Overview of Large-Scale Transport into the Arctic in the Chemistry Climate Model Initiative (CCMI) Simulations

Clara Orbe (NASA GISS), Darryn W. Waugh (Johns Hopkins University), Huang Yang (Johns Hopkins University) and CCMI modelers

Motivation

- The transport of trace gases and aerosols is a major uncertainty in the modeling of Arctic tropospheric composition (e.g. *Shindell et al. (2008), Monks et al. (2015)*).

- There is a poor understanding of the drivers of transport biases in models, specifically as they relate to biases in the large-scale flow versus subgrid-scale processes.

- Looking to the future, few studies have examined how large-scale transport into the Arctic may change in a warmer climate (e.g. *Orbe et al. (2015), Doherty et al. (2017)*).

Motivation

The Chemistry Climate Modeling Initiative (CCMI) Phase 1 experiments (*Eyring et al. (2013)*) provide a unique opportunity to examine the relationship between Arctic transport and large-scale dynamics because they provide:

- Unprecedented number of tropospheric transport (i.e. tracer-independent (*Holzer and Hall (2000)*) diagnostics, including a range of idealized loss and age tracers (*Waugh et al. (2013), Orbe et al. (2016, 2017)*).
- Large number of models submitting both ``specified-dynamics" and "free-running simulations" using the same underlying model code.
- Much more dynamical output, relative to previous atmospheric composition intercomparisons (e.g., TRANSCOM, ACCMIP).

Here we focus mainly on the CCMI multi-model results discussed in:

Orbe, Clara, Huang Yang, Darryn W. Waugh, Guang Zeng, Olaf Morgenstern, Douglas E. Kinnison, Jean-Francois Lamarque et al. "Large-scale tropospheric transport in the Chemistry–Climate Model Initiative (CCMI) simulations." *Atmospheric Chemistry and Physics* 18, no. 10 (2018): 7217-7235.

Yang, Huang, Darryn W. Waugh, Clara Orbe, Guang Zeng, Olaf Morgenstern, Douglas E. Kinnison, Jean-Francois Lamarque et al. "Large-scale transport into the Arctic: the roles of the midlatitude jet and the Hadley Cell." *Atmospheric Chemistry and Physics* 19, no. 8 (2019): 5511-5528.

Orbe, Clara, David A. Plummer, Darryn W. Waugh, Huang Yang, Patrick Jöckel, Douglas E. Kinnison, Béatrice Josse et al. "Description and Evaluation of the specified-dynamics experiment in the Chemistry-Climate Model Initiative." *Atmospheric Chemistry and Physics* 20, no. 6 (2020): 3809-3840.

At the same time, we also provide supporting results from other single model and multi-model studies that afford a more detailed look into processes:

Orbe, Clara, Paul A. Newman, Darryn W. Waugh, Mark Holzer, Luke D. Oman, Feng Li, and Lorenzo M. Polvani. "Air-mass origin in the Arctic. Part II: Response to increases in greenhouse gases." *Journal of Climate* 28, no. 23 (2015): 9105-9120.

Doherty, Ruth M., Clara Orbe, Guang Zeng, David A. Plummer, Michael J. Prather, Oliver Wild, Meiyun Lin, Drew T. Shindell, and Ian A. Mackenzie. "Multi-model impacts of climate change on pollution transport from global emission source regions." *Atmospheric Chemistry and Physics* 17, no. 23 (2017): 14219-14237.

Orbe, Clara, David Rind, Jeffrey Jonas, Larissa Nazarenko, Greg Faluvegi, Lee T. Murray, Drew T. Shindell et al. "GISS Model E2. 2: A Climate Model Optimized for the Middle Atmosphere. Part 2: Validation of Large-Scale Transport and Evaluation of Climate Response." *Journal of Geophysical Research: Atmospheres*: e2020JD033151.

First, we focus on the CCMI hindcast simulations of the recent past, performed both in "specified-dynamics" (REF-C1SD) and free-running (REF-C1) modes in order to address two key questions:

#1 What is the spread in transport to the Arctic among CCMs and how is this related to differences in large-scale dynamics and/or (parameterized) convection?

#2 How does the representation of transport into the Arctic compare between specified-dynamics (SD) and free-running (FR) simulations?

Then we analyze results from the CCMI future (REF-C2) simulations in order to examine:

#1 What is the spread in transport to the Arctic among CCMs and how is this related to differences in large-scale dynamics and/or (parameterized) convection?

#2 How does the representation of transport into the Arctic compare between specified-dynamics (SD) and free-running (FR) simulations?

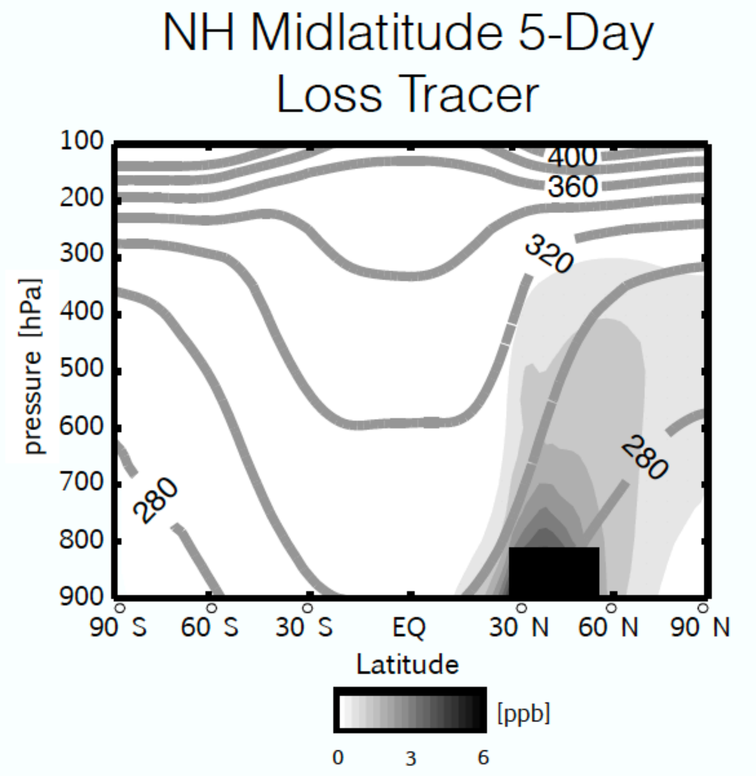
#3 How is large-scale transport into the Arctic projected to change in the 21st century?

A. Experiments

REF-C1SD (1980-2010): observed SSTs and SICs, analysis large-scale flow
REF-C1 (1960-2010): observed SSTs and SICs, free-running
REF-C2 (1960-2100): modeled SSTs and SICs, free-running, RCP 6.0 scenario

B. Transport Diagnostics

Tropospheric transport is inferred from idealized uniform loss tracers with a NH midlatitude source (χ_5 and χ_{50}) (*Orbe et al. (2016, 2017, 2018).*



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REF-C1SD (1980-2010): observed SSTs and SICs, analysis large-scale flow
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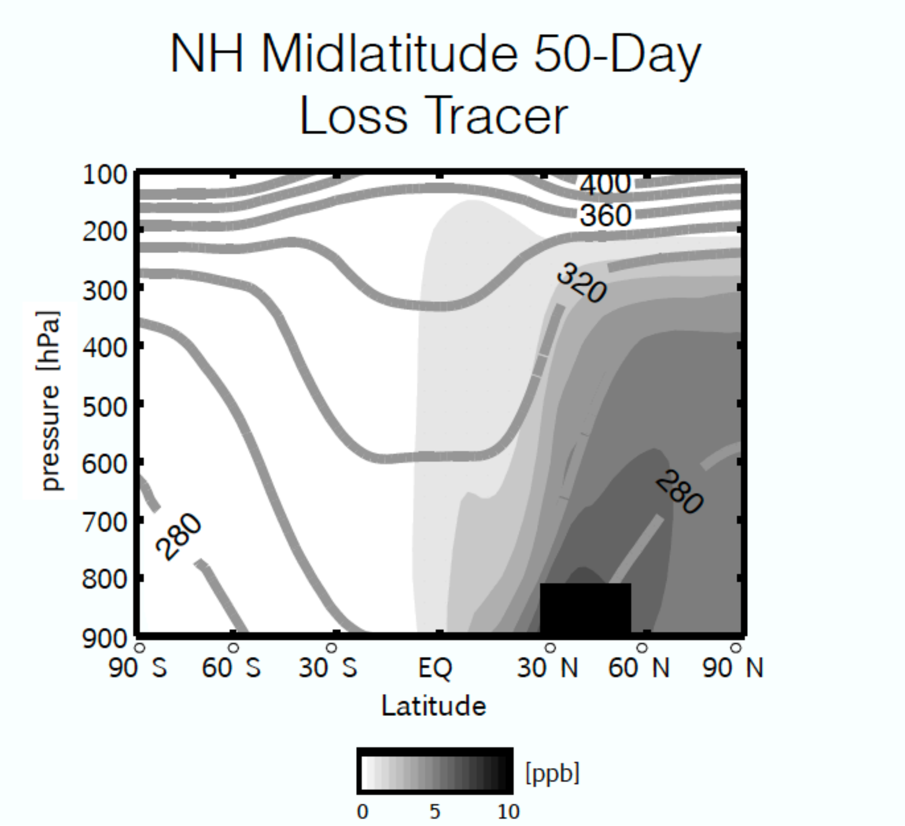

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REF-C1SD (1980-2010): observed SSTs and SICs, analysis large-scale flow
REF-C1 (1960-2010): observed SSTs and SICs, free-running
REF-C2 (1960-2100): modeled SSTs and SICs, free-running, RCP 6.0 scenario

B. Transport Diagnostics

In addition to considering tracers with zonally invariant sources (χ_5 and χ_{50}) we also examine more realistic loss tracers with only land (CO-like) emissions ($\chi_{CO,50}$) (*Shindell et al. (2008), Monks et al. (2015), Doherty et al. (2017), Yang et al. (2019)*).

