Space Weather Impact on Polar Atmospheric Ozone and Climate

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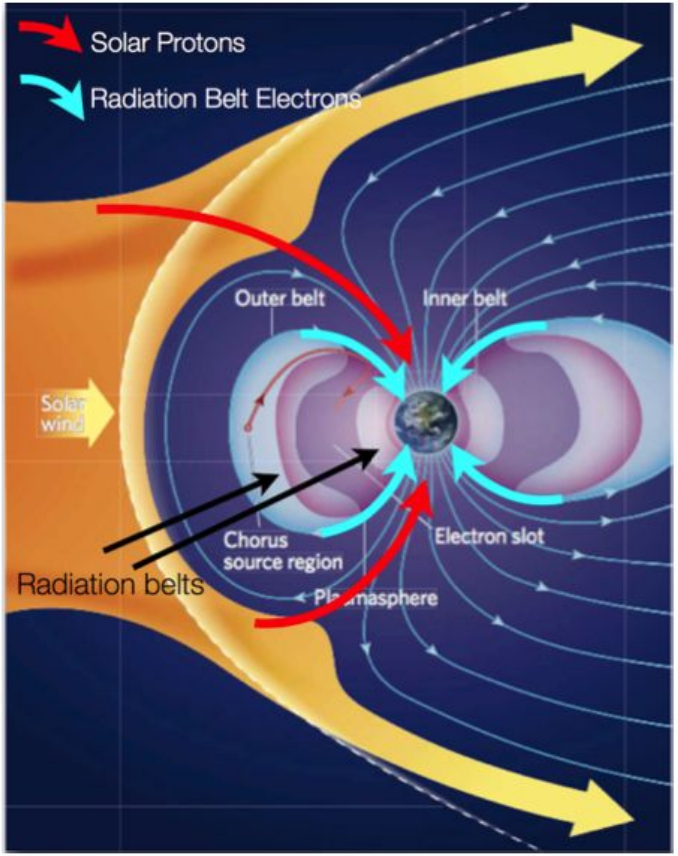
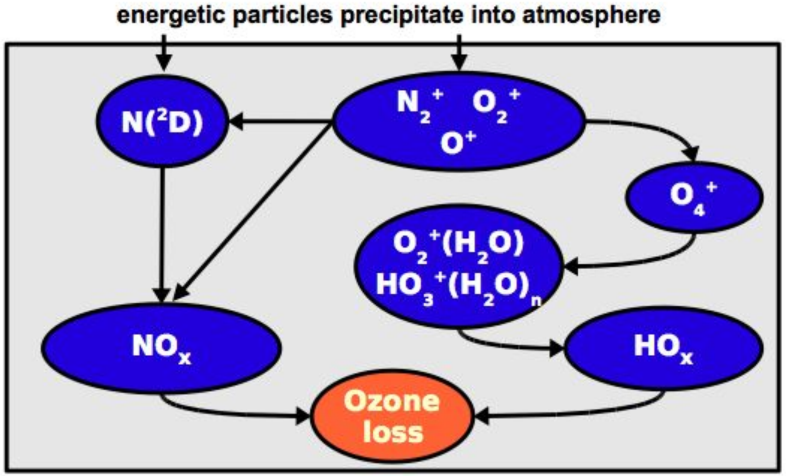
Energetic particle precipitation (EPP) - Atmospheric effects



The concept: particles ionize middle atmosphere, leading to an ozone response.



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EPP impact on polar ozone

- NH polar cap at 40 km altitude
- Simulation with WACCM model

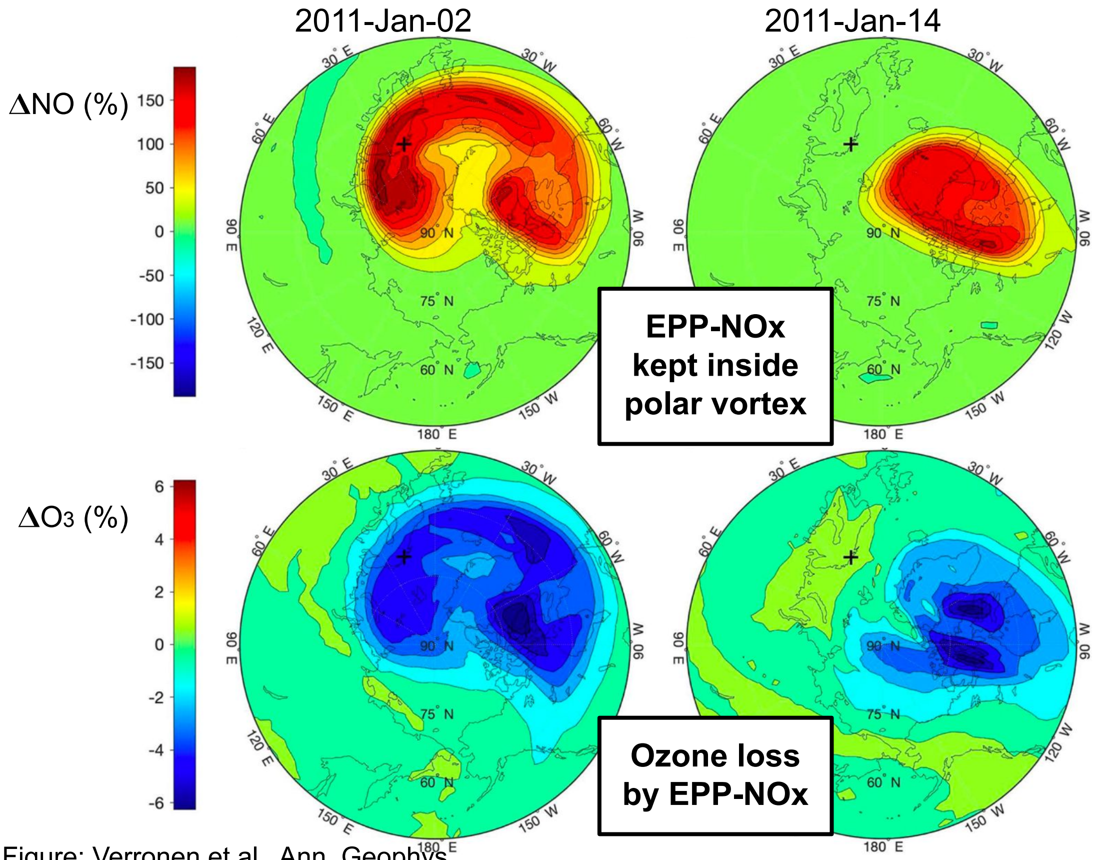
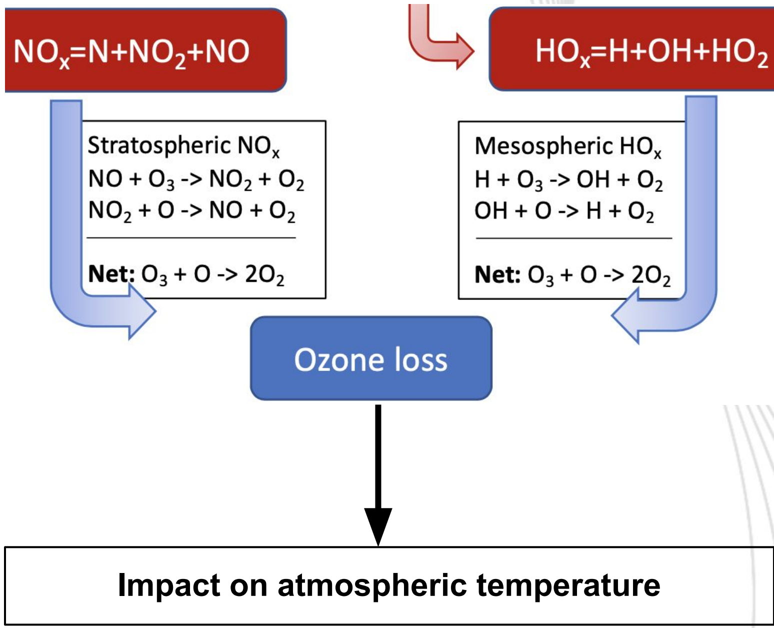


