Observed Statistical Ozone Response to Particle Precipitation

Mick Denton

Outline

- 1. Introduction
- 2. Background
- 3. Solar/Geomagnetic Activity
- 4. Ozonesondes and Satellites
- 5. *Results*
- 6. Summary

Origins of This Work

Work carried out up to now began over 10 years ago...

The Beginning

"My God, Space is Radioactive!"

(Quote attributed to Ernie Ray)

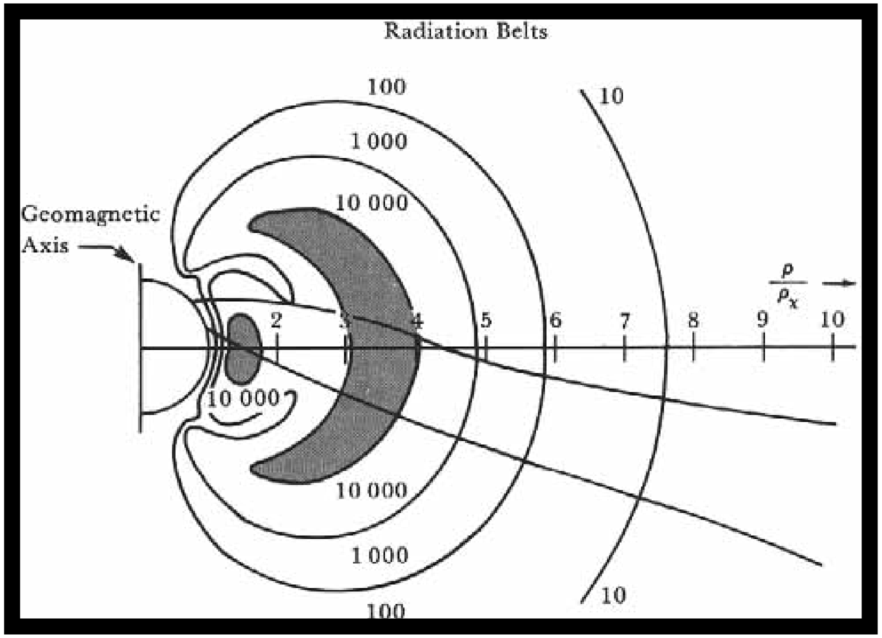
Discovery

Geiger counter on-board first US satellite : Explorer 1.

Detected by Sputnik III but data not analysed.

Two belts with "slot" between them.

Pickering, Van Allen, von Braun.



Inner Radiation Belt

- **Dominated by protons (E >50 MeV)**
- **Formed by CRAND**
- **Inner belt is stable over time.**

Outer Radiation Belt

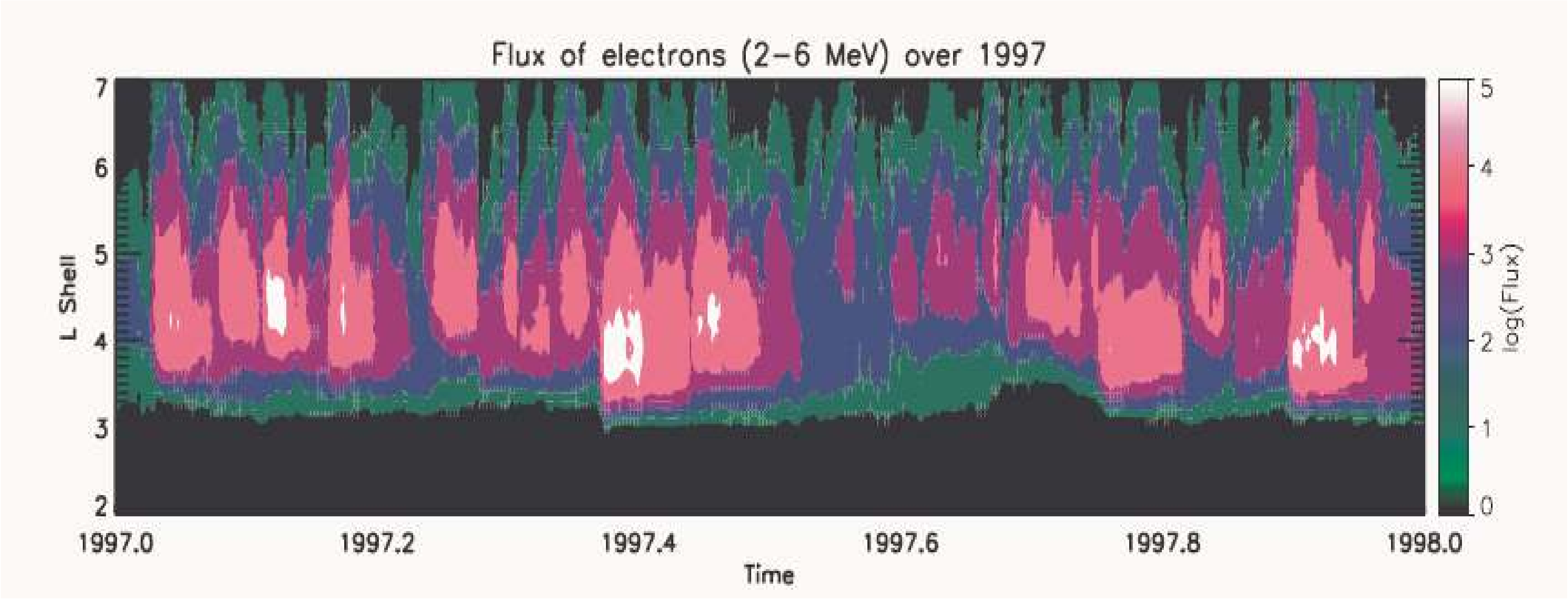
- **Dominated by electrons (E >0.1 MeV)**
- **Formed by ???**
- **Highly variable in time and space.**

Understanding

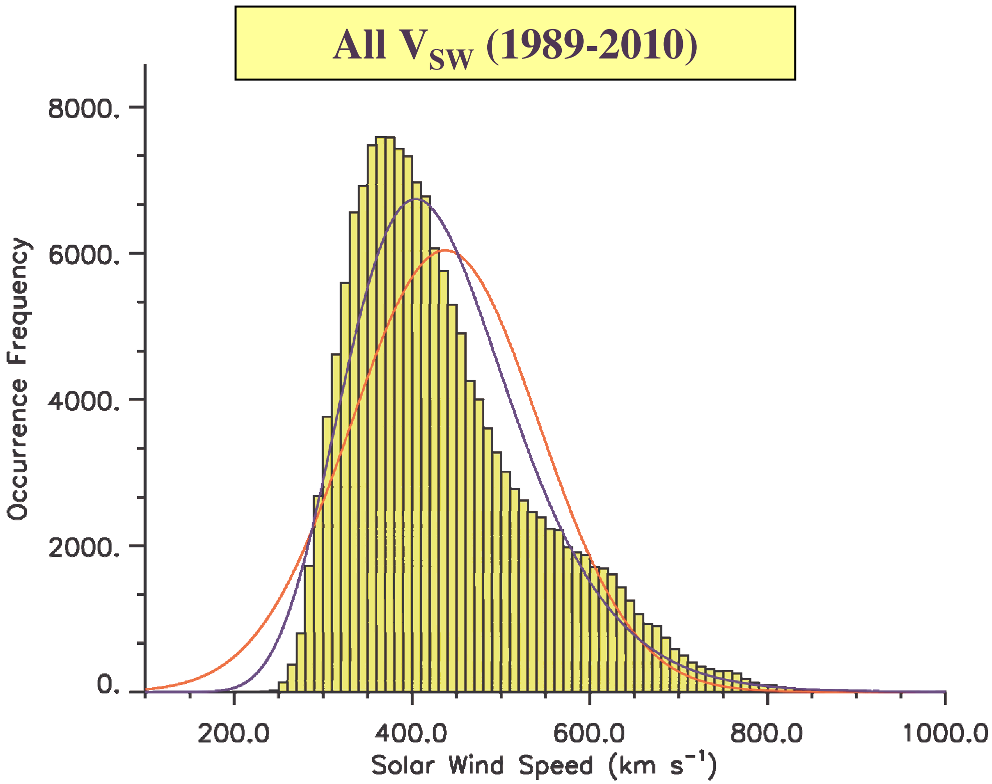
"*The Radiation Belt and Magnetosphere*" by Wilmot Hess, 1968.

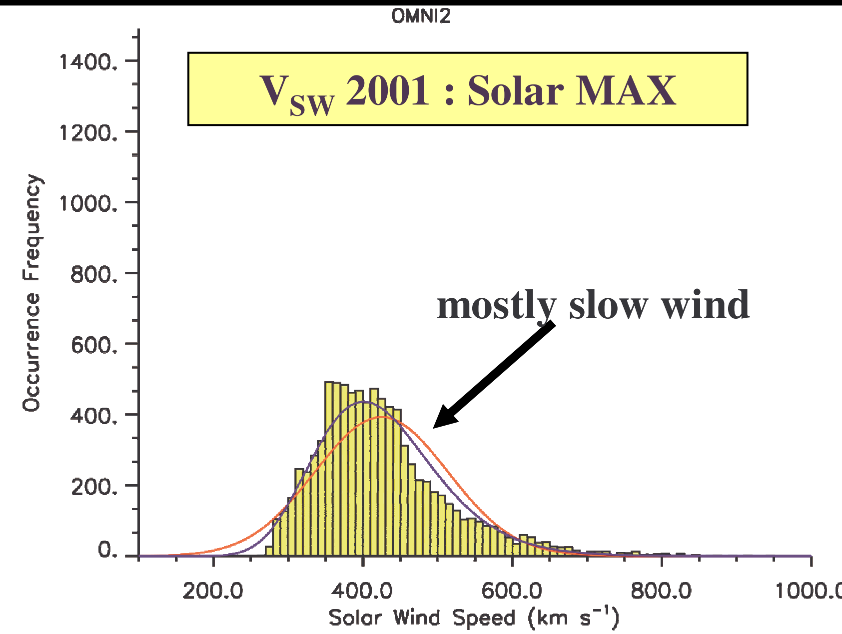
>2500 papers on the subject at that time.

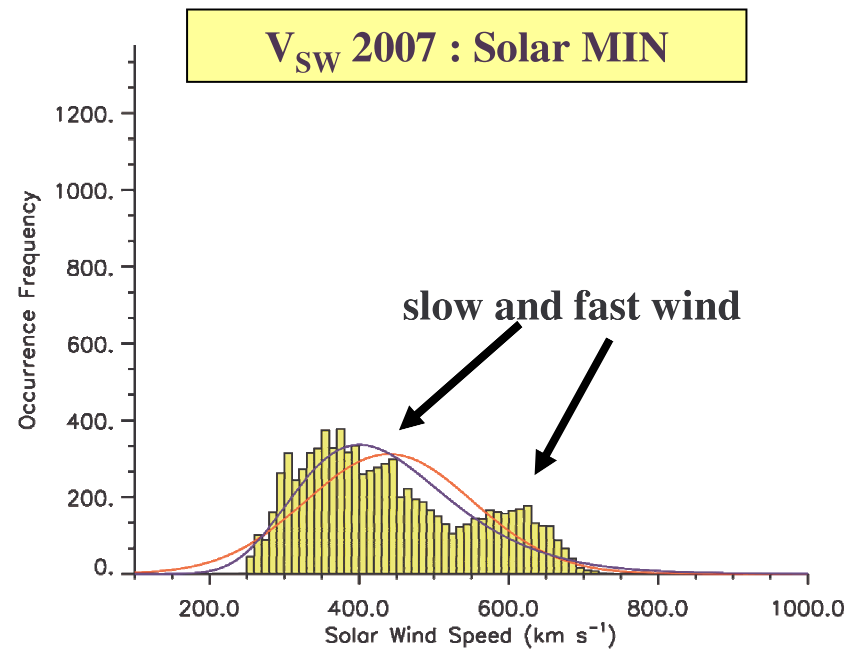
Page 16: "*We have a pretty complete picture of the radiation belt...*"



