The role of the polar vortex in Sun-Earth coupling via the descent of EPP-produced NO_x

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Outline

- The winter Polar Vortex
- The mean meridional circulation
- Sudden Stratospheric Warmings “precondition” the IT
- Top-Down coupling – descent of EPP-NO_x in the vortex
  - Recent progress in modeling
  - EPP-induced vortex strengthening, surface impacts, climate.

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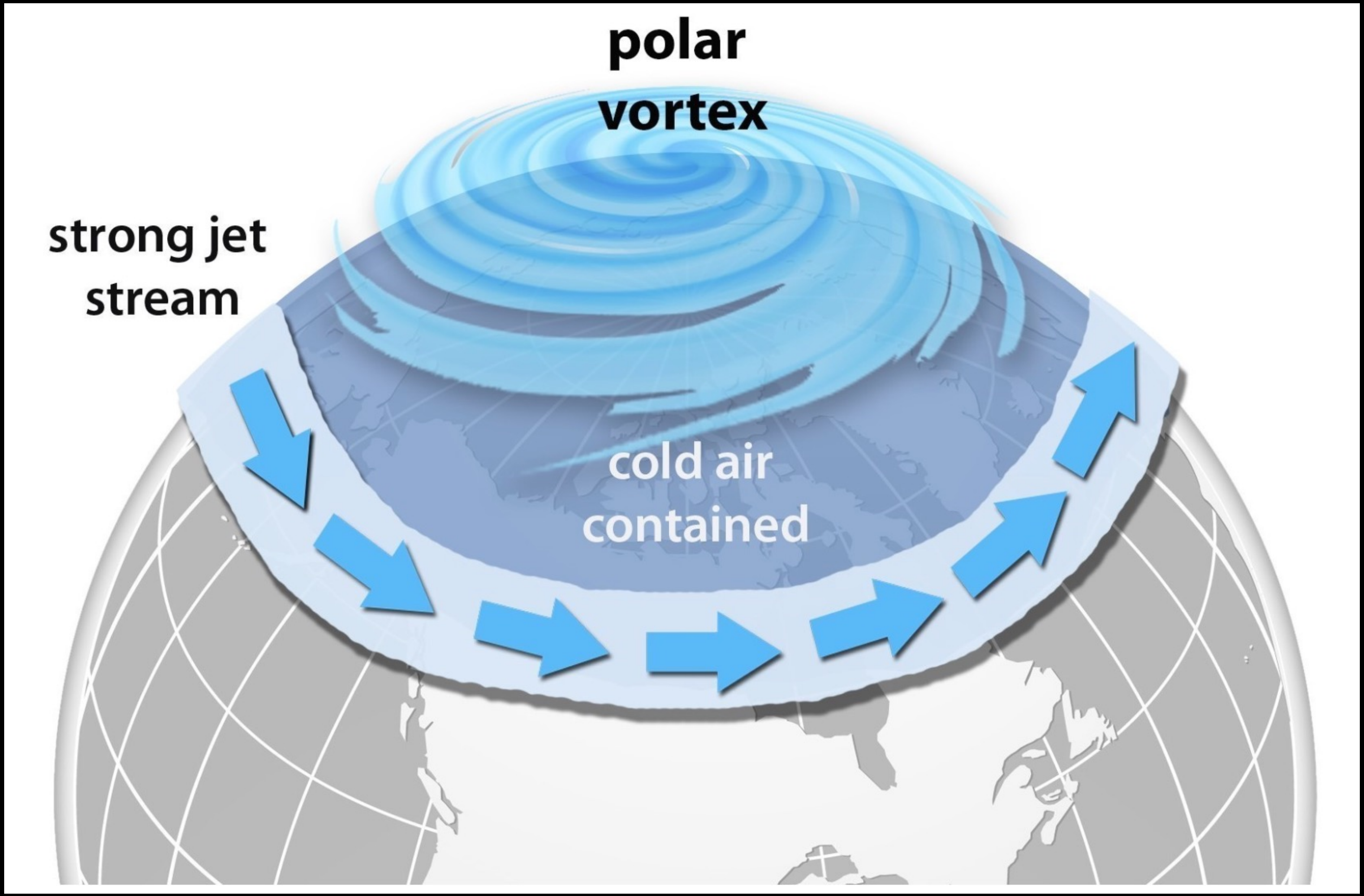
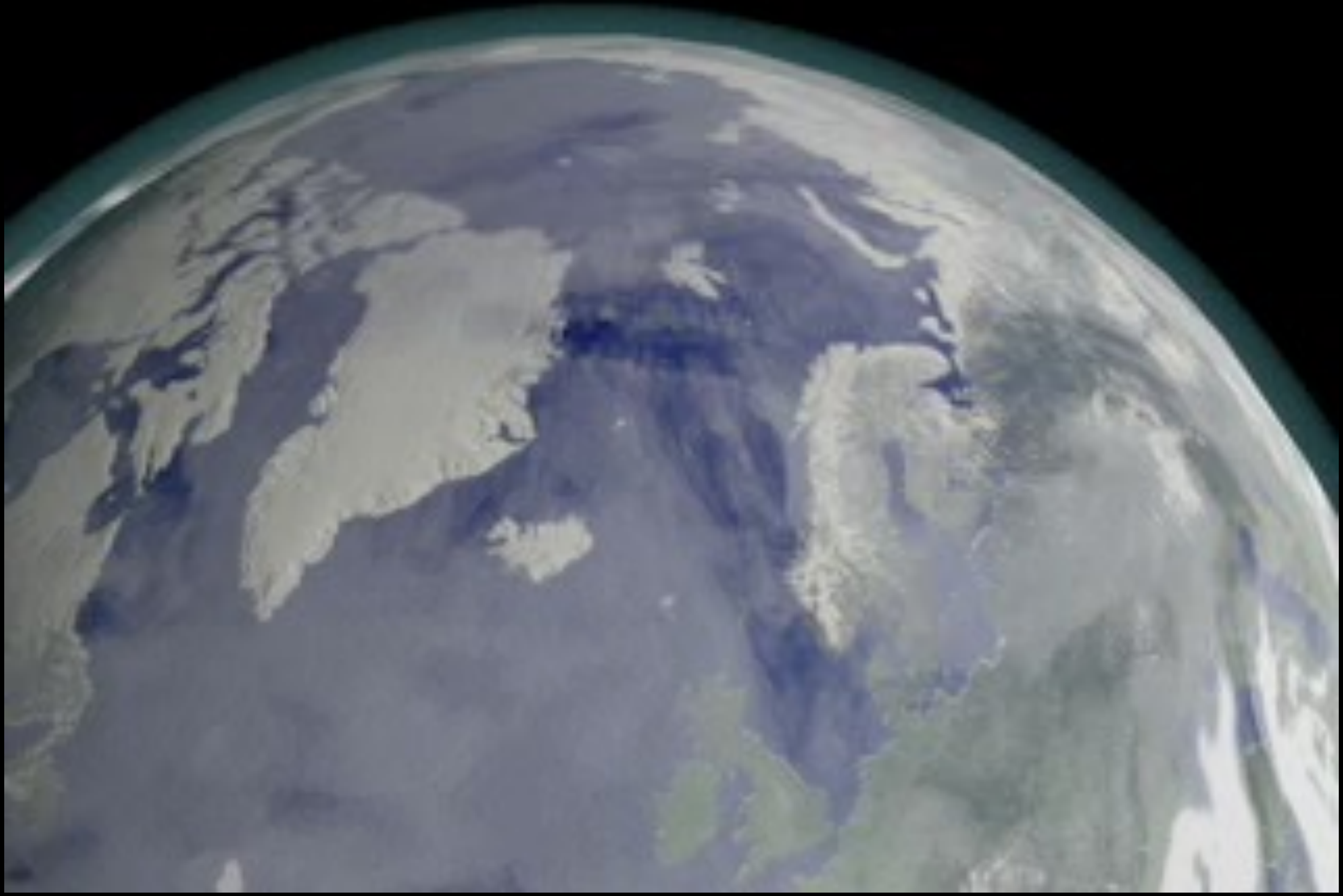
The winter polar vortex



https://www.rmets.org/metmatters/polar-vortex-ssw

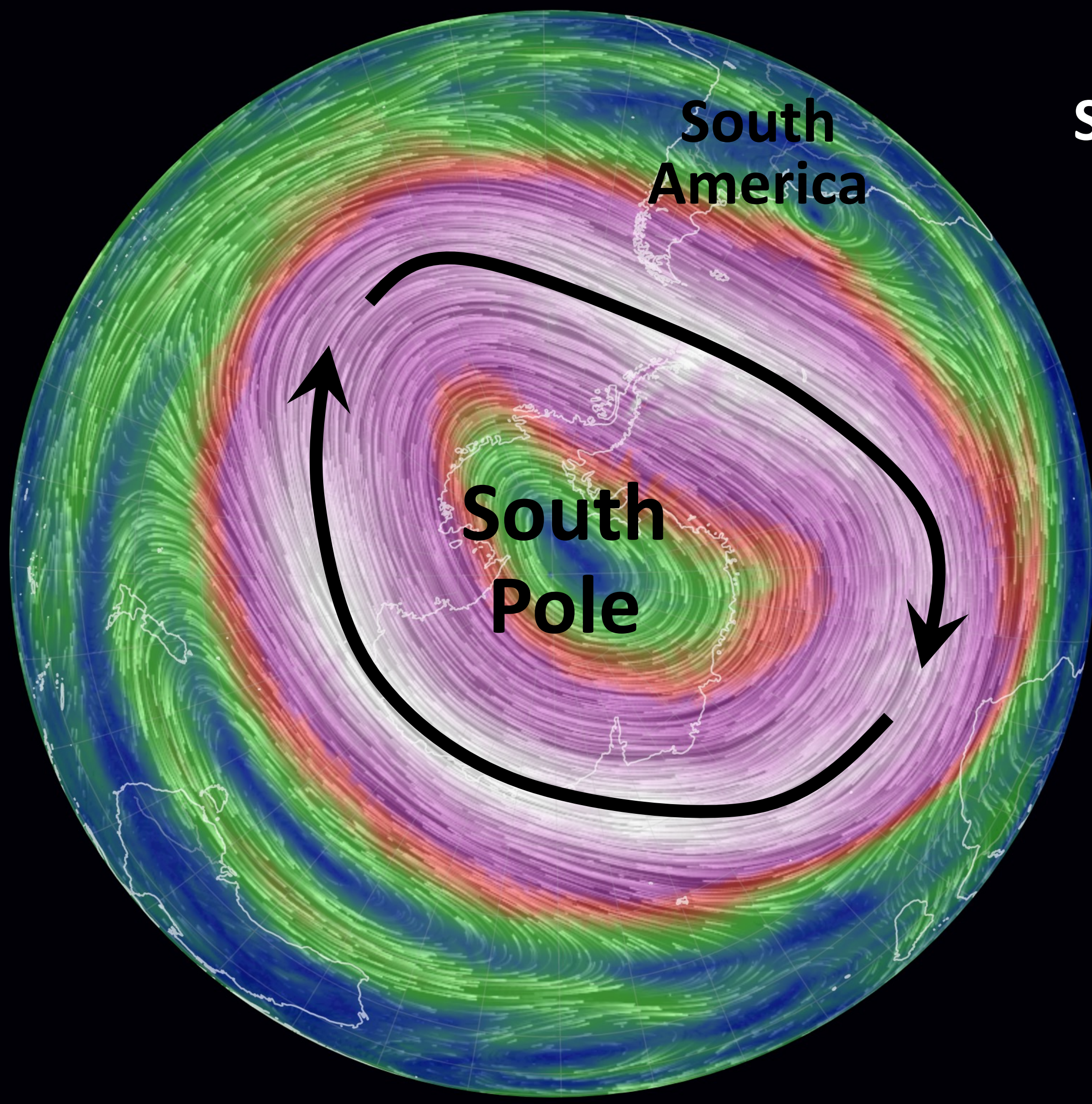
- During winter in the dark polar night there is UV to for O_3 to absorb
- This results in a very cold polar stratosphere
- A west-to-east jet stream encircles the cold air

The Arctic polar vortex wobbles about the pole from day to day due to weather below



What does the polar vortex look like today?