Figure: Verronen et al., Ann. Geophys, https://doi.org/10.5194/angeo-39-883-2021, 2021



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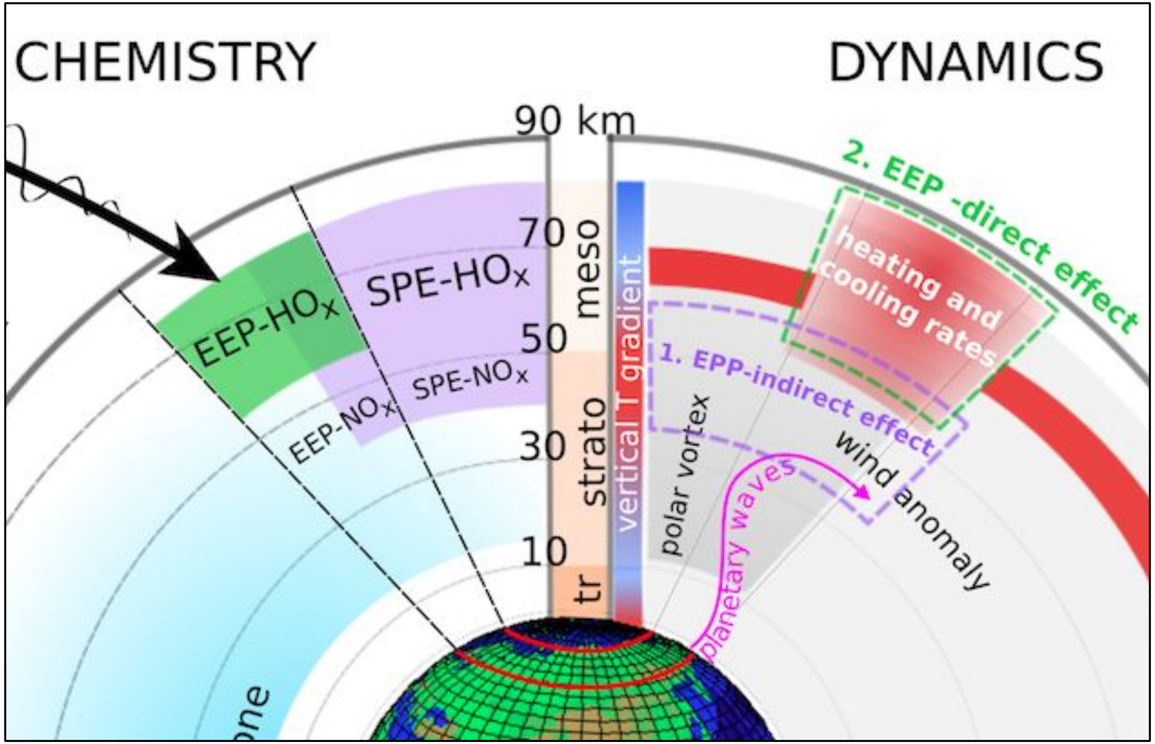
Top-down atmospheric coupling - role of EPP?



Connection between

- solar influence
- ozone and temperature
- winds and waves

For EPP, major atmospheric response

- in polar regions
- during winter months
- by polar vortex modulation

Courtesy of: M. E. Szeląg, Finnish Meteorological Institute

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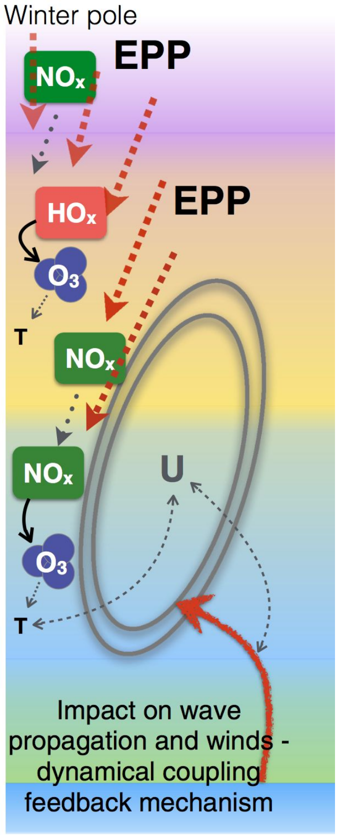
EPP impact on polar vortex dynamics



- Less waves disturbing the polar vortex and therefore stronger vortex
- Anomalously strong polar vortex in late winter, would lead to positive Northern Annular Mode anomalies.

