Towards a better understanding of energetic particle precipitation (EPP) impacts on the middle atmosphere and climate

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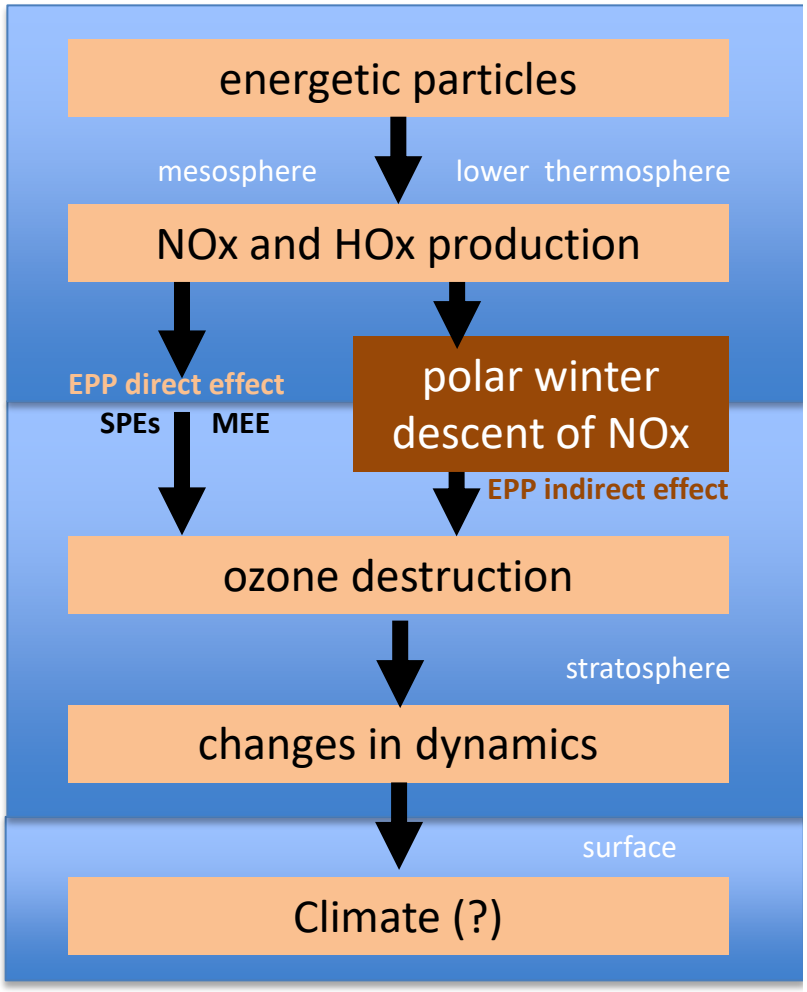
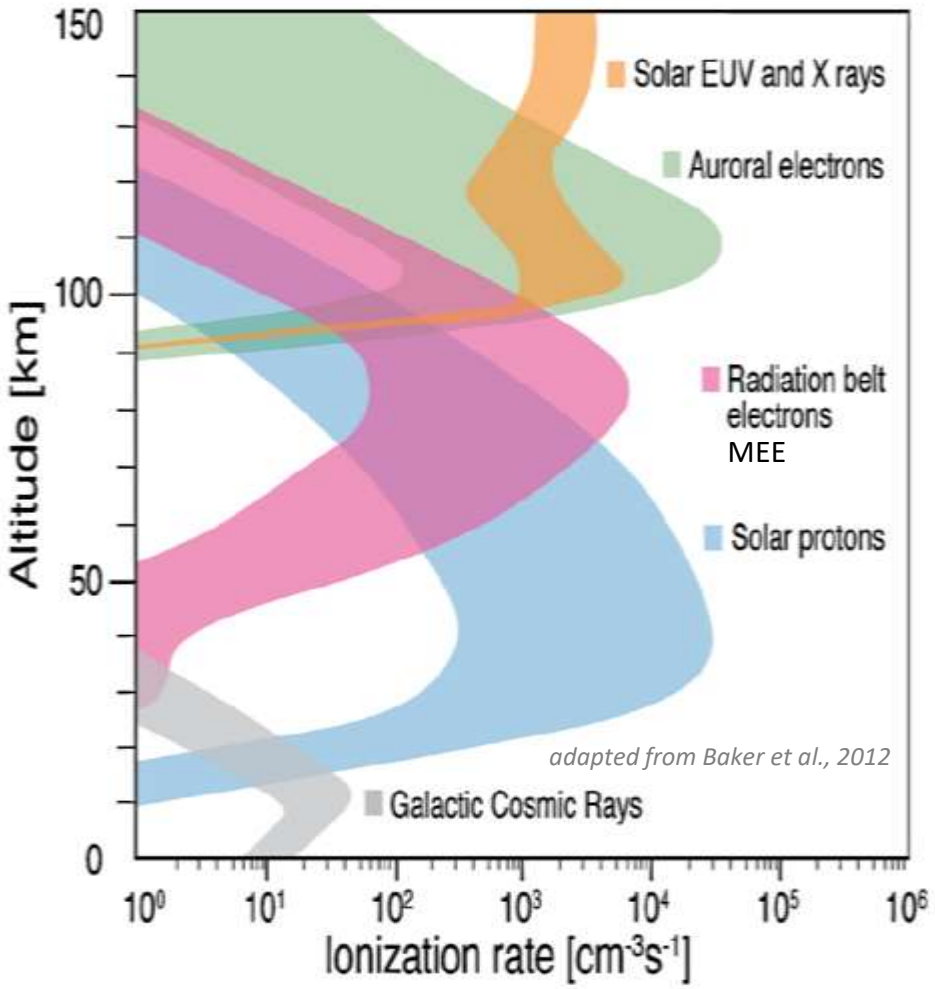
EPP: a solar coupling pathway

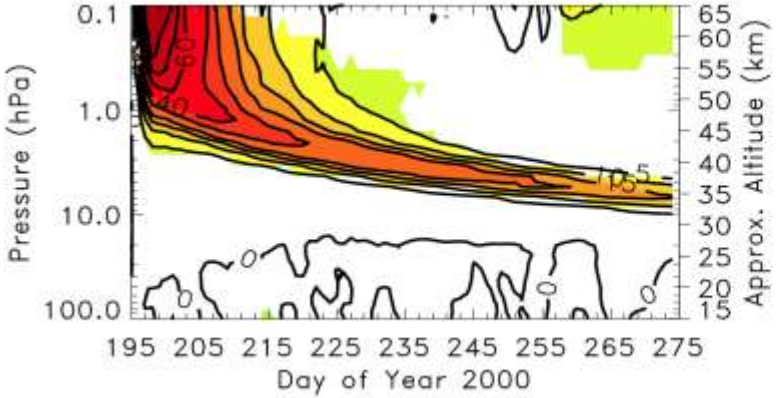




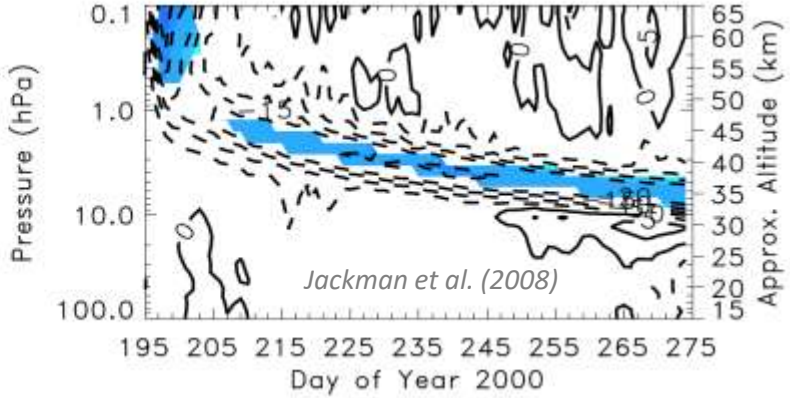
PreSTo: predictability across timecales

1) days to months: SPEs

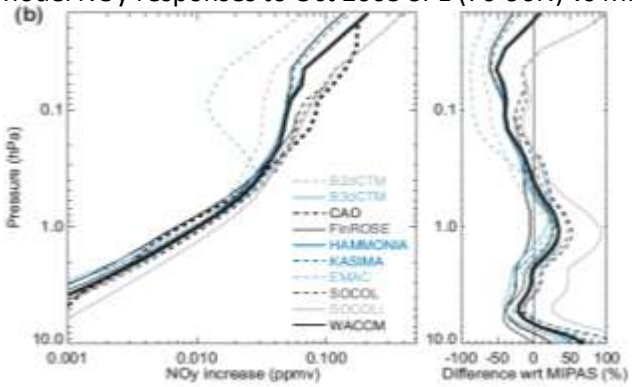
WACCM NOy response to July 2000 SPE (60-90S)



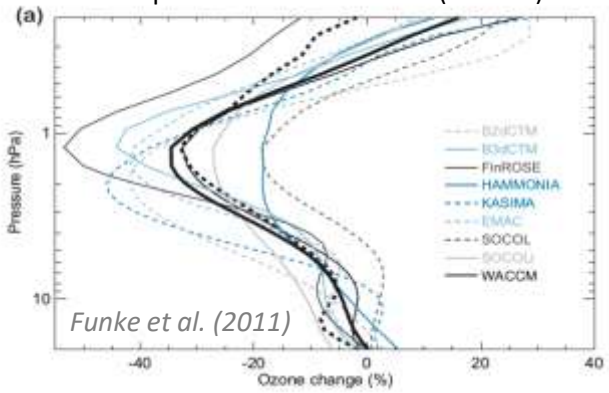
WACCM O3 response to July 2000 SPE (60-90S)



Model NOy responses to Oct 2003 SPE (70-90N) vs MIPAS



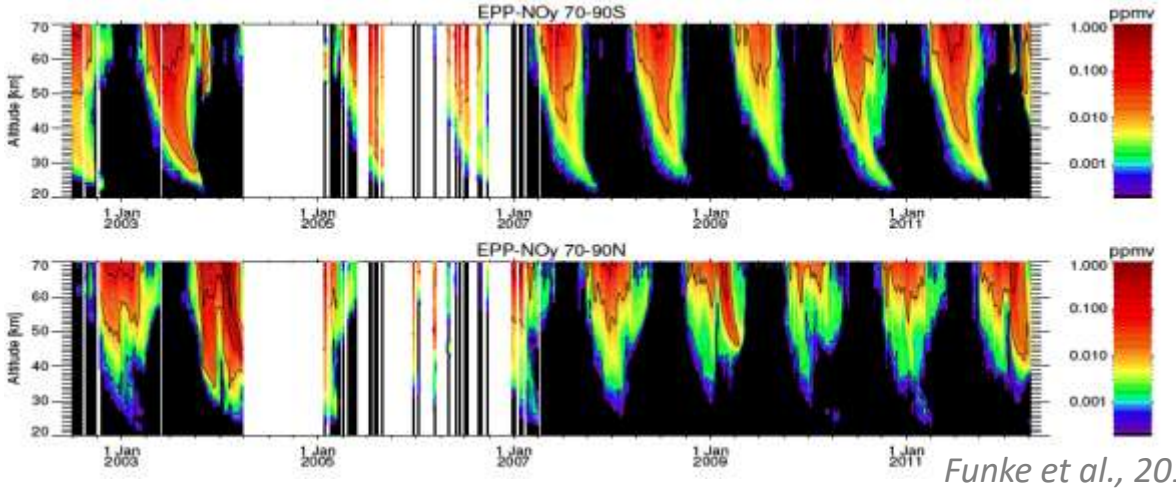
Model O3 responses to Oct 2003 SPE (70-90N) vs MIPAS



- Predictable chemical impacts over months (after occurrence)
- Good representation in atmospheric models.