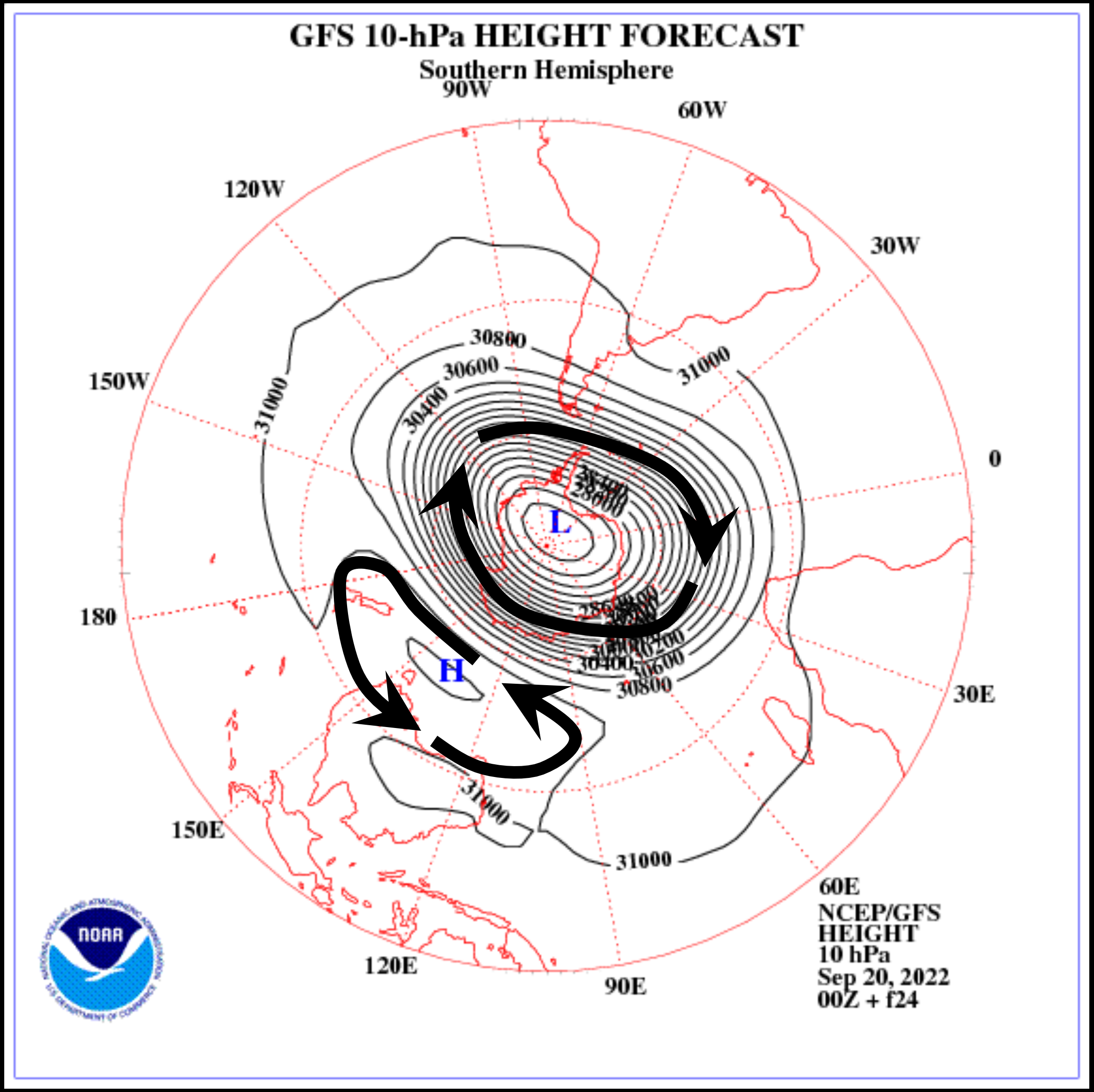
The Antarctic Polar Vortex



Sept 20 2022
~30 km

http://earth.nullschool.net

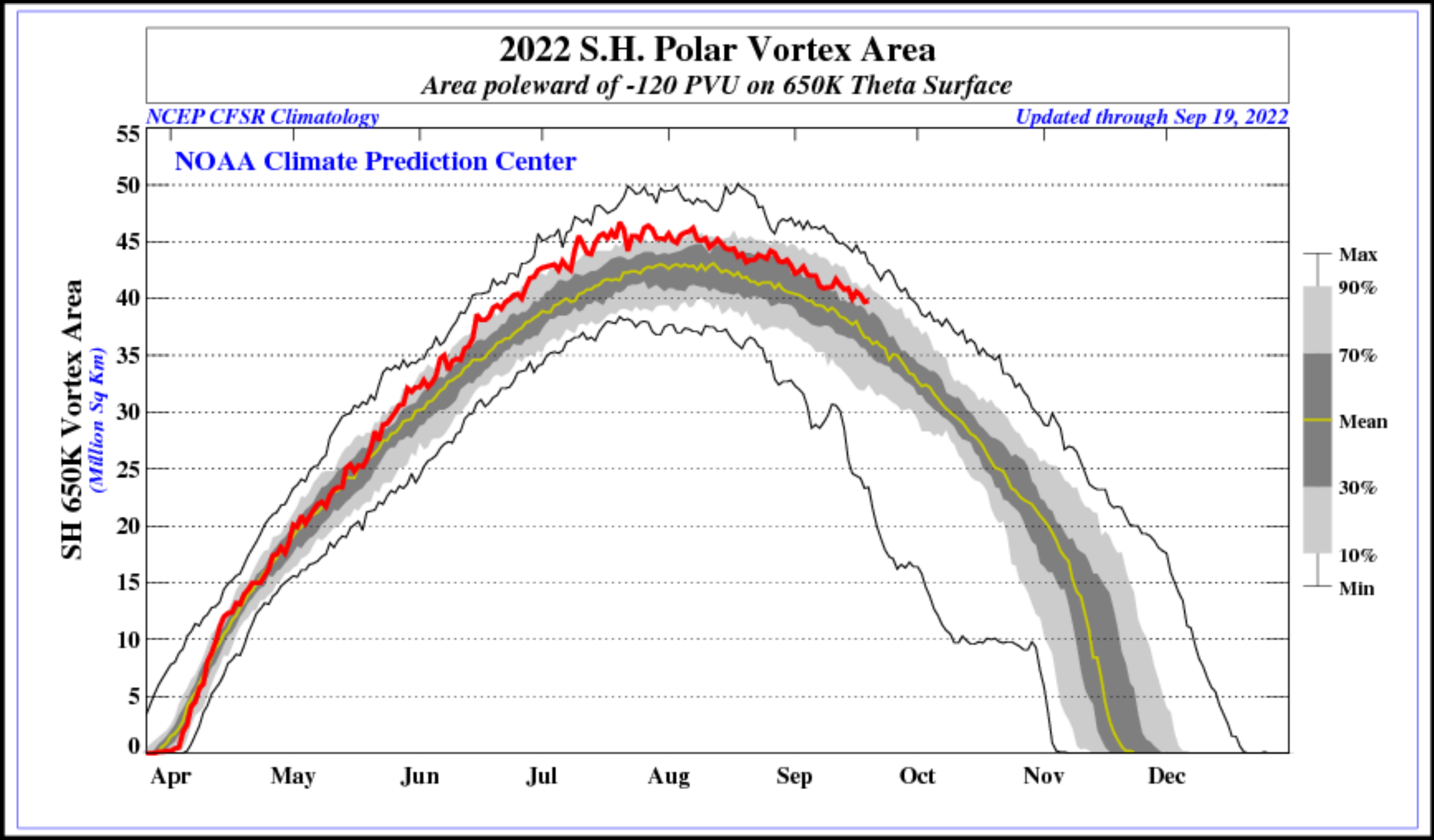
The Antarctic Polar Vortex today, and next week



Sep 21 2022
~30 km

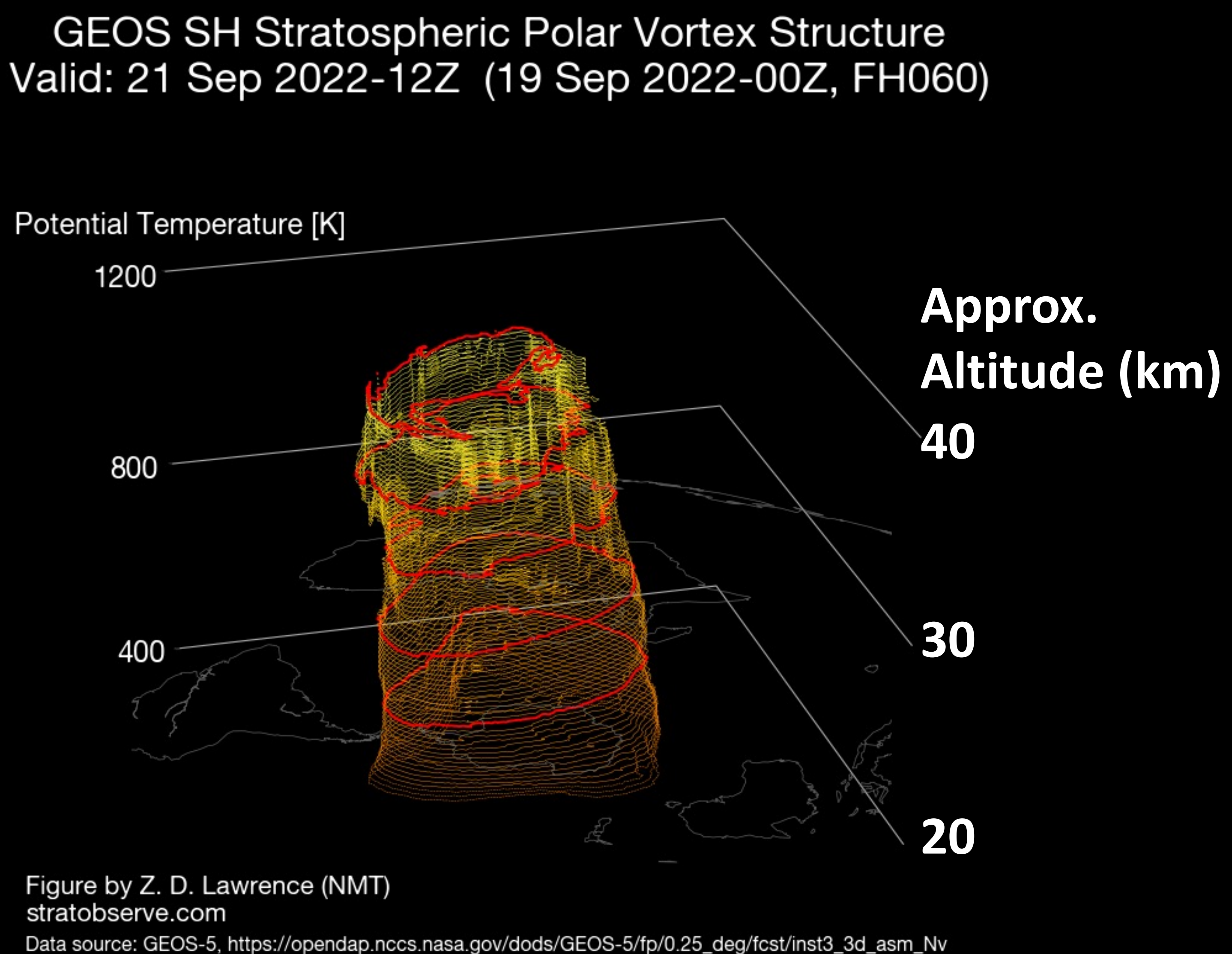
The Climate Prediction Center forecasts out to 16 days
http://www.cpc.ncep.noaa.gov/products/stratosphere/strat_a_f/

The Antarctic Polar Vortex Area this year ~25 km



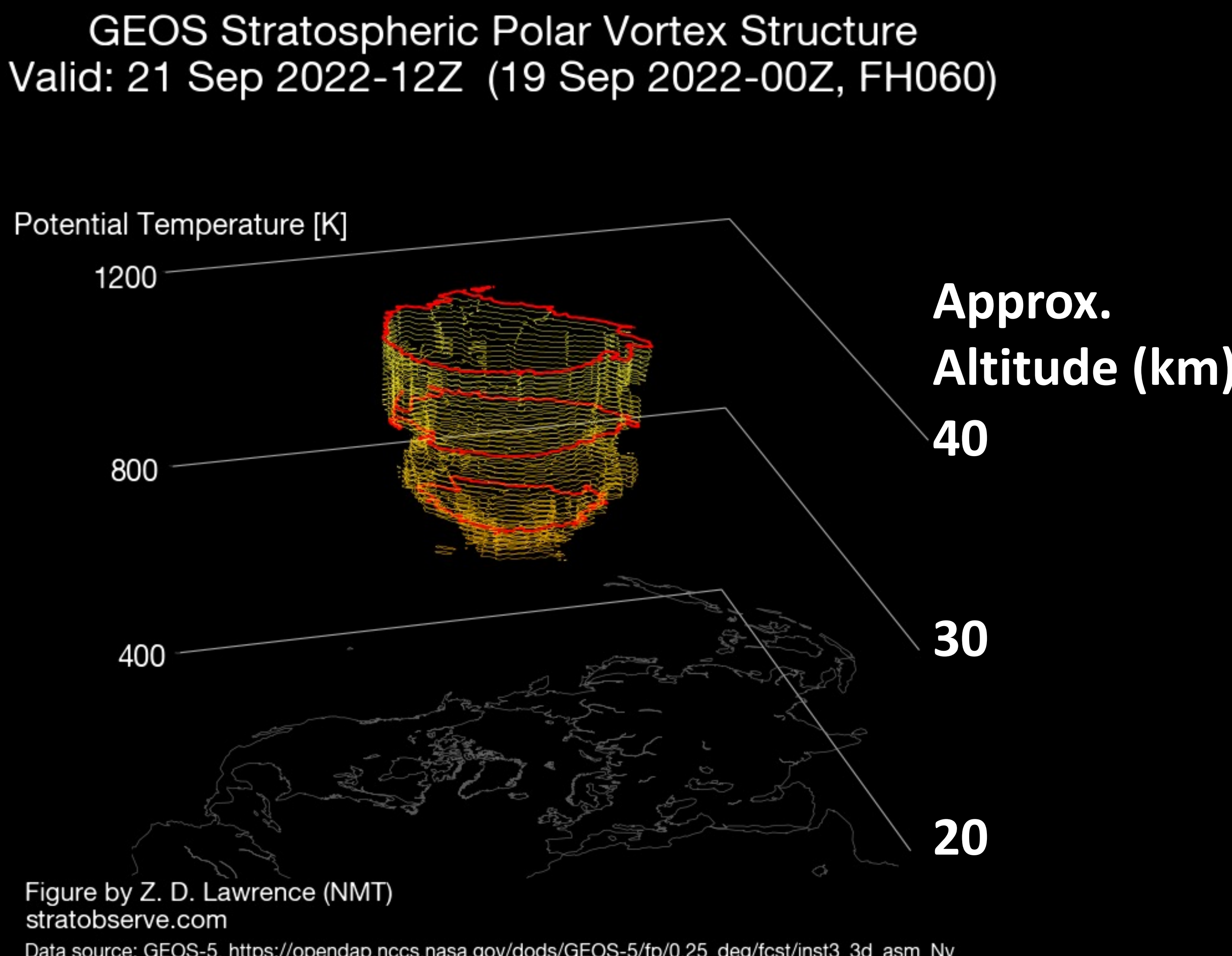
The Climate Prediction Center seasonal evolution and multi-year climatology
https://www.cpc.ncep.noaa.gov/products/stratosphere/

