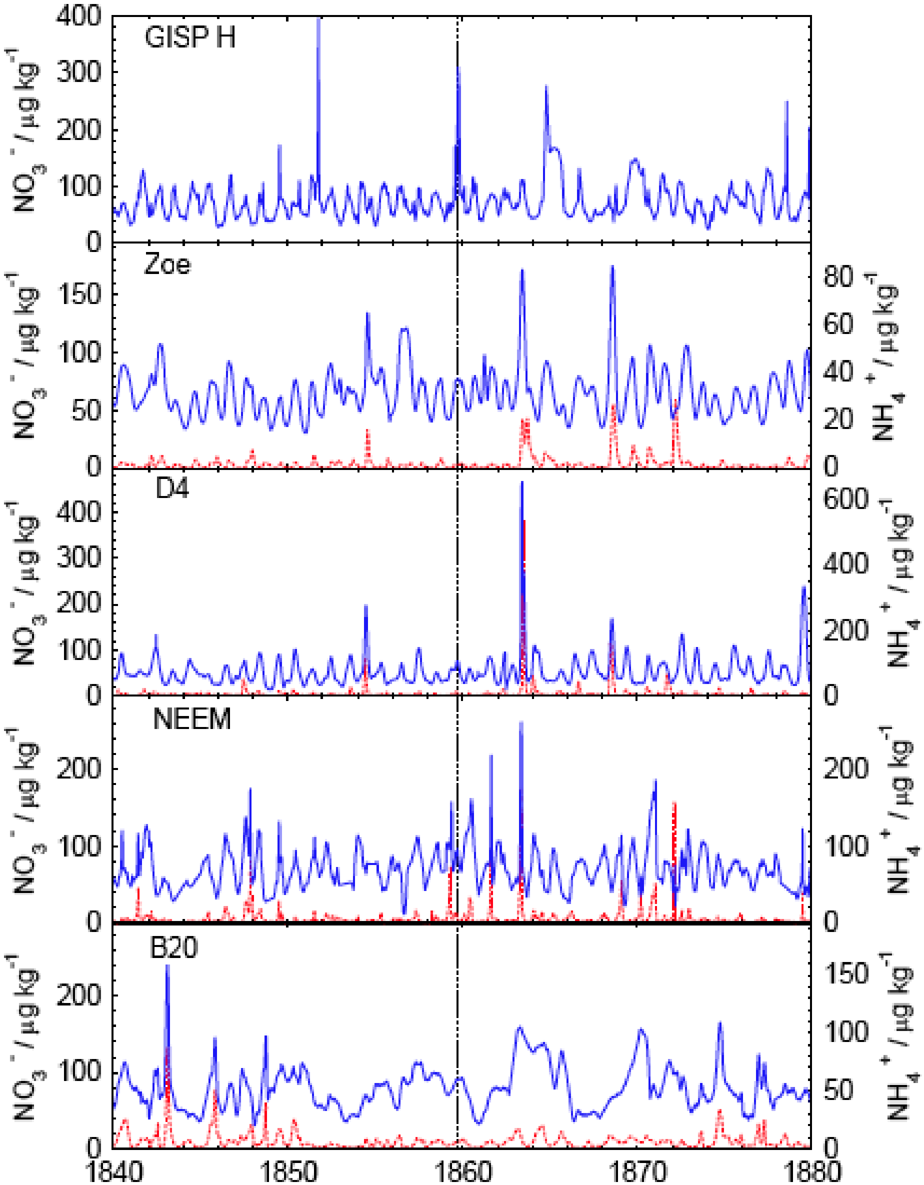
Arctic/Antarctic cores seem to see same large events (from Kepko et al., 2009)



Top: Nitrate data from the 2004 Greenland core with annotated solar events. (~400 samples/year)
Bottom: Nitrate deposition from 1988-1989 Antarctic ice cores. (1.5 cm resolution = ~20 samples/year)

The Controversy Crescendos

- Wolff et al. (GRL, 2012): "The Carrington event not observed in most ice core nitrate records"
    - Analysis of multiple cores show no nitrate spike at "right time"
    - Only (Zeller, McCracken) GISP H core has event in 1859 (and 2nd in 1865), while 2010 Zoe core from Summit and D4 core near Summit have spikes dated 1863 (and 2nd in 1869)
    - Zoe and D cores had full chemistry, allowing for multi-parameter dating and ammonium detection (biomass burning tracer)

