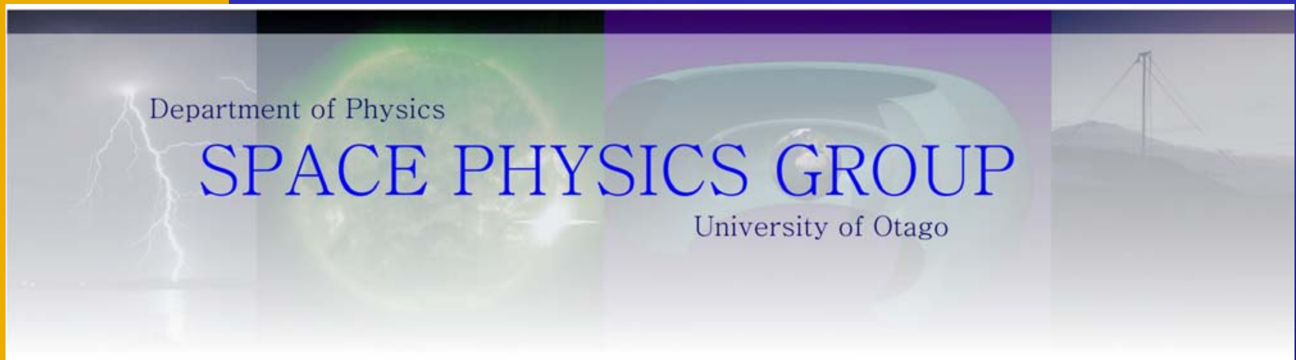
Particle Precipitation and Climate Coupling



Thanks to Annika Seppälä (British Antarctic Survey & Finnish Meteorological Institute) for helping me with material for this presentation!

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WUN Workshop
St John's, Canada
1540-1610, Saturday 23 July 2011

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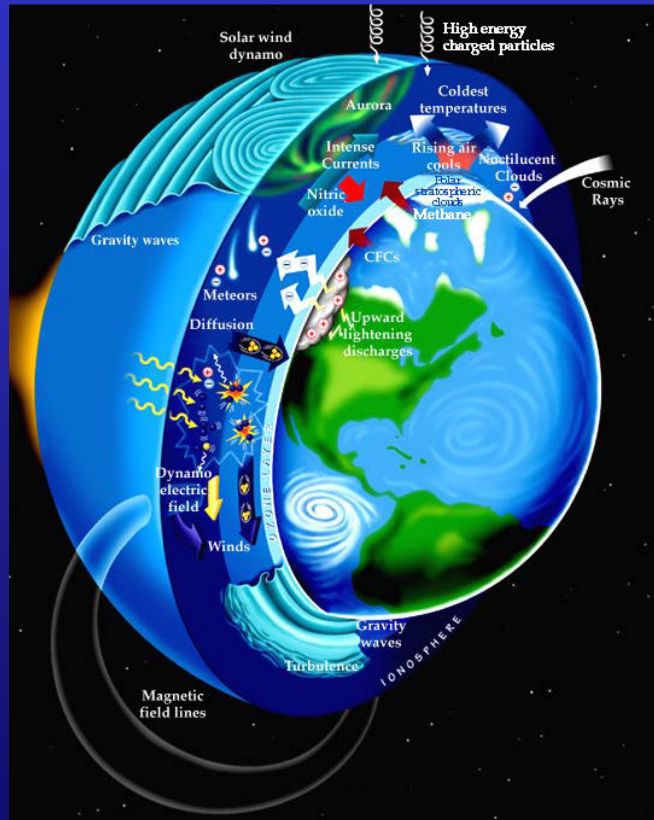
Energetic Particle Precipitation

Losses: overall response of the RB to geomagnetic storms are a "delicate and complicated balance between the effects of particle acceleration and loss" [*Reeves et al.*, GRL, 2003].

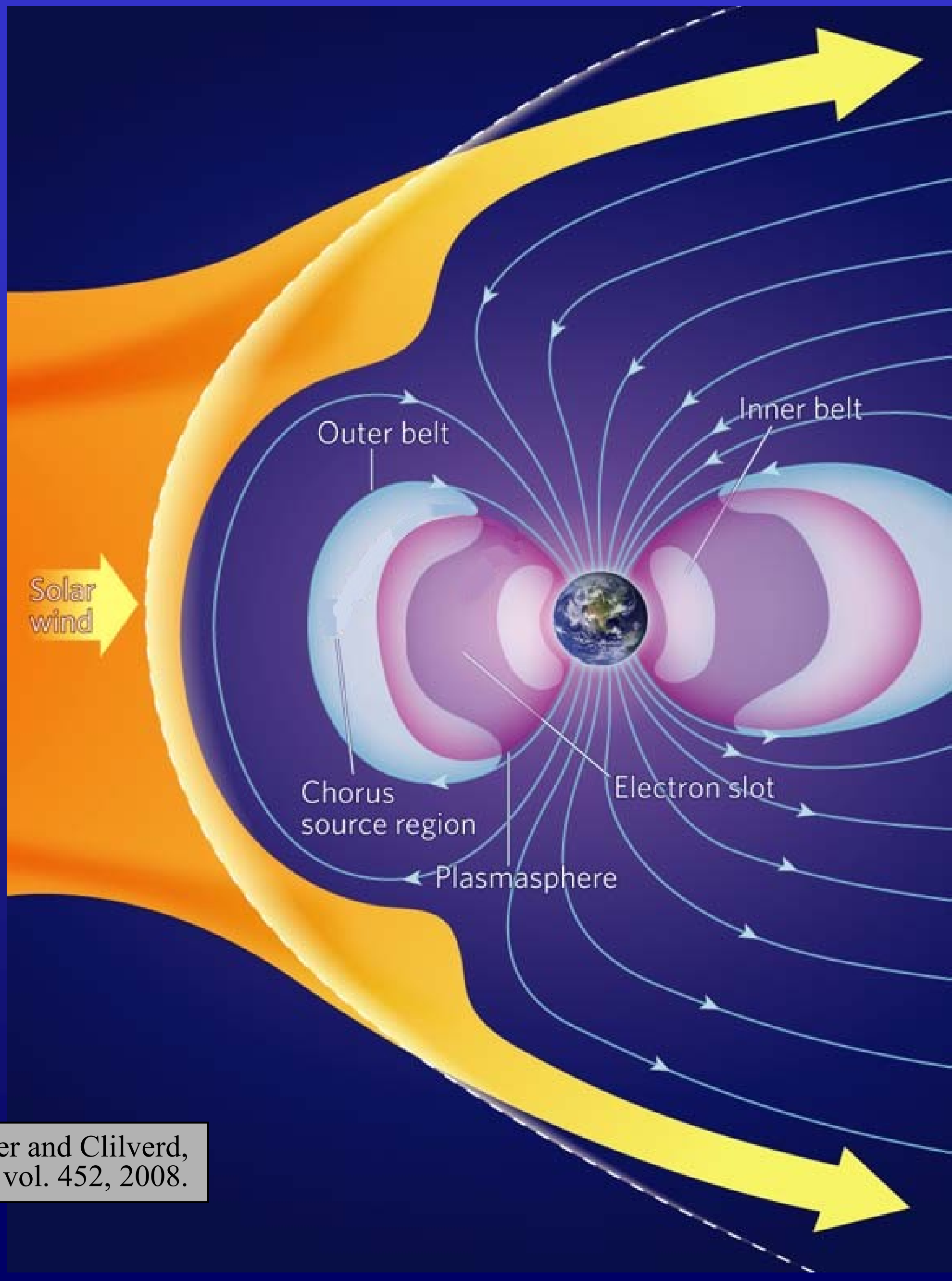
Thus while there has been a lot of focus on the acceleration of radiation belt particles, it is also necessary to understand the losses to understand the radiation belts.

Space Weather links to the atmosphere (and beyond?). In addition, particle precipitation is one way that changes at the Sun, and around the Earth, can couple into the atmosphere - and possibly into the climate.



There are multiple "important" questions which need to be answered to understand RB-losses & the significance of Energetic Particle Precipitation.

Van Allen belts – coupling to the polar atmosphere



Adapted from Rodger and Clilverd, *Nature*, vol. 452, 2008.

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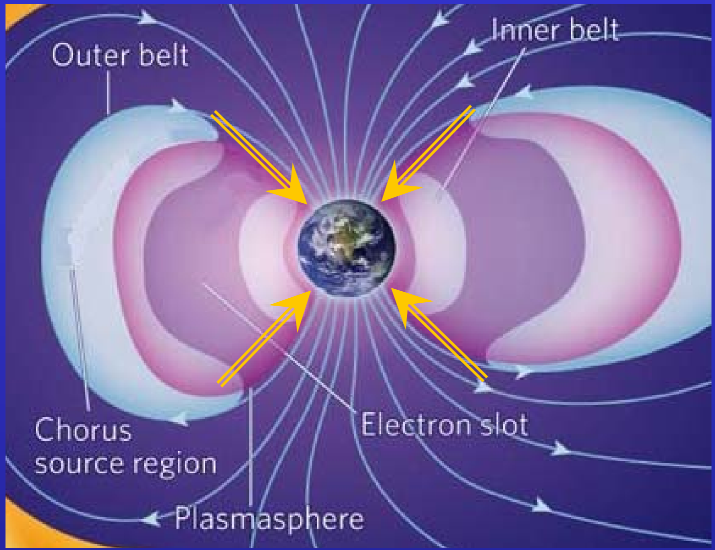
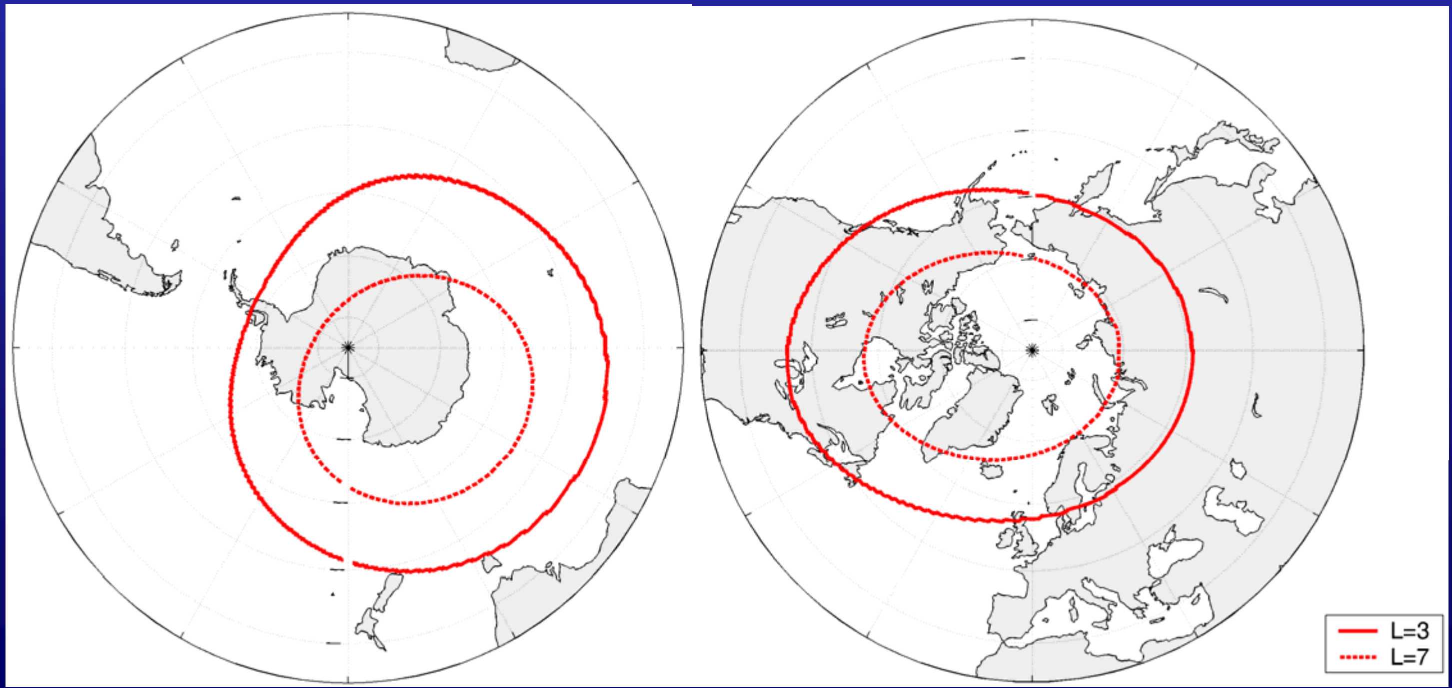
Particle access to the upper atmosphere

<u>Losses:</u> The outer radiation belt deposits energy into the polar atmosphere in both the Antarctic and Antarctic (primarily due to wave-particle interactions with ULF & VLF waves).





Radiation Belt Precipitation

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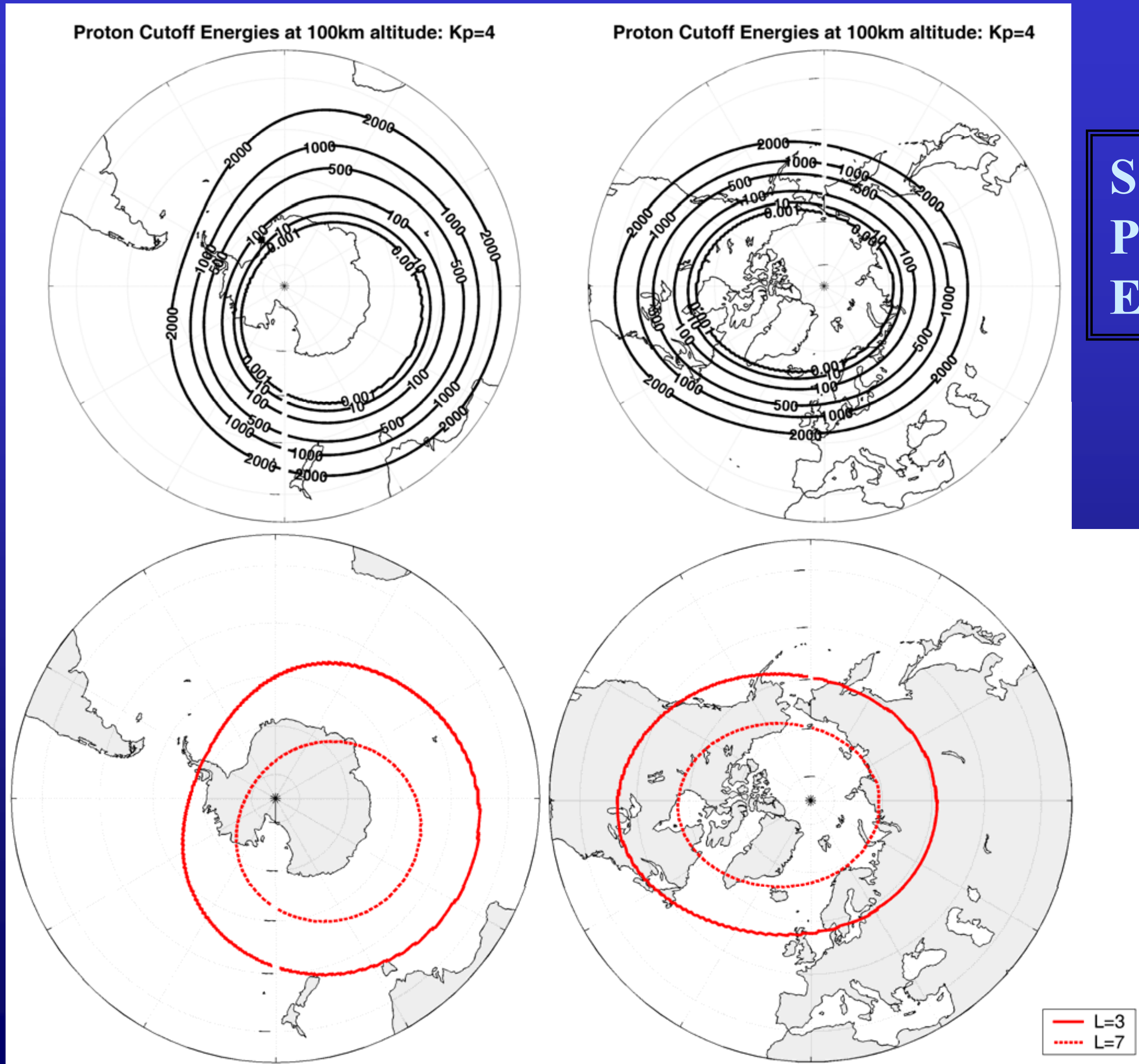
Particle access to the upper atmosphere