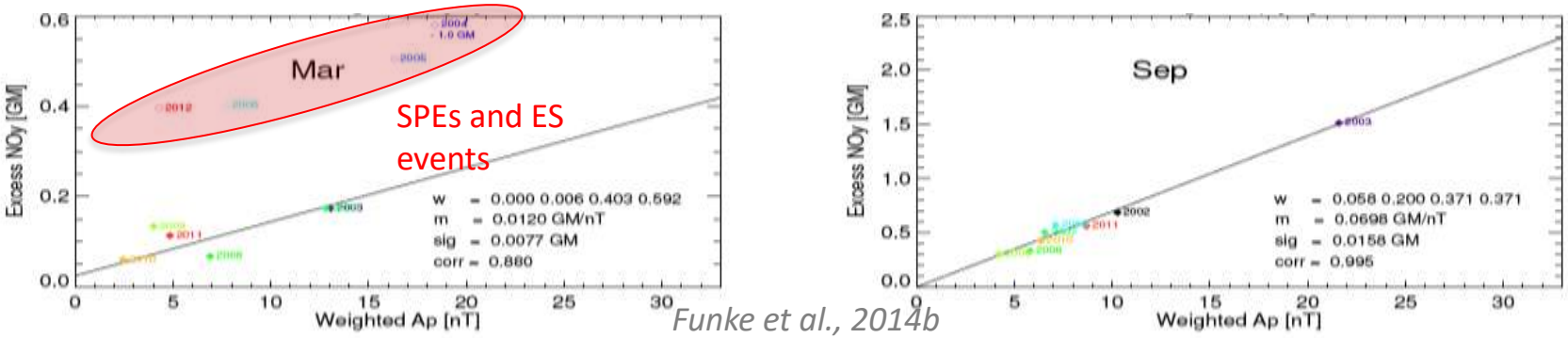
PreSTo: predictability across timecales

2) decadal: EEP indirect (and direct) effect



Funke et al., 2014a

- MIPAS observed NOy enhancements in every winter due to EPP.
- Highly correlated with geomagnetic Ap index (when considering transport lags)



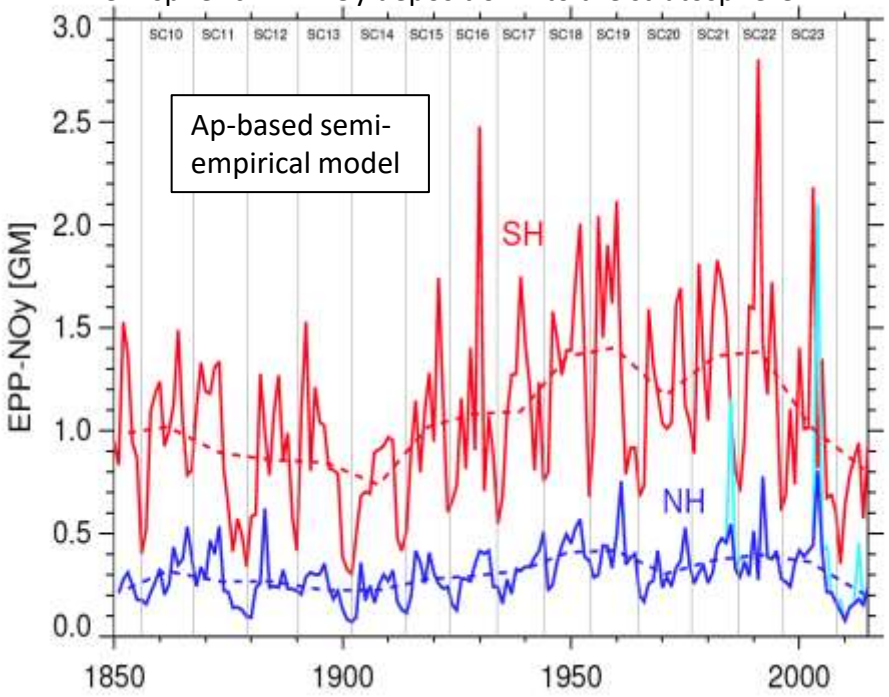
Funke et al., 2014b

- Predictable chemical impacts over solar cycle.

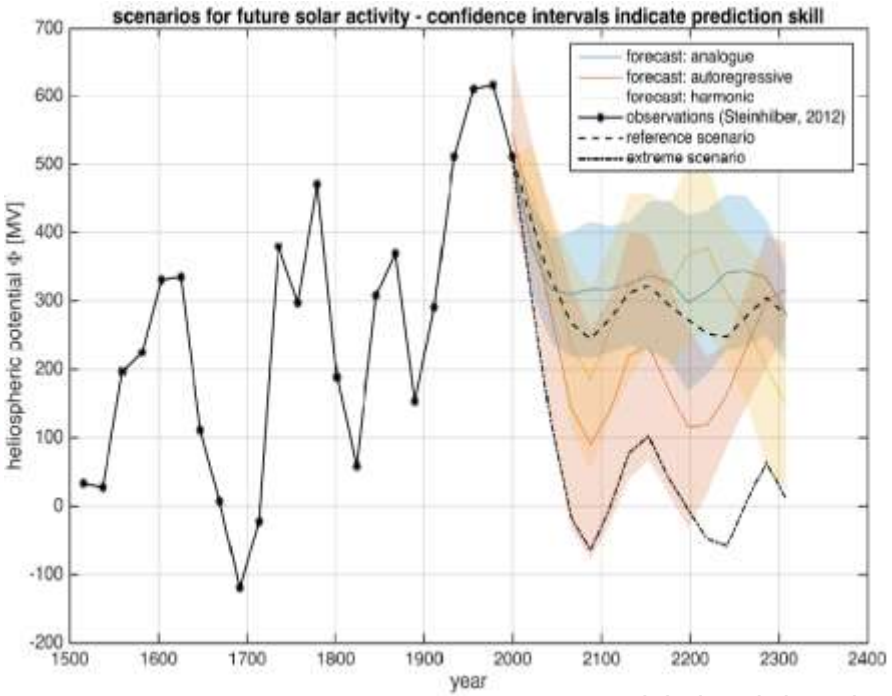
PreSTo: predictability across timecales

2)centennial: EEP indirect (and direct) effect

Hemispheric EPP-NOy deposition into the stratosphere



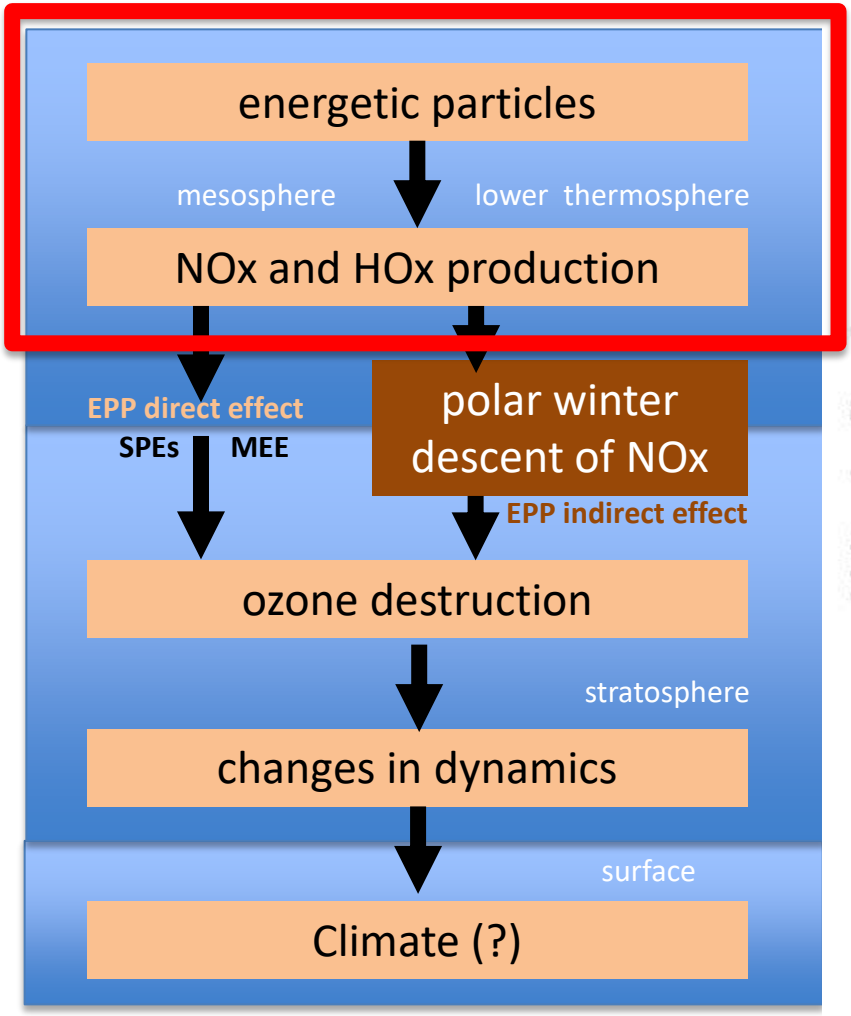
Funke et al. (2016)

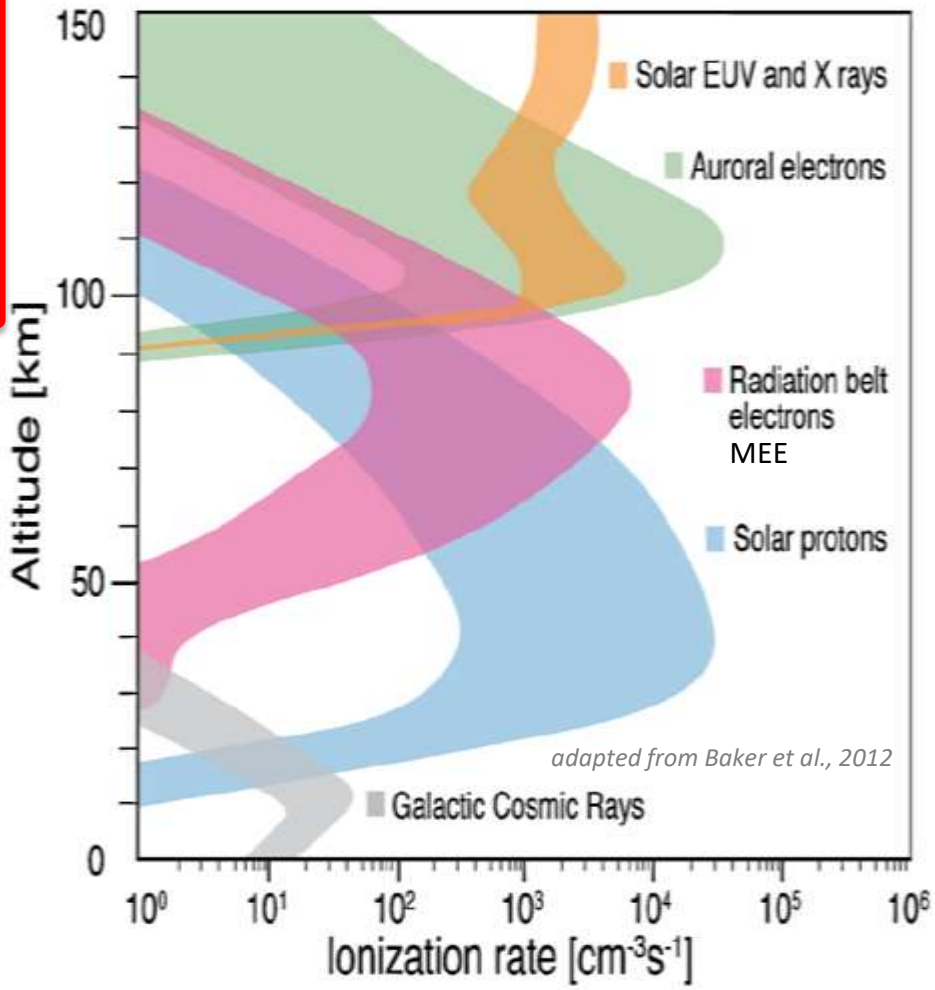


Courtesy T. Dudok de Wit (2015)