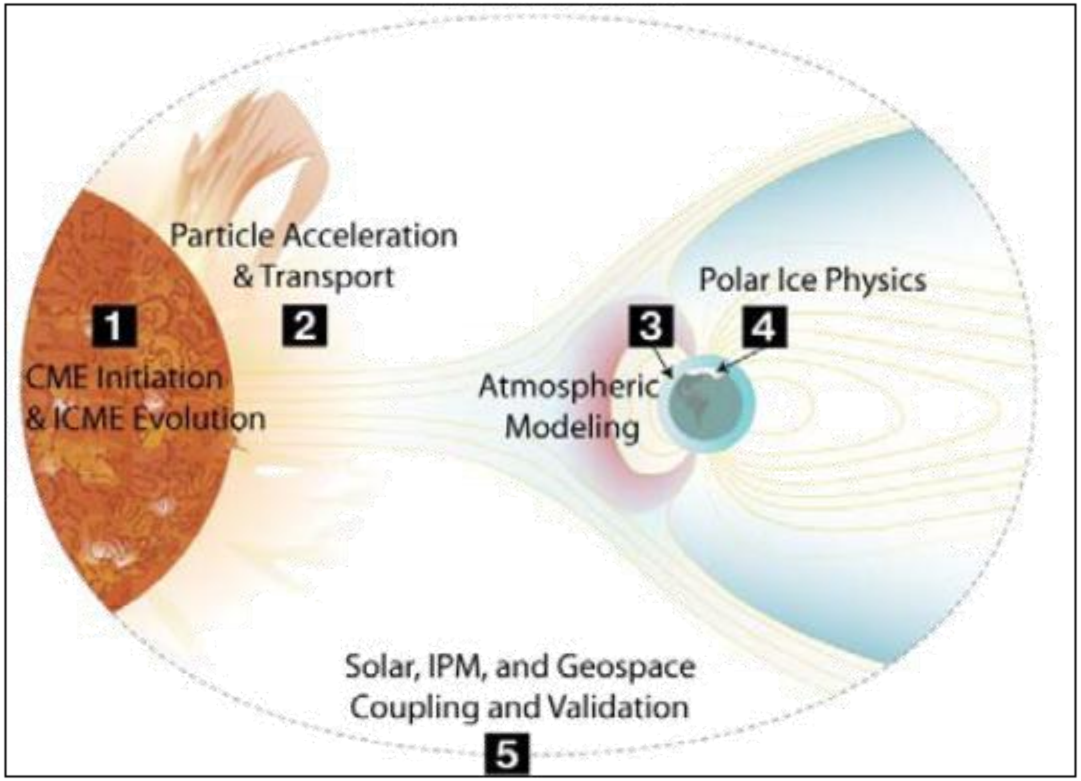


From Controversy toward Resolution

- Speculation that the 1859 event in H core is same as 1863 event seen in cores dated with more constraints
- Likely that H core had similar ammonium enhancement (but only conductivity and nitrate were measured, so don't know)?
- From Wolff Abstract: "**We conclude that an event as large as the Carrington Event did not leave an observable, widespread imprint in polar ice. Nitrate spikes cannot be used to derive the statistics of SEPs.**"
- **Dating issues contested by Smart and Shea at 2012 Extreme Space Weather Event Workshop**
- **Sun-to-Ice project has been catalyst for communities to talk and work together toward resolution of controversy**

“Sun-to-Ice” Project Aims for Closure

- The UNH-led “Sun-to-Ice” (S2I) project funded in late 2011 as part of the US/NSF Frontiers in Earth Systems Dynamic program
- S2I confronts the chain of controversial processes that couple the Sun-Earth system during extreme space weather events, from:
  - solar eruptive phenomena; to
  - CME evolution; to
  - shock formation; to
  - solar particle acceleration; to
  - SEP transport and access to upper atmosphere; to
  - SEP chemistry in middle atmosphere, and finally to
  - the controversial link between atmospheric NO(y) and nitrates in arctic ice



A Highly Interdisciplinary "Sun-to-Ice" Team

- S2I includes solar, heliospheric, magnetospheric, upper atmospheric, and ice core scientists tackling various aspects of the coupled system using a combination of theory, modeling, and experimental work

Key Investigators, Institutions, and Titles	"Sun-to-Ice" Role(s) and Expertise
Harlan Spence, UNH, EOS Director & Prof.	Project Director (PD); project science lead; ice analysis
Nathan Schwadron, UNH, Assoc. Prof.	Deputy PD: coupling coordinator; SEP modeling
Pete Riley, PredSci CFO, Senior Scientist	CME initiation and evolution co-lead
Jon Linker, Predsci, Pres, Senior Scientist	CME initiation and evolution co-lead
Spiro Antiochos, NASA/GSFC	CME initiation theory
Terry Forbes, UNH, Res. Professor	CME initiation theory
Joe Giacalone, UAz, Assoc. Professor	SEP modeling lead
Mihir Desai, SwRI, Staff Scientist	SEP observations and analysis
Gang Li, UAH, Assist. Professor	SEP Accel. Microphysics, PATH Code
Stan Solomon, NCAR, Senior Scientist	Atmospheric modeling lead
Cora Randall, CU ATOC/ LASP, Professor	Atmospheric observations constraining WACCM
Dan Marsh, NCAR, Scientist III	Atmospheric WACCM modeling development
Charley Jackman, NASA/GSFC	Atmospheric modeling
Michael Wiltberger, NCAR, Scientist III	Atmospheric SEP cutoffs; MHD geospace models
Jack Dibb, UNH Res. Associate Professor	Polar ice analysis lead
Ruth Varner, UNH Res. Associate Professor	Director of CEGE, Geoscience Education lead
Erik Froburg, Outreach and Education Specialist	Outreach and Education Specialist, Graduate Student Mentor

S2I Focus Area #1: Space-Age SEP Events and Ice Core Chemistry

- Identify recent space-age, large SEP events for which we have excellent spacecraft and ground observations of SEP properties
- Compare these periods with daily snow pit data sampled at Summit
- Identify events most probably associated with non-SEP sources (biomass burning, sea salt, dust, pollution) using chemical tracers
- Assess whether any remaining events are SEP-source candidates and if/whether they can be explained with NCAR's WACCM

Nitrate deposition at Summit, Greenland following the November 9, 2000 solar proton event