Solar Proton Events

Radiation Belt Precipitation

Particle access to the upper atmosphere

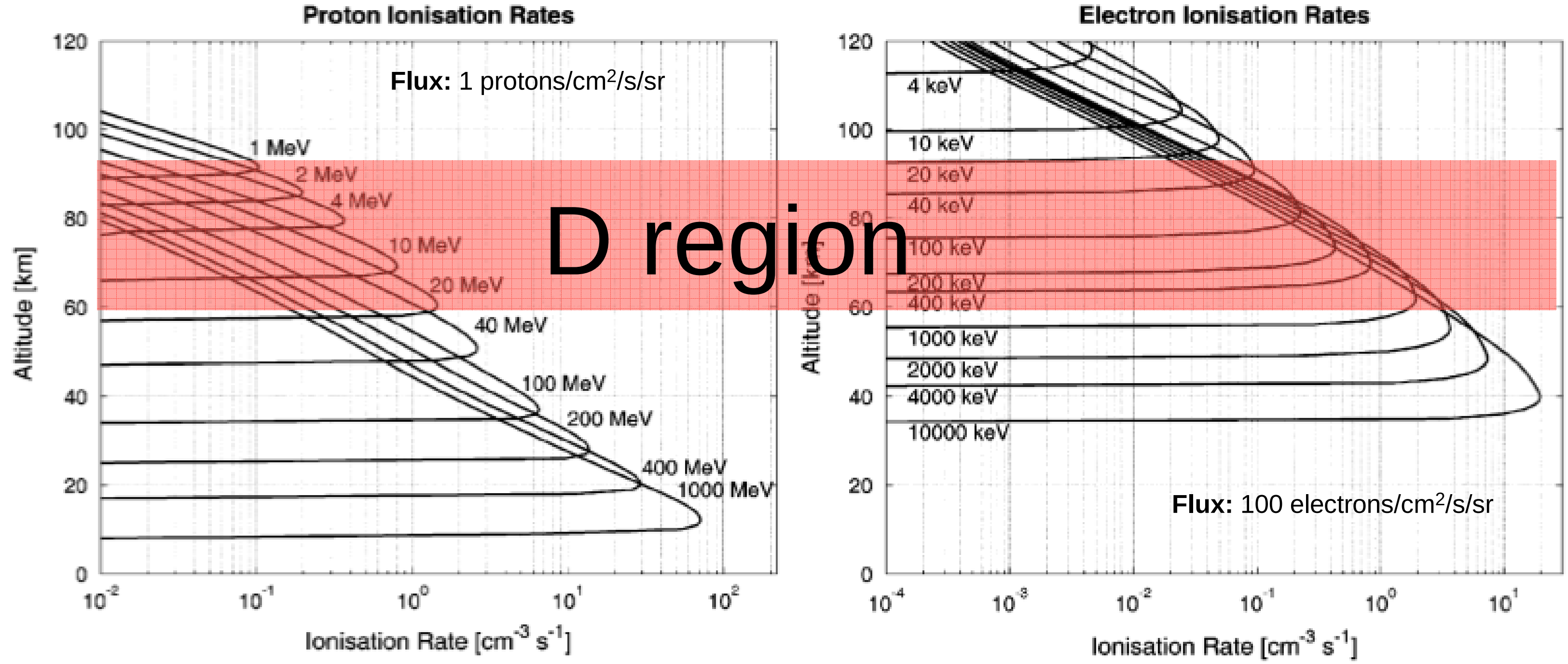


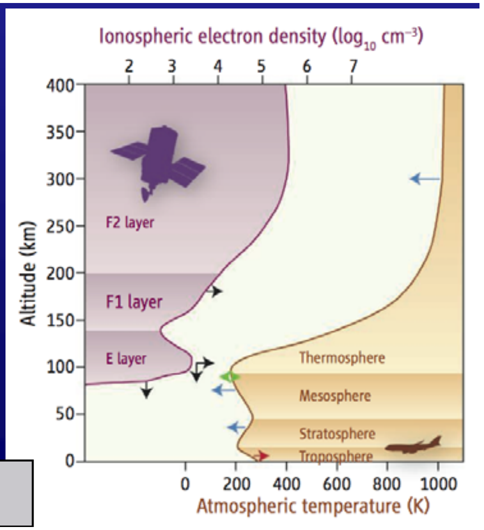
Fig. 3. Altitude versus ionisation rates for monoenergetic beams of protons 1–1000 MeV (left) and electrons 4–4000 keV (right).

Turunen et al., JASTP, 2009.

To produce 1 ion pair/cm^3/s at **60km** altitude

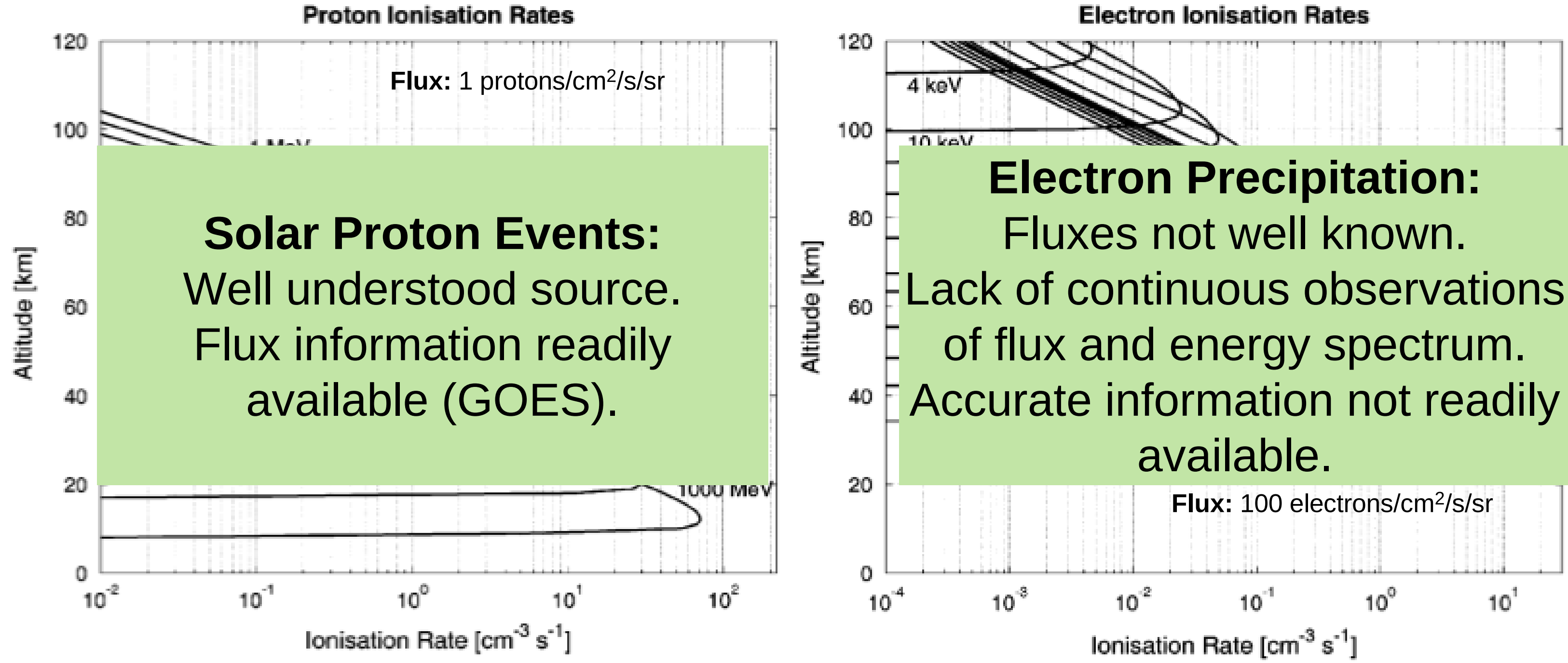
1 × 20MeV proton/cm^2/s

or **100** × 1MeV electrons/cm^2/s



Lastovicka et al., Science, 2006

Particle access to the upper atmosphere



Solar Proton Events:
Well understood source.
Flux information readily available (GOES).

Electron Precipitation:
Fluxes not well known.
Lack of continuous observations of flux and energy spectrum.
Accurate information not readily available.

Fig. 3. Altitude versus ionisation rates for monoenergetic beams of protons 1–1000 MeV (left) and electrons 4–4000 keV (right).

Turunen et al., JASTP, 2009.

To produce 1 ion pair/cm^3/s at **60km** altitude
1 x 20MeV proton/cm^2/s
or **100** x 1MeV electrons/cm^2/s

The potential importance of particle precipitation

Particle precipitation is one of the routes by which the Sun can link to the climate – energetic electrons and protons can change the atmospheric chemistry. And in an environment where humanity is changing the climate, and the polar ozone levels, we need to know about the "natural" variation too!

Particle precipitation

↓

Production of NO_x and HO_x

↓

Destruction of mesospheric and upper stratospheric O_3

↓

Change in radiation balance of mesosphere & stratosphere → "Climate"

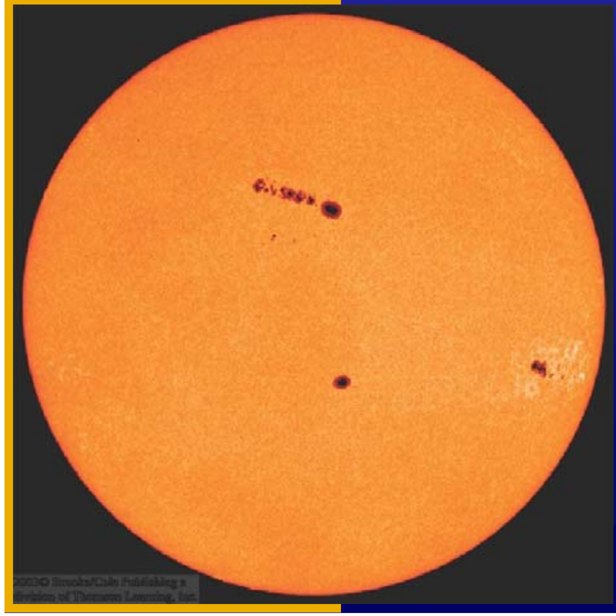
Plus of course the interest in precipitation from a strictly radiation belt physics viewpoint.

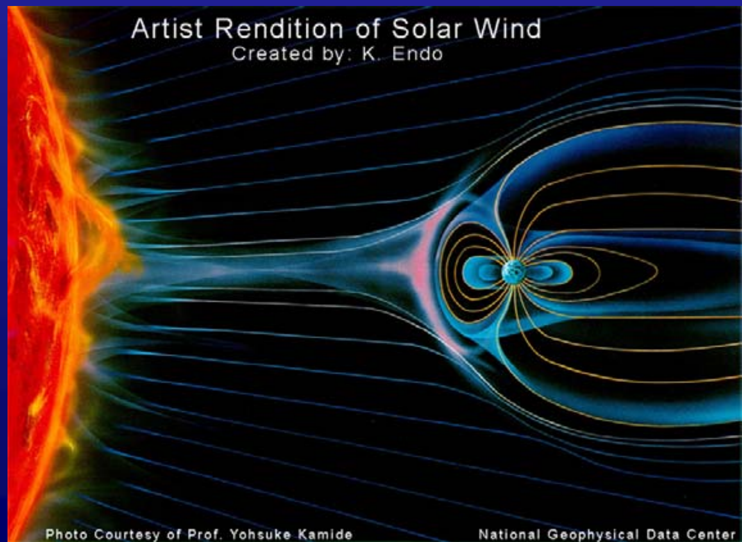
What about solar variability?

There is clear evidence for some link to the Sun, in long term climate records. One good example in the long-term climate record the Maunder minimum. There are also evidence that the 11-year sunspot cycles appears in global temperature data.

The Intergovernmental Panel for Climate Change Working Group 1 (IPCC WG1) recently concluded that:

- in the 700 years prior to 1950 observed climate changes were very likely to be caused by solar irradiance changes & volcanoes.

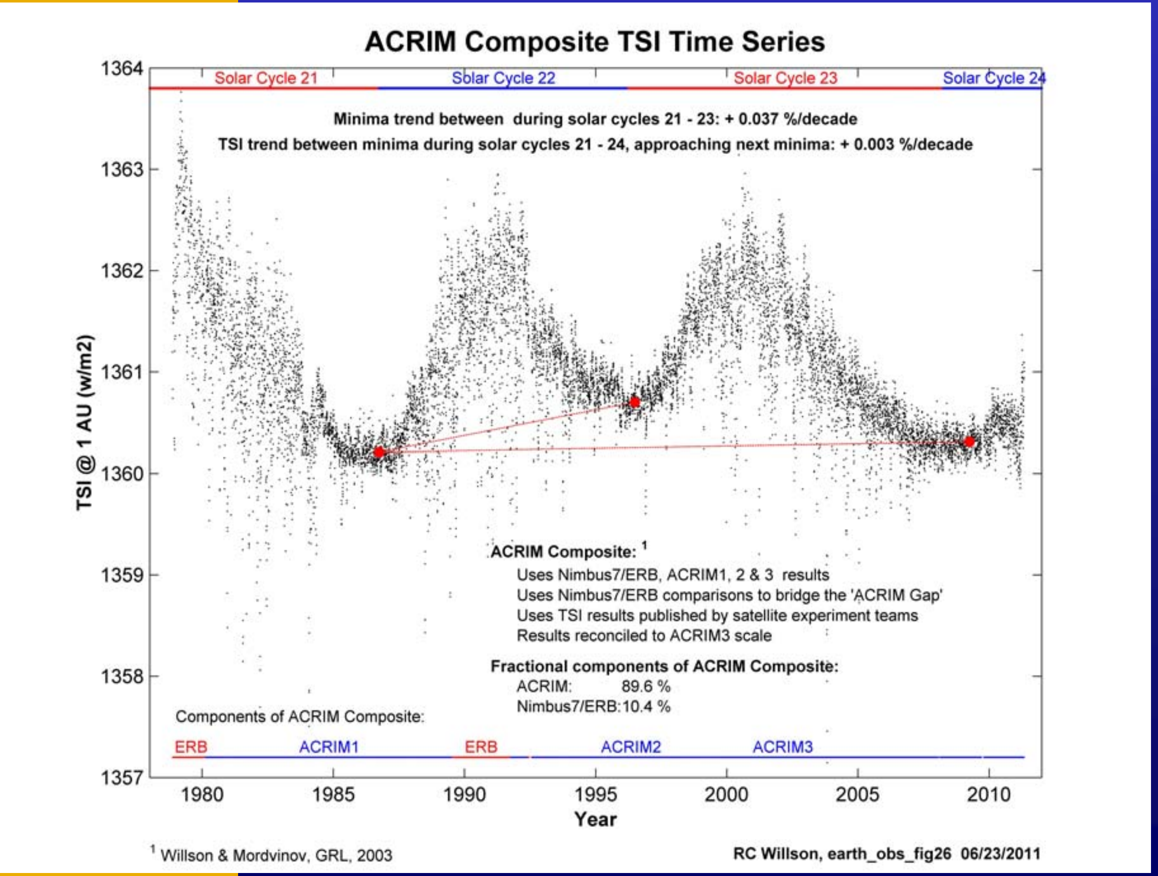




Here "**very likely**" is >90% probability and "**likely**" is >66% probability.