The Antarctic Polar Vortex today, in 3-dimensions



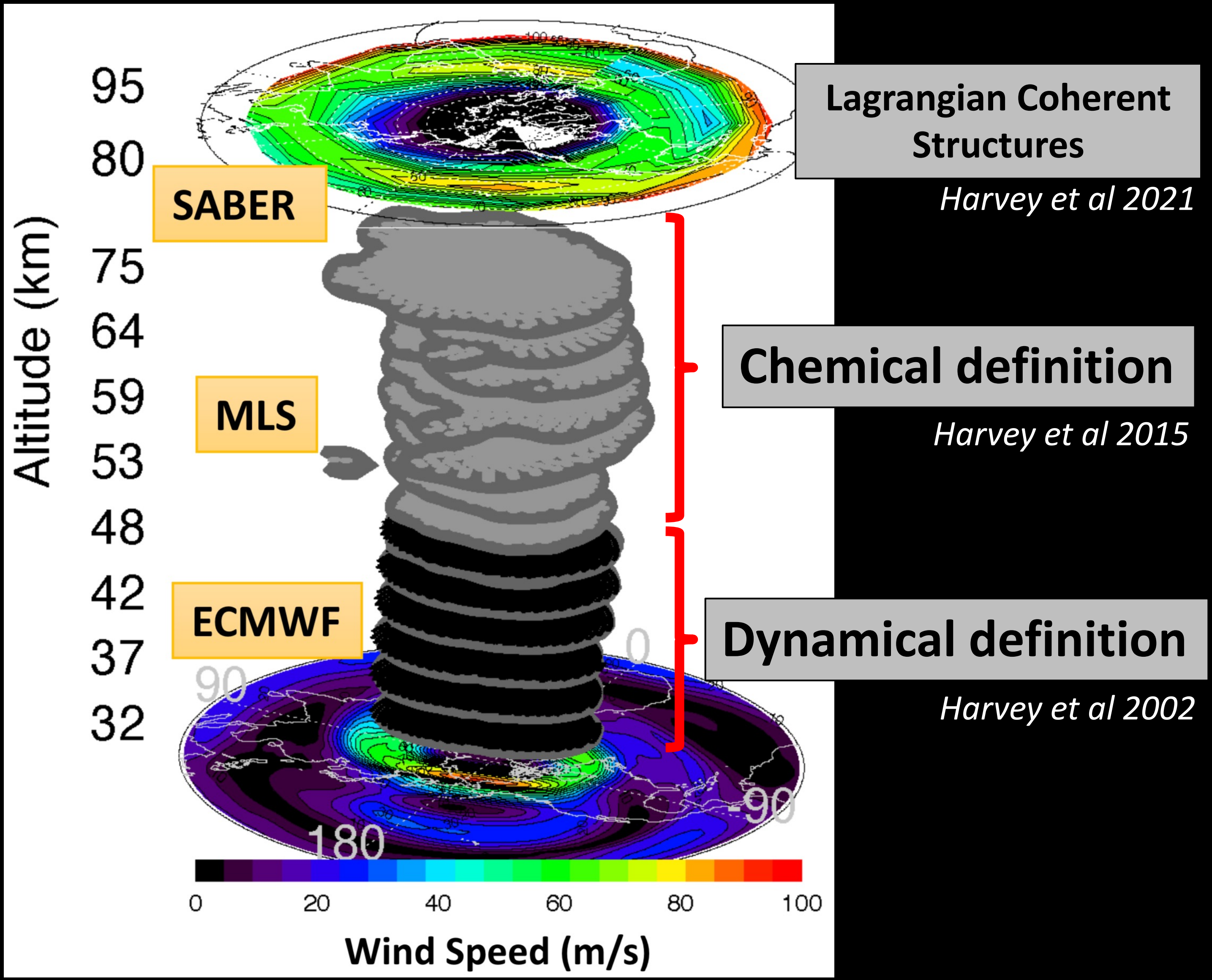
Zak Lawrence - https://stratobserve.com/misc_vort3d

The Arctic Polar Vortex is still forming



Zak Lawrence - https://stratobserve.com/misc_vort3d

Defining the polar vortex from the tropopause to the mesopause



Would your research benefit from knowledge of the vortex?

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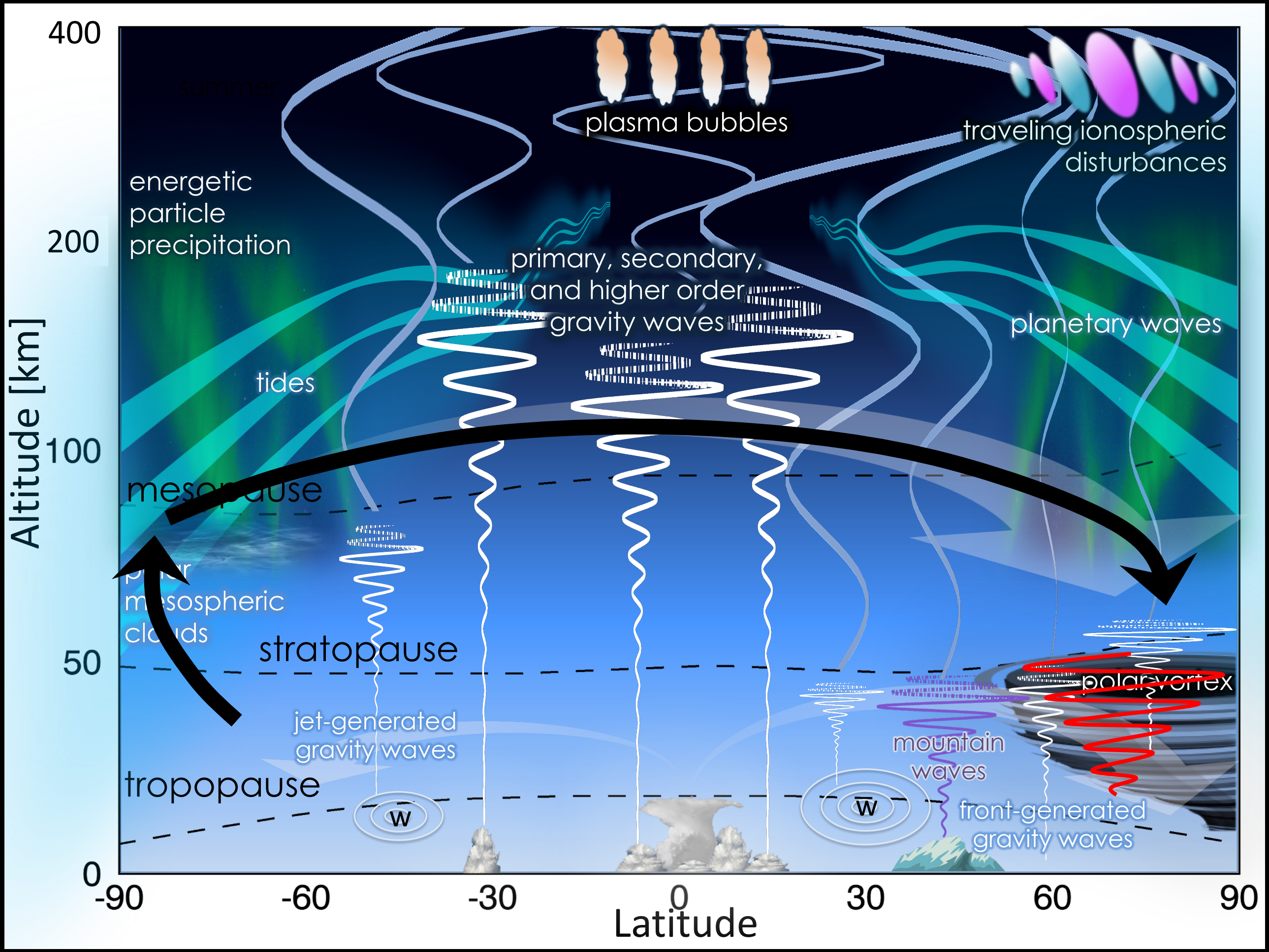
Mean meridional circulation, polar vortex, waves, and connections to the IT



Top-down

Bottom-Up

Courtesy of Laura Holt

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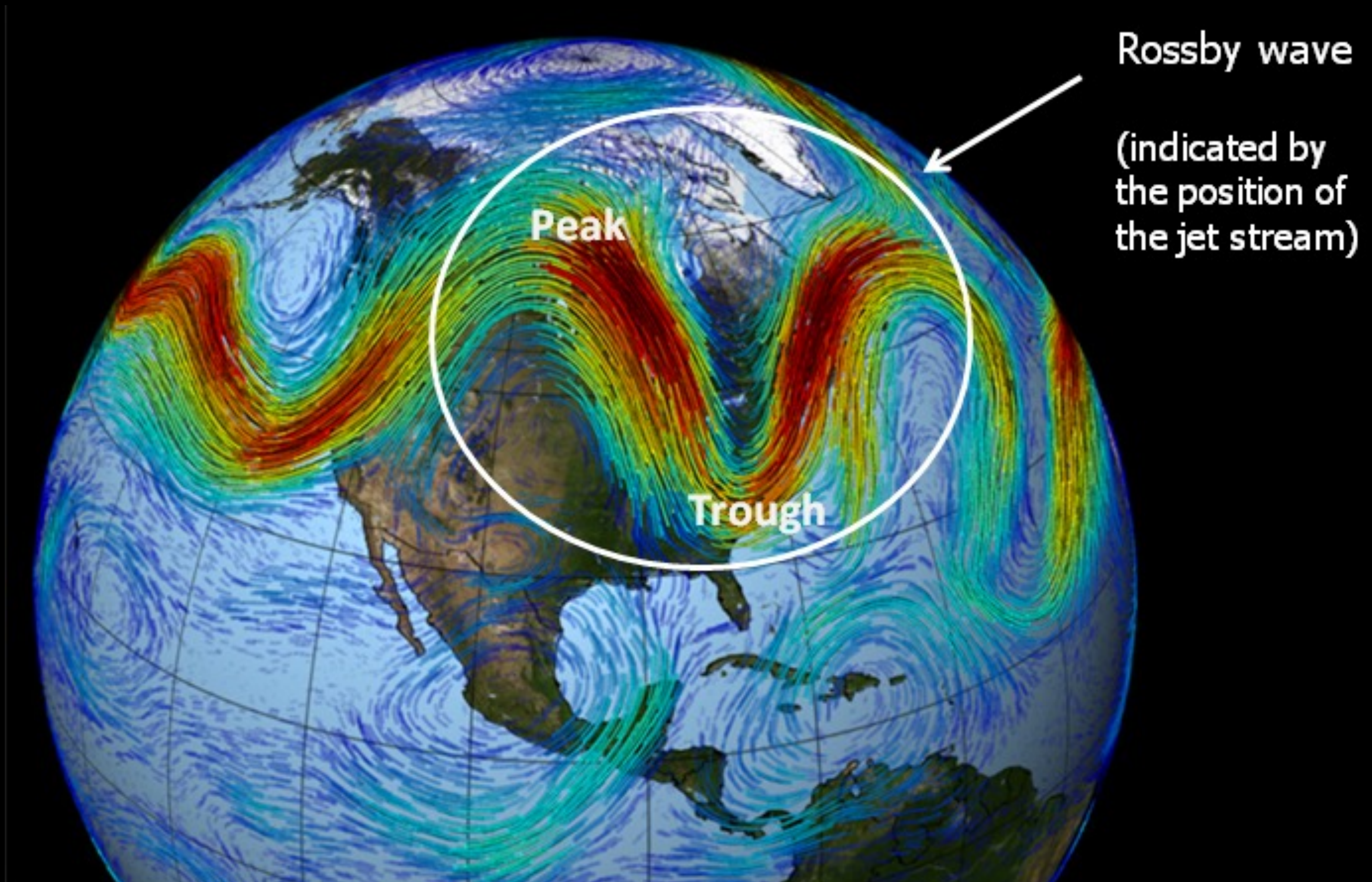
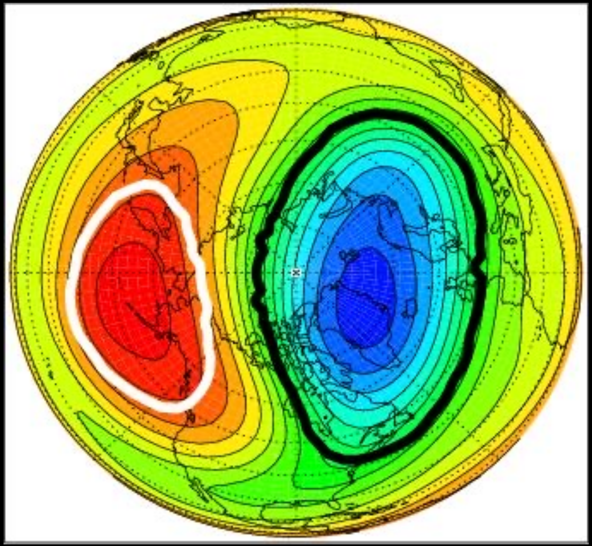
Planetary waves form in the upper tropospheric jet stream due to weather systems below