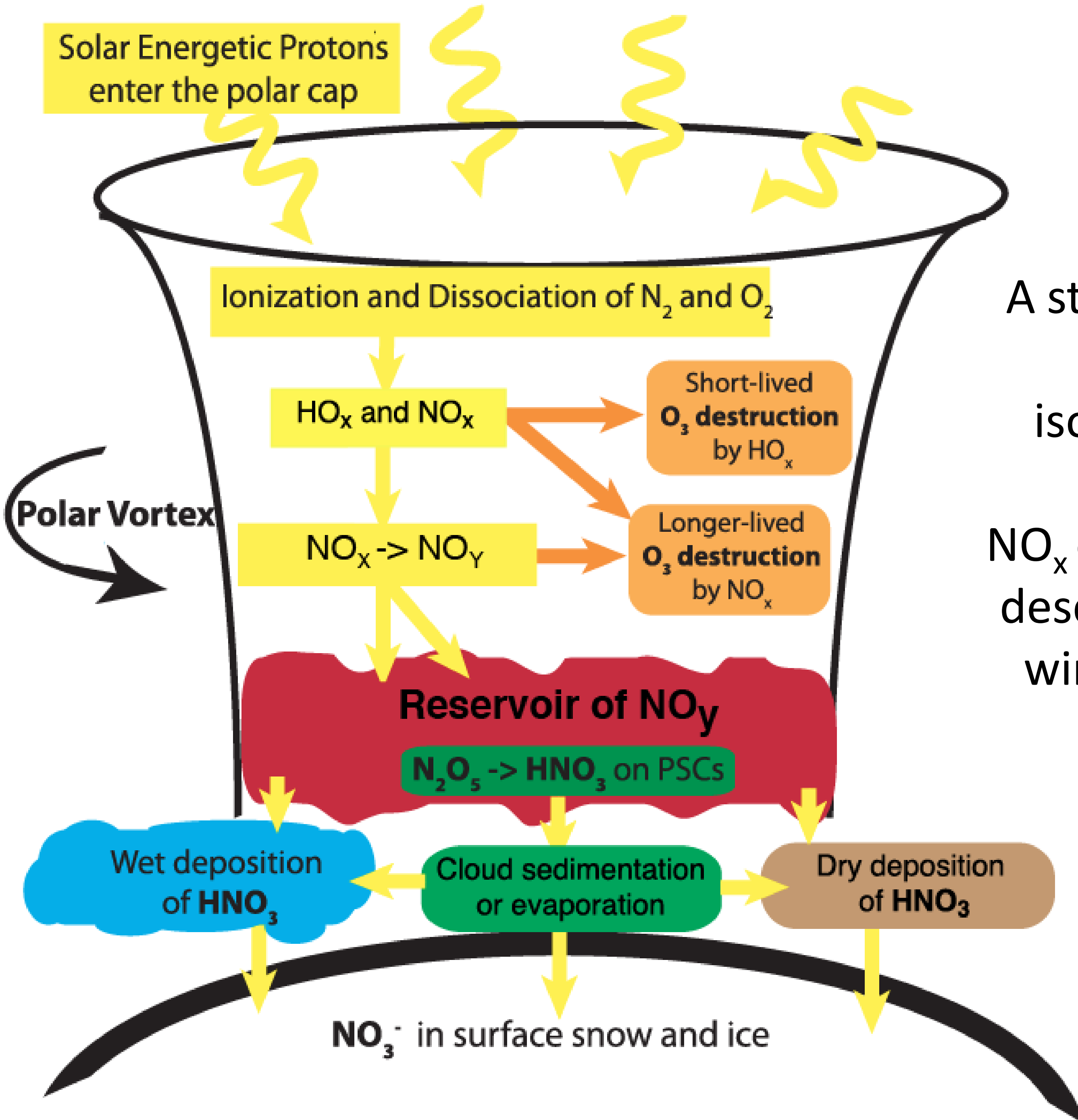
K .A. Duderstadt, J.E. Dibb, C.H. Jackman, C.E. Randall, S.C. Solomon, M.J. Mills, N.A. Schwadron, *H.E. Spence*

JGR-Atmospheres preprint available at:

http://onlinelibrary.wiley.com/doi/10.1002/2013JD021389/abstract

This study screens two years of surface snow measurements at Summit, Greenland for tropospheric sources of nitrate using ion correlations (NH_4^+, SO_4^{2-}, Na^+, Ca^{2+}). Global climate model simulations (WACCM) are used to assess the contribution of solar proton events to nitrate spikes not accounted for by ion correlations.