Models: Hindcast Experiment

Simulation Name	Model (Reference)	Horizontal Resolution	Vertical Levels (Model Top)	Large-Scale Flow (Free/Nudging/CTM)	Convective Parameterization
GEOS-CTM	NASA Global Modeling Initiative Chemical Transport Model Strahan et al., (2013)	2° x 2.5°	72 (0.01 hPa)	MERRA (CTM)	Moorthi and Suarez (1992) Bacmeister et al. (2006)
GEOS-C1SD	Goddard Earth Observing System Version 5 GCM Reinecker et al. (2007); Molod et al. (2015)	" "	" "	MERRA (Nudging)	" "
GEOS-C1	" "	" "	" "	Free-running	" "
WACCM-C1SDV1/V2	Whole Atmosphere Community Climate Model Version 4 (WACCM-4) Marsh et al. (2013); Solomon et al. (2015); Garcia et al. (2016)	1.9° x 2.5°	88 (140 km)	MERRA (Nudging)	Hack (1994) (shallow) Zhang and MacFarlane (1995) (deep)
WACCM-C1	" "	" "	" "	Free-running	
CAM-C1SD	Community Atmosphere Model Version 4 (CAM4)-Chem Tilmes et al. (2015)	1.9° x 2.5°	56 (1 Pa)	MERRA (Nudging)	
CAM-C1	" "	" "	" "	Free-running	" "
EMAC-L47-C1	ECHAM/ Modular Earth Submodel System (MESSy) Atmospheric Chemistry (EMAC) Jöckel et al. (2010); Jöckel et al. (2016)	T42	47 (0.01 hPa)	Free-running	Tiedtke (1989); Nordeng (1994)
EMAC-L47-C1SD	" "	" "	" "	ERA-Interim (nudging)	
EMAC-L90-C1	" "	" "	90 (0.01 hPa)	Free-running	" "
EMAC-L90-C1SD	" "	" "	" "	ERA-Interim (nudging)	" "
MRI-C1SD	Earth System Model MRI-ESM1r1 Yukimoto et al. (2012, 2011); Deushi and Shibata (2011)	TL159 " "	80 (0.01 hPa) " "	JRA-55 (Nudging) " "	Yoshimura et al. (2015)
MRI-C1	" "	" "	" "	Free-running	" "
CMAM-C1SD	Canadian Middle Atmosphere Model (CMAM) Jonsson et al. (2004); Scinocca et al. (2008)	T47	71 (0.0008 hPa)	ERA-Interim (Nudging)	Zhang and McFarlane (1995)
CMAM-C1	" "	" "	" "	Free-running	" "
NIWA-C1	National Institute of Water and Atmospheric Research UK Chemistry and Aerosols (NIWA-UKCA) Morgenstern et al. (2009, 2013); Stone et al. (2016)	3.75° x 2.5°	60 (84 km)	Free-running	Hewitt et al. (2011)
SOCOL-C1	Solar-Climate-Ozone Links (SOCOL) v3 Stenke et al. (2013); Revell et al. (2015)	T42	39 (0.01 hPa)	Free-running	Nordeng (1994)
NIES-C1SD	CCSRNIES-MIROC3.2 Imai et al. (2013); Akiyoshi et al. (2016)	T42	34 (0.01 hPa)	ERA-Interim (Nudging)	Arakawa and Schubert (1974)
NIES-C1	" "	" "	" "	Free-running	" "
MOCAGE-CTM	Modele de Chimie Atmosphérique de Grande Echelle (MOCAGE) Josse et al. (2004); Guth et al. (2016)	2° x 2°	47 (5 hPa)	ERA-Interim (CTM)	Bechtold et al. (2001)
ULAQ-C1	University of L'Aquila (ULAQ)-CCM Pitari et al. (2014)	T21	126 (0.04 hPa)	Free-running	Grewe et al. (2001)
ACCESS-C1	National Institute of Water and Atmospheric Research UK Chemistry and Aerosols (NIWA-UKCA) Morgenstern et al. (2009, 2013); Stone et al. (2016)	3.75° x 2.5°	60 (84 km)	Free-running	Hewitt et al. (2011)

Among the hindcast runs (REF-C1, REF-C1SD) we consider 23 simulations performed in both specified-dynamics ( ) and free-running modes.

Models: Hindcast Experiment

Simulation Name	Model (Reference)	Horizontal Resolution	Vertical Levels (Model Top)	Large-Scale Flow (Free/Nudging/CTM)	Convective Parameterization
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GEOS-C1	" "	" "	" "	Free-running	" "
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WACCM-C1	" "	" "	" "	Free-running	
CAM-C1SD	Community Atmosphere Model Version 4 (CAM4)-Chem Tilmes et al. (2015)	1.9° x 2.5°	56 (1 Pa)	MERRA (Nudging)	
CAM-C1	" "	" "	" "	Free-running	" "
EMAC-L47-C1	ECHAM/ Modular Earth Submodel System (MESSy) Atmospheric Chemistry (EMAC) Jöckel et al. (2010); Jöckel et al. (2016)	T42	47 (0.01 hPa)	Free-running	Tiedtke (1989); Nordeng (1994)
EMAC-L47-C1SD	" "	" "	" "	ERA-Interim (nudging)	
EMAC-L90-C1	" "	" "	90 (0.01 hPa)	Free-running	" "
EMAC-L90-C1SD	" "	" "	" "	ERA-Interim (nudging)	" "
MRI-C1SD	Earth System Model MRI-ESM1r1 Yukimoto et al. (2012, 2011); Deushi and Shibata (2011)	TL159 " "	80 (0.01 hPa) " "	JRA-55 (Nudging) " "	Yoshimura et al. (2015)
MRI-C1	" "	" "	" "	Free-running	" "
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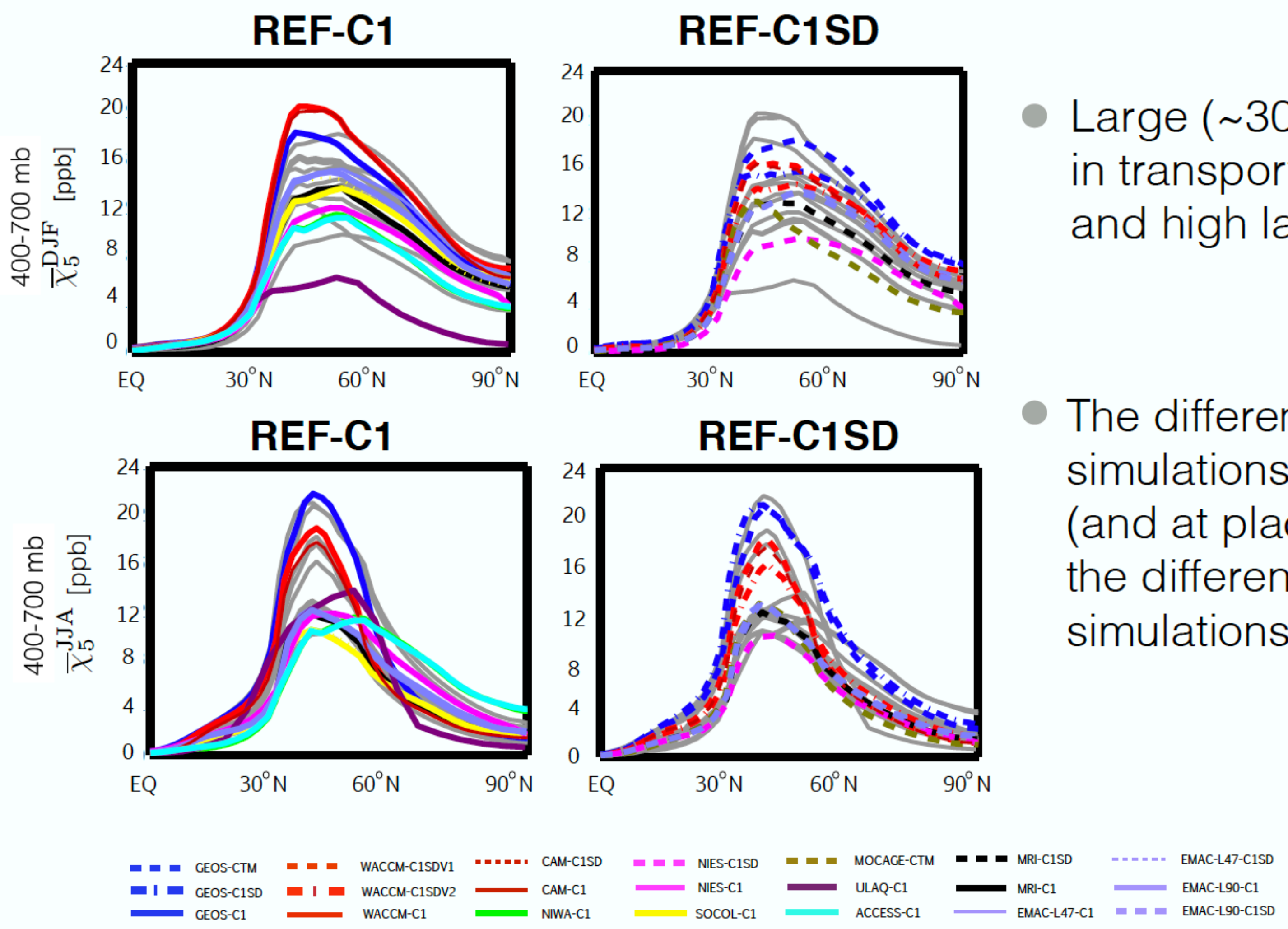
Among the future runs (REF-C2, RCP 6.0) we consider all nine available simulations that integrated the NH midlatitude idealized loss tracers.

