Using WACCM to study extreme Solar Proton Events, their atmospheric impacts, and potential paleoclimate signatures

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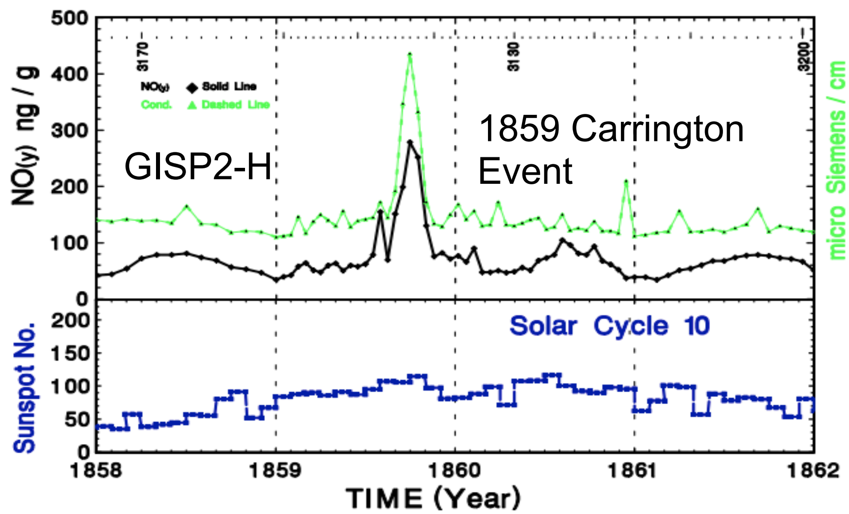
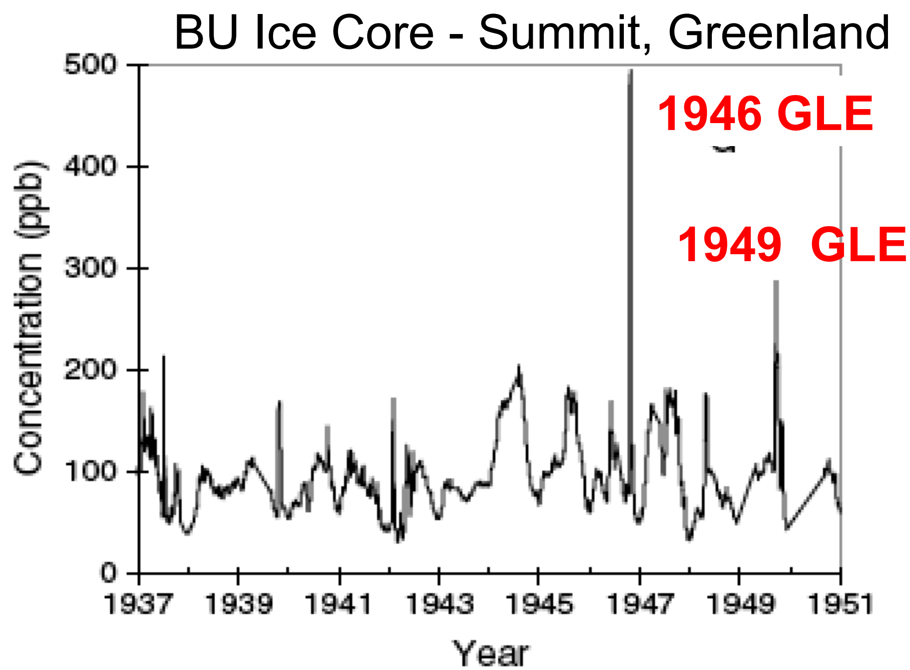
Original goal: Calibrate nitrate enhancements in polar ice to unlock historic information of extreme solar events.
SUN
TO
ICE
• Strength & frequency of future solar extreme events.
• Solar influences on climate.
Image: Steele Hill / NASA
Photo: Katrine Gorham

Are spikes in nitrate ions in ice cores signatures of solar energetic particle events?



Smart et al. [2006]



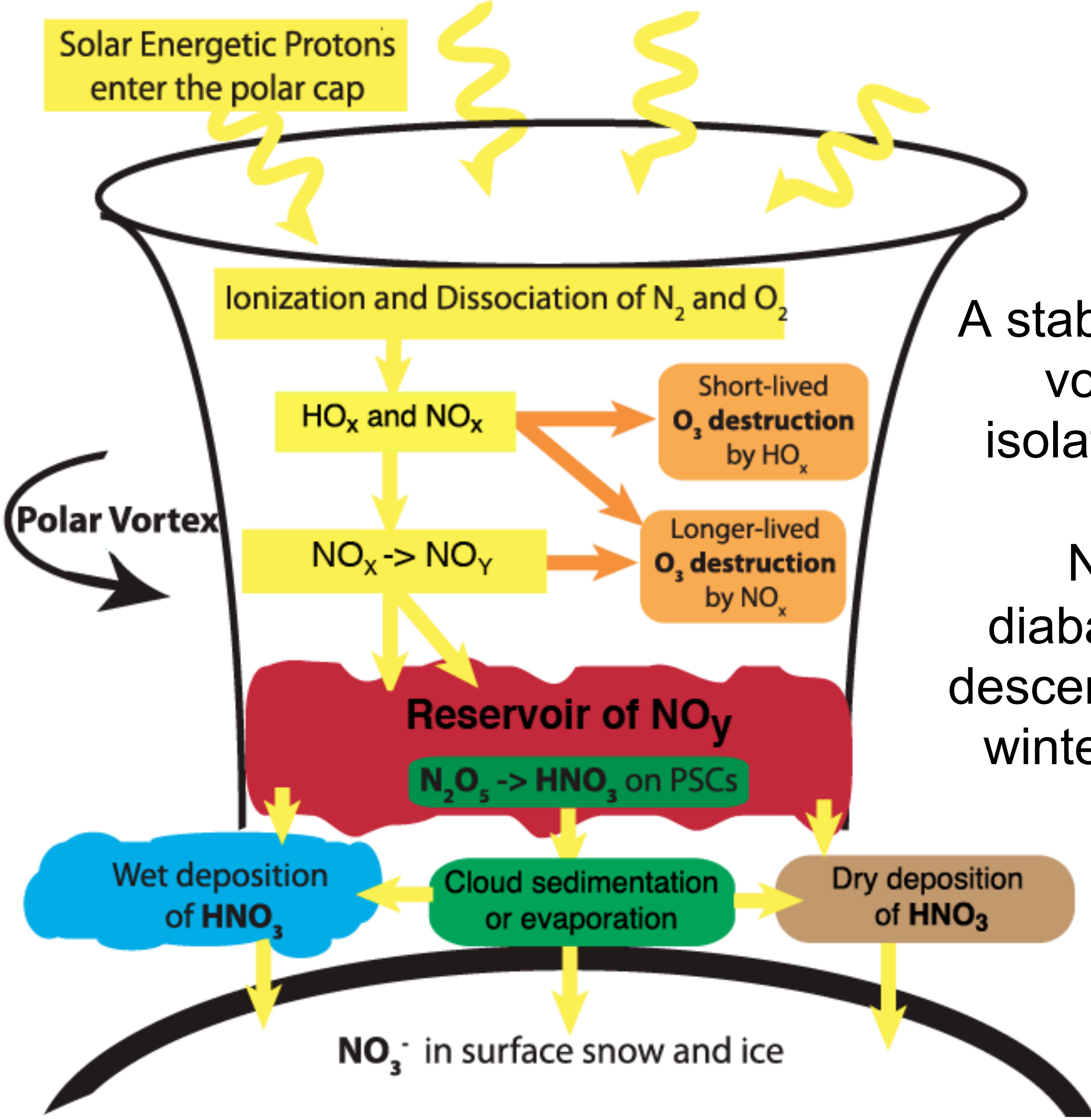
Adapted from Smart et al. [2014]

Conclusion: WACCM suggests spikes likely from *non-SPE* sources.

[continental polluted plumes, biomass burning sources, or post-depositional processing]

Use WACCM to study upper atmospheric processes that could results nitrate spikes at the surface.

Polar Night



A stable polar vortex isolates air.

NO_x diabatically descends over winter pole.

Offline: Solar Proton Flux -> ion pair profile

WACCM: HOx, NOx, O3 chemistry, polar vortex, downward transport, deposition

Use WACCM to study two potential methods of odd nitrogen production

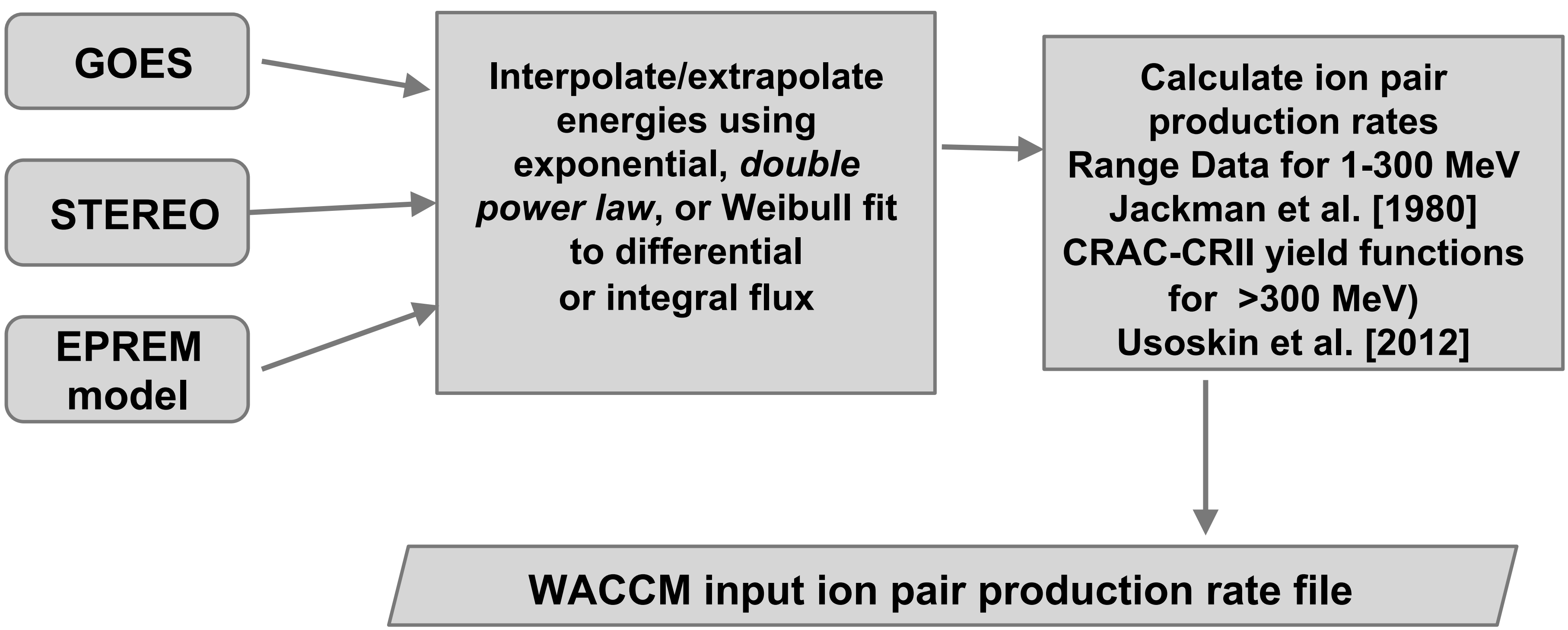
1. High fluence solar proton events -- production of NO_y in upper stratosphere / mesosphere followed by slow descent within the polar vortex. (*traditional approach*)