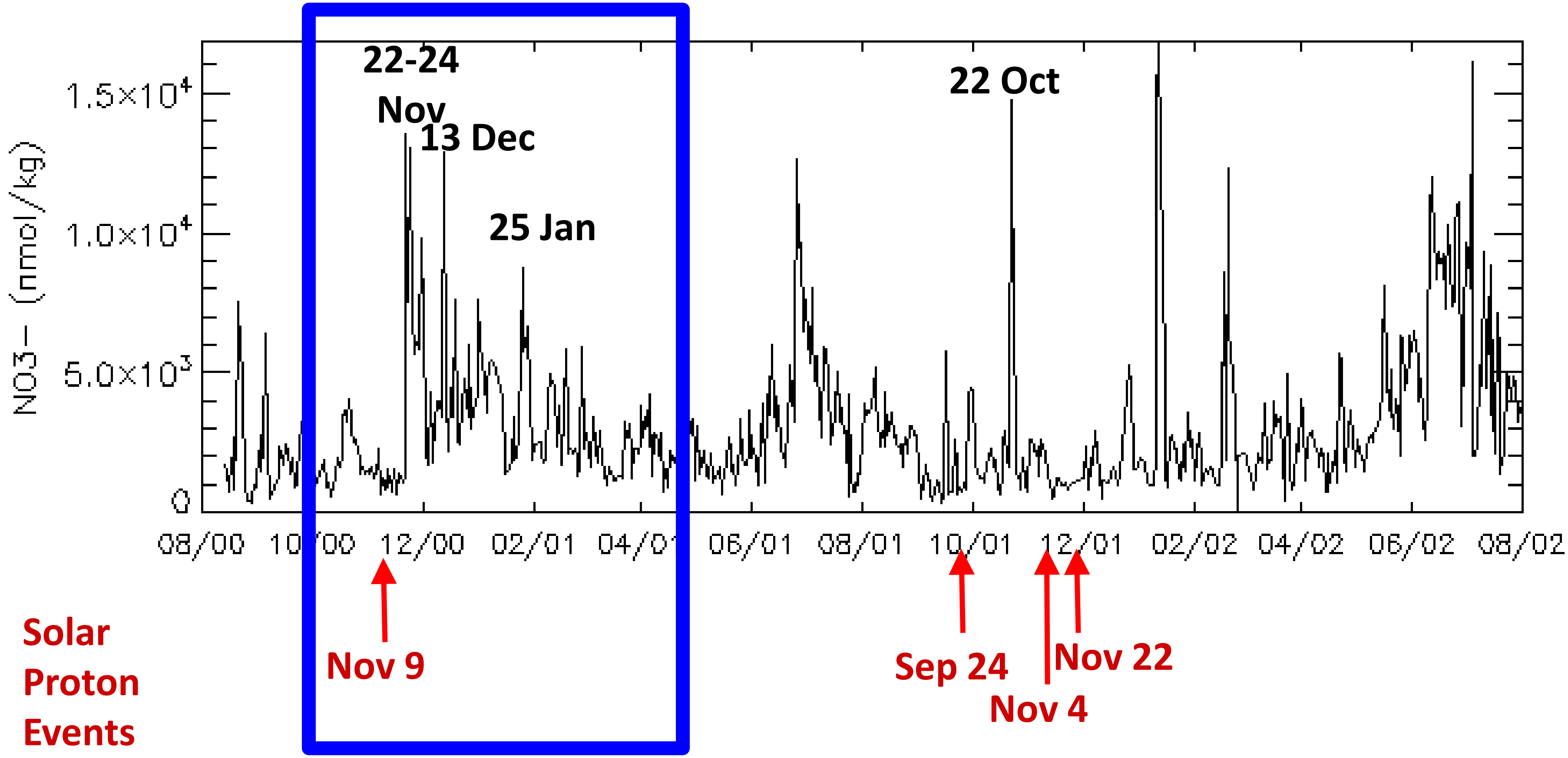
Polar Night



A stable polar vortex isolates air.

NO_x diabatically descends over winter pole.

Nitrate spikes in Summit snow (2000-2002) not accounted for by soluble ion correlations. *(Candidates for SPE events)*