Solar Wind Speed : OMNI Statistics

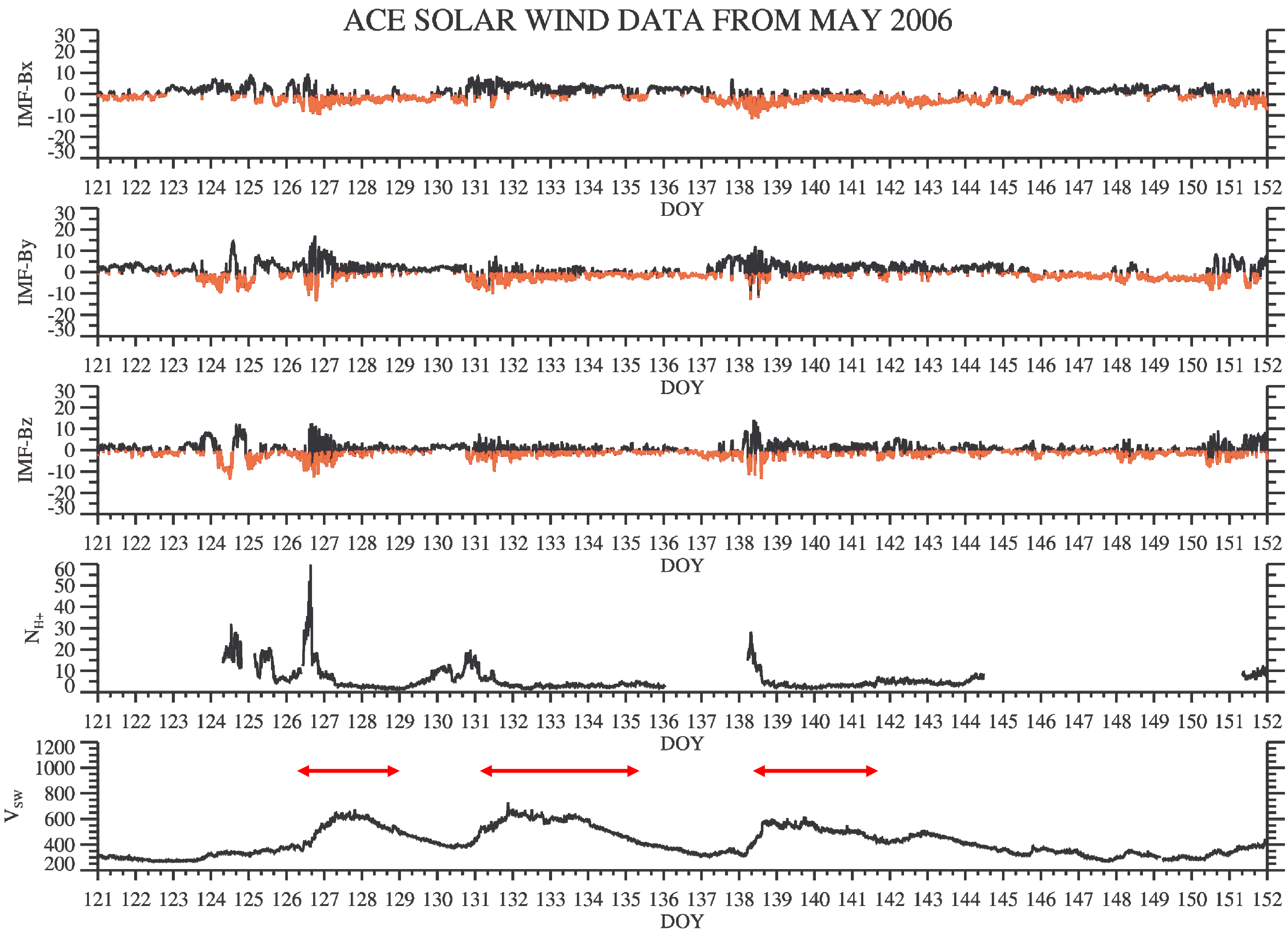






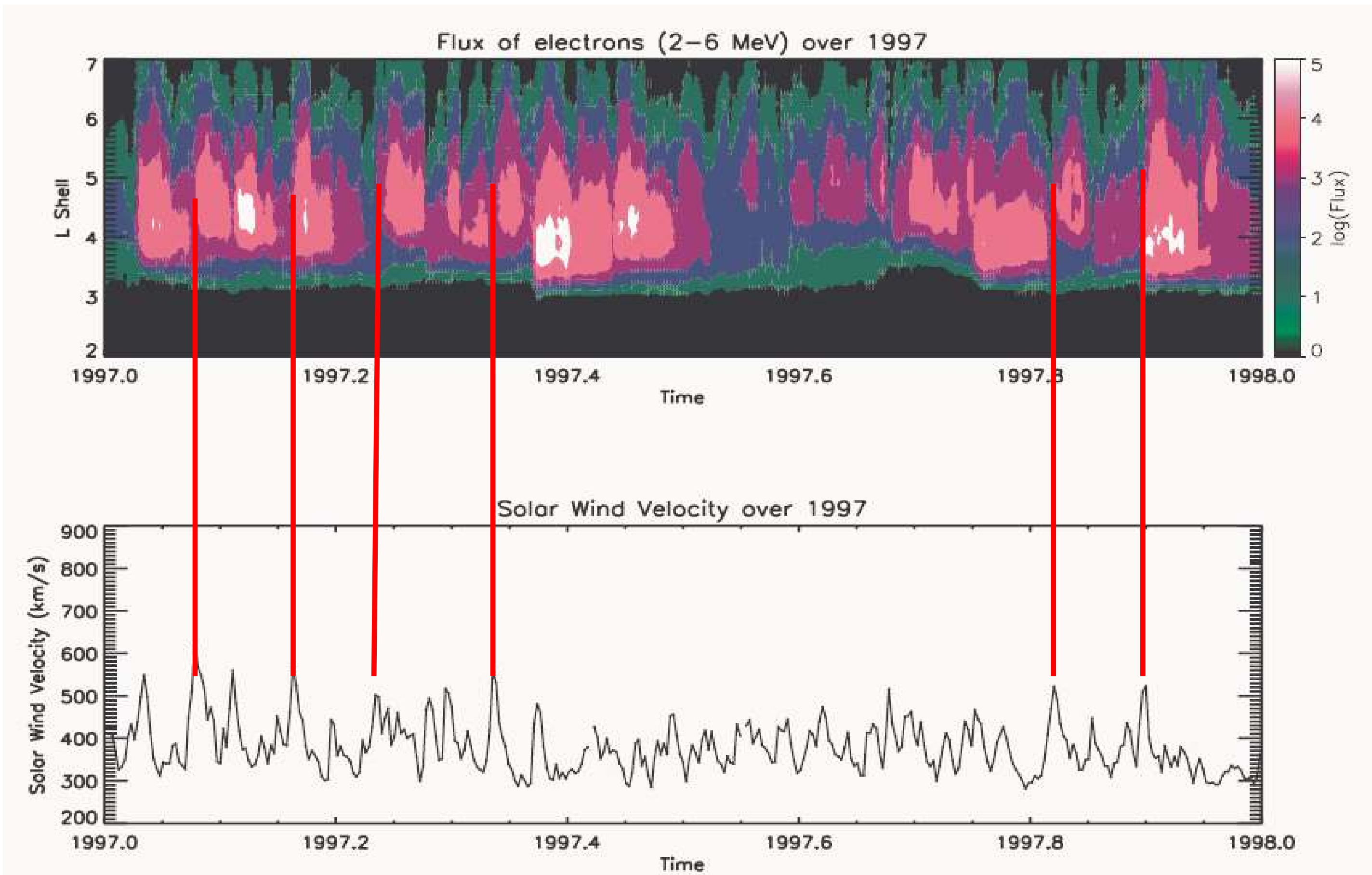
Fast solar wind most often detected at Earth in the declining phase, but can occur at any point in the solar cycle.

Solar Wind Speed : OMNI Statistics



What Controls the Electron Flux in the Outer Radiation Belt?

It has long been known that the electrons we count in the outer radiation belt fluctuate wildly....the flux can increase/decrease by up to five orders of magnitude in a 24 hour period. Why?

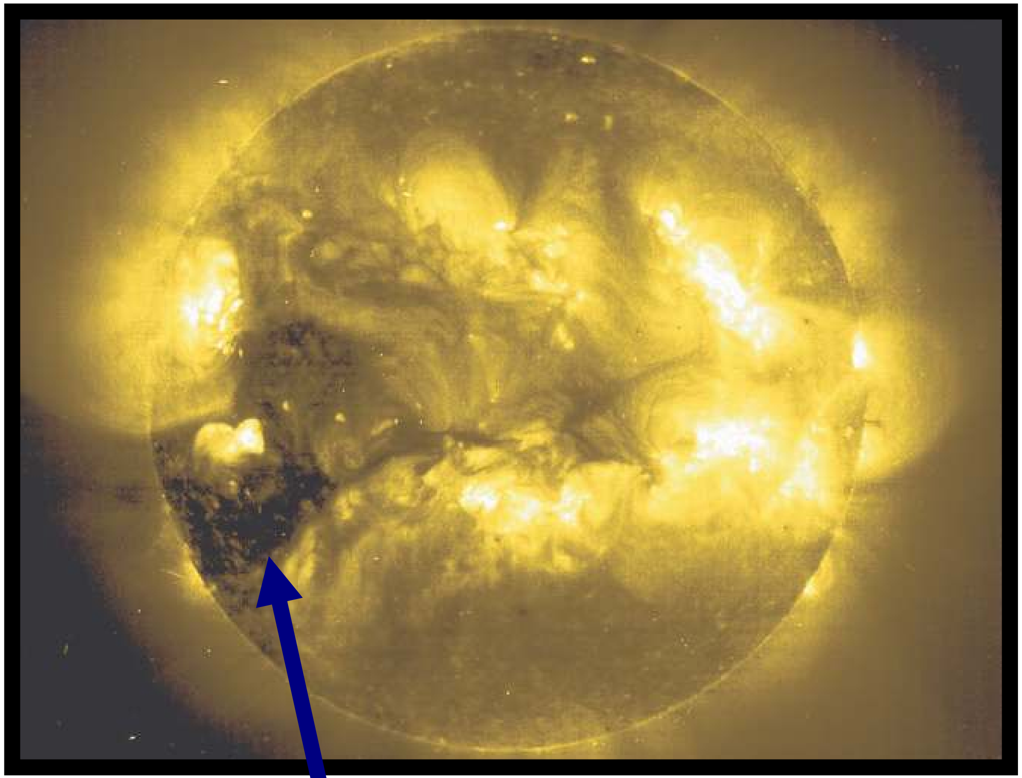


One things we do know about electrons in the outer belt is that the flux measured tends to increase when the solar wind speed is high.

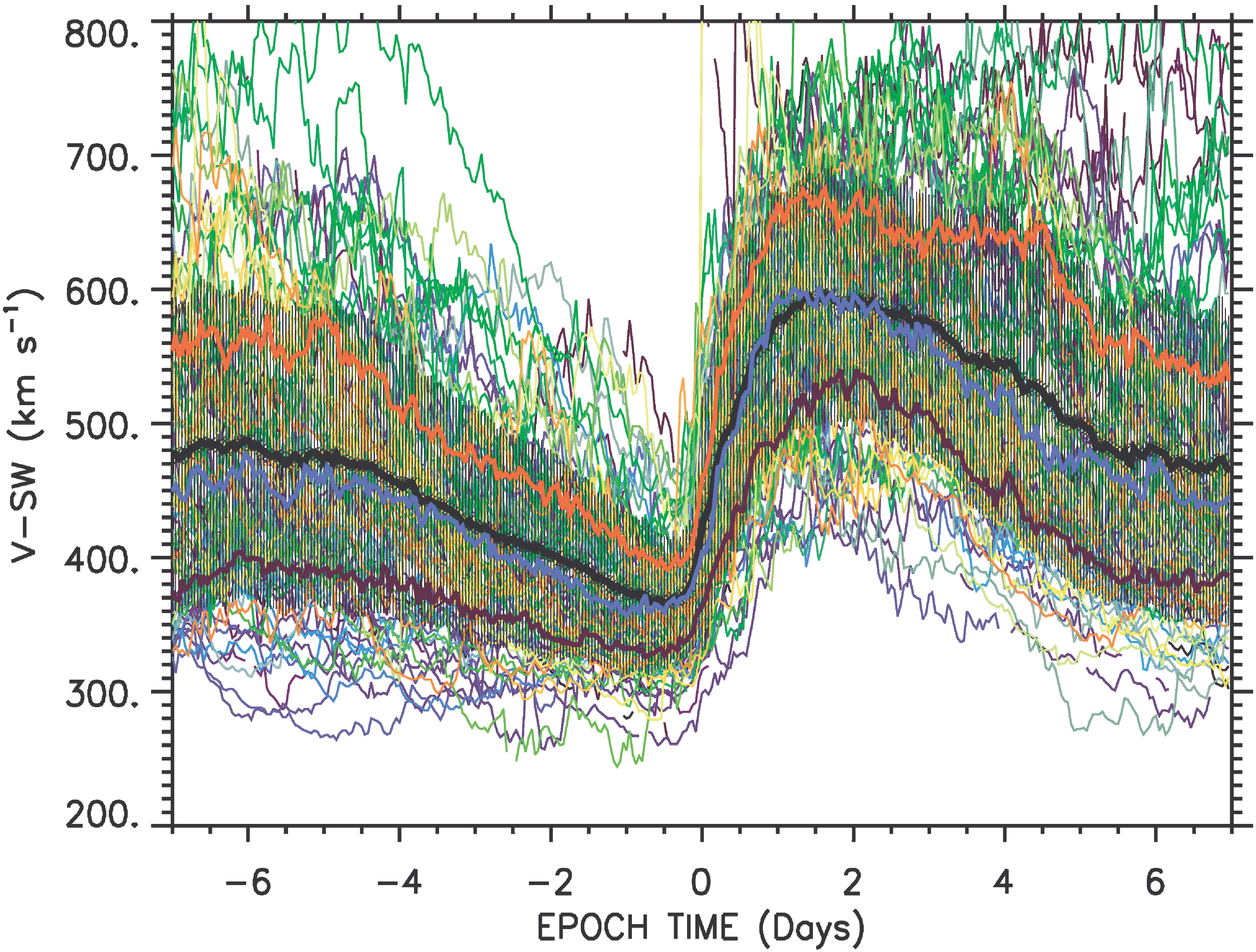
What Controls the Electron Flux in the Outer Radiation Belt?

