EPP EFFECT ON STRATOSPHERIC COMPOSITION, DYNAMICS AND SURFACE CLIMATE.

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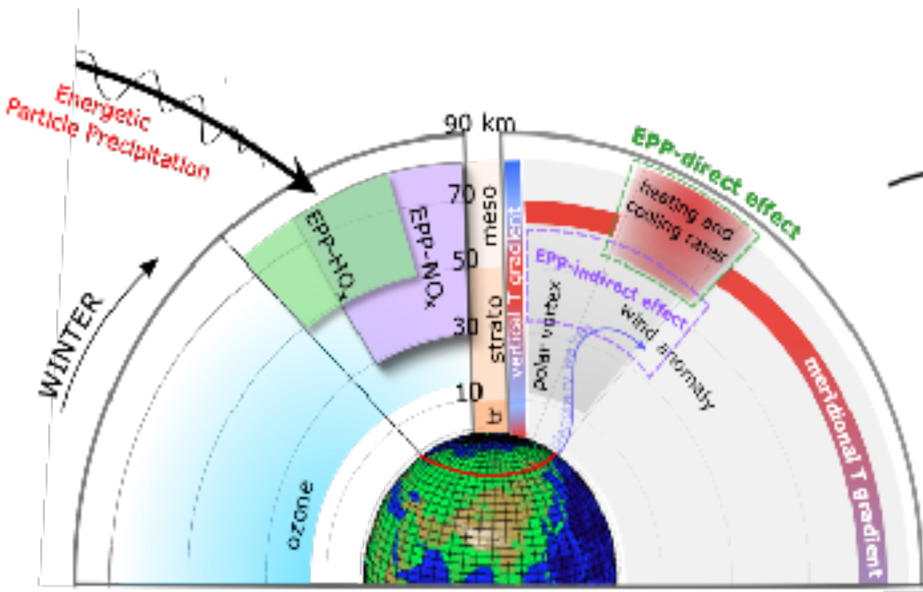
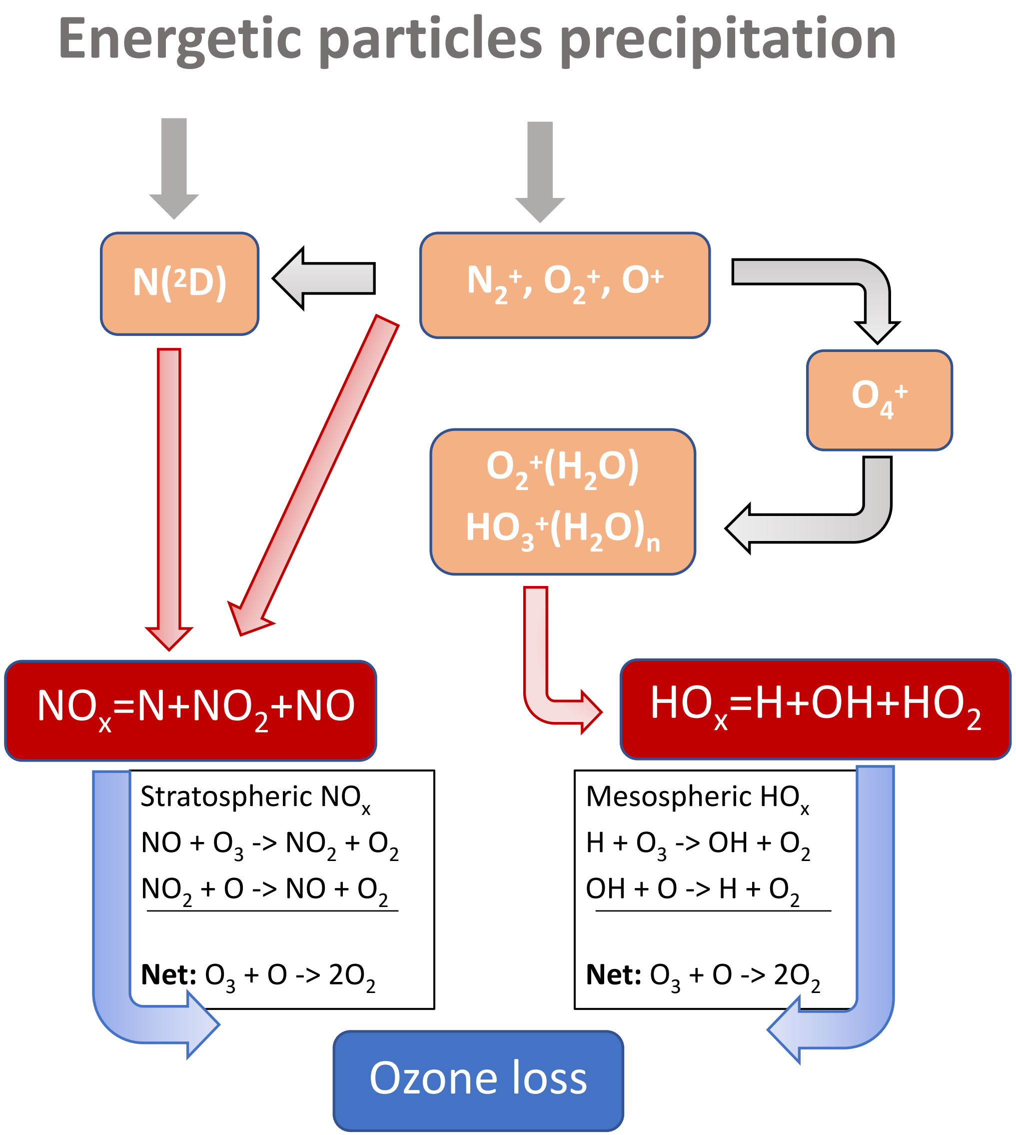
Objectives

EPP → **ATMOSPHERIC CHEMISTRY** → **ATMOSPHERIC DYNAMICS** → **Regional climate**



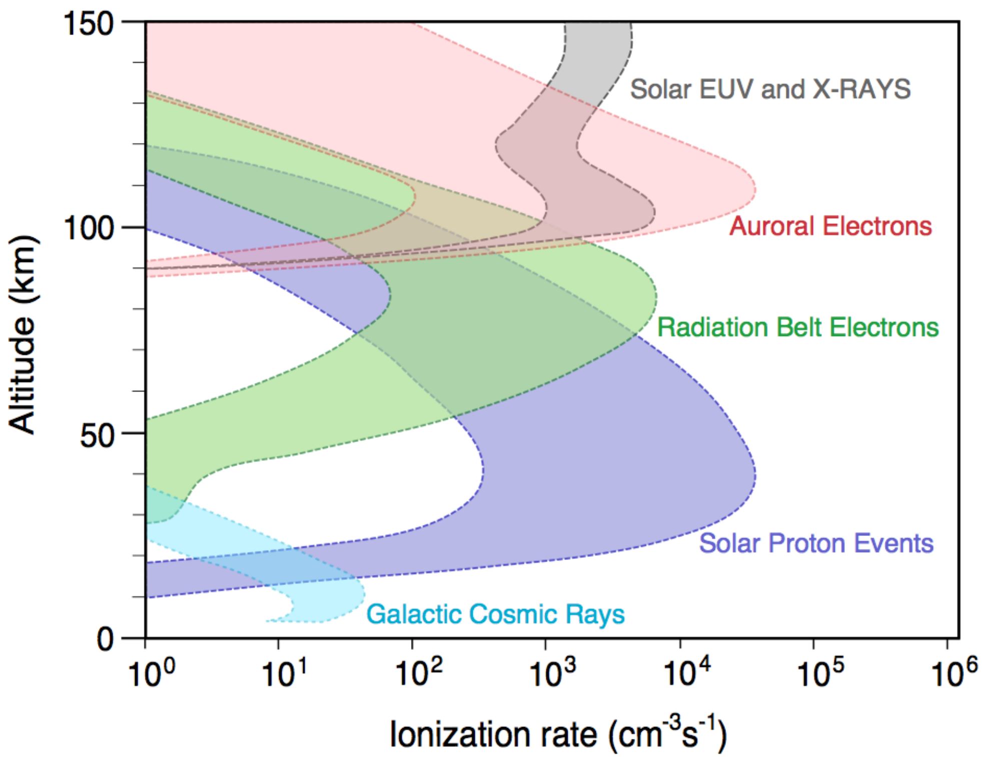
EPP: main concept



- EPP into the atmosphere
- D-region ion chemistry
- Enhanced production of NO_x and HO_x species
- Catalytic ozone destruction
  - NO_x in the stratosphere
  - HO_x in the mesosphere