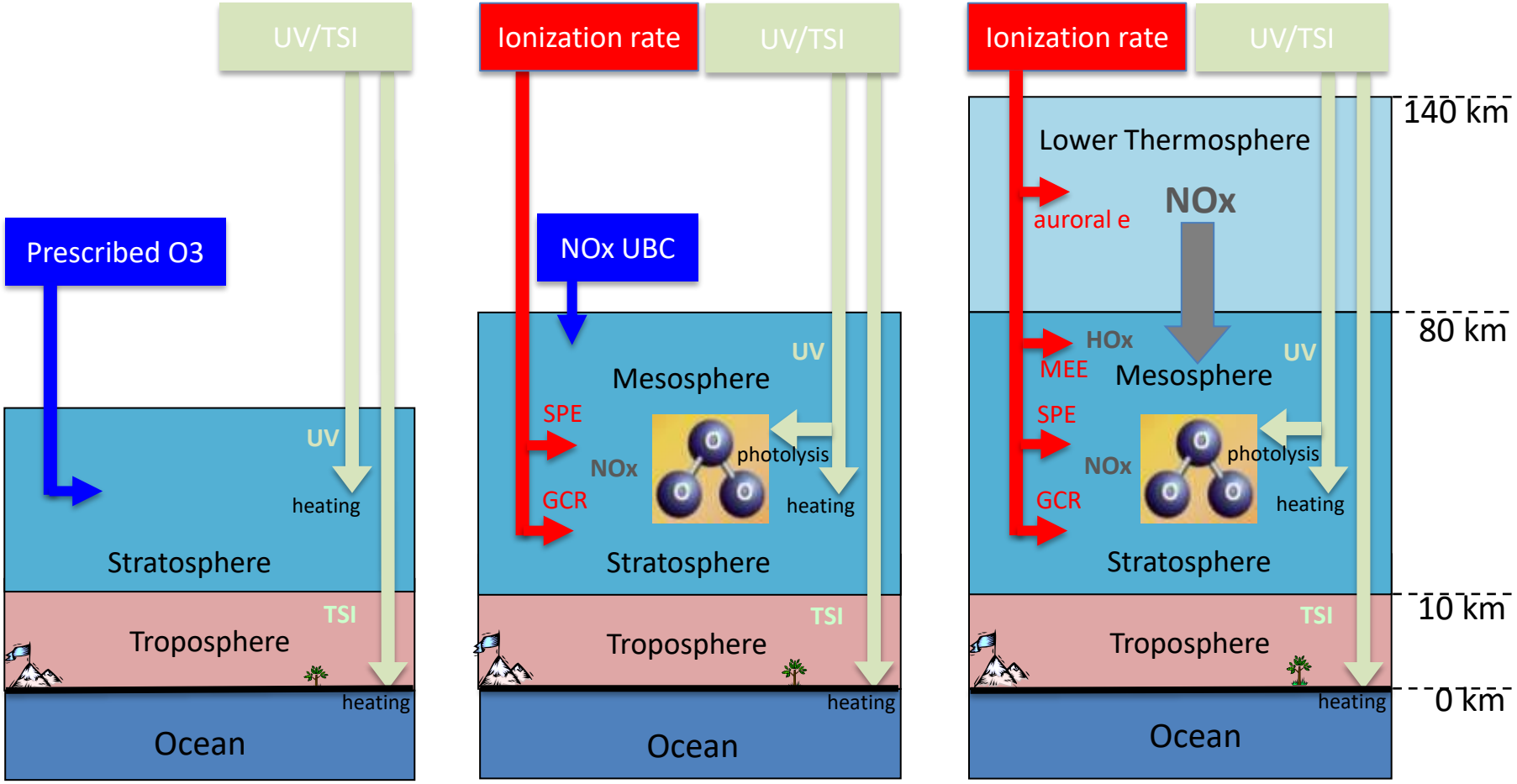
- Estimation of EPP chemical impacts for probabilistic scenarios of future solar activity.

EPP forcing + radical formation





EPP forcing in climate models



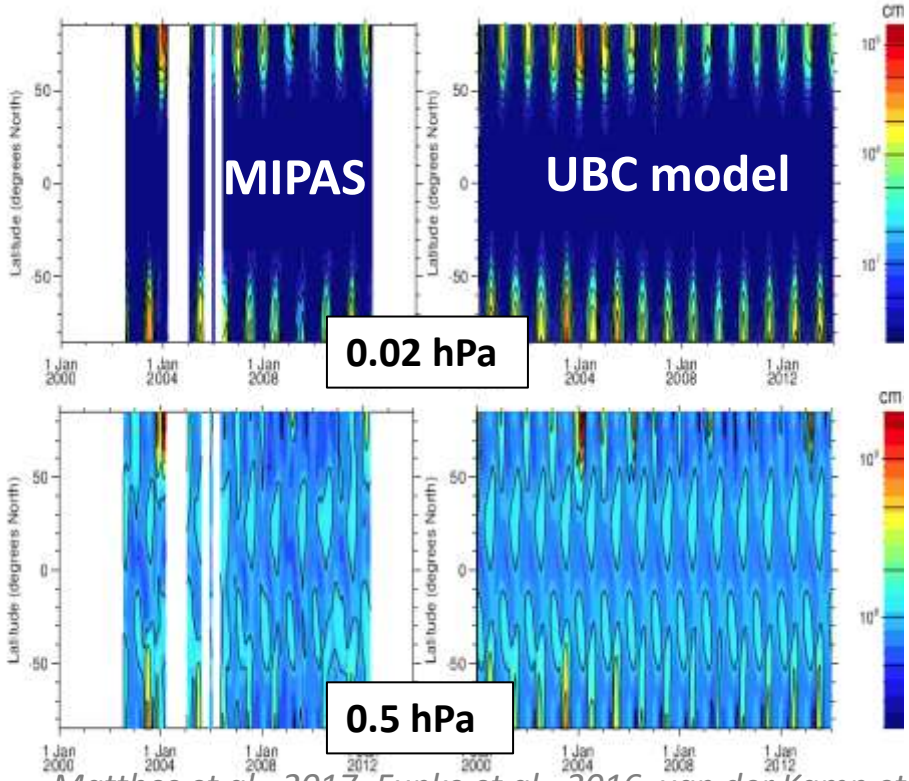
a) "Low-top" model without interactive chemistry

b) "Medium-top" model with interactive chemistry

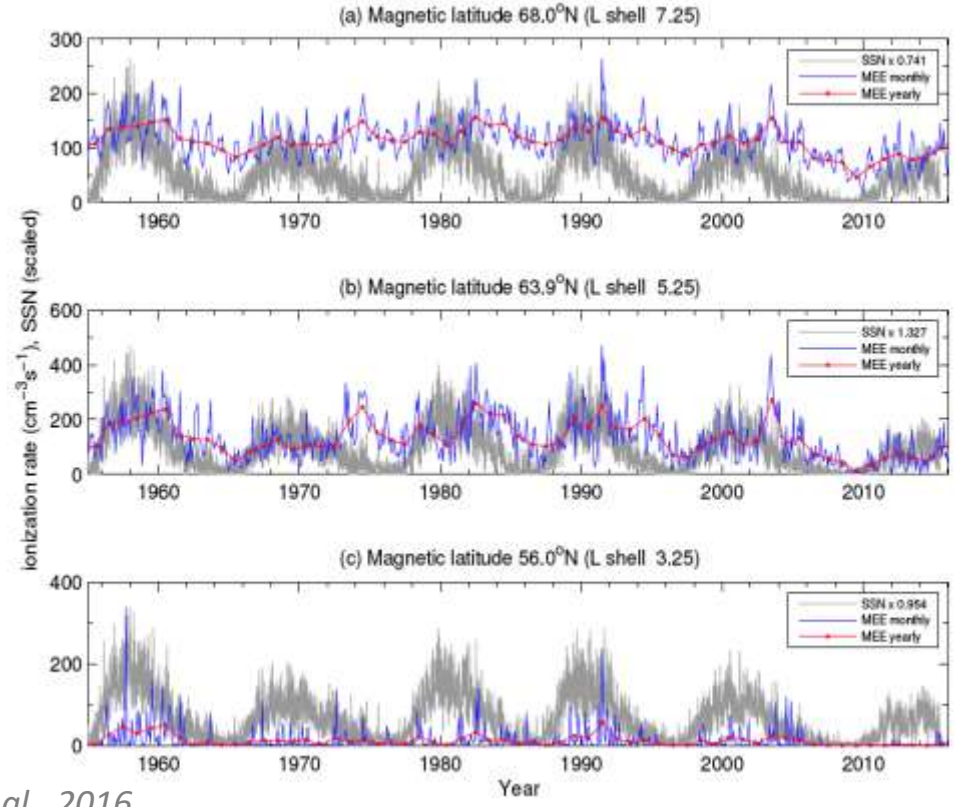
c) "High-top" model with interactive chemistry

EEP in CMIP6 solar forcing

Ap-driven NOy UBC (MIPAS-derived)



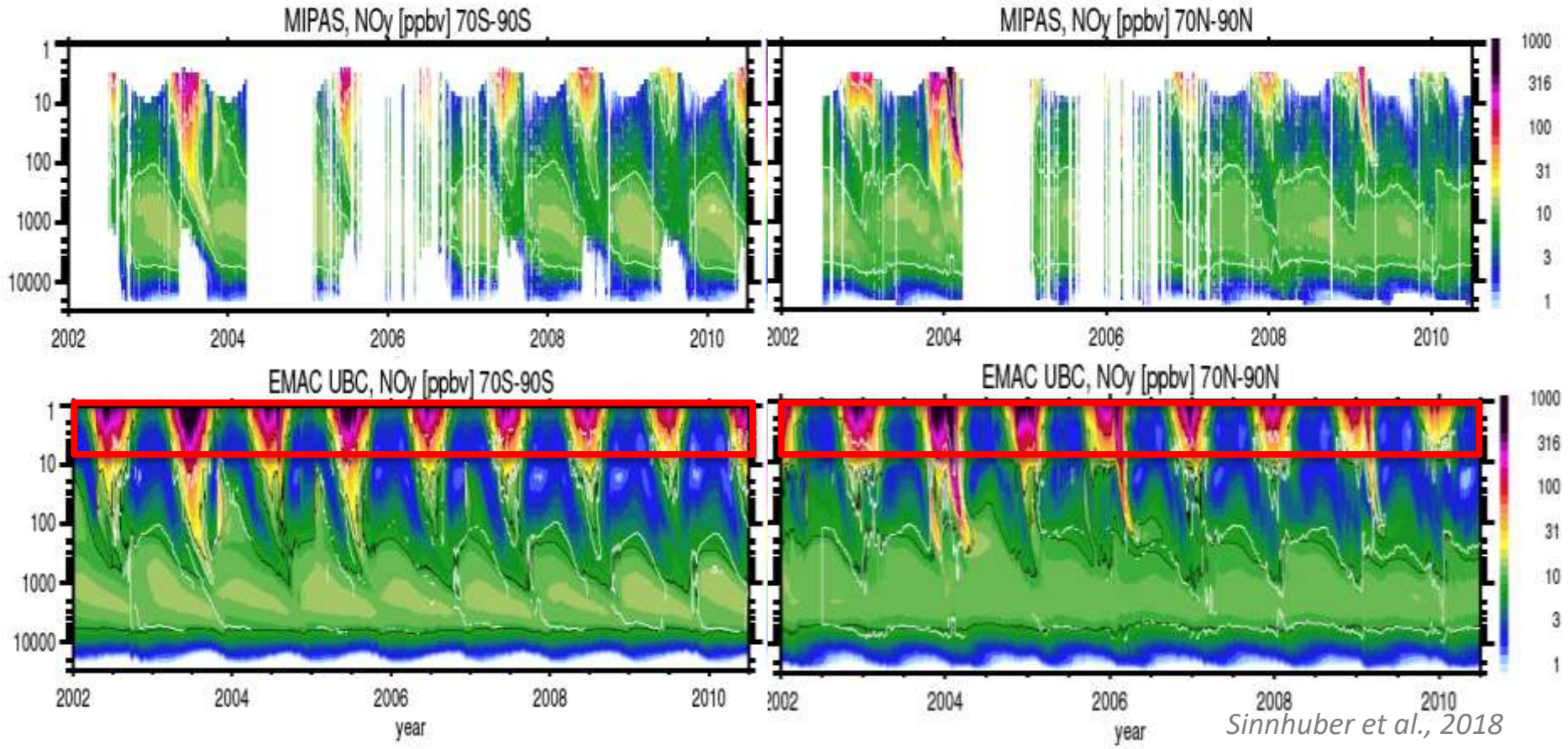
Ap-driven MEE ionization rate (POES-derived)



Matthes et al., 2017, Funke et al., 2016, van der Kamp et al., 2016

- Inclusion of particle forcing in CMIP for the first time.
- Allows for longterm climate simulations due to Ap parameterization.