- DJF: for high geomagnetic activity levels more planetary waves are refracted towards the equator, away from the polar region

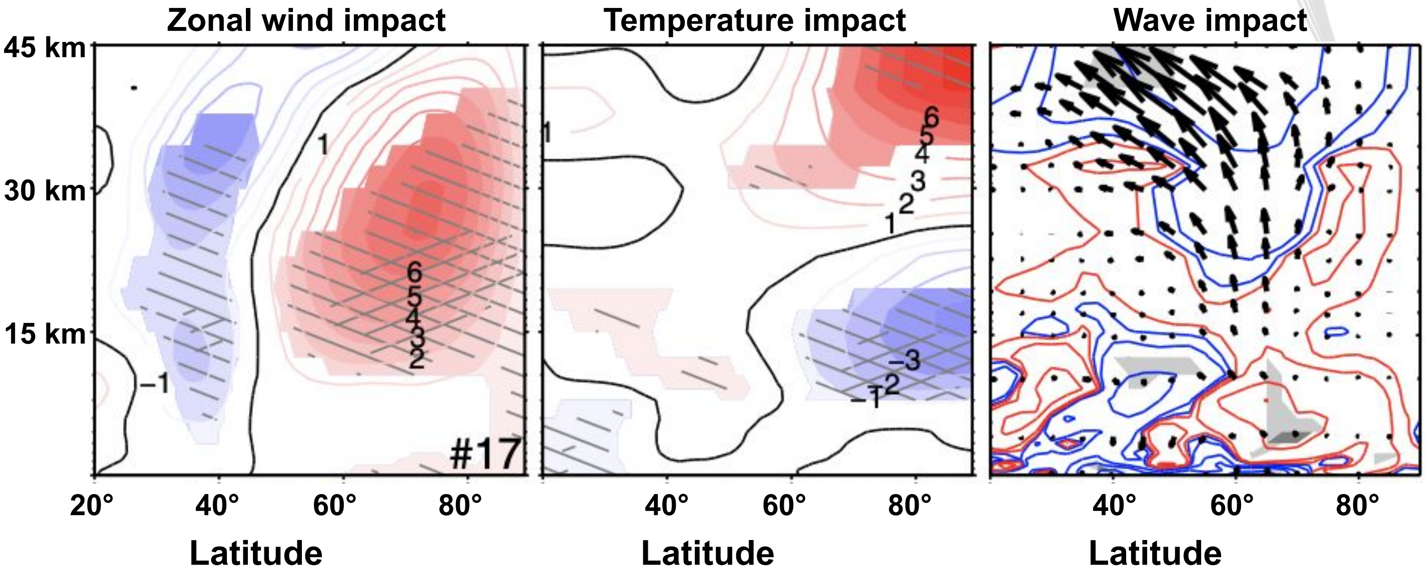
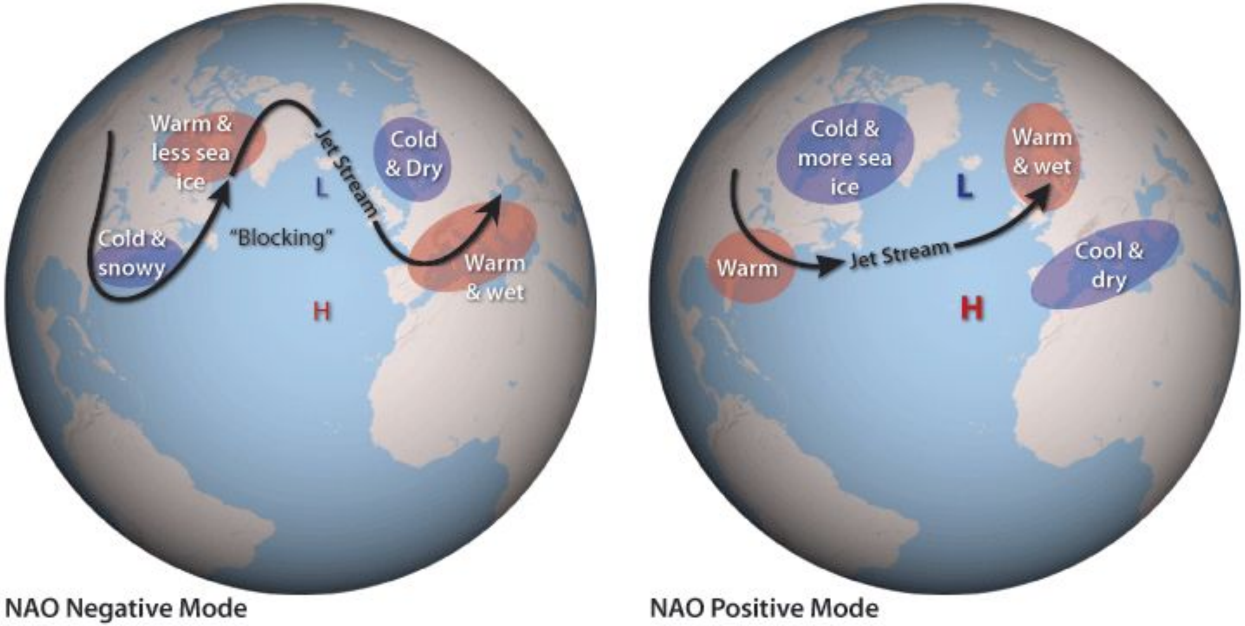


Figure from: Seppälä et al., 2013

Proposed EPP influence on North Atlantic Oscillation (NAO)

Regional wintertime anomalies related to the variability of NAO



NAO is a climate pattern, a natural form of climate variability

It depends on the strength of pressure difference between high and mid latitudes

And modulates the Atlantic Jet Stream.

It's connected to polar vortex strength.