EPP populations

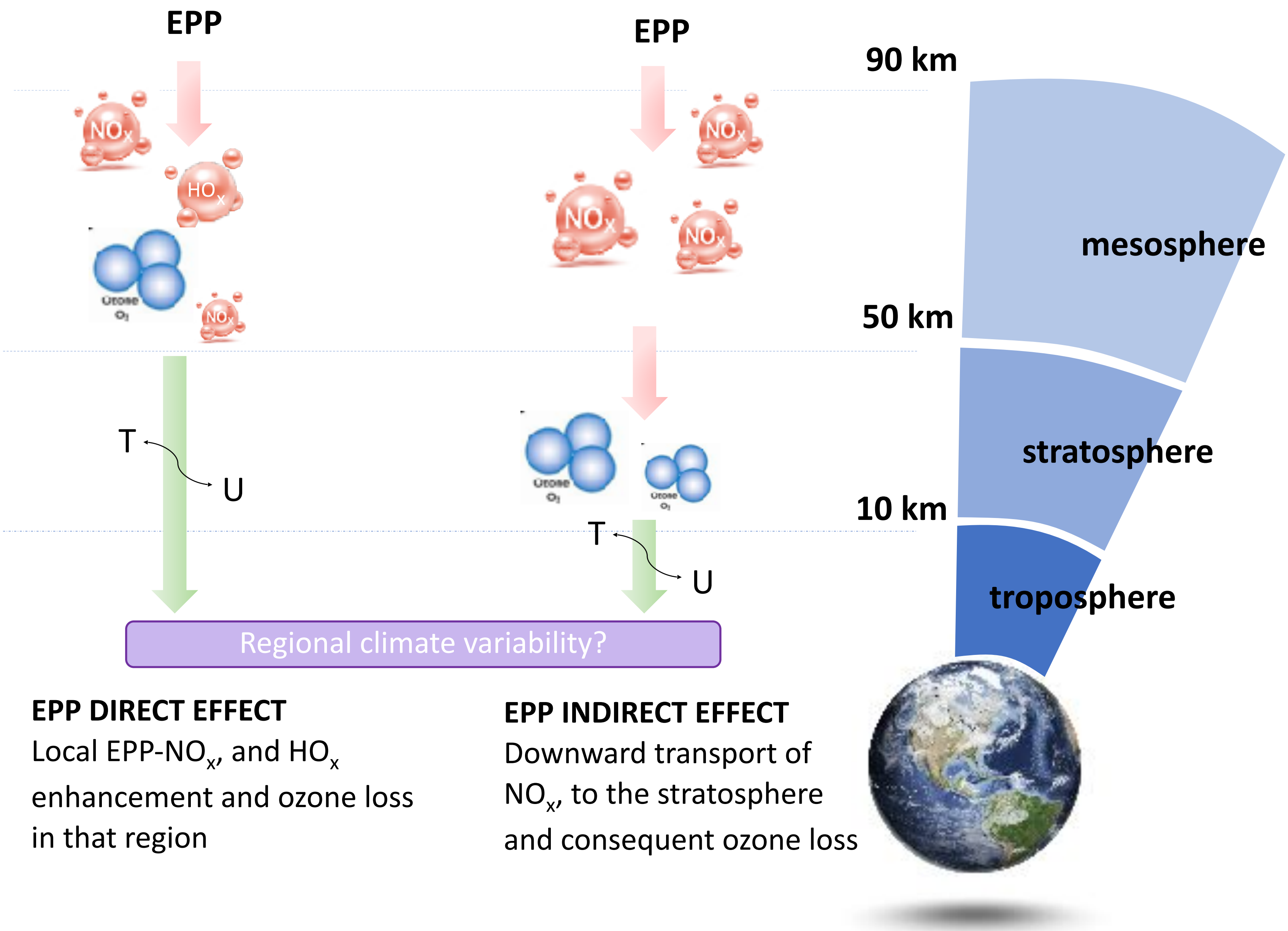
Energy deposition



- EPP affect different regions in the atmosphere
- EPP energy determines the penetration depth

- auroral electrons: < 30 keV
- medium energy electrons: 30 keV-300 keV
- high energy electrons: 300 keV- several MeV
- SPE: up to 500 MeV
- GCR: 1 MeV -5×10^{13} MeV

Direct and indirect EPP effect



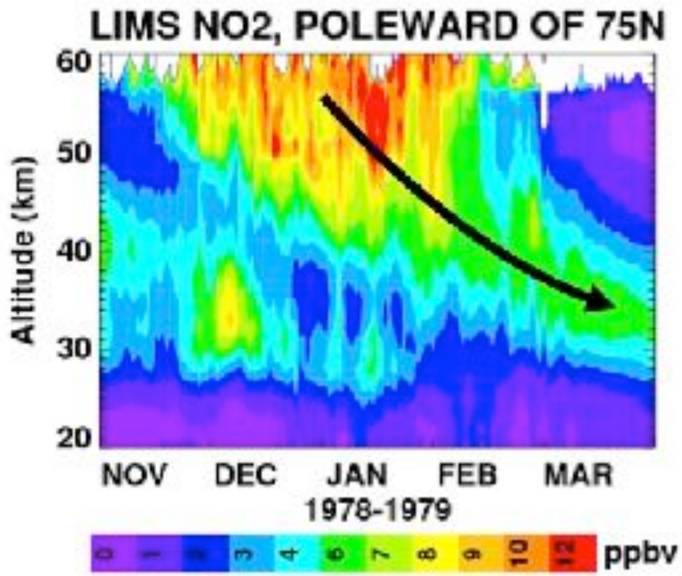
EPP DIRECT EFFECT
Local EPP-NO_x, and HO_x enhancement and ozone loss in that region

EPP INDIRECT EFFECT
Downward transport of NO_x, to the stratosphere and consequent ozone loss