UBC application in “medium” top models

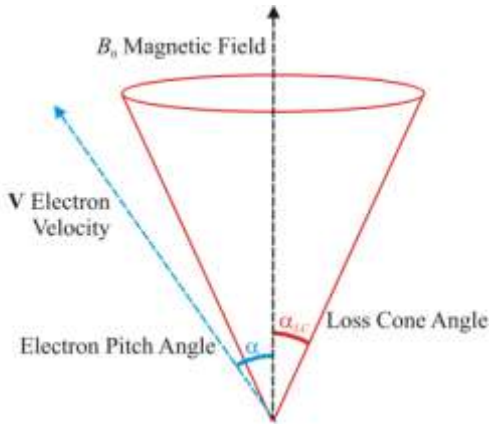


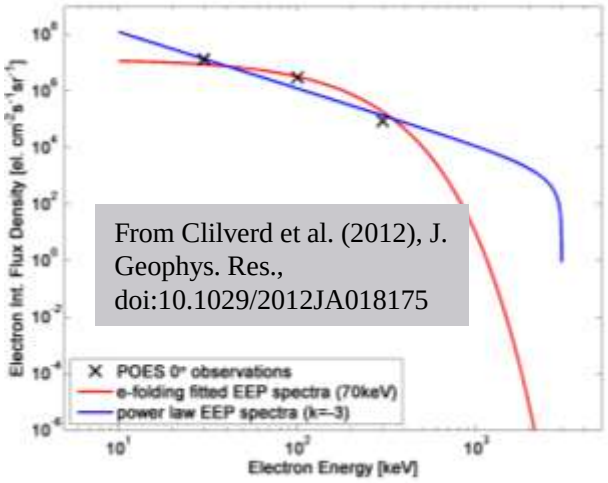
Sinnhuber et al., 2018

- Very good agreement with observations, but…
- extrapolation of EPP impact for 2002-2012 conditions
- no representation of EPP source region (and processes acting therein)

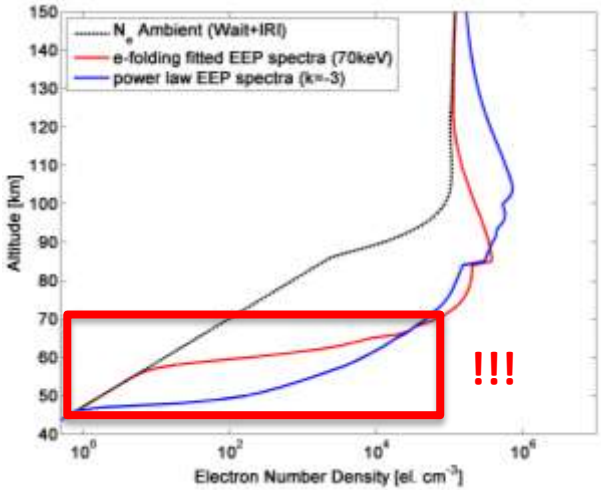
Precipitating electron fluxes

Known issues with the POES SEM-2 electron channel





From Clilverd et al. (2012), J. Geophys. Res., doi:10.1029/2012JA018175

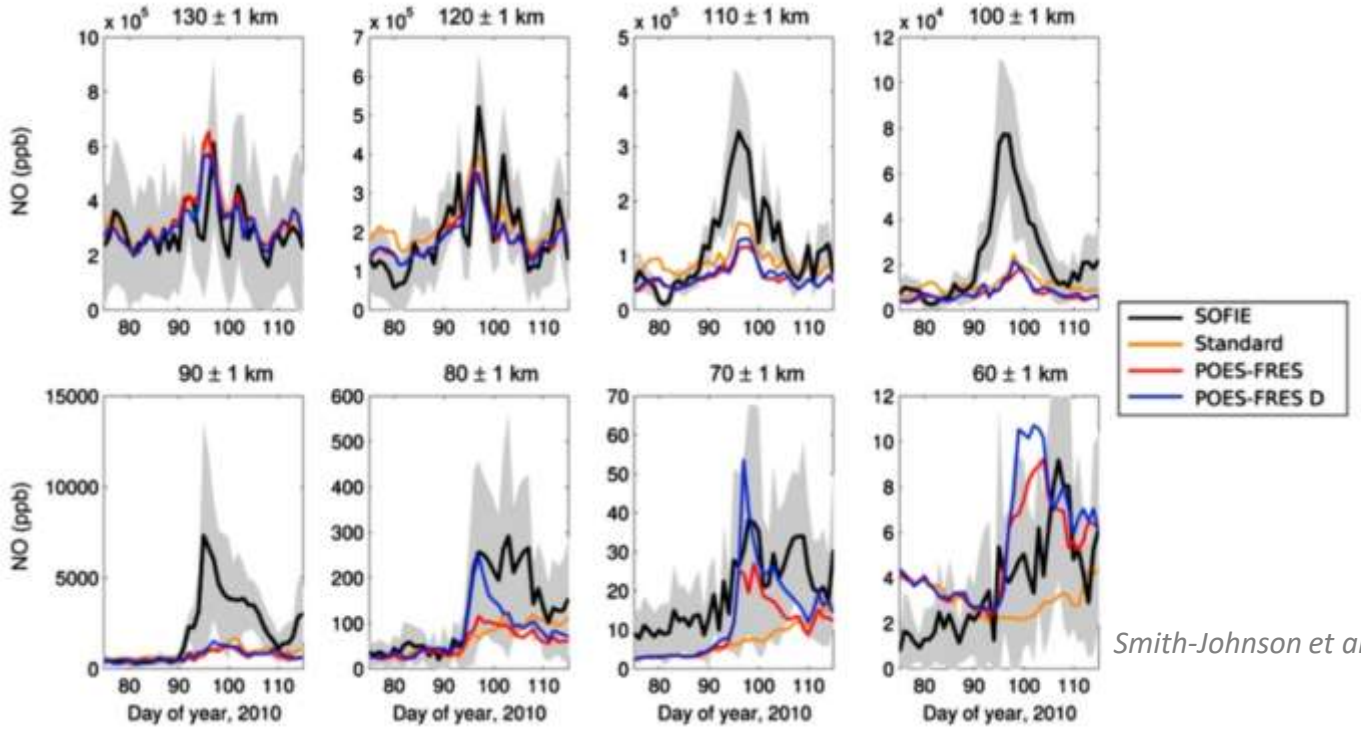


- **"geometry factor"** of 0-deg electron telescopes: SEM-2 observes only a small fraction of precipitating electrons in the loss cone.
- **Energy discrimination**: 3 integral channels of SEM-2 are insufficient to constrain energy spectrum, leads to uncertainties in modeling of ionospheric impact.
- **Proton contamination** (particularly during SPEs!)

…makes it difficult to constrain direct EPP impact in the mesosphere by radiation belt electrons!

Impact of D-region ion chemistry on NO formation

2010 EEP events: WACCM model results versus SOFIE NO observations



Smith-Johnson et al., 2018

Both inclusion of MEE ionization and proper modeling of chemical radical formation are important….

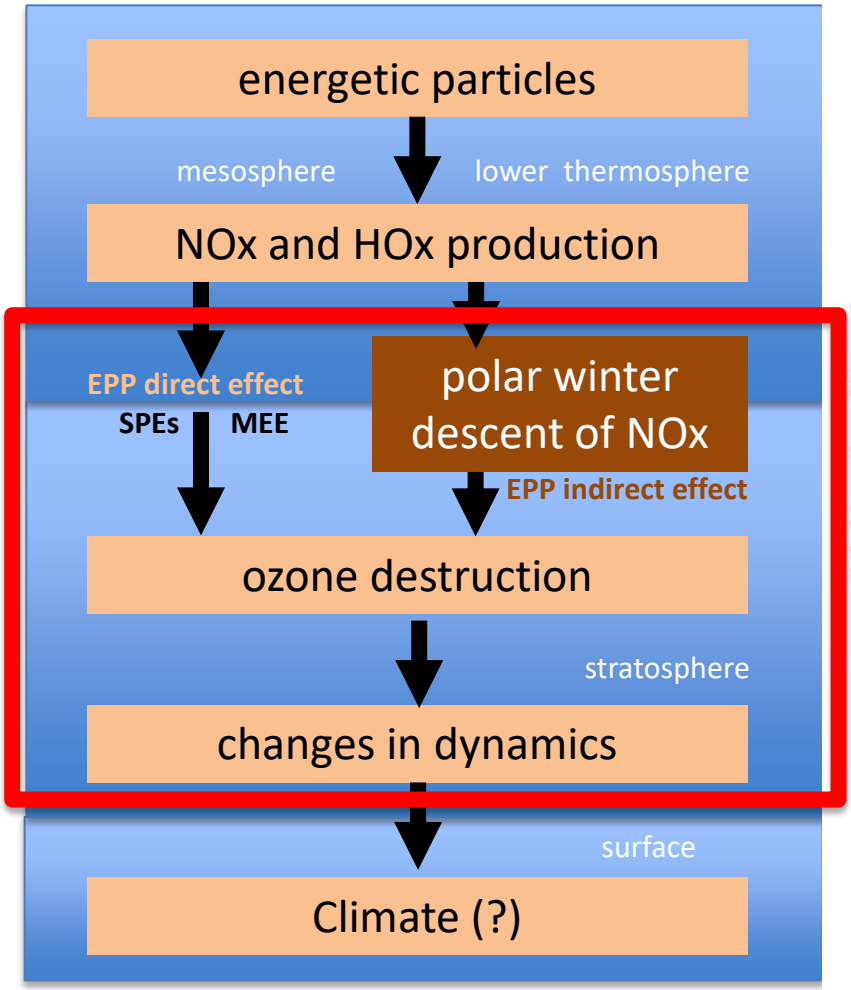
Open issues & requirements for future progress

