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Direct and indirect impacts of energetic particle precipitation into the Earth‘s (middle) atmosphere

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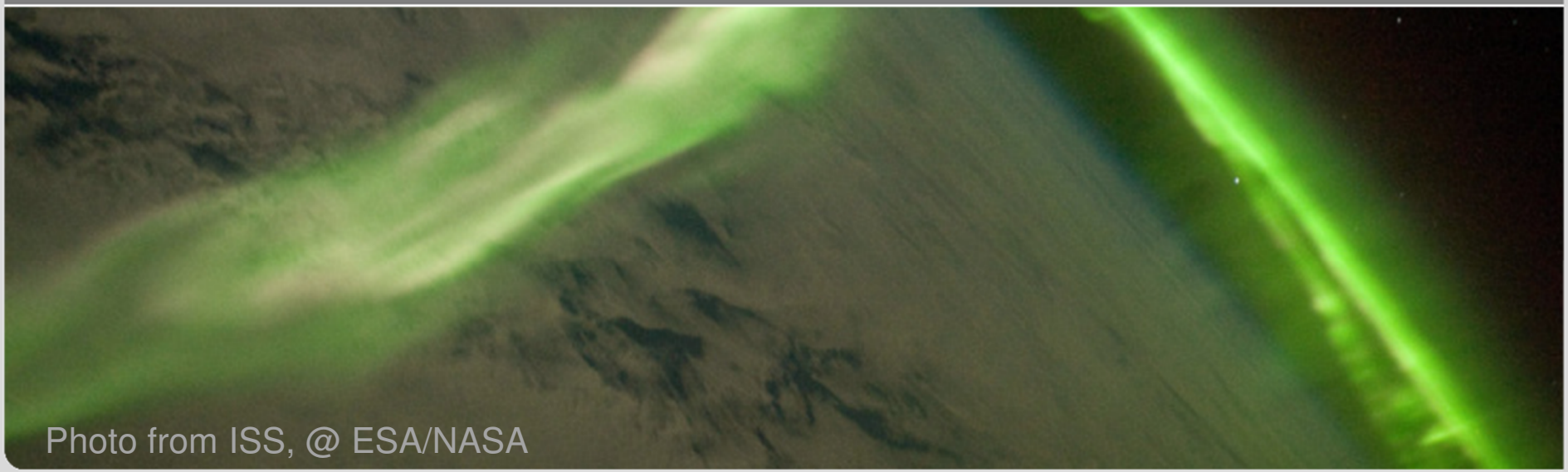
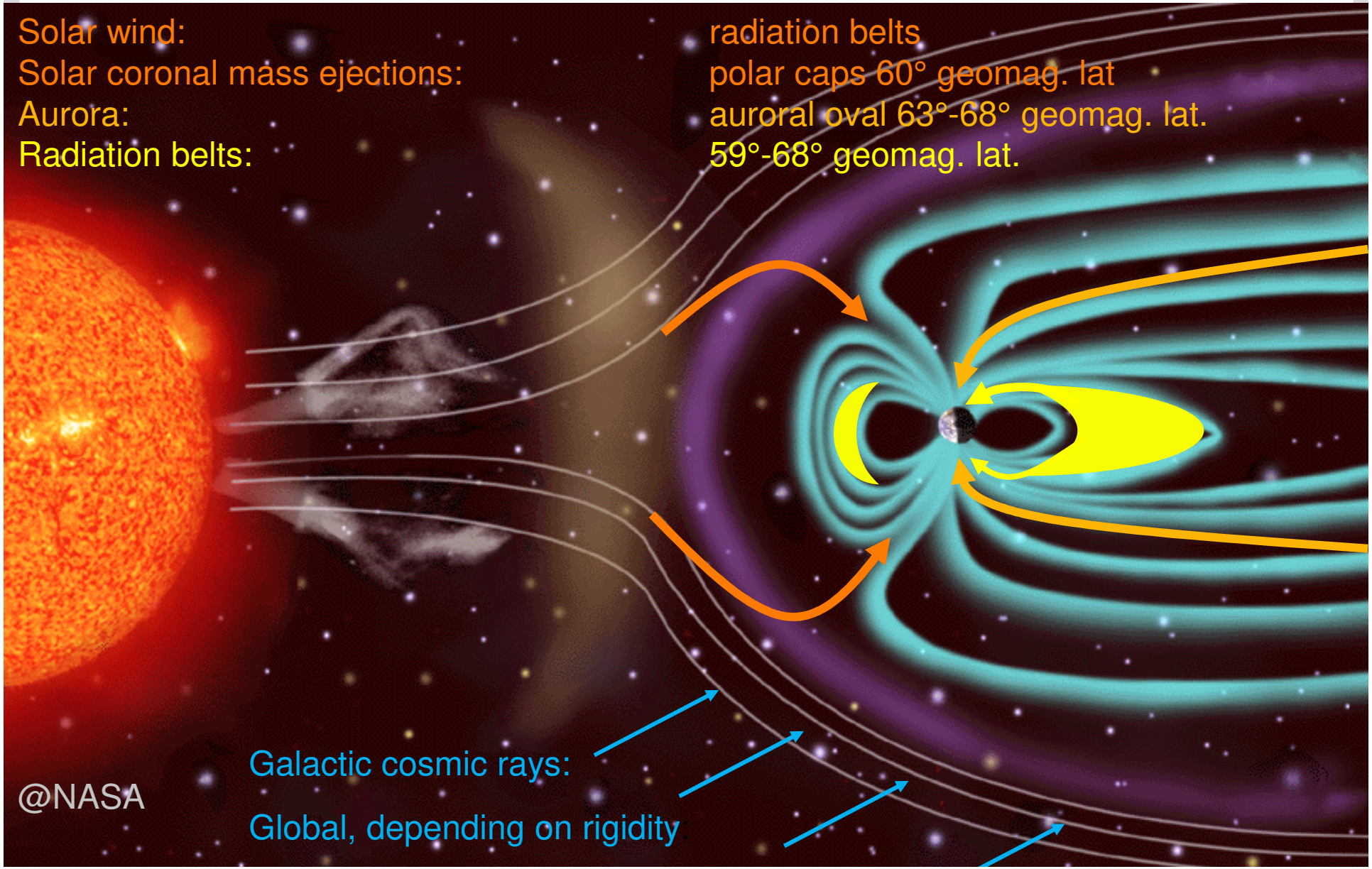
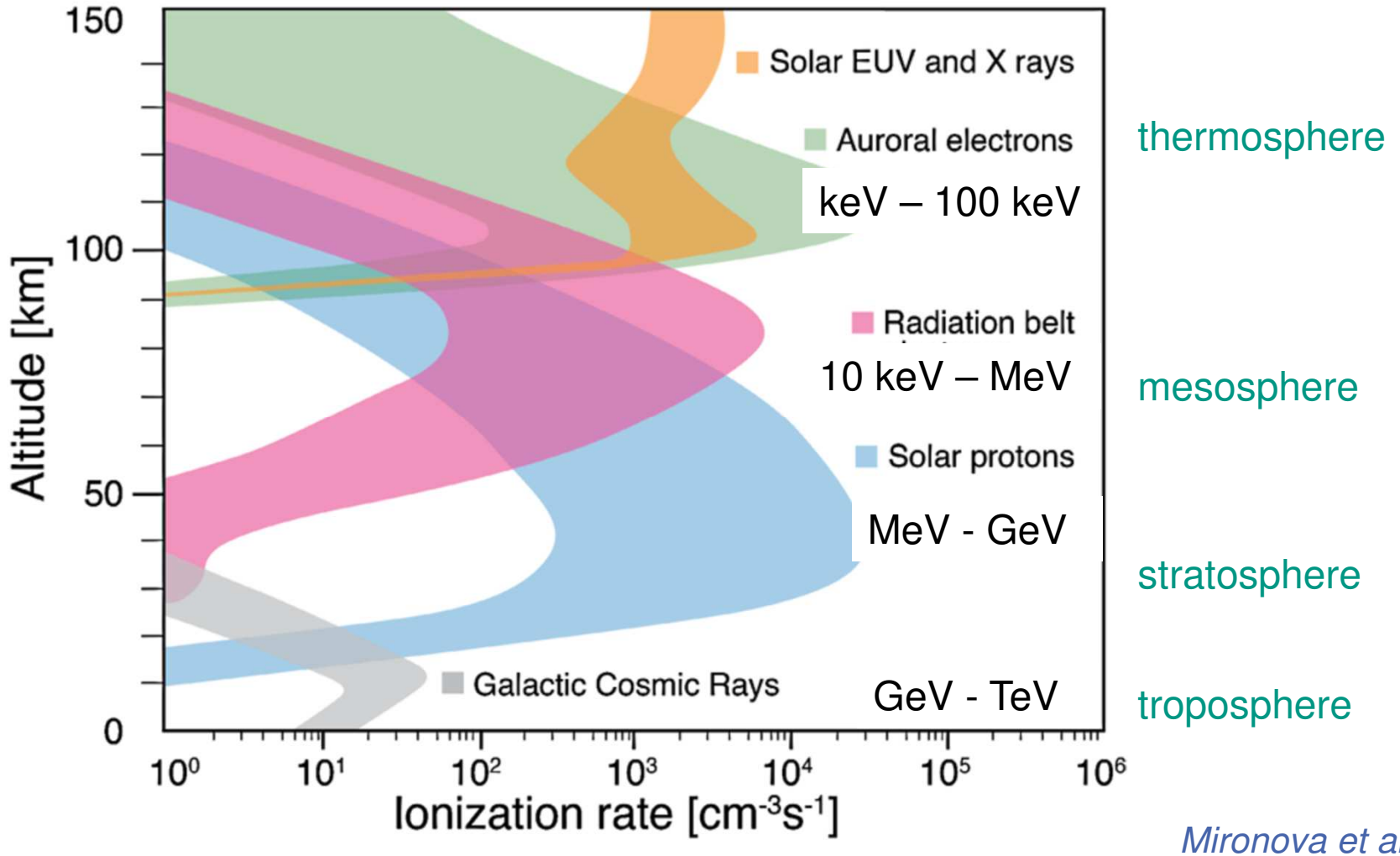


Energetic particles precipitating into the atmosphere



Variability of precipitating energetic particles

Altitude range of atmospheric ionization



Mironova et al., 2015

Talk outline

I Atmospheric impact: mechanism and observational evidence

II Recent modelling studies

Particle impact on the neutral atmosphere

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Primary interaction process: collision with most abundant species

Excitation:	$M + e^-, p^+ \rightarrow M^* + e^-, p^+$	$M = N_2, O_2, O$
Ionization:	$M + e^-, p^+ \rightarrow M^+ + e^- + e^-, p^+$	$M = N_2, O_2, O$
Dissociation:	$M_2 + e^-, p^+ \rightarrow M + M^* + e^-, p^+$	$M = N, O$
Dissociative ionization:	$M_2 + e^-, p^+ \rightarrow M^+ + M^* + e^- + e^-, p^+$	$M = N, O$