Indirect EPP effect: NO_x observations

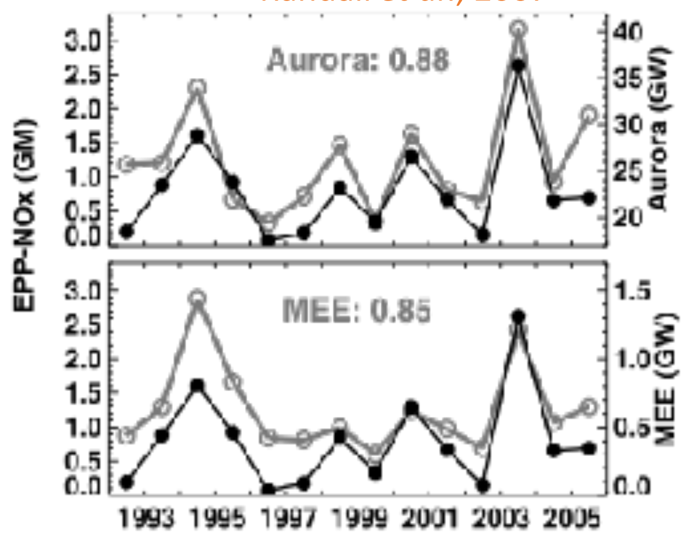
1 First evidence of EPP IE

Russell *et al.*, 1984



2 EPP-NO_x from HALOE in the SH

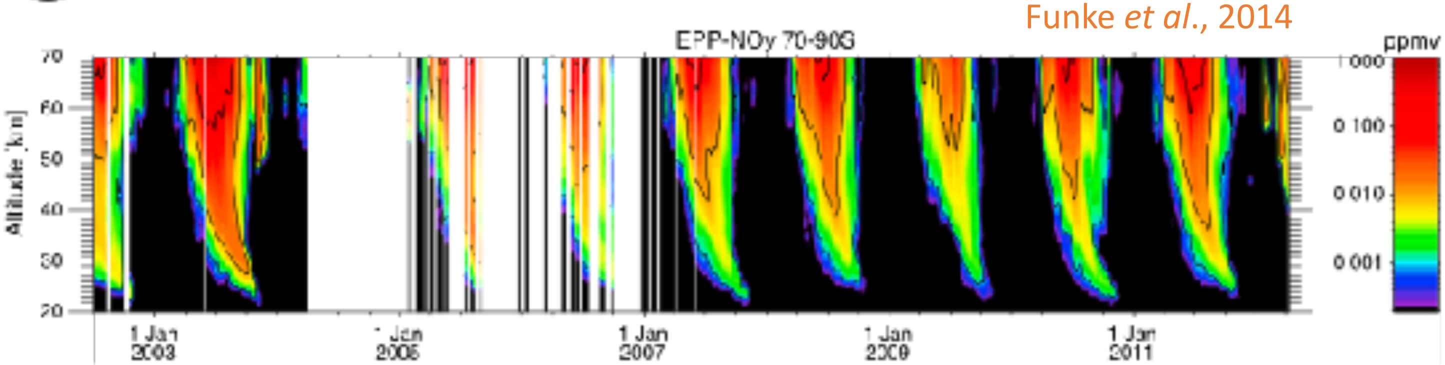
Randall *et al.*, 2007



- Annual EPP-NO_x
- High correlation with MEE and aurora
- Interannual variations in EPP-NO_x in the SH are primarily driven by the EPP source and less by dynamics.

3 Temporal evolution of the EPP-NO_y from MIPAS

Funke *et al.*, 2014

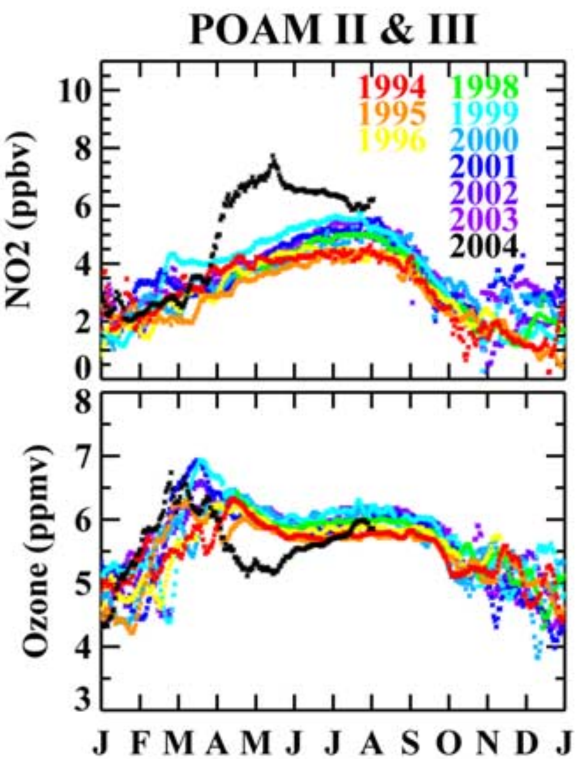


- Strong descent inside the polar vortex annually
- EPP-NO_y accounts for **up to 40%** of the stratospheric and lower mesospheric total NO_y column.

Indirect EPP effect: O_3 reduction

1 Stratospheric effects of EPP

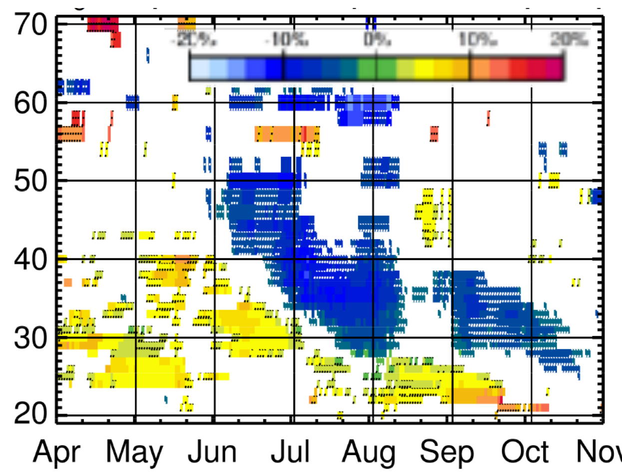
Randall *et al.*, 2005



- **NO_2 and O_3 ppbv, 40 km**
- EPP-NO_x enhancemnt in 2004 caused ozone reduction due to enhanced descent

2 EPP induced intra-seasonal variability of ozone

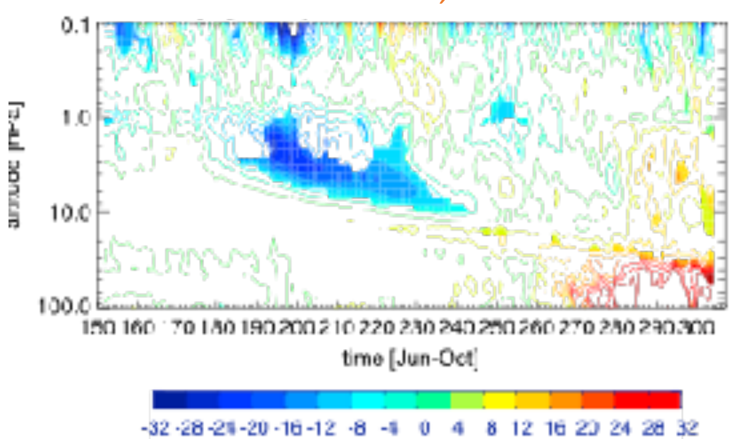
Fytterer *et al.*, 2015



- O_3 differences between high and low Ap years from merged data set (MIPAS, SABER, SMR)
- Clear negative Ap signal from 50 km in June down to about 25 km in October