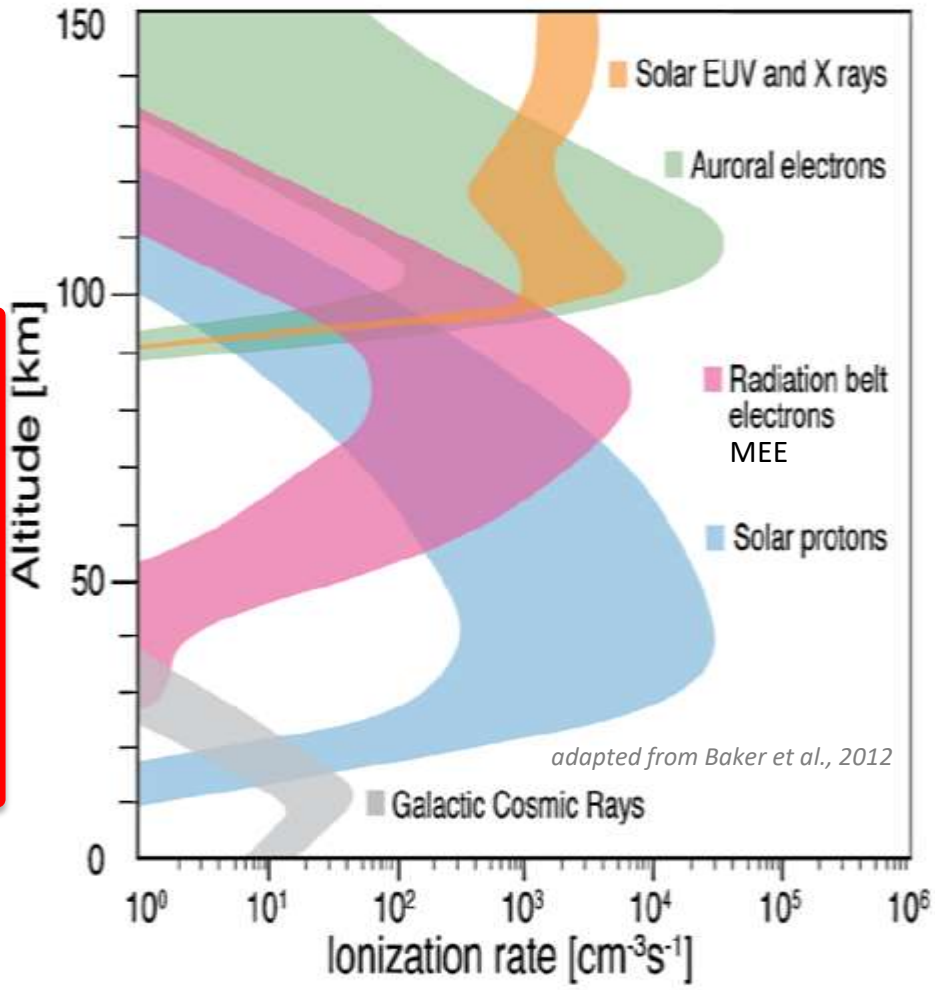
- MEE contribution most uncertain!
- New **particle flux sensors** with better **pitch angle** and **energy resolution** are required
- Theoretical studies on pitch angle dependence, i.e. **loss cone reconstruction** (e.g. Nesse-Tyssøy et al. 2019)
- **Validation** of short-term chemical impact with **satellite observations** (e.g. mesospheric OH, thermospheric NO)
- **Diurnal variations** of EEP ionization (e.g., van der Kamp et al., 2019)
- From particle flux observation to **proxy models** for climate applications
- **Uncertainty characterization** of EPP-induced atmospheric ionization
- MLT resolving (whole atmosphere) models are required for full implementation
- Uncertainties in **D region ion chemistry** -> laboratory work

PreSTo could…

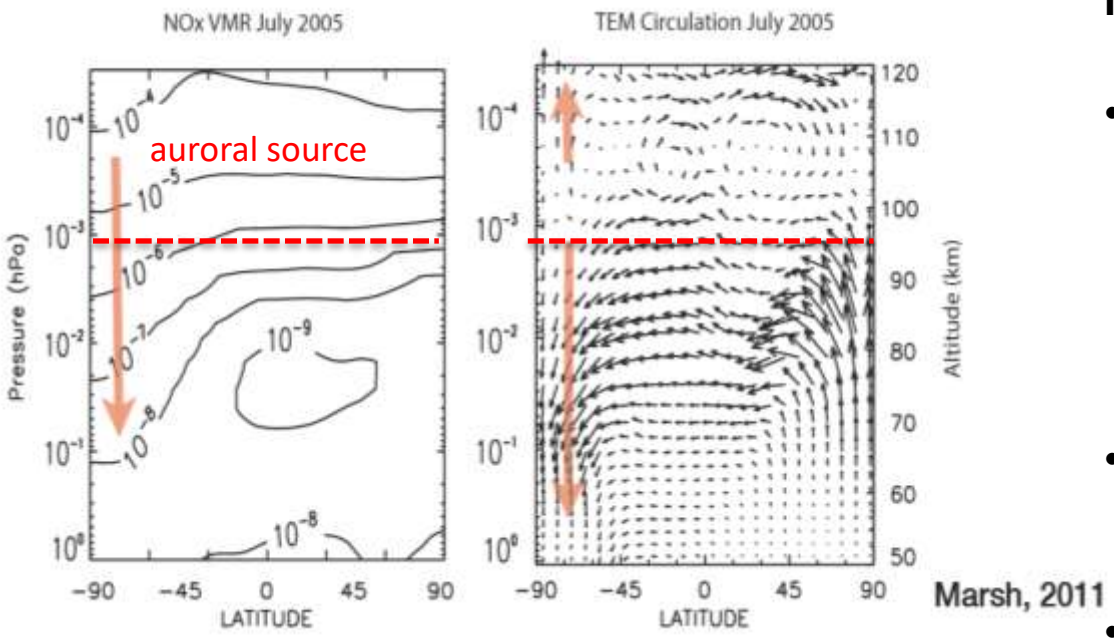
- provide the collaborative framework for transdisciplinary efforts involving atmosphere, magnetosphere, interplanetary space, and space climate.
- Assess observational needs and priorities.

Transport, ozone, and dynamics





Dynamics: EPP indirect effect

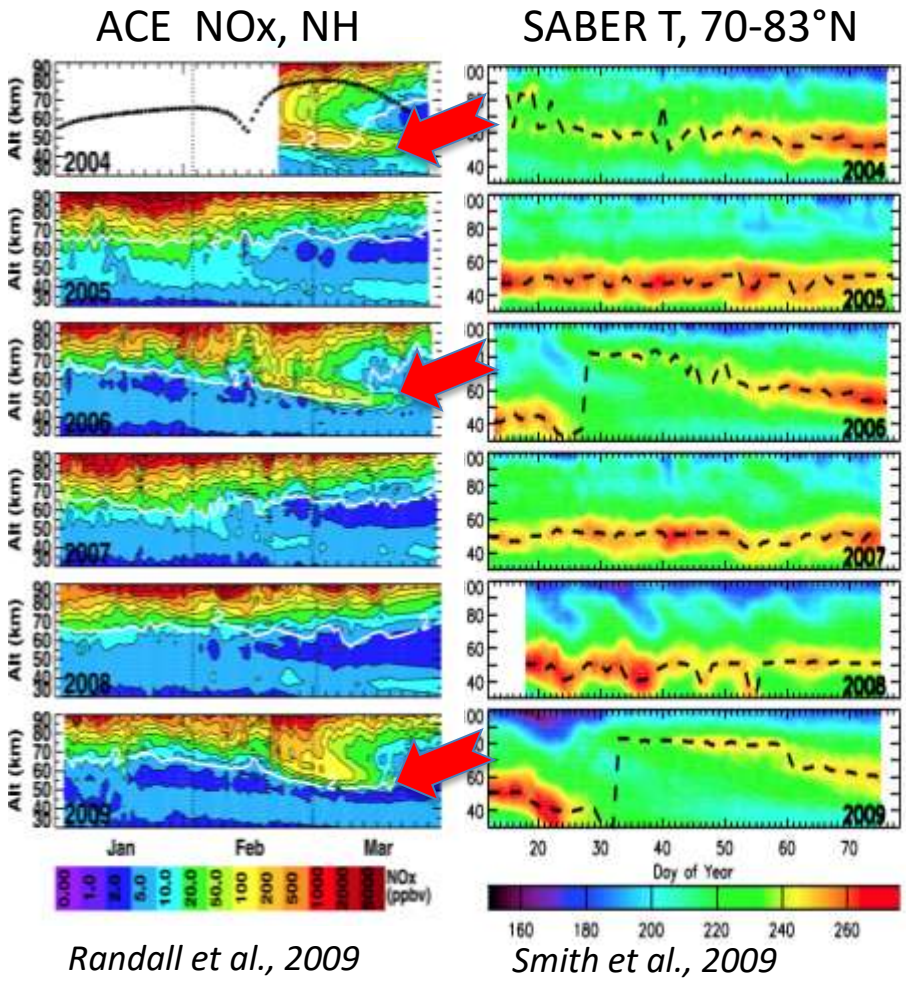


MLT dynamics

- Auroral NOx source in the winter thermosphere is not connected to the middle atmosphere via TEM circulation.
- NOx injection is controlled by diffusion.
- Knowledge on vertical shape of ionization rate profile is crucial!

Uncertainties in modeled NOx depositions and hence representation of EPP indirect effects.

Dynamics: NH variability



Randall et al., 2009

Smith et al., 2009

Pronounced dynamical variability in the NH related to wave activity:

Very strong EPP IE after SSWs and associated “elevated stratopause” (ES) events.

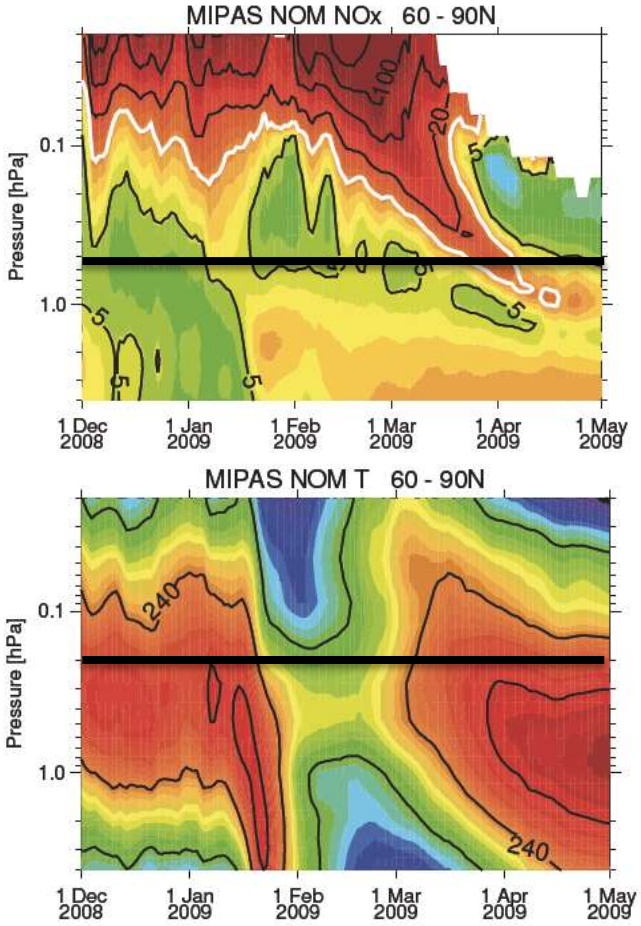
Randall et al. 2009, Holt et al., 2013

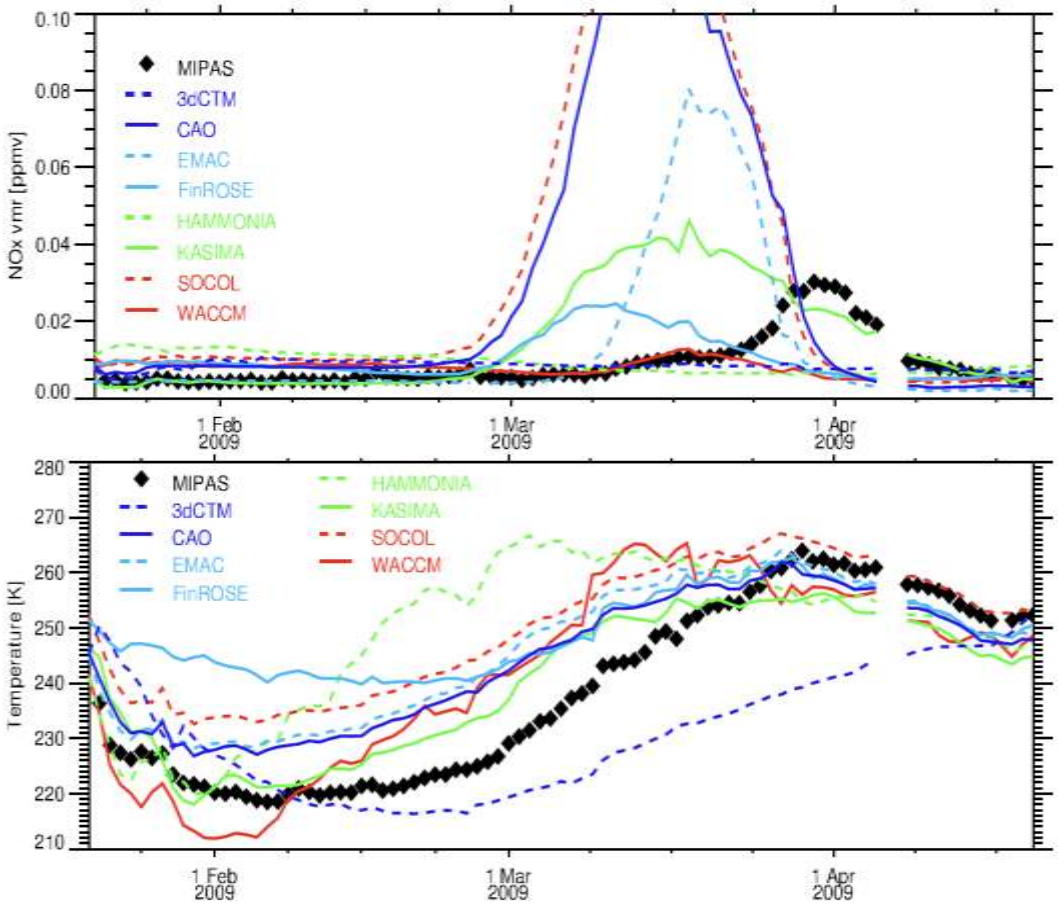
Strongly controlled by unresolved GWD in models.

