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

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Motivation

- Differences in large-scale tropospheric transport among models contribute to differences in aerosol distributions in the Arctic and to the interhemispheric gradients of GHGs and ODSs (e.g. *Shindell et al. (2008), Patra et al. (2011), Monks et al. (2015)*).

- It is not clear, however, whether these uncertainties are driven by large-scale flow biases and/or subgrid-scale processes.

- Few studies have examined how tropospheric transport (e.g. transport to the Arctic, interhemispheric exchange) will change in a warmer climate (e.g. *Holzer and Boer (2001), Doherty et al. (2017)*).

Motivation

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

- Unprecedented number of tropospheric transport diagnostics, including a range of both idealized loss and age tracers (*Waugh et al. (2013), Eyring 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 composition intercomparisons (e.g. TRANSCOM, ACCMIP).

Motivation

Here we use the Chemistry Climate Modeling (CCM) Initiative experiments (*Eyring et al. (2013)*), consisting of hindcast simulations over the recent past, performed both in "specified-dynamics" (REF-C1SD) and free-running (REF-C1) modes to evaluate:

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

#2 Is tropospheric transport better constrained in specified-dynamics (SD)(versus free-running (FR)) simulations?

Motivation

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

#2 Is tropospheric transport better constrained in specified-dynamics (SD)(versus free-running (FR)) simulations?

#3 *How is transport to the Arctic and interhemispheric transport projected to change by the end of the 21st century?*

Methods

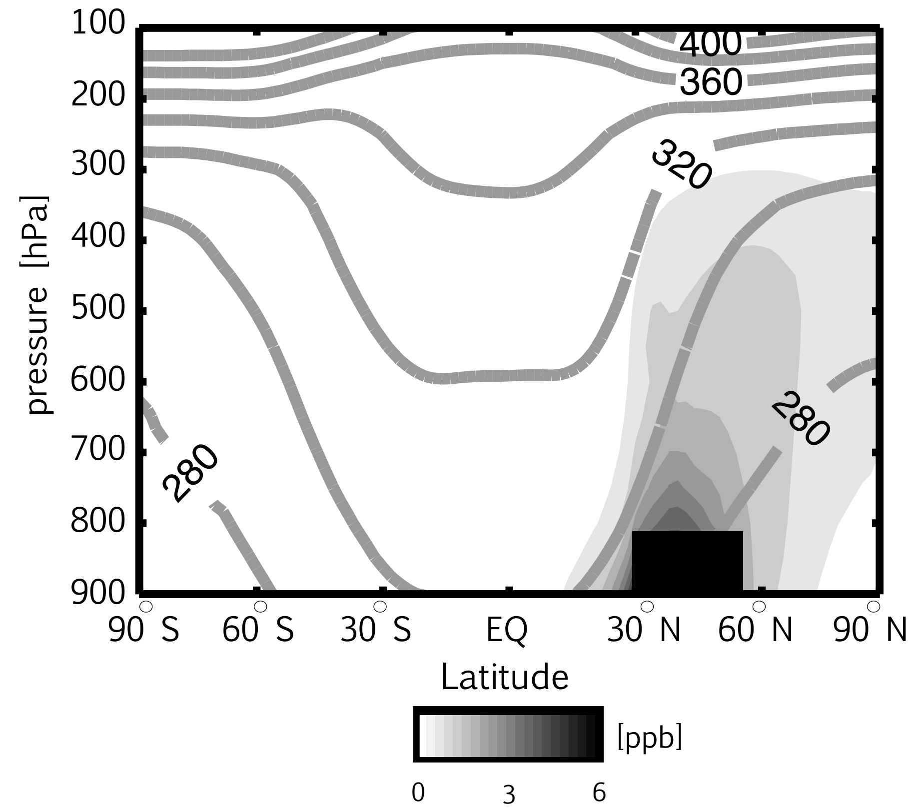
A. *Experiments*:

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 6.5 scenario

B. Transport Diagnostics:

Tropospheric transport is inferred from idealized loss tracers with a NH midlatitude source (χ_5 and χ_{50}) as well as a NH midlatitude mean age tracer (Γ_{NH}) (*Waugh et al. (2013), Eyring et al. (2013), Orbe et al. (2016,2017)).*

NH Midlatitude 5-Day Loss Tracer



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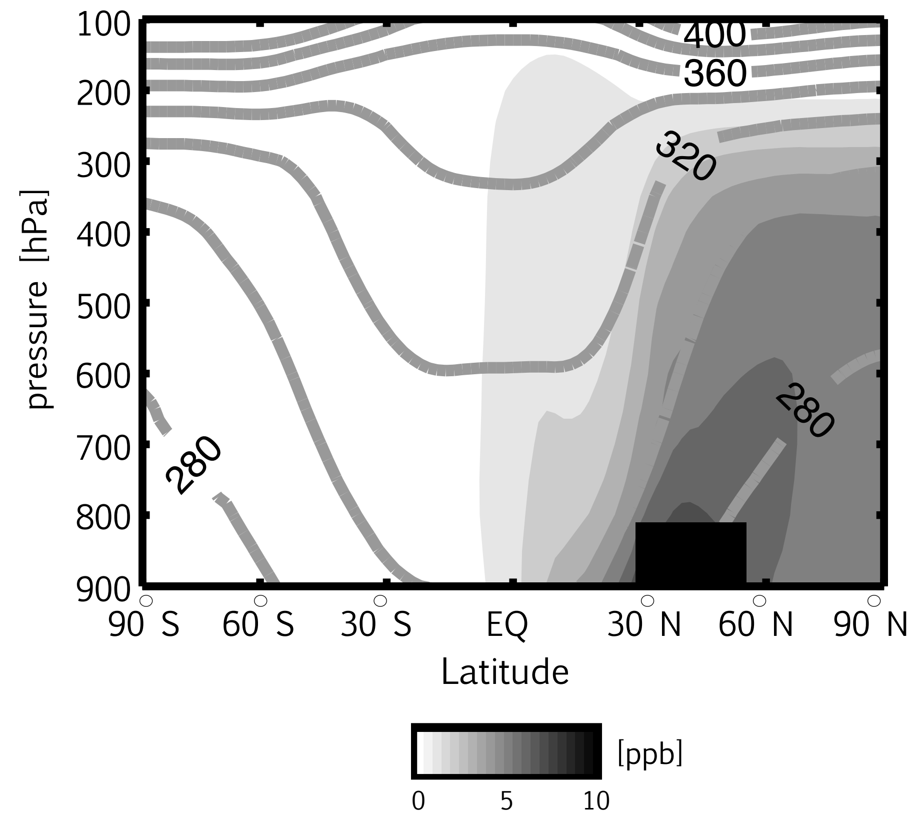
NH Midlatitude 50-Day Loss Tracer