3 EPP: A major driver of the ozone budget in the Antarctic

Damiani *et al.*, 2016

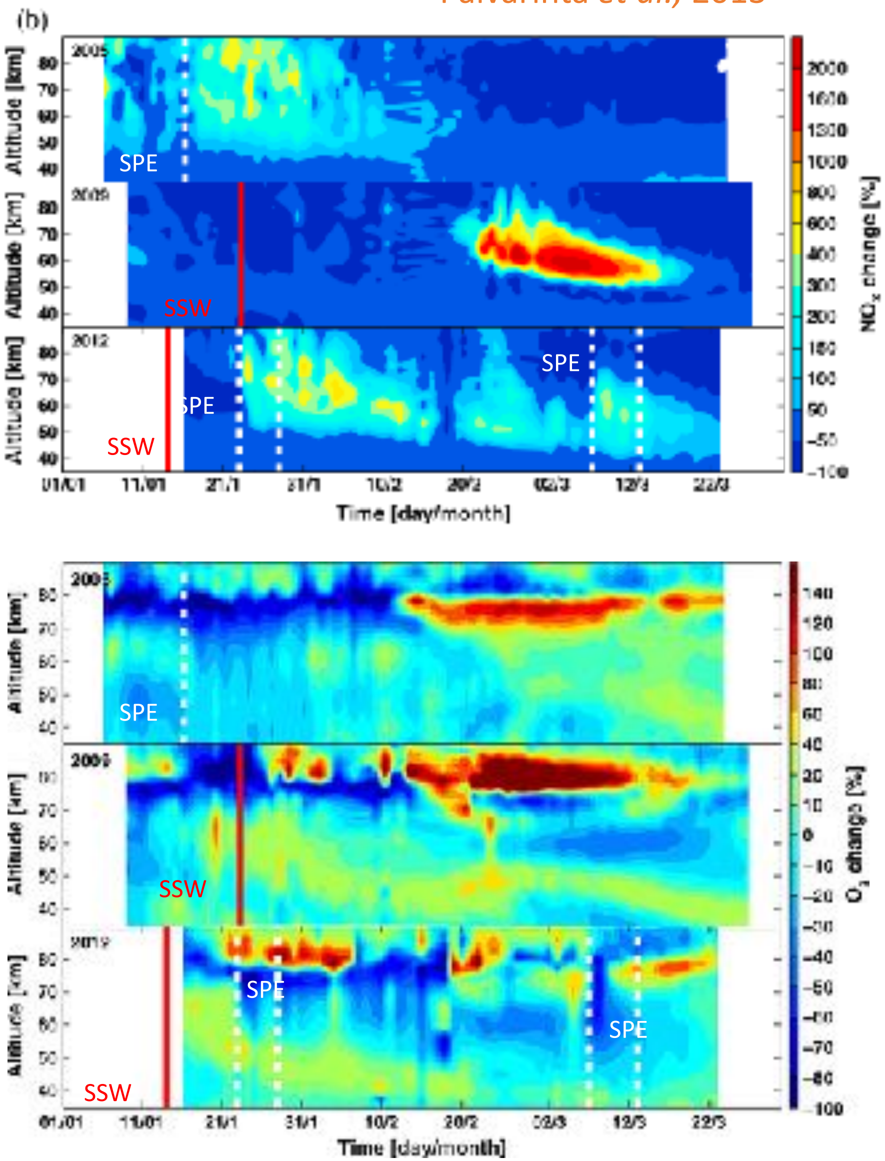


- MLS O_3 differences (high - low EPP-NO_y)
- Clear response of O_3 to EPP activity at about 10-15 % on average.

Indirect EPP effect: SSW

ACE-FTS

Päivärintä *et al.*, 2013



- NO$_x$ connection between the MLT and stratosphere can be intensified not only by EPP but also sudden stratospheric warmings (SSWs)
- Strong downward transport associated with SSW intensifies the descent inside the polar vortex

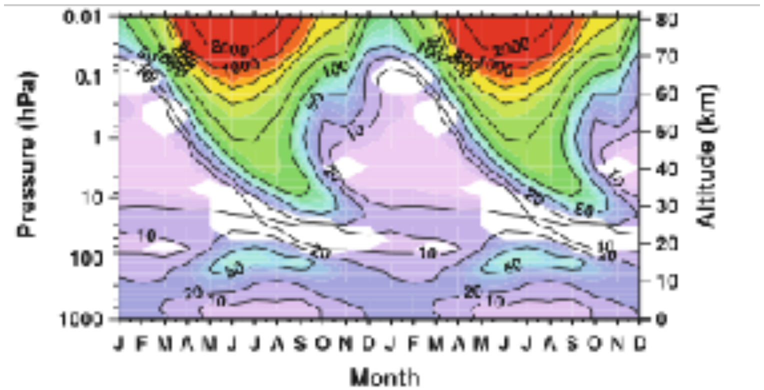
Observations

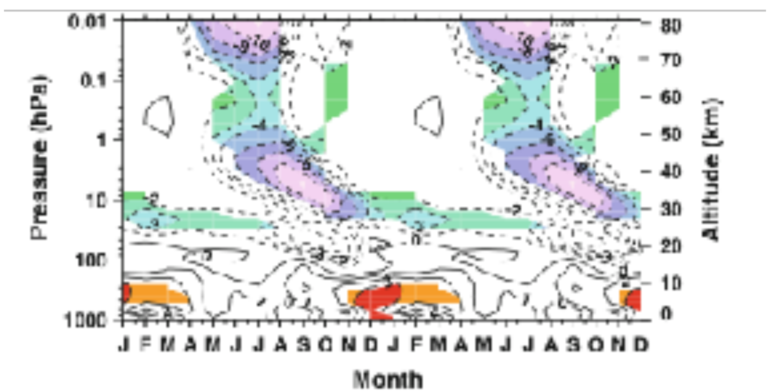
- NO$_x$ increased due to SPEs and SSWs by a factor of 1-25 between 40-90 km
- Ozone loss of the order of 10–90%
- The largest mesospheric NO$_x$ enhancement observed in 2009 following the major SSW
- In 2012 (SPEs + SSW) enhanced amounts of NO$_x$ were transported down to 40 km resulting in the largest NO$_x$ changes in the upper stratosphere

Indirect EPP effect: models

1 **Influence of the EPP on chemical composition of the atmosphere**

Rozanov *et al.*, 2012

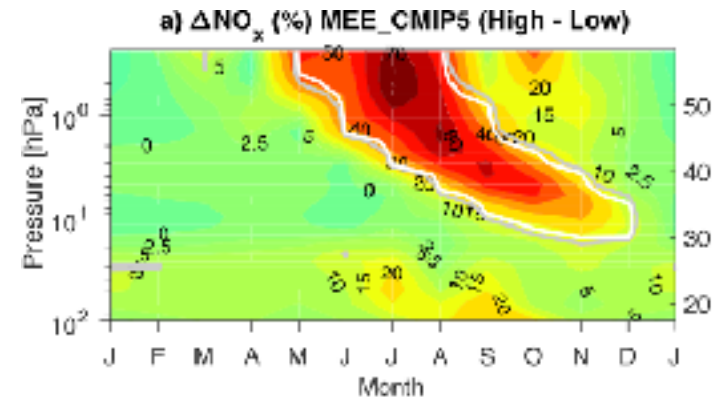


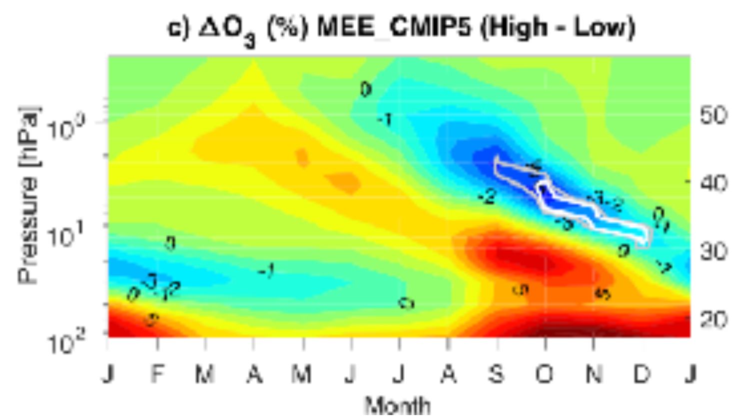


- chemistry-climate model SOCOL
- NO_x increase of about 50% visible down to about 26 km in SH
- O_3 depletion by up to 12%