-> possible model biases

HEPPA-II Intercomparison project

SPARC SOLARIS-HEPPA activity to evaluate model representation of the 2008/2009 NH winter

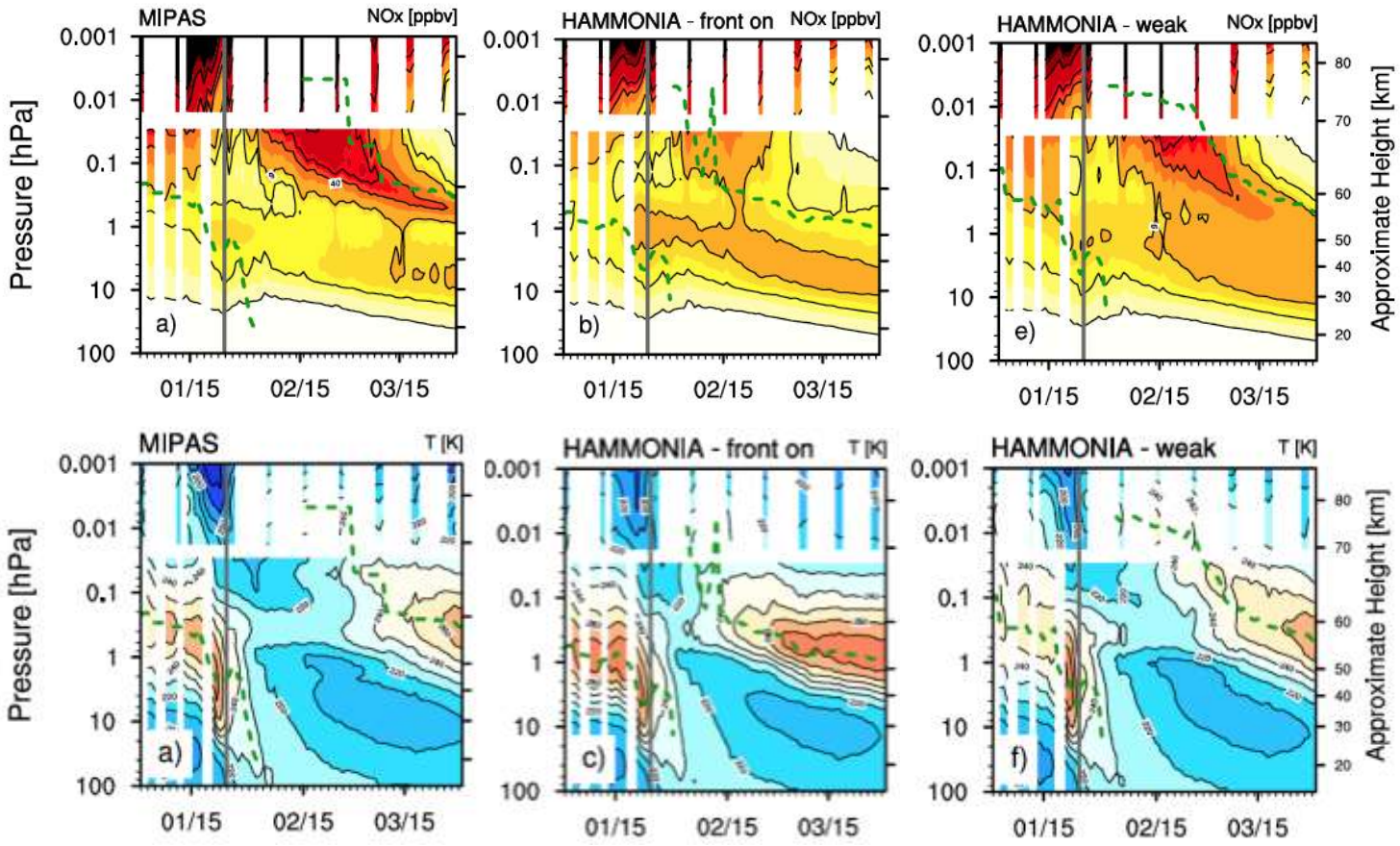




Funke et al., ACP, 2017

Large model biases in amplitude and timing of descending EPP-NOx

Sensitivity to GWD parameterization

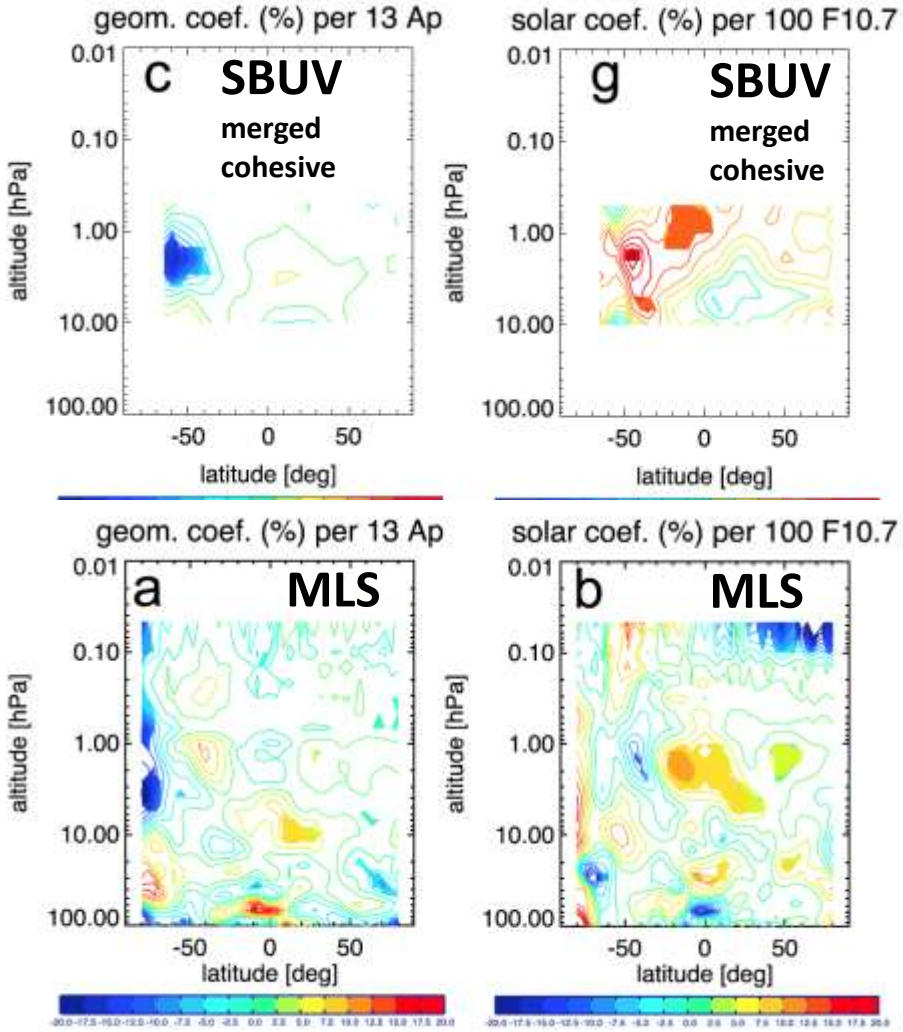


Meraner et al. (2016)

Agreement with observations can be achieved by tuning GWD scheme.

Observed ozone responses

Regression to August composites of SBUV (1979-2014) and MLS (2005-2014):

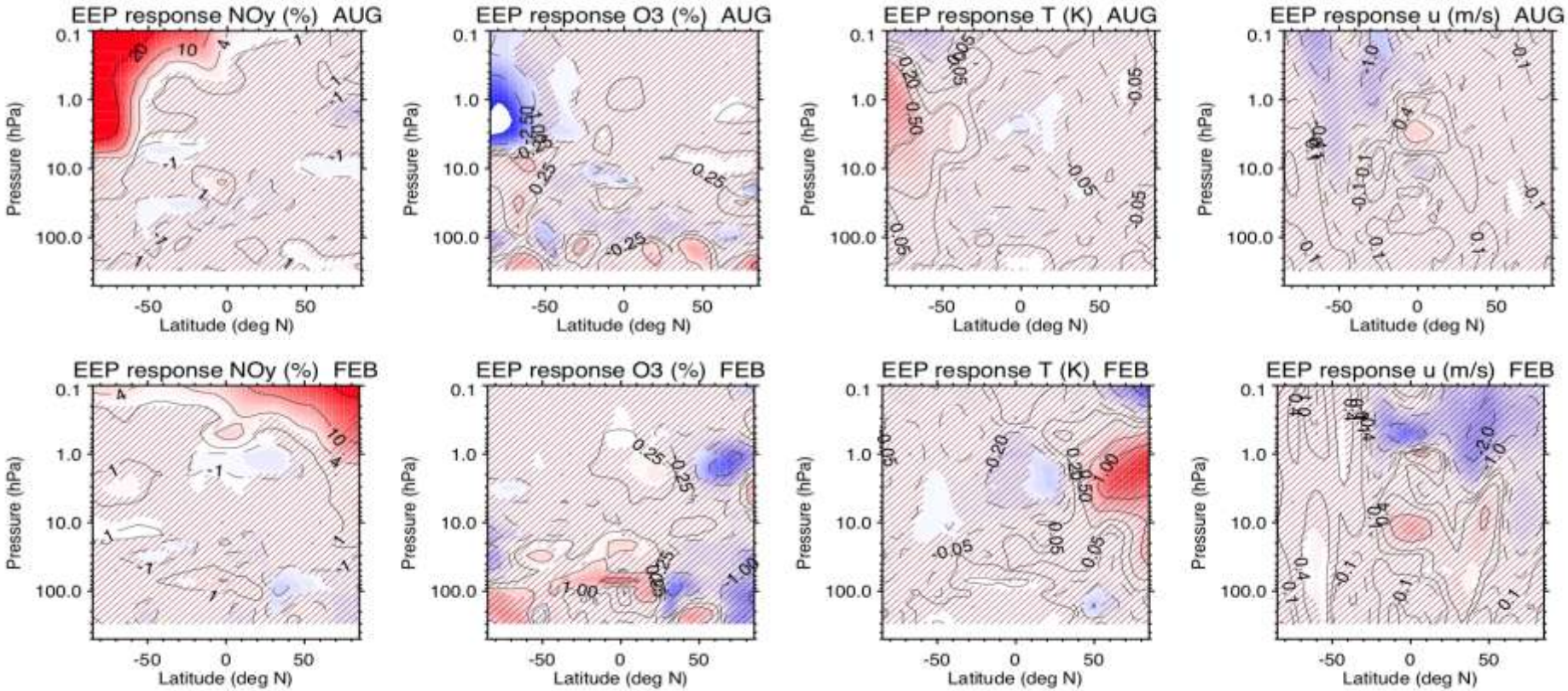


- Stratospheric O3 responses to solar variations commonly estimated with MLR using F10.7 (or similar) as predictor.
- Inclusion of Ap in MLR: large particle-induced response in the polar mid-stratosphere
- Distinguishable signals for F10.7 and Ap