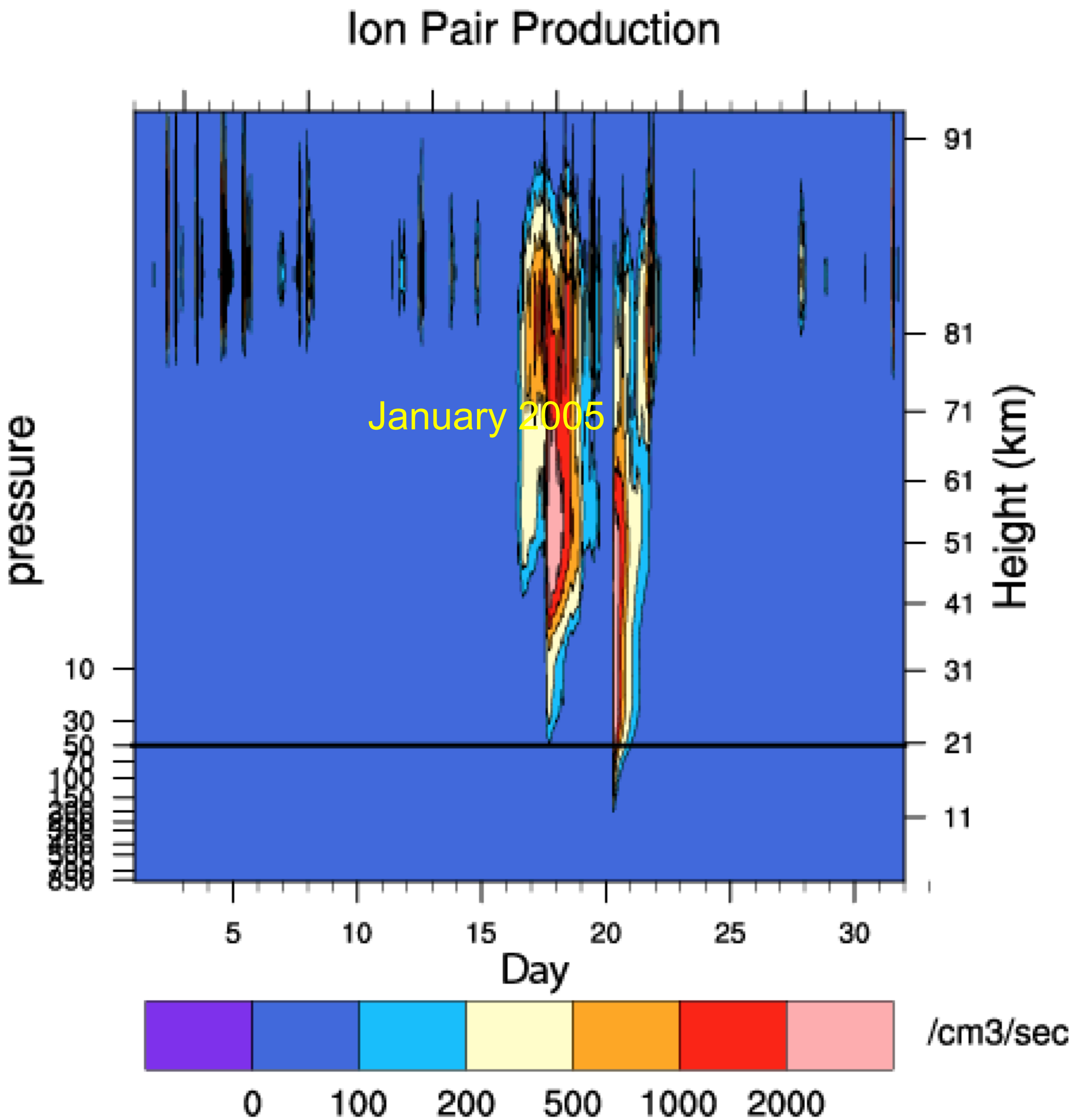
2. Production of NO_x (NO_x -> NO_y) directly in troposphere or lower stratosphere by "hard" spectrum (high energy) solar proton events. (*recently argued by Smart et al. [2014]*)

WACCM Ion Pair Production input ("offline")

Default SPE file: 1963-present *daily average* ion pair production rates calculated from from energies *1-300 MeV (satellite data)*.

Goal: **Higher resolution** (30 min) to capture the prompt and delayed components of SPE spectrum. **Higher energy tail** to look at "hard" spectrum events that produce ion pairs in the lower atmosphere. **Hypothetical events**.





Our goal:

1)Greater time resolution

2) "Harder" spectra -- higher energies -- lower altitudes

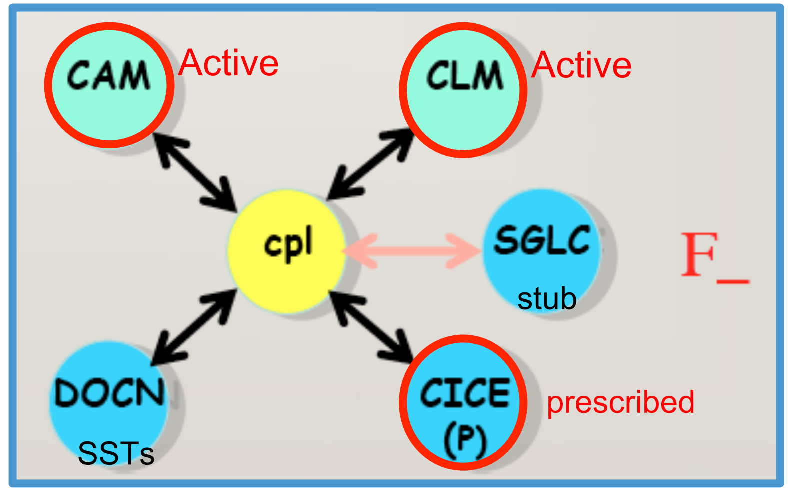
3) Hypothetical events (including from energetic particle models like EPREM)

WACCM

Whole **A**tmosphere
Community **C**limate **M**odel

(cesm1_0_5 FSDW)