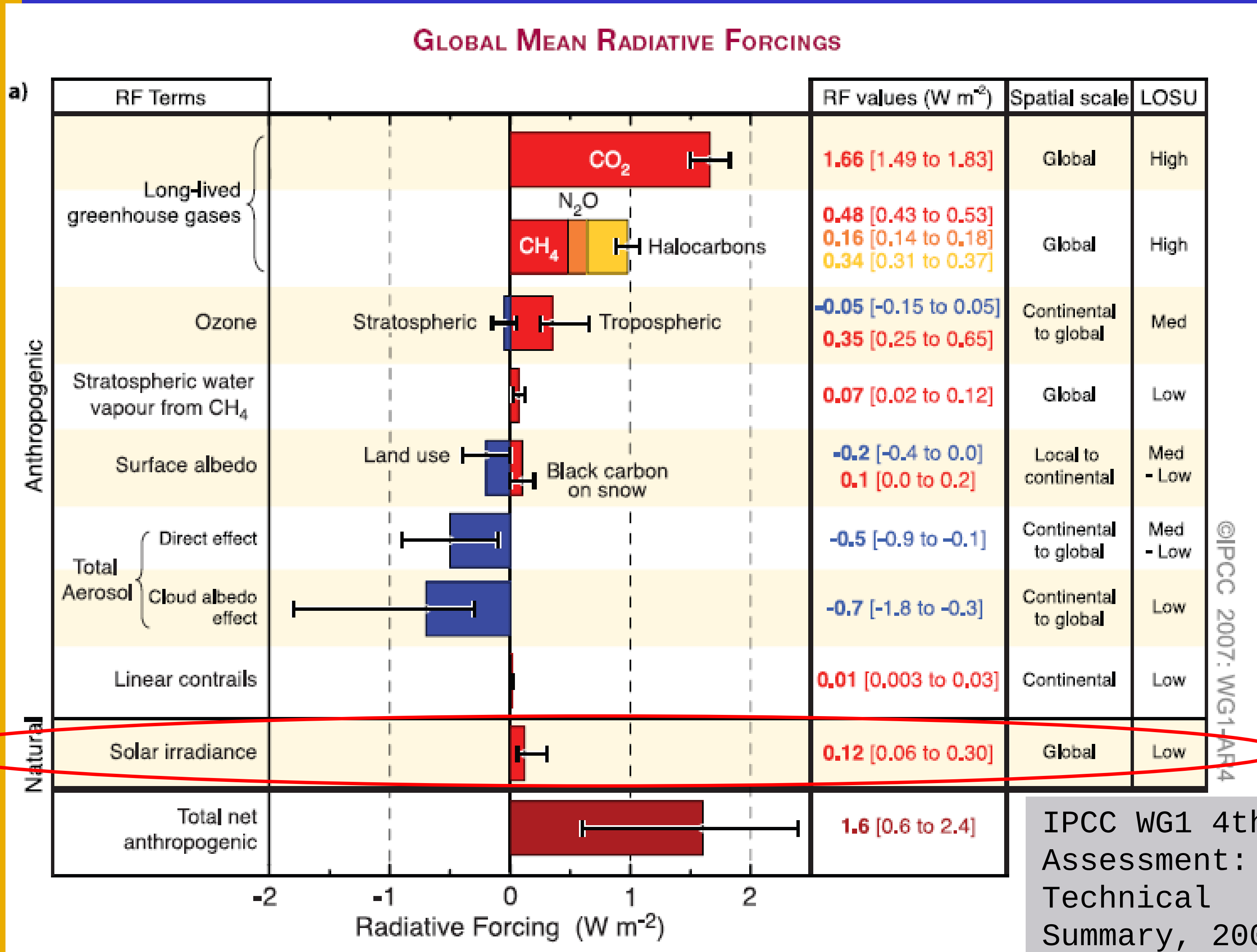
Total Solar Irradiance

Of course total solar irradiance (summed over all wavelengths) hardly changes. This used to be know as the solar constant, but satellite measurements show that it varies by ~0.08% over the 11-year sunspot cycle (less power during solar minimum).



By the way, the total solar power arriving at the Earth from the Sun is ~1.7 $\times 10^{17}$ W, roughly the same as the output from 2 million billion 100 watt lightbulbs distributed just above the atmosphere of the Earth. **Its a useful number to know!**

WG1-AR4 Summary Plot



IPCC WG1 4th Assessment: Technical Summary, 2007

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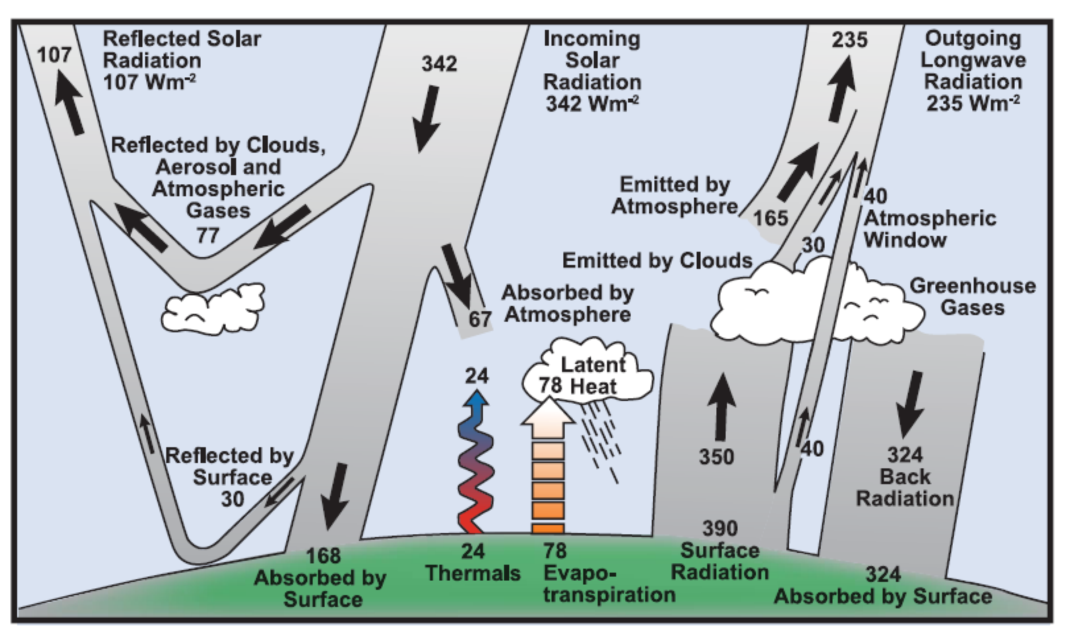
Solar variability mechanisms: End of Story?

Actually, no. The 2007 WG1 4AR focuses strongly on Total Solar Irradiance, and not much else. It briefly considers another possible mechanism, clouds and cosmic rays.

"Empirical associations have been reported between **solar-modulated cosmic ray ionization of the atmosphere** and **global average low-level cloud cover** but evidence for a systematic indirect solar effect remains **ambiguous**. …

Together with the lack of a proven physical mechanism and the plausibility of other causal factors affecting changes in cloud cover, this makes the association between galactic cosmic ray-induced changes in aerosol and cloud formation **controversial**."

IPCC WG1 4th Assessment: Technical Summary, 2007



IPCC WG1 4th Assessment, Chpt 1, FAQ, Fig 1., 2007

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Solar variability mechanisms: End of Story? - II

Chapter 1 of the WG1 4AR includes a section on solar variability which ends with the statement:

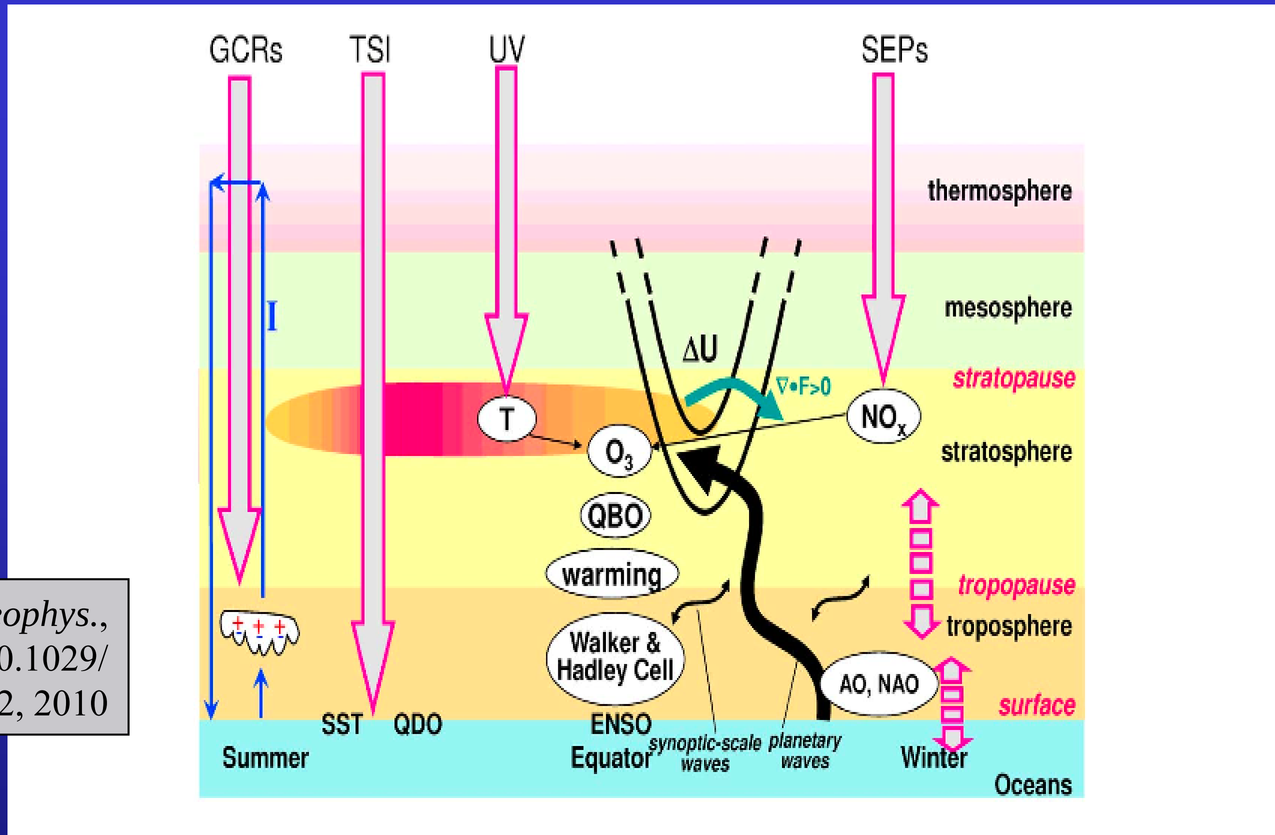
"The effects of galactic cosmic rays on the atmosphere (via cloud nucleation) and those due to shifts in the solar spectrum towards the ultraviolet (UV) range, at times of high solar activity, are largely unknown. The latter may produce changes in tropospheric circulation via changes in static stability resulting from the interaction of the increased UV radiation with stratospheric ozone. **More research to investigate the effects of solar behaviour on climate is needed before the magnitude of solar effects on climate can be stated with certainty.** "

IPCC WG1 4th Assessment: Section 1.4.3, 2007

Which actually leaves us considerably more relevance than I realized when these documents originally came out!

In fact, the WG1 4AR doesn't seem to address all the mechanisms which have been forward, providing comments only on cosmic rays/clouds and UV (and TSI).

Solar influences on Climate



Gray et al., *Rev. Geophys.*, doi:10.1029/ 2009RG000282, 2010

Two broad categories of solar forcing mechanisms, involving solar irradiance variations (TSI & UV) and the modulation of corpuscular radiation (GCR, Solar protons, electron precipitation). In both cases the forcing is likely to be very small. “However, even a very weak forcing can cause a significant climate effect if it is present over a long time or if there are non-linear responses giving amplifying feedbacks.”

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The potential importance of particle precipitation

Particle precipitation is one of the routes by which the Sun can link to the climate – energetic electrons and protons can change the atmospheric chemistry. And in an environment where humanity is changing the climate, and the polar ozone levels, we need to know about the "natural" variation too!

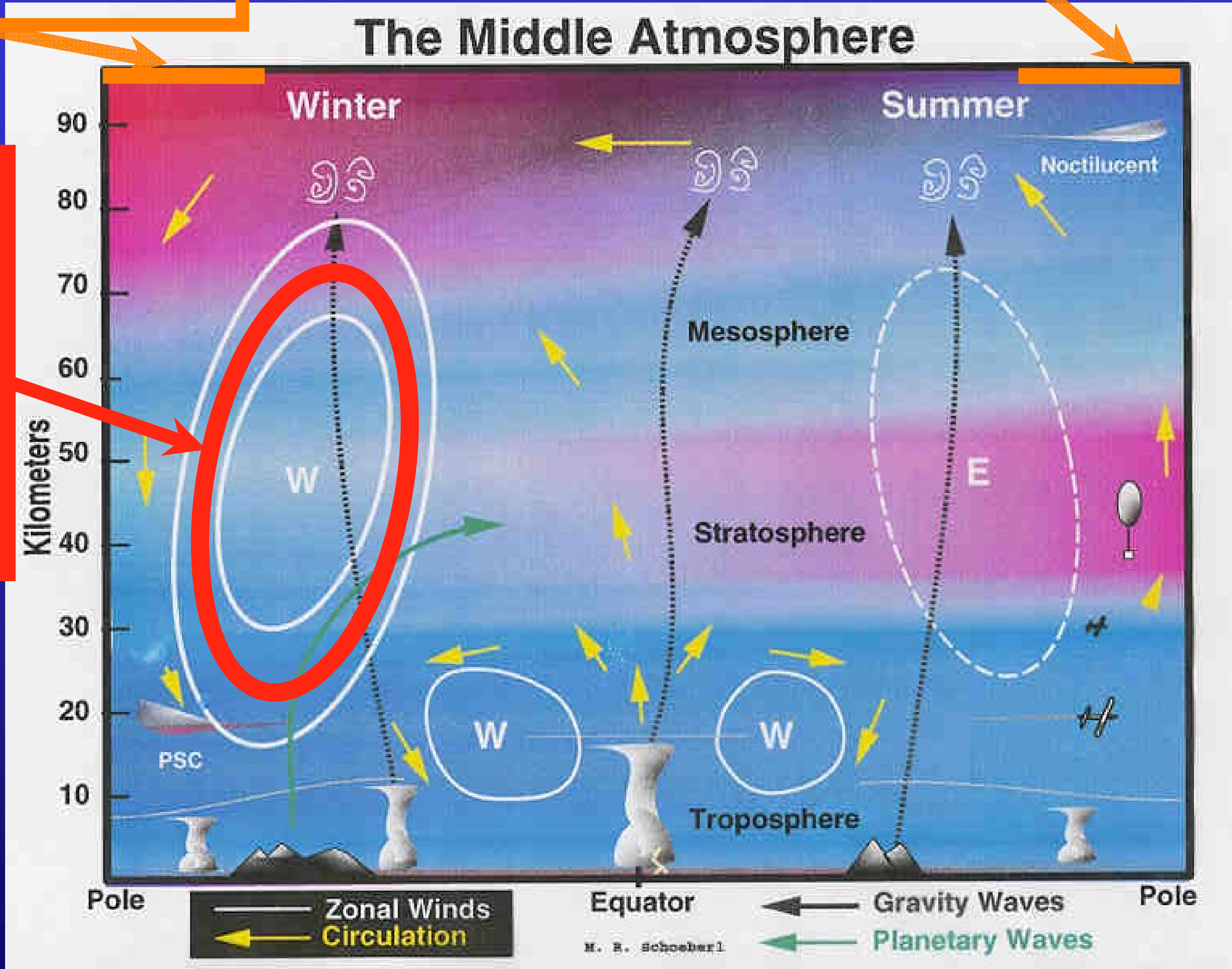
- Particle precipitation
- ↓ Production of NO_x and HO_x
- ↓ Destruction of mesospheric and upper stratospheric O_3
- ↓ Change in radiation balance of mesosphere & stratosphere → "Climate"

Plus of course the interest in precipitation from a strictly radiation belt physics viewpoint.