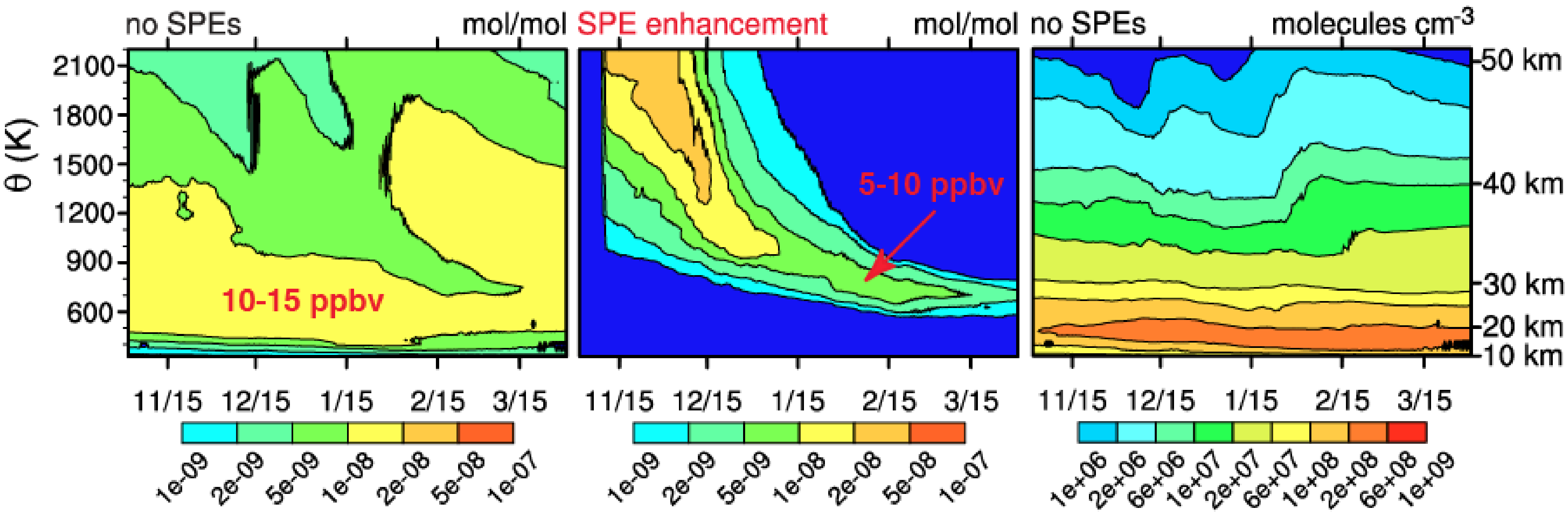


*Focus WACCM simulations on Nov 22-24, Dec 13, and Jan 25, spikes occurring in **polar winter** that are not attributed to tropospheric sources.*

9 November 2000 SPE (WACCM)

Vortex-Averaged Total Odd Nitrogen (NO_y)

$NO_y = NO+NO_2+NO_3+2N_2O_5+HNO_3+HO_2NO_2+ClONO_2+BrONO_2$



Diabatic descent within polar vortex.

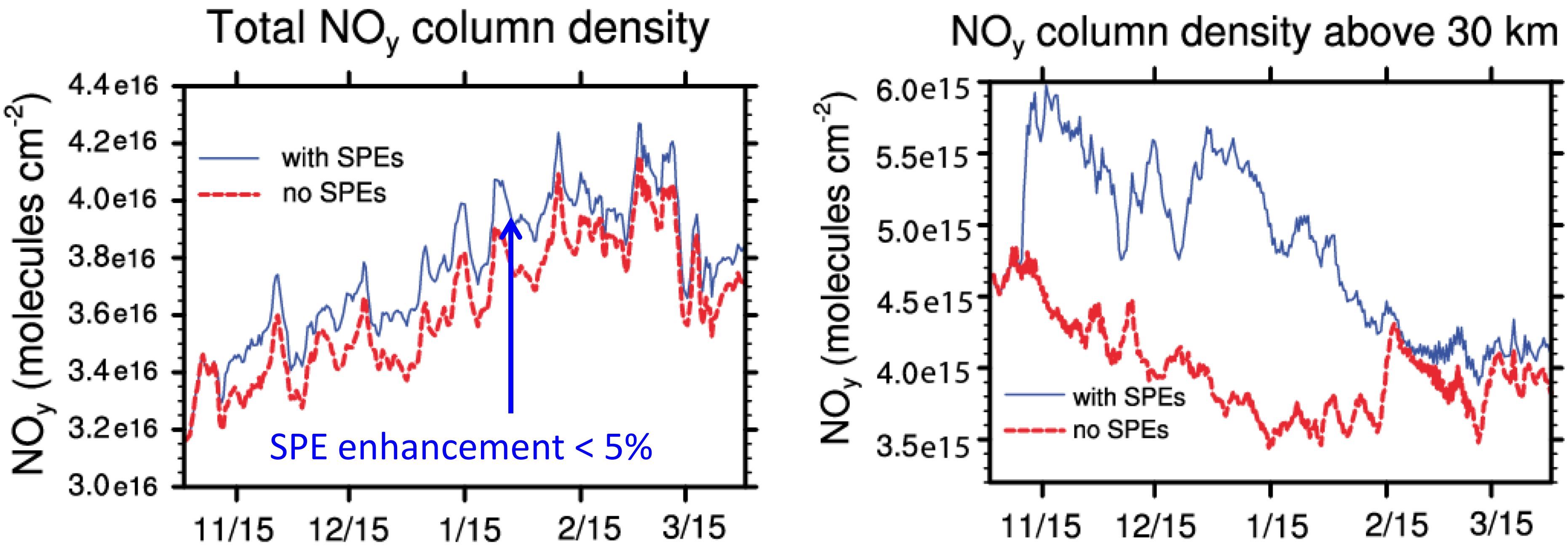
Thick background pool of 10-15 ppbv NO_y in lower stratosphere