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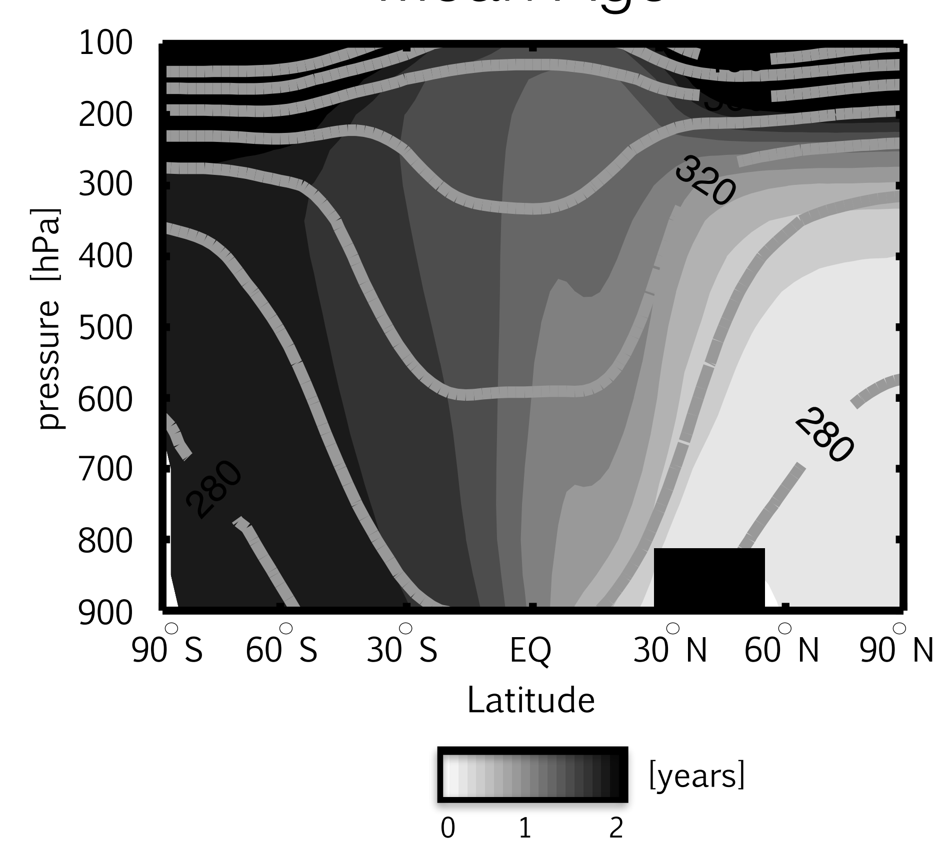
NH Midlatitude
Mean Age



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REF-C1 (1960-2010): observed SSTs and SICs, free-running
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B. Transport Diagnostics:

In addition to examining tracers with zonally invariant sources (χ_5 , χ_{50} , Γ_{NH}) we will also examine more realistic tracers with only land (CO-like) emissions (χ_{CO50}) (*Shindell et al. (2008), Monks et al. (2015), Doherty et al. (2017),Yang et al. (2018, Under Review)).*

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: Future 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)
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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)
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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)
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Among the future runs (REF-C2, RCP 6.5) we consider nine simulations that integrated the NH midlatitude idealized tracers.

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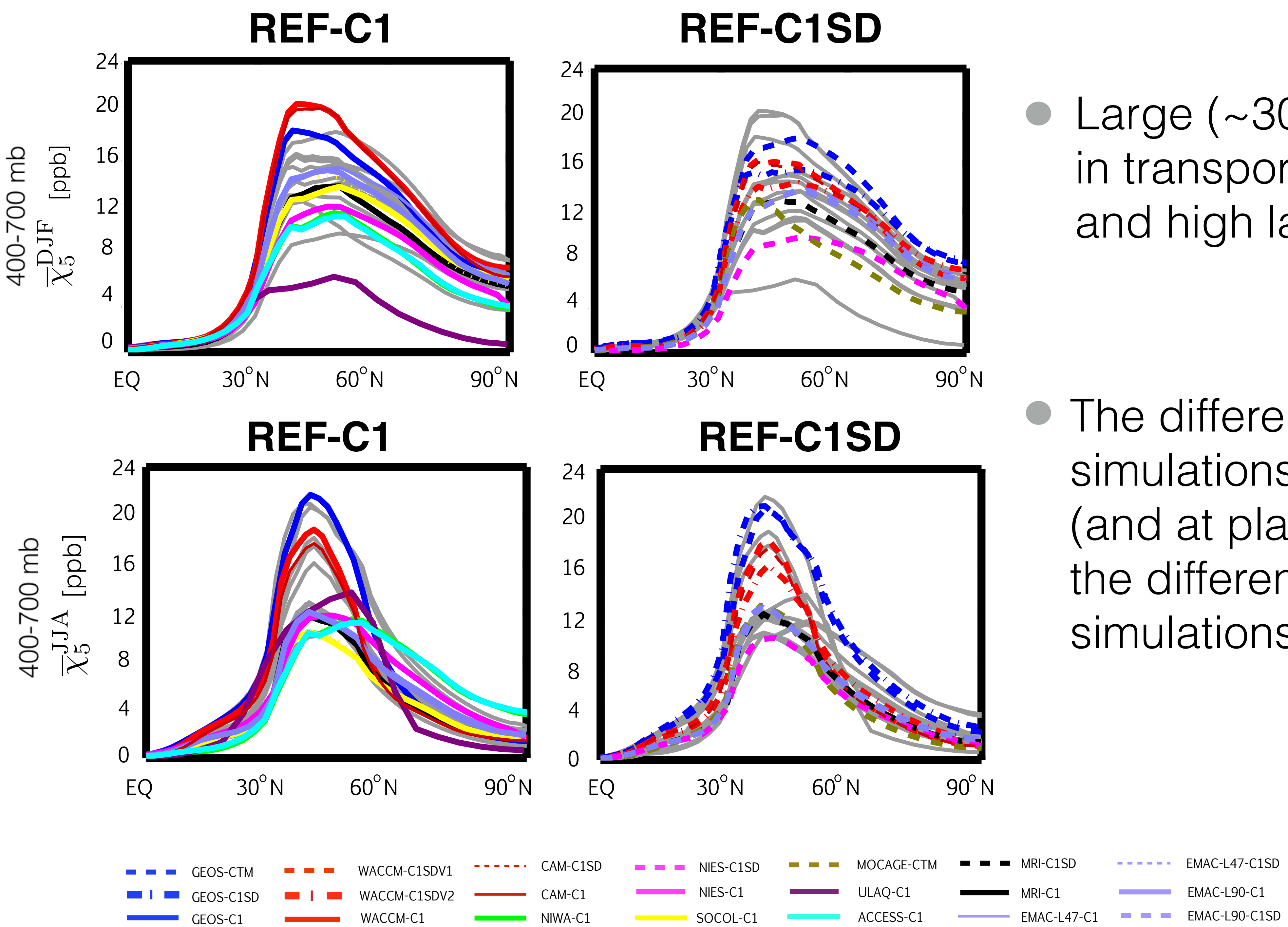
I. Transport to the Arctic
- Hindcast
- Future