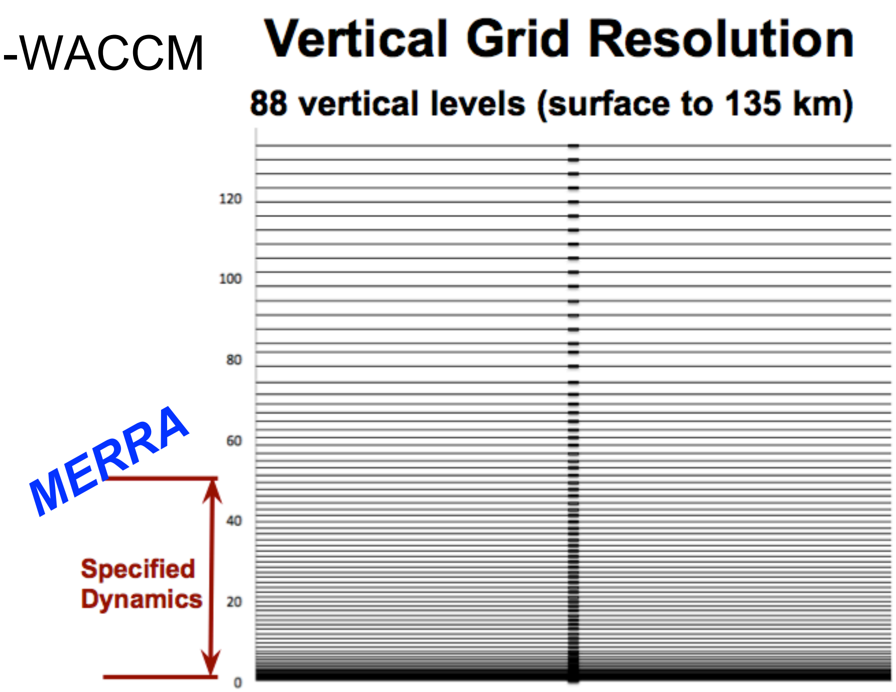
Fixed Ocean



$$\Delta\lambda \times \Delta\theta = 1.9 \times 2.5$$

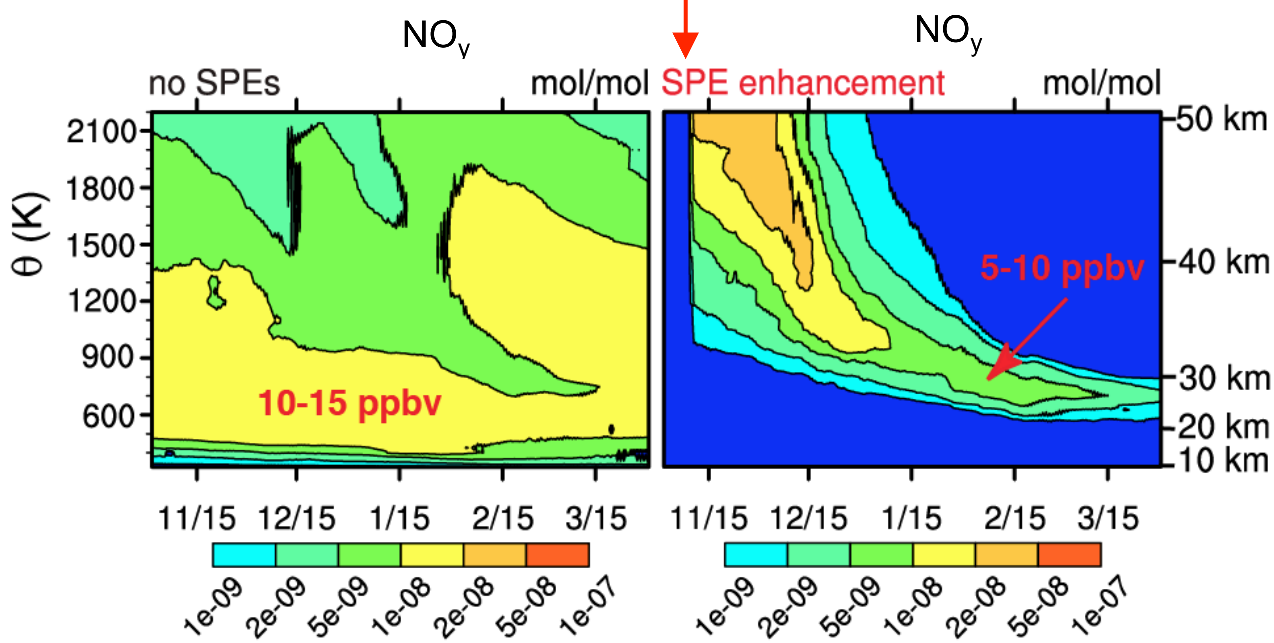
nlon=144, nlat=96

SD-WACCM



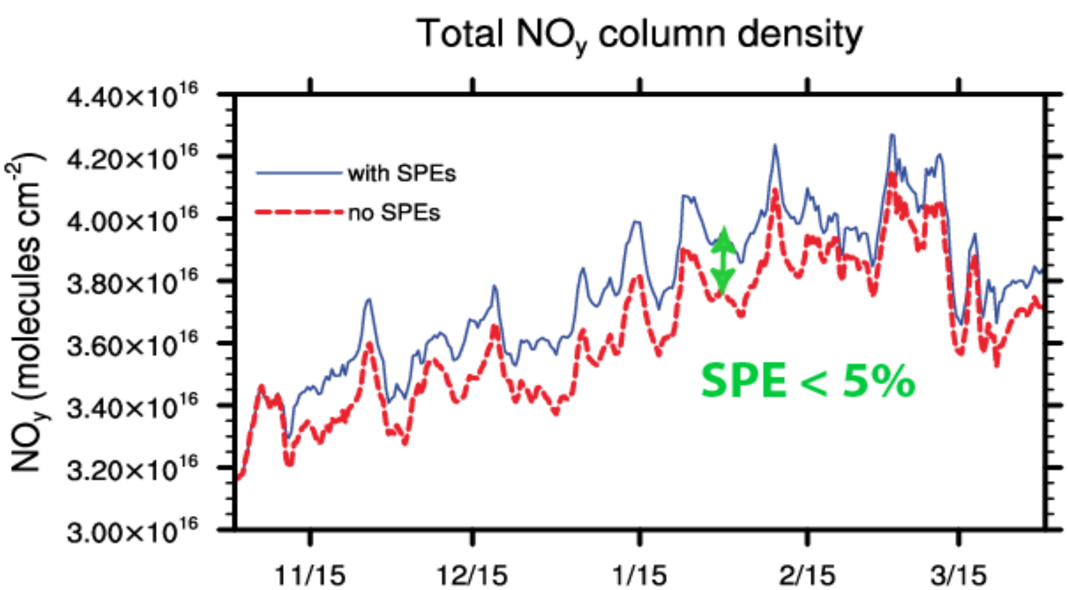
WACCM

9 Nov 2000 SPE



Vortex-averaged **total odd nitrogen**
$NO_y = NO+NO_2+NO_3+2N_2O_5+HNO_3+HO_2NO_2+ClONO_2+BrONO_2$

WACCM shows a thin layer of SPE-enhanced No_y compared to the thick background pool of NO_y in the lower stratosphere.

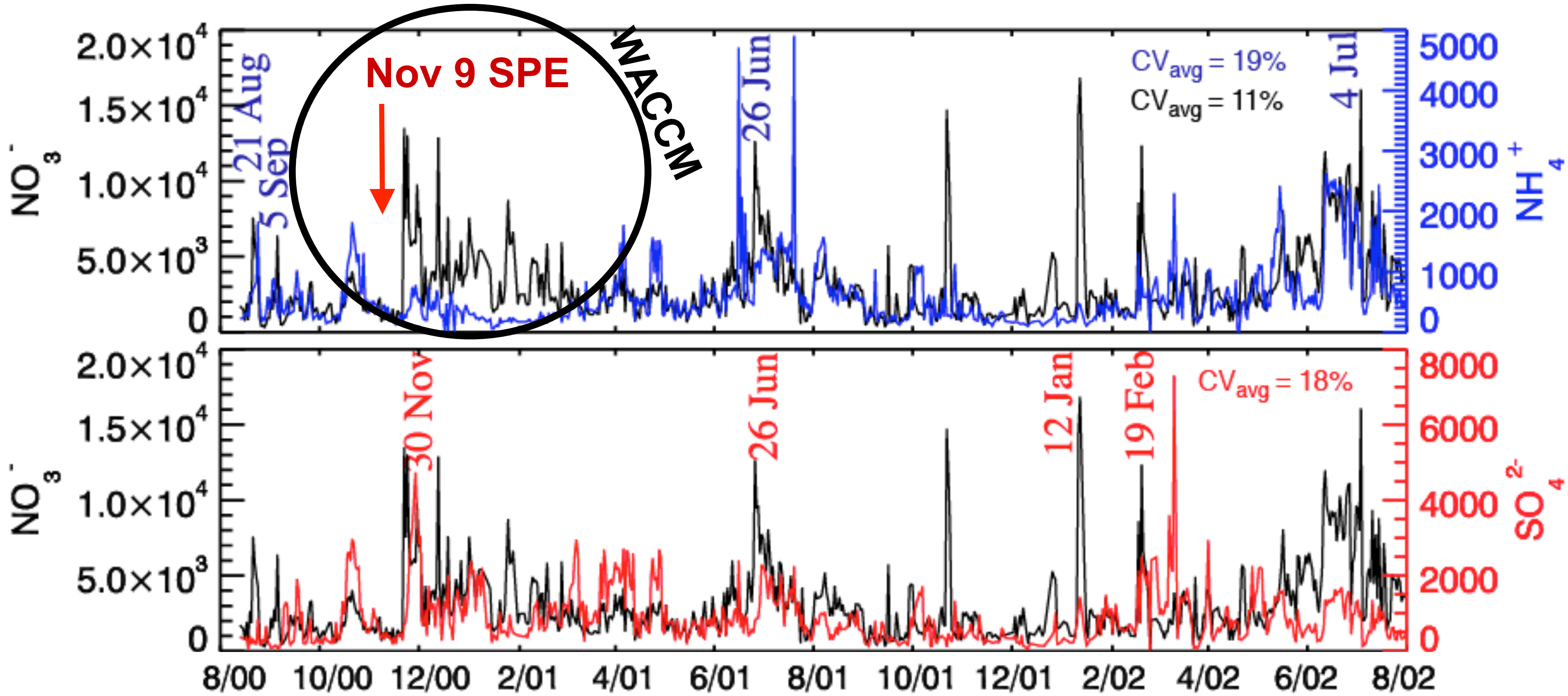


SPE enhancement of total column NO_y is ***not large enough*** to explain The 4-5 fold spikes in nitrate ions in snow and ice.

Duderstadt et al. [2014]

Daily surface snow at Summit, Greenland

Correlations of nitrate (NO_3^-) with NH_4^+, SO_4^{2-}, Na^+, Ca^{2+}

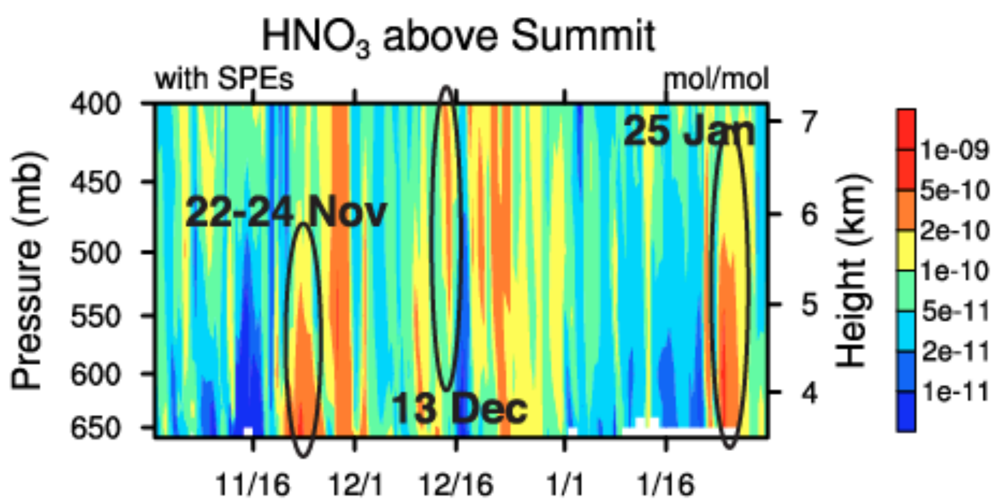


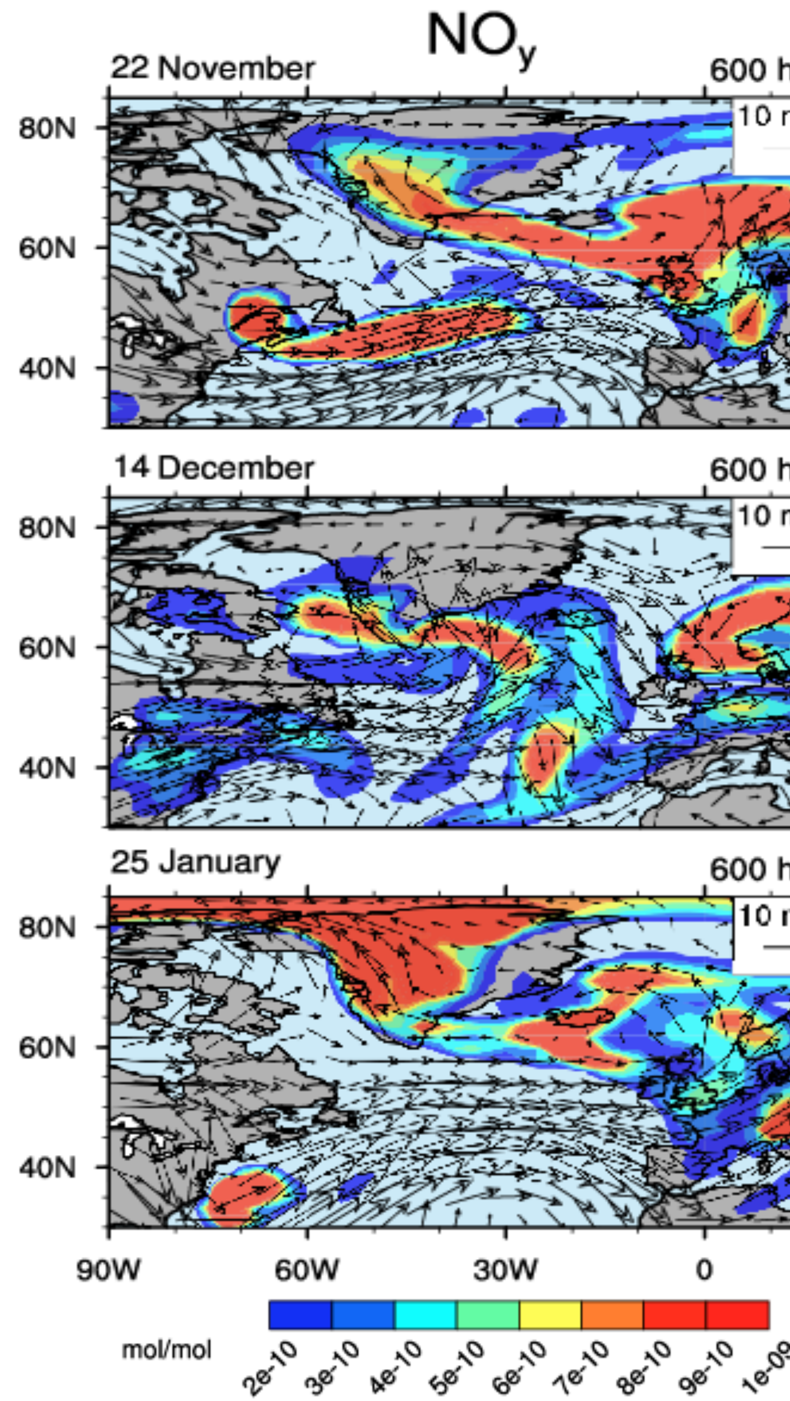
Dibb et al. [2007]

SO_4^{2-} (sulfate) → Anthropogenic Pollution

NH_4^+ (ammonium) → Biomass Burning

WACCM shows polluted plumes from North America and Europe reaching Summit during periods of nitrate enhancement.