→ Formation of ions and excited species, in particular N^*, O^*, and O_2^+

Reactions of excited species and ions

$N^* + O_2 \rightarrow NO + O$

$O_2^+ + N_2 \rightarrow NO^+ + NO$

$NO^+ + e^- \rightarrow N^* + O$

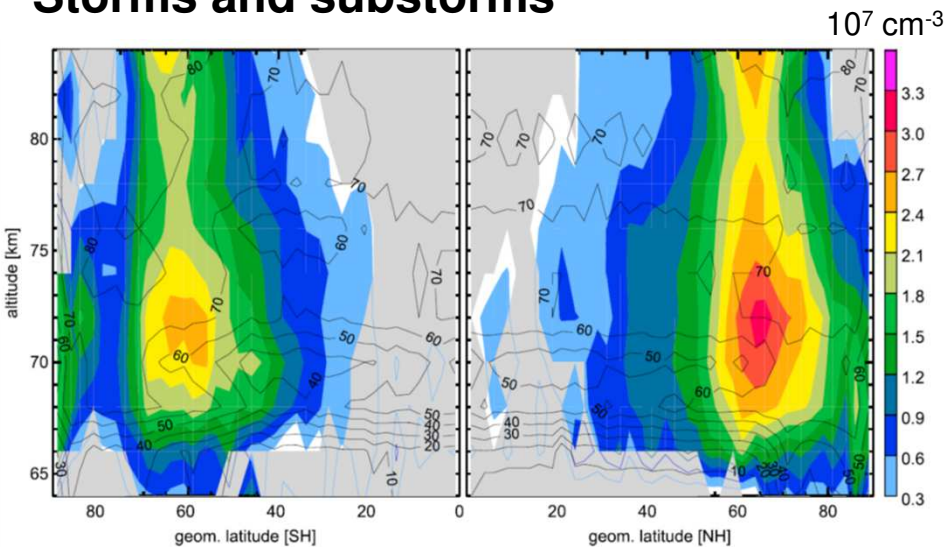
→ There are a number of follow-up reactions, many forming nitric oxide **NO**

e.g., Nicolet, JGR, 1965

Observational evidence:

NO production by energetic particles

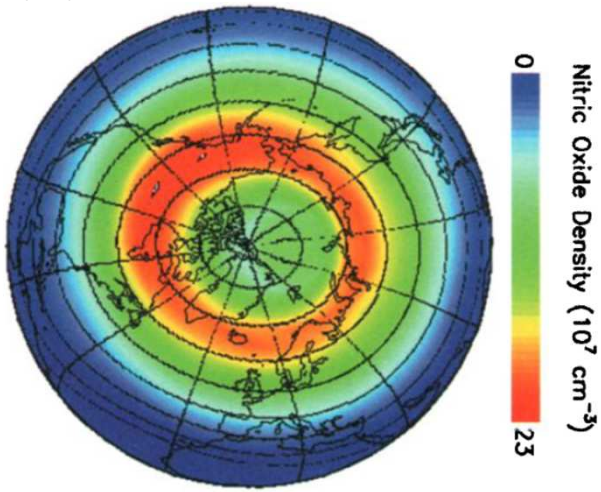
Storms and substorms



NO, 64-84 km, SCIAMACHY, 2002-2012

Sinnhuber et al., JGR, 2016

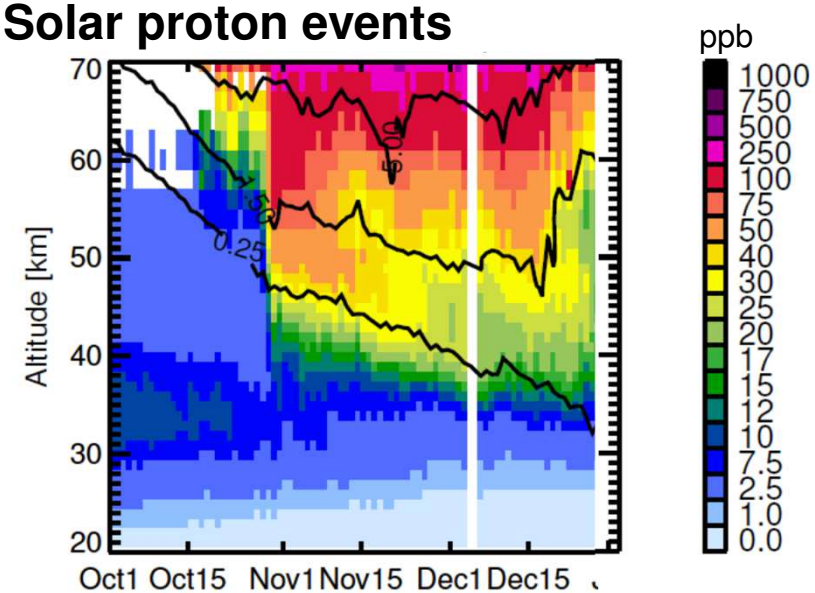
Aurora



NO, 106 km, SNOE, 1998-1999

Barth et al., GRL, 2001

Solar proton events



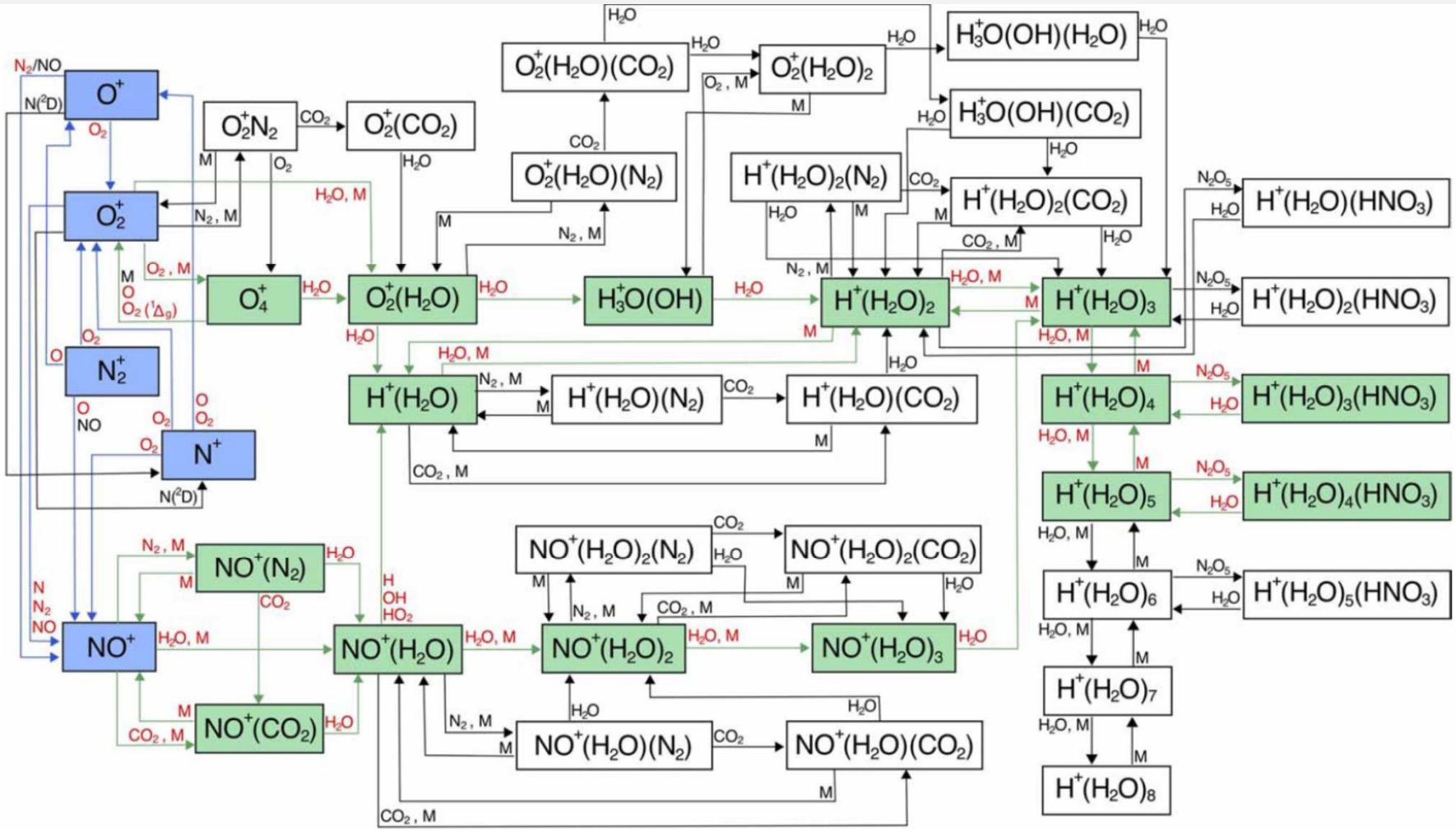
$NO+NO_2$, > 40 km, MIPAS, October 2003

Sinnhuber et al., ACP, 2014

Particle impact on the neutral atmosphere

Cluster ion formation in the ionospheric D-region

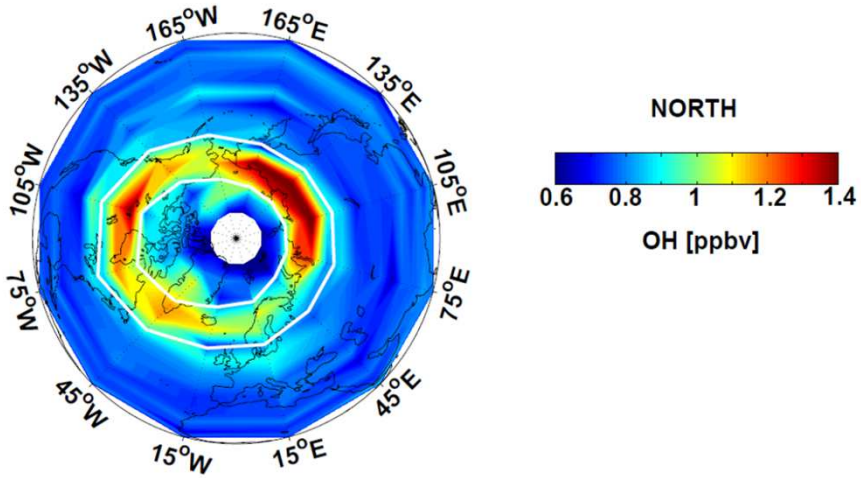
Primary ions → large cluster ions → release of **H, OH, …**