High-speed Solar-wind Streams (HSSs)

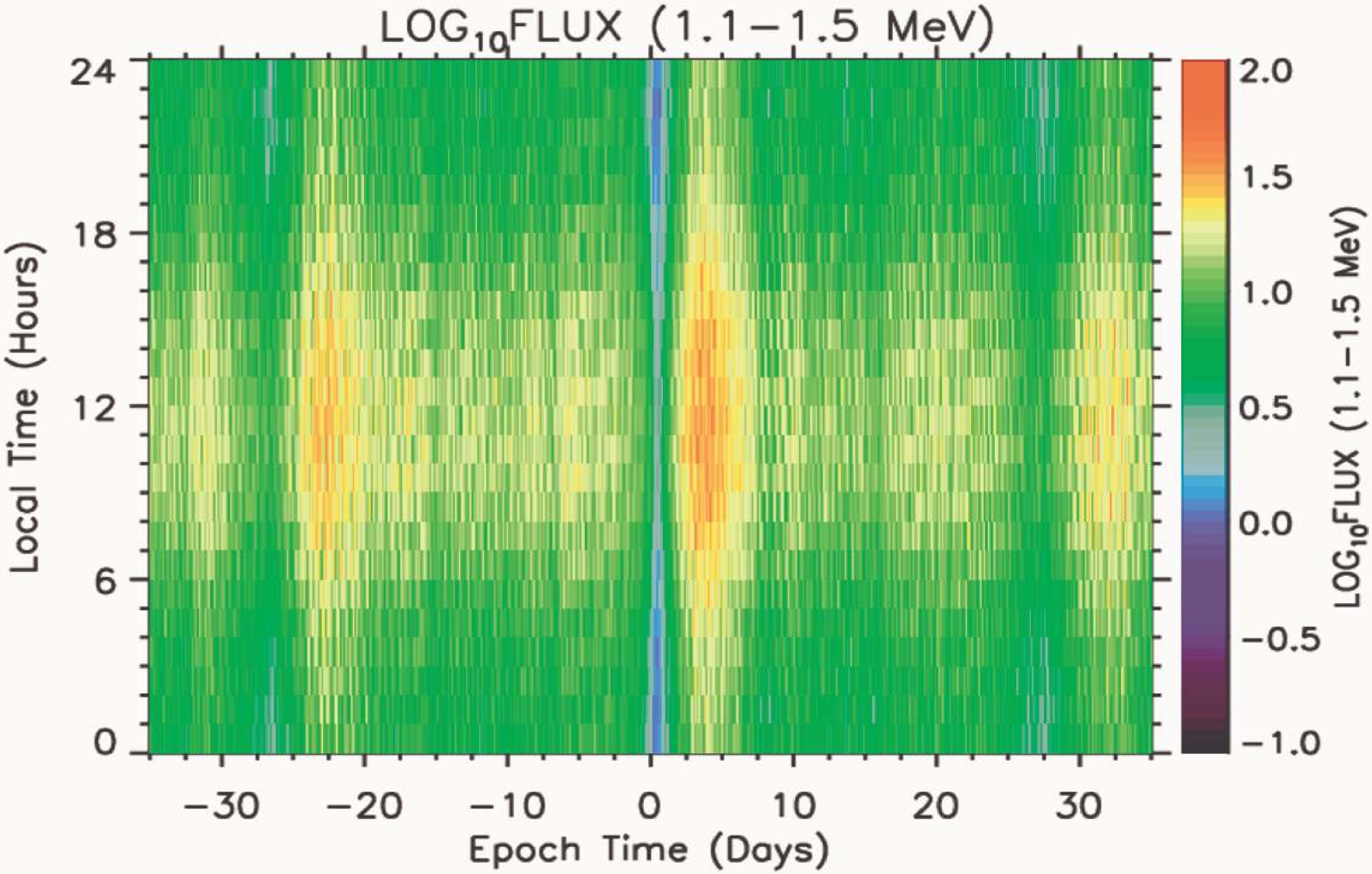
These are similar, **repeatable** structures in the solar wind that are related to coronal holes - the source of fast solar wind.



Source of 'fast' wind


800.
700.
600.
500.
400.
300.
200.
V–SW (km s^{-1})
−6
−4
−2
0
2
4
6
EPOCH TIME (Days)

What Controls the Electron Flux in the Outer Radiation Belt?



54 Years Later...

NASA launches the Radiation Belt Storm Probes (RBSP) mission (Van Allen Probes)

Members of the RBSP/ECT team at KSC for the launch of the RBSP satellite.

So What Are the Major Loss Mechanisms?

⦿ Outwards radial transport (minutes)

Particles drift outwards and collide with the magnetopause

⦿ EMIC-induced losses to the atmosphere (minutes)

Interactions driven by anisotropies in plasma

⦿ Chorus-induced losses to the atmosphere (microbursts <1 second)

Cyclotron-resonant interaction leads to rapid losses over short time scales

⦿ Plasmaspheric hiss losses (~days)

Recent evidence supports the idea that hiss evolves from discrete chorus waves.

Differentiating between the different loss mechanisms is not simple...
(VAN-ALLEN / BARREL / VLF /, etc.)

Origins of This Work

If particles in the radiation belts precipitate in the atmosphere, they must have an effect.

Can we quantify this effect and set upper/lower bounds for its importance?

Particle Precipitation

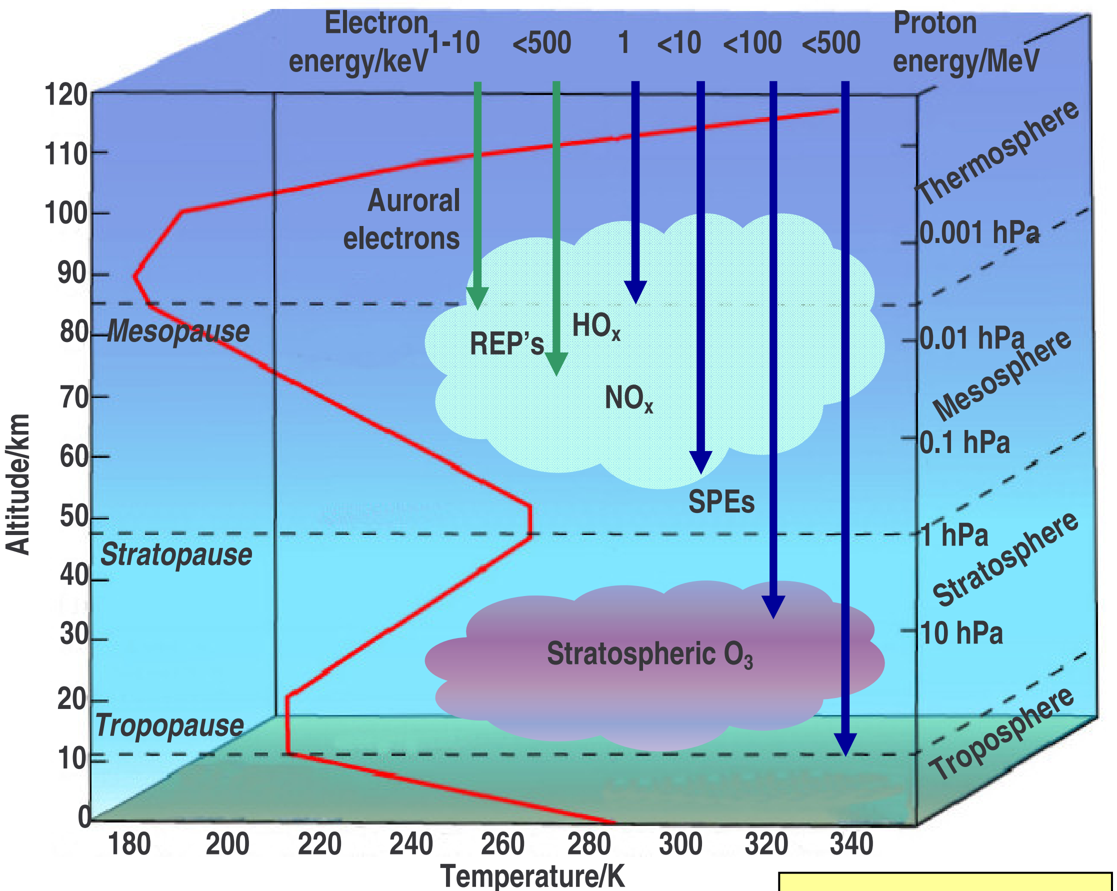
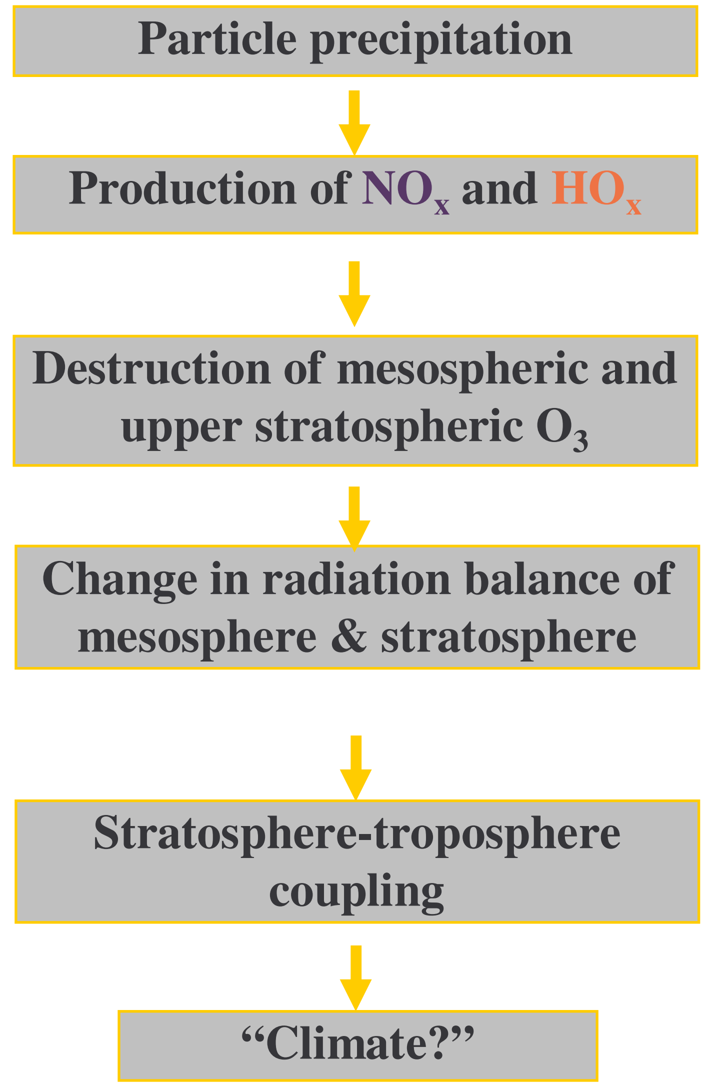


Figure by Craig Rodger



NO_x = N, NO, NO_2 — **Indirect** route to O_3 destruction

HO_x = H, OH, HO_2 — **Direct** route to O_3 destruction

Why Do We Care?

Two Main Issues For Stratospheric/Mesospheric Ozone

1. **Separating the cause of "natural" and "un-natural" variations**
   (i.e. separating natural variations from anthropogenic changes and/or space-weather related effects)

2. **Predicting future ozone levels and climate**
   (usually via global models)

Regardless of how good models may be, OBSERVATIONS provide direct in-situ measurements of natural/un-natural O_3 variations.

Measuring Stratospheric Ozone

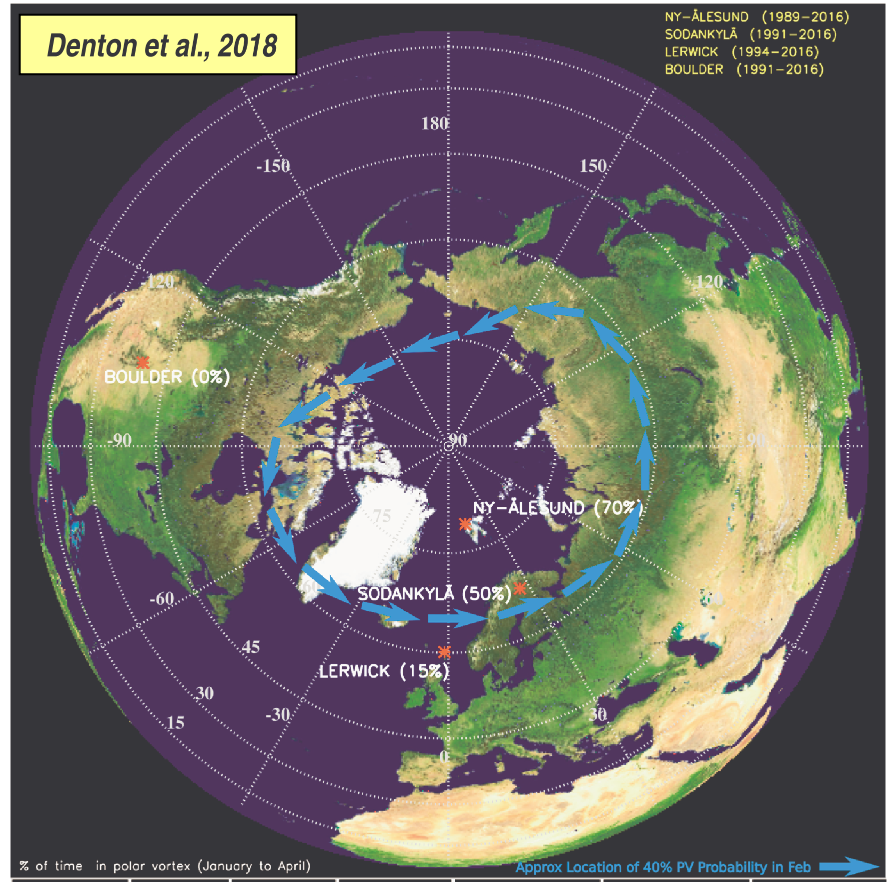
Launching a 'sonde' from Sodankylä, Finland.