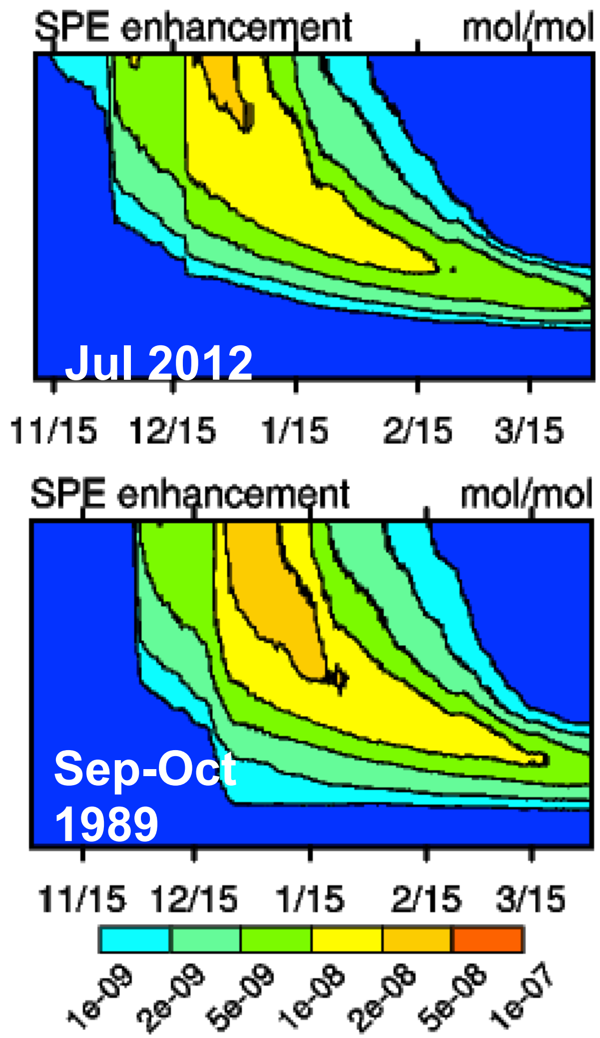


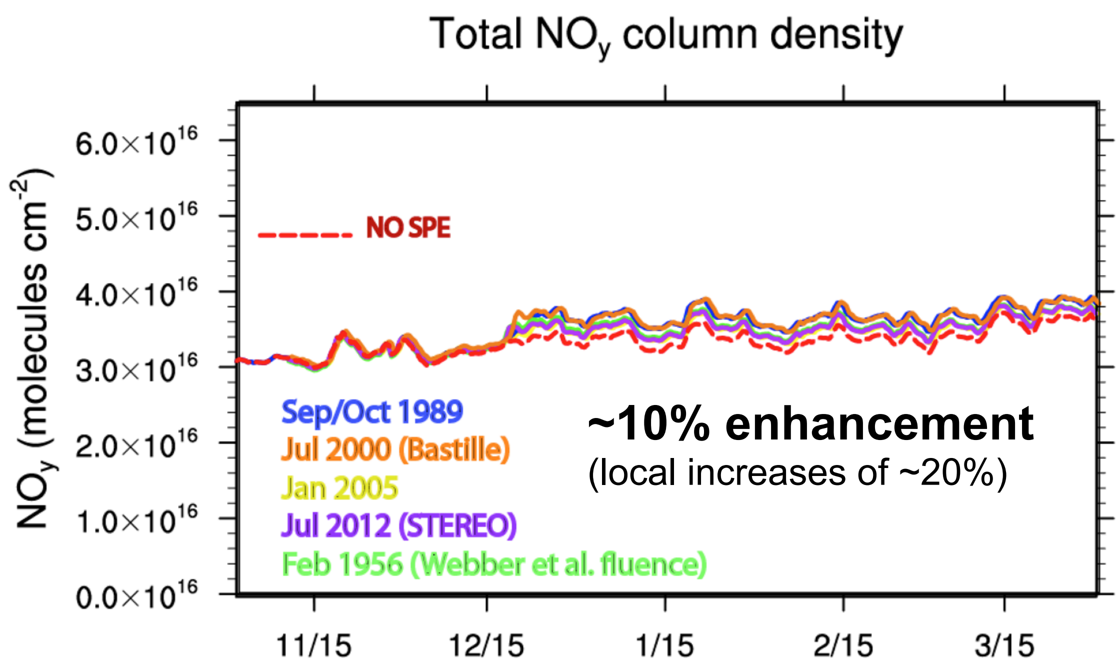


Repeat with several recent SPEs placed in stable vortex 2004-2005 winter

(including STEREO A July 2012 “Carrington-like” SPE that missed Earth)