2 **Polar ozone response to MEE over decadal time scale**

Andersson *et al.*, 2018

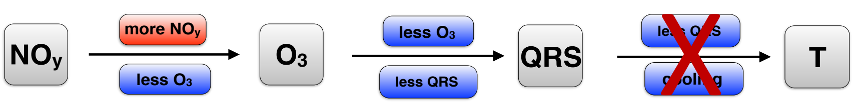




- WACCM model
- NO_x increase of about 20-40% visible down to about 30 km
- O_3 depletion by up to 7%

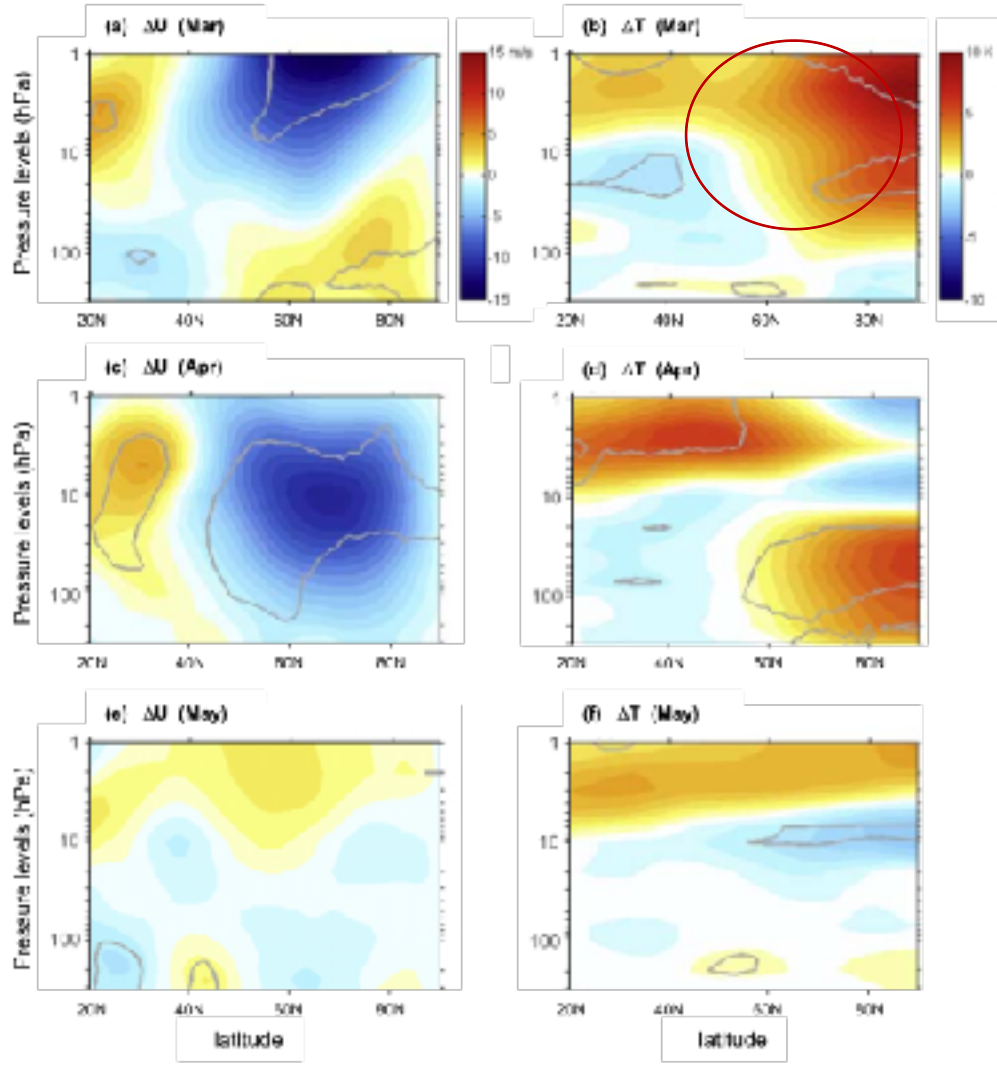
Indirect EPP effect: dynamics

- Statistical study from reanalysis data: **ERA-40 Reanalysis** (1957-2002) and **ECMWF** Operational analyses (2002-2006)
- EPP leads to stratospheric ozone reduction in the late winter/spring
- From chemistry:



- The spring Ap signals show the opposite sign to that expected due to in situ cooling effects caused by catalytic destruction of stratospheric ozone by descending EPP-NO_x

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



Lu *et al.*, 2008

Indirect EPP effect: longitudinal variations

Why EPP-NO_x effects should be studied in 3D?

- EPP-NO_x indirect effect exhibits longitudinal variations
- Zonally asymmetric descent into the top of the polar vortex
- Lagrangian Coherent Structures that confined NO-rich air to polar latitudes

Harvey *et al.*, 2021 and the next talk!

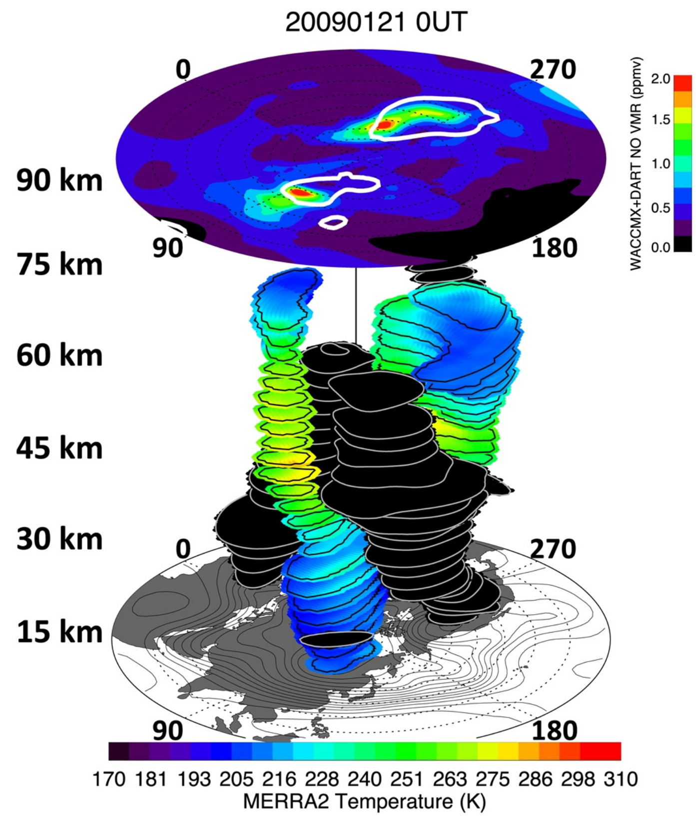
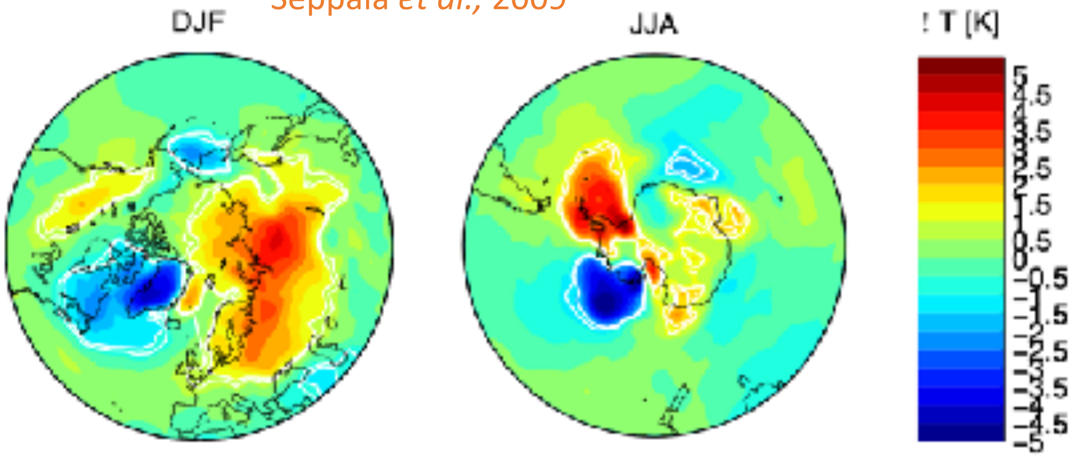