❖ Ozonesonde observations from four sites: 1989-2016

❖ Study annual and seasonal changes in ozone

❖ Effect of SPEs on O_3

❖ Effect of SSWs on O_3

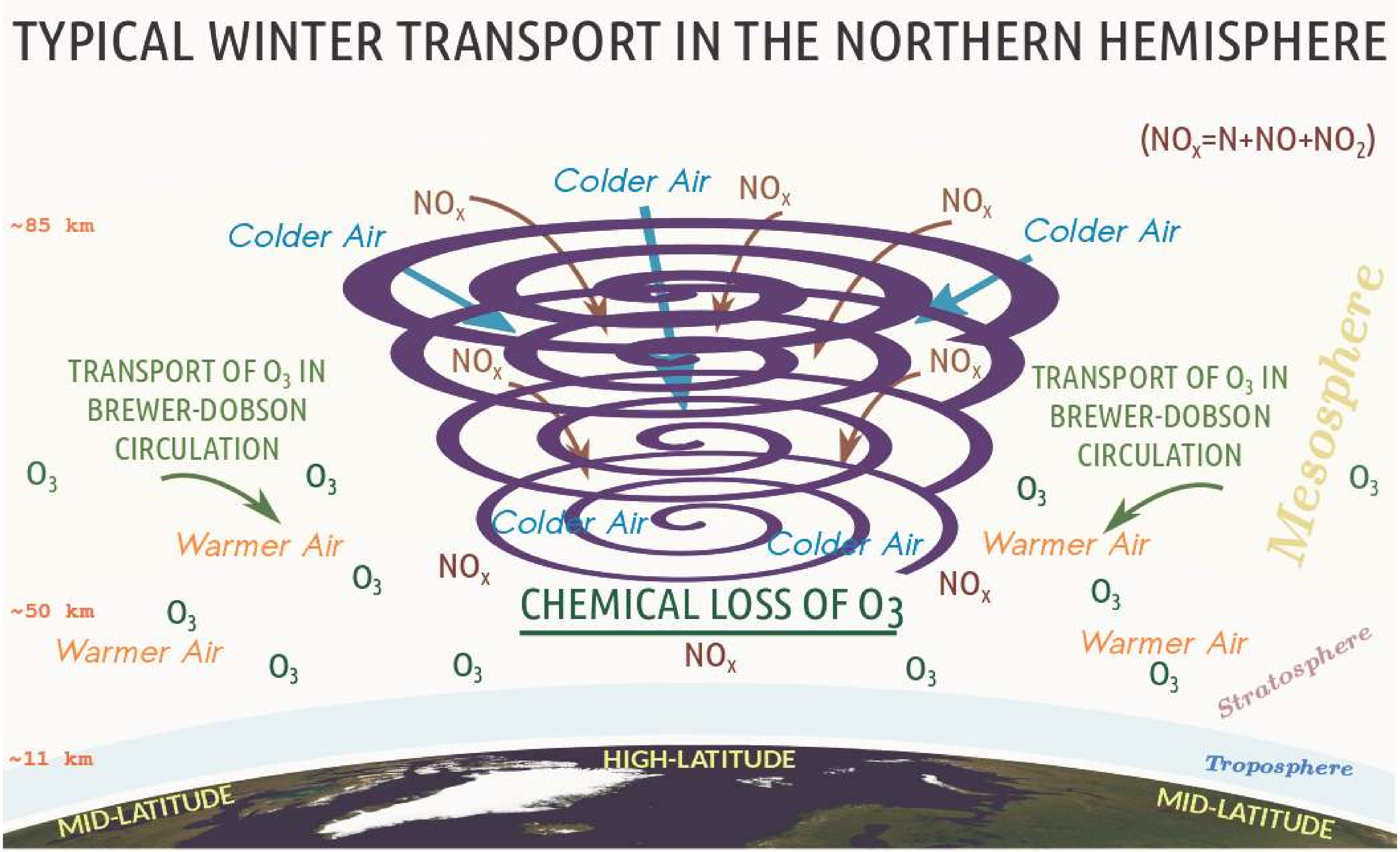


Sites	Latitude (GLAT)	Longitude (GLONG)	Magnetic Latitude (CGM)	Average Time in PV (Jan-Apr)	#Ozonesondes in Analysis	Reference
Ny-Ålesund	78.90	12.00	76.15	~70%	2350 (1991-2016)	*Rex et al.* [2000]
Sodankylä	67.37	26.63	26.63	~50%	1886 (1989-2016)	*Kivi et al.* [2007]
Lerwick	60.15	-1.15	58.03	~15%	1289 (1994-2016)	*Smedley et al.* [2012]
Boulder	40.01	-105.27	48.90	~0%	1287 (1991-2016)	*Johnson et al.* [2002]

Quantify statistical changes in stratospheric ozone during these events.

Most study to date has been single events. Difficult to remove seasonal bias in the data.

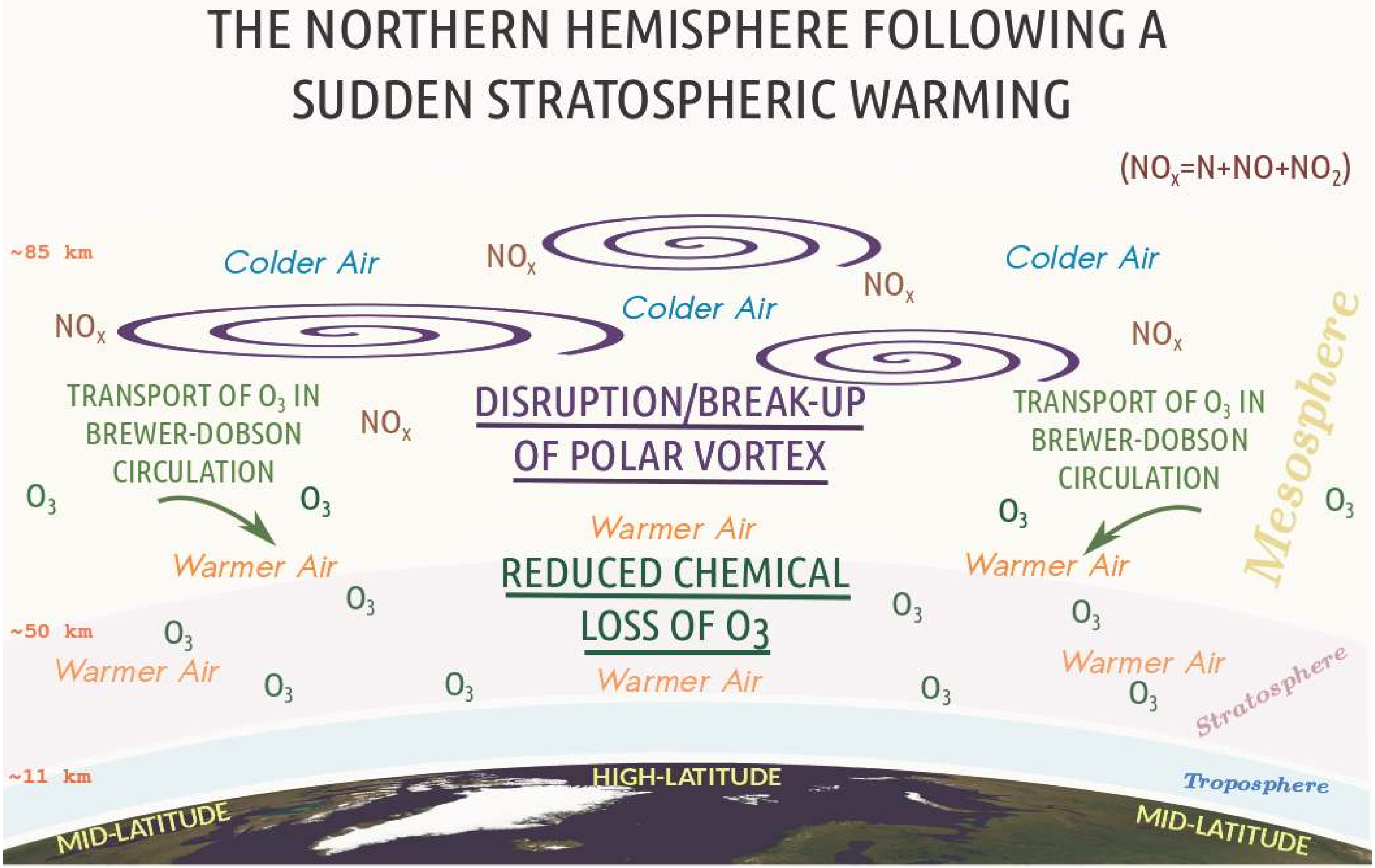
Overview



=Polar Vortex (PV)

Denton et al., 2018

Overview



Denton et al., 2018

Overview

Examine Two Types of Event:

(a) Solar Proton Events (SPEs).

Precipitation creates extra/new NO_x in the mesosphere

Descent of this additional NO_x in the winter PV

Greater reduction in stratospheric ozone (less ozone)

191 events (1989-2016)

(b) Sudden Stratospheric Warmings (SSWs).

Disruption of the PV

Rapid increase in temperature

Reduced descent of NO_x

Reduced winter destruction of ozone (more ozone)

37 events (1989-2016)

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(c) But what about HSSs...?

Introduction to Solar Proton Events (SPEs)

- Solar Proton Events are high fluxes of protons due to energetic events in the solar wind (shocks).

- Energetic protons penetrate into the atmosphere to depths that are dependent on the incident energy (More energetic = lower altitude).

- For energies > ~few MeV the protons will penetrate to the mesosphere/stratosphere where they can create NO_x and HO_x families of particles.

  HO_x is short-lived (DIRECT route to ozone destruction)

  NO_x is long-lived in darkness (INDIRECT route to ozone destruction).

JUL-OCT

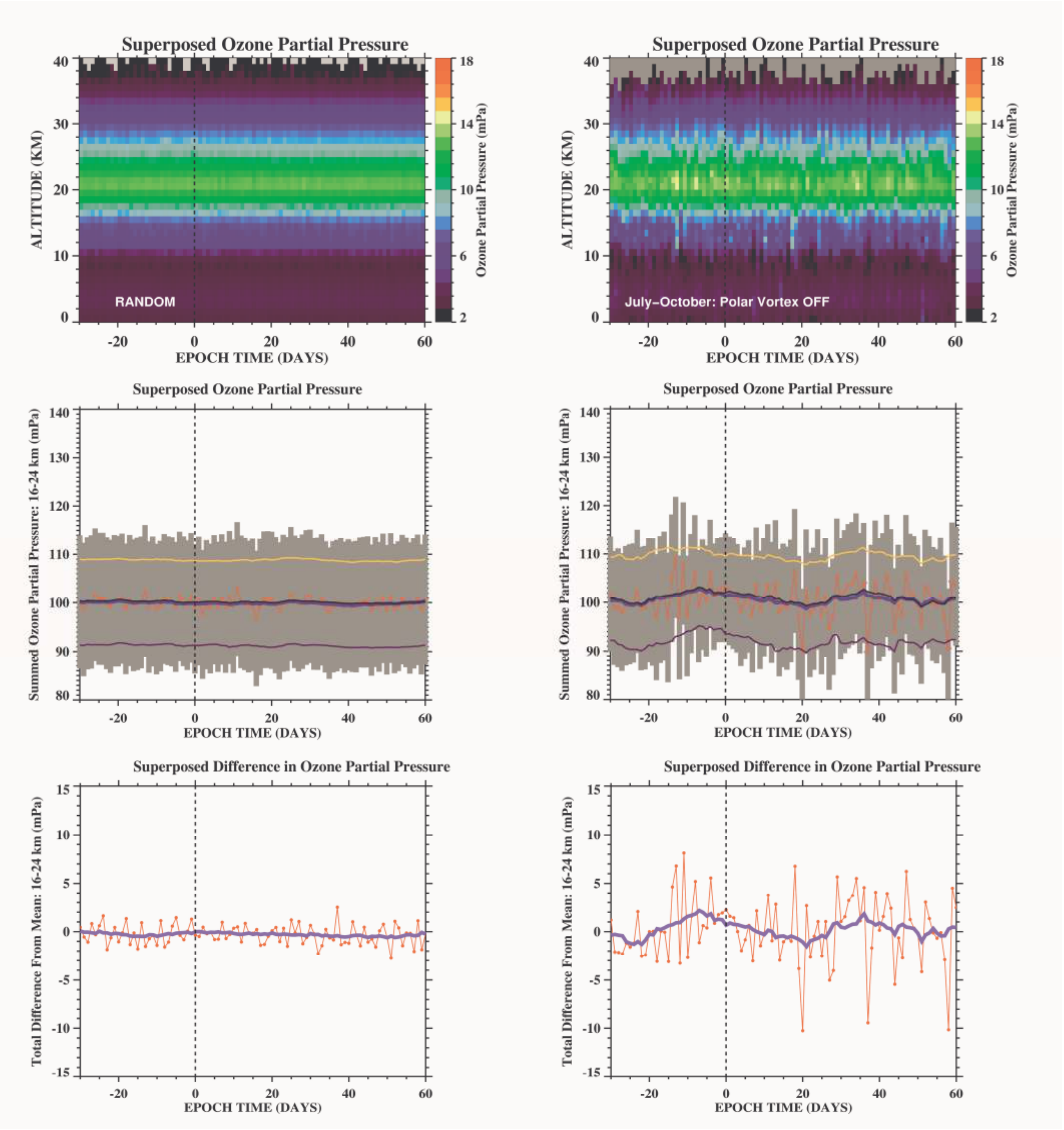
❖ Compare ozone partial pressure as a function of time before/after the arrival of SPEs

❖ 191 SPEs between 1989-2015

❖ Compare results against random events

❖ Subtract monthly mean from each data-point to reveal seasonally adjusted changes in O_3