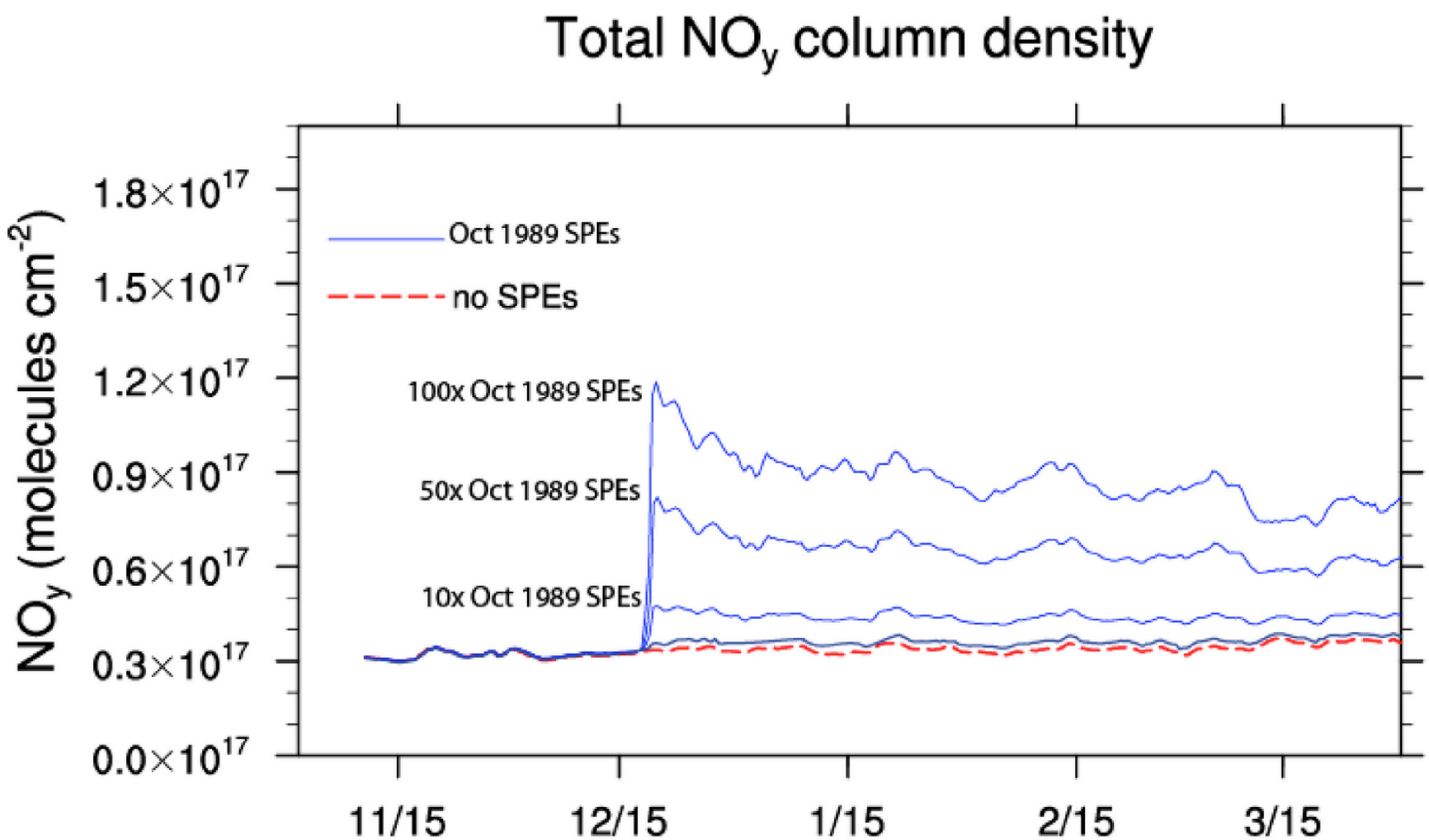
Vortex-average NO_y





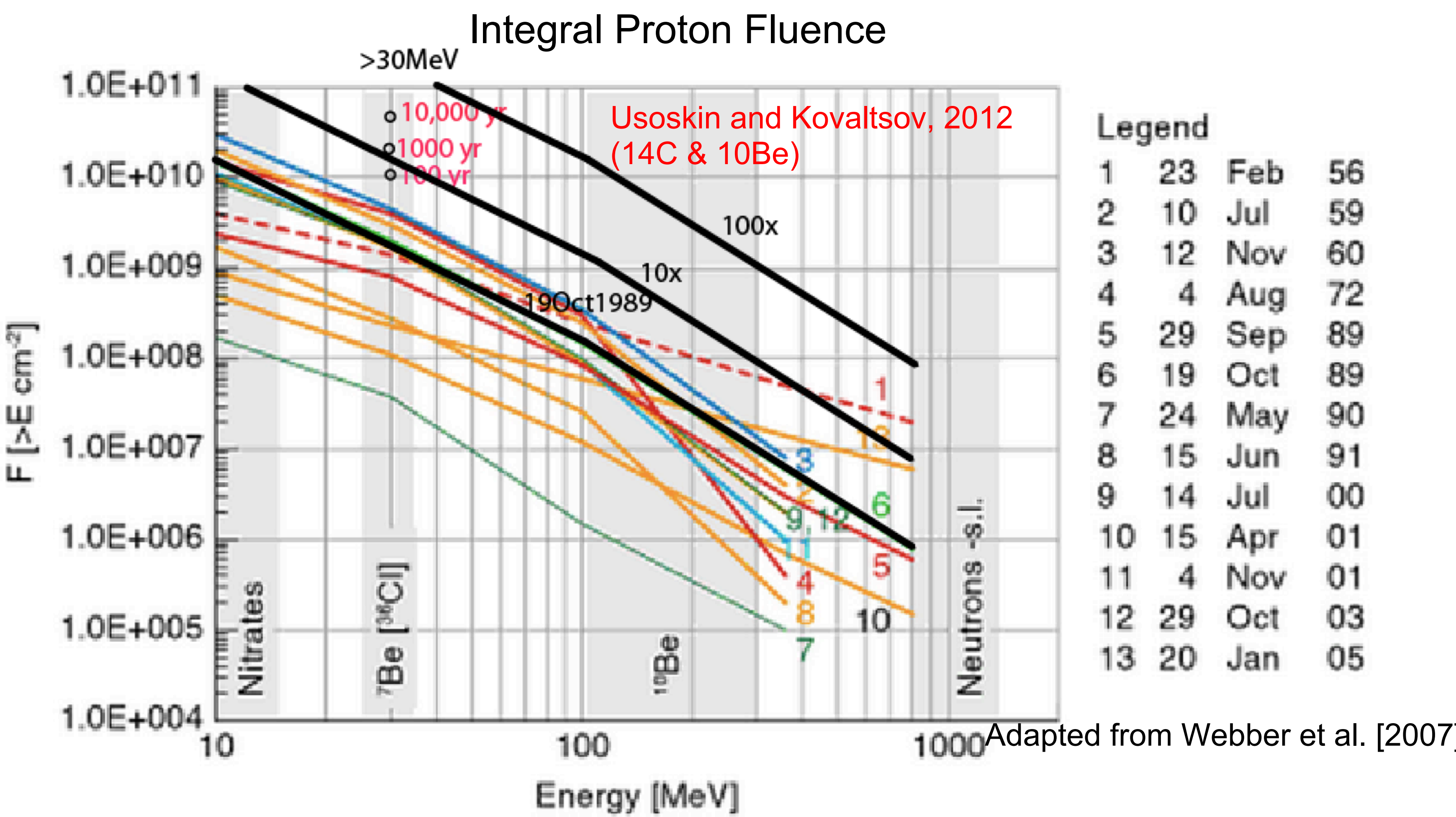
Enhanced NO_y from all events not large enough for 4-5x spike in nitrate

Method 1: Consider series of Oct 1989 SPEs...the largest fluence in satellite era and then multiply by 10, 50, 100
...placed in stable polar vortex winter (2004-5)



***100x October 1989 SPEs** necessary to achieve **4 fold** increases in total column NOy enhancements as seen in nitrate at the surface!!!*

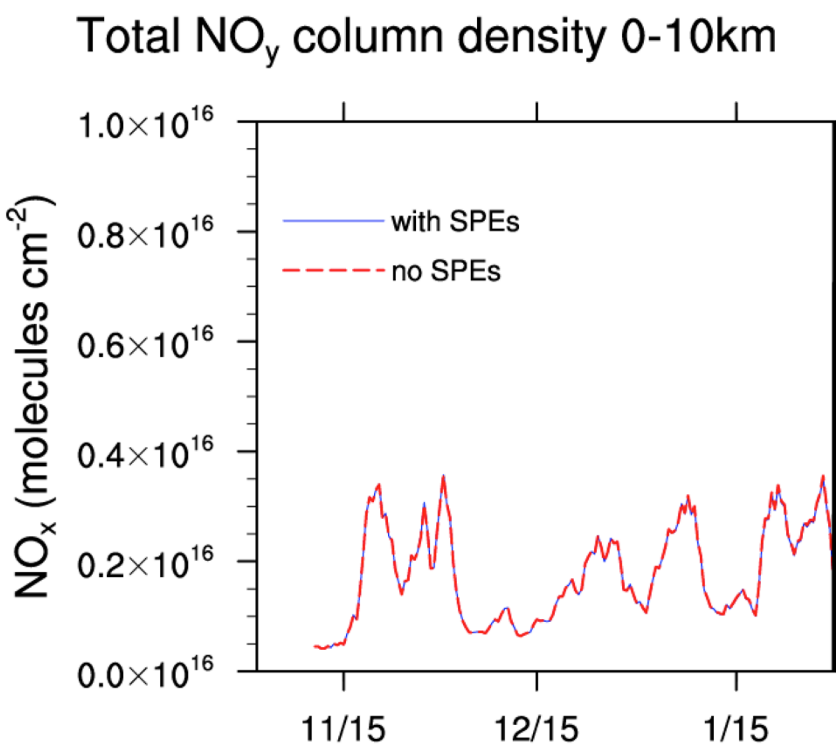
Probability of an event 100 times the Oct 1989 SPEs…>10,000 yrs



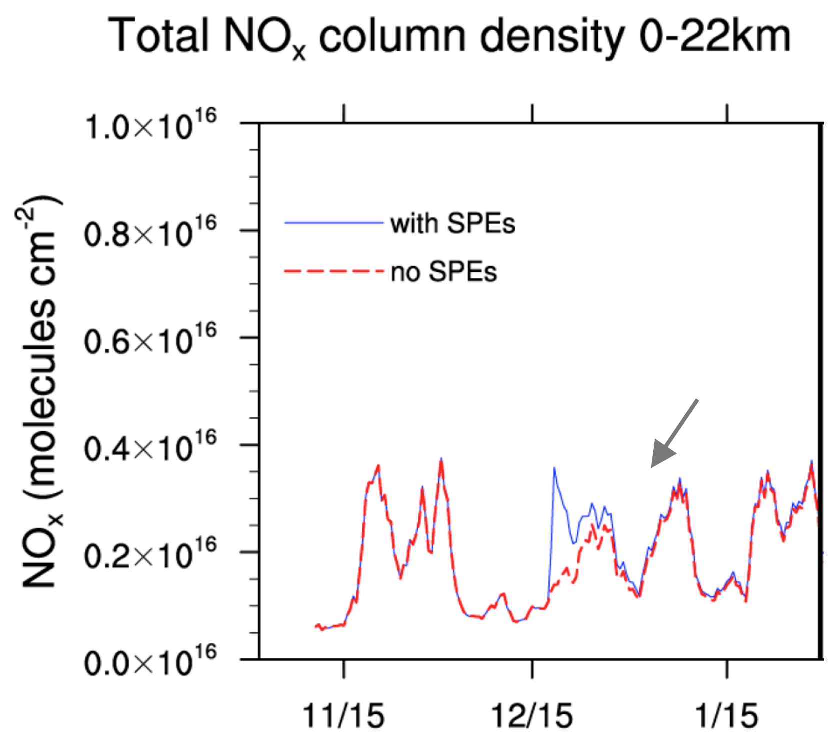
Adapted from Webber et al. [2007]

• Miroshnechenko and Nymmik [2013]..recent SPEs and sunspot data >30 MeV of 6x10^10 cm-2 is likely to occur every 2.6 x 10^5 years.

Method 2: 1000 times the 20 Jan 2005 SPE
(“hardest” event in satellite era)
[placed in 2004-2005 winter…and including an “upper-limit” tail to 1000 GeV]

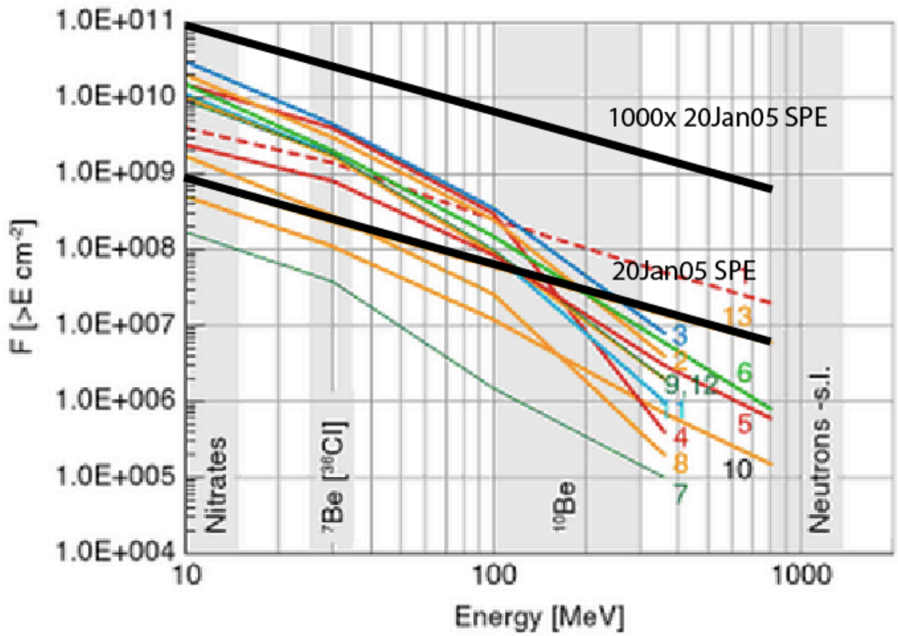


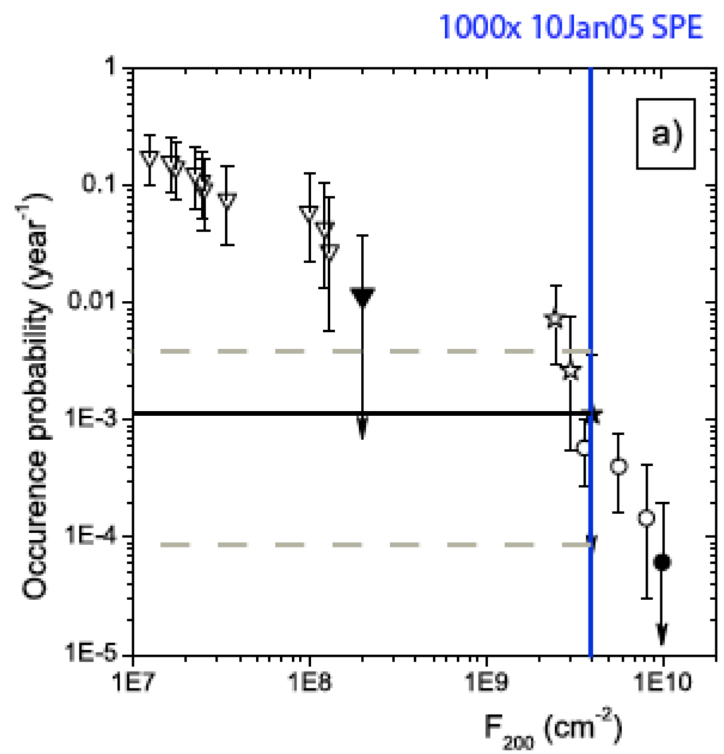
No significant increase in tropospheric NOx.