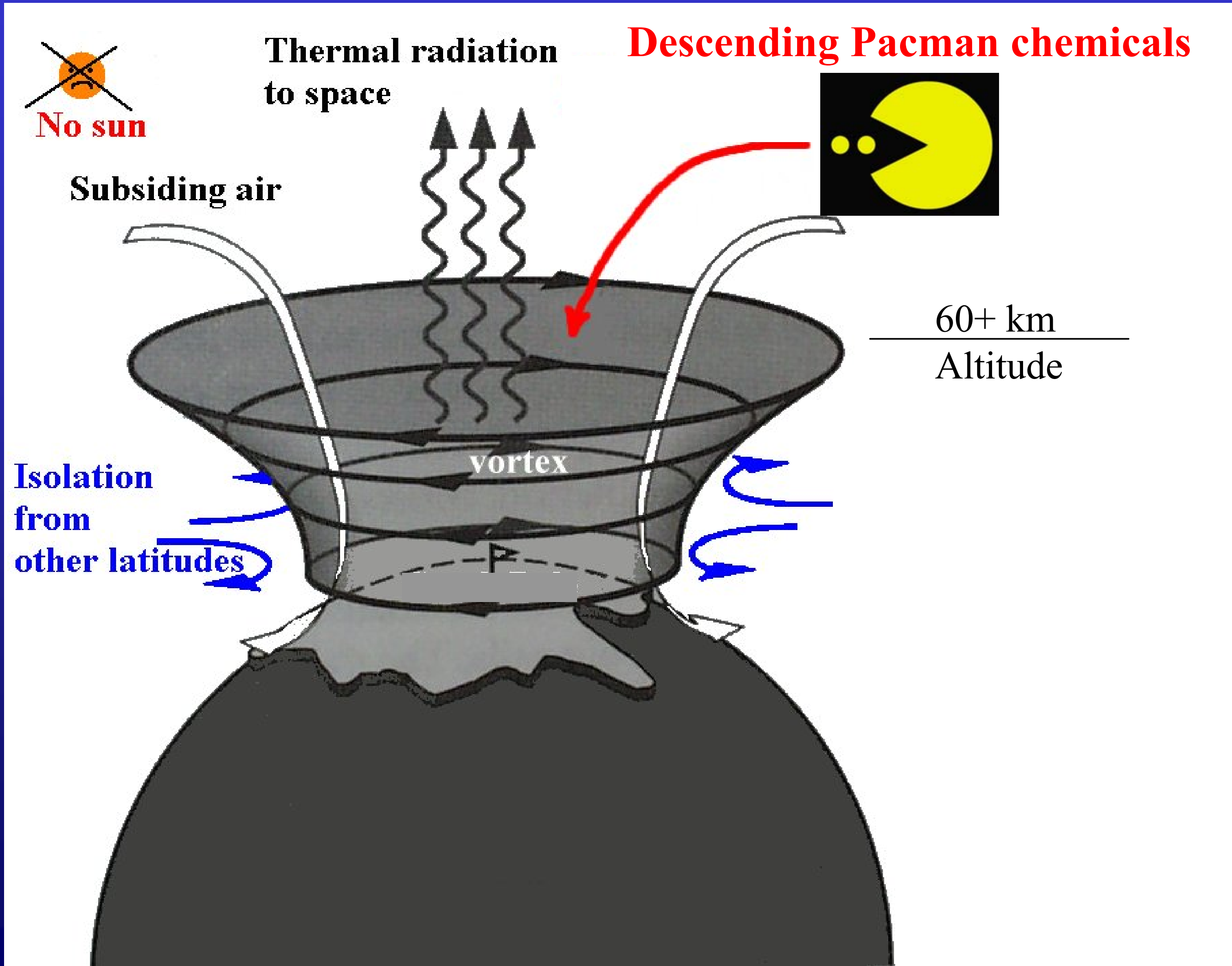
Lets look at this chain and what we know now, i.e., what we can see happening in data.

Polar caps - access regions for particle precipitation

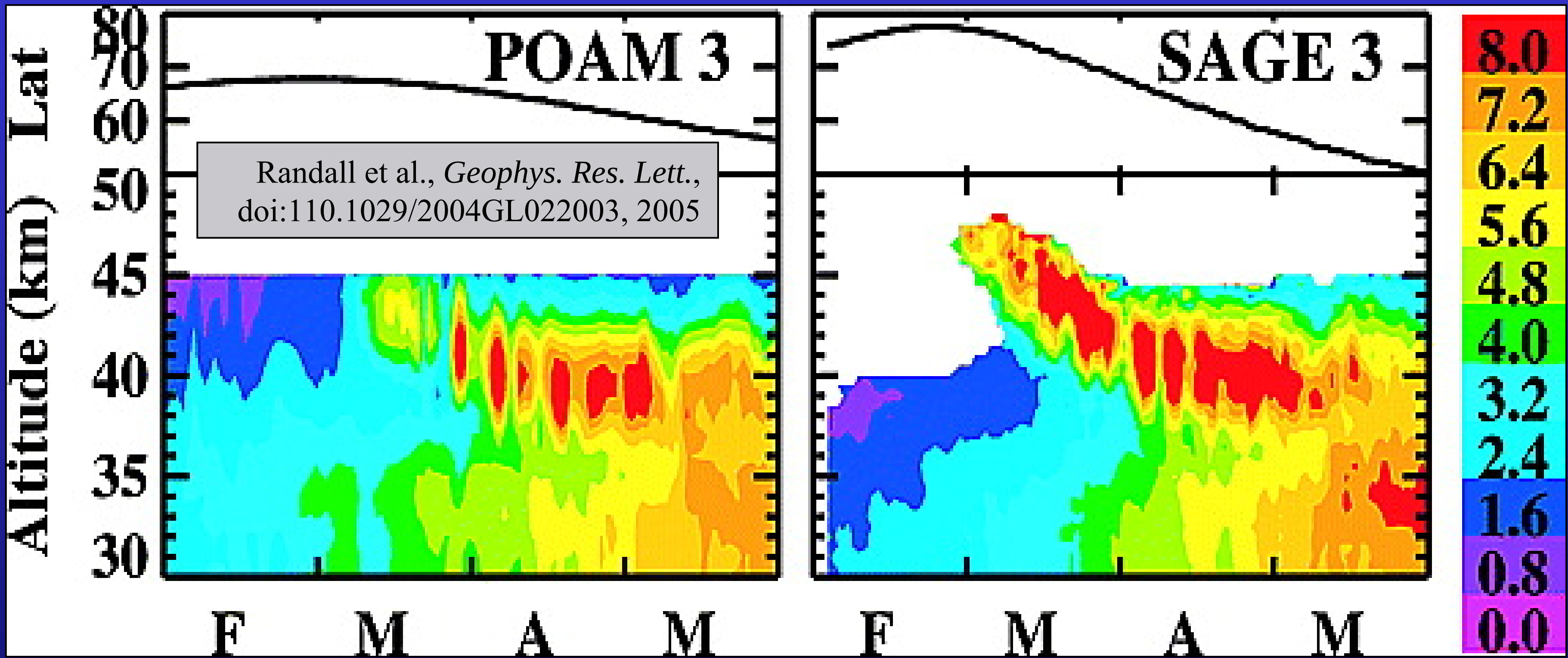
Strong winds acting as a transport barrier. Isolates polar air forming the Polar vortex.



The Northern Polar Vortex



Spring-time descent inside the polar vortex

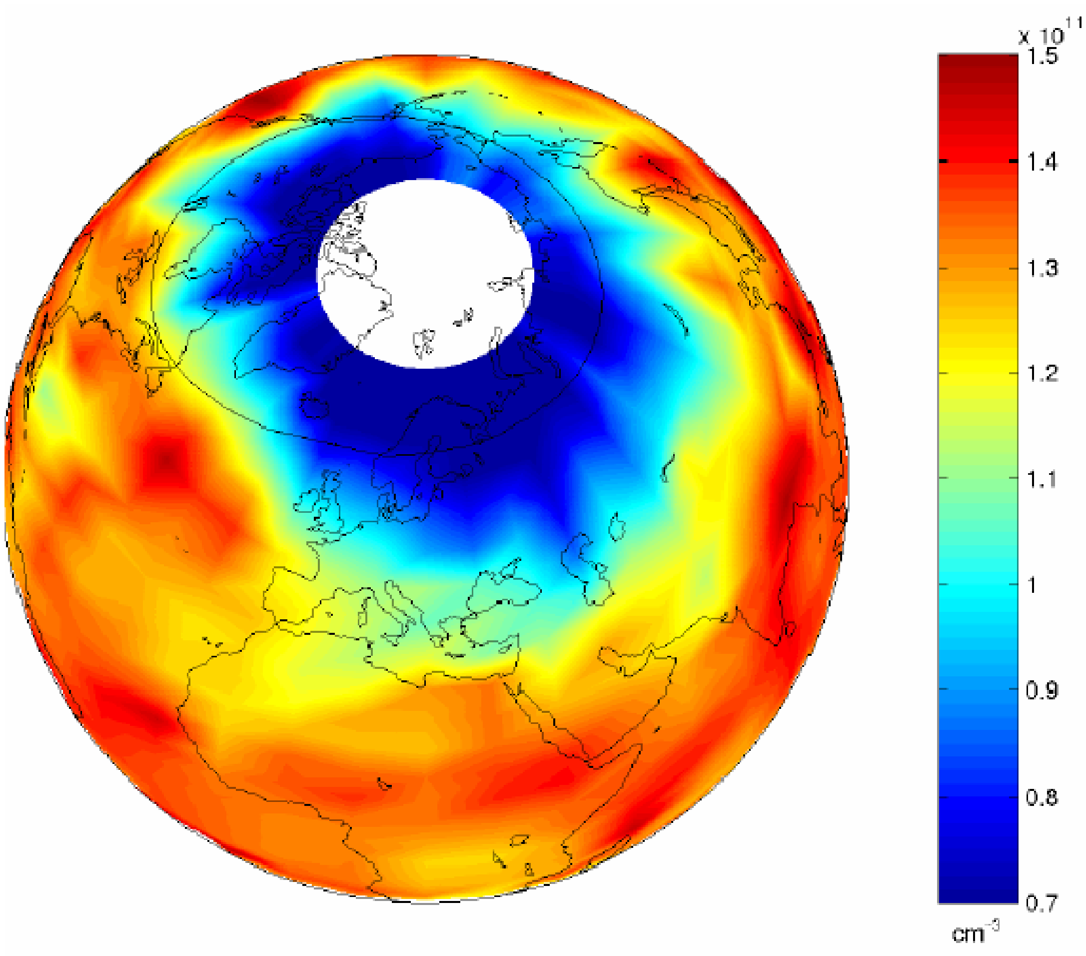


Northern hemisphere, 2004 NO_2 mixing ratio

These measurements couldn't determine the true source of the NO_2 because there has been a lack of measurements in the polar cap during the winter. The NO_2 was linked to a decrease in stratospheric O_3.

We know some of this chain happens:
solar proton event-driven O_3 losses in the Arctic

Observed Mesospheric Ozone Depletion



GOMOS onboard ENVISAT is a star occultation measurement
--> good global data coverage

GOMOS observed losses after a Solar Proton Event (SPE) proving that large ionisation increases can cause polar O_3 losses.

GOMOS data on northern hemispheric O3 after the Oct/Nov 2003 SPE (from A.Seppala, 2005)