So, when EPP is strong :

- **stronger polar vortex**
- **positive anomaly of North Atlantic Mode?**

Courtesy of: NOAA, 2016

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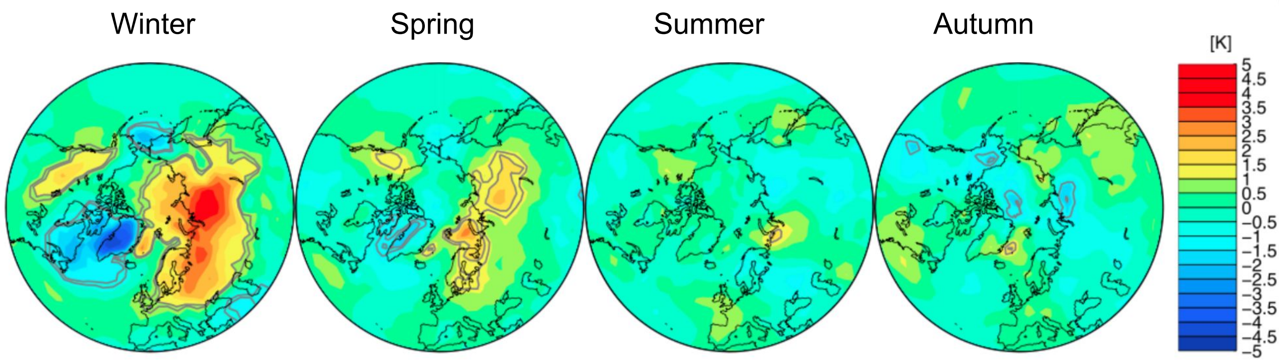
Proposed EPP influence on regional climate

Surface Air Temperature responds to particle precipitation activity



ERA-40 data, from Seppälä et al., *J. Geophys. Res.*, 2009

Regional wintertime anomalies similar to NAO patterns

Figure: Temperature difference between years of high and low EPP.

- A solar cycle effect.
- From a 40-year data set.
- T variability up to ± 5 K.

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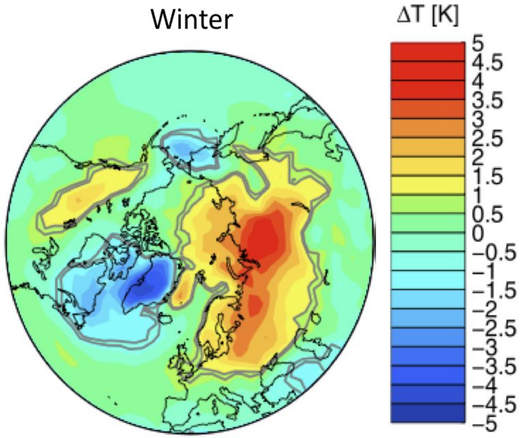
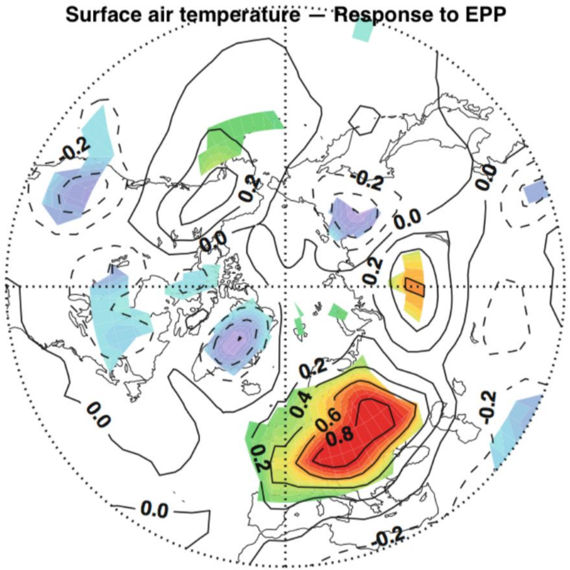
Surface temperature impact from EPP is currently underestimated in simulations!



Observations: ±5 K

Figure *from:*
Seppälä et al., J. Geophys. Res. (2009).



Simulation: ±1 K

Figure *from:*
Rozanov et al., Surv. Geophys. (2012).

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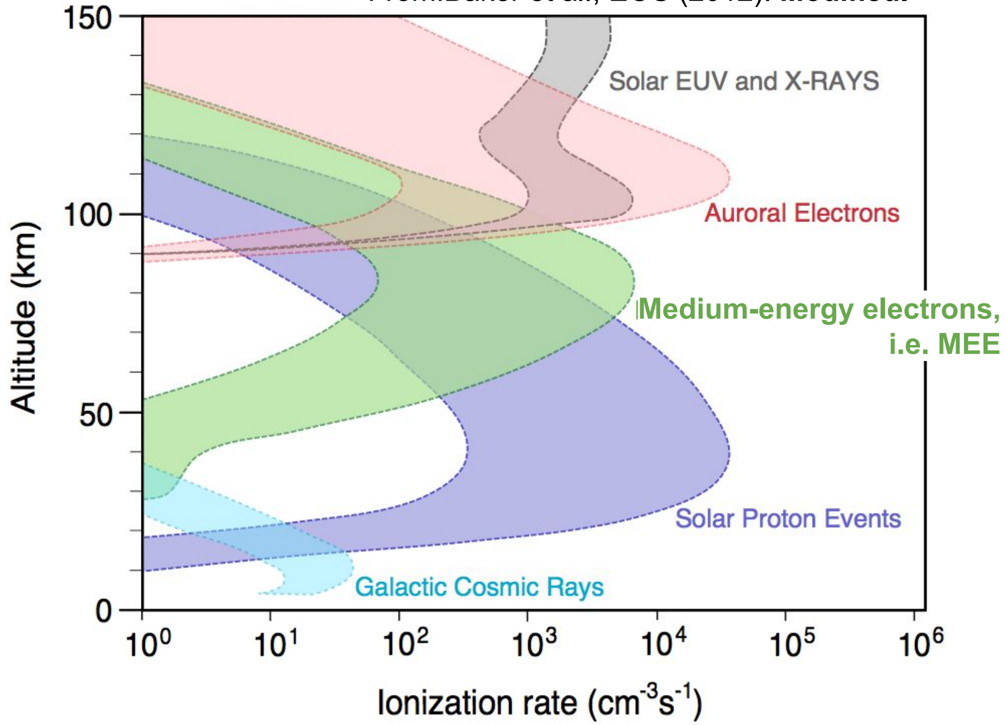
Medium-energy electrons (MEE) - key importance?