LITTLE CHANGE IN OZONE WHEN PV IS NOT PRESENT



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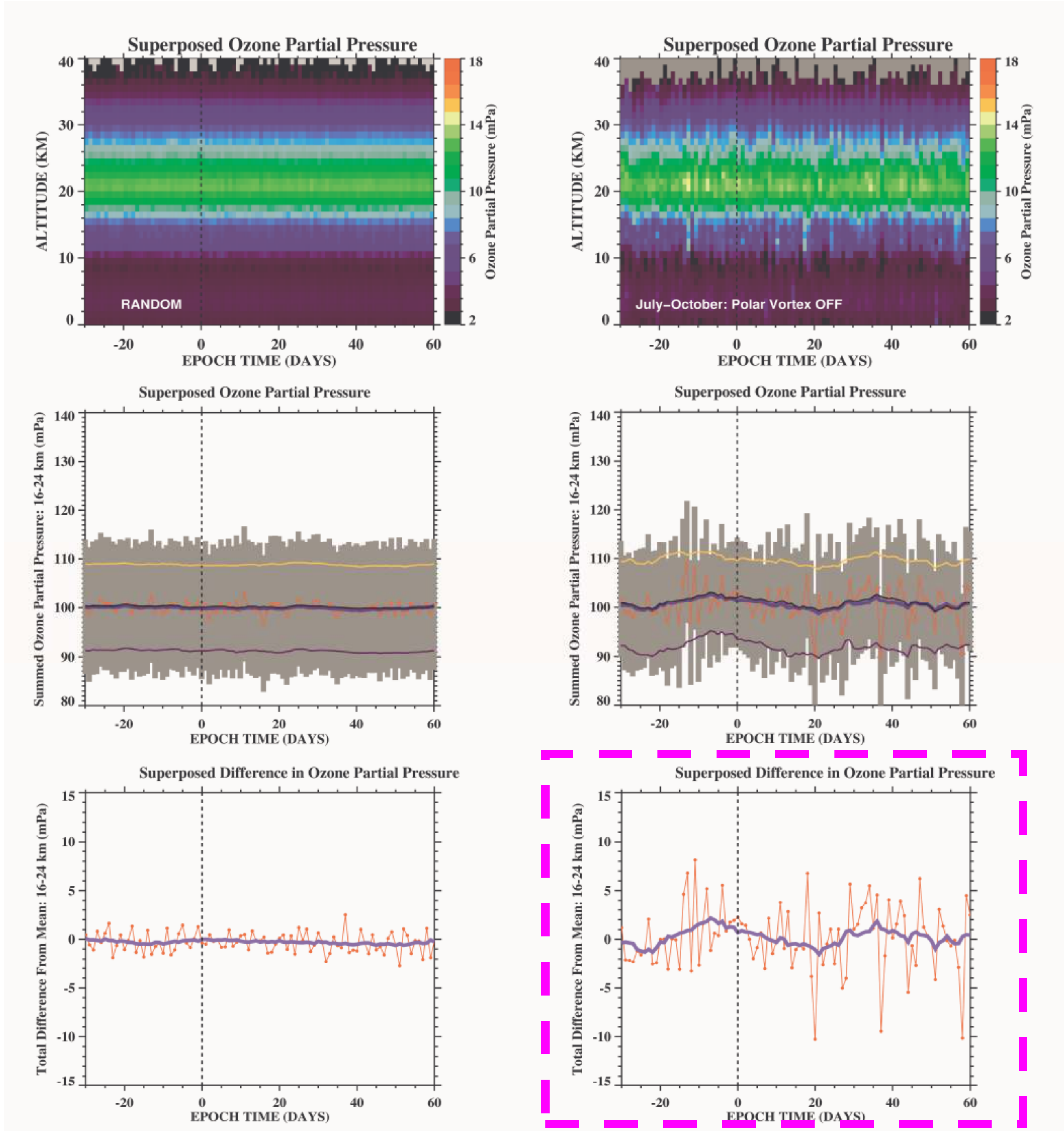

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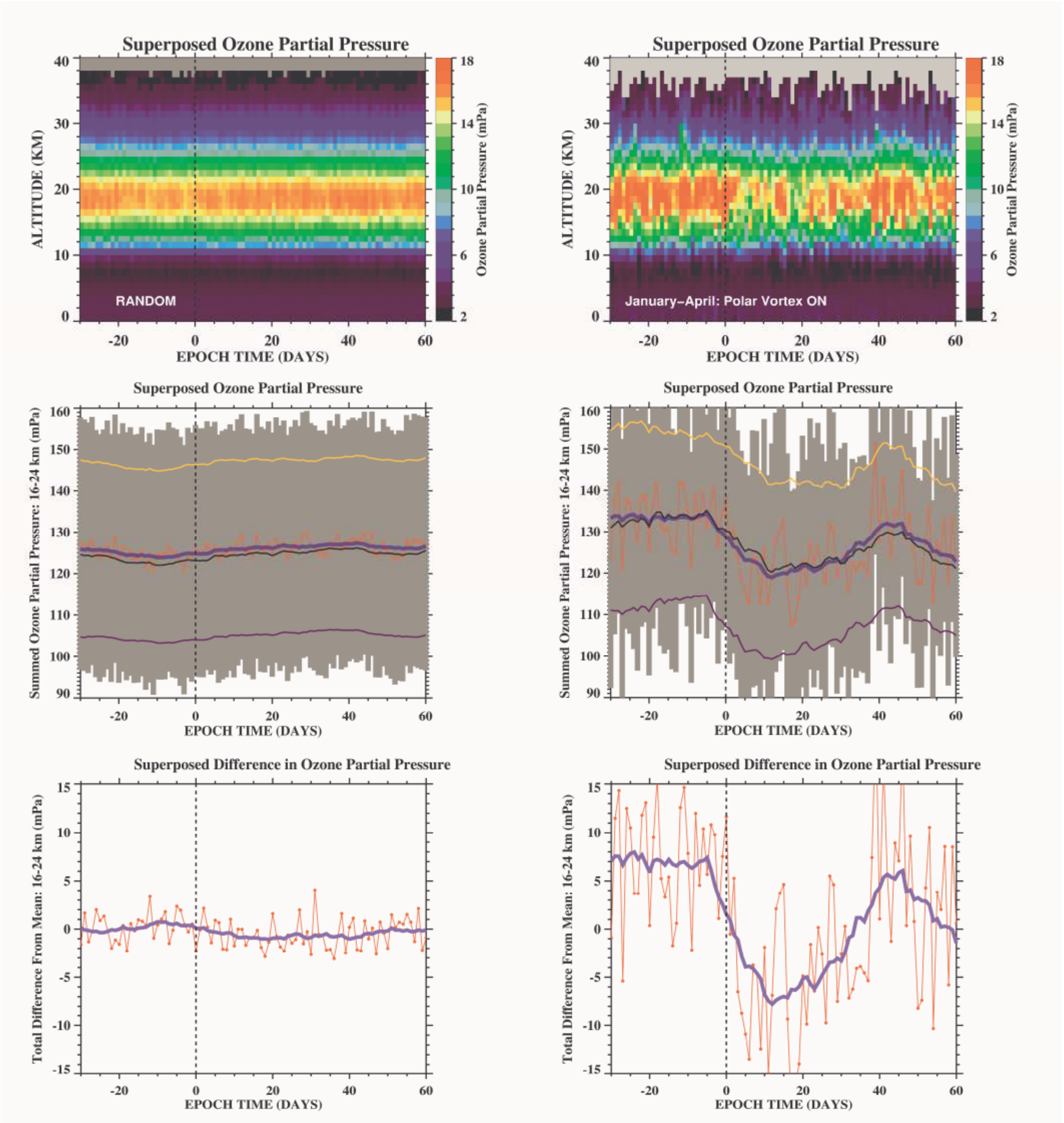

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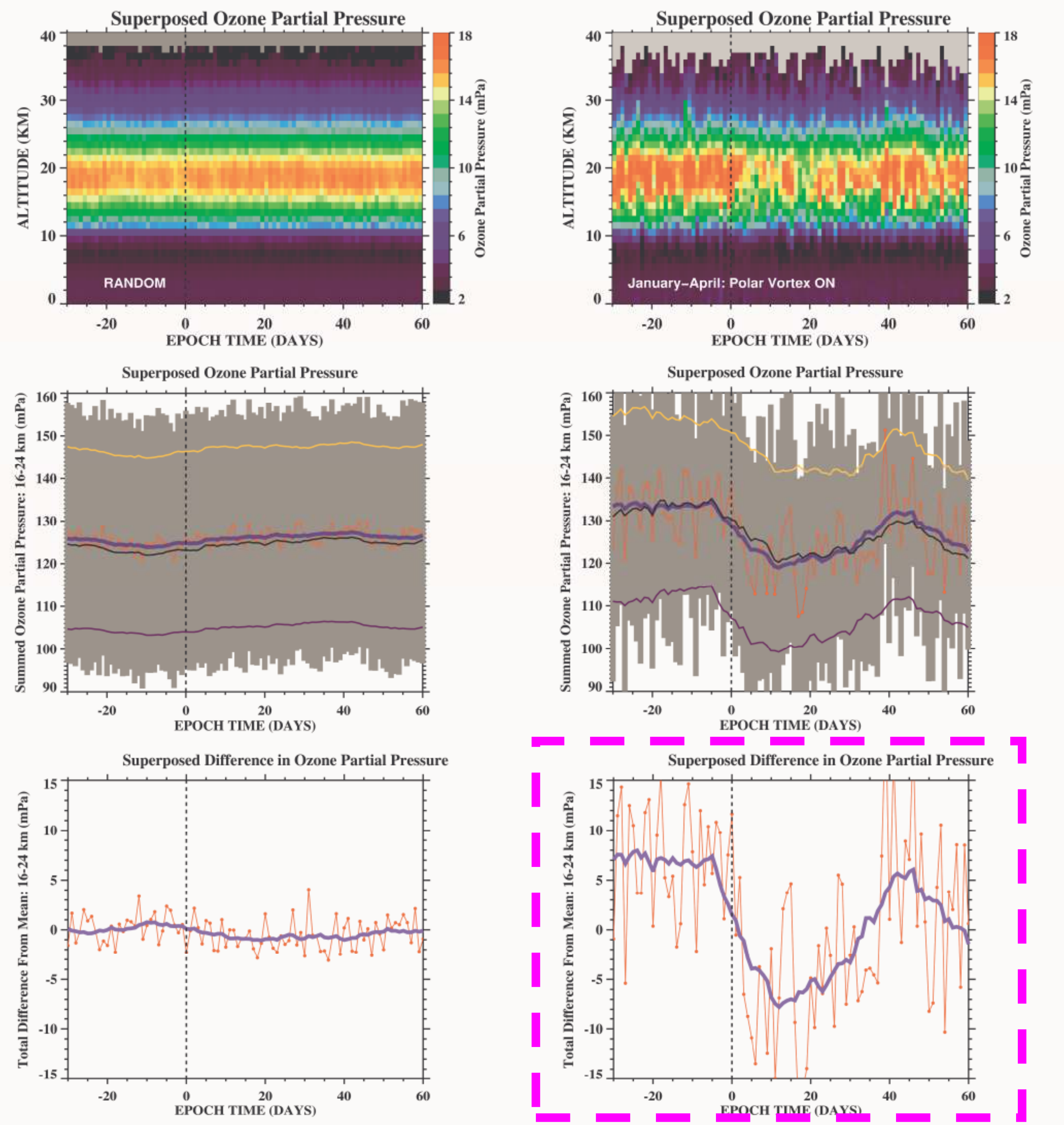
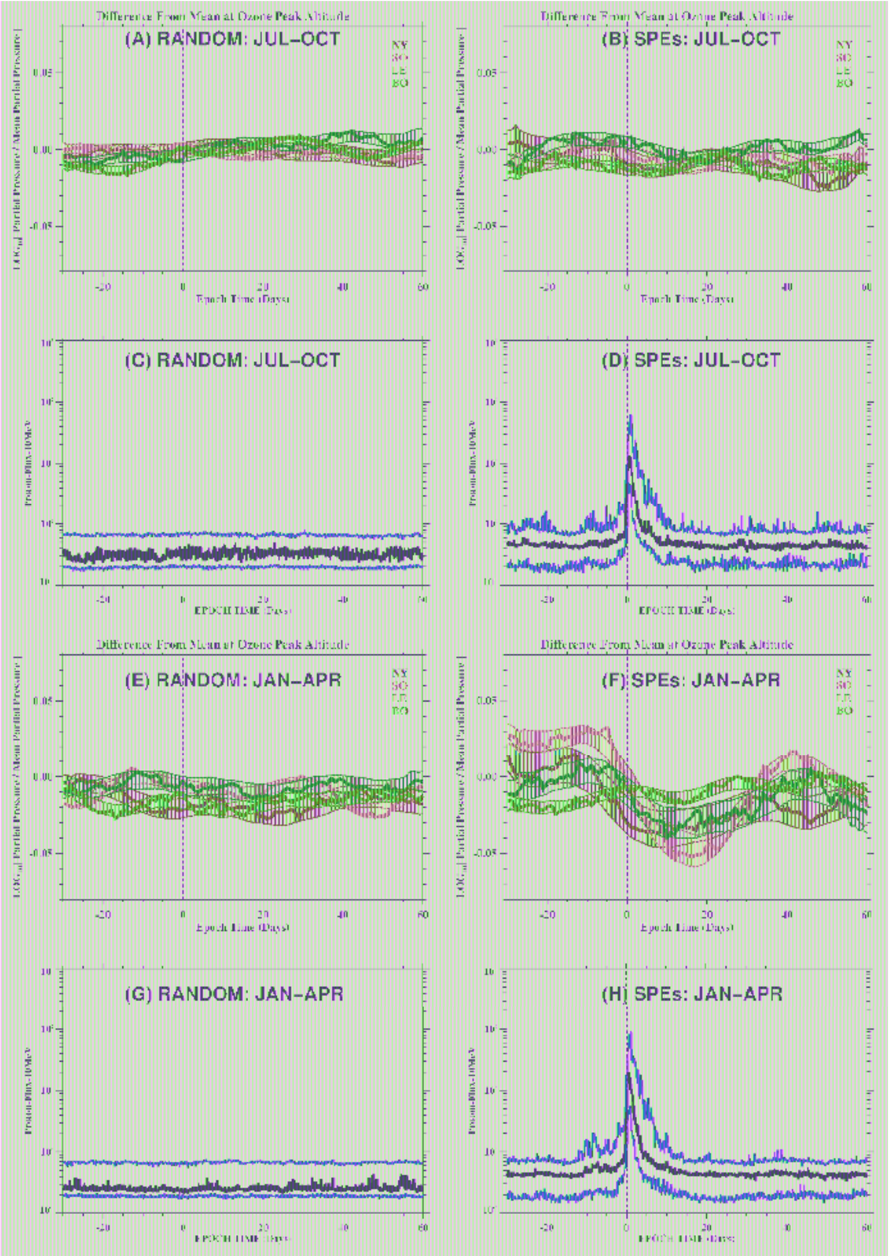


Summary (SPEs)

Summary of results for:

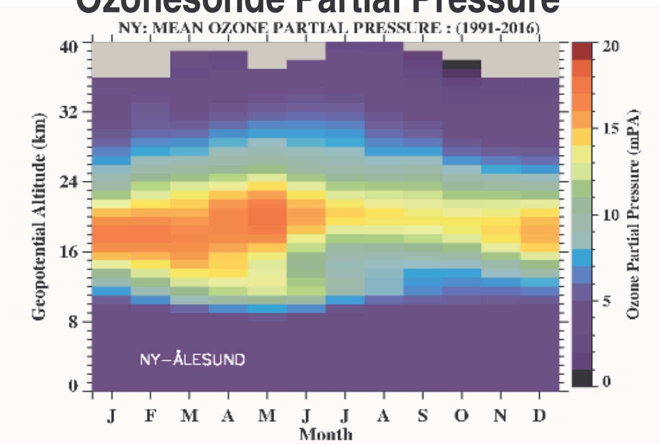
Ny-Ålesund (70% in PV)
Sodankylä (50% in PV)
Lerwick (20% in PV)
Boulder (0% in PV)