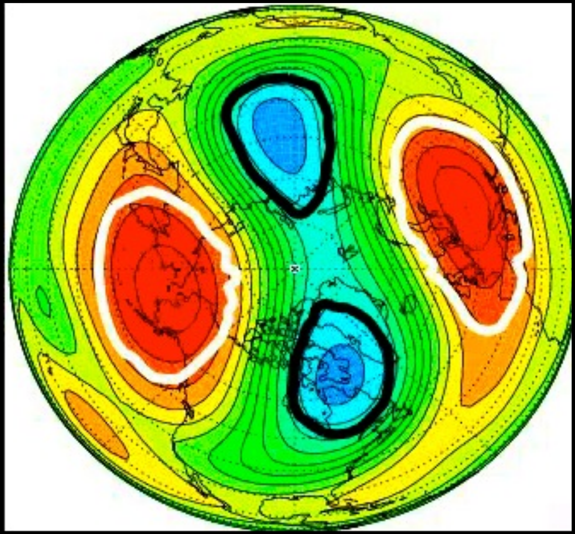
They propagate upward and amplify and "disturb" the polar vortex

Sudden Stratospheric Warmings (SSWs) are large disruptions to the polar vortex

- (1) Vortex *displaced* from pole
  - a.k.a. “Minor”, “Wave 1”
  - <u>One anticyclone</u>

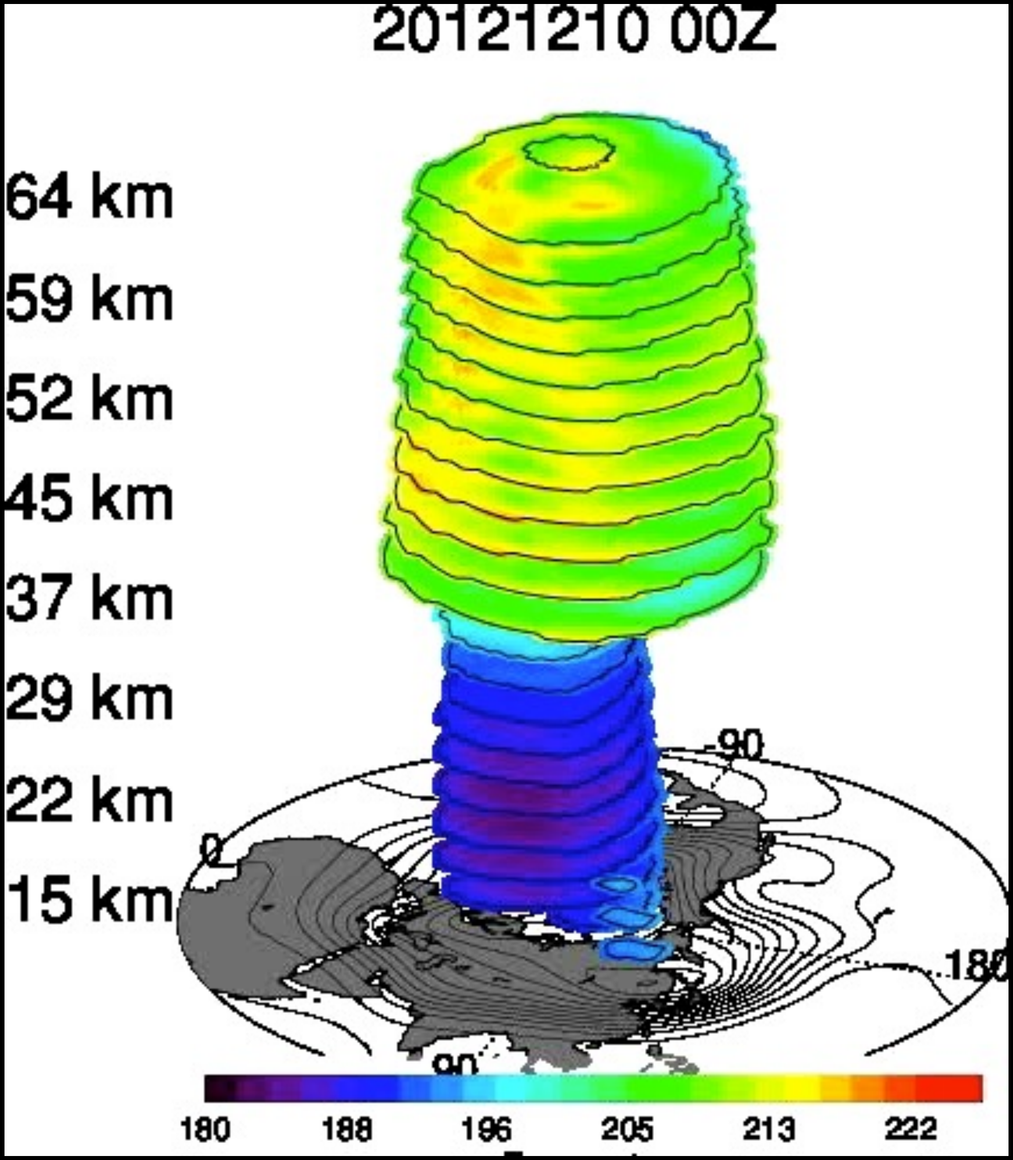


- (2) Vortex *split*
  - a.k.a. “Major”, “Wave 2”
  - <u>Two anticyclones</u>



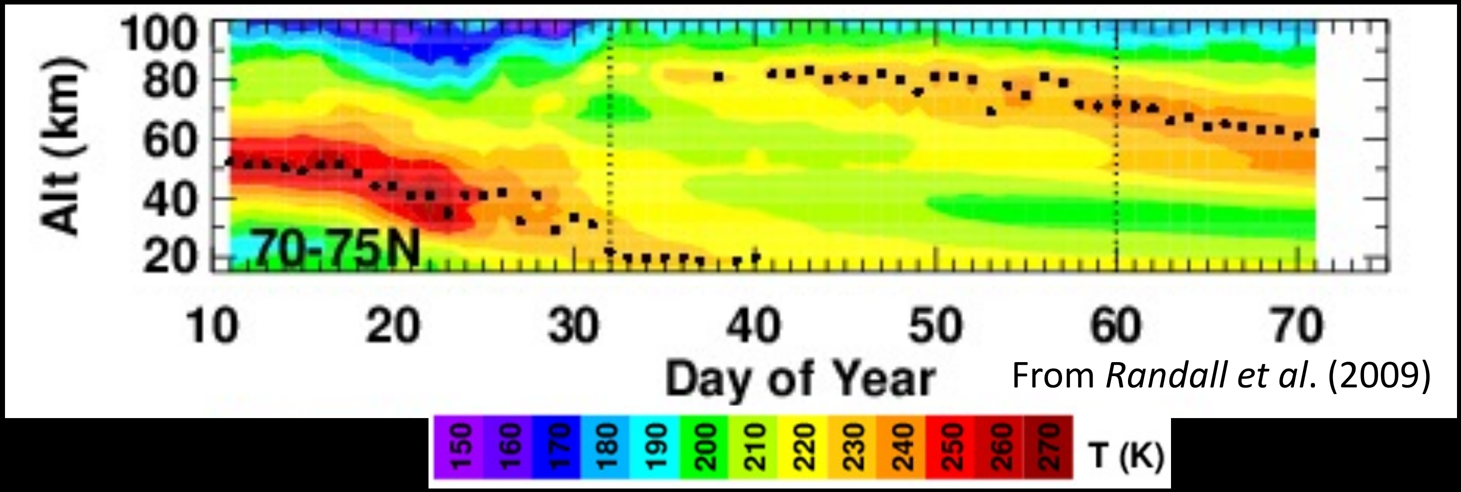
The **Arctic vortex is weaker** and more variable than in the Antarctic due to land-ocean contrasts.

Polar vortex split in January 2013



Example of an Elevated Stratopause (ES) event

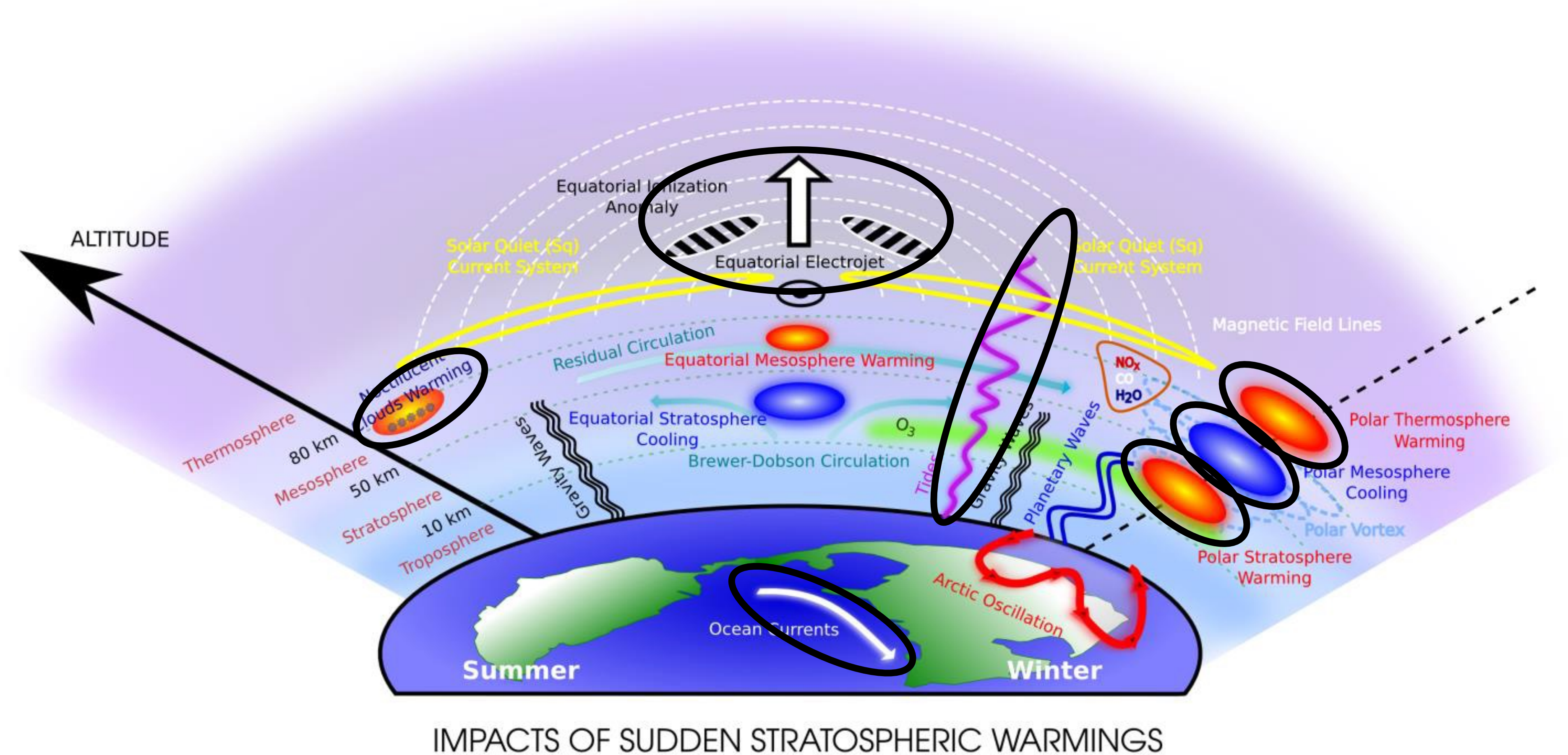
SABER temperature in 2009



From *Randall et al*. (2009)

- PWs reverse the winds and filter GWs
- ES due to adiabatic warming in “mesosphere”
- Indicates enhanced descent, driven by gravity waves
- Downward transport of NOx follows these events