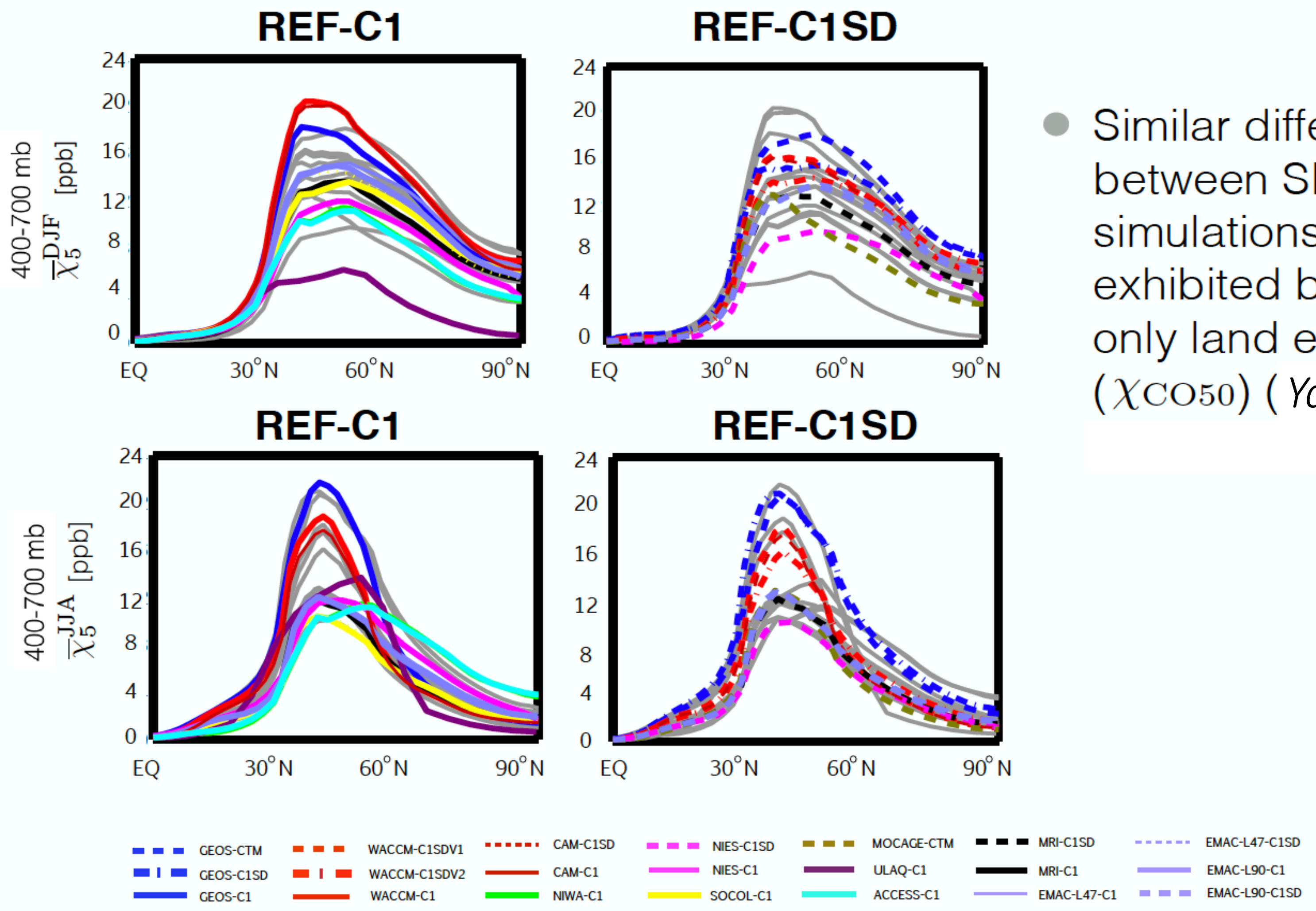
Transport in Hindcast Experiment



Orbe et al. (2018, ACP)

- Large (~30-40%) differences in transport over NH middle and high latitudes.
- The differences among SD simulations are as large (and at places larger) than the differences among FR simulations.

Transport in Hindcast Experiment

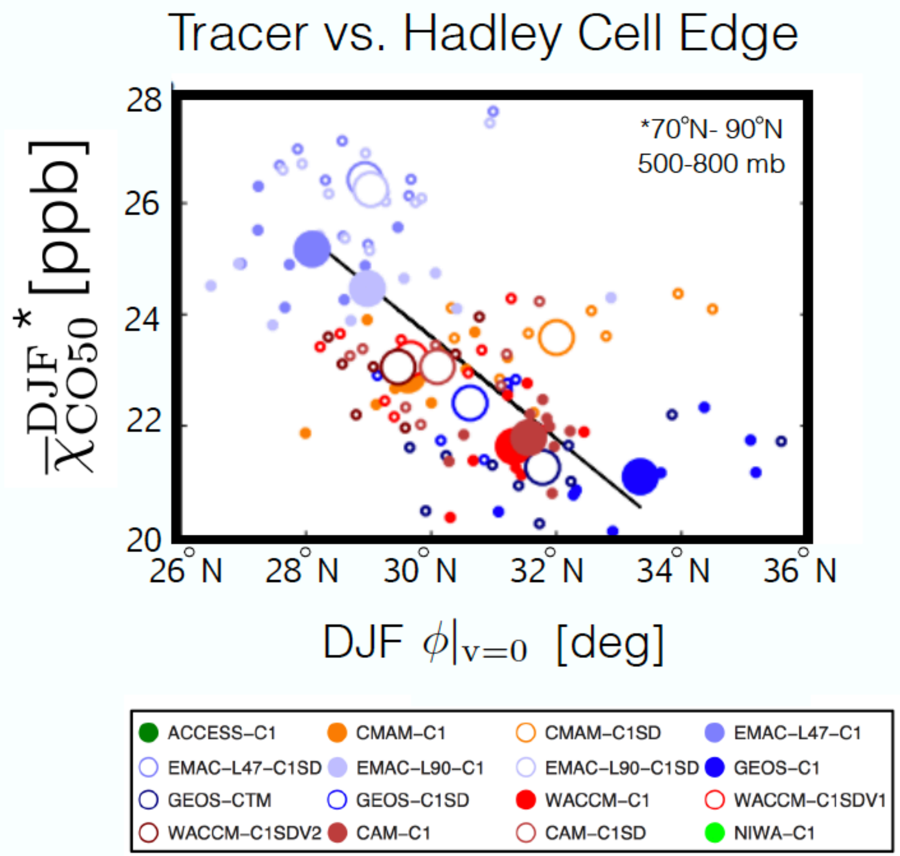


Orbe et al. (2018, ACP)