II. Interhemispheric Transport
- Hindcast
- Future

Among the future runs (REF-C2, RCP 6.5) we consider nine simulations that integrated the NH midlatitude idealized tracers.

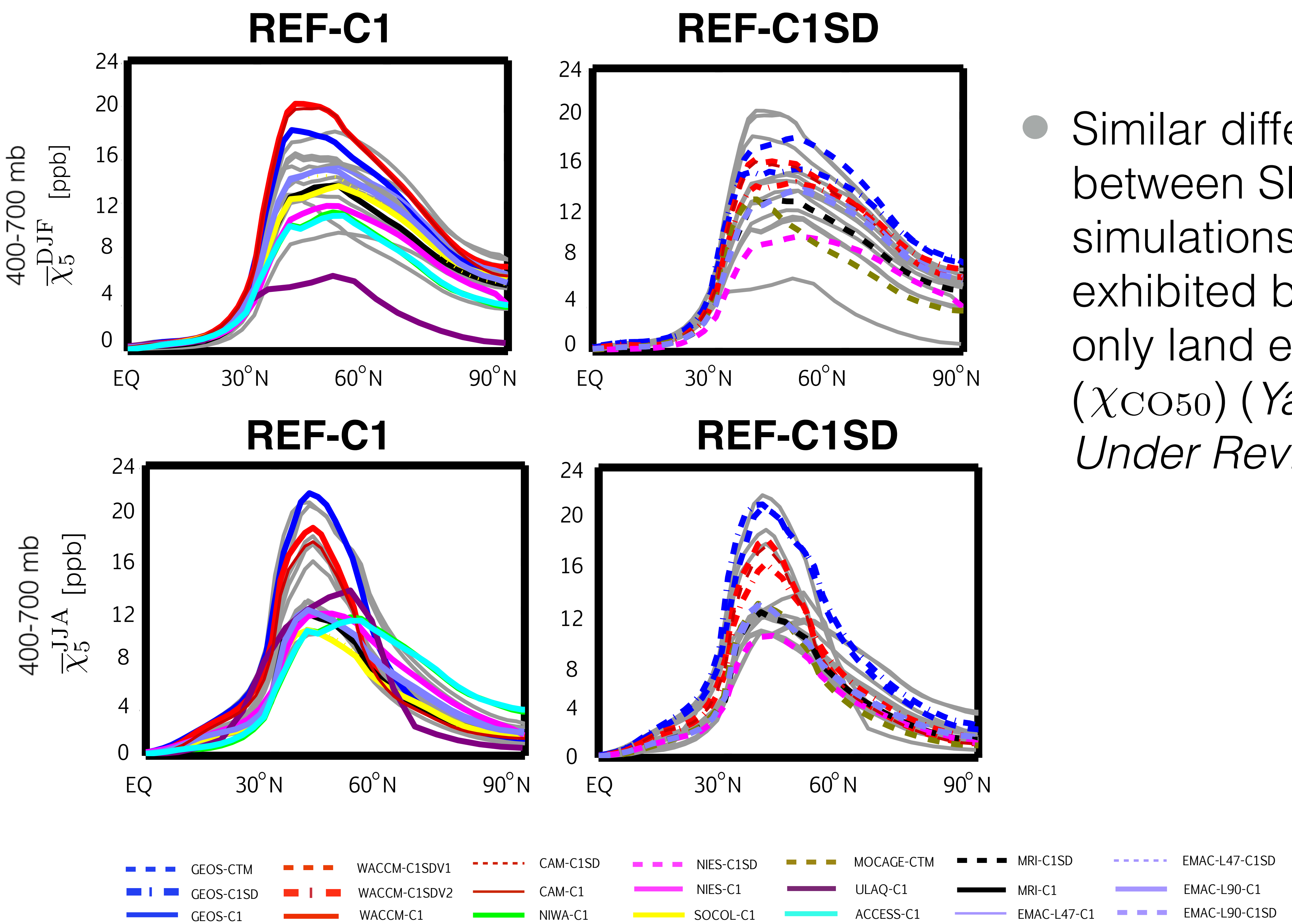
Transport to the Arctic



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 to the Arctic



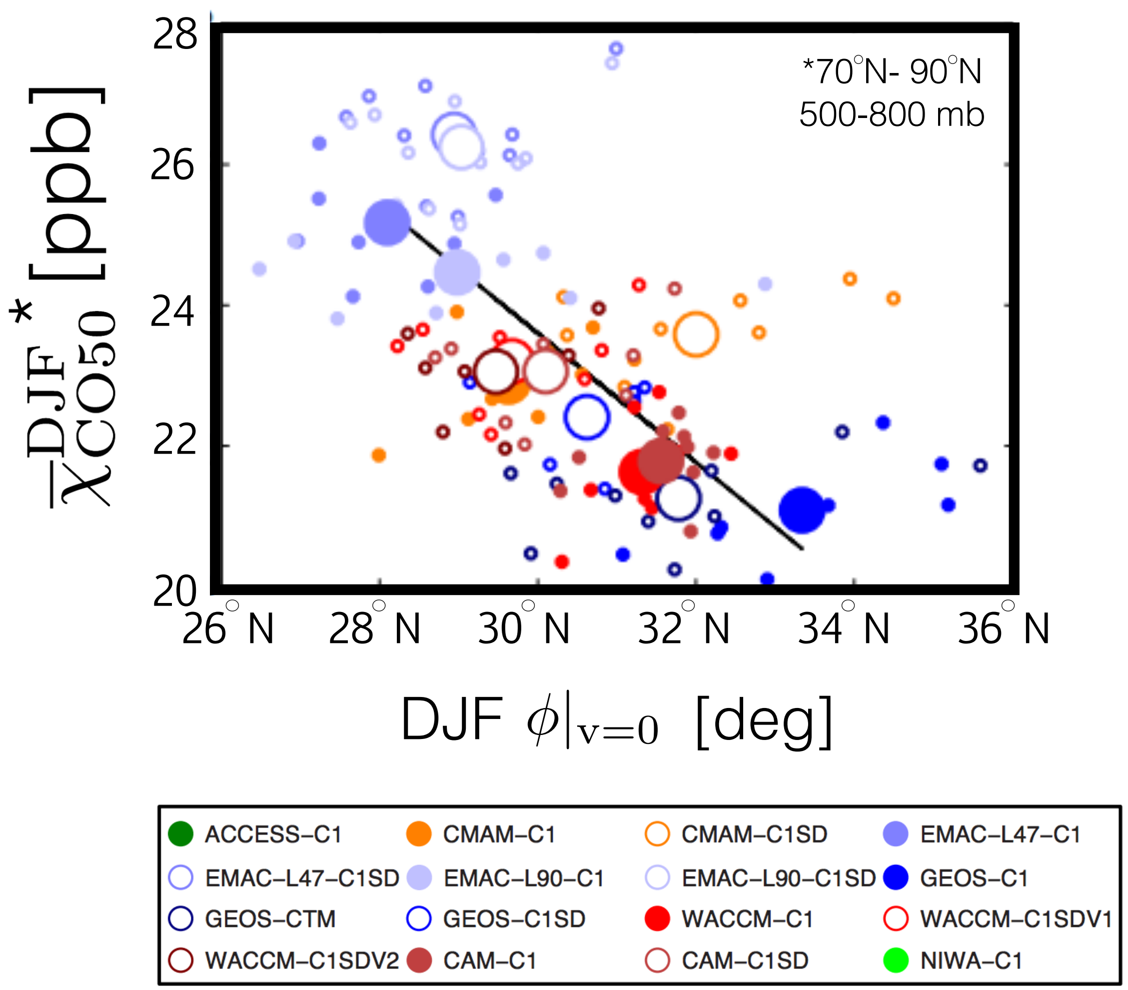
- Similar differences between SD and FR simulations are also exhibited by tracers with