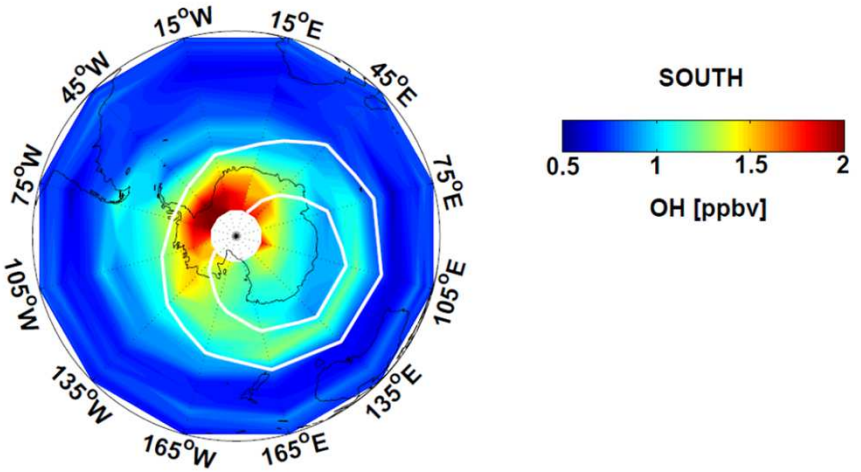


Schematic view from Verronen, JAMES, 2016:
Idea goes back to Swider and Keneshea et al., 1973; Solomon et al., 1981

Observational evidence:

OH production by energetic particles





Storms and substorms:

OH for days with high electron fluxes

MLS, 70 – 78 km, 2005 – 2009

Andersson et al., ACP, 2014

Particle impact on the neutral atmosphere

Catalytic ozone loss

$H + O_3 \rightarrow OH + O_2$
$OH + O \rightarrow H + O_2$

HOx (H, OH, HO_2) cycles:
> 45 km
Bates and Nicolet, 1950

$NO + O_3 \rightarrow NO_2 + O_2$
$NO_2 + hv \rightarrow NO + O$
$NO_2 + O \rightarrow NO + O_2$

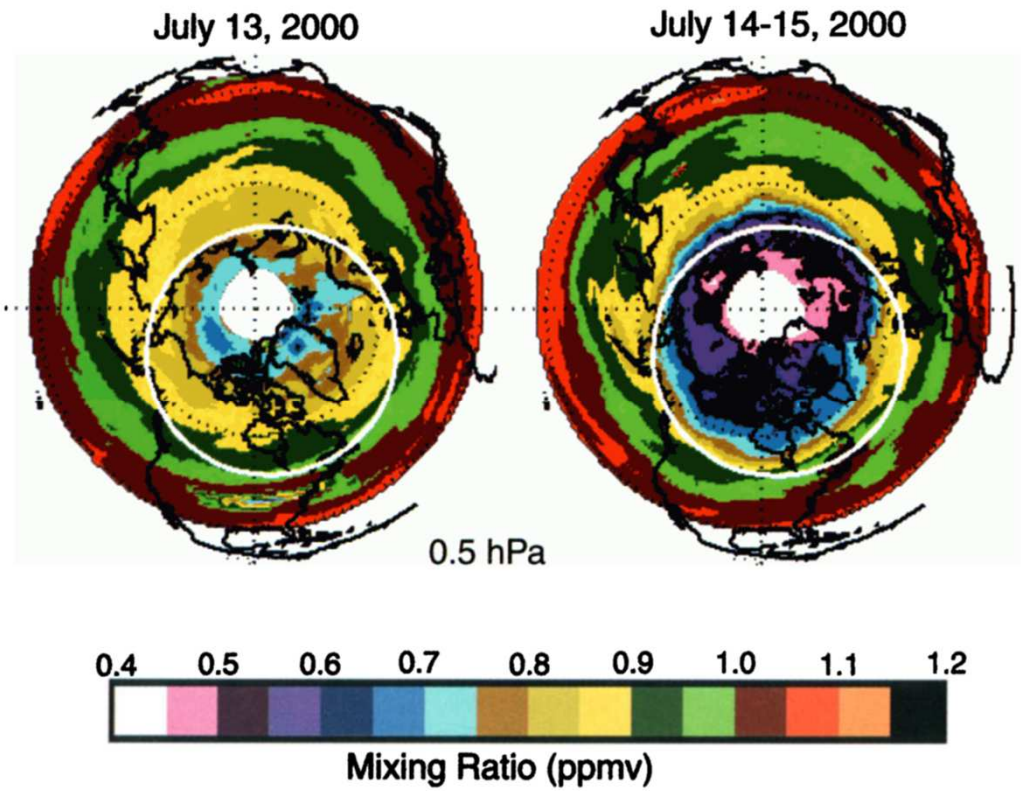
NOx (N, NO, NO_2) cycles:
< 45 km
Crutzen, 1970

Energetic particle precipitation is a source of ozone loss

Crutzen, Science, 1975, for large solar proton events

Observational evidence:

Ozone loss during the July 2000 (Bastille) solar proton event



Ozone before and during event

SBUV2 on NOAA 14

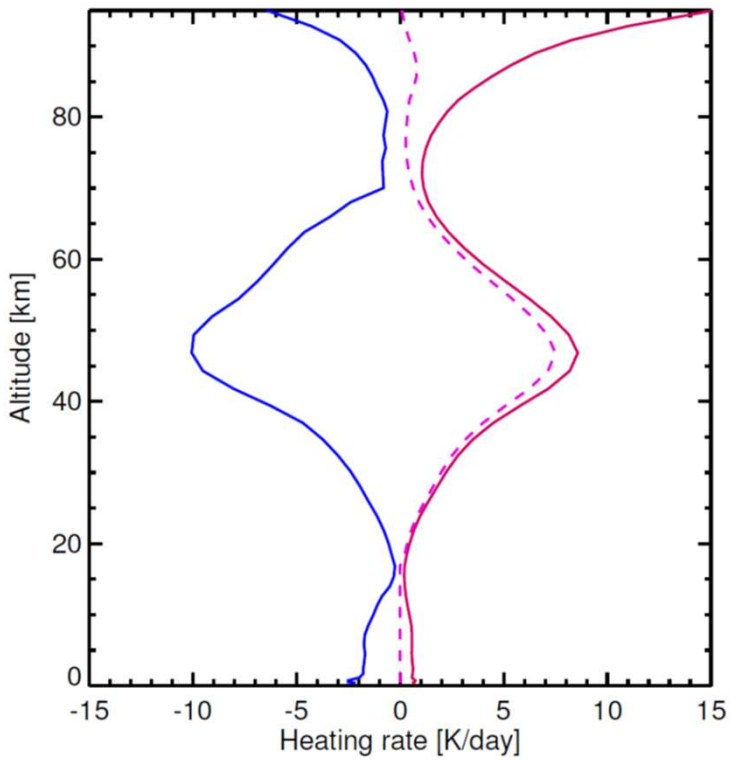
~50 km

Jackman et al., GRL, 2001

Particle impact on the neutral atmosphere

Radiative feedback

Radiative heating and cooling rates
July global mean daily mean



Longwave contributions:
Cooling by thermal emission

Shortwave contributions:
Heating by absorption of solar light

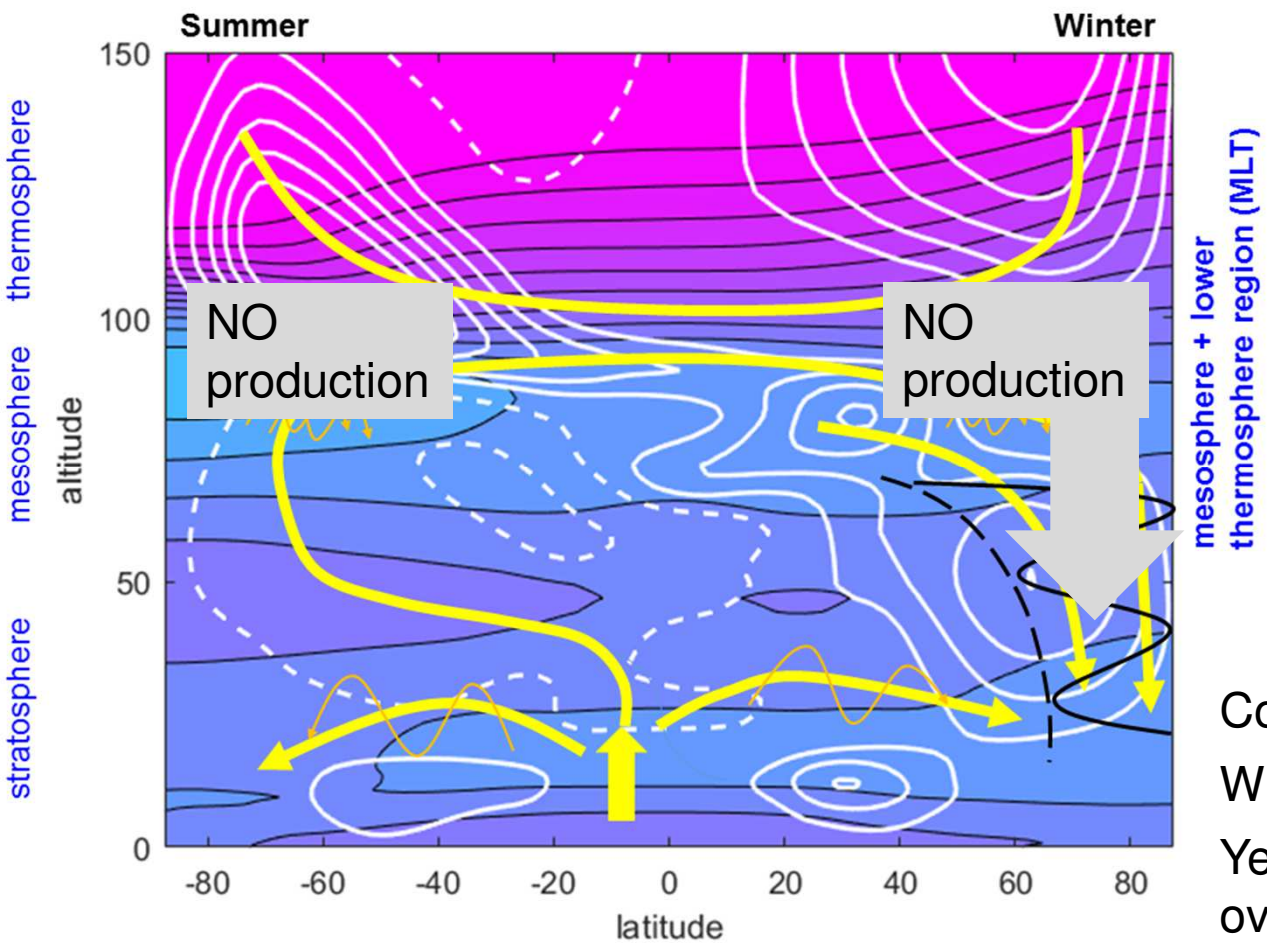
O_3 contribution:
dominates heating in stratosphere and mesosphere