- Similar differences between SD and FR simulations are also exhibited by tracers with only land emissions (χ_{CO50}) (*Yang et al. (2019)).*

Transport in Hindcast Experiment

Land-Only Sources



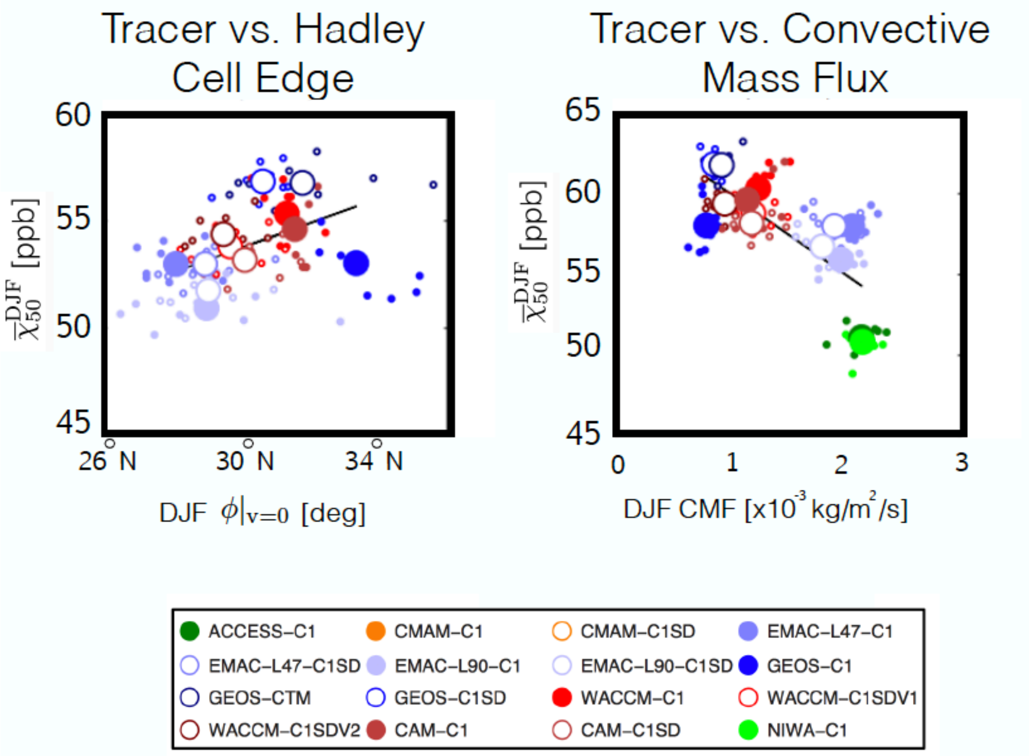
#1 For tracers with land-only emissions ($\overline{\chi}^{DJF}_{CO50}$), transport efficiency to the Arctic depends sensitively on the poleward edge of the Hadley Cell (*Yang et al. (2019)*).

Specified-Dynamics

Free-Running

Transport in Hindcast Experiment

Land and Ocean Sources



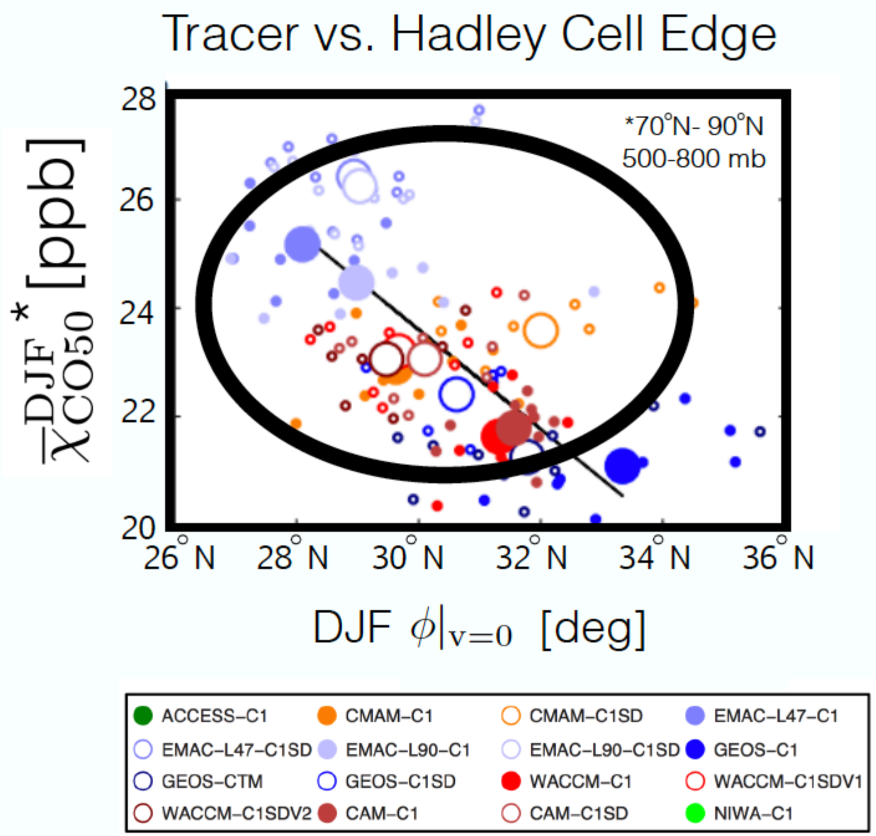
#2 By comparison, tracers with both ocean and land sources ($\overline{\chi}_{50}^{DJF}$) depend also on convection over oceans (*Orbe et al. (2018), Yang et al. (2019)*) and less sensitively on midlatitude jet location and/or Hadley Cell edge.