only land emissions (χ_{CO50}) (*Yang et al. (2018, Under Review in ACPD)*).

Orbe et al. (2018, ACP)

Transport to the Arctic

Land-Only Sources

Tracer vs. Hadley Cell Edge



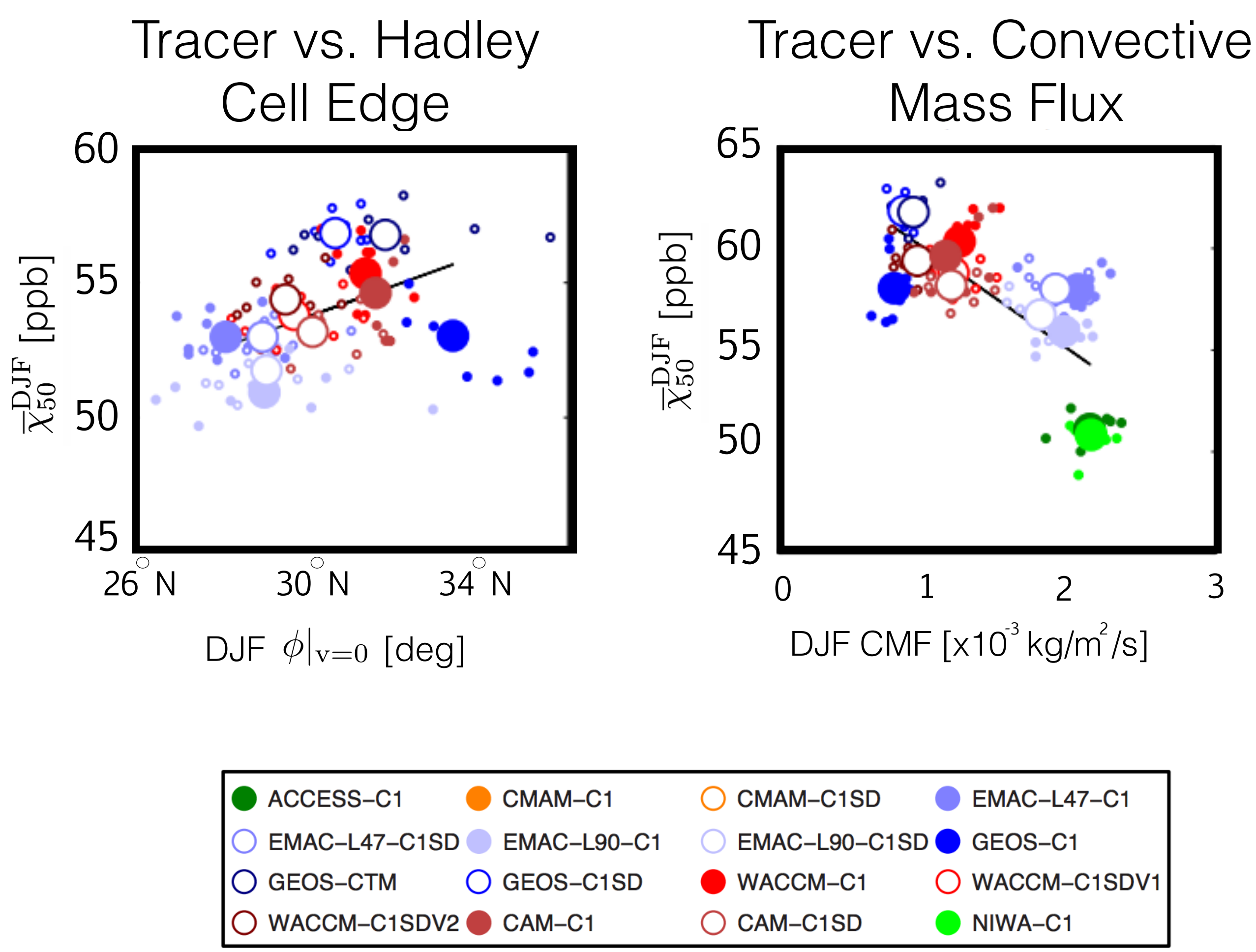
#1 For tracers with land-only emissions ($\overline{\chi}_{\mathrm{CO50}}^{\mathrm{DJF}}$), transport efficiency to the Arctic depends sensitively on the poleward edge of the Hadley Cell (*Yang et al. (2018), Under Review*)