- **No change in ozone for random events**
- **No change in ozone in summer (no PV)**
- **Stratospheric ozone decreases rapidly for in excess of 30 days, but only for sites in PV (not Boulder). Overall decrease is ~10%.**

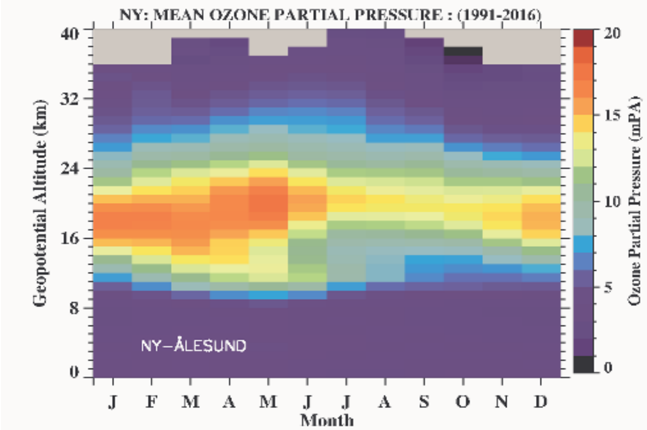
AURA/MLS v Ozonesondes

Ozonesonde Partial Pressure

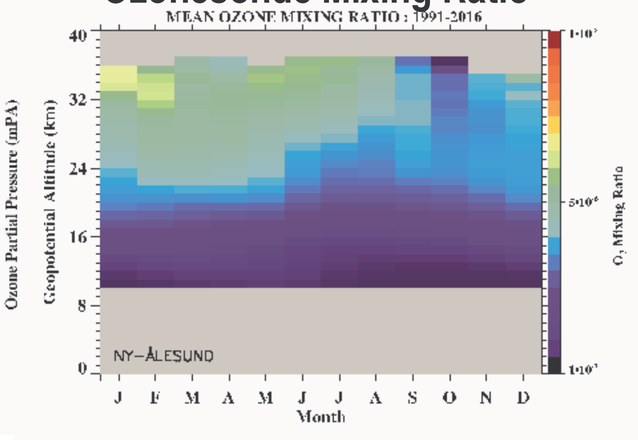


Mean Annual Ozone

Ozonesonde Partial Pressure



Ozonesonde Mixing Ratio



Mean Annual Ozone

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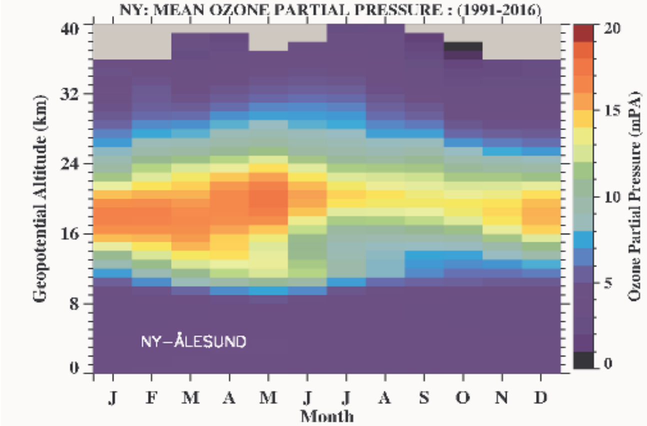

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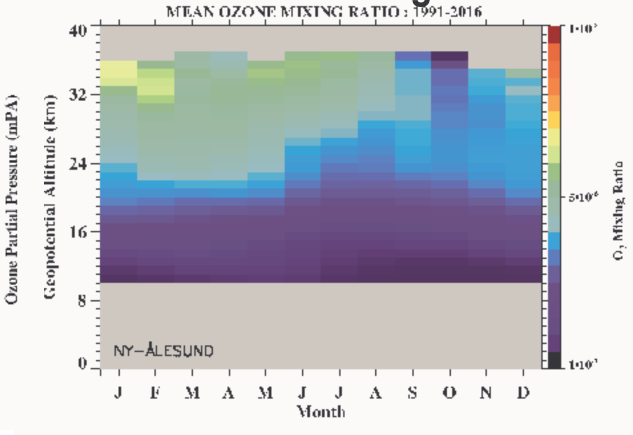
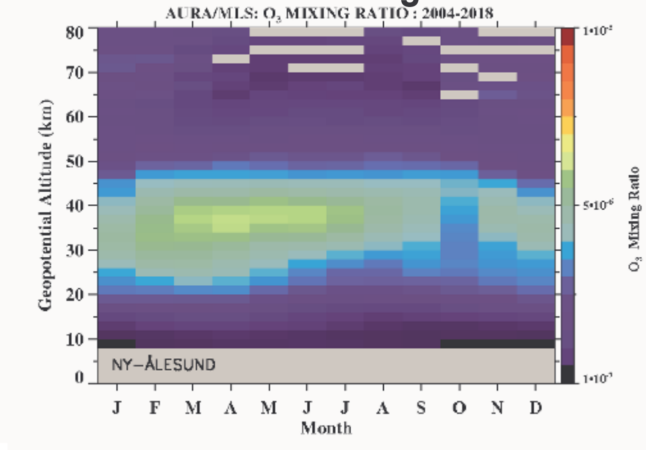
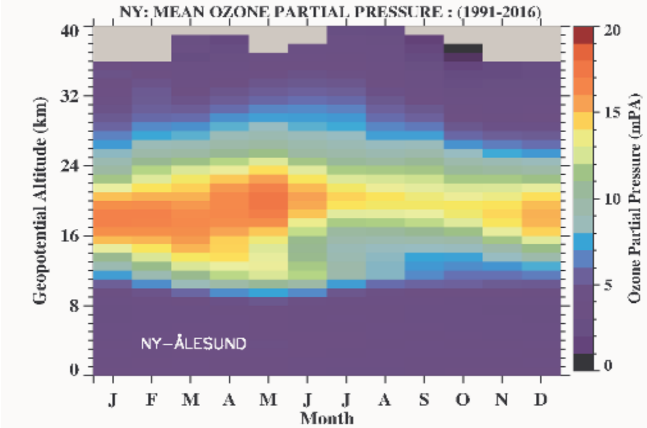


AURA/MLS Mixing Ratio



Mean Annual Ozone

Ozonesonde Partial Pressure



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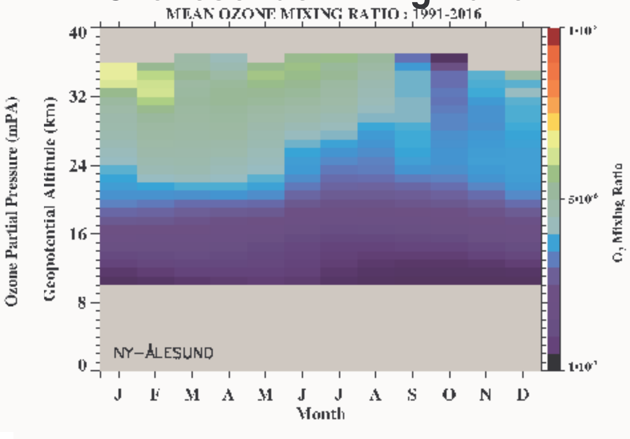

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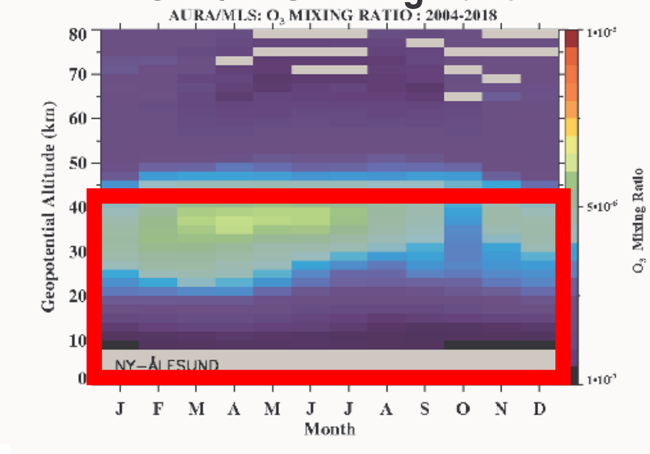
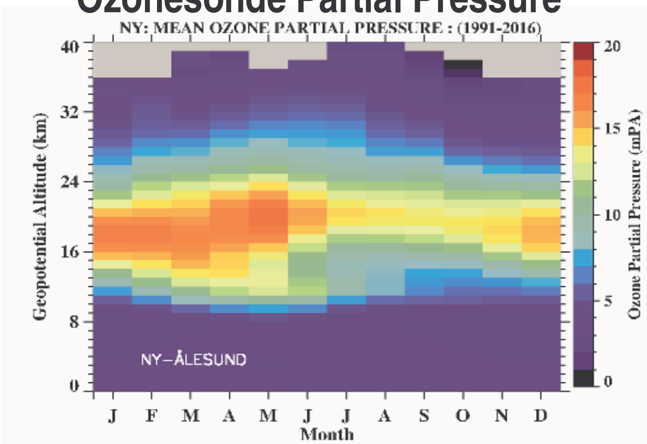


Mean Annual Ozone

Ozonesonde Partial Pressure



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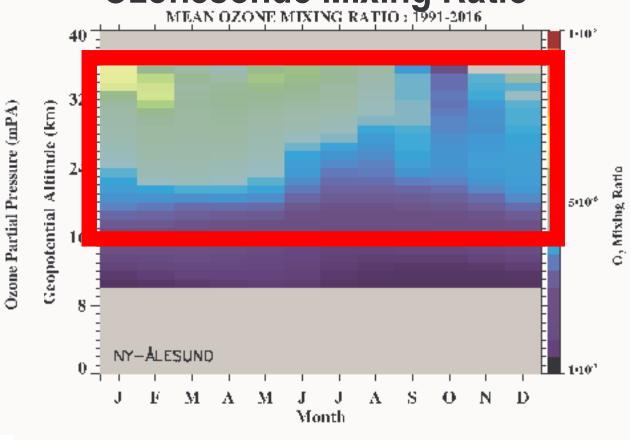
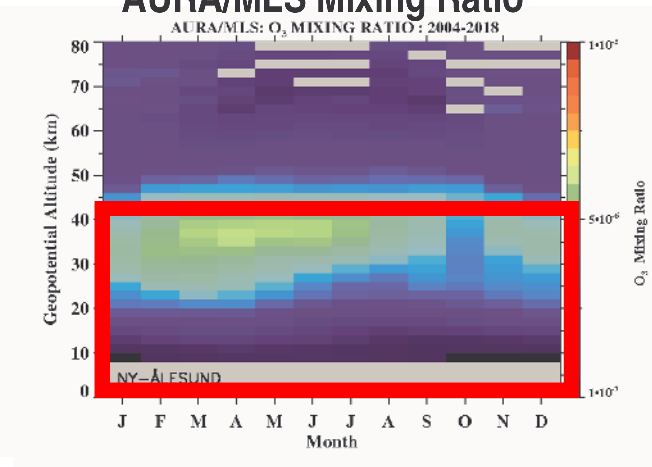