Specified-Dynamics

Free-Running

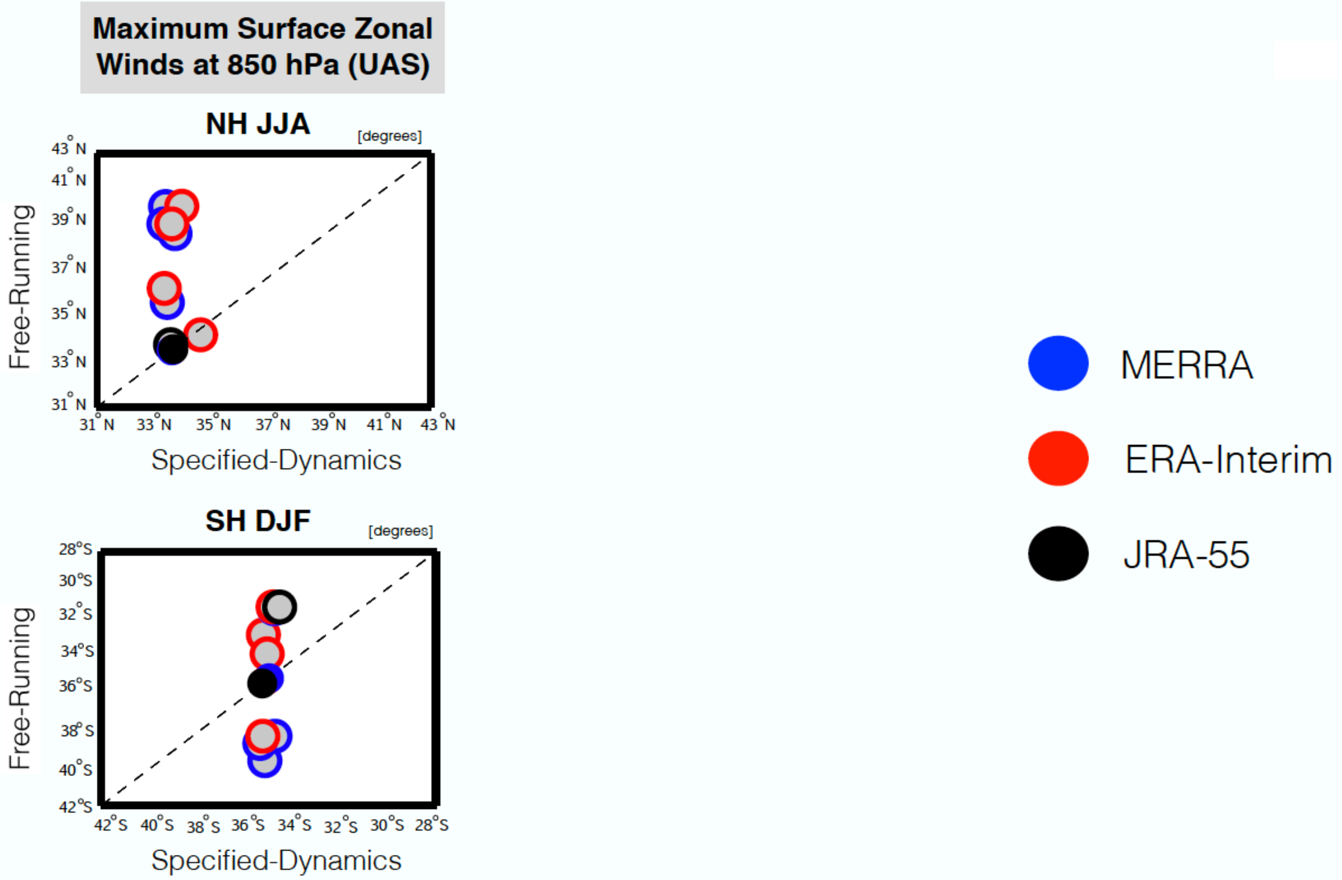
Transport in Hindcast Experiment

Land-Only Sources



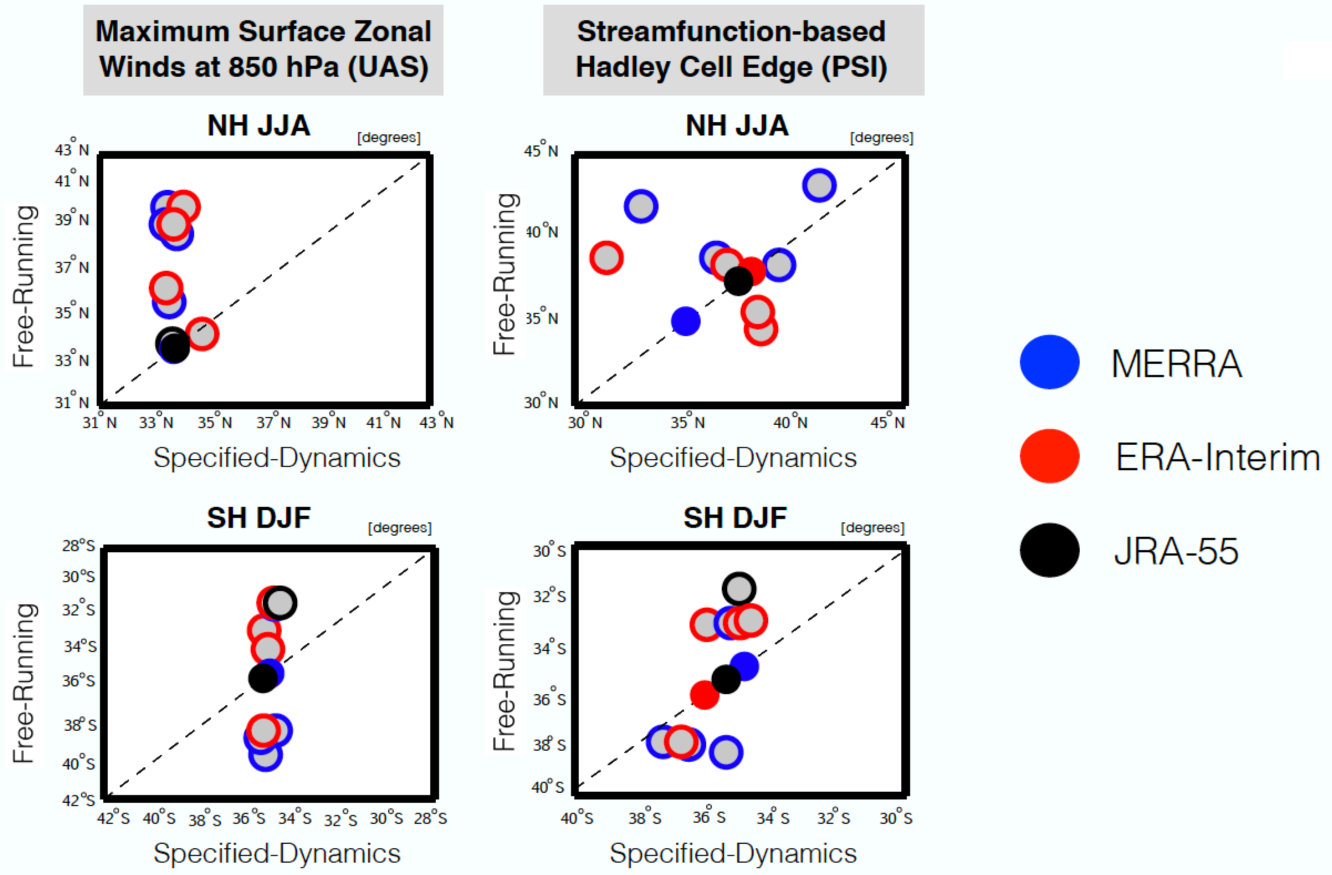
Note that the differences in Hadley Cell edge among specified-dynamics simulations (○) are as large as the differences among free-running simulations (●). This is somewhat surprising.

Transport in Hindcast Experiment



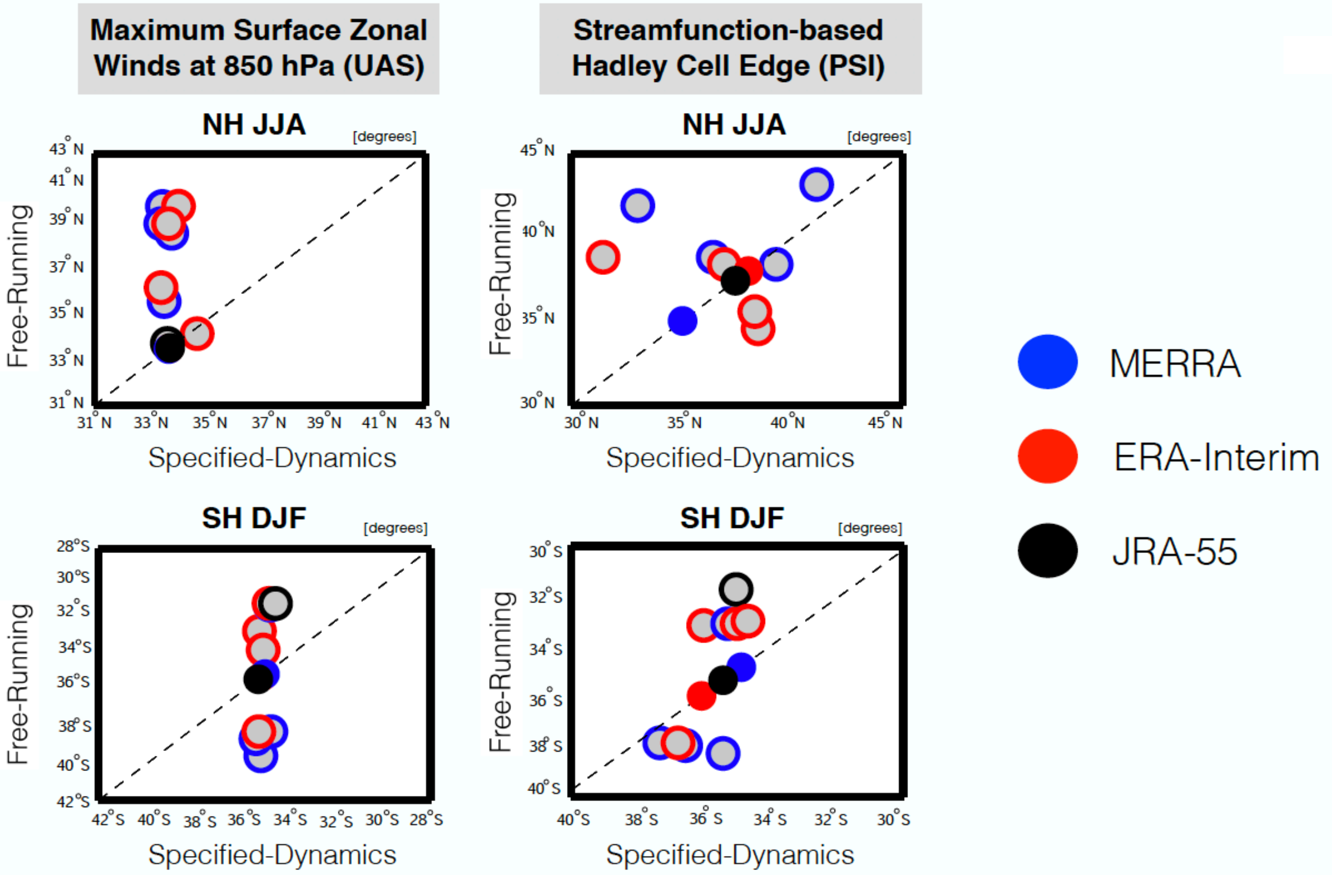
This reflects the fact that, while the zonal winds are well constrained in specified-dynamics simulations…

Transport in Hindcast Experiment



This reflects the fact that, while the zonal winds are well constrained in specified-dynamics simulations, the meridional and vertical component of the flow is not (*Orbe, Plummer et al.*, (2020)).