Specified-Dynamics

Free-Running

Transport to the Arctic

Land and Ocean Sources



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

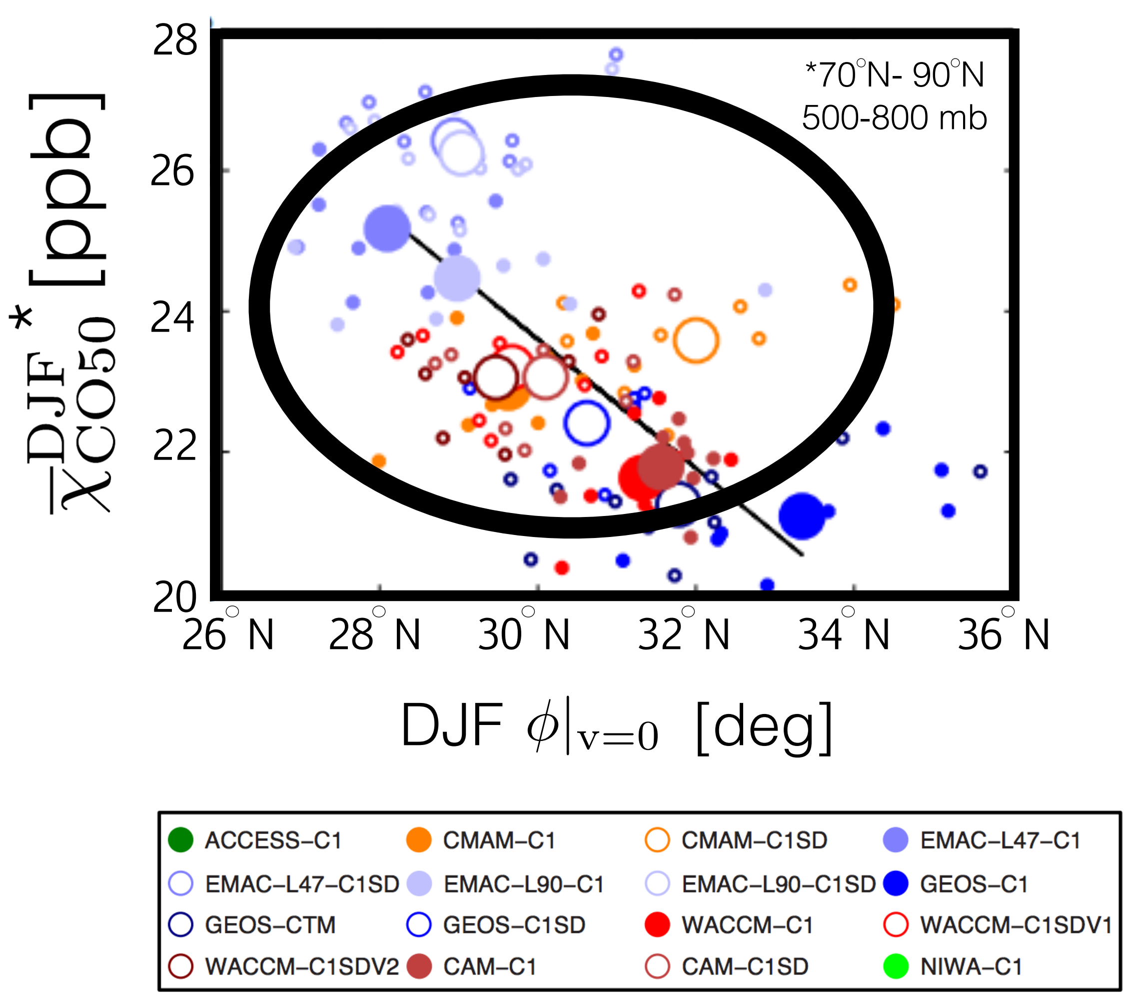
○ Specified-Dynamics

● Free-Running

Transport to the Arctic

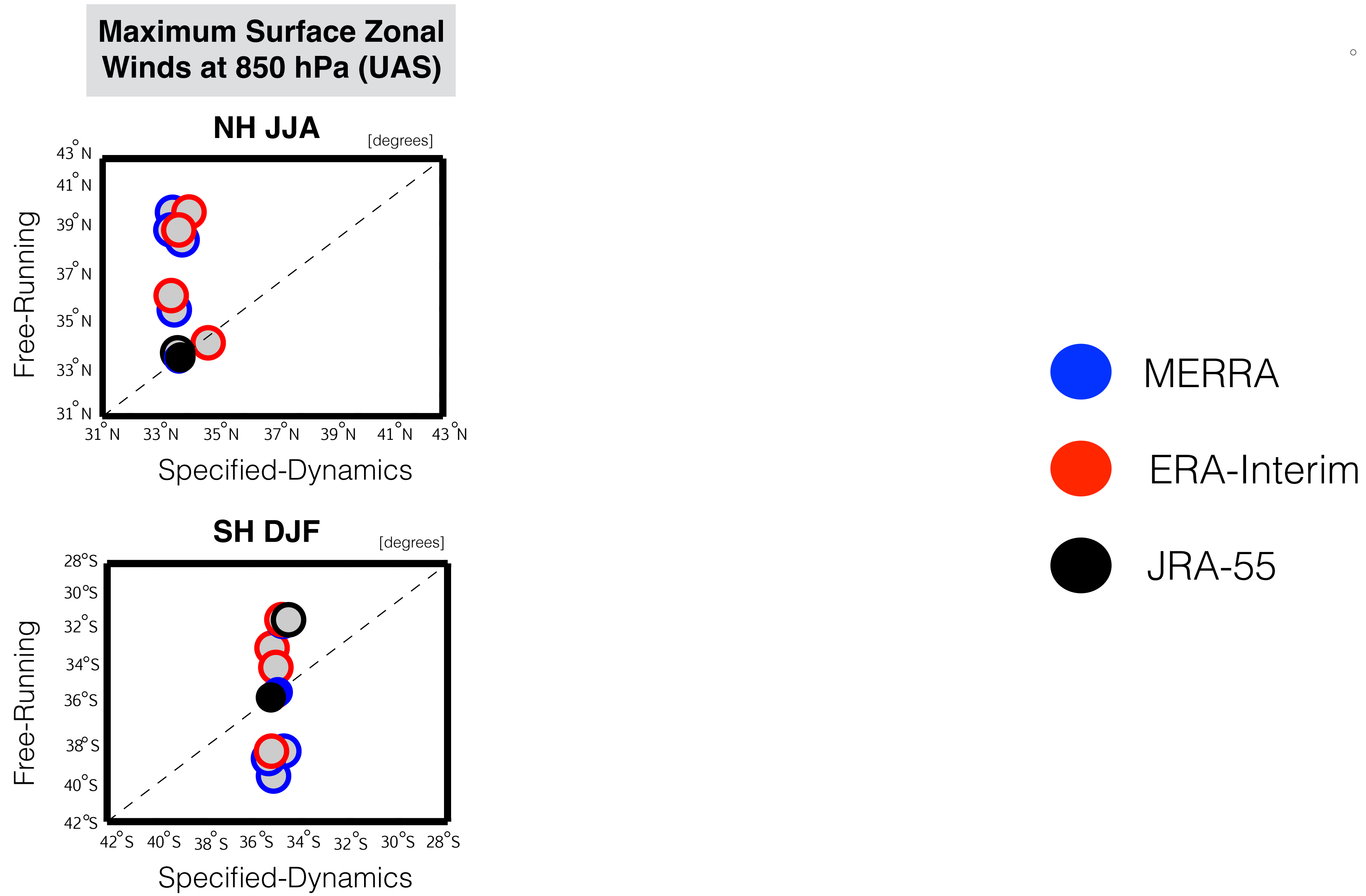