Effects of SSWs are observed throughout the ocean-atmosphere-ionosphere system



Pedatella et al. (2018) EoS

SSWs precondition the atmosphere to respond differently to EPP

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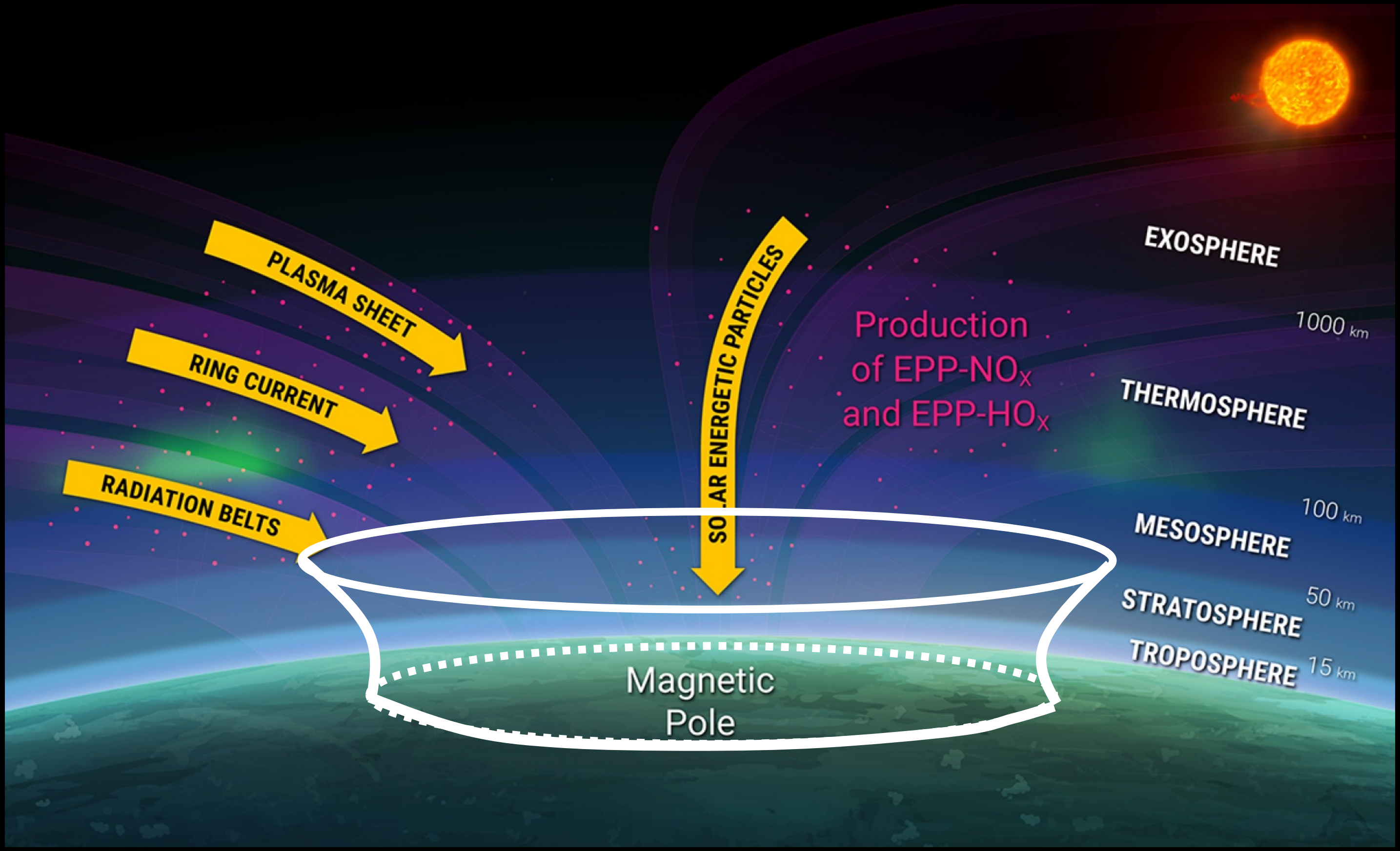
Precipitating energetic electrons and solar protons produce HO_x and NO_x, which destroy ozone catalytically



Courtesy of Dan Baker & Allison Jaynes, CU Boulder/LASP

- **Descent in the vortex transports the EPP-NOx downward**

EPP INDIRECT EFFECT (EPP-IE)

Randall et al. (2006)

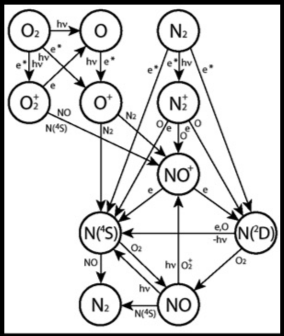
- NO_x formed in MLT via EPP

↓↓↓

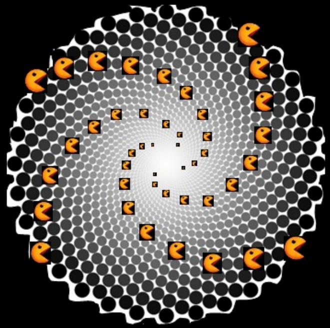
- Descends in polar vortex during winter

↓↓↓

- Ozone destroyed (~22-40 km)

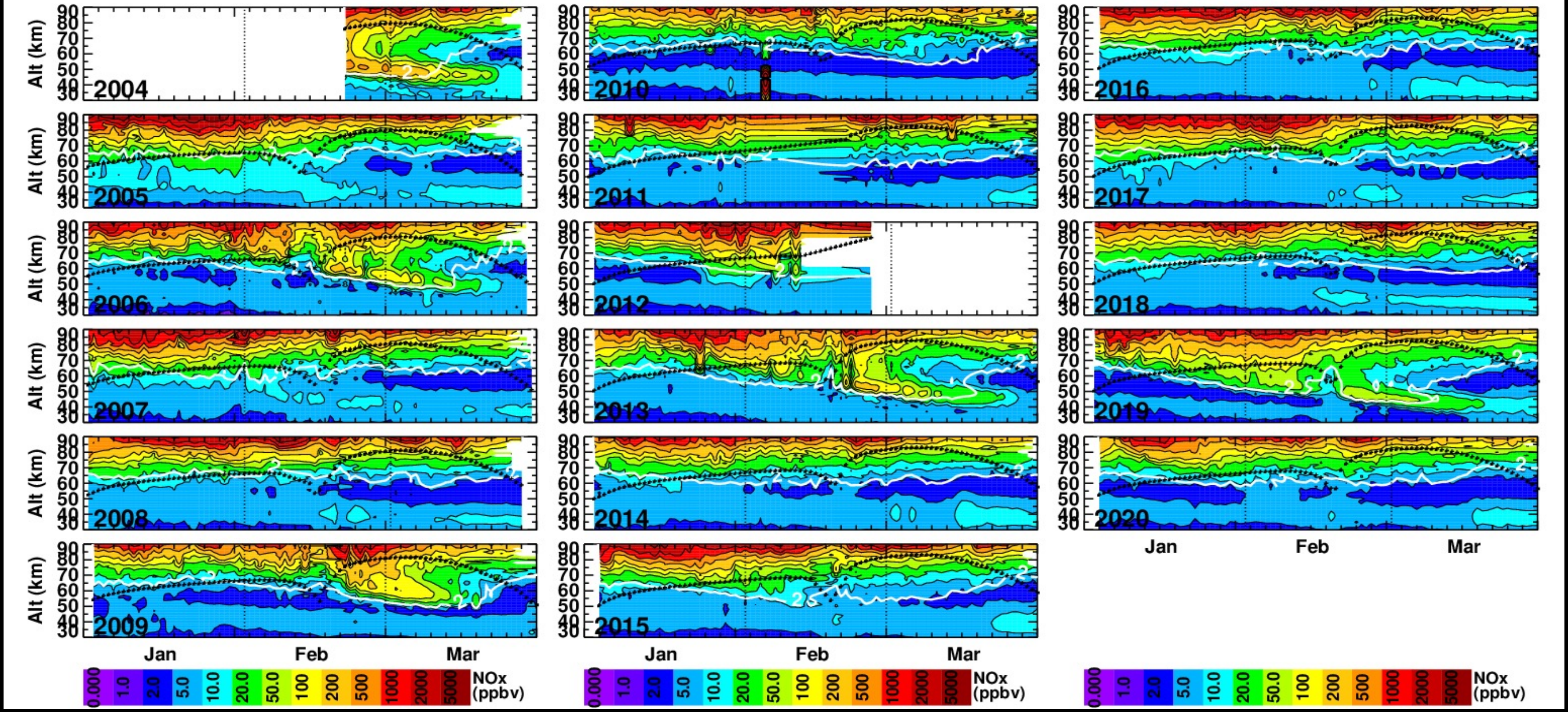


Courtesy of Charles Barth

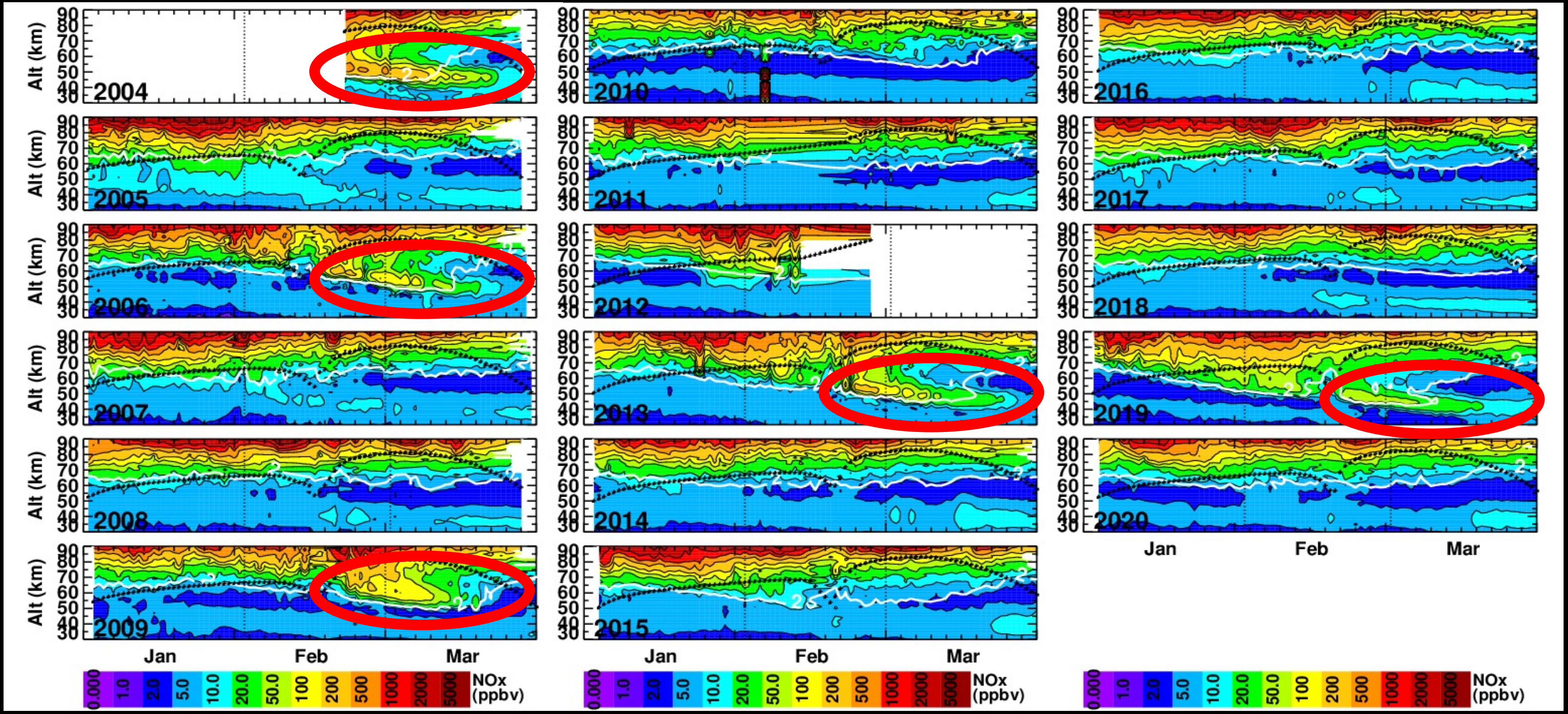


Courtesy of Cora Randall

ACE-FTS shows significant variability of EPP-IE in NH



Years with largest EPP IE: Sudden Stratospheric Warming (SSW) followed by Elevated Stratopause (ES)