Figure 2. 3-D representation of the Arctic polar vortex (colored by temperature) and stratospheric anticyclones (colored black) on January 21, 2009, at 00 UT based on MERRA-2. An NH polar map of 90 km NO VMR from WACCMX + DART hovers above the split vortex. White contours in the NO map indicate where model GPH deviates by more than 1 km below the zonal mean, indicative of PW troughs. GPH, geopotential height; NH, Northern Hemisphere; PW, planetary wave; VMR, volume mixing ratio.

EPP: surface air temperature response

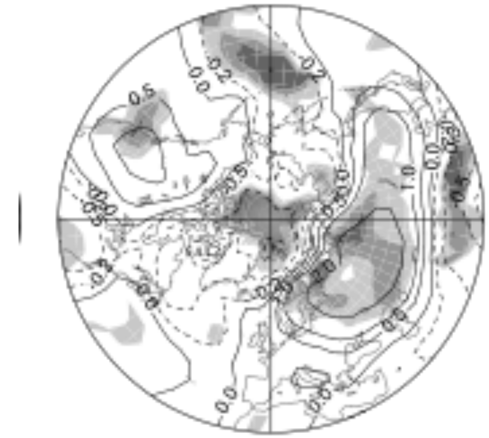
Reanalysis data

Seppälä *et al.*, 2009



CCM model

Rozanov *et al.*, 2005



- Statistically significant differences in winter- time polar SAT between years with high and low Ap.
- The are visible in both hemispheres, up to ±4.5 K.
- Results agree with model predictions

- Changes SAT in NH due to EPP
- EPP effect is strongest over high latitudes, resulting in the SATs increasing over Europe, Russia and the U.S. by up to 2.5 K

EPP indirect effect takes place during polar spring and contradicts tropospheric temperature analyses showing changes starting during the winter season

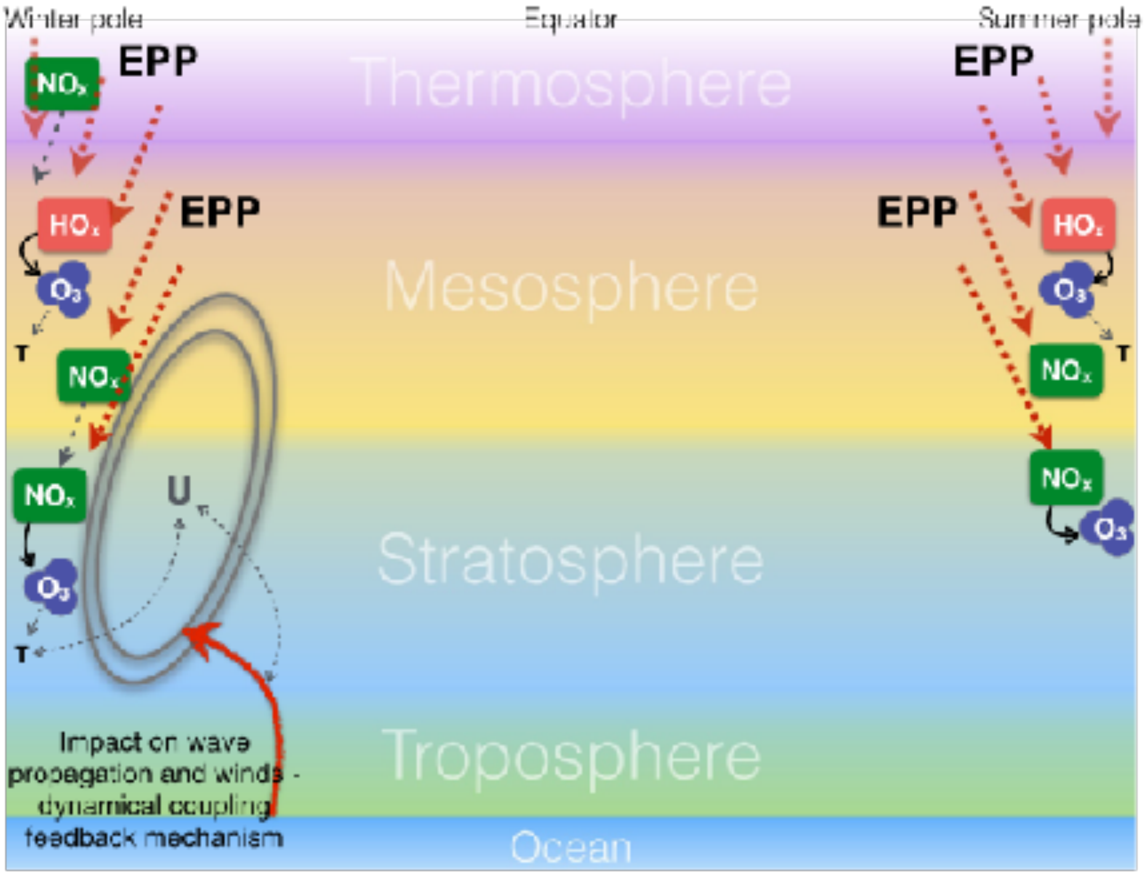
→

Early winter chemical-dynamical coupling, starting before the EPP indirect effect, might play a major role in transferring any EPP signals downwards.

Dynamical coupling

EPP impact on the atmosphere

Seppälä *et al.*, 2014



Direct and indirect impacts from EPP. EPP ionisation is focused on the polar regions leading to production of HO_x and NO_x. Transport processes shown with grey dotted lines, coupling mechanisms indicated with grey dashed lines. Direct chemical impacts shown with black arrows.