Land-Only Sources

Tracer vs. Hadley Cell Edge



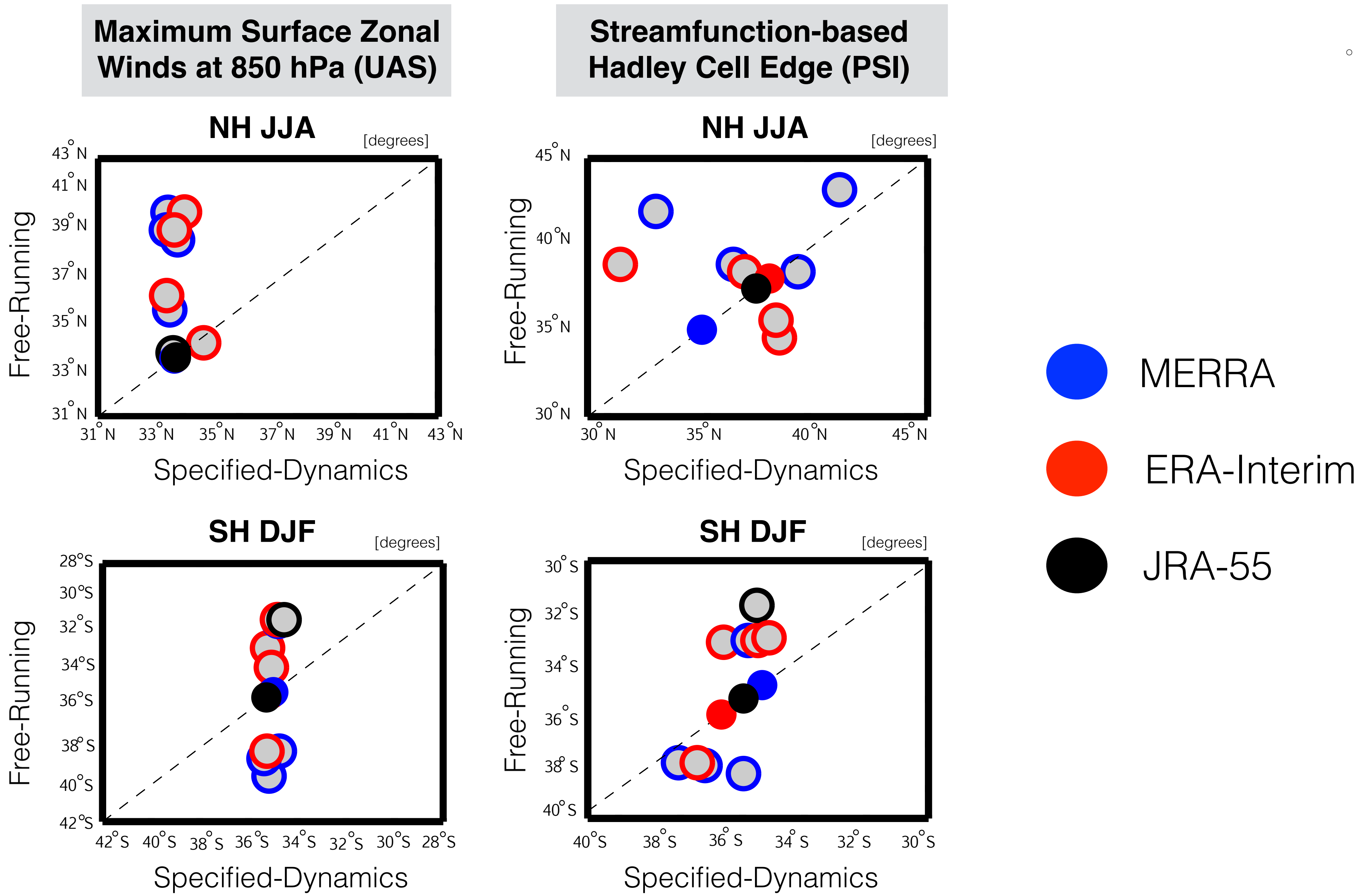
Note that the differences in Hadley Cell edge among specified-dynamics simulations (○) are as large as the differences among free-running simulations (●). This is somewhat surprising.