Energetic particle precipitation should affect energy balance of the middle atmosphere
– *but no direct observational evidence so far*

Particle impact on the neutral atmosphere

The so-called „indirect effect“

Solomon et al., JGR, 1982; Randall et al., JGR, 2007



Contours: temperature

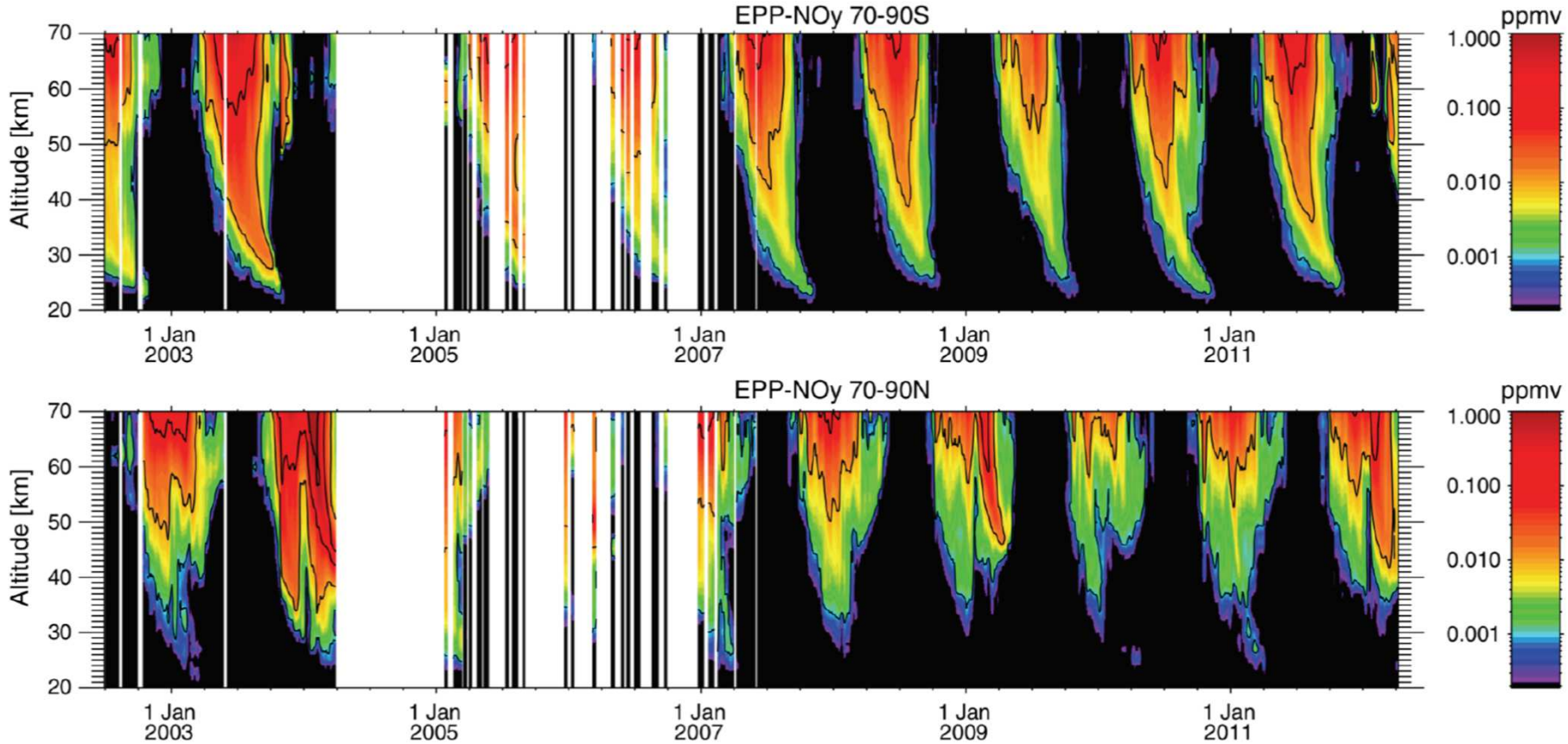
White lines: zonal wind

Yellow lines: meridional overturning circulation

Observational evidence

The indirect effect: downwelling of NOy in polar winter

MIPAS/ENVISAT NOy at high latitudes (70-90°S/N), 2002-2012 *Funke et al., JGR, 2014*

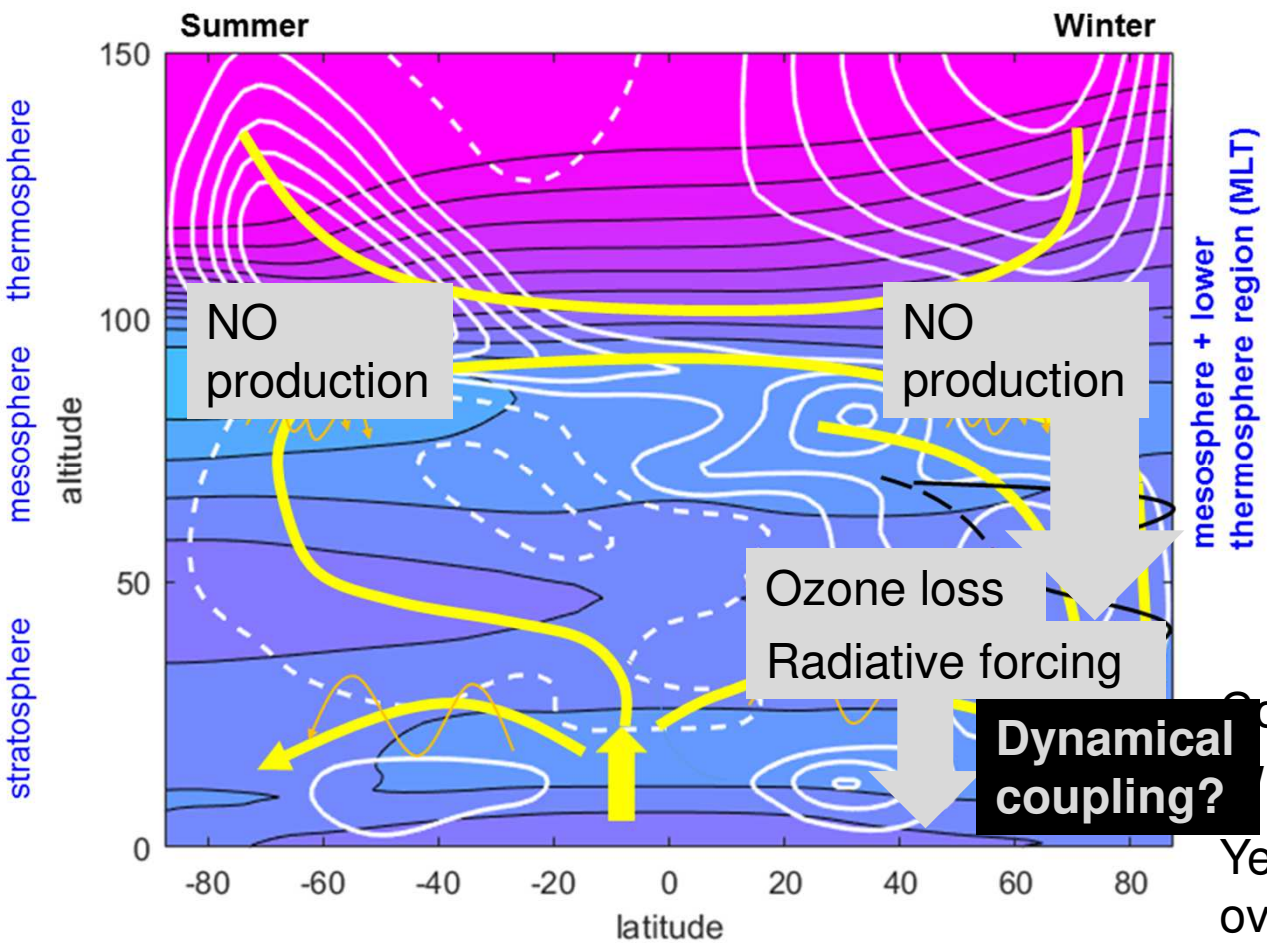


Downward transport into the stratosphere observed in every winter, modulated by geomagnetic activity

Particle impact on the neutral atmosphere

The so-called „indirect effect“

Solomon et al., JGR, 1982; Randall et al., JGR, 2007



Contours: temperature

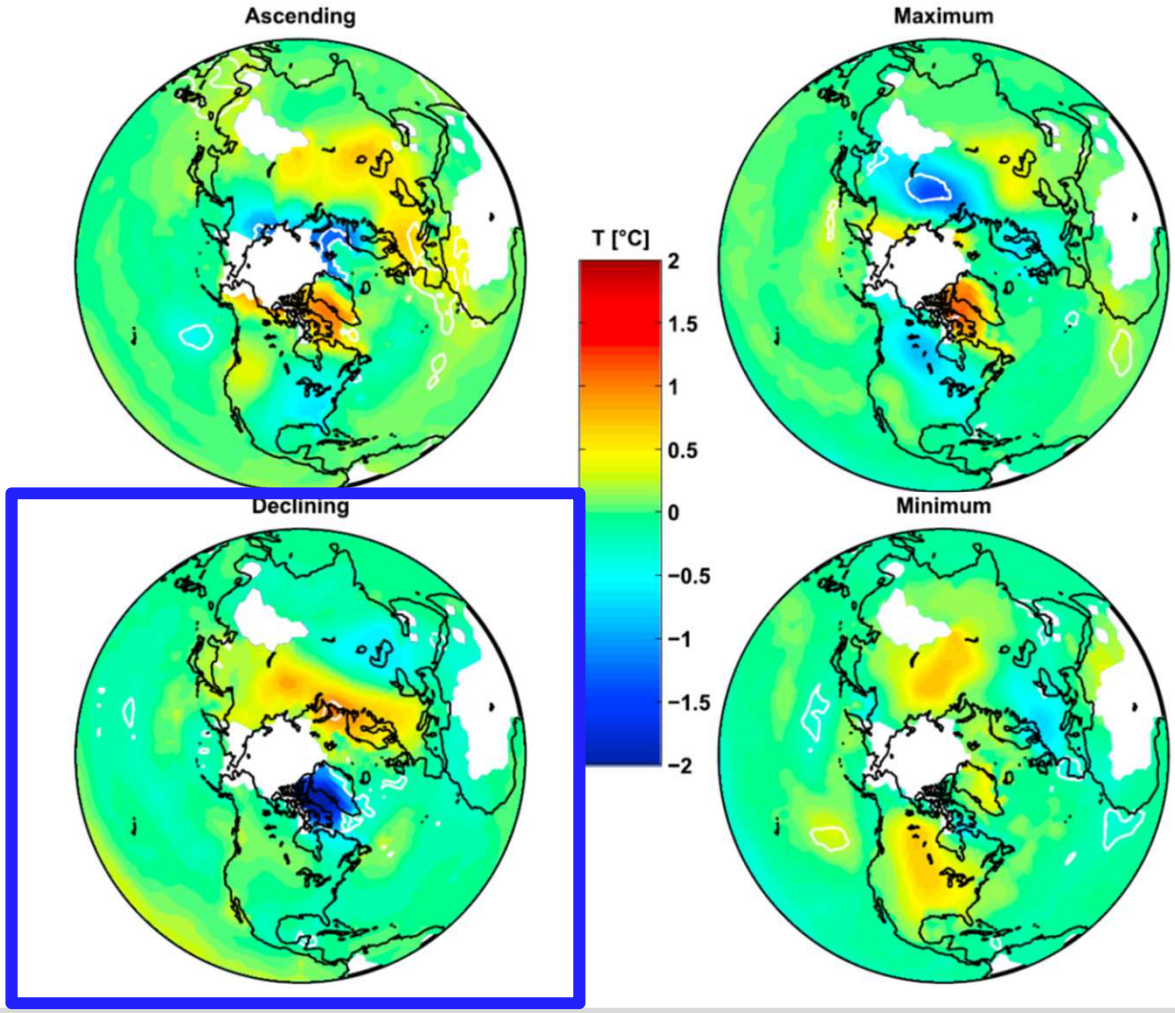
White lines: zonal wind

Yellow lines: meridional overturning circulation

Observational evidence

Surface impact?