Transport in Hindcast Experiment

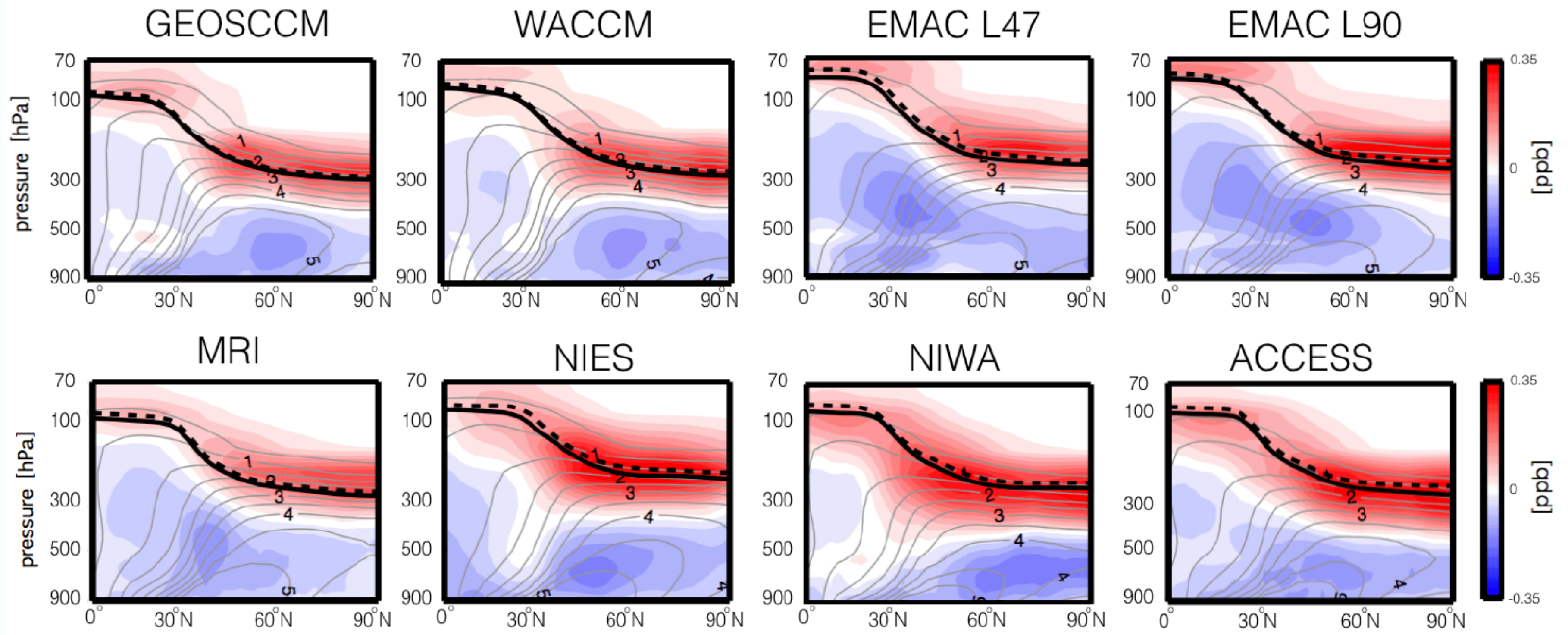


Note that differences among specified-dynamics simulations are not obviously related to the use of different analysis products (●, ●, ●), but rather to how the fields are implemented.

Future Changes in Transport into the Arctic

- In response to future warming all CCMI models project increased concentrations of NH midlatitude surface tracers over the Arctic upper troposphere and lower stratosphere and reduced burdens in the mid-to-lower troposphere.

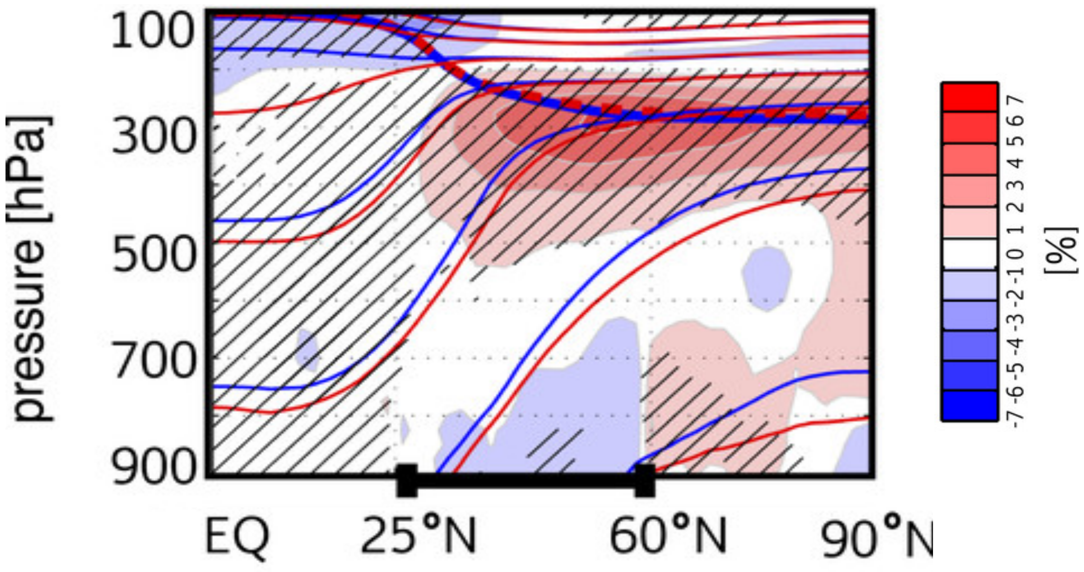
2090s-2000s $\delta\chi_{\mathrm{NH50}}$



Future Changes in Transport into the Arctic

- This response is similar to the transport response documented in previous studies using **different tracers** (air-mass fractions considered in *Orbe et al. (2015)* (bottom), χ_{CO50} in *Doherty et al. (2017)*) …

$$\Delta \overline{f}^{\mathrm{DJF}}(\mathbf{r}|\Omega_i)$$

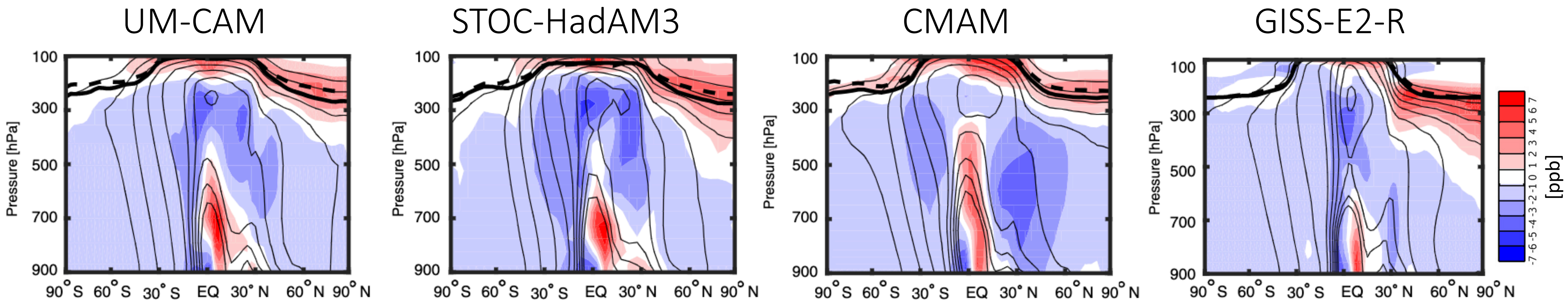


Orbe et al. (2015)

Future Changes in Transport into the Arctic

- … as well as **different multi-model ensembles** (ACCMIP ensemble under RCP 8.5 scenario presented in *Doherty et al. (2017)*) …