Thin layer (~5 km) of 5-10 ppbv SPE-enhanced NO_y at 25-30 km

Slow **downward transport**

Densities of NO_y peak below 20 km

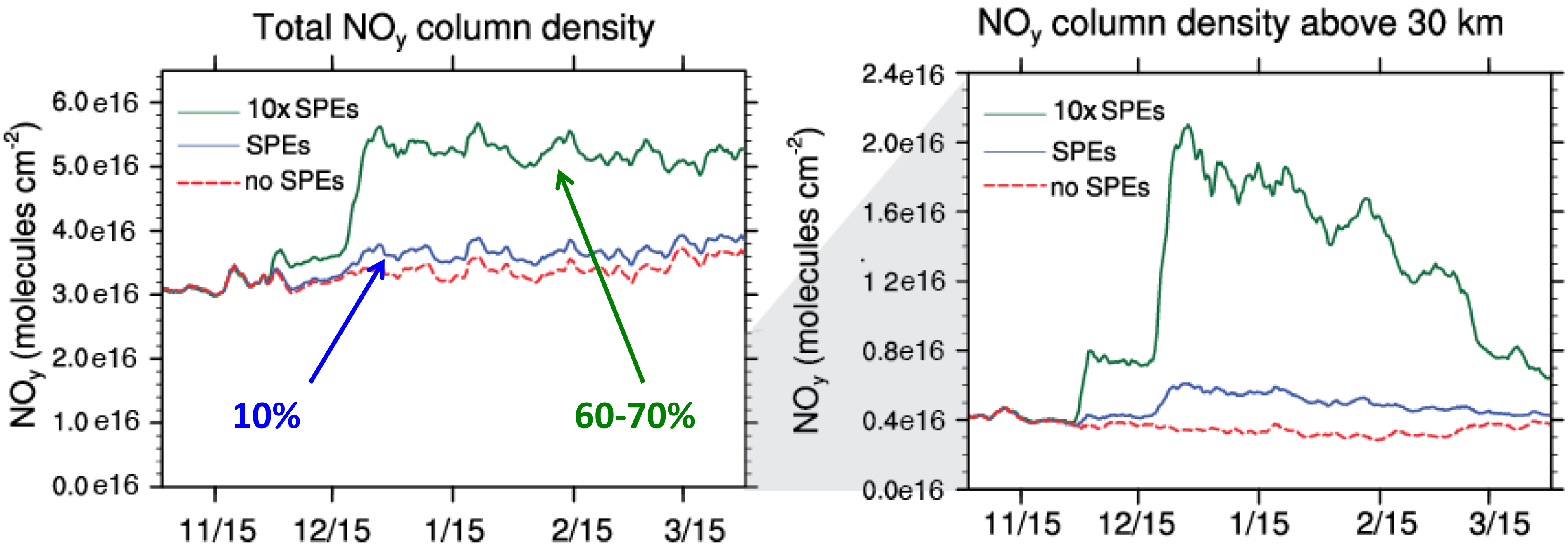
9 November 2000 SPE (WACCM)



SPE enhancement (5% vortex-averaged and 20% local maxima) is ***not large enough*** to explain the 4-5 fold spikes in nitrate ions in snow and ice.

Consider the largest SPE in past 50 years…

- **Sep-Oct 1989 SPEs placed in a stable polar vortex winter (2004-5)**
- **10 times Sep-Oct 1989 SPEs placed in 2004-2005**



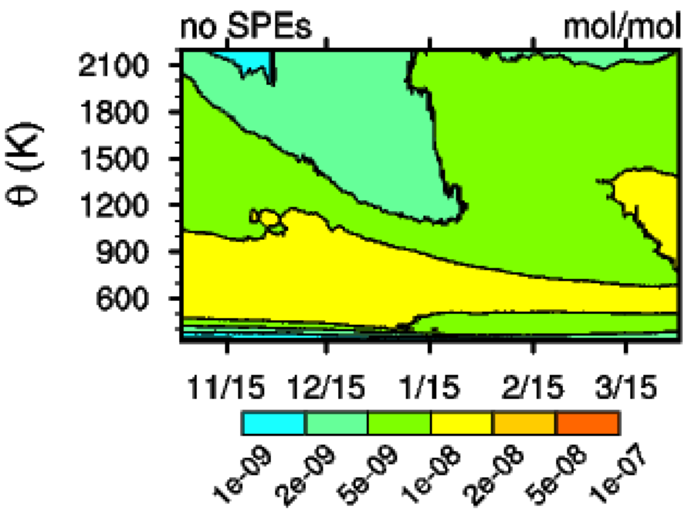
NO_y enhanced by ~10% (maximum local 20%) with Sep-Oct 1989 SPEs.

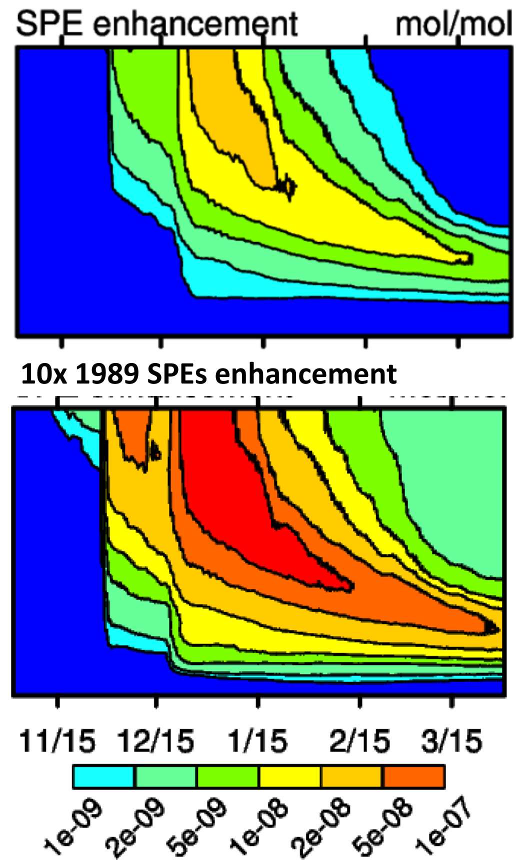
NO_y enhanced by 60-70% (maximum local 100%) with **10x** Sep-Oct 1989 SPEs