From:Baker et al., EOS (2012). **Modified.**



- Contribution of all EPP should included for the assessment of decadal effects
- Major part of direct D-region comes from SPEs and MEE (E > 30 keV)
- Useful MEE flux observations
  - are available from MEPED/POES satellites
  - cover a period between 1998 - present
  - suffer from the measurement geometry and proton contamination

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Ozone impact from solar energetic particles cools the polar stratosphere

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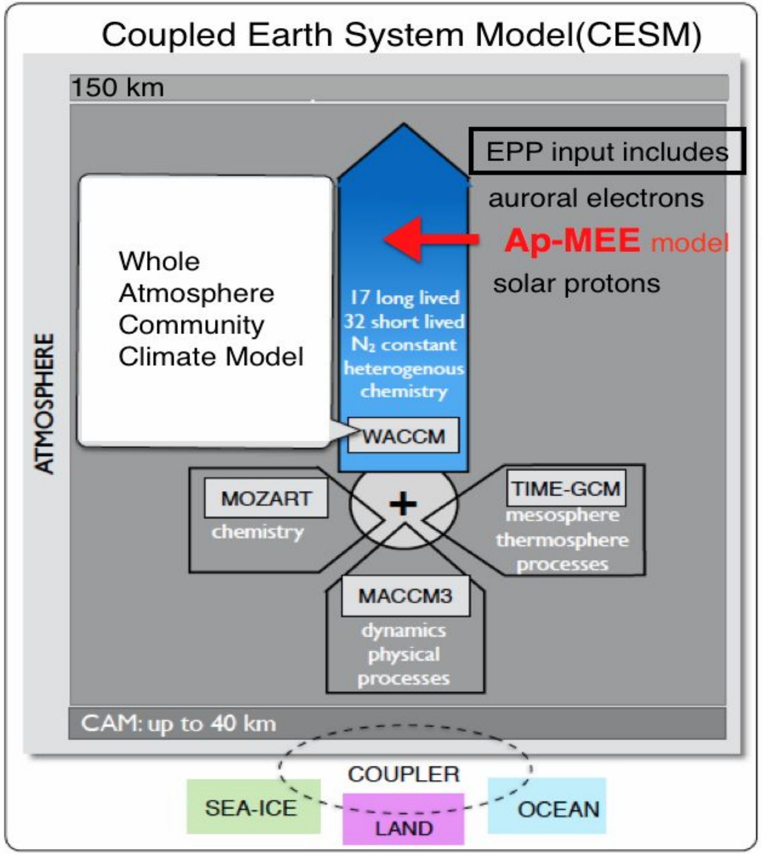
Our CESM / WACCM model

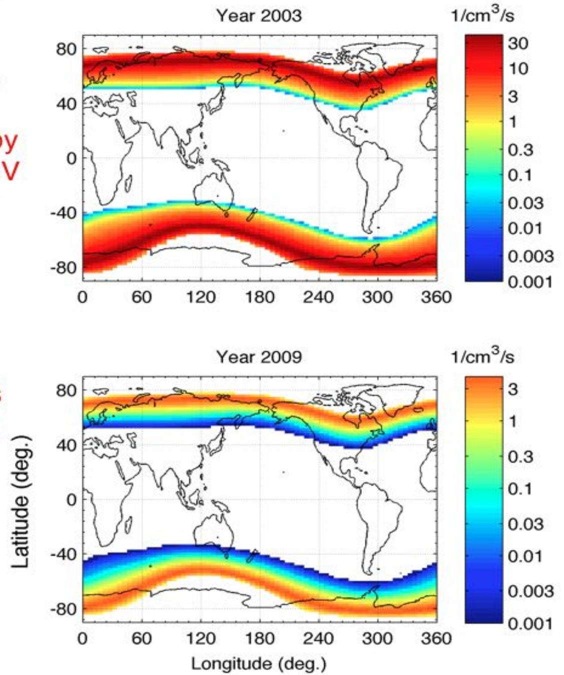


New: Radiation belt electrons from a model: Based on MEPED/POES observations, driven by the geomagnetic Ap index [van de Kamp et al., J. Geophys. Res., 2016]

Ionization by 30-1000 keV electrons

Maximum impact at 60-90 km

Continuous time series from 1850



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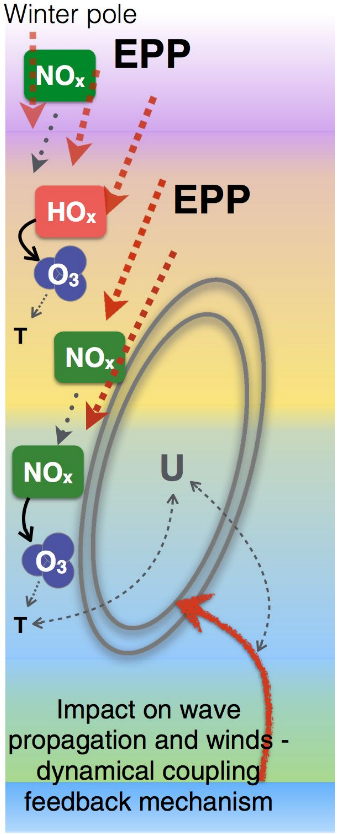
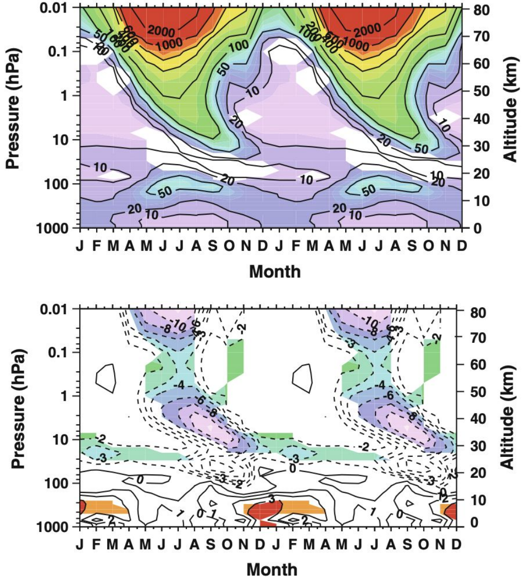
Previously: impact on polar NOx and ozone in winter