Transport to the Arctic



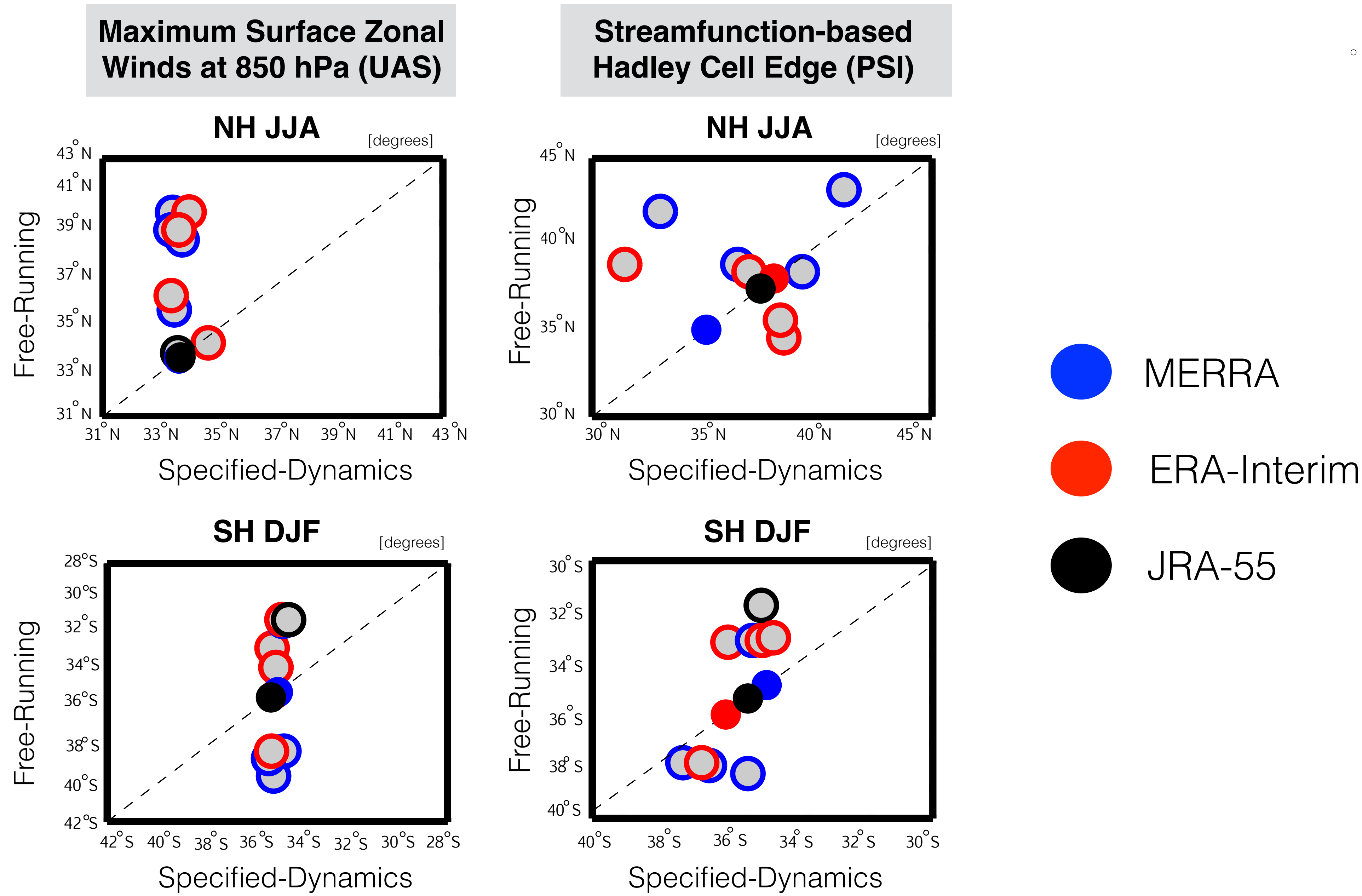
This reflects the fact that, while the zonal winds are well constrained in specified-dynamics simulations…