AURA/MLS Mixing Ratio

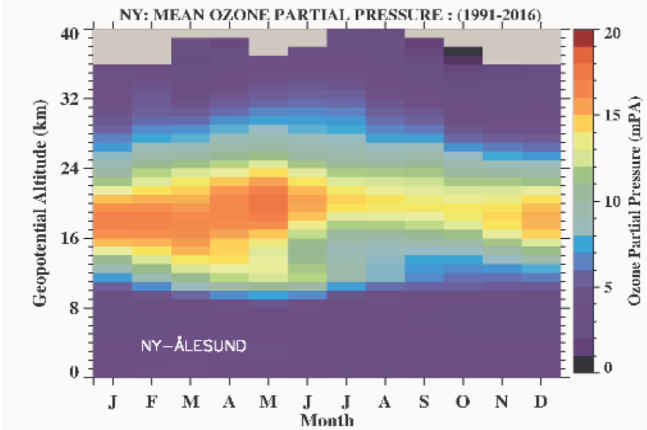


1991-2016

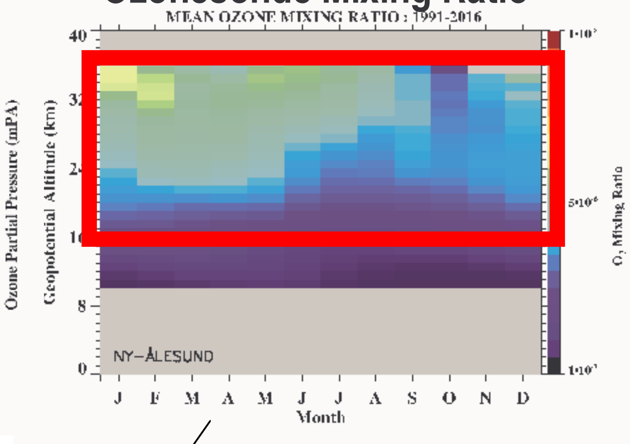
2004-2018

Mean Annual Ozone

Ozonesonde Partial Pressure



Ozonesonde Mixing Ratio



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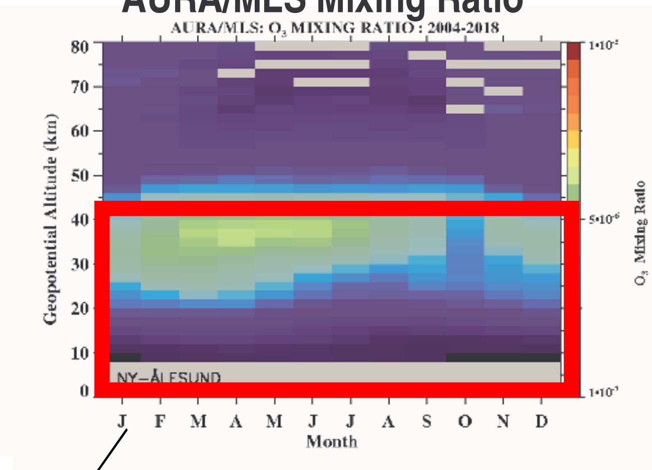
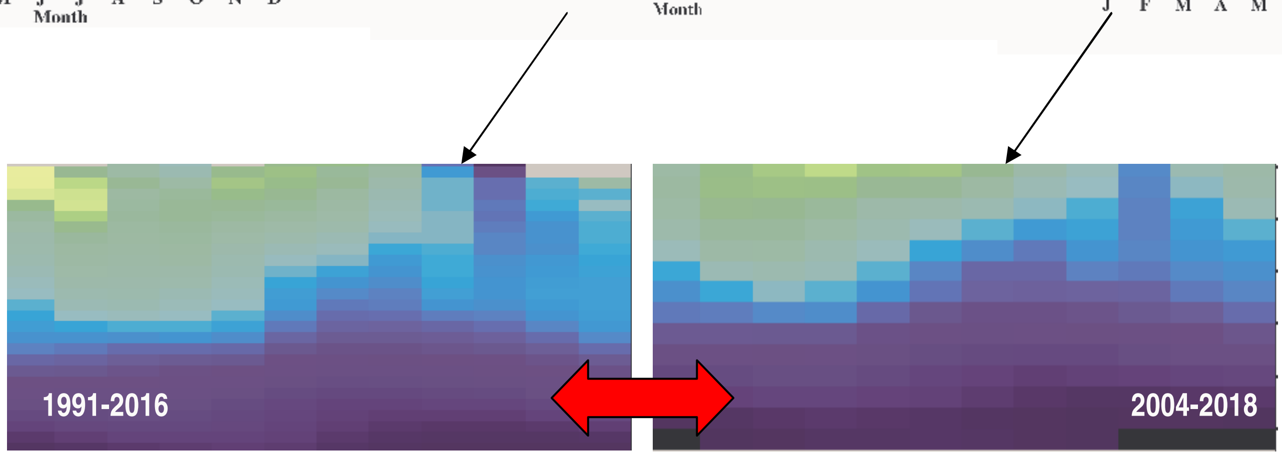
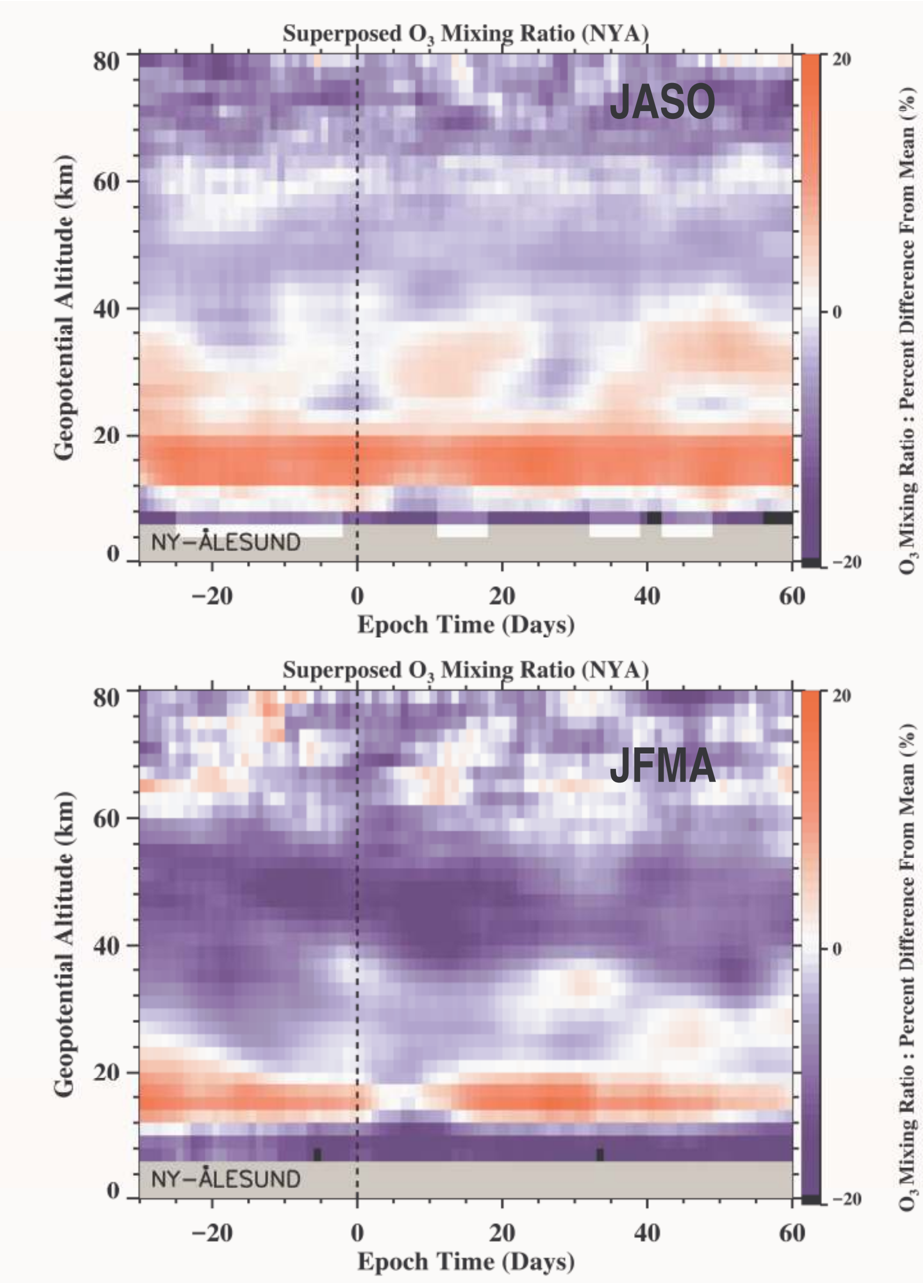




Ozonesonde and AURA/MLS Agree Reasonably Well...

Summary (SPEs)



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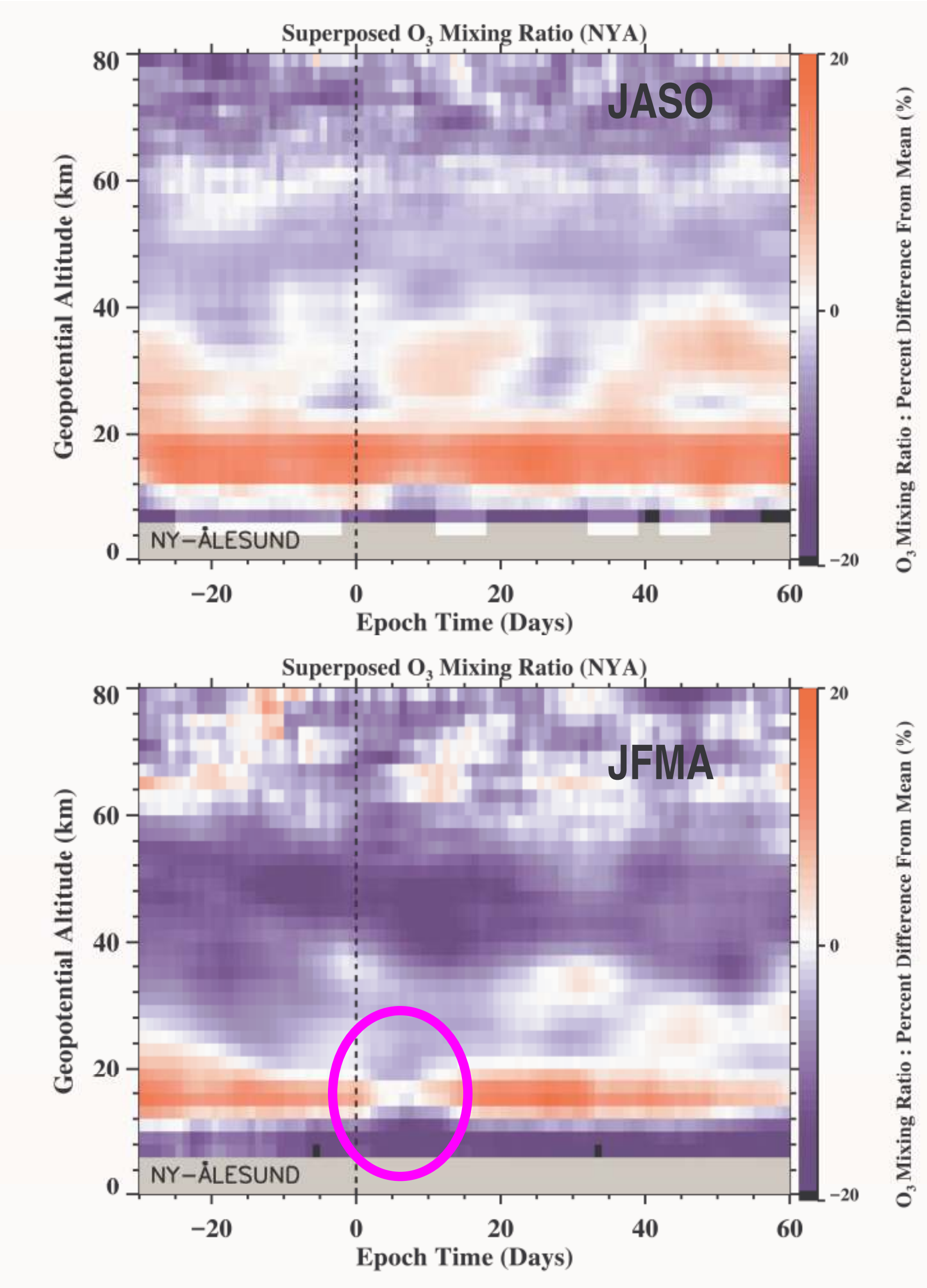

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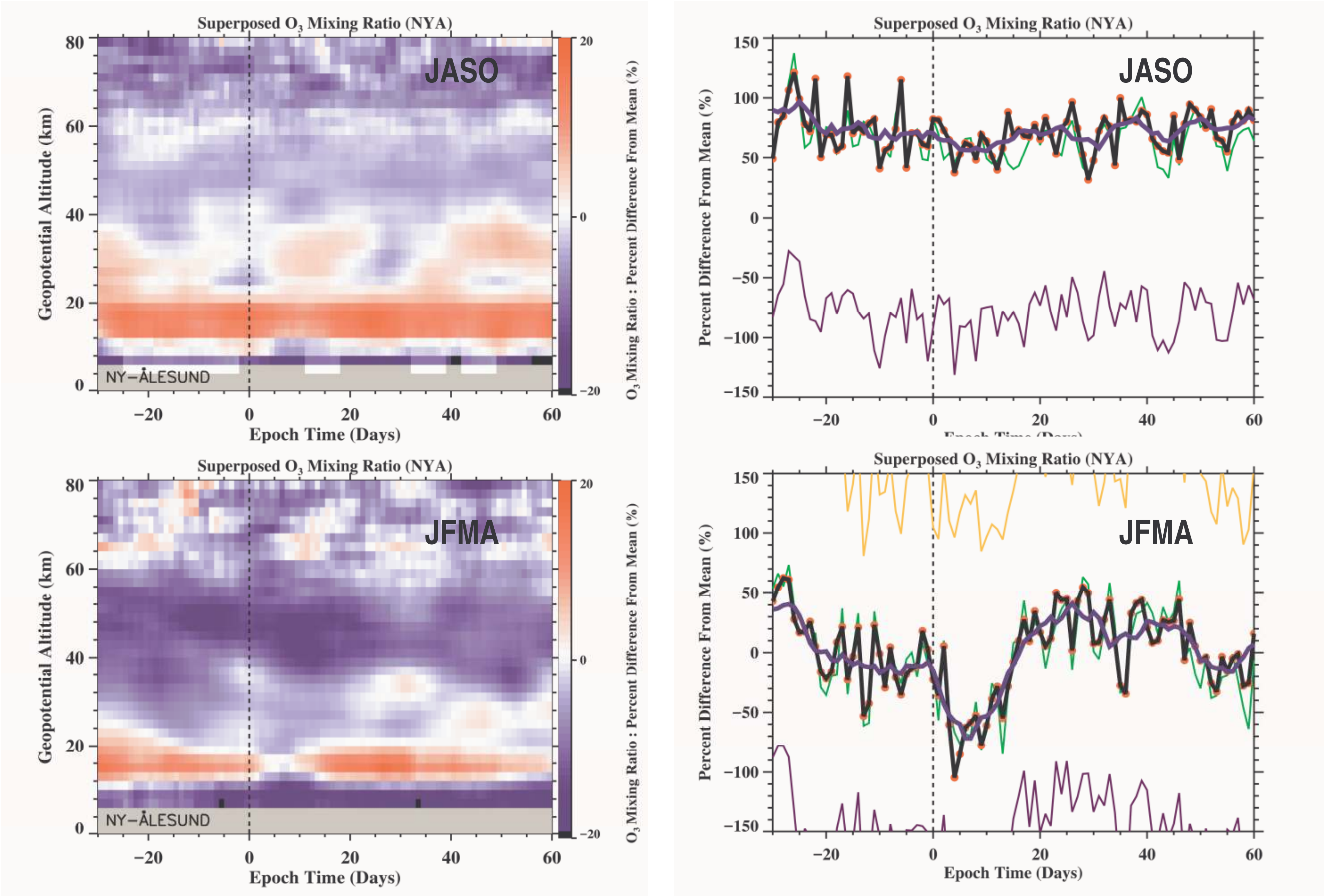


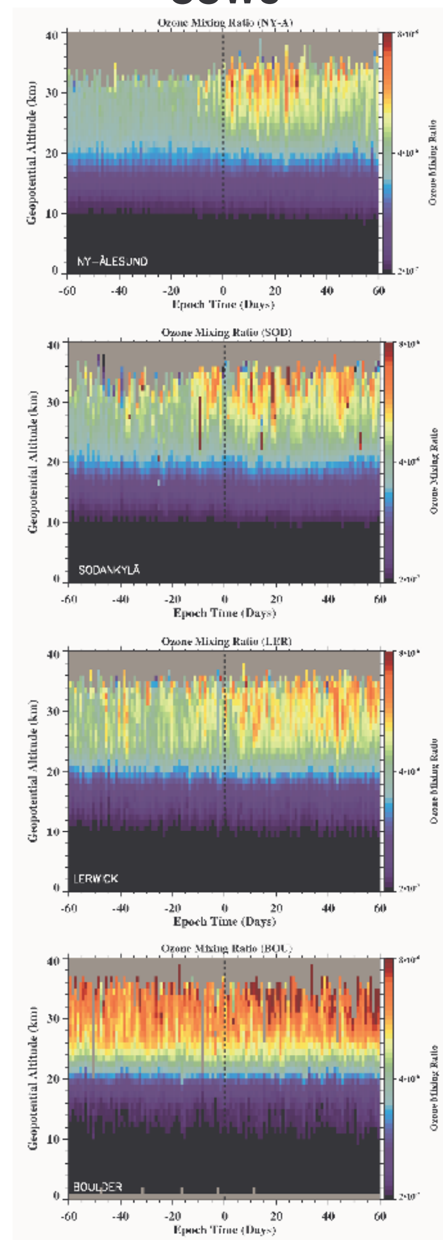
Ozonesonde Data from Four Sites

Same ozonesonde balloon data as before, now plotted as "volumetric mixing ratio".