Damiani et al., GRL, 2016

Dynamical EPP responses

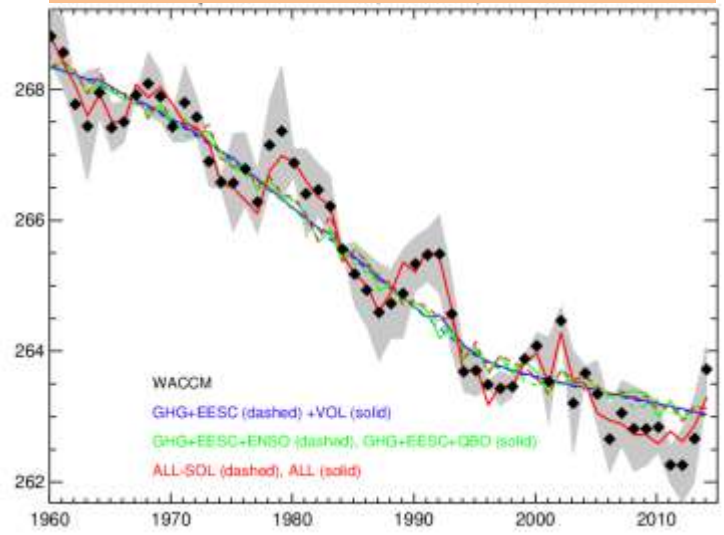
MLR analysis of WACCM CCMI REF-C2 simulations (3 members 1960-2100)

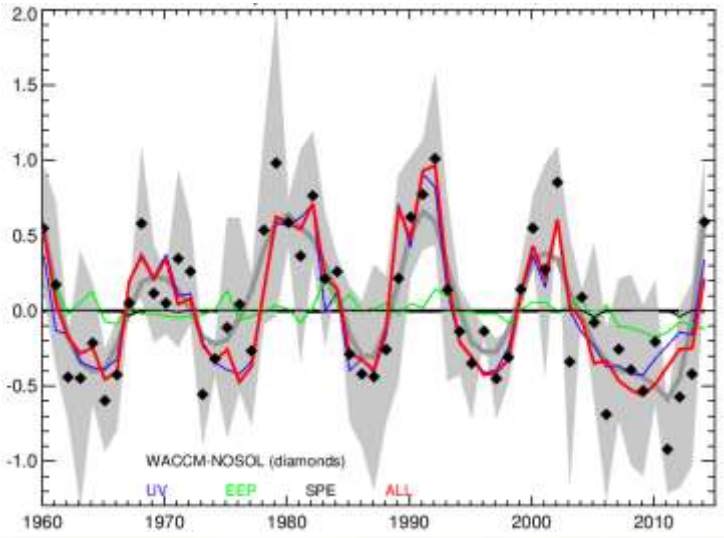


Standard analysis tools like MLR provide clear chemical signals, but no statistically significant dynamical effects.

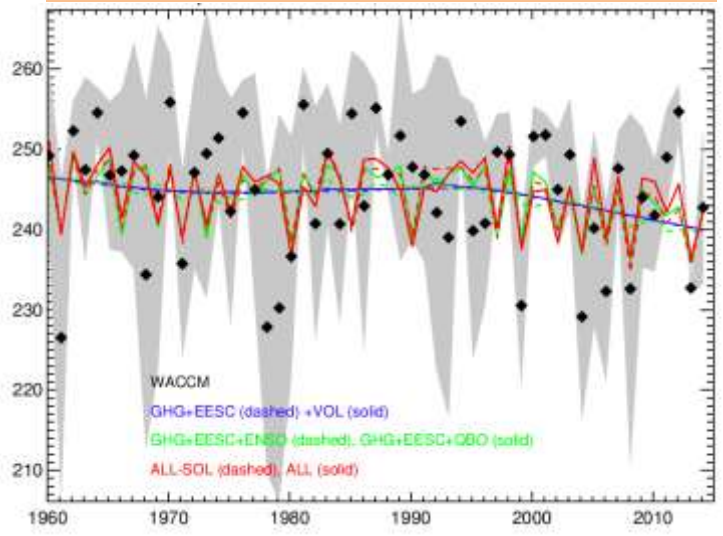
Dynamical signals are difficult to detect in polar winter…

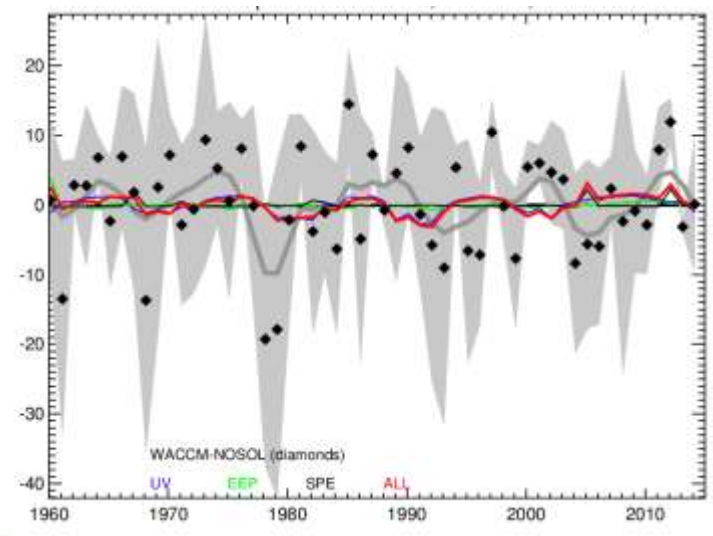
T@ 1hPa Tropics (Feb)





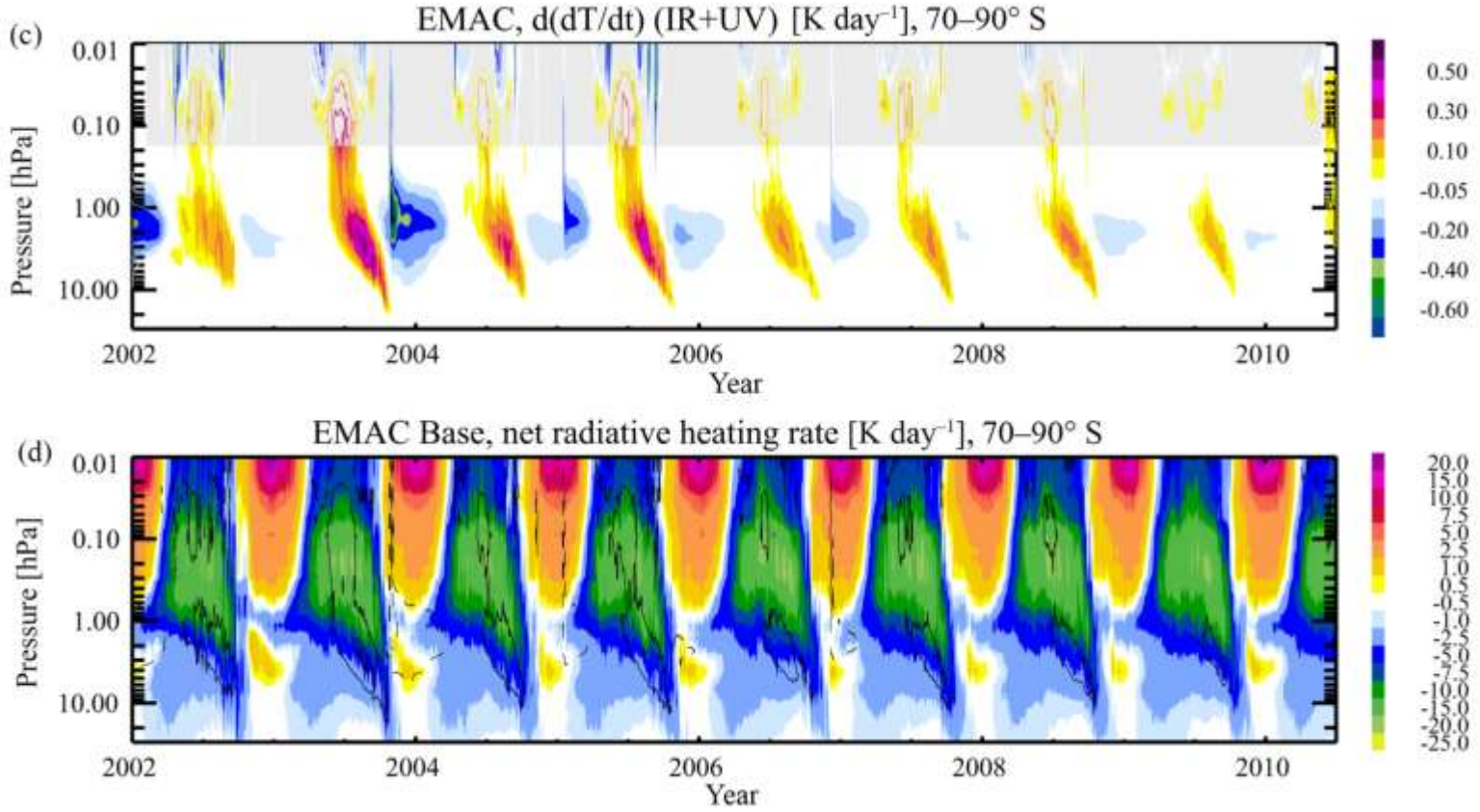
T@ 1hPa Polar winter (Feb)





Dynamical EPP responses

Shortwave and longwave heating rate response to EPP in EMAC



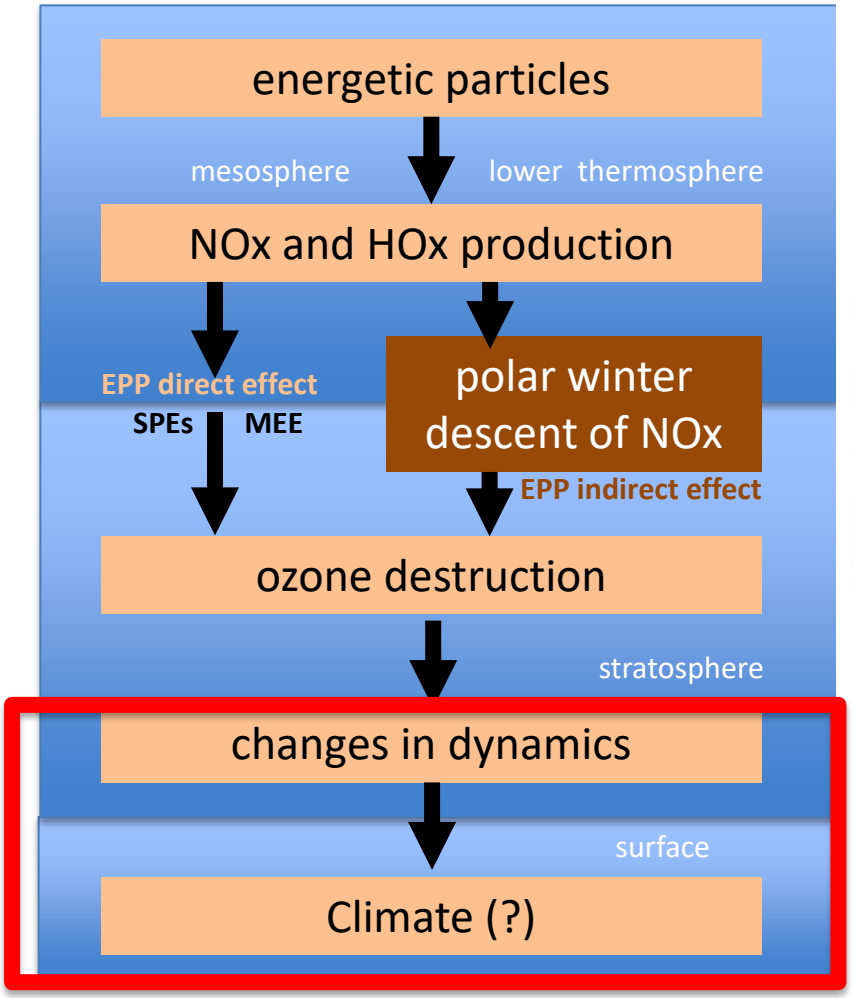
- Alternating pattern of heating (polar night) and cooling (spring)
- Results in complex temperature (and wind) responses