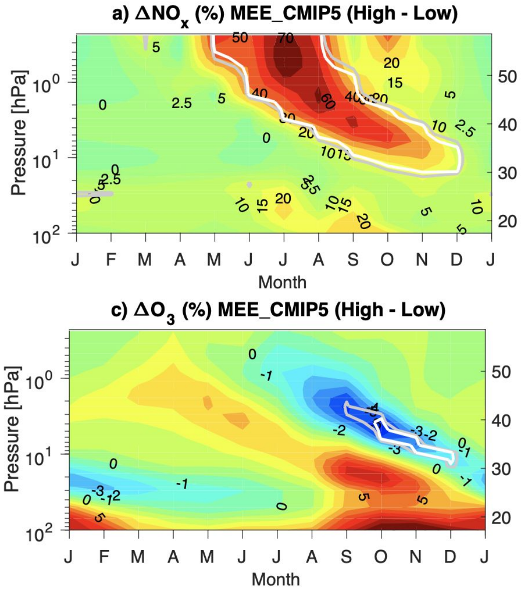


Rozanov *et al.*, 2012



- chemistry-climate model SOCOL
- 46-year long runs
- NO_x increase of about 50% visible down to about 26 km in SH
- O_3 depletion by up to 12%

Andersson *et al.*, 2018

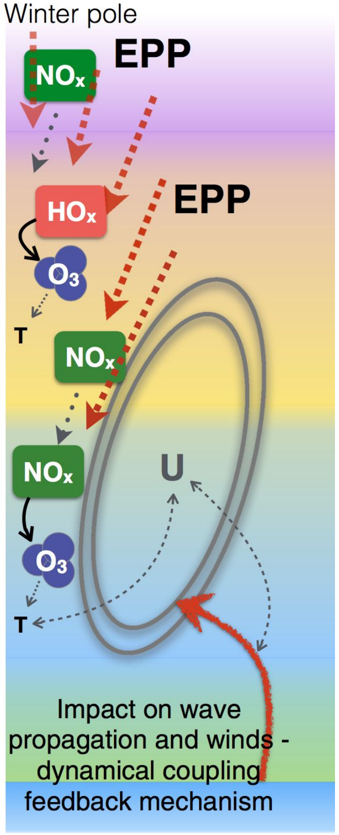


- WACCM model
- 3x50-year long runs
- NO_x increase of about 20-40% visible down to about 30 km
- O_3 depletion by up to 7%

NOx descent inside polar vortex

Indirect effect on springtime ozone

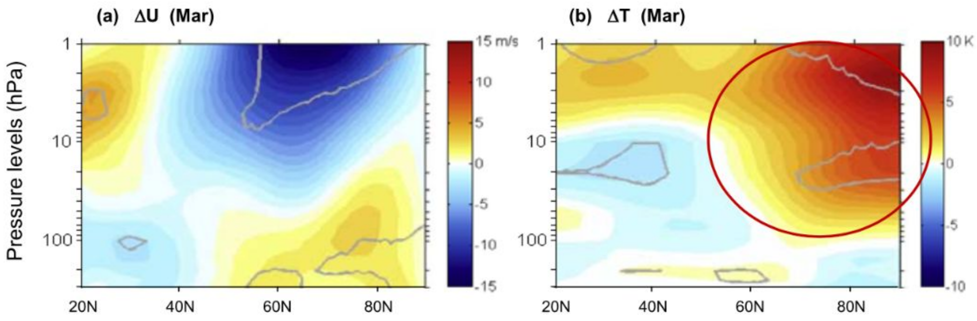
Previously: EPP (Ap) impact on polar stratospheric T in NH



Statistical study from reanalysis data: **ERA-40 Reanalysis** (1957-2002) and **ECMWF** Operational analyses (2002-2006)

Lu et al. J. Geophys. Res. (2008)

Geomagnetic perturbations on stratospheric circulation in late winter and spring: high-low



ΔU = zonal wind ΔT = temperature

Conclusion: Temperature changes are not from ozone depletion but dynamical

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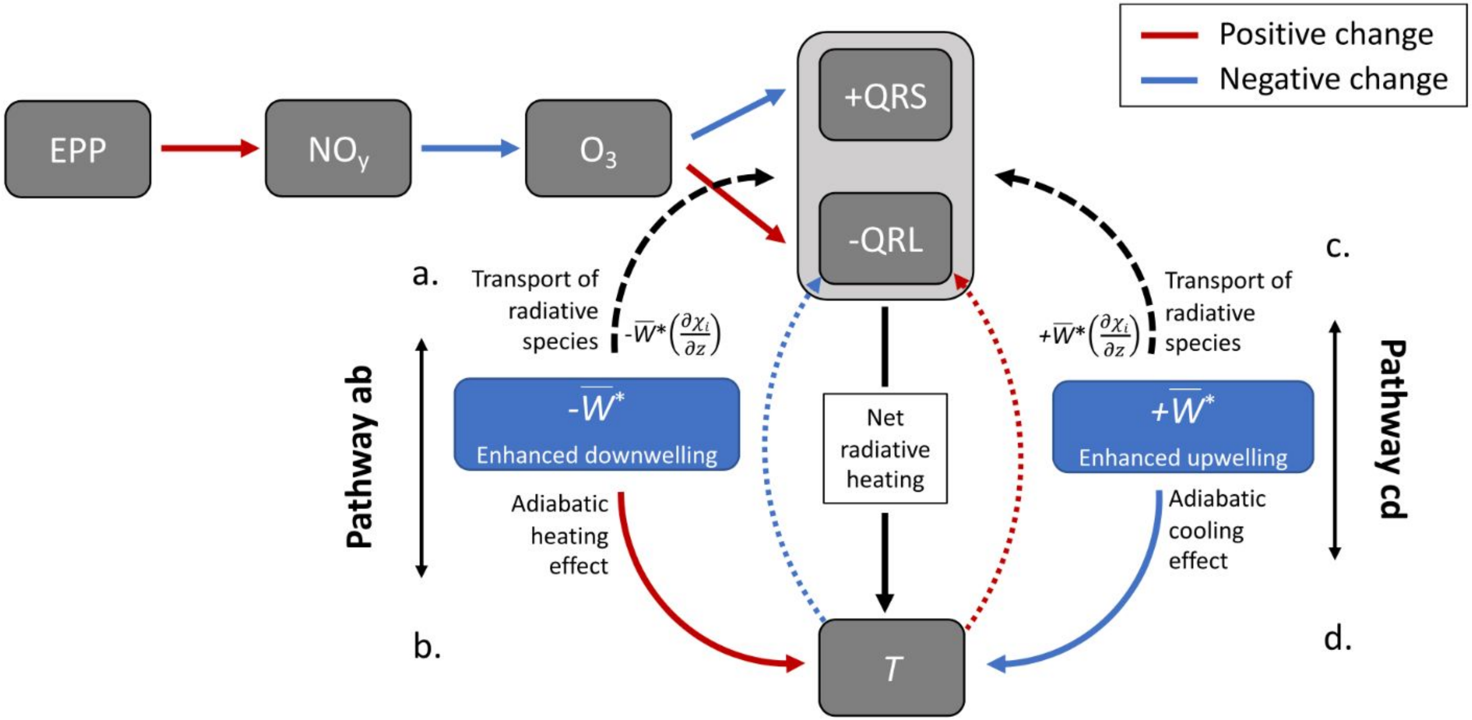
Chemical and dynamical heating