2090s-2000s $\delta\chi_{CO50}$

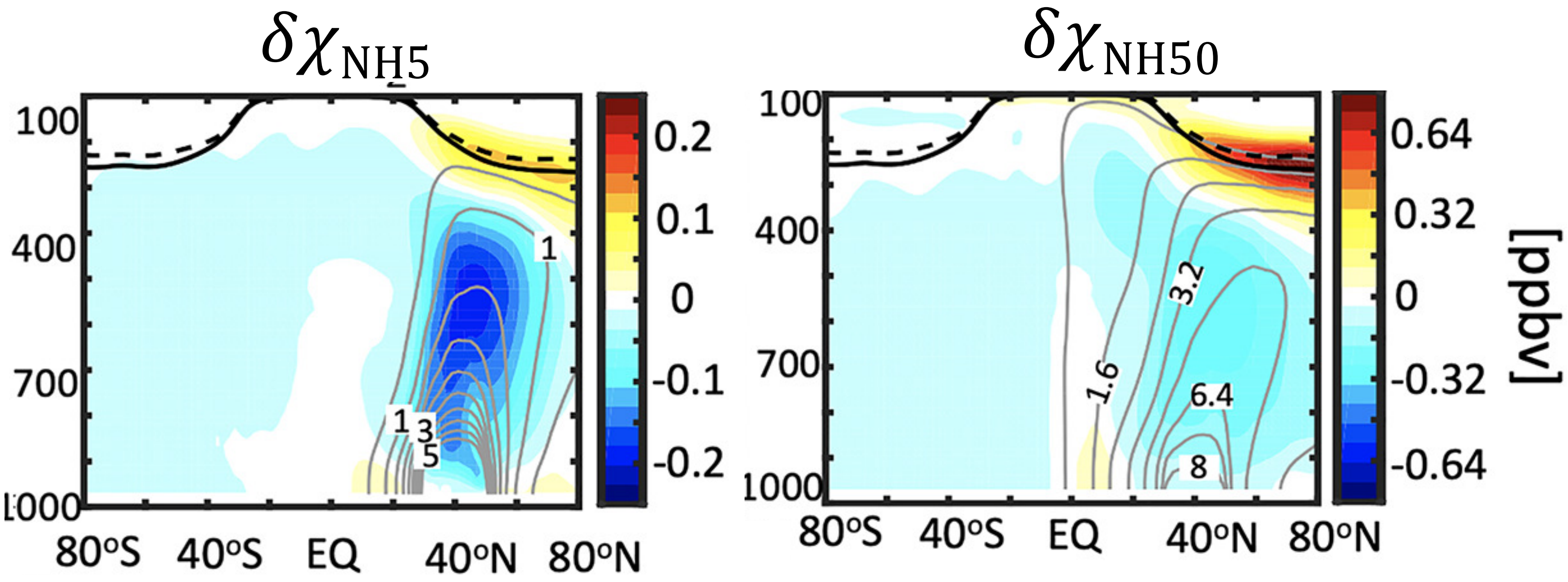


Doherty et al. (2017)

Future Changes in Transport into the Arctic

- … and different forcings (abrupt 4xCO_2 examined in *Orbe et al. (2020)*). This suggests that these changes are robust across transport metric, model ensemble and forcing type (i.e. abrupt vs. transient).

4xCO_2 – Pre-Industrial control

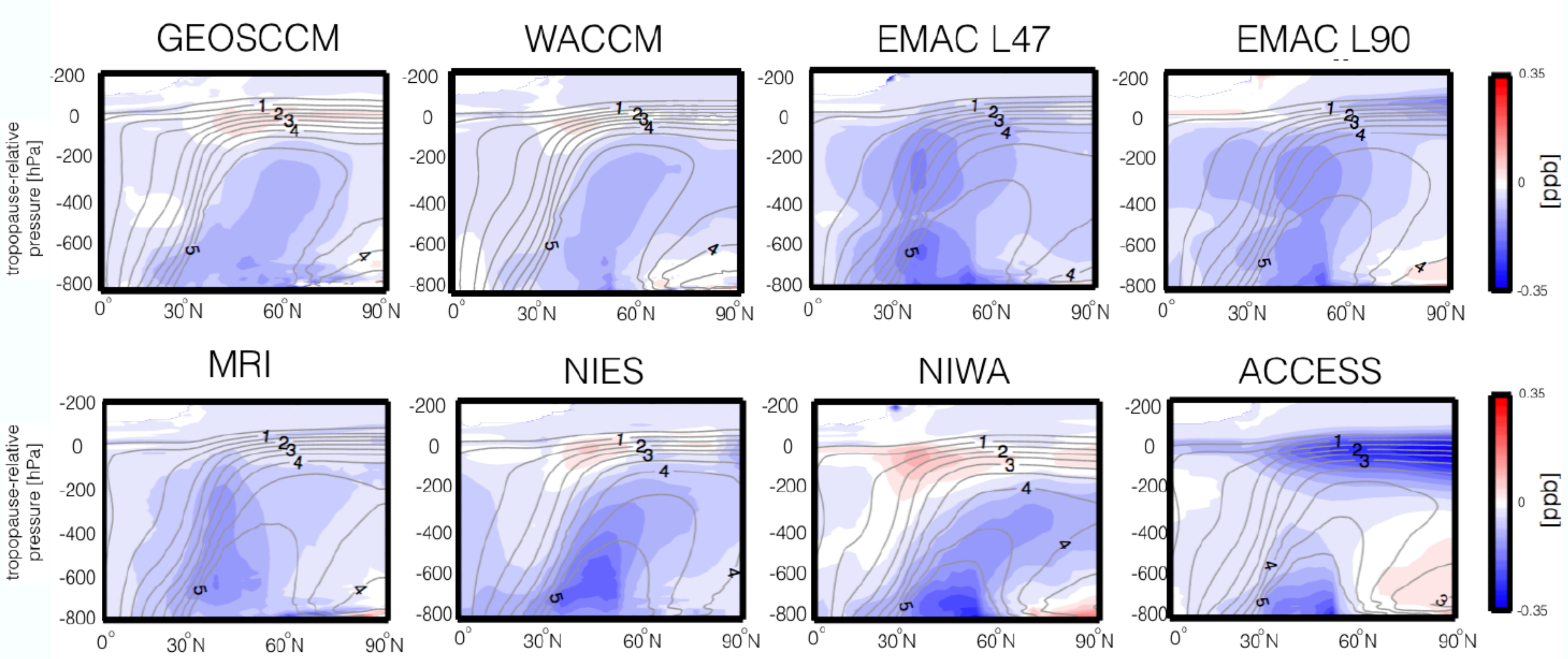


Orbe et al. (2020)

Future Changes in Transport into the Arctic

- The increased concentrations of midlatitude tracers at the tropopause largely reflect an increase in tropopause height (*Holzer and Boer (2001), Fang et al. (2011), Doherty et al. (2017)*).

2090s-2000s $\delta\chi_{\mathrm{NH50}}$ (tropopause-relative coordinates)