Indirect EPP effect

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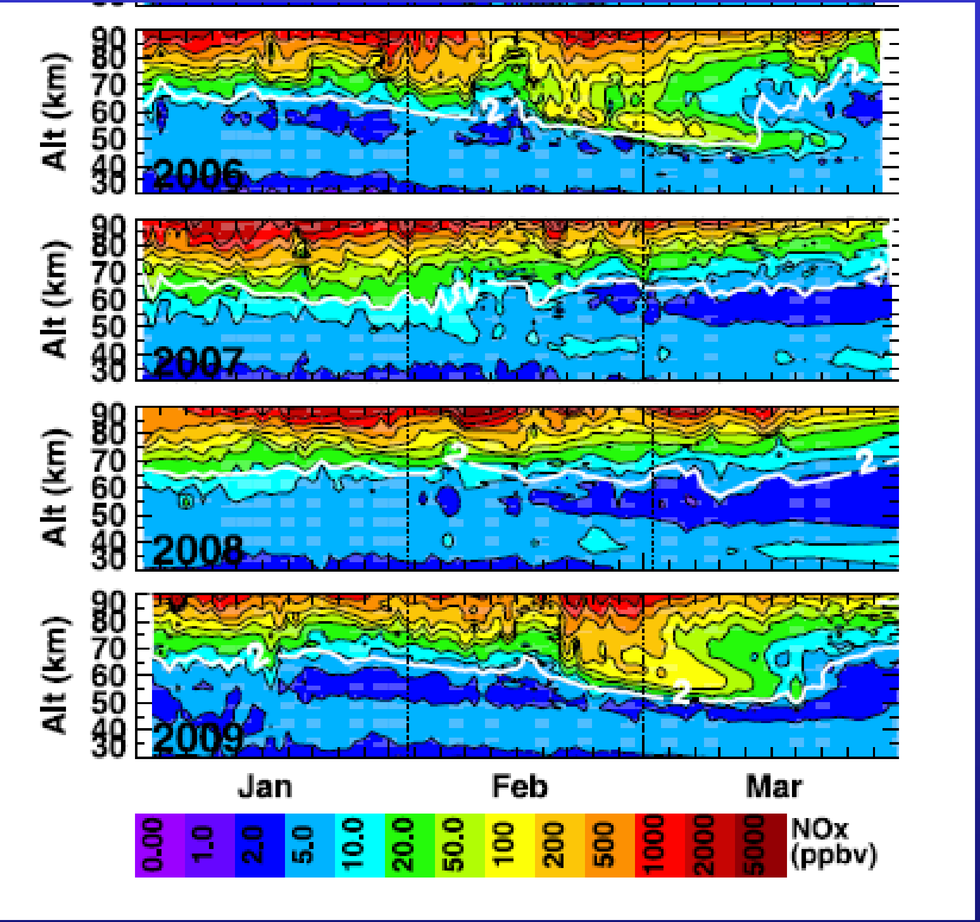
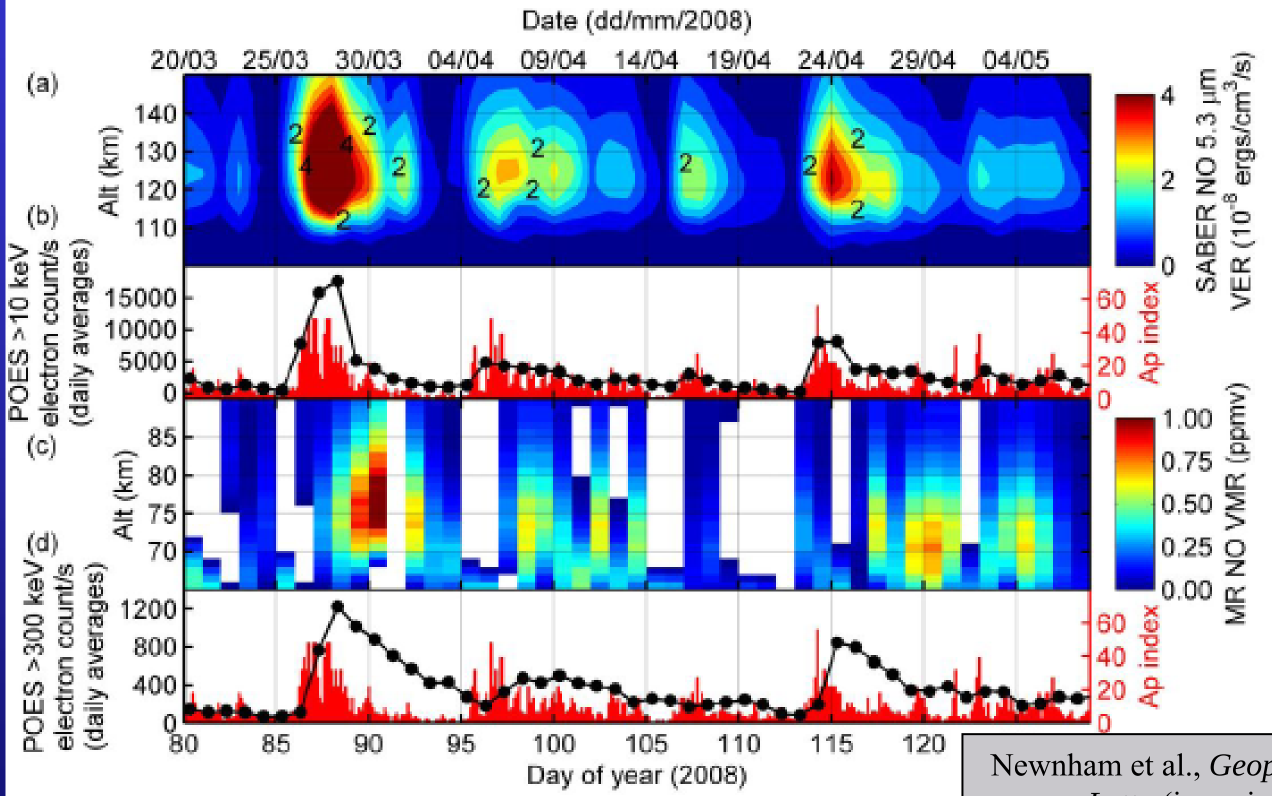


Randall et al., *Geophys. Res. Lett.*, 36, doi:10.1029/2009GL039706, 2009.

Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) solar occultation observations of descending NO_x in the Arctic winters. The primary source for the indirect effect is believed to be low-energy particle precipitation (i.e., auroral electrons and protons producing NO_x at ~100km or so).

Direct EPP effect

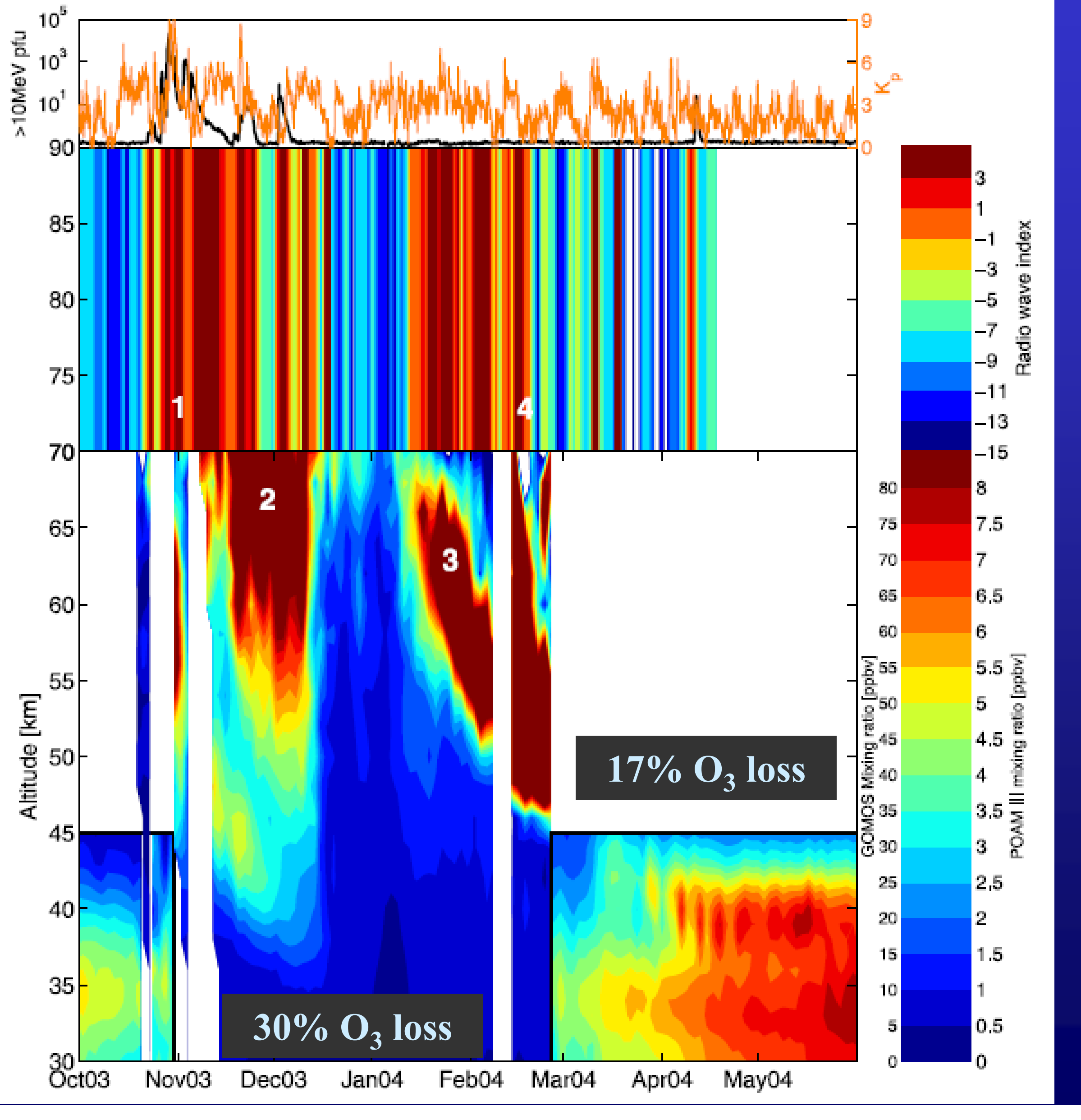
Figure 2. (a) SABER NO 5.3 μm VER for 65°S-75°S; (b) POES/SEM-2 trapped and quasi-trapped electron flux for >10 keV channel and 3-hour average Ap index; (c) Microwave radiometer daily average NO VMR; (d) POES/SEM-2 trapped and quasi-trapped electron flux for >300 keV channel and 3-hour average Ap index.



Newnham et al., *Geophys. Res. Lett.*, (in review), 2011.

NO observations from the British Antarctic Survey radiometer located at Troll station, Antarctica (65° geomagnetic latitude). NO increases at ~75km by 2-3 orders of magnitude due to multiple days of ~300keV precipitation. This effect is far too fast for transport.

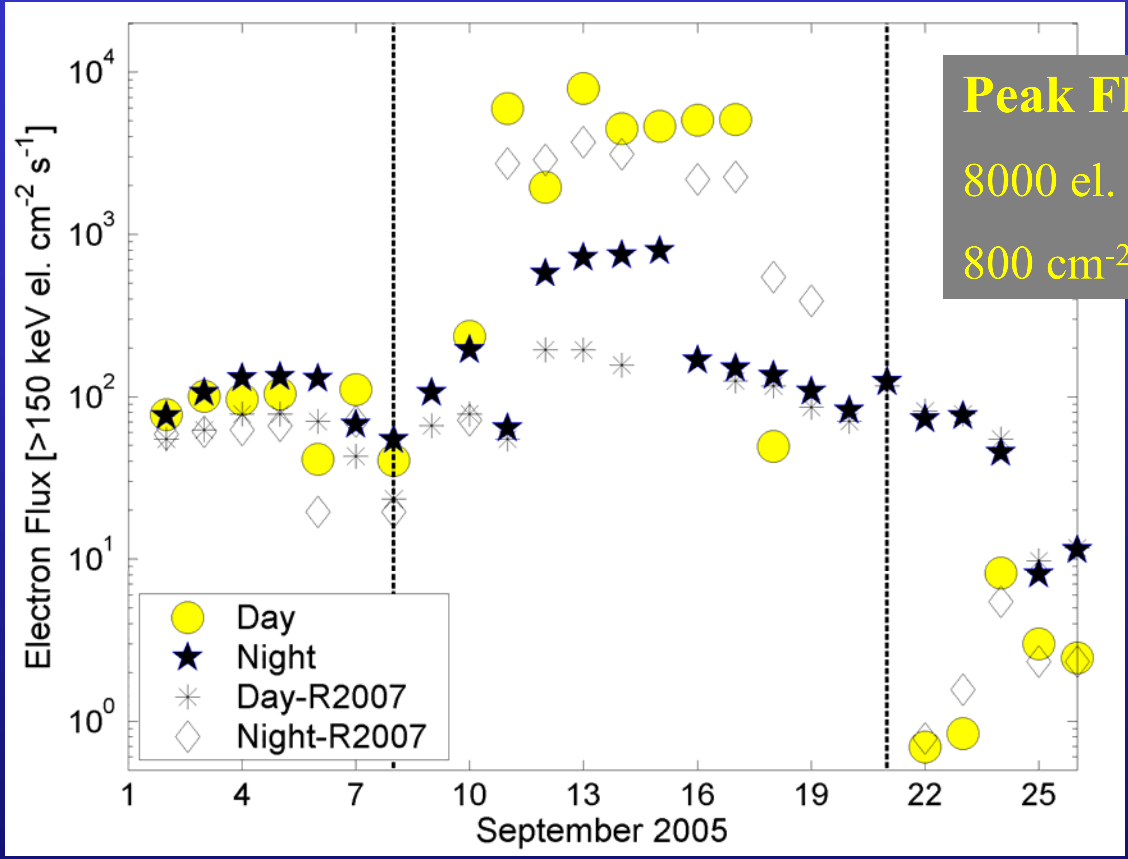
NO_x decent and stratospheric O_3 loss has been observed together too.



Seppälä et al., *J. Geophys. Res.*, doi:10.1029/2006JD008326, 2007.

Updated Electron Precip. Flux Values

Precipitation fluxes required to reproduce the changes in subionospheric propagation observed (NAA -> CAM).



Peak Fluxes:

8000 el. cm^{-2}s^{-1} at midday

800 cm^{-2}s^{-1} at midnight.

This work is taken from:

R-2007; **Rodger et al., JGR, A11307, doi:10.1029/2007JA012383, 2007**.
and **Rodger et al., *JGR.*, 115, A11320, doi:10.1029/2010JA015599, 2010.**

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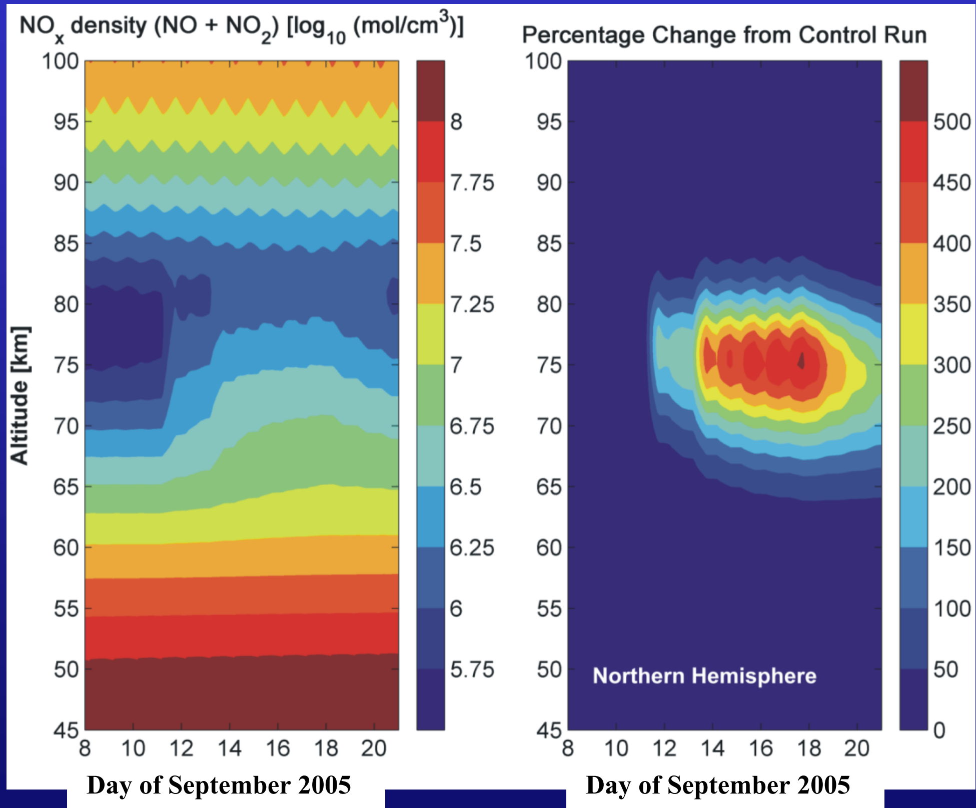
LATMOS

Model the neutral atmosphere changes: NOx

Energetic electron precipitation results in the enhancement of odd nitrogen (NO_x) and odd hydrogen (HO_x), which play a key role in the ozone balance of the middle atmosphere. Using SIC, we can look at the electron precipitation produced changes, during this storm period.



Factor of 5-6 increase that is most significant in the ~65-85 km altitude range

Looks impressive, but it is important?

The NO_x increase builds up primarily across the time-span when the >150 keV electron precipitation fluxes peak, and then start to recover due to photodisocciation.