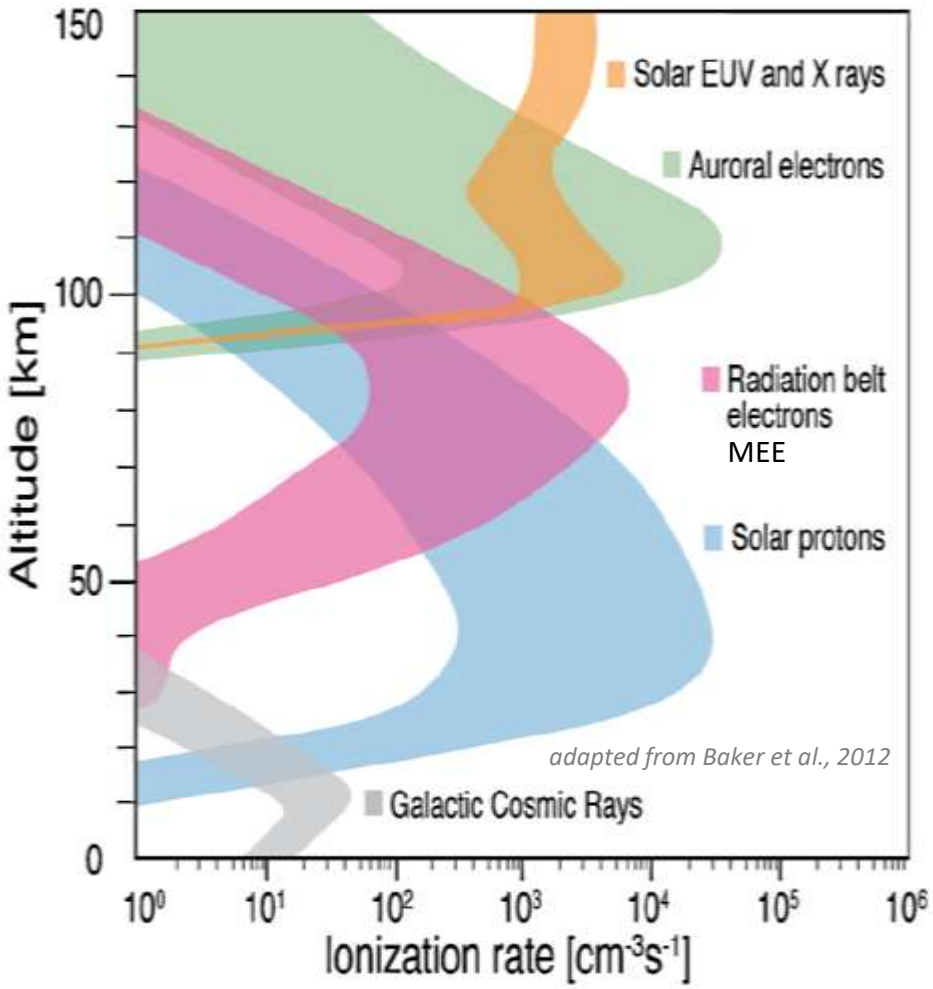
Open issues & requirements for future progress

- **Continuity** of **MA** trace gas, T (and wind) **observations** -> long-term changes:
  - direct chemical impacts (changing ionization levels due to secular variations of the Sun)
  - coupling to the stratosphere (changing circulation patterns as consequence of greenhouse gas forcing)
- **Dynamical representation** of the MLT in **climate models**: role of **small scale waves** as drivers for polar winter circulation -> improved GW parameterizations, model resolution.
- Better understanding of **dynamical coupling mechanisms** -> process-oriented model studies, idealized experiments, advanced statistical methods

PreSTo could…
- Assess observational needs and priorities
- Promote whole atmosphere model development & improvement
- Coordinate efforts targeting atmospheric small scale waves and their impact on circulation

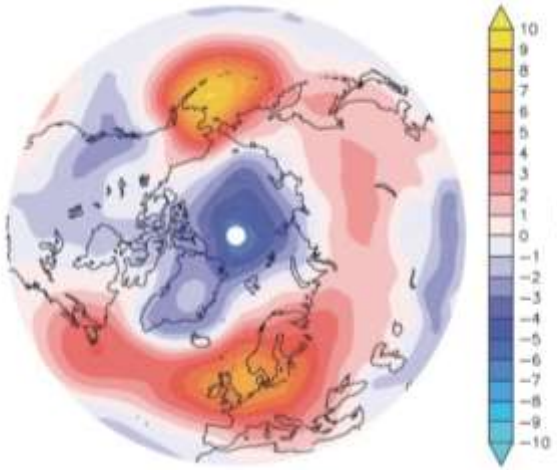
Surface climate





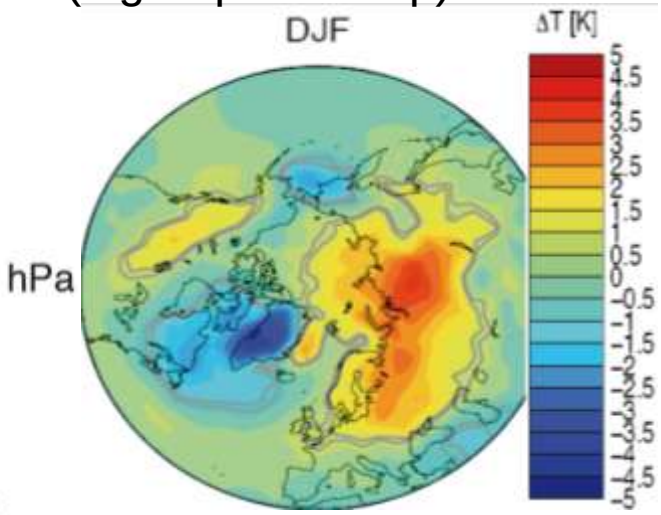
EPP: Evidence for surface effects

EMAC, DJF surface press. changes (EPP-no EPP), no SSW years



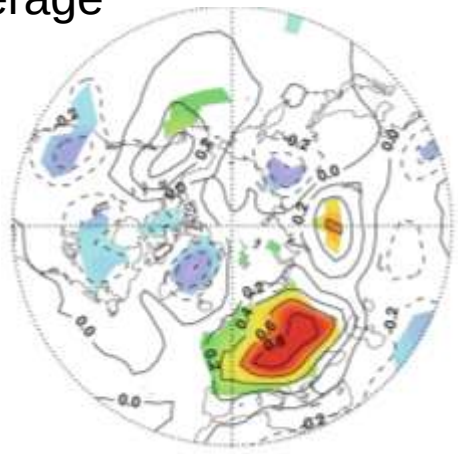
Baumgaertner et al., 2011

NCEP reanlysis, DJF surface T changes (high Ap – low Ap)



Seppälä et al., 2009

SOCOL, surface temp. changes (EPP-no EPP), 1960-2010 annual average

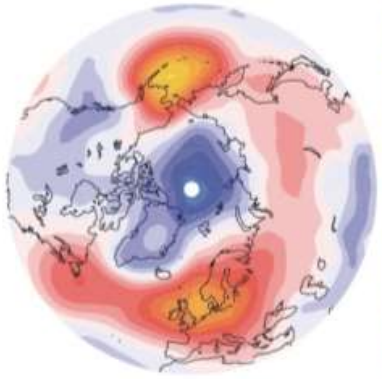


Rozanov et al., 2012

- A stronger Northern Hemisphere vortex and a NAO+ type surface signal for strong geomagnetic activity.
- But: too short simulations/reanalysis records for a robust signal detection?

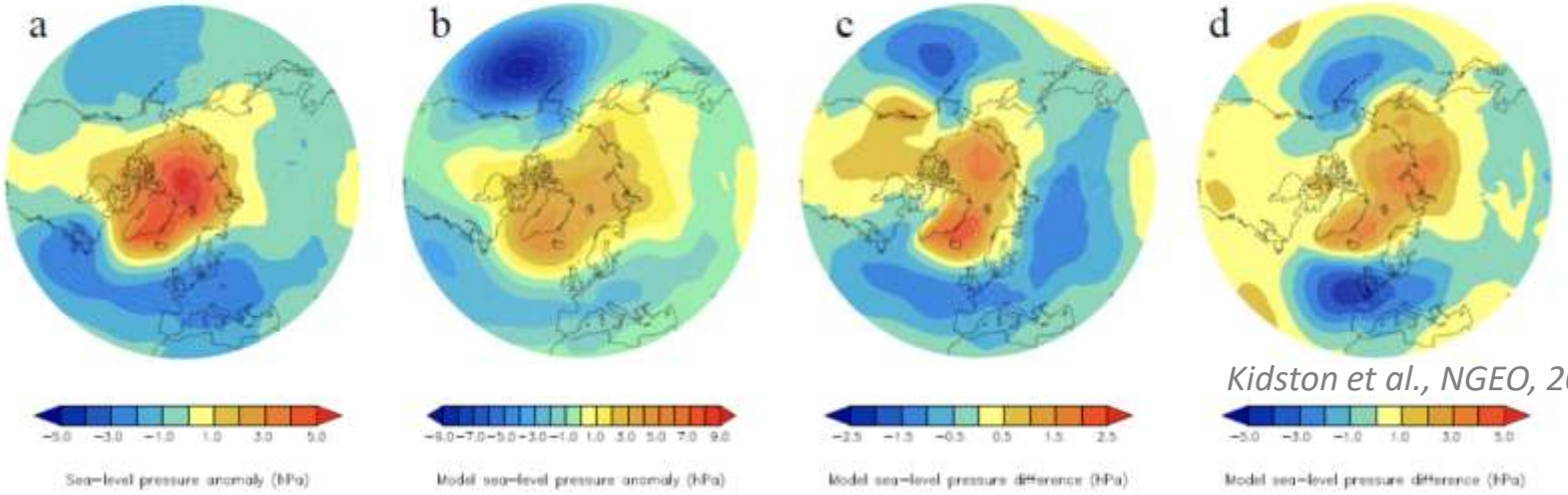
NAO responses across timescales

Energetic particles



Baumgaertner et al., ACP 2011

Monthly | Seasonal | Decadal | Centennial



Kidston et al., NGEO, 2014

SSW | **ENSO** | **Solar UV** | **GHG**

Open issues & requirements for future progress

- Unequivocal evidence for **particle-induced surface climate signals** remains to be provided! -> focus on **detection** rather than prediction…
- **Coordinated model experiments** (long transient simulations) with inclusion of EPP -> CMIP6 is a first step…
- Development of **advanced statistical analysis methods** (e.g., DLM, cross-term analysis, etc.)

PreSTo could…

- Engage with WCRP and IPCC
- Coordinate cross-disciplinary efforts targeting statistical analysis methods (relevant for many aspects of the Sun-Earth system, not only climate)

Summary

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- provide the collaborative framework for transdisciplinary efforts involving atmosphere, magnetosphere, interplanetary space, and space climate.
- Assess observational needs and priorities.

PreSTo could…
- Promote whole atmosphere model development & improvement
- Coordinate efforts targeting atmospheric small scale waves and their impact on circulation

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