Winter surface air temperature anomalies throughout the solar cycle



Based on NASA GISS data

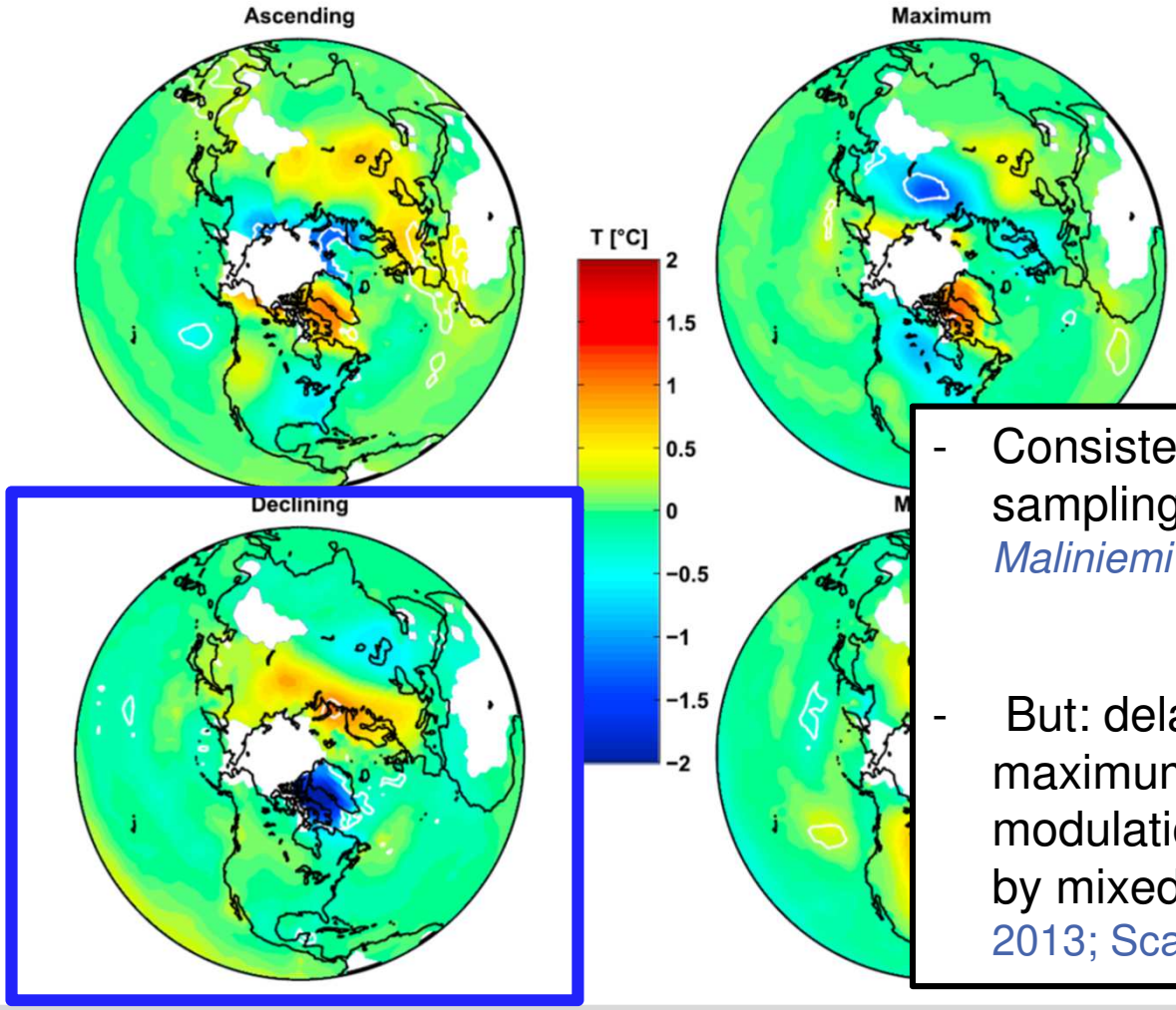
1880 – 2009

Maliniemi et al., JGR, 2014

Observational evidence

Surface impact?

Winter surface air temperature anomalies throughout the solar cycle



Based on NASA GISS data

1880 – 2009

Maliniemi et al., JGR, 2014

- Consistent observations in different samplings, e.g. *Seppälä et al., 2009; Maliniemi et al., 2013; 2016*

- But: delayed response to solar maximum also interpreted as modulation of solar irradiance impact by mixed-layer ocean, e.g., Gray et al., 2013; Scaife et al., 2013

Observational evidence

Surface impact?

Winter (DJF) surface air temperature anomalies throughout the solar cycle

Ascending Maximum

Dynamical coupling from the wintertime stratosphere to tropospheric weather systems:

1. Stratosphere:
Strength of zonal wind → reflection and dissipation of planetary (Rossby) waves

2. Downward coupling:
Reflection of planetary waves OR poleward/downward movement of wave dissipation
→ impact on strength and position of subpolar tropospheric jet

Dynamical coupling is still not well understood, but

→ „Top-down“ solar forcing of the climate system

→ Could improve weather forecasts > 8 days

Model studies

1. Process understanding

→ Model-measurement intercomparisons in WCRP SPARC Solaris Heppa experiments:

Heppa I: Solar proton event *(Funke et al., 2011)*

Heppa II: indirect effect in Northern hemisphere *(Funke et al., 2017)*

Heppa III: NO production during a geomagnetic storm: ongoing

2. Impact on constituents not well covered by observations

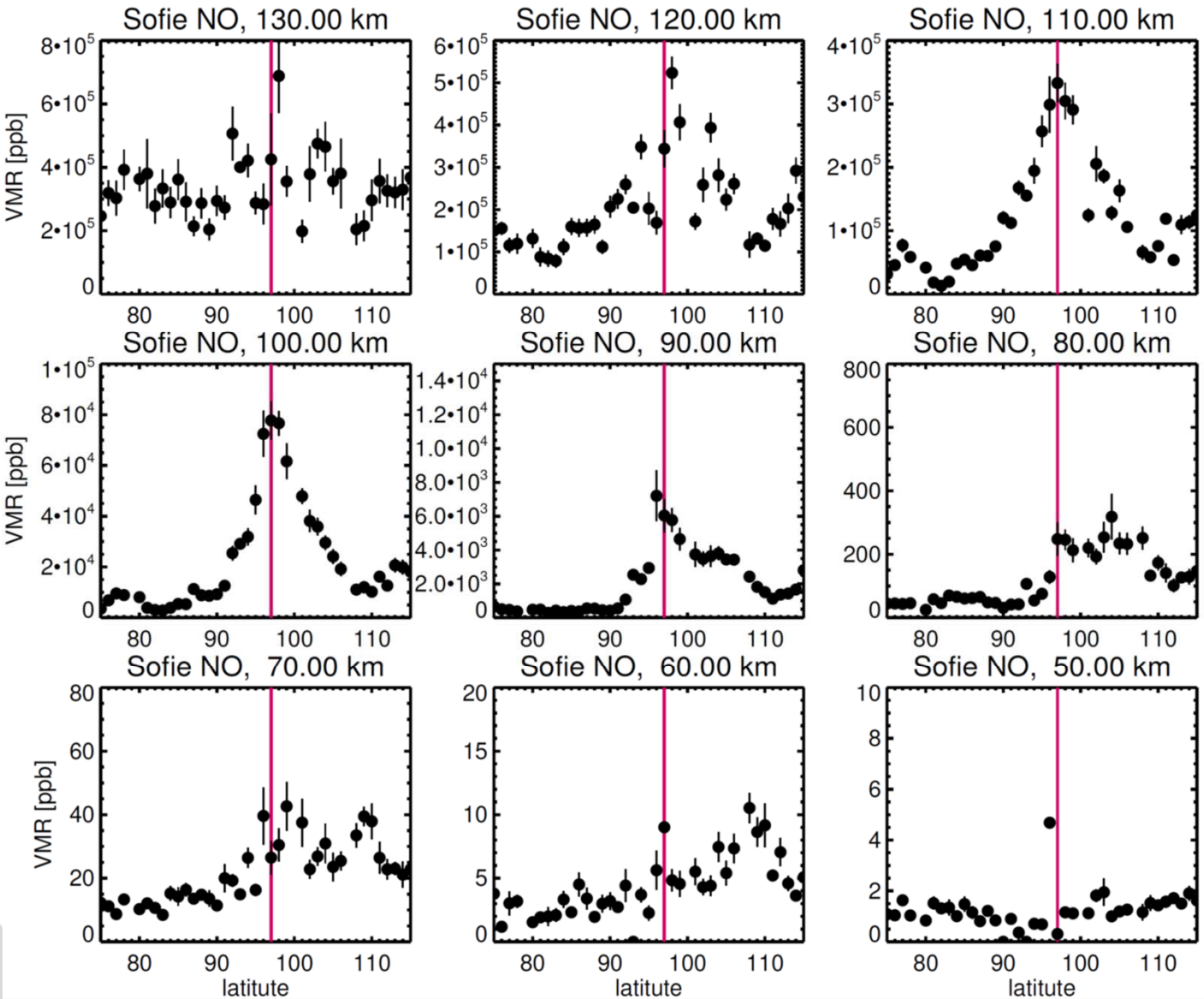
→ ozone loss, radiative balance, middle atmosphere emperatures, …