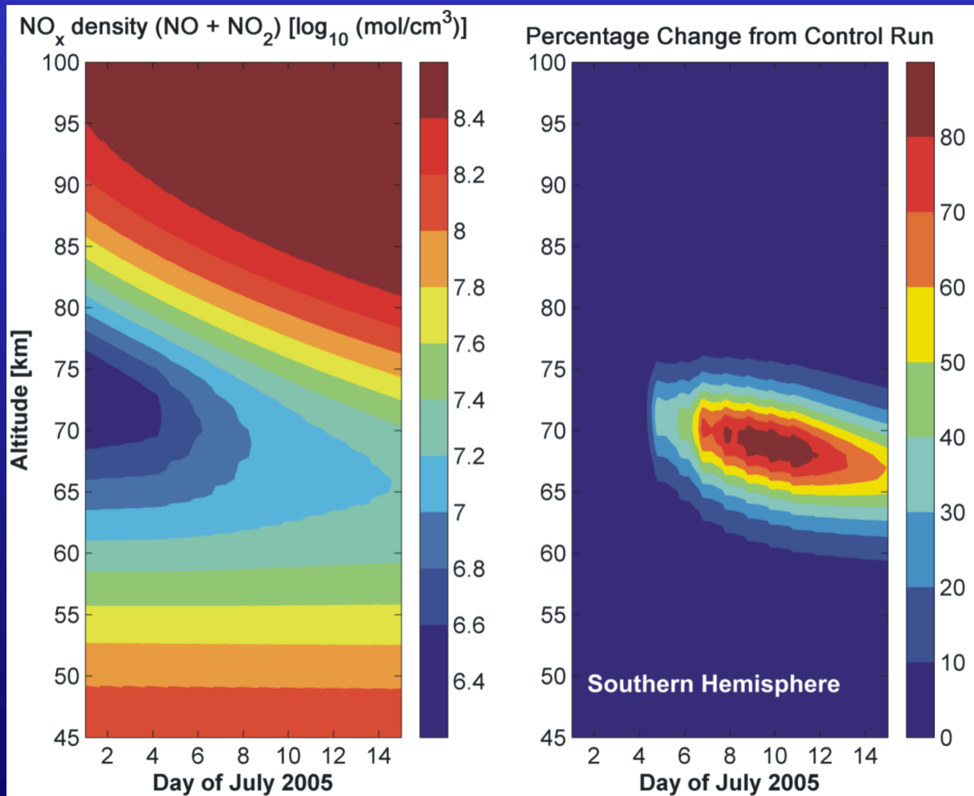
Model the neutral atmosphere changes: O_3

NO_x and HO_x increases caused by energetic particle precipitation have been associated with in-situ ozone loss in the polar middle atmosphere. This has been experimentally observed during Solar Proton Events. So what about for electron precipitation?

In the case studied here there is an **essentially insignificant level** of ozone loss (<1% most of the time, brief peaks at ~3%).

Model the neutral atmosphere changes: NOx

However, we considered the Northern Hemisphere during late summer-early autumn. The dark atmosphere, particularly the polar winter atmosphere, is very different. So lets take a Southern Hemisphere case (same *L*-shell) in deep SH winter.

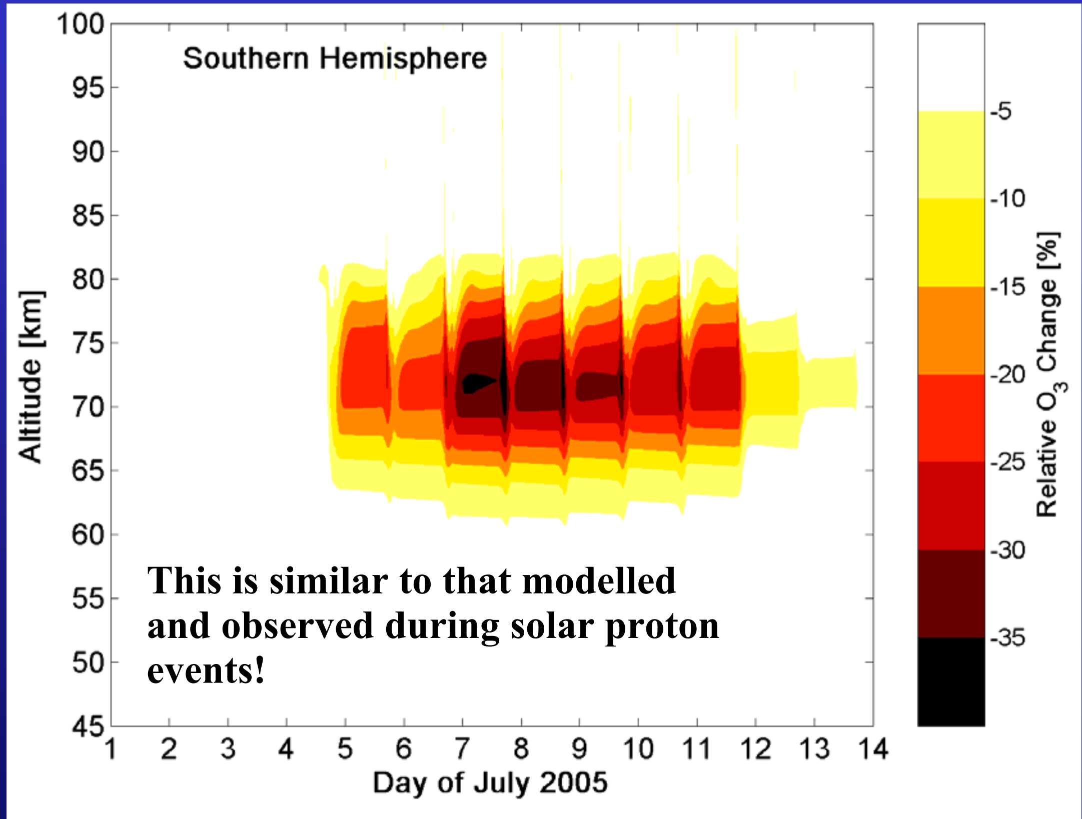


While the percentage change is not so big, the absolute changes are larger, and persist longer.

Again, looks a bit impressive, but it is important?

Model the neutral atmosphere changes: O_3

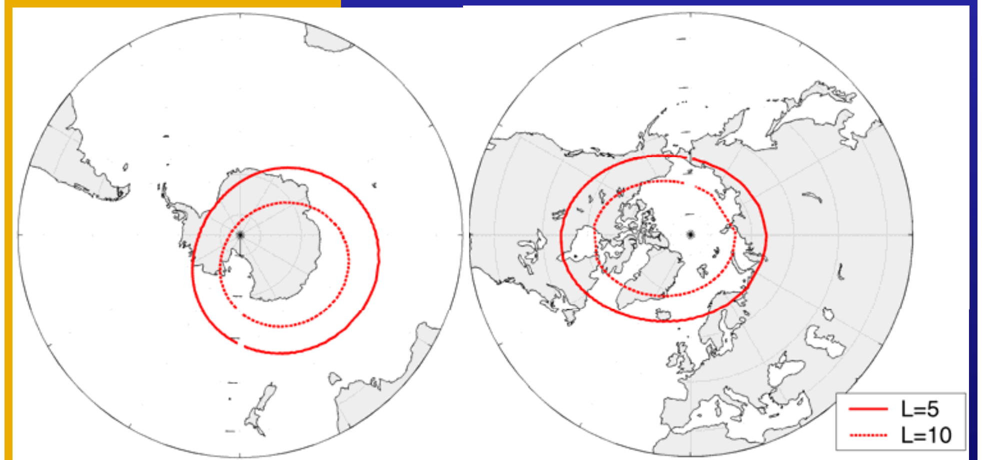
We know the response to particle precipitation is dependent upon hemisphere and season (this has also been experimentally observed during Solar Proton Events). So if we look at the Southern Hemisphere and winter, then yes, it's a very different picture!



In this case, because of seasonal asymmetries in background chemical composition, we get a **significant *in-situ* O_3 change**!

And a link to Climate?

Rozanov et al. [GRL, 2005] fed their chemistry-climate model (CCM) with NO_x changes calculated on a daily basis from particle fluxes reported by the NOAA/TIROS Space Environment Monitor (SEM-1) onboard the POES spacecraft for 1987. The two hemispheres were treated separately, and only “high latitude” data from *L*=5-10 was considered. They then looked at the change when NO_x was included in the model run (relative to when it wasn’t).



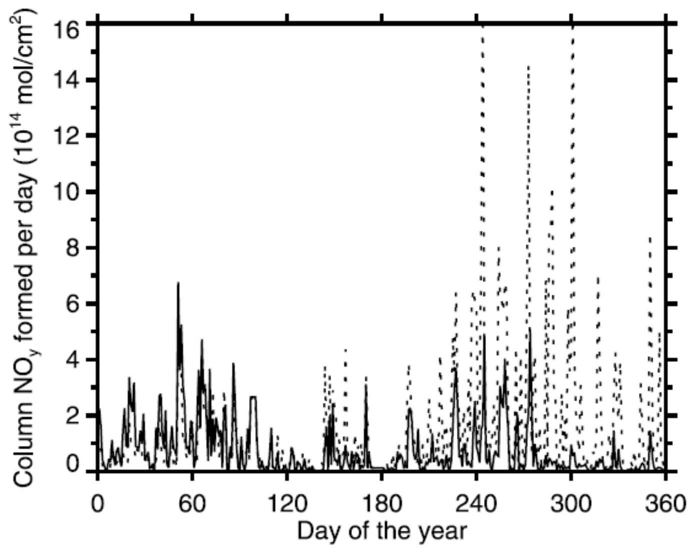


Figure 1. Daily formation of column NO_y during 1987 for the Northern (solid line) and Southern (dotted line) hemispheres between 60 and 90 km, and for values of the McIlwain parameter between 5 and 10.

Rozanov et al., *Geophys. Res. Lett.*, doi:10.1029/2005GL023041, 2005

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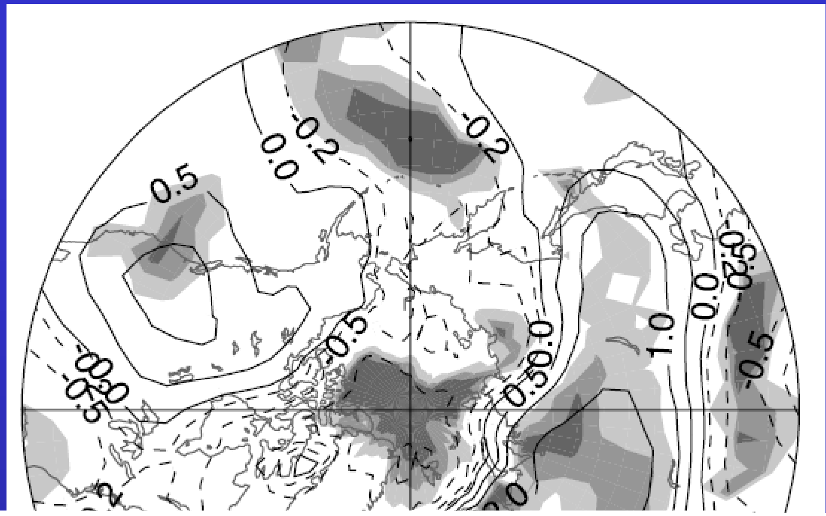
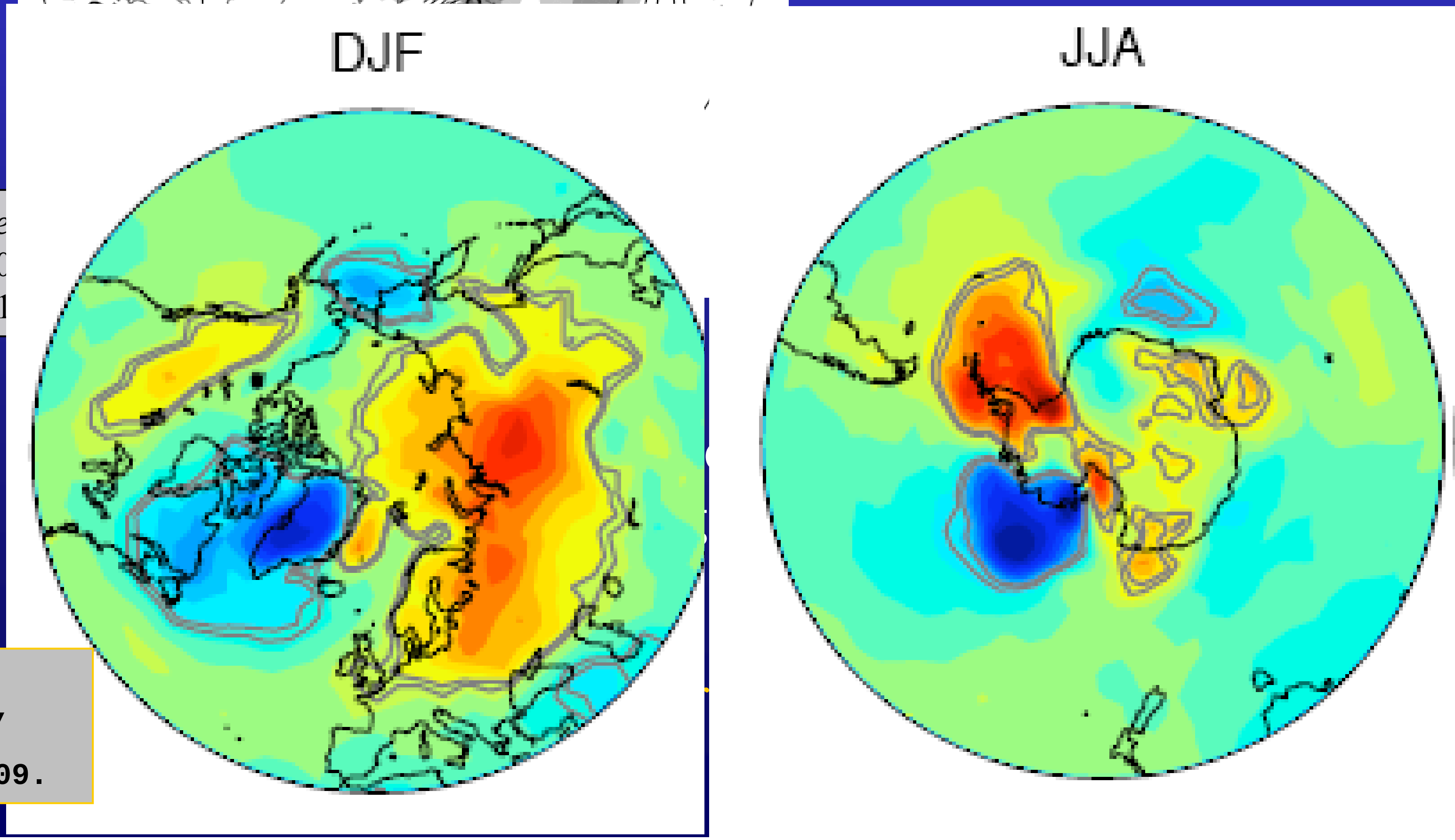


The calculations presented in *Rozanov et al.* [GRL, 2005] lead to a particle precipitation driven surface air temperature variation of -0.5 to +2 K, relative to the no precipitation case. They argued that their

Rozanov et al., *Ge*
Res. Lett., doi:10
2005GL023041



Seppälä et al.,
***J. Geophys. Res.*,**
doi:10.1029/
2008JA014029, 2009.

Why is energetic particle precipitation (possibly) important?