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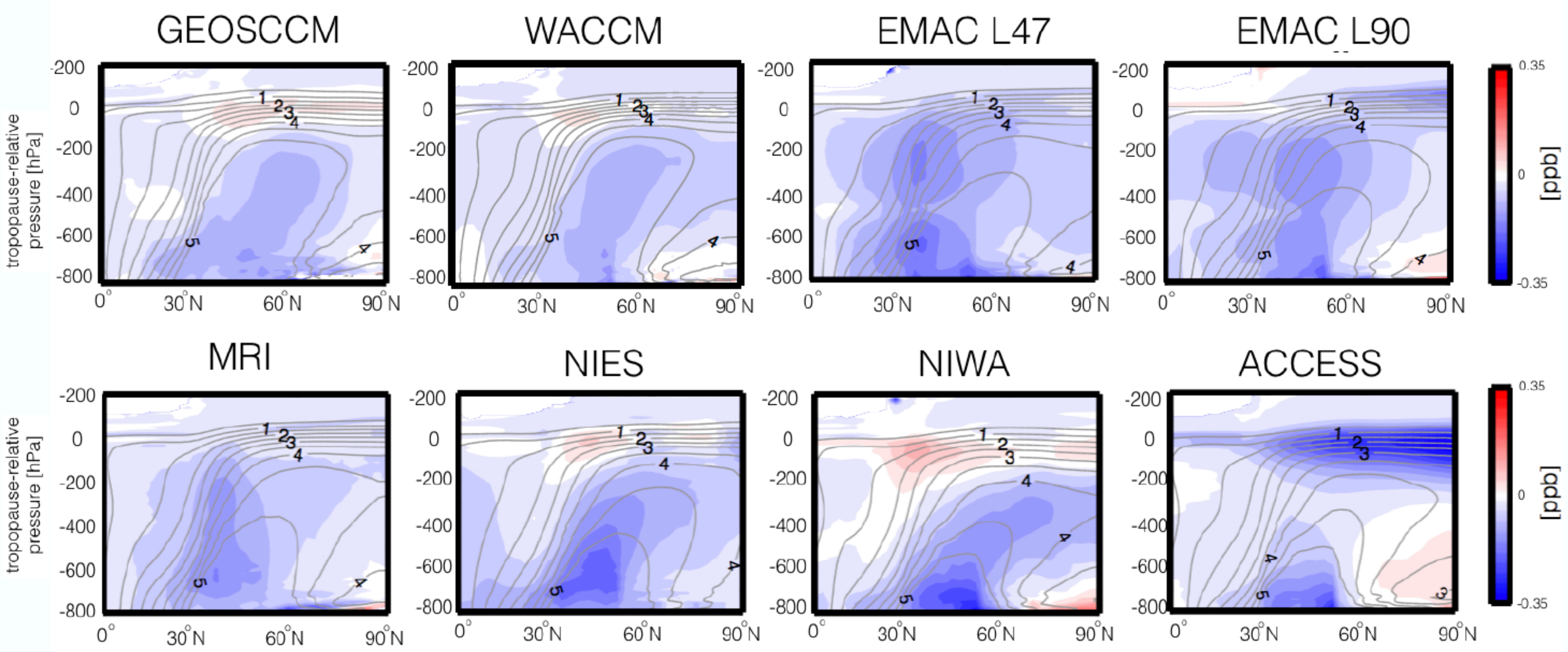
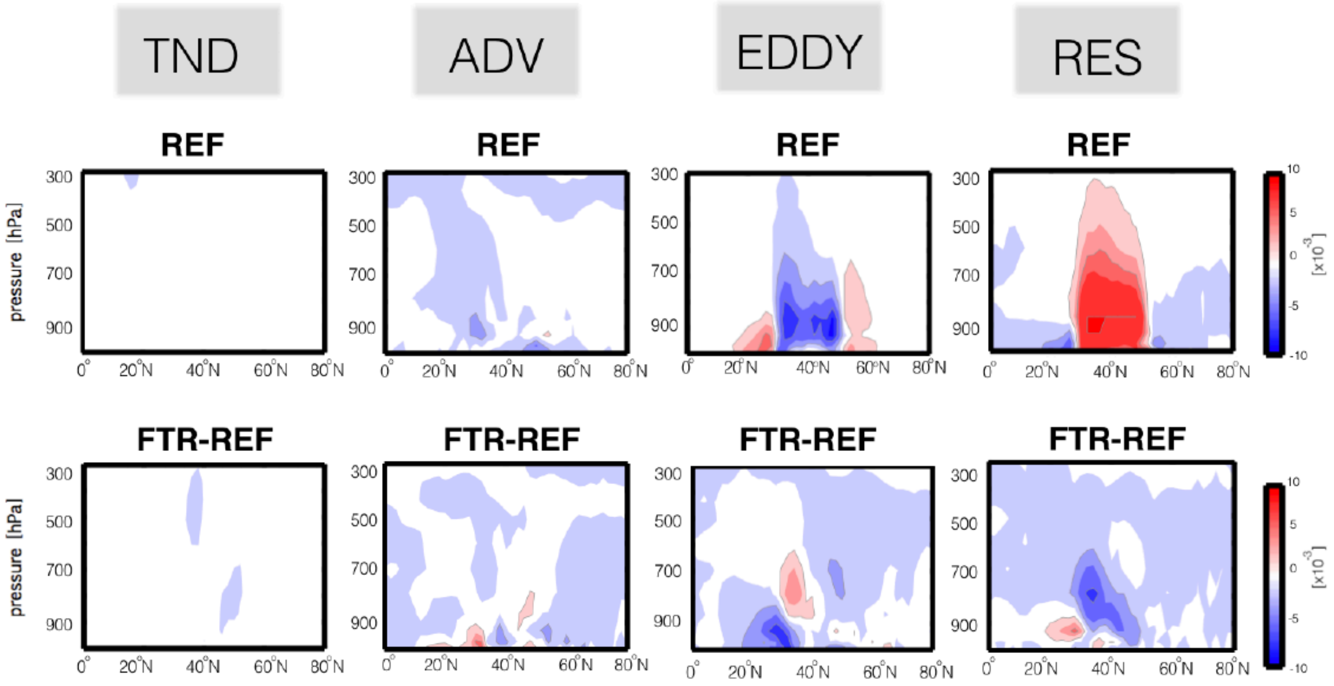
Future Changes in Transport into the Arctic

- The drivers of reduced concentrations in the middle Arctic troposphere are less clear.

2090s-2000s $\delta\chi_{\mathrm{NH50}}$ (tropopause-relative coordinates)



Future Changes in Transport into the Arctic



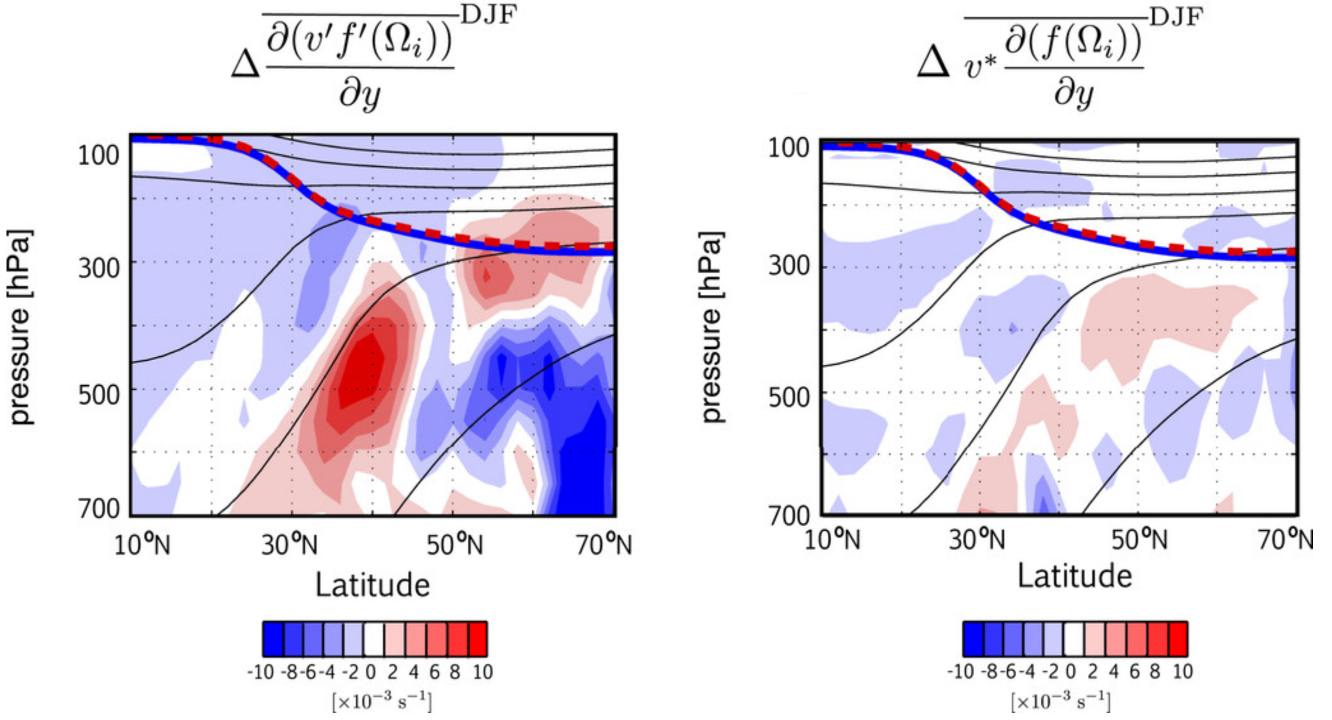
$$\overline{\chi}_t = -\overline{v}^*\overline{\chi}_y - \overline{w}^*\overline{\chi}_z + \nabla\cdot\mathbf{M} + \overline{L} + \overline{X}$$

TND ADV EDDY RES

Tracer budgets, cast in terms of the Transformed Eulerian Mean as in *Abalos et al. (2017)*, indicate that loss tracer concentrations primarily reflect a balance between eddy-induced mixing and transport by (parameterized) convection.

Future Changes in Transport into the Arctic

- This is consistent with *Orbe et al. (2015)* who, using slightly different tracers and only one model, showed that eddy-driven transport changes dominate the response (reduced midlatitude tracer concentrations) over the mid-to-lower Arctic.



Orbe et al. (2015)

Summary

- There are large (40%) differences in how models represent transport into the Arctic. These differences are as large (if not) larger in specified-dynamics runs compared to free-running simulations.
- Differences in transport to the Arctic in the CCMI models are related to the meridional extent of the Hadley Cell edge, which is poorly constrained in reanalysis-driven simulations, and to differences in (parameterized) convection.
- Models consistently project reduced burdens of midlatitude tracers over the Arctic mid-to-lower troposphere and enhanced burdens in the upper Arctic troposphere in a warmer climate. These changes are consistent with changes in meridional eddy transport and with a rise in tropopause height.

Thank you for your attention and please email me your questions at **clara.orbe@nasa.gov**.