EPP-induced ozone loss

↓

Changes in long-wave cooling and short-wave heating

↓

Impact on T and zonal wind

↓

Changes in wave propagation

↓

Changes in the radiative budget and mean meridional circulation connects back to the temperature and the polar vortex strength

↓

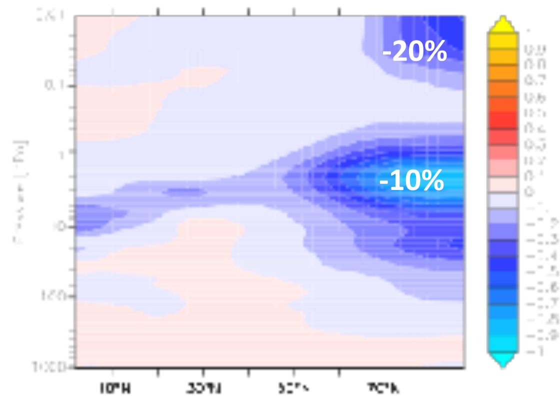
Strong vortex leads to positive NAM and surface temperature anomalies

EPP: surface response

- ECHAM5: surface air temperature response to geomagnetic activity
- EPP - NO_x leads to ozone depletion
- Ozone loss reduce radiative cooling and thus temperature increase in the polar winter mesosphere
- Changes in the radiative budget and mean meridional circulation cool the lower stratosphere and strengthen the polar vortex
- Strong vortex leads to positive Northern Annular Mode anomalies
- NAM anomalies propagate to the surface resulting in temperature anomalies

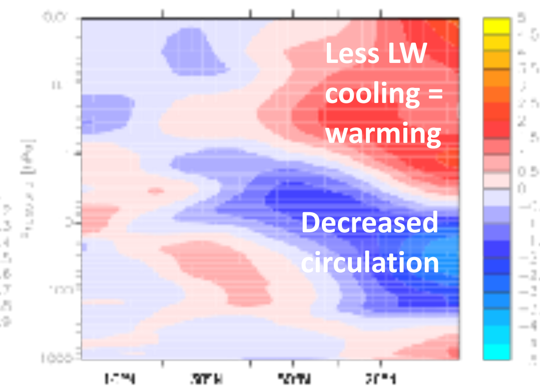
Baumgaertner *et al.*, 2011

DJF

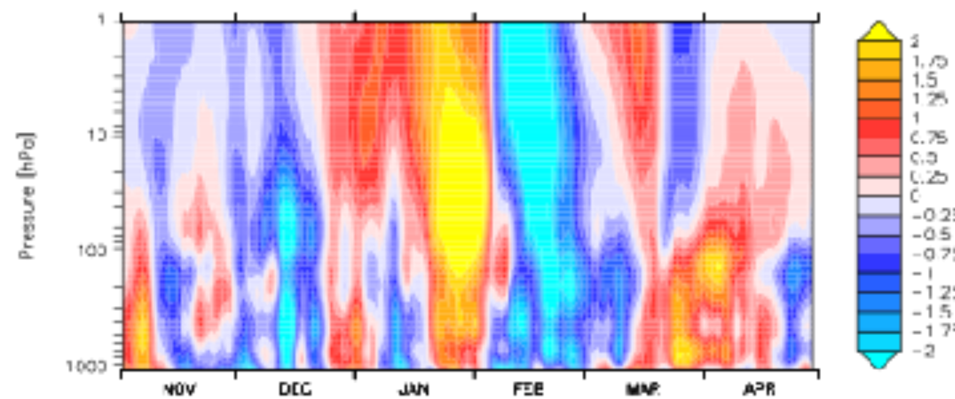


Climatological change of O_3

DJF



Climatological change in T

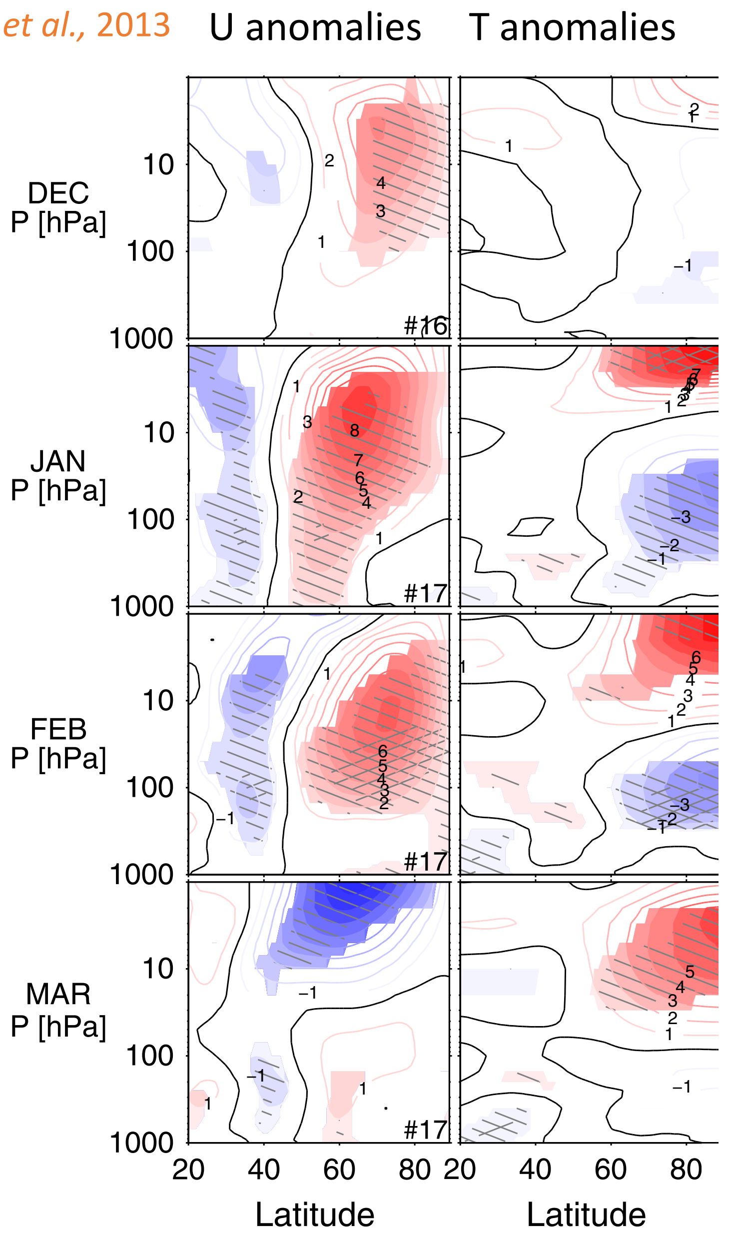


NAM index: red-yellow/blue colours indicate positive/negative differences.