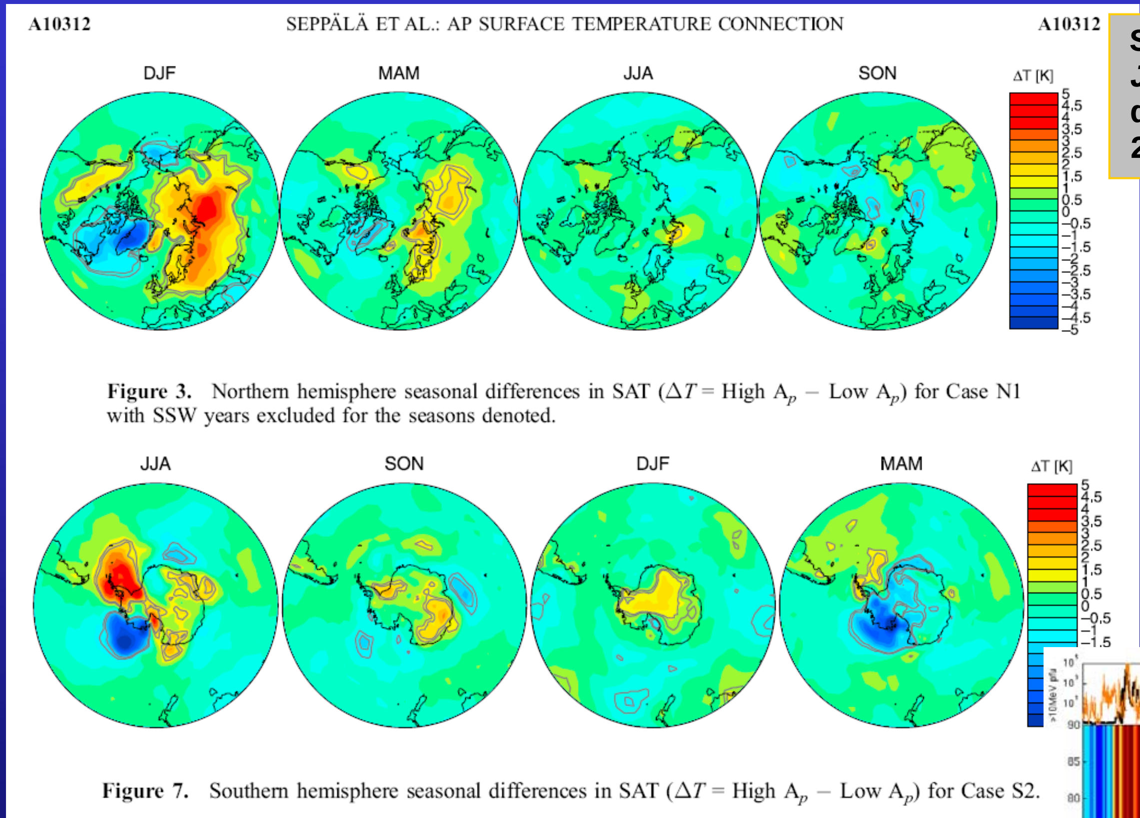
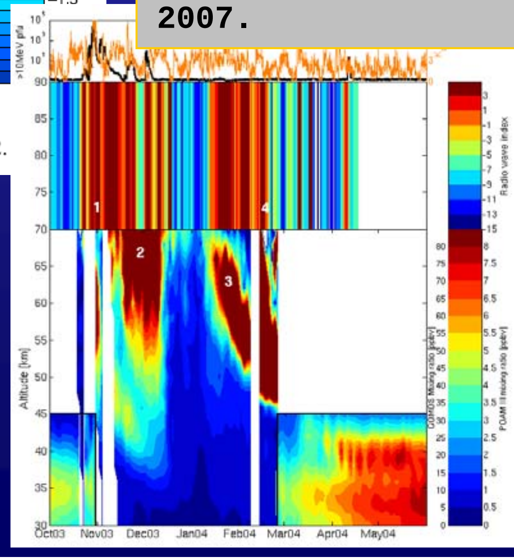


Figure 3. Northern hemisphere seasonal differences in SAT (ΔT = High A_p − Low A_p) for Case N1 with SSW years excluded for the seasons denoted.

Figure 7. Southern hemisphere seasonal differences in SAT (ΔT = High A_p − Low A_p) for Case S2.

Seppälä et al., *J. Geophys. Res.*, doi:10.1029/2008JA014029, 2009.

Seppälä et al., *J. Geophys. Res.*, doi:10.1029/2006JD008326, 2007.



Thus we need to measure energetic particle precipitation, and examine EEP consequences, to see if it can explain the experimentally observed link between geomagnetic storms and polar surface temperatures.

More Modelling

Baumgaertner et al. [ACP, 2011] added an EPP-NOx source (here Ap-index driven parameterization) into the ECHAM5/MESSy chemistry general circulation models to see how dynamics and temperature respond – holding all other conditions fixed to avoid SST or UV variations.

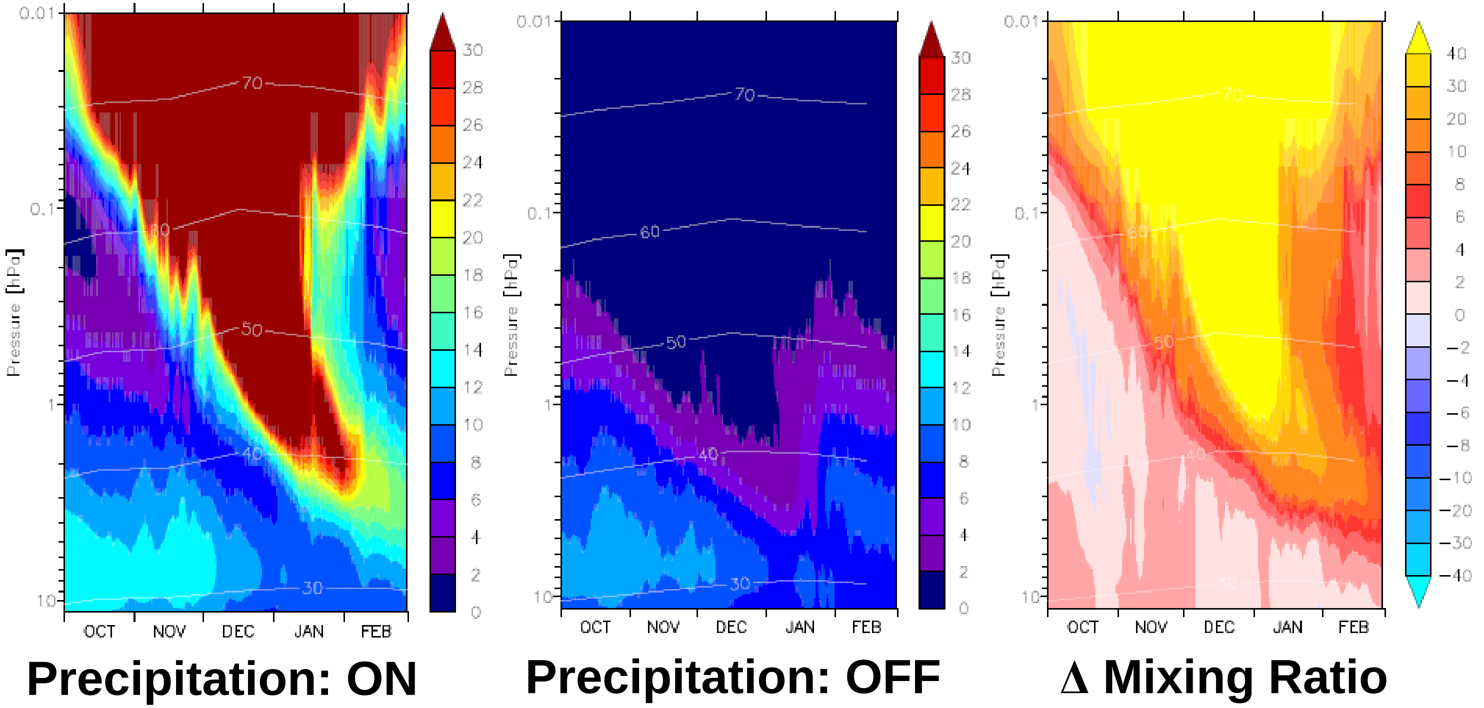
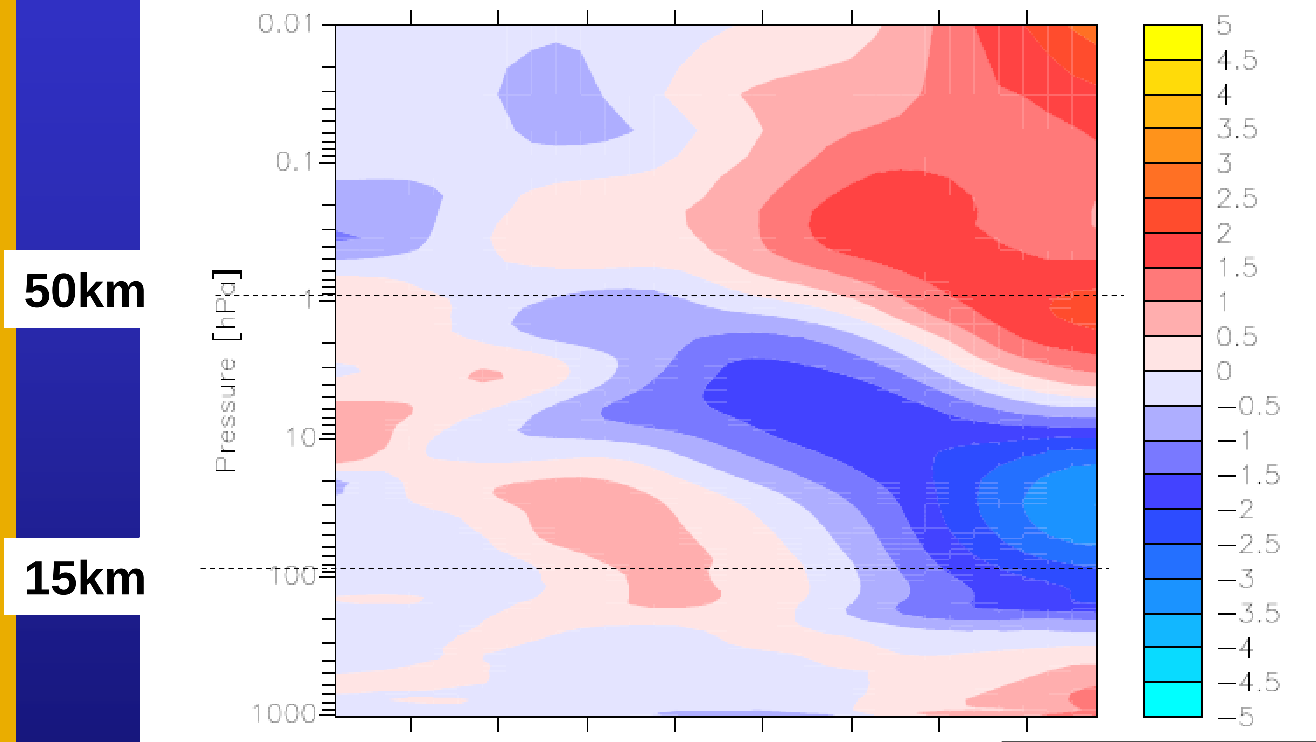


Fig. 6. Left: zonal mean NO_x mixing ratios (nmol mol^{-1}) from simulation S-EPP for an exemplary Northern Hemisphere winter poleward of 60° N. Middle: as left panel, but from simulation S-noEPP. Right: mixing ratio difference $NO_x^{S-EPP} - NO_x^{S-noEPP}$. Red-yellow/blue colours indicate positive/negative differences. The white contour lines denote the altitude in km in all panels.

Baumgaertner et al., *Atmos. Chem. Phys.*, doi:10.5194/acp-11-4521-2011, 2011

More Modelling

Baumgaertner et al. [ACP, 2011] added an EPP-NOx source (here driven by an Ap index linked parameterization) into the ECHAM5/MESSy models.



Baumgaertner et al., *Atmos. Chem. Phys.*, doi:10.5194/acp-11-4521-2011, 2011

Fig. 9. Climatological DJF change of temperature (K), $\Delta T = T^{S-EPP} - T^{S-noEPP}$. Red-yellow/blue colours indicate positive/negative differences.

How enhanced NO_x in mesosphere and stratosphere communicates to surface level changes is currently under investigation.

More Evidence – complex response?

There is a question as to how the "geomagnetic storm" response (which could well be the NOx/HOx produced ozone changes in the mesosphere and stratosphere) couples to the troposphere and surface.

This is an active research area. I am aware of some work looking for evidence of changes in planetary wave and gravity wave filtering.

Working in this area, some collaborators of mine have been looking for changes in temperature, zonal winds, and Eliassen-Palm flux (which can be used as a measure of wave activity). They have shown large changes in the dynamics of the polar vortex location depending on:

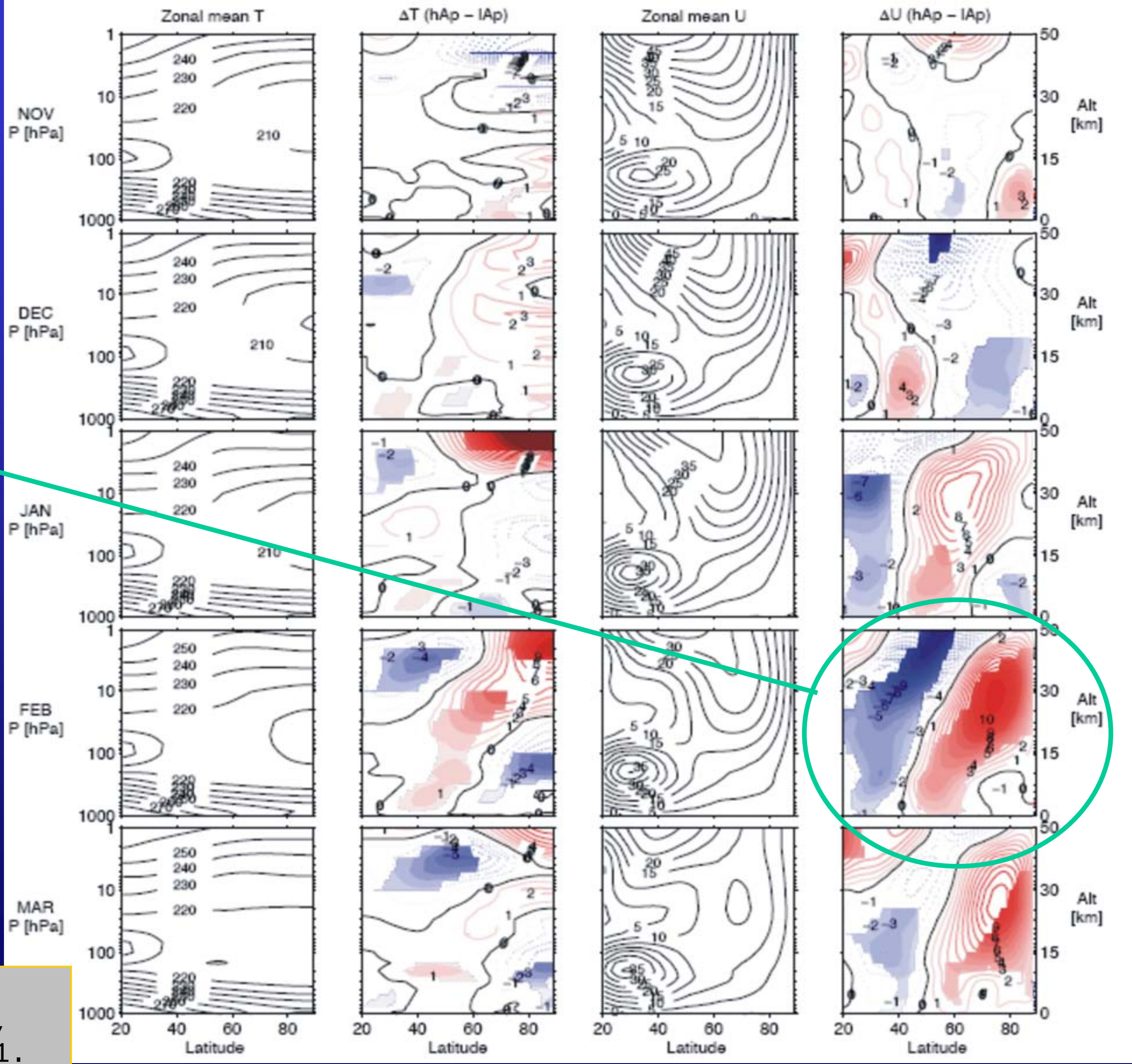
the solar cycle (assumed to be UV changes) AND

geomagnetic storm activity (arranged by Ap)

we assume the latter is a rough proxy for particle precipitation from the radiation belts.