3.5 fold increase in NOx in lower stratosphere at start of event...yet within background NOx variability.

Probability of 1000x 20 Jan 2005 SPE once every 1000 years





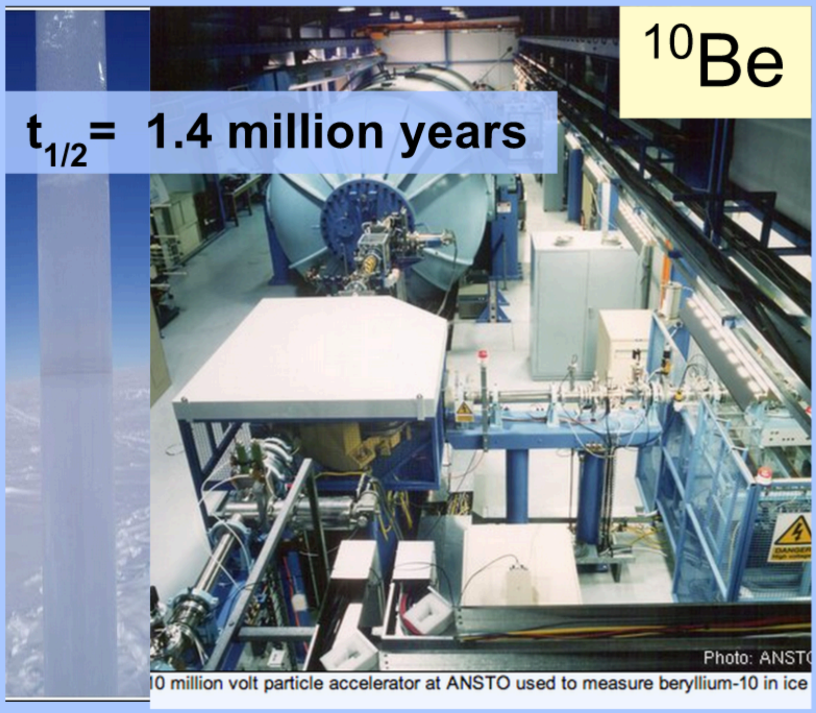
Kovaltsov et al., [2014]

• Suggestions that **774-775 AD possible SPE is 25-50 times stronger than 1956 SPE** (1956 fluence inferred from GLEs) [Usoskin et al., 2013]. 1956 event is ~40x the 20Jan05 SPE...**so perhaps nitrate could be seen from the 775 AD event.**

What's Next for Sun-to-Ice?

Applying WACCM to the Cosmogenic Radionuclide Problem

^{7}Be, ^{10}Be, ^{14}C, ^{36}Cl



What's Next for Sun-to-Ice?

Applying WACCM to the Cosmogenic Radionuclide Problem

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- **Paleoclimate simulations with WACCM**, branching from existing CESM simulations. There is a large archive of paleoclimate studies using CESM. However, these studies only extend to ~40 km while WACCM reaches ~120 km, including additional chemistry and dynamics that likely influence global and regional climate patterns.
- Rely on recent observations (e.g., IBEX and LRO-CRaTER), models (e.g, EPREM and CORHEL), and contemporary theory to estimate the **strength of the heliospheric magnetic field and local interstellar medium**.
- Use the growing archive of 10Be ice cores and 7Be atmospheric observations. Over a decade of high resolution **7Be at Summit, Greenland**, ongoing accelerator mass spectrometry (AMS) measurements of 10Be in ice cores from sites such as the West Antarctic Ice Sheet Divide (WAIS), and existing **datasets of 10Be, 14C, and 36C**l.
- Focus on the impact of solar variability on regional climate modes such as **the Northern Annular Mode (NAM) and Asian Monsoon**. The NCAR Whole Atmosphere Working Group has placed a high priority on using WACCM to study the coupling of the stratosphere and troposphere on climate variability as well as studying of effects of solar variability (specifically the 11-year solar cycle) on stratosphere ozone, temperature, and geopotential height. These processes are central to modeling the impact of solar variability on regional climate modes.
- Quantify the **timescales of solar variability that can reasonably be inferred from current paleoclimate archives**. For example, can we identify the strength of individual extreme solar events or are we limited to variability on solar cycle timescales and secular trends?

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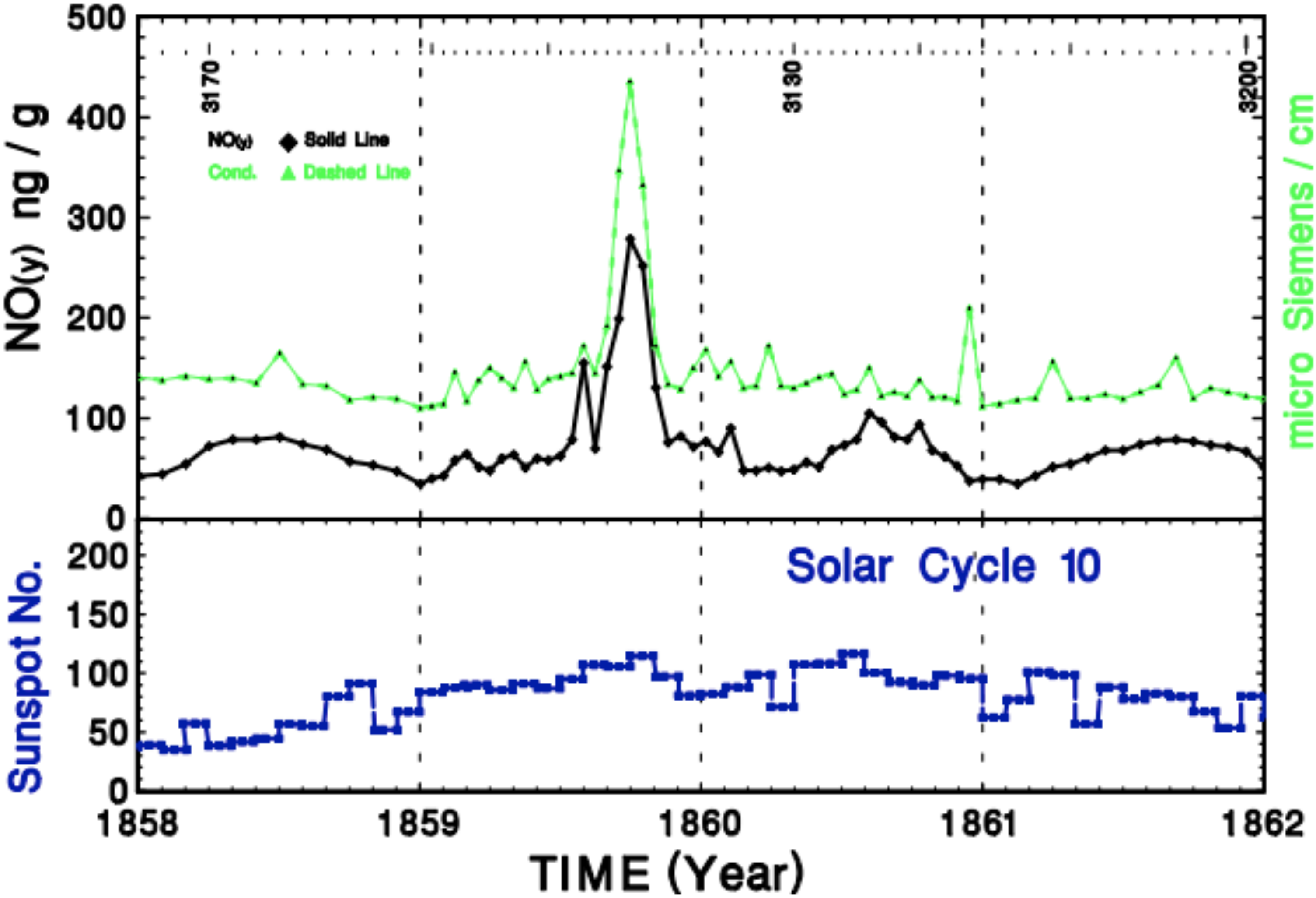
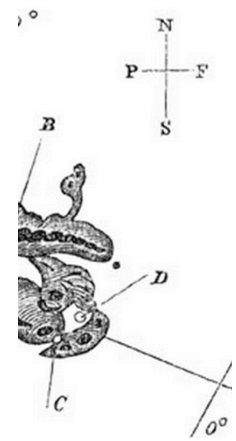
Thank You

Extra Slides

GISP2-H Ice Core -- Summit, Greenland
Carrington Event -- 1859

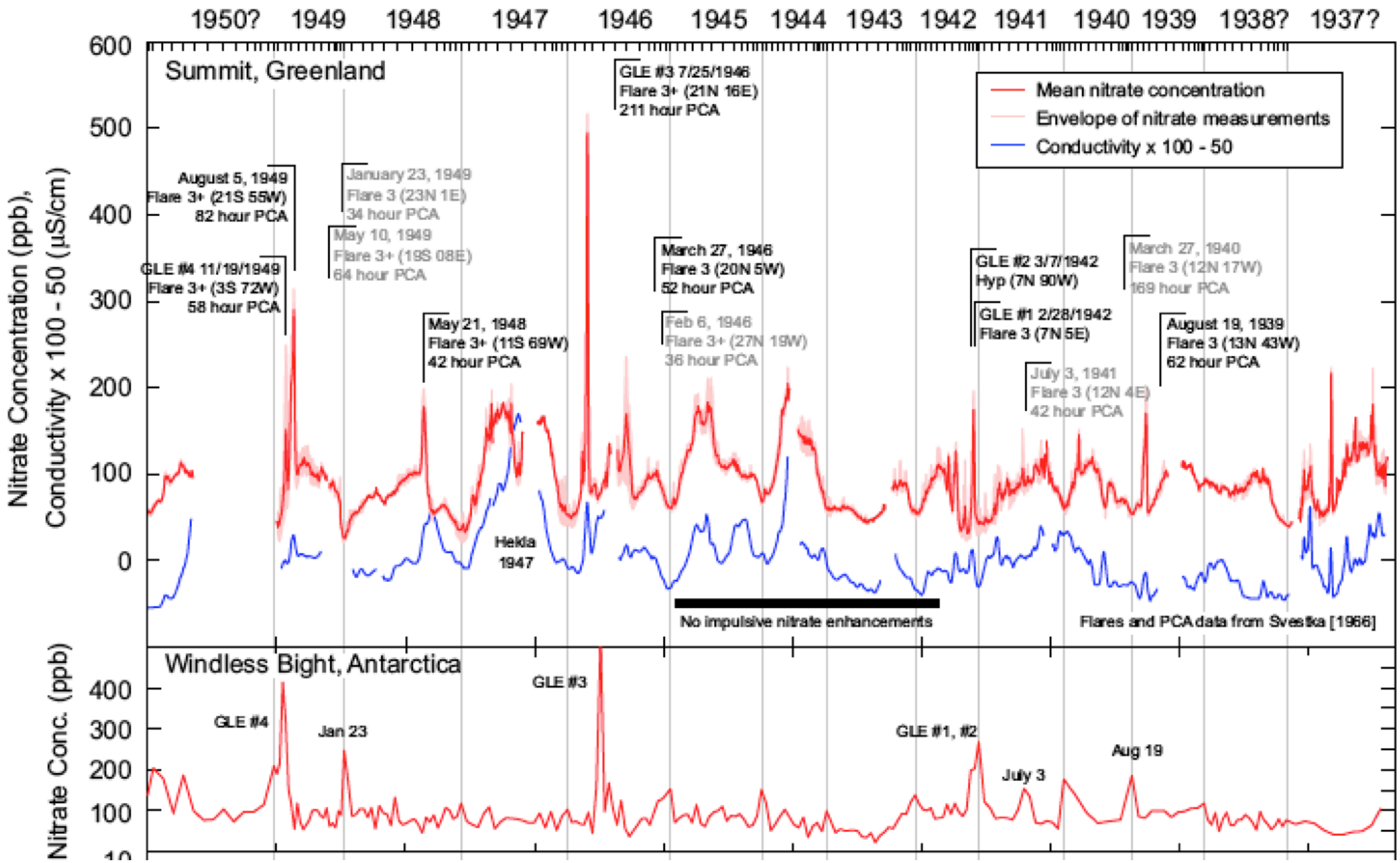


Smart et al. [2006]