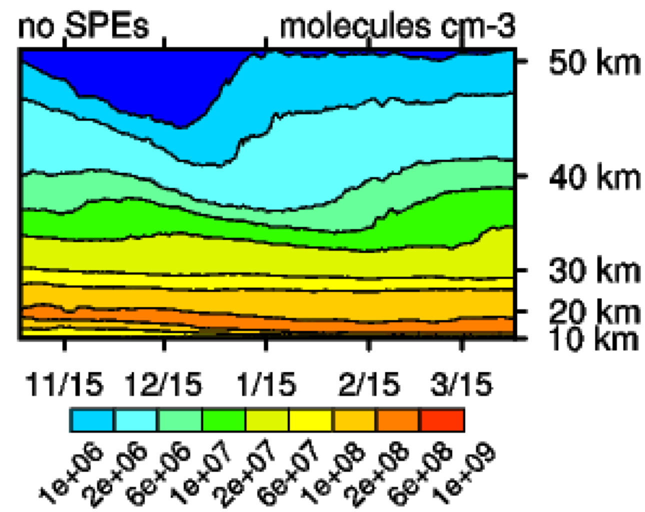
Total column NO_y enhancement not sufficient to explain 4-5 fold nitrate spikes at the surface.

1989 Sep-Oct SPEs in 2004-2005 winter

Vortex-averaged NO_y







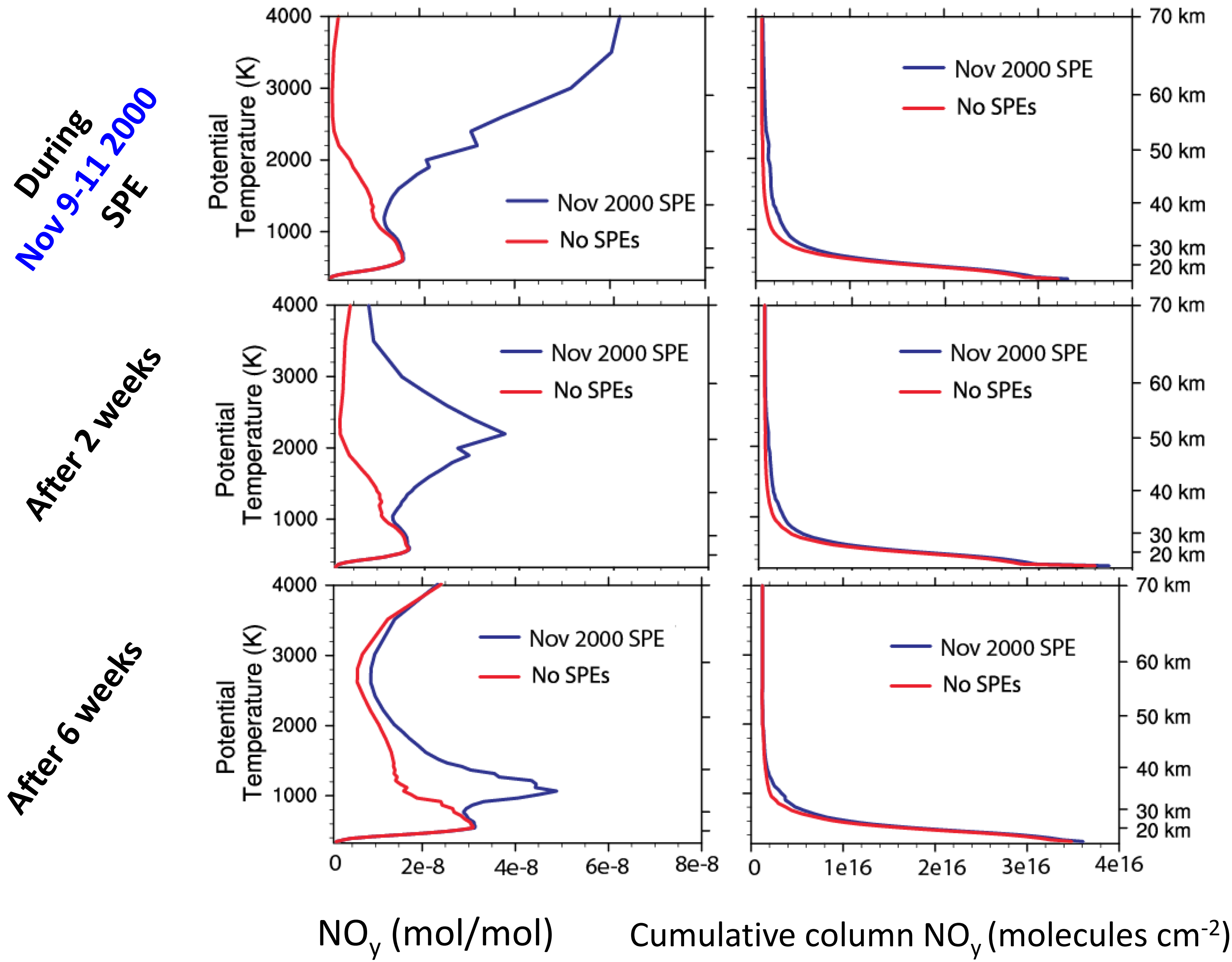
Background **5-15 ppbv** NOy in lower stratosphere.