More Evidence – complex response?

ERA40 re-analysis, northern hemisphere only. HIGH SOLAR CYCLE

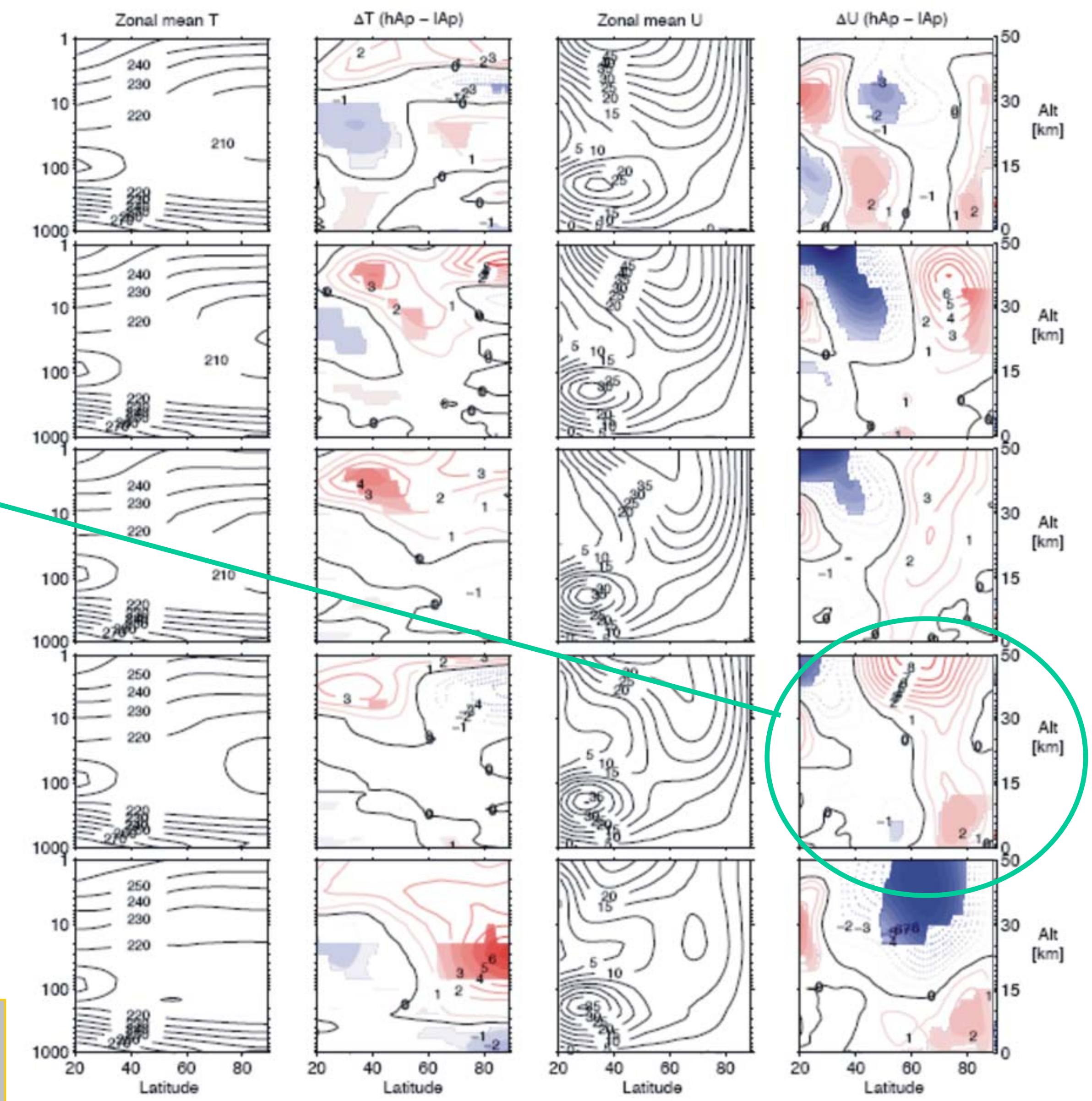


HS cycle case shows large zonal wind response to geomagnetic activity in late winter → pole-ward shift of the jet?

Seppälä et al., *Geophys. Res. Lett.*, in preparation, 2011.

More Evidence – complex response?

ERA40 re-analysis, northern hemisphere only. LOW SOLAR CYCLE



VERY different response to geomagnetic storms for low solar cycle conditions – evidence for preconditioning and a complex response.

Seppälä et al., *Geophys. Res. Lett.*, in preparation, 2011.

Measuring Particle Precipitation is “Tricky”

In order to feed atmospheric, ionospheric and coupled chemistry models, researchers would like access to long-time scale databases of time resolved particle precipitation measurements. **There is a gap for observations of precipitation of electrons at energetic (>10keV) and relativistic (>300keV) energies.**

Ones first instinct is to turn to satellites to provide these.

However, there is currently no appropriate satellite database available!

Definitive answers are very difficult to provide from satellite measurements alone because of the complexity in measuring electron fluxes unambiguously in the whole bounce-loss cone without contamination from fluxes in the drift-loss cone or trapped fluxes.

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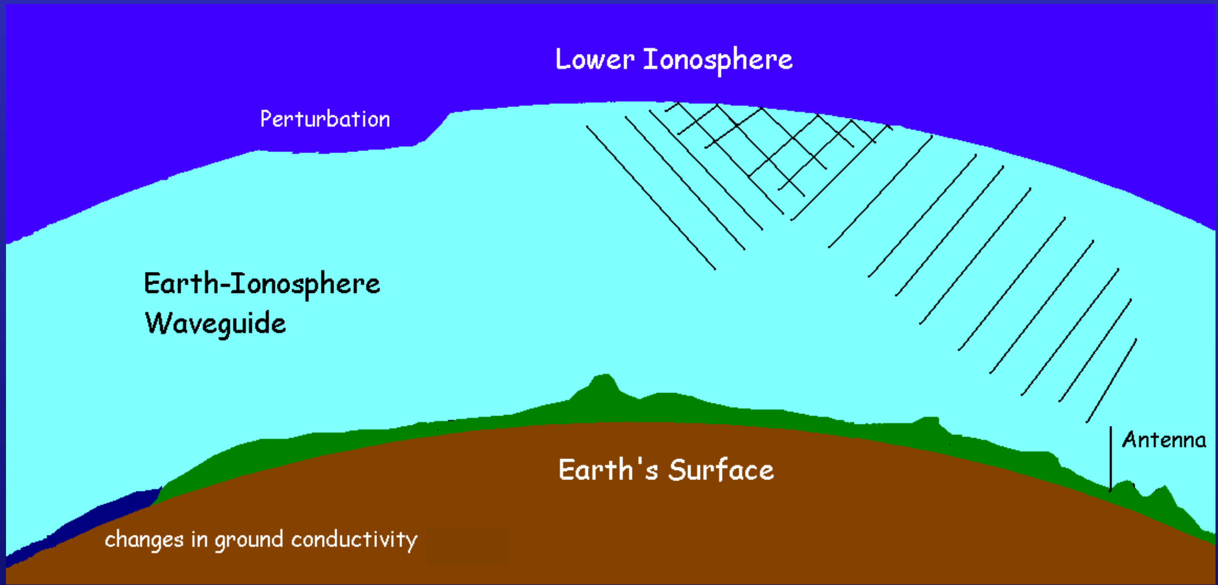
NEW ZEALAND

MARSDEN FUND
TE PŪTEA RANGAHAU A MARSDEN

We have been awarded a New Zealand Marsden Funded project to investigate this very issue:
"Evaluating the Impact of Excess Ionization on the Atmosphere (EI EI A)"

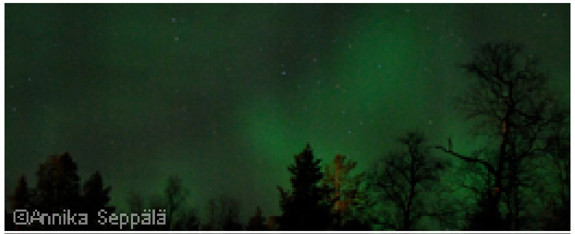
For electrons >100keV, the bulk of the precipitated energy is deposited into the middle and upper atmosphere (30-100km), and can be detected through changes in subionospheric VLF propagation.

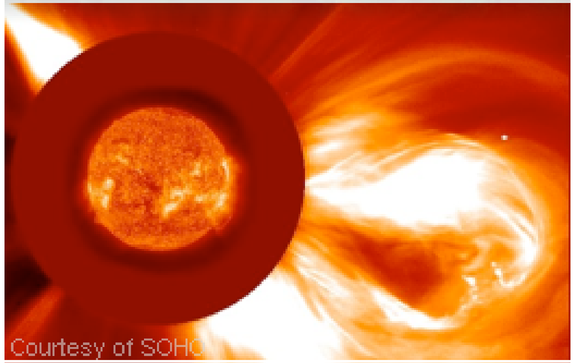


We rely upon the idea that while the bounce loss cone might be hard to fully measure from space, the atmosphere detects the entire bounce loss cone by definition, and we use the atmosphere as a BLC detector.

INTERNATIONAL SPACE SCIENCE INSTITUTE

Geospace Coupling to Polar Atmosphere





How does the forcing from the Sun and the near-Earth space induce changes in the polar atmosphere from low to high altitudes, particularly through precipitation of high energy particles?

The International ISSI team

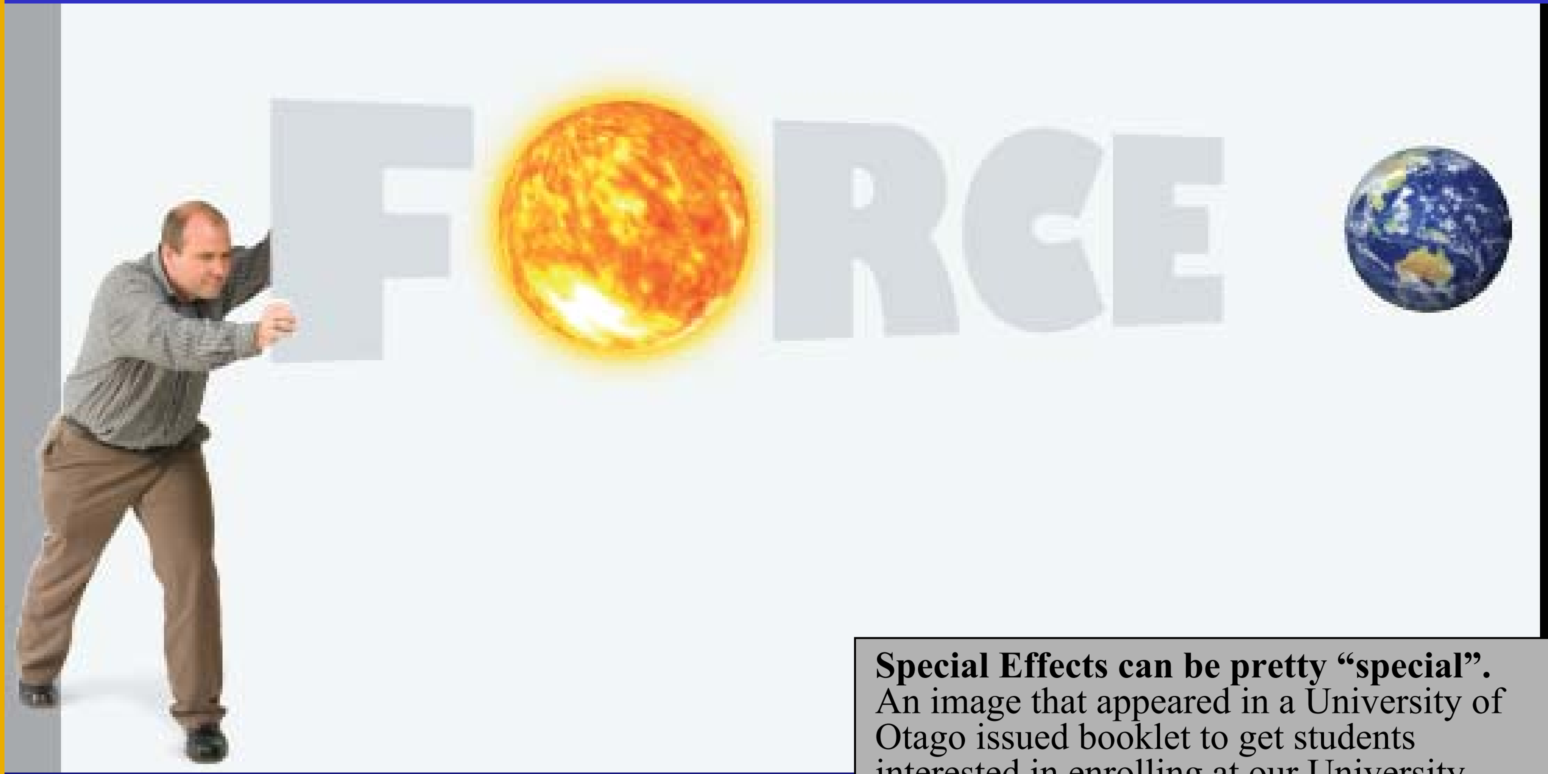
Geospace coupling to Polar Atmosphere aims to bring together a team of scientist to study the impact of the near-Earth space to the polar atmosphere and lower ionosphere. Our science interests lie on examining how the forcing from the Sun and the near-Earth space induces changes in this region extending from low to high altitudes, particularly through precipitation of high energy particles. Our goal is to use a variety of different data sets from ground based and satellite platforms together with state of the art models of the atmosphere and ionosphere to achieve a unified global picture of the geospace impact on the Earth's atmosphere through the polar regions.

The team

Annika Seppälä, Team Leader, *British Antarctic Survey, United Kingdom*
Mark Clilverd, *British Antarctic Survey, United Kingdom*
Thomas Ulich, *University of Oulu/Sodankylä Geophysical Observatory, Finland*
Carl-Fredrik Enell, *University of Oulu/Sodankylä Geophysical Observatory, Finland*
Antti Kero, *University of Oulu/Sodankylä Geophysical Observatory, Finland*
Daniel Marsh, *National Center for Atmospheric Research, United States*
Craig Rodger, *University of Otago, New Zealand*
Eugene Rozanov, *PMOD/WRC and IAC ETHZ, Switzerland*
Tatiana Egorova, *PMOD/WRC and IAC ETHZ, Switzerland*
Pekka Verronen, *Finnish Meteorological Institute, Finland*
Sanna-Mari Salmi, *Finnish Meteorological Institute, Finland*
Esa Turunen, *EISCAT Scientific Association, Sweden*

Thankyou!

Acknowledgement: The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement n°263218.



Special Effects can be pretty "special". An image that appeared in a University of Otago issued booklet to get students interested in enrolling at our University.

Are there any questions?

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Conclusions

- Energetic particle precipitation couples to the atmosphere through production of NO_x (and HO_x).
- Links to natural solar climate variability.
- Particle effects on atmospheric chemistry are being added to climate models.
- Proton precipitation well known and good measurements exist. ✓
- Electron Precipitation levels not known well enough - mostly using proxies i.e. A_p or K_p indices ✗