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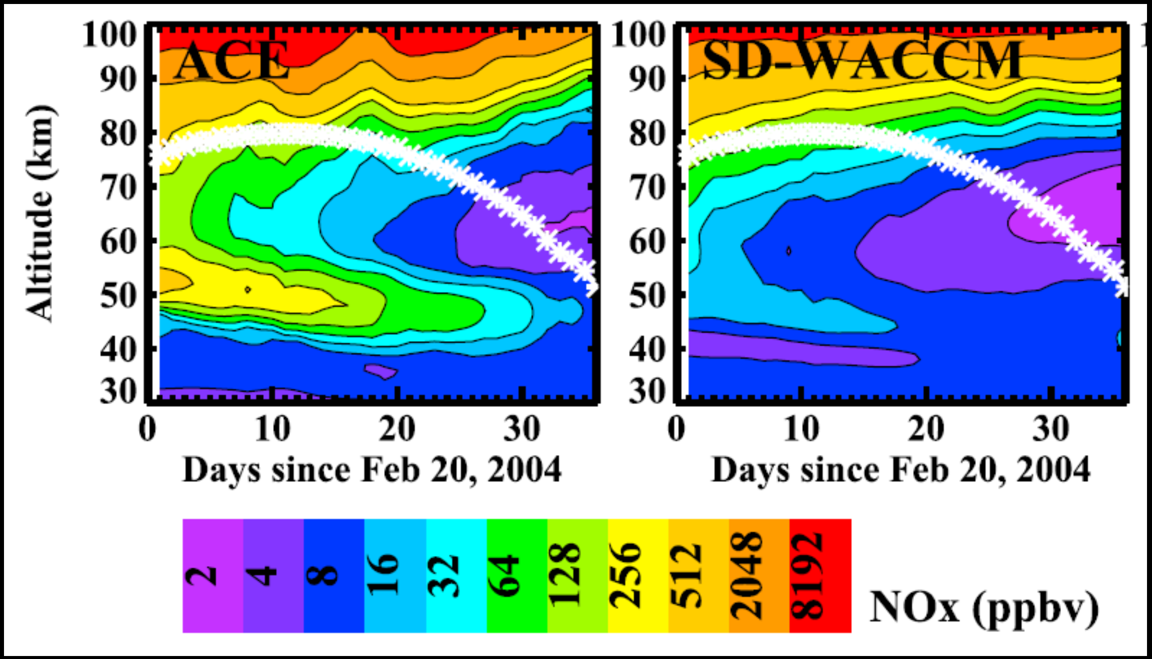
Randall et al. (JGR 2015): SD-WACCM underestimates EPP-IE in NH 2004

- Included auroral EPP + SPEs
- Specified dynamics only in troposphere & stratosphere

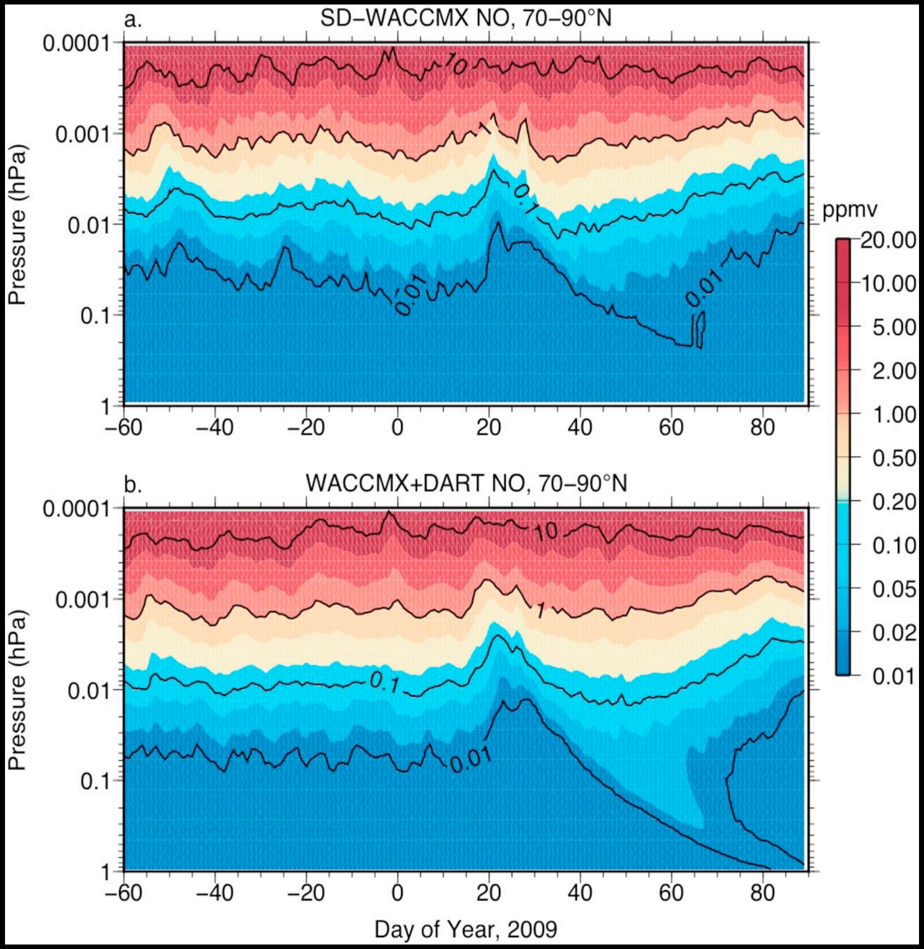
Model-measurement disagreements attributed to:

- Errors in transport during dynamically active winter
- Missing higher energy EPP during geomagnetically active winter



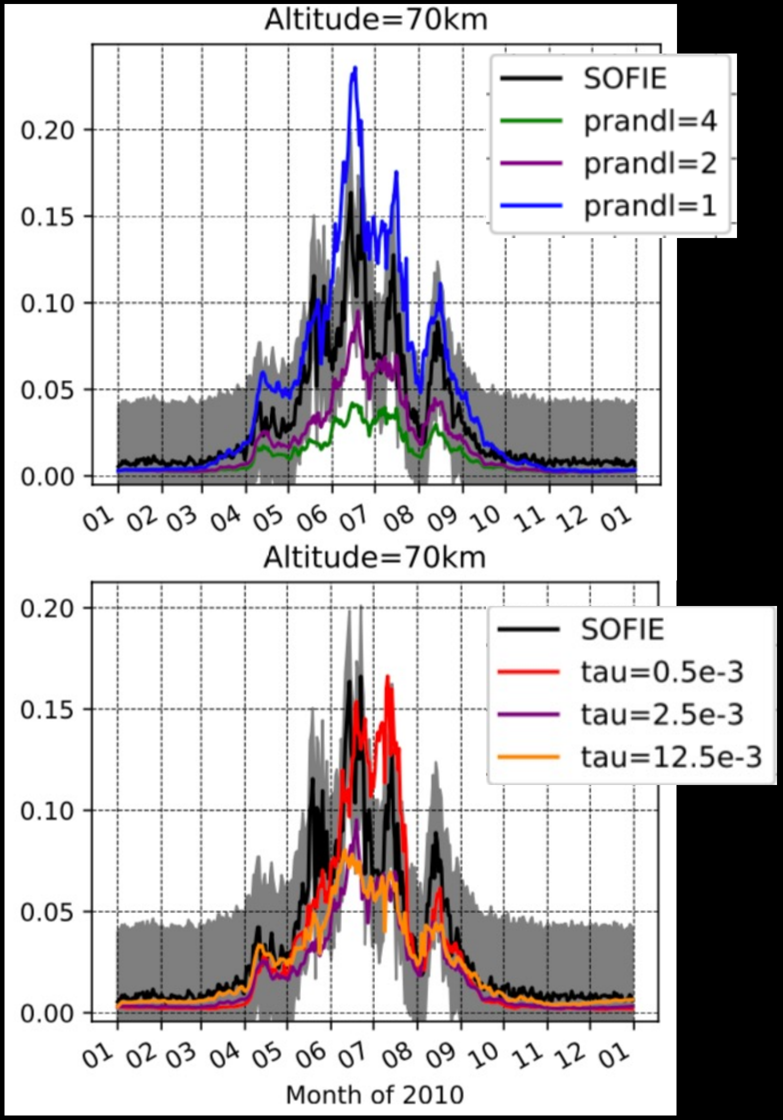
Pedatella et al. (JGR, 2018) simulated NH 2009 winter with WACCMX+DART

- WACCMX + Data Assimilation Research Testbed (DART)
- Assimilates SABER and MLS temperatures; constrains meteorology up to ~95-100 km
- Simulates more descent of EPP-NOx, but still underestimates observed NOx
  - No MEE
  - Idealized auroral electron precipitation pattern with constant 2 keV characteristic energy
  - Chemical reaction rate errors



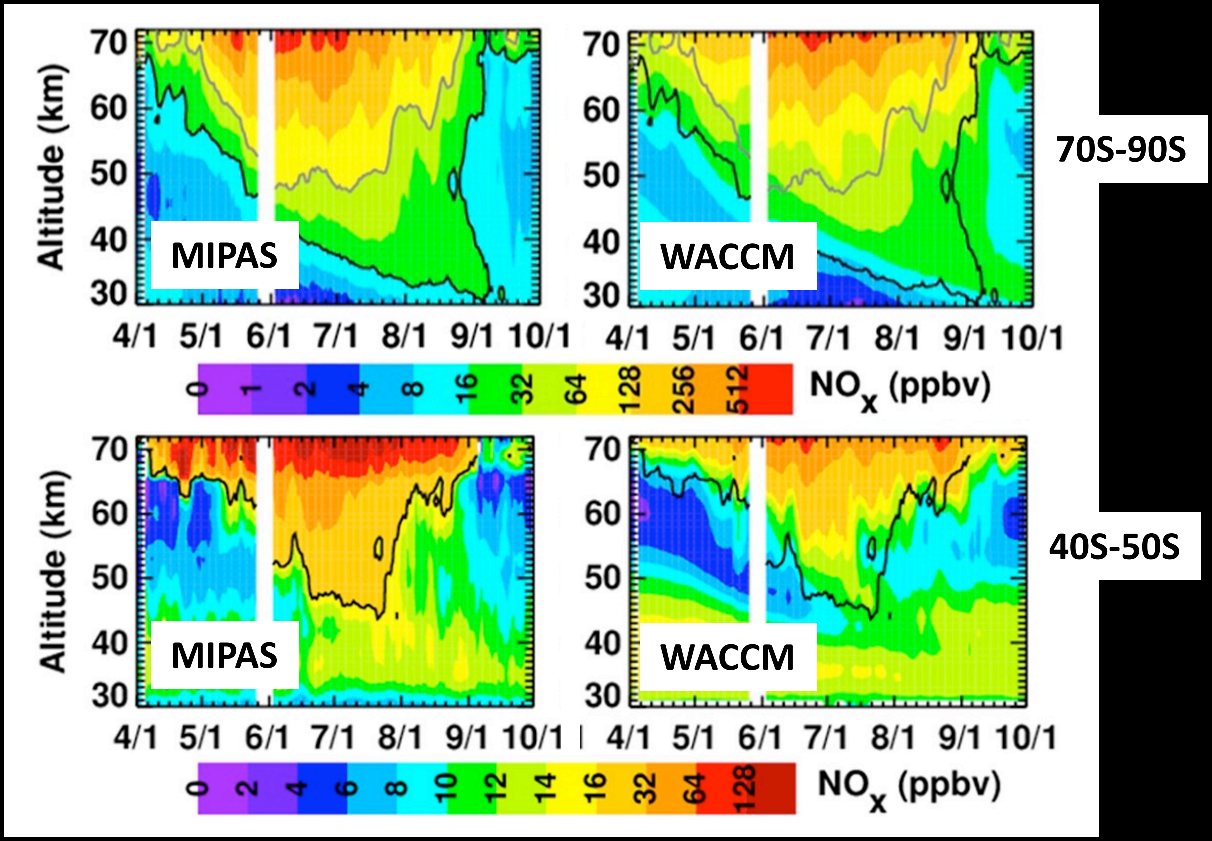
Smith-Johnsen et al. (JGR 2022): Improved dynamics lead to improved EPP-IE in SD-WACCM

- SH 2010
- SOFIE NO in black
- Increased the eddy diffusion (blue line)
- Decreased the amplitude of non-orographic GWs (red line)
- Leads to improved agreement with observations in winter NO_x descent.