3. Long-term impact on the climate system

→ e.g., CMIP6: chemistry-climate model experiments 1850-2100 including solar TSI, spectral irradiance, and particle forcing (*Matthes et al., GMD, 2017*) for next IPCC report: analysis ongoing

Heppa III: Geomagnetic storm in April 2010

SOFIE/AIM NO observations, 70°-80°S, March 16 – April 30



The Heppa III team:

Hilde Nesse Tyssoy, Miriam Sinnhuber, Timo Asikainen, Stefan Bender, Koen Hendrickx, Joshua Pettit, Cora Randall, Thomas Reddmann, Eugene Rozanov, Christine Smith Johansen, Timofei Sukhodolov, Max van de Kamp, Pekka Verronen, Jan-Maik Wissing, Olesya Yakovchuk

Heppa III: Geomagnetic storm in April 2010

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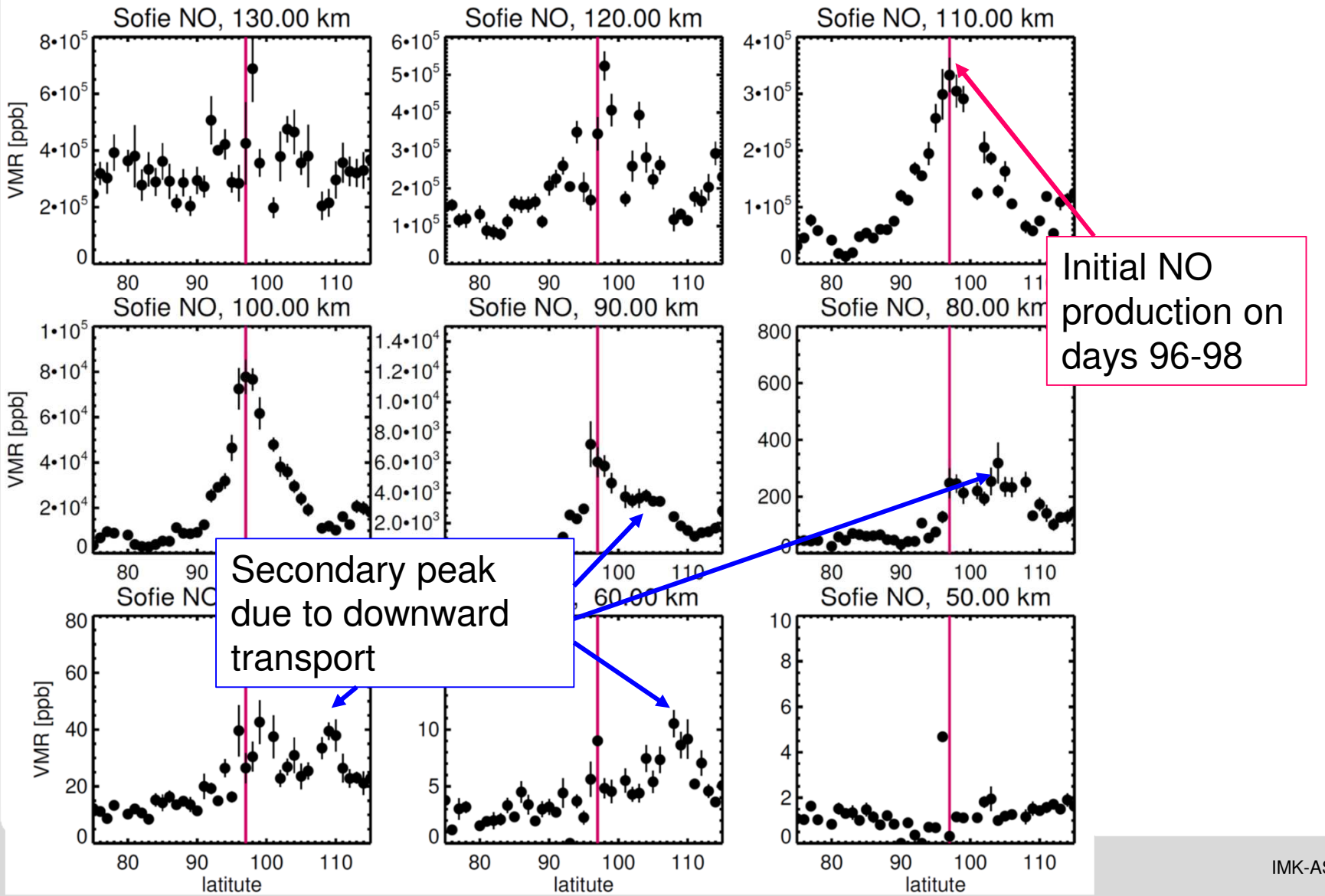


Heppa III: Geomagnetic storm in April 2010

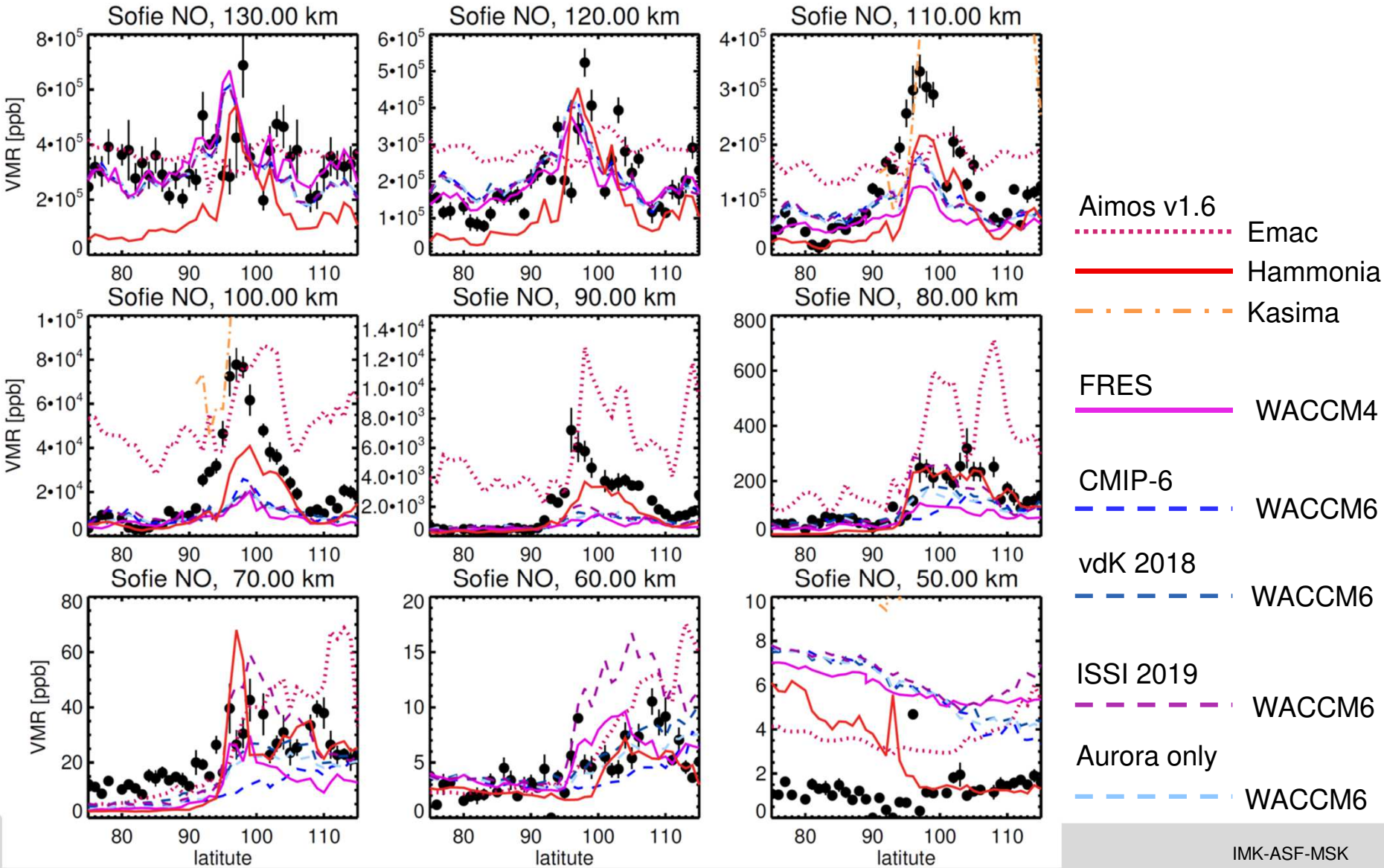
Model experiments with four global chemistry-climate models

8 ionization rate data-sets all based on POES electron flux observations

Model / IPR	AIMOS v1.6	CMIP6	FRES	ISSI 2019	AIMOS v1.9 (aurora)	vdK18 zonal	vdK18 MLT	WACCM aurora
WACCM	planned	yes	yes	yes	planned	yes	tests	yes
KASIMA	yes	planned			planned			
HAMMONIA	yes	planned						
EMAC/EDITh	yes	planned			planned			