QRS = shortwave heating, **QRL** = longwave cooling, **w*** = vertical wind anomaly

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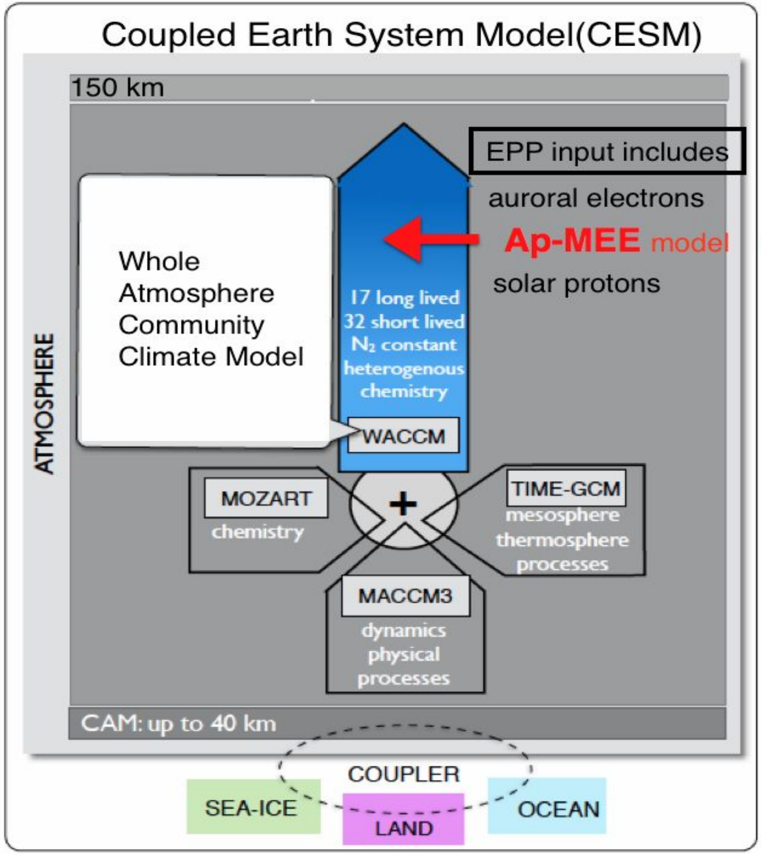
Repeating CMIP5 simulations, but with Ap-MEE



An ensemble simulation:
36 years of high EPP, 33 years of low EPP

- CMIP5 setup (compset "B55TRWCN"), active ocean and sea ice components.
- The observed forcings:
  - radiatively active species at surface
  - daily solar spectral irradiance
  - volcanic sulfate heating,
  - Quasi-Biennial Oscillation (QBO).
- Interactive chemistry, **free running dynamics**.

- 5-ion chemistry for the thermosphere (no D-region chemistry). ⇒ **HO_x/NO_x production parameterized**.
- **CMIP6 recommendation of EPP included**.
  - Daily mean, zonal mean ionization

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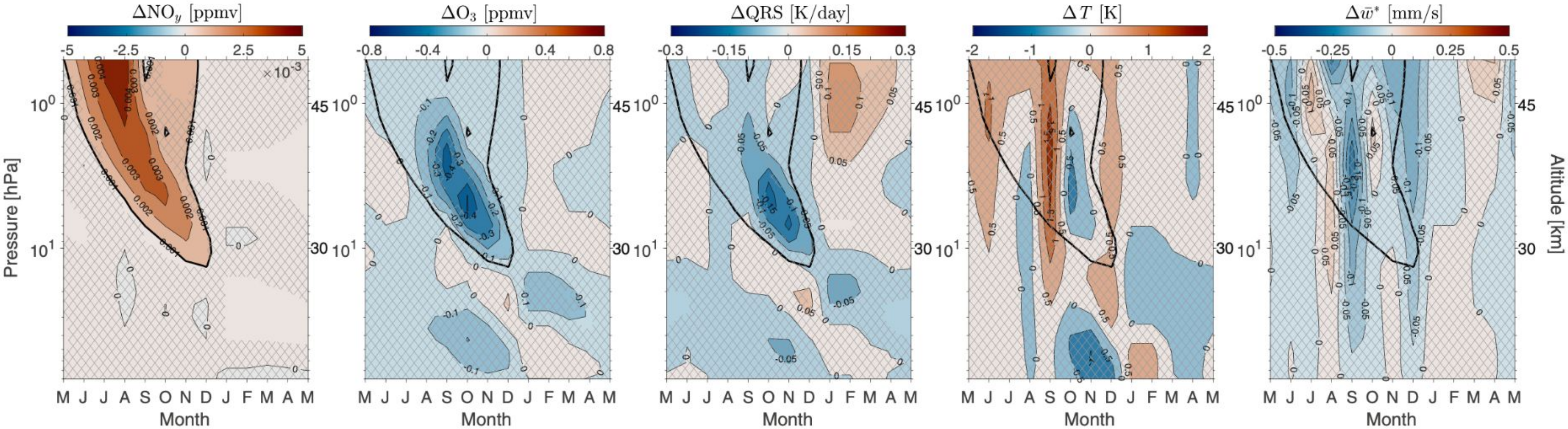
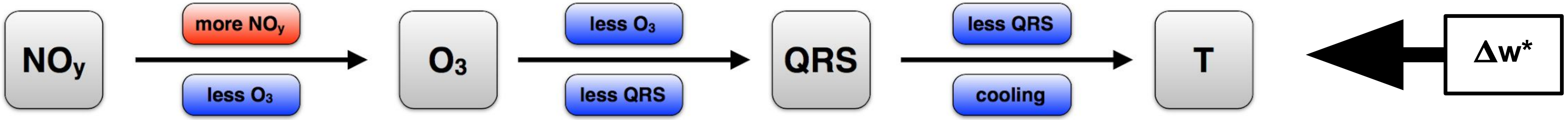
Response in the SH polar region (high EPP - low EPP)