Pettit et al. (JGR 2021): MEE fluxes included in SD-WACCM improves simulation of SH 2003 winter

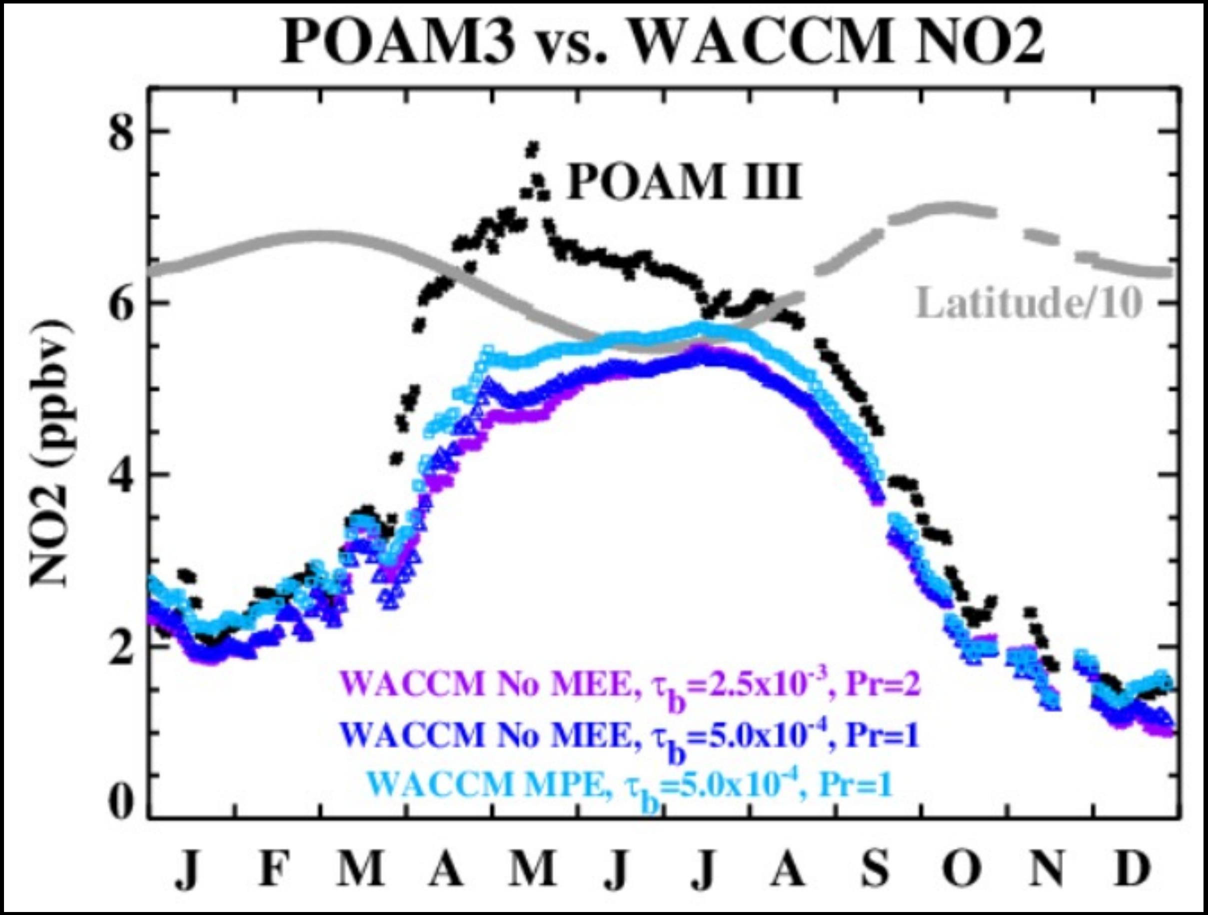
- SH is more dynamically stable than NH
- 2003: Moderately high geomagnetic activity
- WACCM NOx is similar to MIPAS qualitatively
- Significant EPP-NO_x descent even at mid-latitudes
- But descending NOx is underestimated, especially 40S-50S.



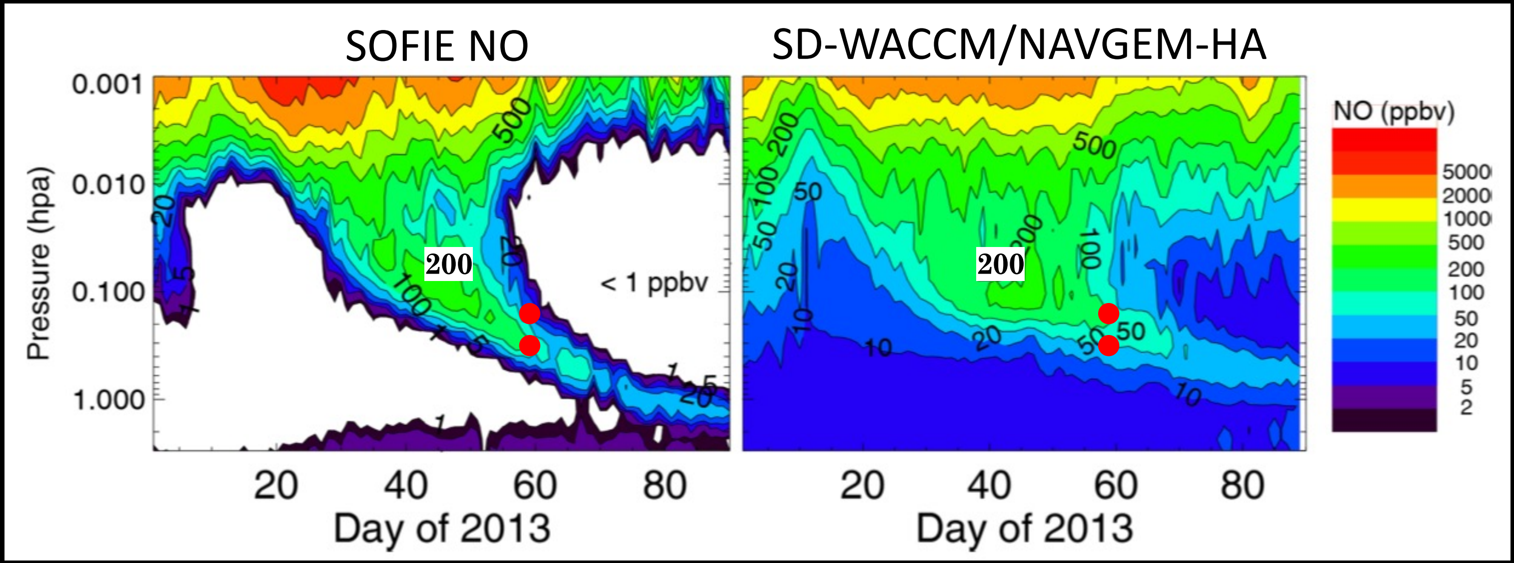
Need to include both enhanced dynamics and MEE in WACCM

Randall et al. (in prep): MEE fluxes AND improved dynamics still results in EPP-IE underestimates

- SH 2003
- Purple: No MEE, standard dynamics.
- Dark Blue: No MEE, enhanced dynamics
- Light Blue: MEE and enhanced dynamics
- Next step: add secondary GWs and associated rapid mixing



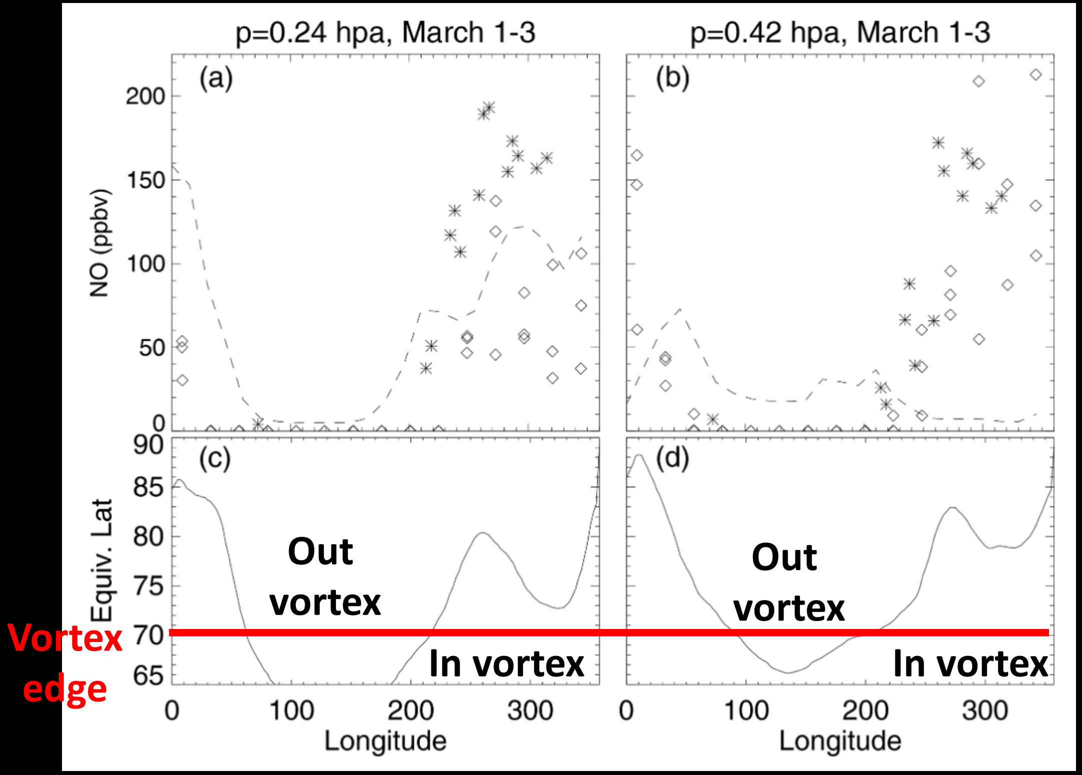
Siskind et al. (ACP 2021): SD-WACCMX/NAVGEM-HA zonal mean NO matches SOFIE in ES year 2013



- NAVGEM-HA assimilates MLS and SABER temperature, so dynamics constrained in mesosphere – improves simulation of zonal average EPP-IE
- Only need auroral energy electrons to simulate mesospheric NOx in geomagnetically quiescent periods
- However, model-measurement differences in 3D morphology in mesosphere suggest gravity wave deficiencies lead to errors in transport
- Let's look more closely at 1-3 March

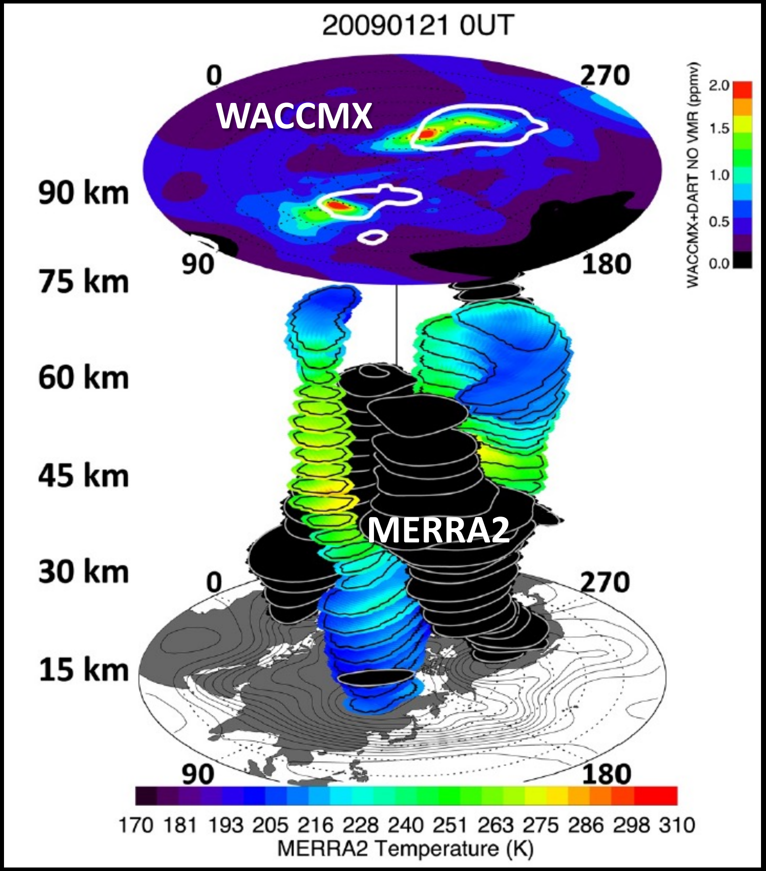
Siskind et al. (ACP 2021): SD-WACCMX/NAVGEM-HA zonal asymmetry out of phase with obs

- Longitude structure of NO in WACCM matches obs at 0.24 hPa but not at 0.42 hPa.
- SOFIE sampled inside and outside the vortex on this day
- Need to look at descent in 3-dimensions.