Heppa III: Geomagnetic storm in April 2010

Preliminary results of model-obs intercomparison



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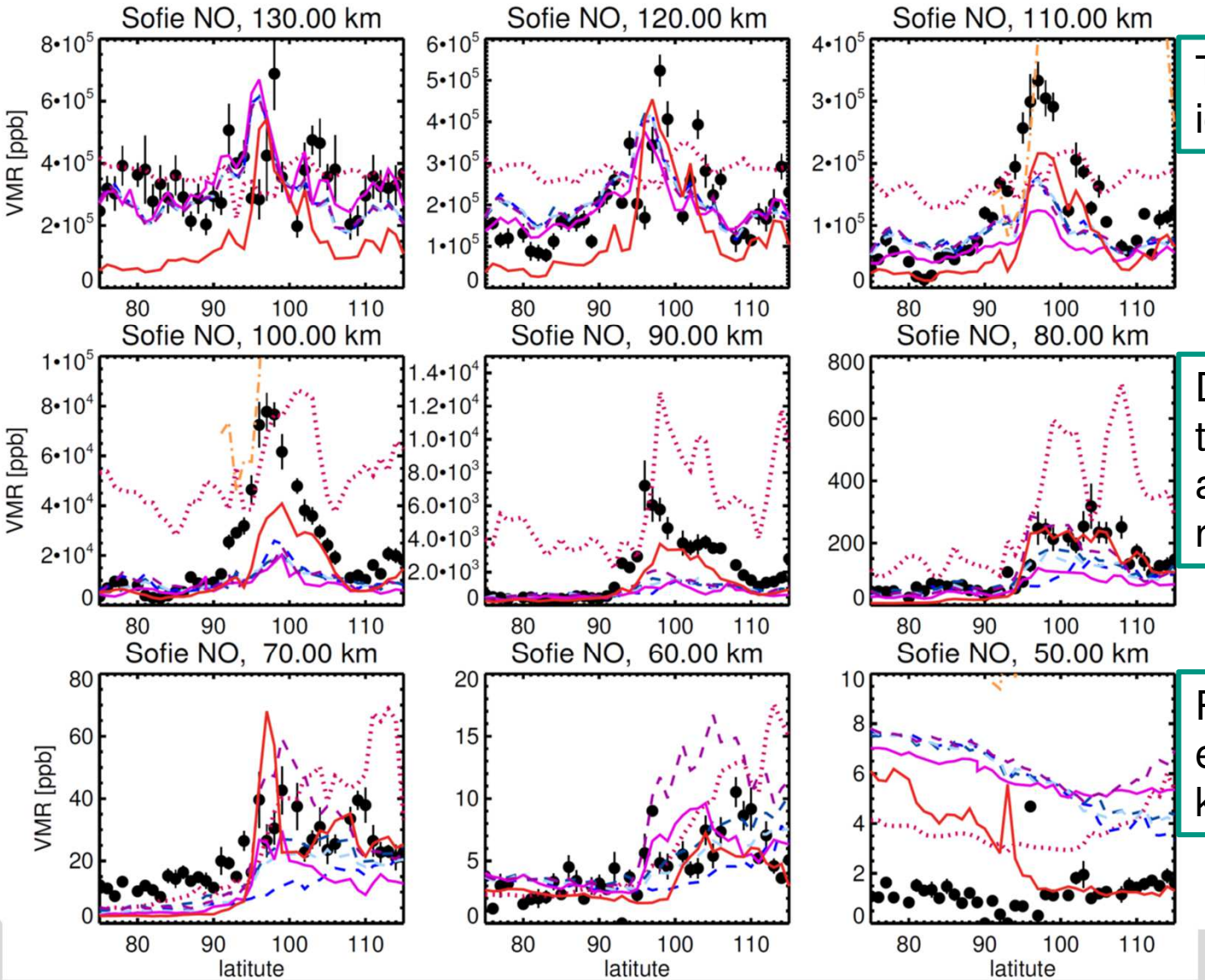


Temperature and ionization rates

Aimos v1.6

Emac

Hammonia

Kasima

Downward transport/mixing and ionization rates

WACCM6

vdK 2018

WACCM6

Relativistic electrons >> 300 keV

Aurora only

WACCM6

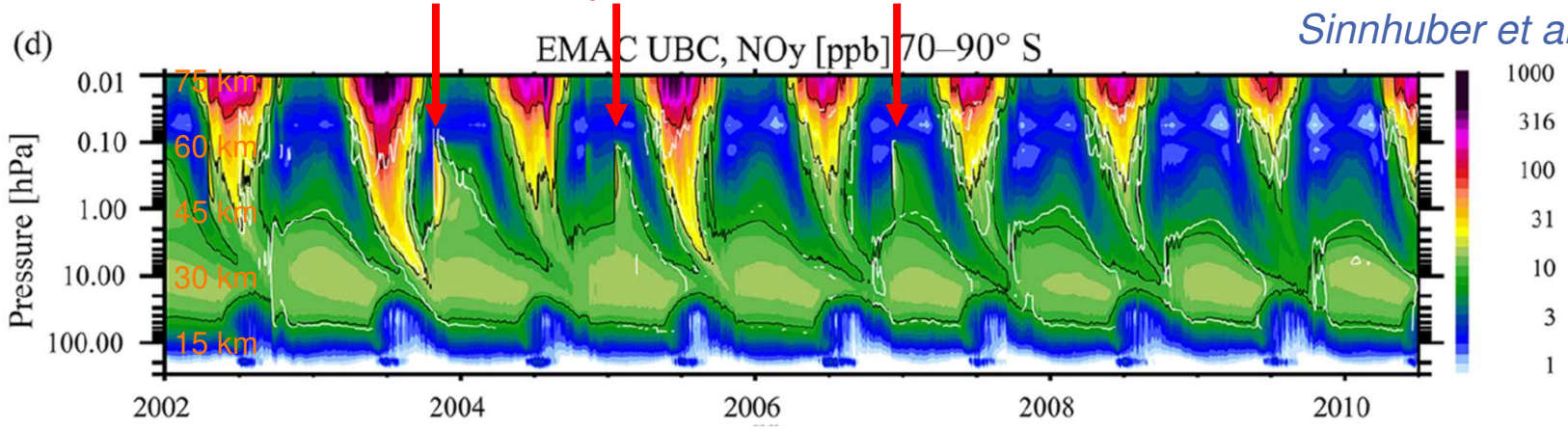
Model study: particle impact in the middle atmosphere

Chemistry-climate model EMAC, 70°-90°S, 2002-2010

NOy

Solar proton events

Sinnhuber et al., ACP, 2018



NOy
ppb

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Institute of Meteorology and Climate Research

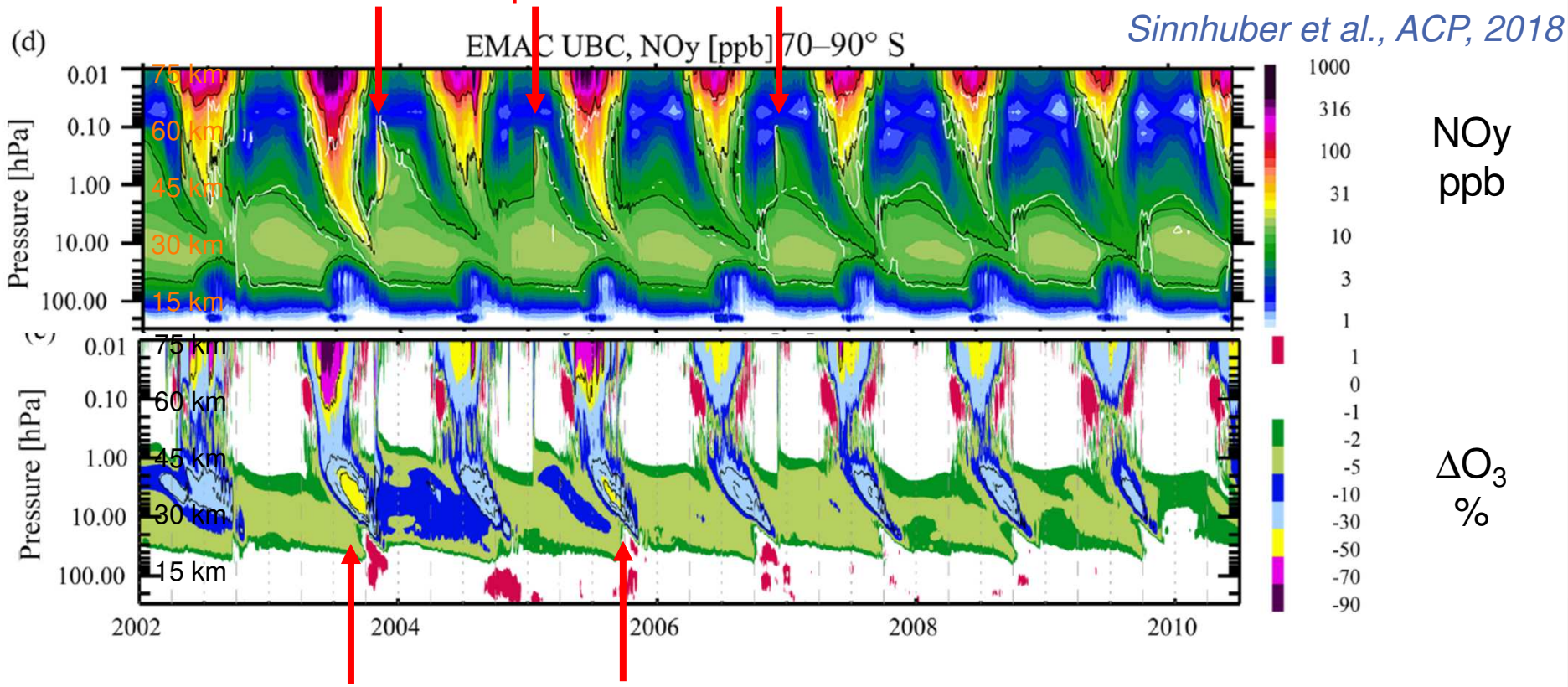
Model study: particle impact in the middle atmosphere

Chemistry-climate model EMAC, 70°-90°S, 2002-2010

NOy and ozone loss relative to model run without particle impact

Solar proton events

Sinnhuber et al., ACP, 2018



> 30% upper stratosphere loss in some winters

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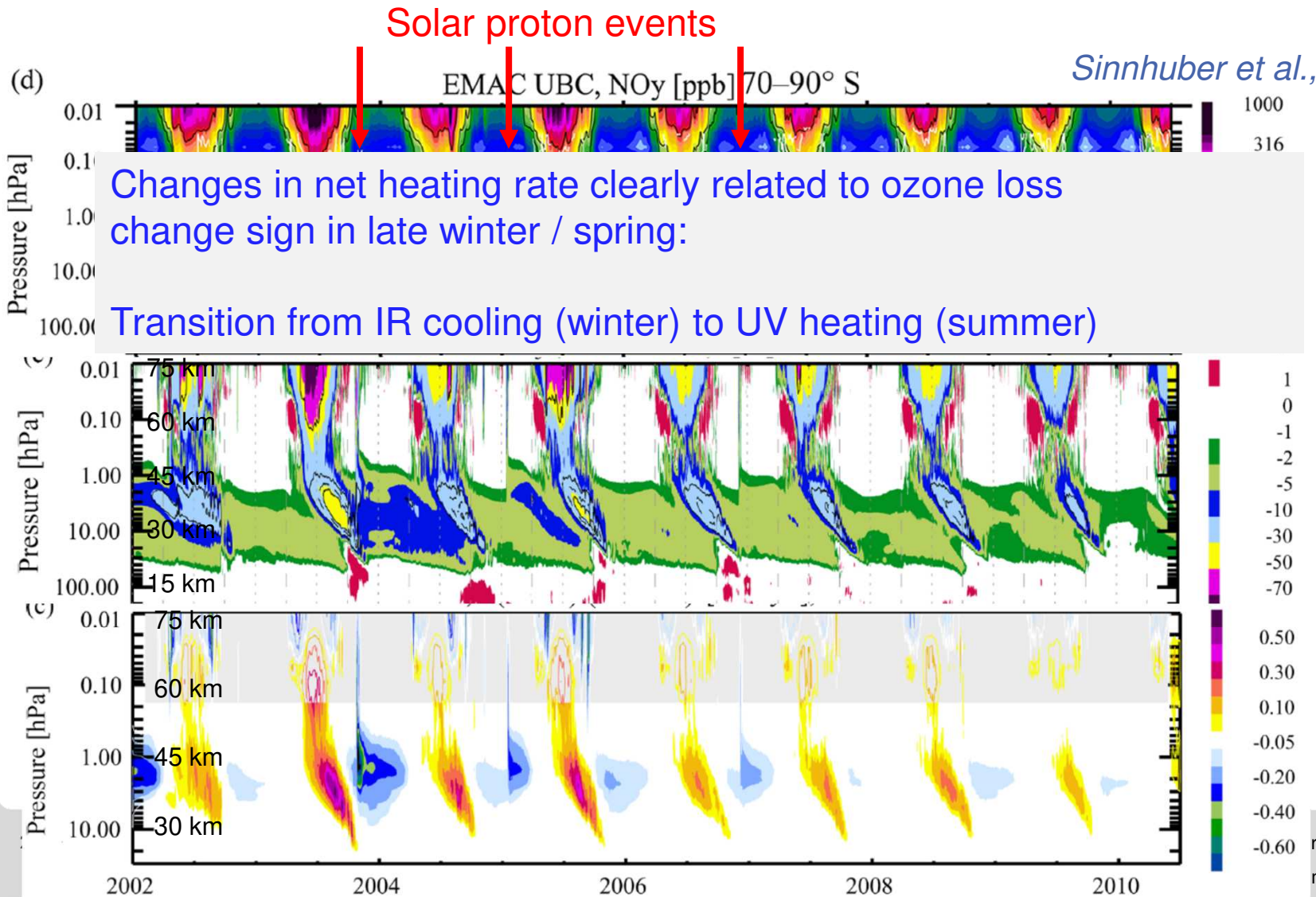
Model study: particle impact in the middle atmosphere