Carrington [1859]

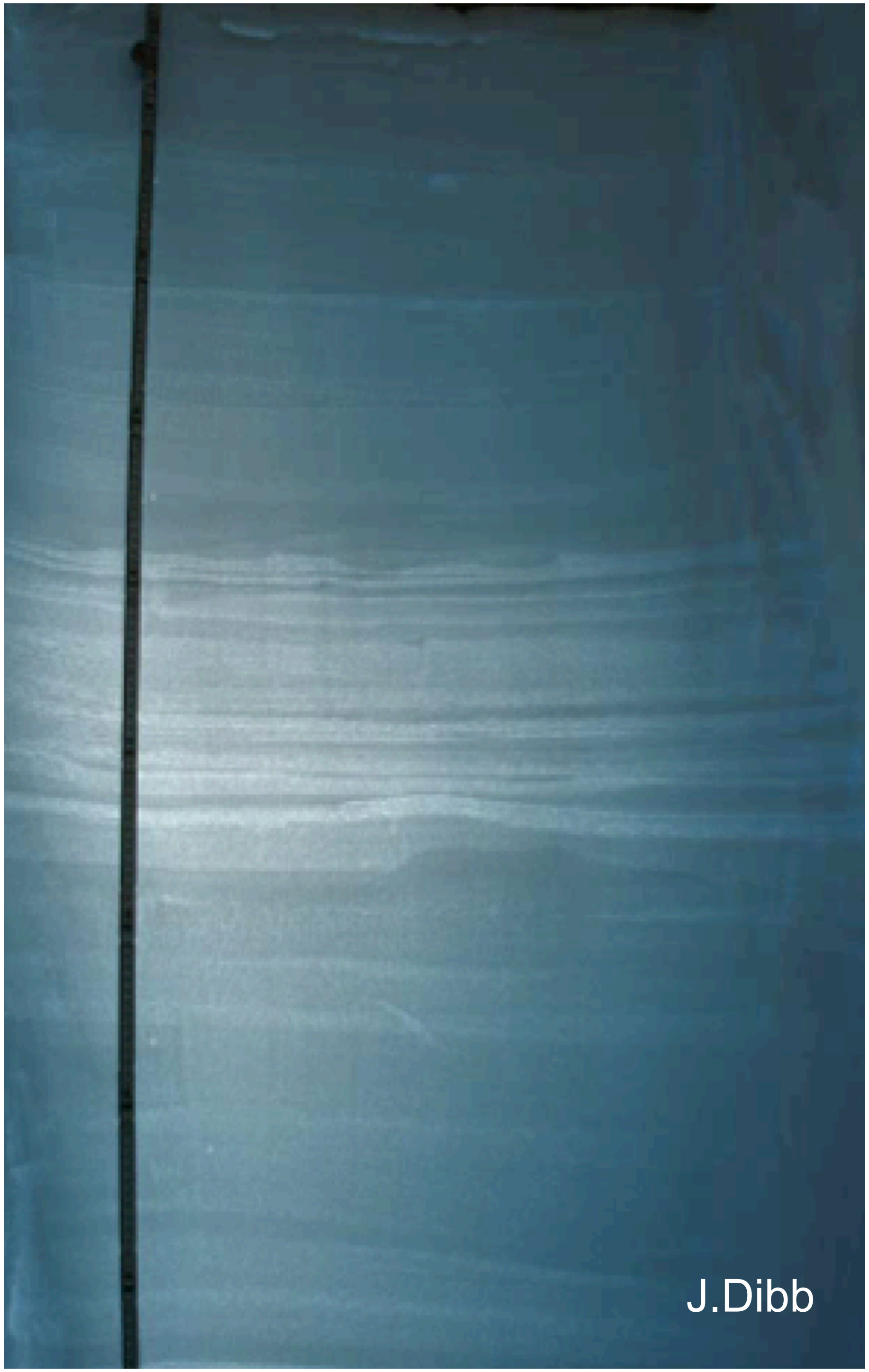
"BU" core -- Summit Greenland
GLEs 1940-1950

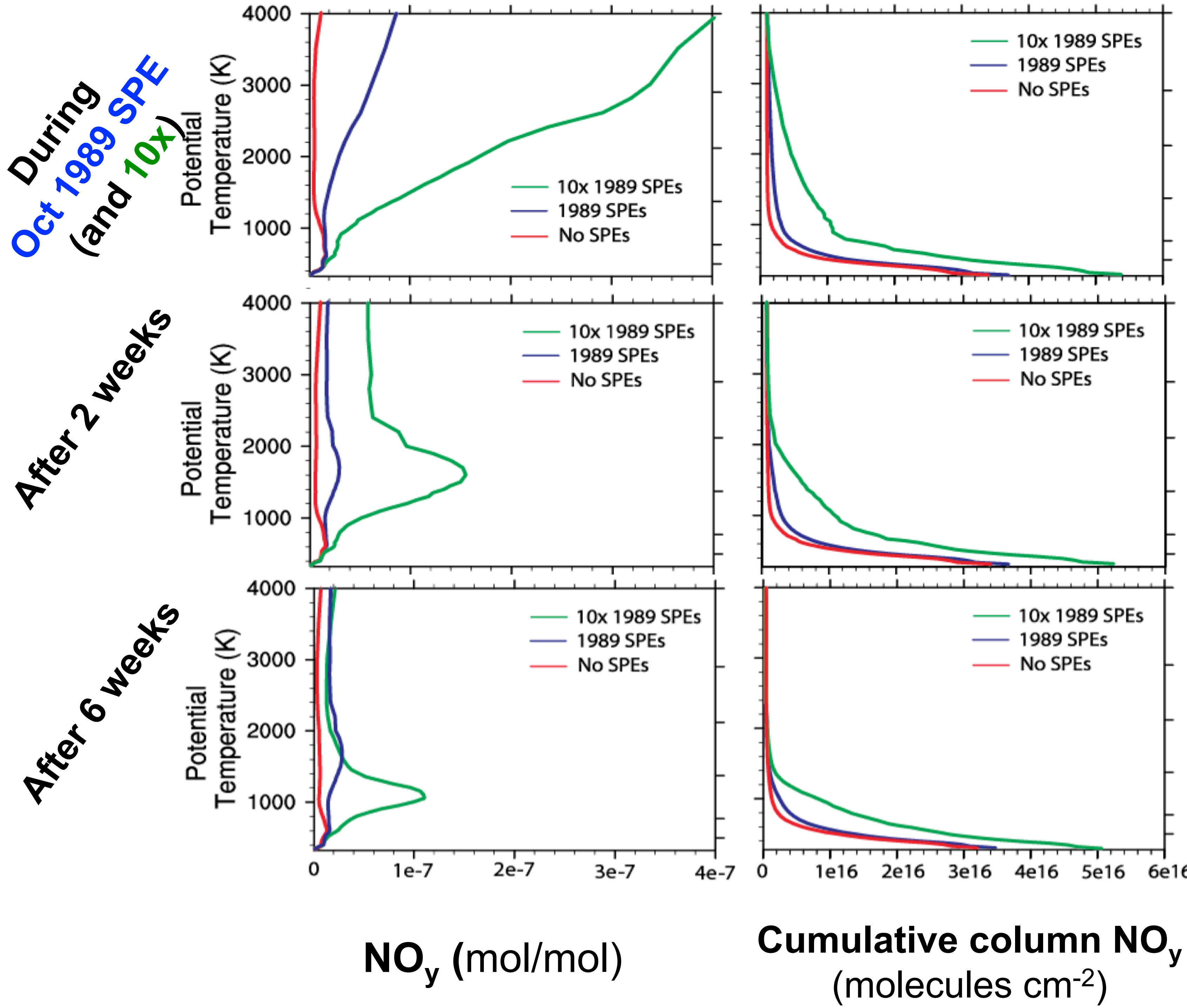


adapted from *Kepko et al.* [2009]

What else could explain nitrate spikes in ice?