Harvey et al., JGR 2021: EPP-NOx exhibits zonally asymmetric descent into the top of the polar vortex following the 2009 SSW

- WACCMX + DART
- Lagrangian coherent structures (transport barriers) near 90 km confined EPP-NOx to the polar region
- 5x stronger descent at planetary wave trough longitudes, mostly driven by large-scale vertical advection
- EPP effects must be studied in 3D



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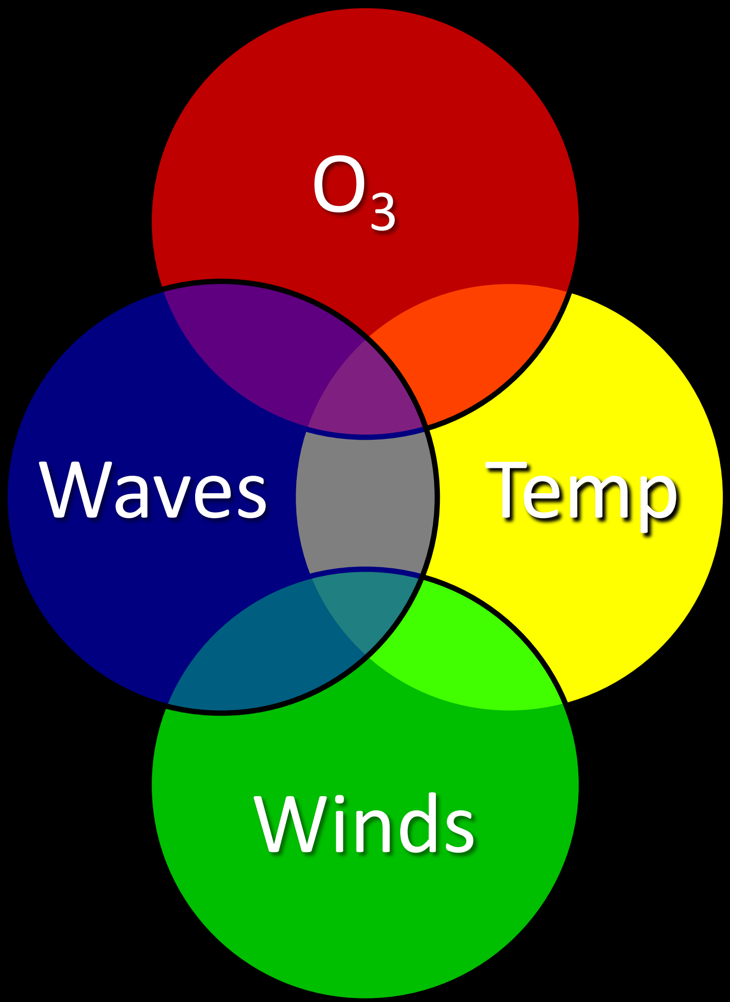
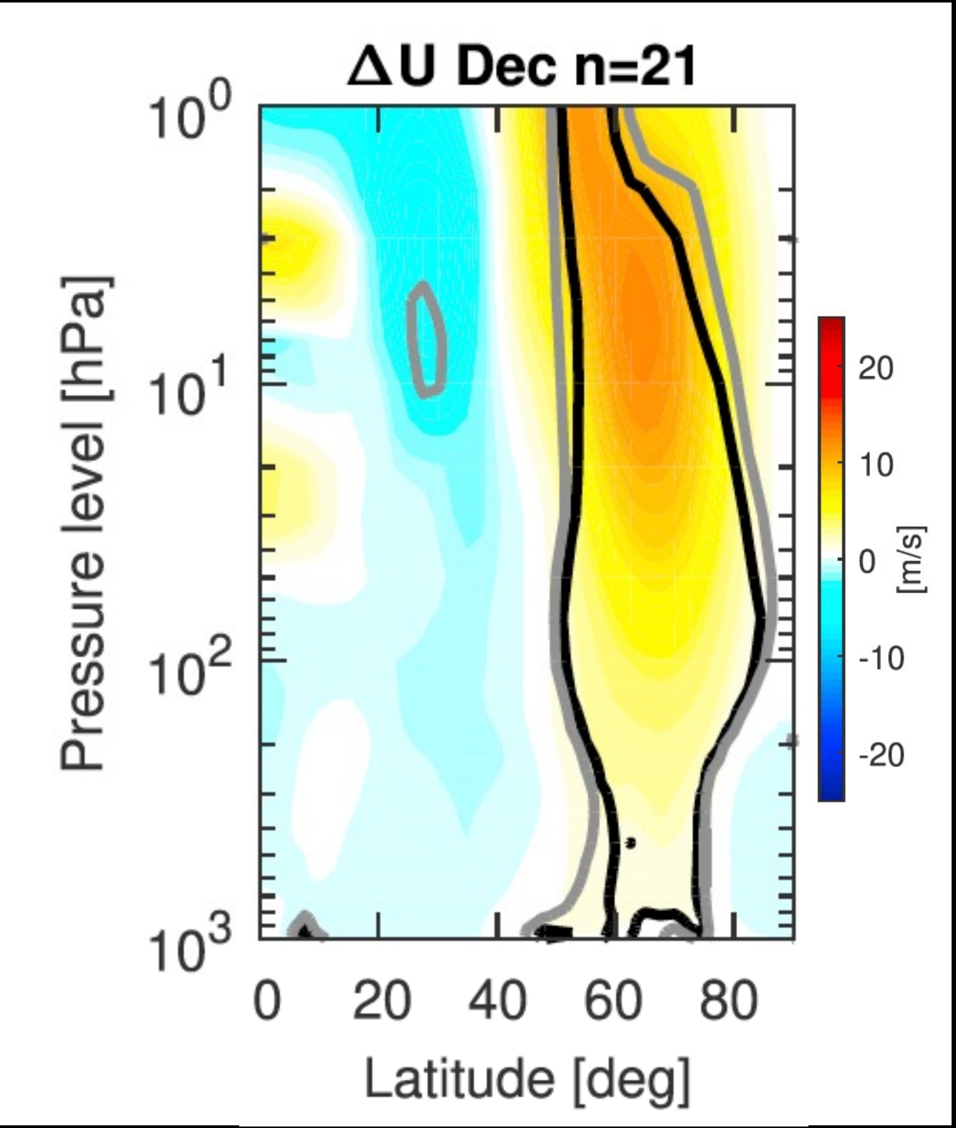
Changes in polar ozone can trigger a redistribution of solar and magnetospheric energy at Earth, coupling the upper and lower atmosphere



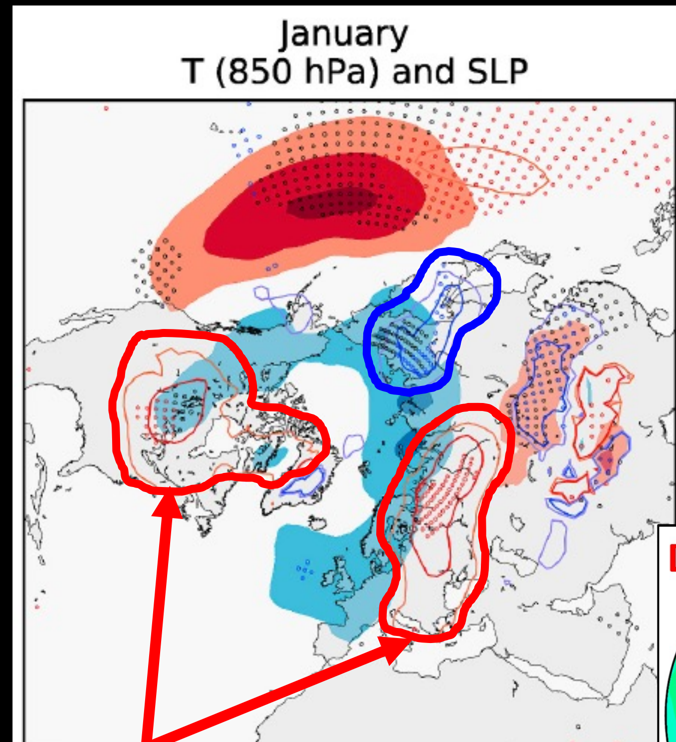
Salminen et al., JGR 2019: EEP strengthens the polar vortex; modulated by QBO

- ERA Interim reanalysis data, 1980-2016
- EEP-induced O_3 loss causes cooling in lower stratosphere
- Regression analysis: Stronger westerlies Dec-Mar with higher EPP (POES)
- **Stronger EEP signal when QBO-E during previous summer**



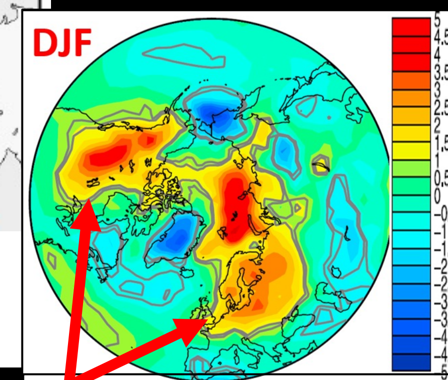
Guttu et al., JASTP 2020: MEE strengthening of NH polar vortex leads to surface effects

- 20 ensembles of WACCM MEE vs. no MEE, 1997-2007
- Mechanism: MEE-NOx-induced catalytic O_3 loss advected to mid latitudes->reduced zonal asymmetry in O_3 shortwave heating
- Planetary wave activity decreases: Stronger vortex
- Downward propagation of PW changes via wave-mean flow interactions projects onto the northern annular mode
- Warmer lower troposphere over N. America and Europe



Lower limit on MEE impact (CMIP6 MEE)

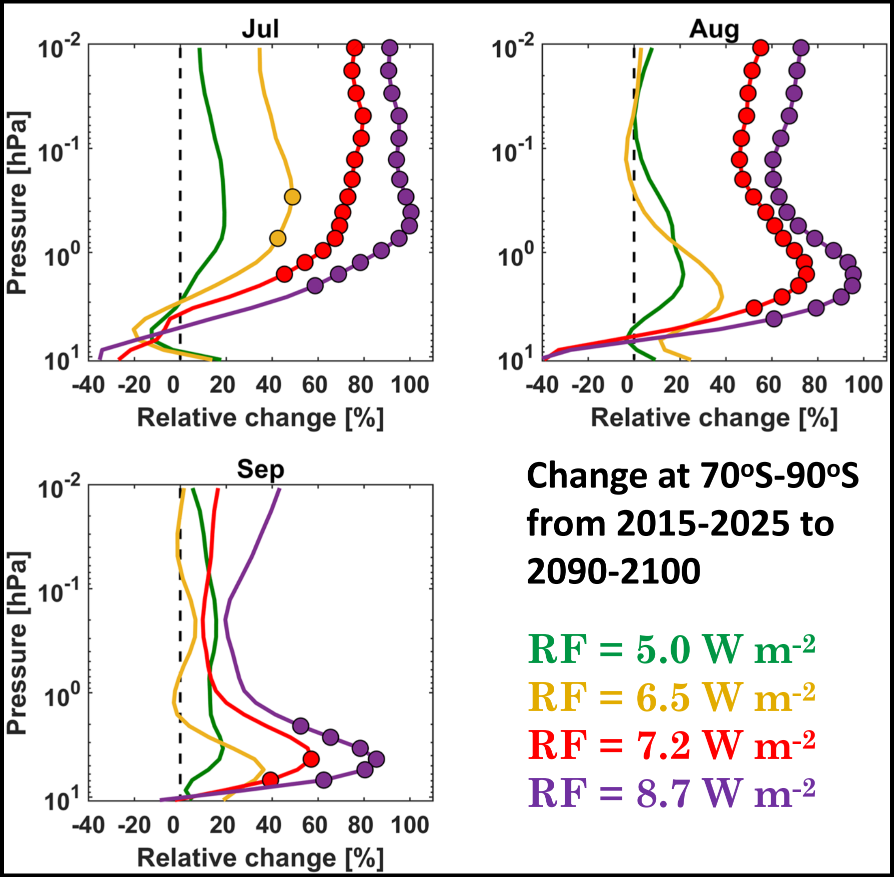
Pattern of modeled surface air temperature response to MEE is consistent with earlier reports of EPP effects from reanalysis data.



Seppälä et al., 2009

Maliniemi et al., GRL 2020 (and ACP 2021): Future increases in radiative forcing will result in more descent of EPP-NOx

- WACCM simulations with various CMIP6 scenarios for future radiative forcing
- Mean meridional circulation predicted to increase
- Descent in winter polar region accelerates, bringing down more EPP-NOx
- EPP-NOx will become more important to SH ozone as chlorine loading diminishes and meridional circulation increases



Summary

- The winter polar vortex is a fast jet stream in the stratosphere and mesosphere encircling a region with confined descent.
- Planetary wave disturbances to the vortex drive variability in the whole atmosphere-ionosphere system.
- Top-down coupling – It is well accepted that EPP impacts the middle atmosphere through both the Direct and Indirect Effects.
- Models generally capture EPP effects, but underestimates them
  - Enhanced model dynamics and adding MEE still results in NO_2 underestimates at 40 km.
- EPP likely strengthens the vortex, esp. when QBO-E
- EPP likely strengthens the vortex, esp. prior to SSWs
- EPP may impact surface meteorology via EPP-induced vortex strengthening, but complex mechanism and unclear statistical significance.
- The EPP-IE may increase with a warming climate.

Thank You!

***Hendrickx et al.*, ACP 2018:** Too little NO_x descent attributed to errors in D-region chemistry, no MEE, and/or too high altitude of auroral production

***Seppälä et al.*, GRL 2018:** Relativistic electron microbursts should be considered in models of EEP effects.

***Smith-Johnsen et al.*, JGR 2018:** Models should include the full energy spectrum and D region chemistry.

***Mironova et al.*, GRL 2019:** EEP ionization rates calculated from Bremsstrahlung x-rays measured via balloon in 1961-2006 (suggests CMIP6 rates are too low).

***Marshall et al.*, Adv. Space Res. 2020:** AEPEX (Atmospheric Effects of Precipitation through Energetic X-rays) cubesat mission to measure EEP via detection of Bremsstrahlung x-rays; launch in 2022.

***Perot and Orsolini,* JASTP 2021:** Demonstrate value of Odin/SMR – the only currently operational instrument capable of measuring NO globally – showing large EPP-IE after 2019 SSW and ES.

***Duderstadt et al.*, JGR 2021:** Demonstrate use of van Allen Probes MagEIS data to estimate EEP.

***Tartaglione et al.*, Ann Geophys. 2020:** Analysis of Japanese 55-year Reanalysis (JRA-55) including consideration of spatial and temporal autocorrelations suggests that there is no statistically significant response of NH seasonal mean stratospheric temperatures to geomagnetic activity.

***Verronen et al.*, Ann. Geophys. 2021:** EEP during pulsating aurorae (PsA) leads to EPP-IE and up to 8% ozone loss in wintertime upper stratosphere – PsA should be included in models.