Peak number density occurs below 20 km

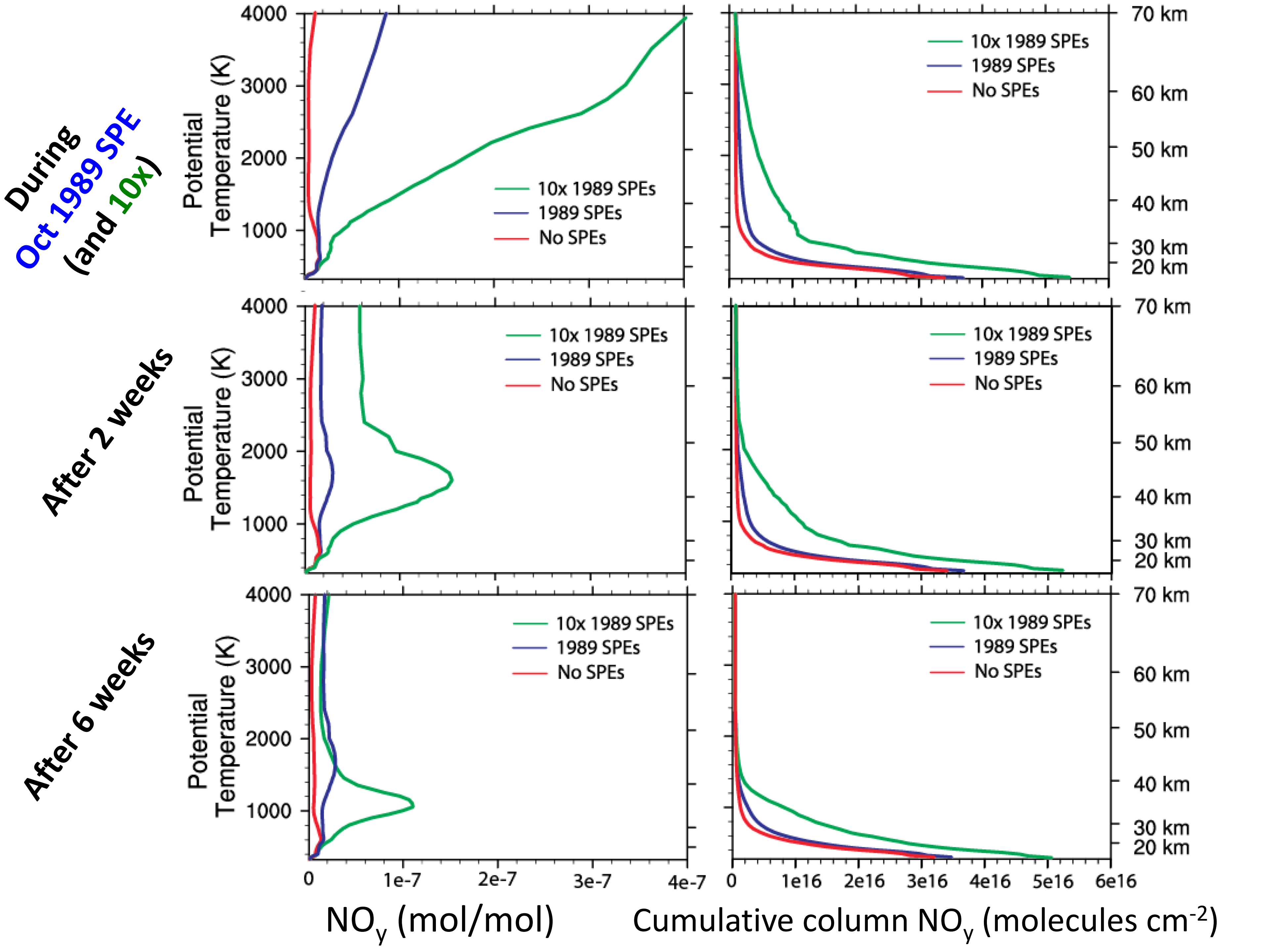
Thin layer of enhanced NOy around 30-35 km.

10-20 ppbv for Sep-Oct 1989 SPEs

> 50 ppbv for 10x Sep-Oct 1989 SPEs



During
Nov 9-11 2000
SPE
After 2 weeks
After 6 weeks
Potential Temperature (K)
4000
3000
2000
1000
Nov 2000 SPE
No SPEs
70 km
60 km
50 km
40 km
30 km
20 km
0
2e-8
4e-8
6e-8
8e-8
1e16
2e16
3e16
4e16
NO$_y$ (mol/mol)
Cumulative column NO$_y$ (molecules cm^{-2})



During
Oct 1989 SPE
(and 10x)
After 2 weeks
After 6 weeks
Potential Temperature (K)
4000
3000
2000
1000
10x 1989 SPEs
1989 SPEs
No SPEs
70 km
60 km
50 km
40 km
30 km
20 km
0
1e-7
2e-7
3e-7
4e-7
1e16
2e16
3e16
4e16
5e16
6e16
NOy (mol/mol)
Cumulative column NOy (molecules cm-2)

Conclusions

- ***SPEs significantly increase reactive nitrogen and decrease ozone*** in the stratosphere following November 2000 events.
- ***No convincing evidence that SPEs are related to impulsive nitrate spikes.***
- Tropospheric sources provide an alternative explanation for nitrate spikes at Summit during the winter of 2000-2001.

Remaining Sun-to-Ice Questions

- ***How large would an SPE have to be*** to produce discernable nitrate spikes at the surface, given the limits of solar flare energy?
- ***Longer-term variations*** in nitrate related to solar activity continue to be of interest (Gleissberg cycles, millennial variations, etc.).
- ***Are there alternative proxies*** for SPEs in the ice core or other geologic records? On what timescale can cosmogenic radionuclides (e.g., ^{14}C and ^{10}Be) or other isotopes be used to study solar variability?


THE END?
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