EPP: dynamical coupling

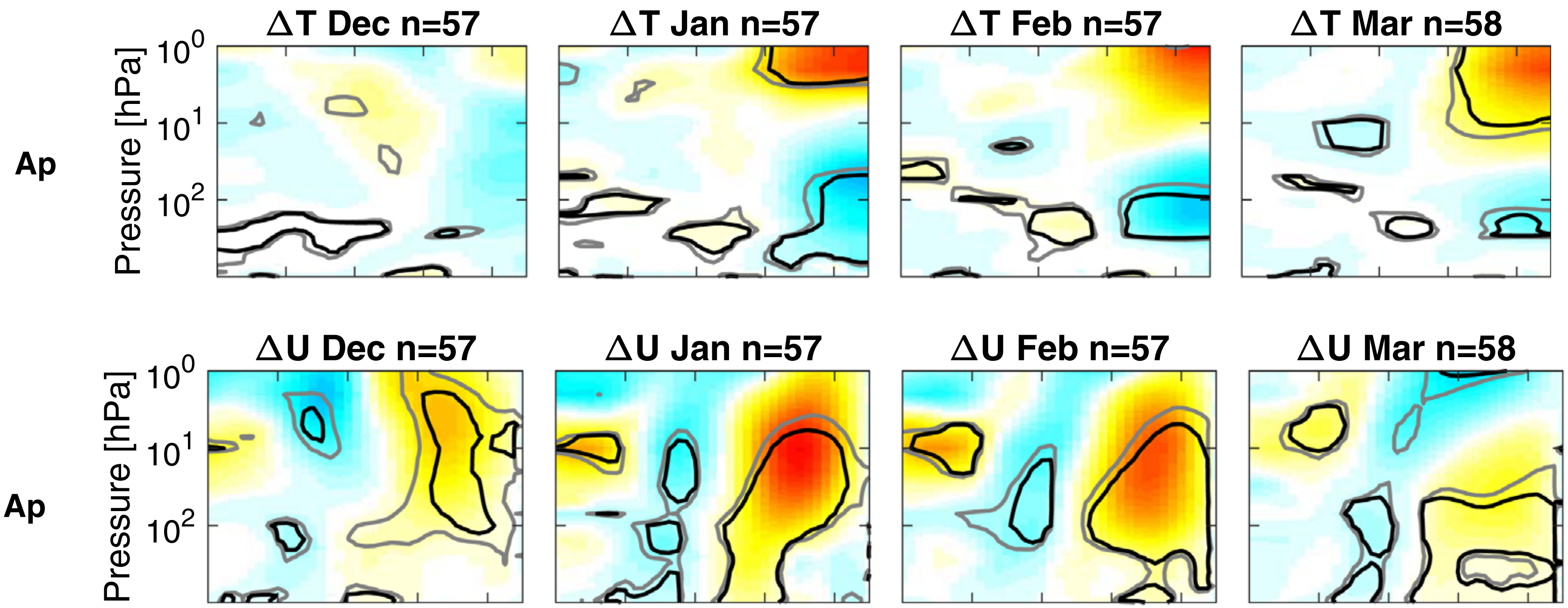
- ECMWF ERA reanalysis data -> geomagnetic activity signatures in wintertime stratosphere wind, temperature, and wave response
- DJF: for high geomagnetic activity levels more planetary waves are refracted towards the equator, away from the polar region
- Less waves disturbing the polar vortex and therefore stronger vortex
- Decreased mean meridional circulation causes cooling the polar stratosphere
- Anomalously strong polar vortex in late winter, would lead to positive NAM anomalies.

Seppälä *et al.*, 2013



EPP dynamical coupling

Wind and temperature response to Ap



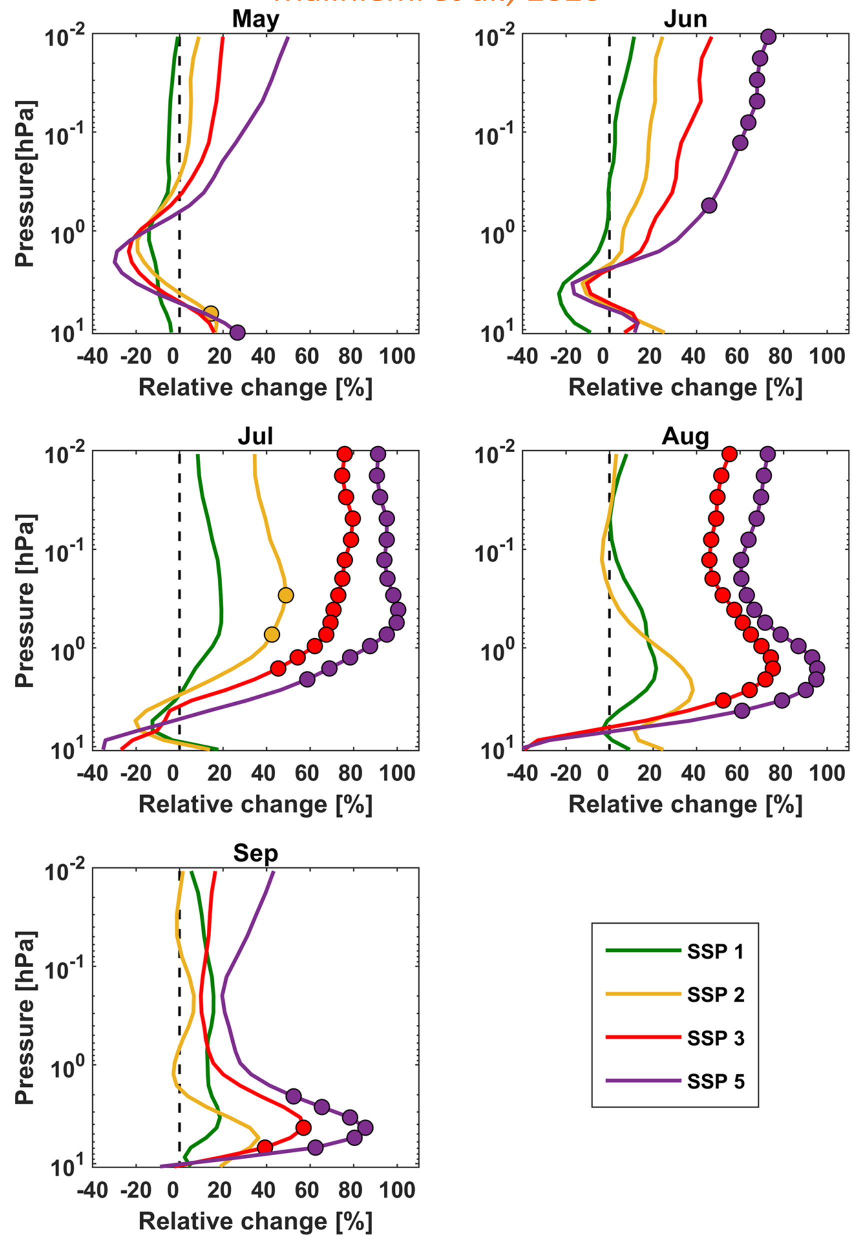
Salminen *et al.*, 2020

- ERA-40 and ERA-Interim reanalysis
- Contribution from different drivers to the northern polar vortex variability: EEP, solar irradiance, ENSO, volcanic aerosols and QBO
- EEP effect accounts for about 10-20% polar vortex variability
- All the other drivers together account for up to 35%

EPP in the future

- WACCM simulations of SH polar NO_x distribution during the 21st century under different future scenarios
- Radiative forcing increase to preindustrial era: 5.0 W/m² in SSP1, 6.5 W/m² in SSP2, 7.2 W/m² in SSP3, and 8.7 W/m² in SSP5.
- Increase of mean meridional circulation
- Stronger polar mesospheric descent in all future scenarios that will bring more EPP-NO_x
- With the decline of stratospheric chlorine species, ozone depleting EPP-NO_x will be more important in the future

Maliniemi *et al.*, 2020



Summary

- EPP impact on the middle atmosphere chemistry and dynamics through direct and indirect effect is **well established**

- There is **increasing evidence** that EPP might play and important role in regional climate variability

- However, the chemical-dynamical EPP coupling mechanism from thermosphere down to the surface **is complex and remains challenging** with a lots of uncertainty and different processes involved

- **Necessary steps** in understanding potential links between EPP and regional climate variability
  - Adequate representation of MEE/EPP forcing
  - Model dynamics that captured well descent from the MLT region down to the stratosphere
  - Long simulations for a statistically robust separation of any EPP signals from the background dynamical variability
  - Continuous observations of EPP as well atmospheric composition
  - One coherent mechanism that incorporates all the processes involved