Temperature response: w* anomaly masks the ozone impact

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Sensitivity simulations with controlled EPP

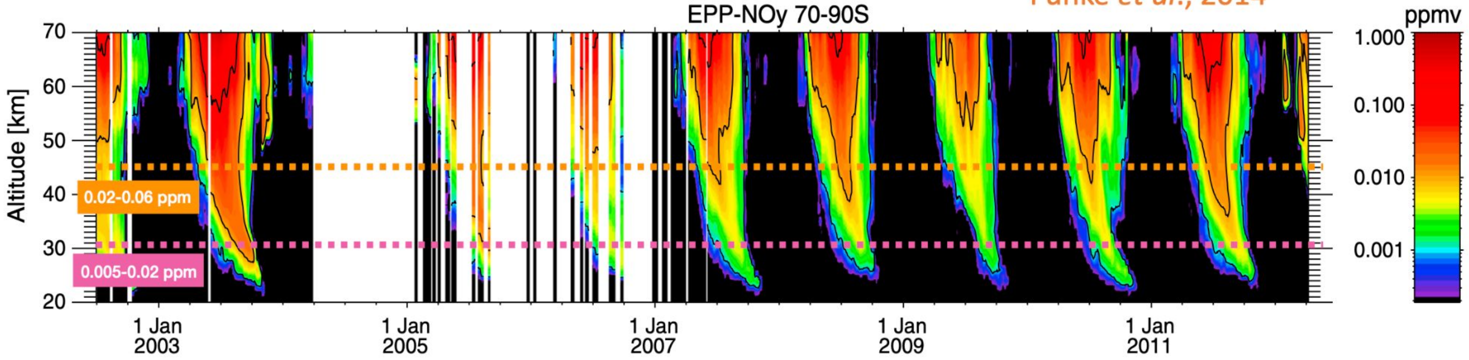
Year 2000 repeated, **50-year simulation sets**, constant EPP, free-running dynamics

Set	Description	*Ap*	*Kp*	*F10.7/F10.7a*	MEE
FW^{max}	high solar irradiance, high EPP	27	4	210/210	10 × 2003 mean
FW^{min}	low solar irradiance, low EPP	1	0.1	40/40	–

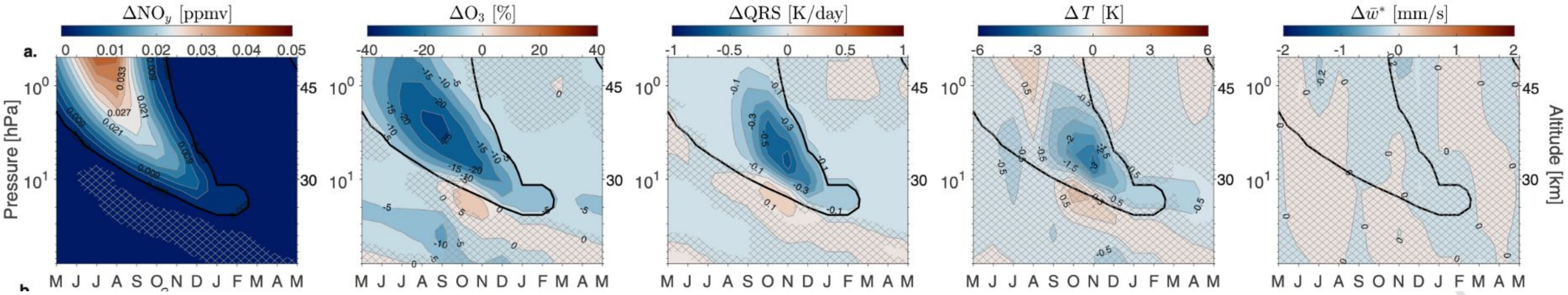
Note increased EPP: to match the amount of stratospheric NOy seen in MIPAS satellite-based observations.

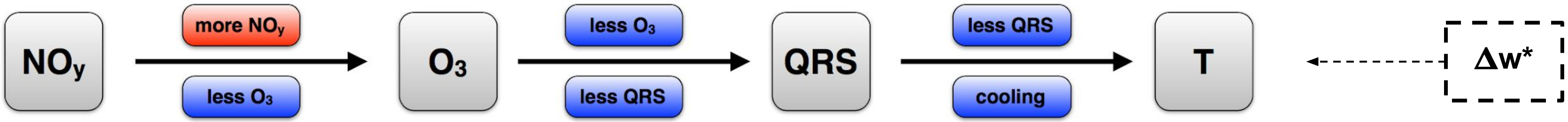
Temporal evolution of the EPP-NO_y from MIPAS

Funke *et al.*, 2014



Sensitivity experiment: EPP impact (FW^{max} - FW^{min})





Realistic amount of NOy ⟶ **EPP impact on temperature clear** ⟵ long data set to reduce Δw*

25% depletion of ozone leading up 3 K cooling at 25 - 40 km

Summary: space weather and regional climate variability

Space weather activity affects atmospheric ozone and has potential **implications for tropospheric climate.**

Connection between **ozone, polar vortex dynamics, and ground-level regional climate variability** has been proposed.

Open questions about the dynamical response that propagates to the troposphere.

Solar energetic particle precipitation (EPP) is not yet considered in most climate models.

Observations show +/-5 degree **decadal variability in ground-level temperatures**, driven by solar EPP activity.

Understanding the related **coupling mechanisms from upper to lower atmosphere and climate** is one of the **grand challenges** in solar-terrestrial science today.

It is **essential to know the natural climate variability**, so that we can accurately **assess the human influence on climate** on regional and decadal scales.

In the context of the global warming and the stratospheric ozone recovery, **addressing this grand challenge directly supports the work of Intergovernmental Panel on Climate Change (IPCC).**