Chemistry-climate model EMAC, 70°-90°S, 2002-2010

NOy, ozone loss, and changes in net radiative heating

Sinnhuber et al., ACP, 2018



Changes in net heating rate clearly related to ozone loss change sign in late winter / spring:

Transition from IR cooling (winter) to UV heating (summer)

NOy ppb

ΔO_3 %

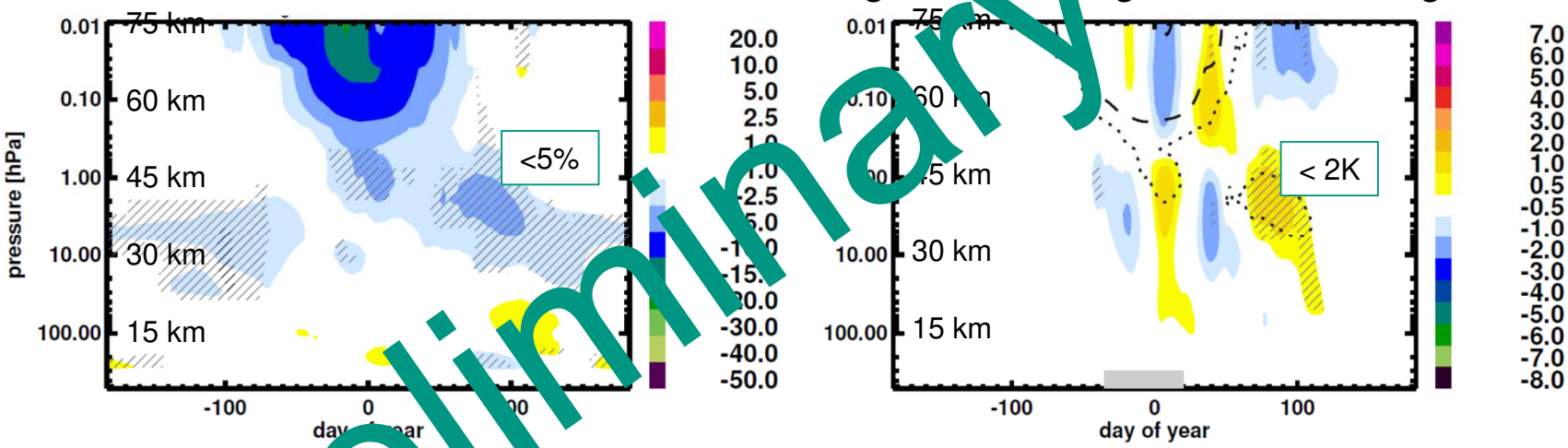
Net heating K/day

Model study: particle impact in the middle atmosphere

Four free-running chemistry-climate models with high/low particle forcing

40 years each, 70°-90°N

High-low forcing: mean T change, K



Preliminary

ROMIC-SOLIC project:

Miriam Sinnhuber, Sabine Barthlott, Bernd Funke, Tim Kruschke, Markus Kunze, Ulrike Langematz, Katja Matthes, Thomas Reddmann, Stefan Versick

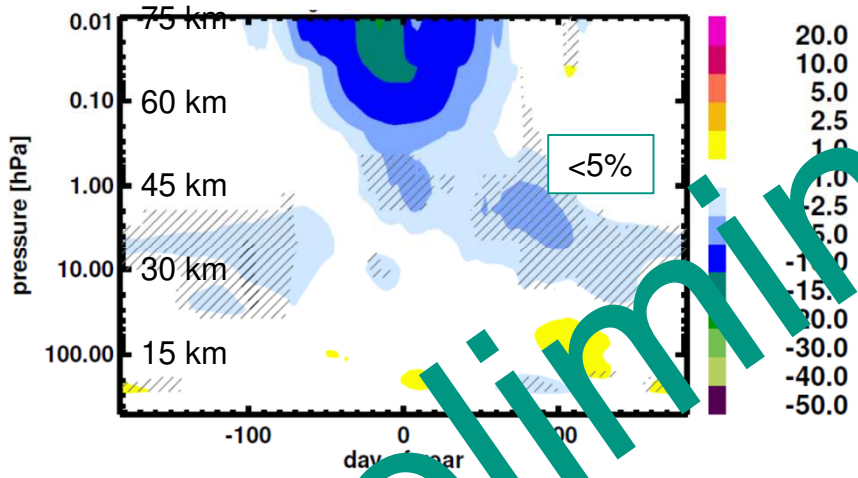
Dr. Miriam Sinnhuber
Institute of Meteorology and Climate Research

Model study: particle impact in the middle atmosphere

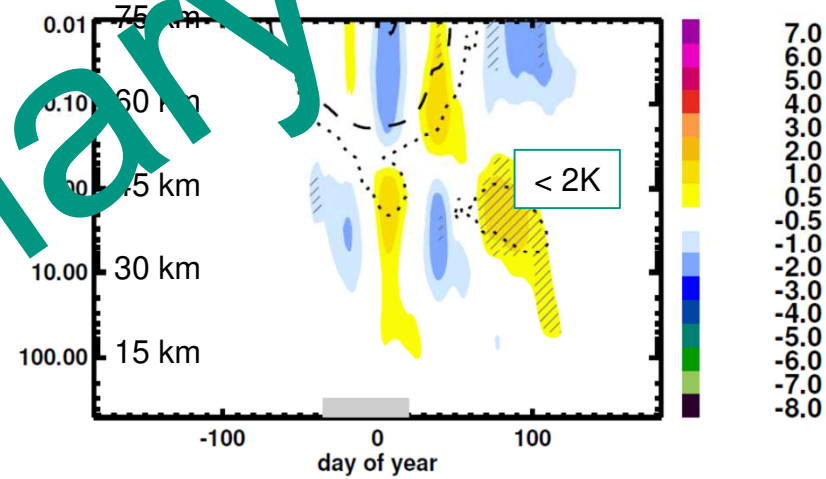
Four free-running chemistry-climate models with high/low particle forcing

40 years each, 70°-90°N

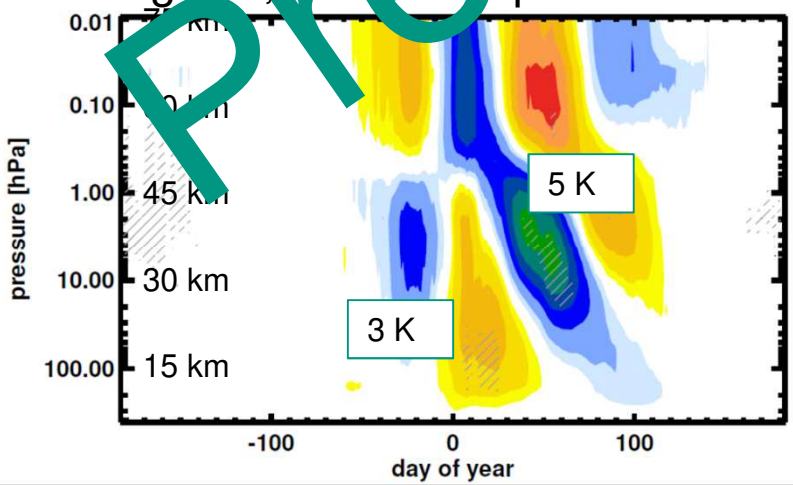
High-low forcing: mean ozone change, %



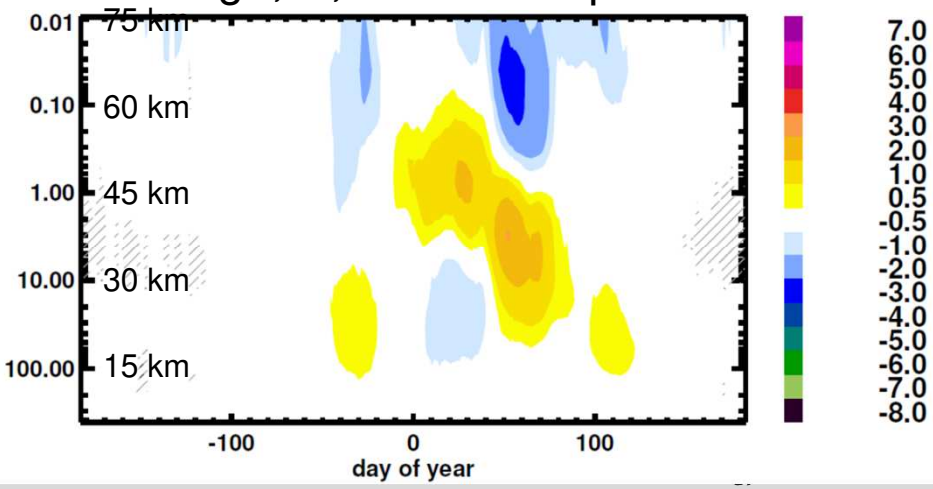
High-low forcing: mean T change, K



T change, K, QBO east phase



T change, K, QBO west phase



Summary

Energetic particle precipitation strongly affects chemical composition of the atmosphere down to ~30 km, both directly and indirectly

→ Good observational evidence, well understood

Chemical changes imply changes in radiative heating which might initiate dynamical coupling down even to tropospheric weather systems

→ Observational evidence, but attribution to particle precipitation difficult

Model studies with chemistry-climate models show only small changes on average, much larger changes if middle atmosphere dynamical systems considered

→ Preliminary results, but consistent with some observations

→ Suggests large-scale dynamical (wave) coupling

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