- Tropospheric sources
  biomass burning,
  pollution,
  dust
- Post-depositional processing
  wind,
  photolysis,
  migration within snow
- Dating uncertainties

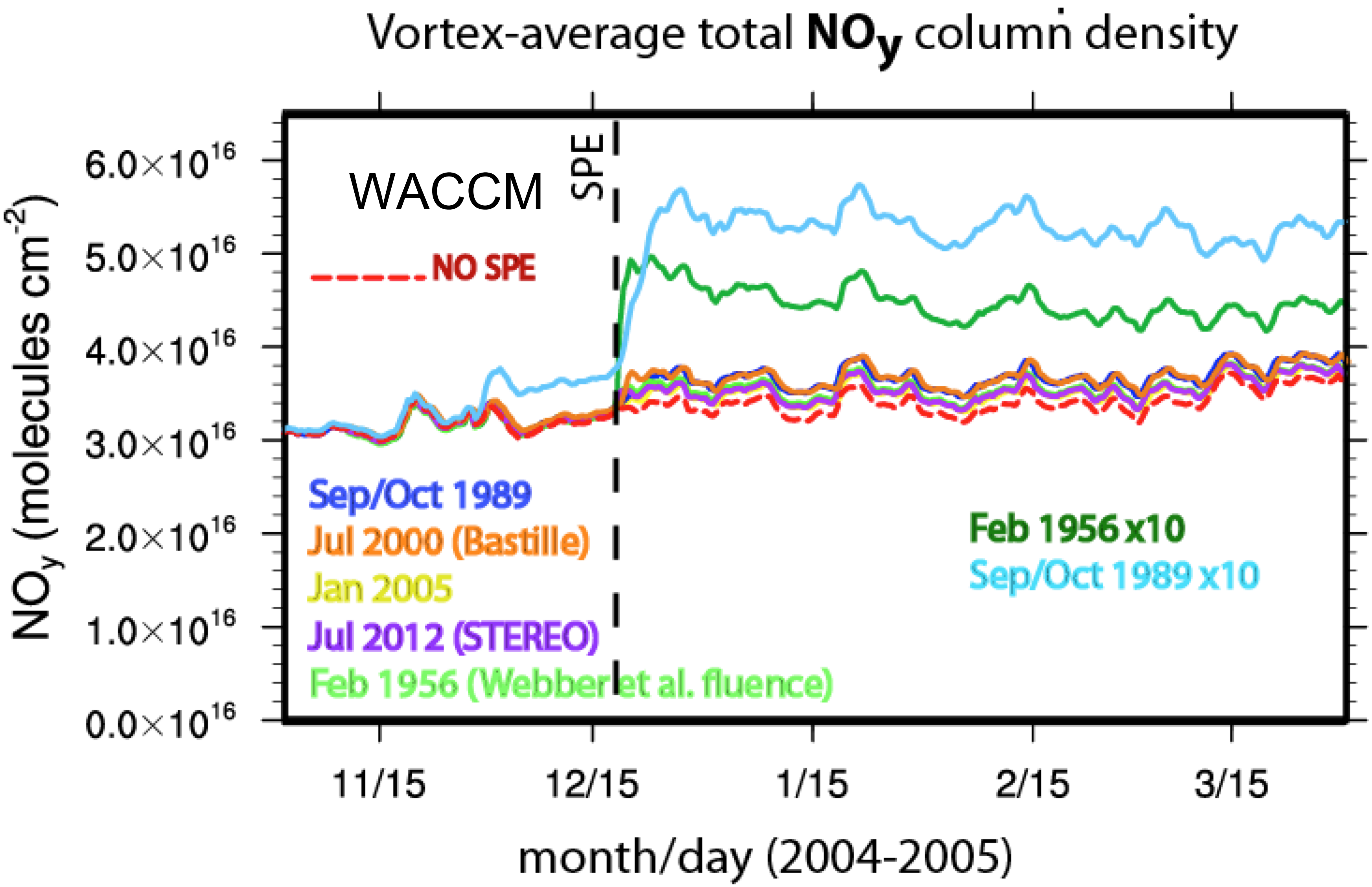




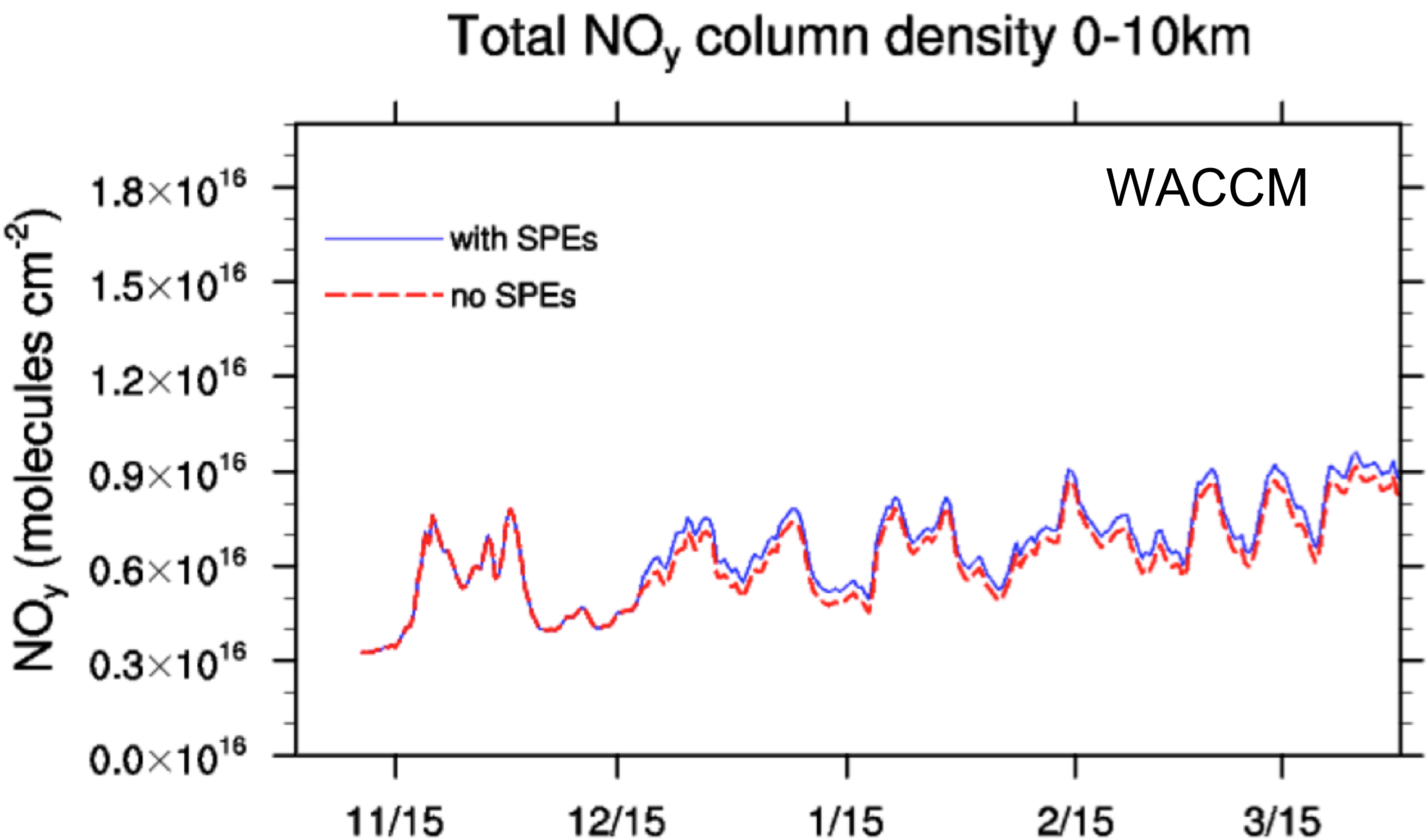
During
Oct 1989 SPE
(and 10x)
After 2 weeks
After 6 weeks
Potential Temperature (K)
4000
3000
2000
1000
10x 1989 SPEs
1989 SPEs
No SPEs
70 km
60 km
50 km
40 km
30 km
20 km
0
1e-7
2e-7
3e-7
4e-7
1e16
2e16
3e16
4e16
5e16
6e16
NOy (mol/mol)
Cumulative column NOy (molecules cm-2)

Several SPEs placed in stable vortex winter of 2004-2005

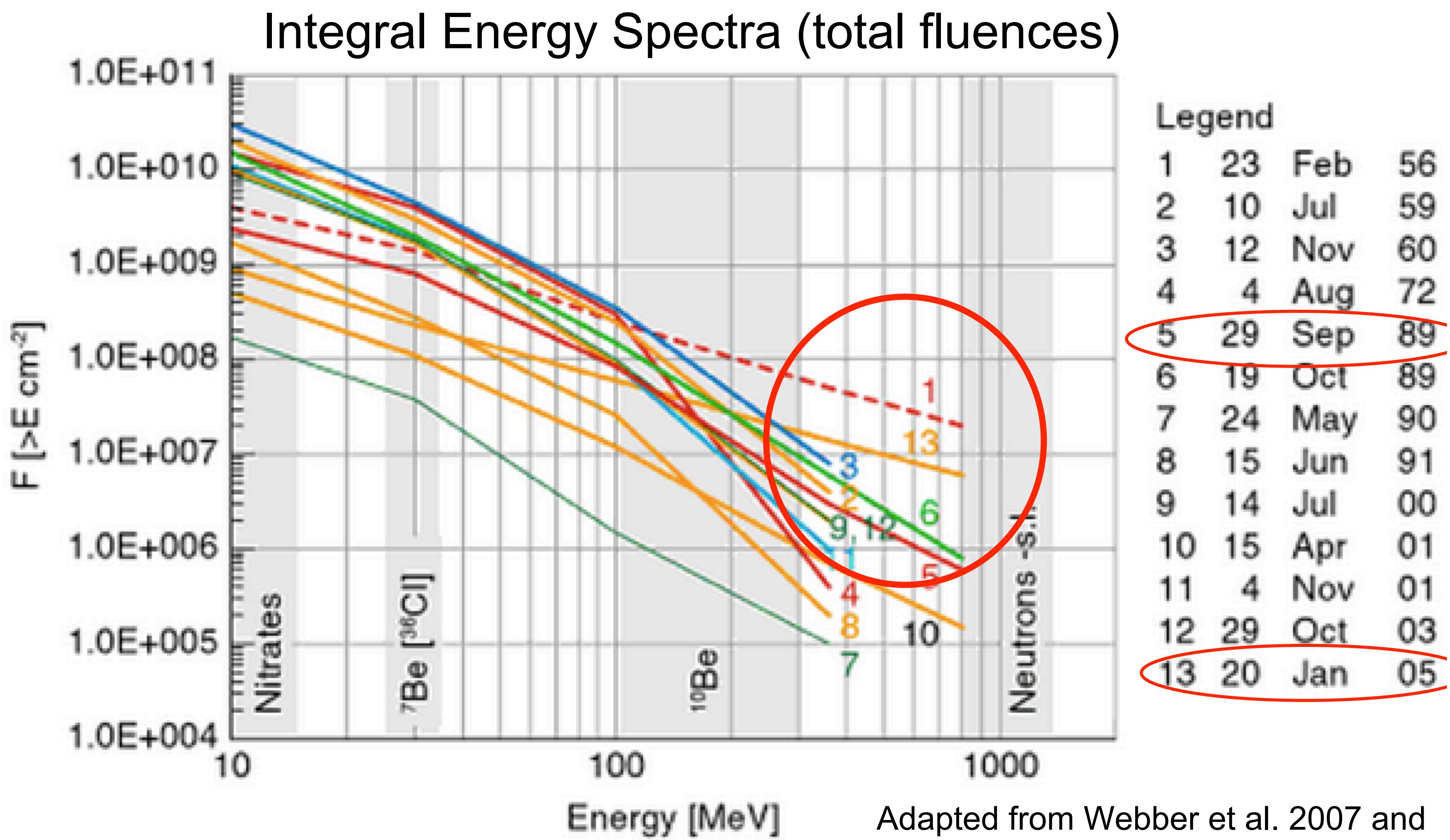
(Sep/Oct 1989 SPEs begin earlier so highest Oct flux coincides with other cases)



Tropospheric impact of **hypothetical 1956x10** event (based on 20 Jan 2005 SPE flux spectra)...*minimal impact on NO_x*



Consider “harder” (higher proton energy) SPEs that might produce NO_y (NO_x) directly in the troposphere



Adapted from Webber et al. 2007 and Beer et al., 2012