<u>We note:</u>

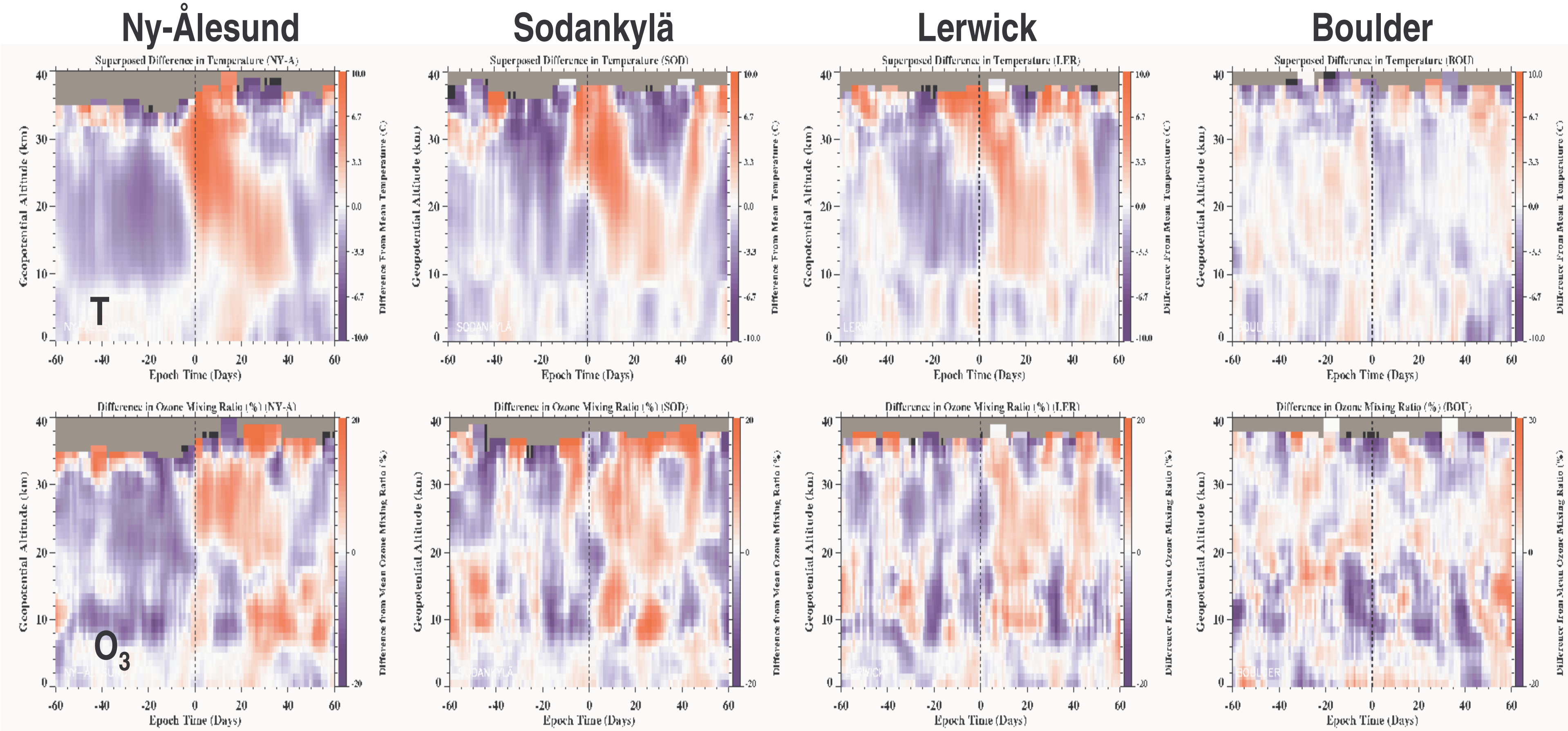
- **Rapid increase in ozone mixing ratio with the onset of SSWs**
- **Strongest increase at sites in the PV.**
- **No effect for sites outside the PV.**

SSWs



Denton et al., 2018

Summary of Ozonesonde Observations



Seasonally-detrended results.

~20% O_3 increase (above mean)

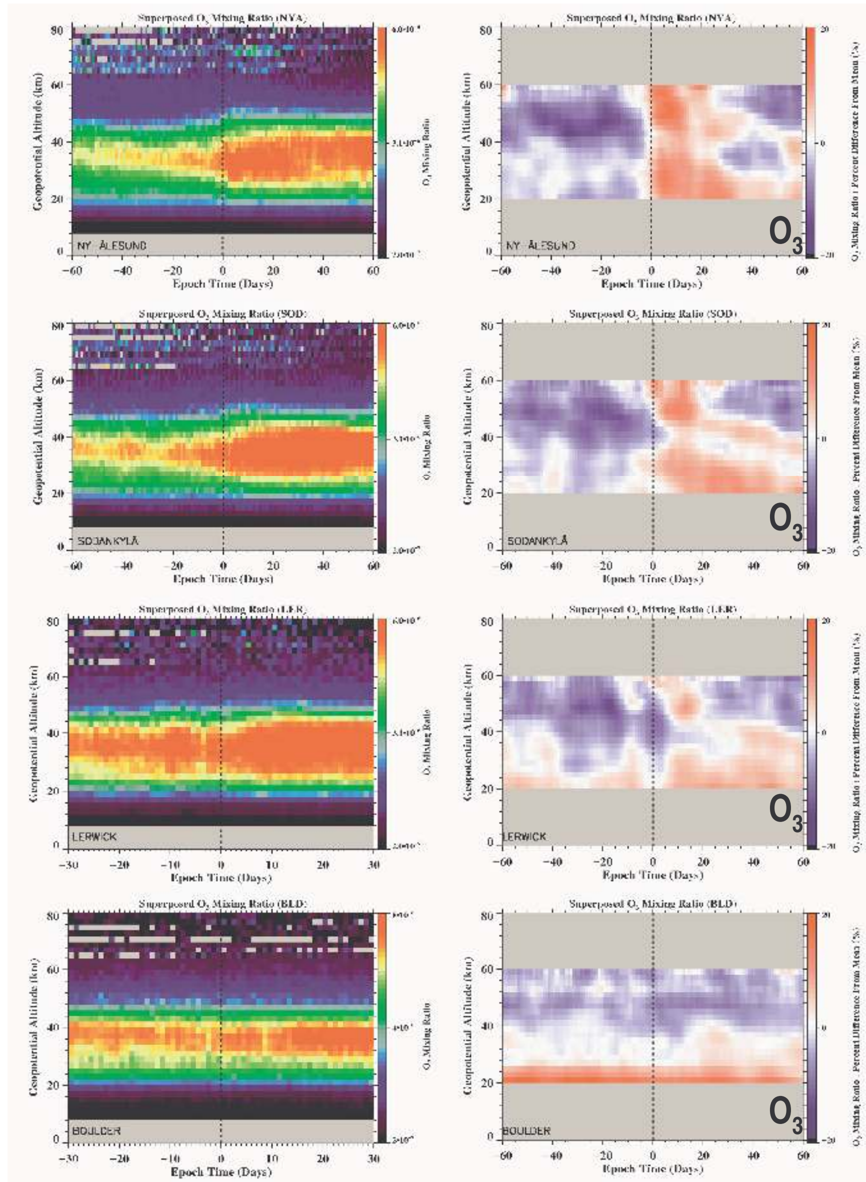
~15°C increase in T (above mean)

O_3 chemistry is complex and temperature dependent

Denton et al., 2018

NASA AURA/MLS Ozone Observations

- Rapid increase in ozone with the onset of SSWs
- Strongest increase at sites in the PV.
- No effect for sites outside the PV.
- Increase in O_3 occurs in stratosphere and mesosphere.
- Good quantitative agreement between ozonesondes and balloons (~20% increase in O_3).



Denton et al., 2018

Summary (SSWs)

- We've quantified the average statistical changes that occur during SSWs
- Mean duration of increase in T in stratosphere is ~40 days.
- ~20% increase in O_3 (above annual mean) that persists ~40 days
- We've also looked at effects on other chemistry (NO_2, H_2O, etc) and neutral winds.

- Essential to account for seasonal variations to quantify underlying changes!

Overall Summary

We've attempted to quantify the average statistical increase/decrease of O_3 in response to SPEs and SSWs.

SPEs reduce ozone during polar winter (*descent in polar vortex*)

SSWs increase ozone during polar winter (*disrupt polar vortex*)

We are unaware of any study that has taken both these effects into account.

<u>What happens if a SPE is quickly followed by a SSW?</u>

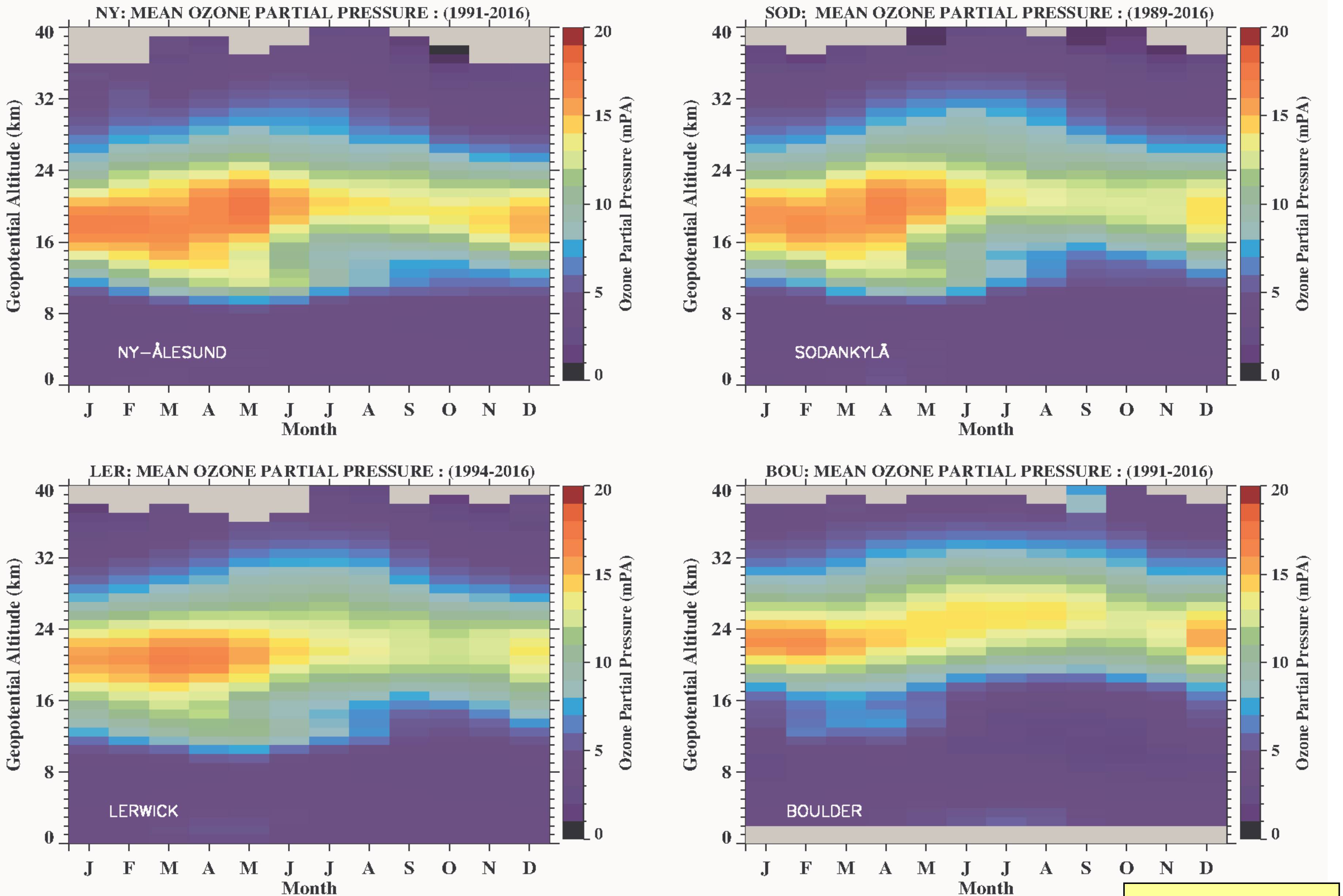
What Questions Need to be Addressed?

- We don't understand the competing effects of SSWs and SPEs
- It's not clear if O_3 changes for SPEs are coupled directly to PFU
- No-one has clearly demonstrated that stratospheric O_3 responds at all to energetic particle precipitation from the magnetosphere/radiation-belts

Thanks

R. Kivi
T. Ulich
M. A. Clilverd
C. J. Rodger
P. von der Gathen
M. Lester

Mean Annual Ozone



Denton et al., 2018