Transport to the Arctic



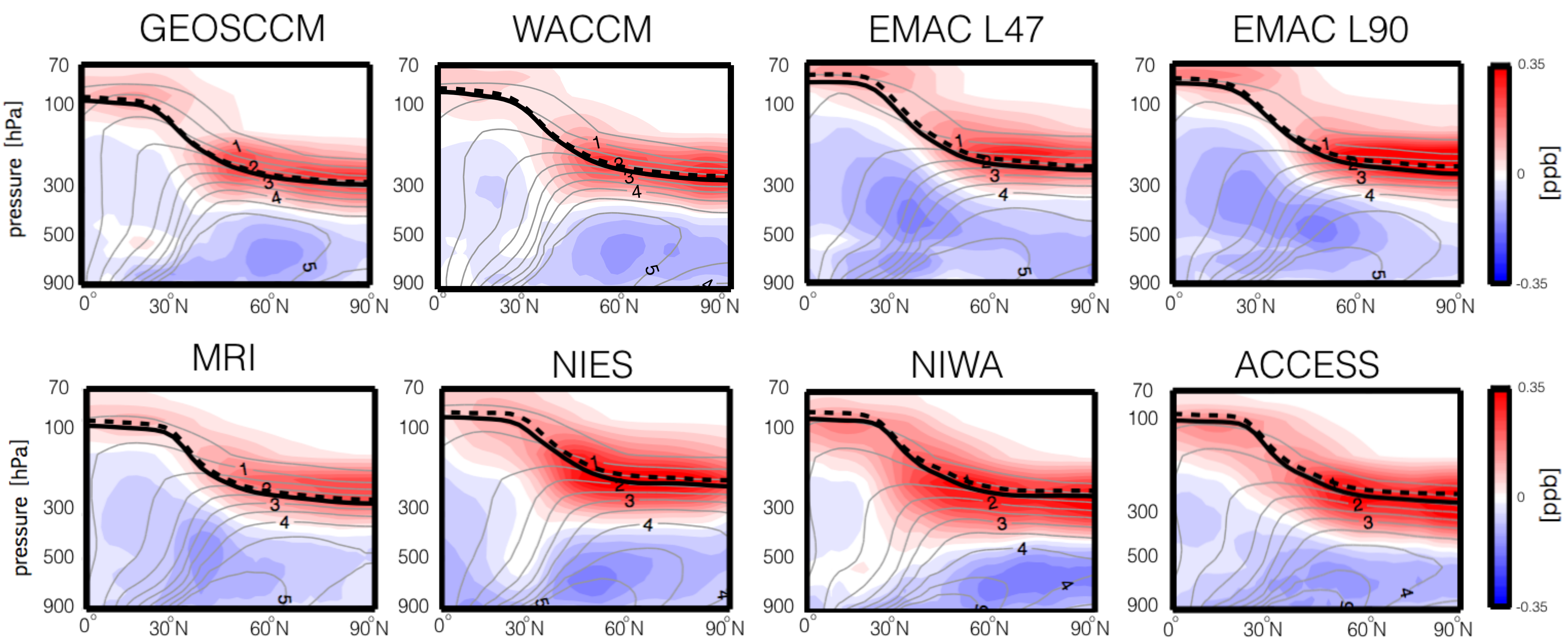
This reflects the fact that, while the zonal winds are well constrained in specified-dynamics simulations, the meridional and vertical component of the flow is not (*Orbe, Plummer et al., In Prep*).

Transport to the Arctic



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.

Changes in Transport to the Arctic over the 21st Century

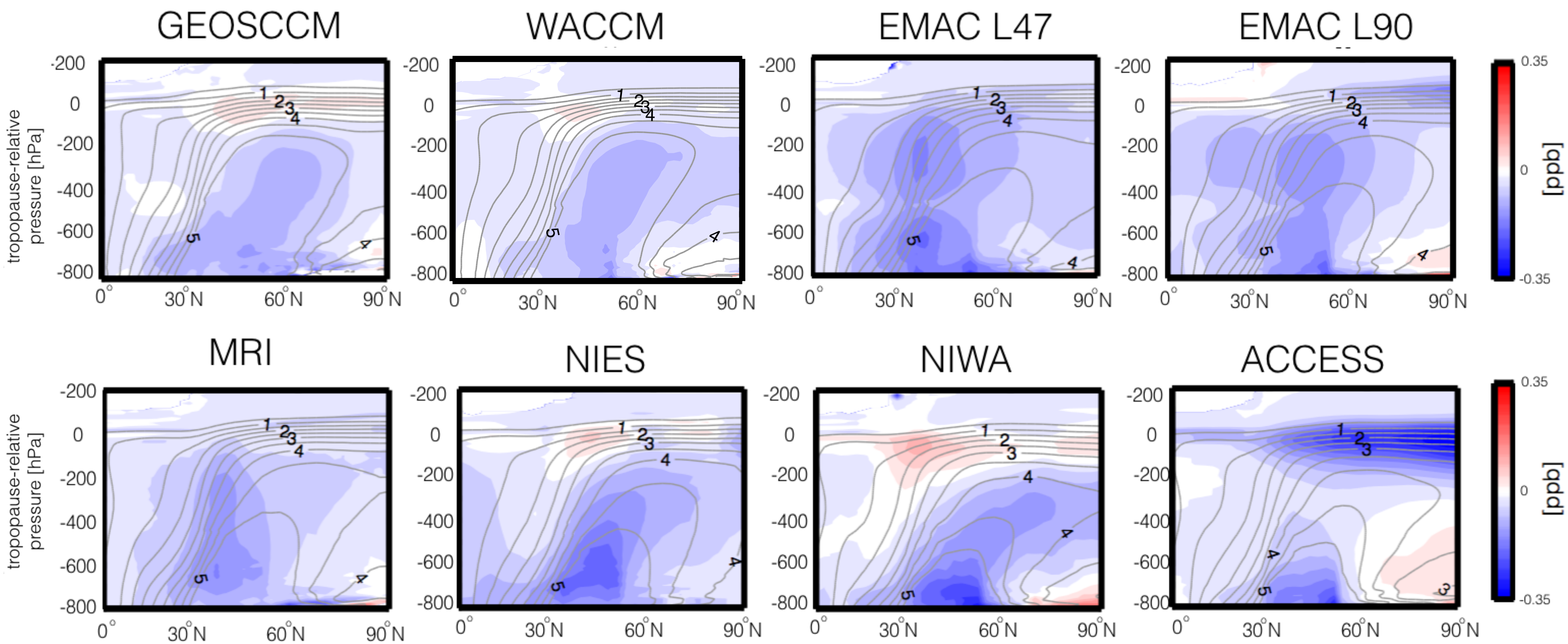


Robust response among CCMI models:

#1 Increased concentrations at the tropopause (——) and UTLS

#2 Reduced concentrations throughout the troposphere

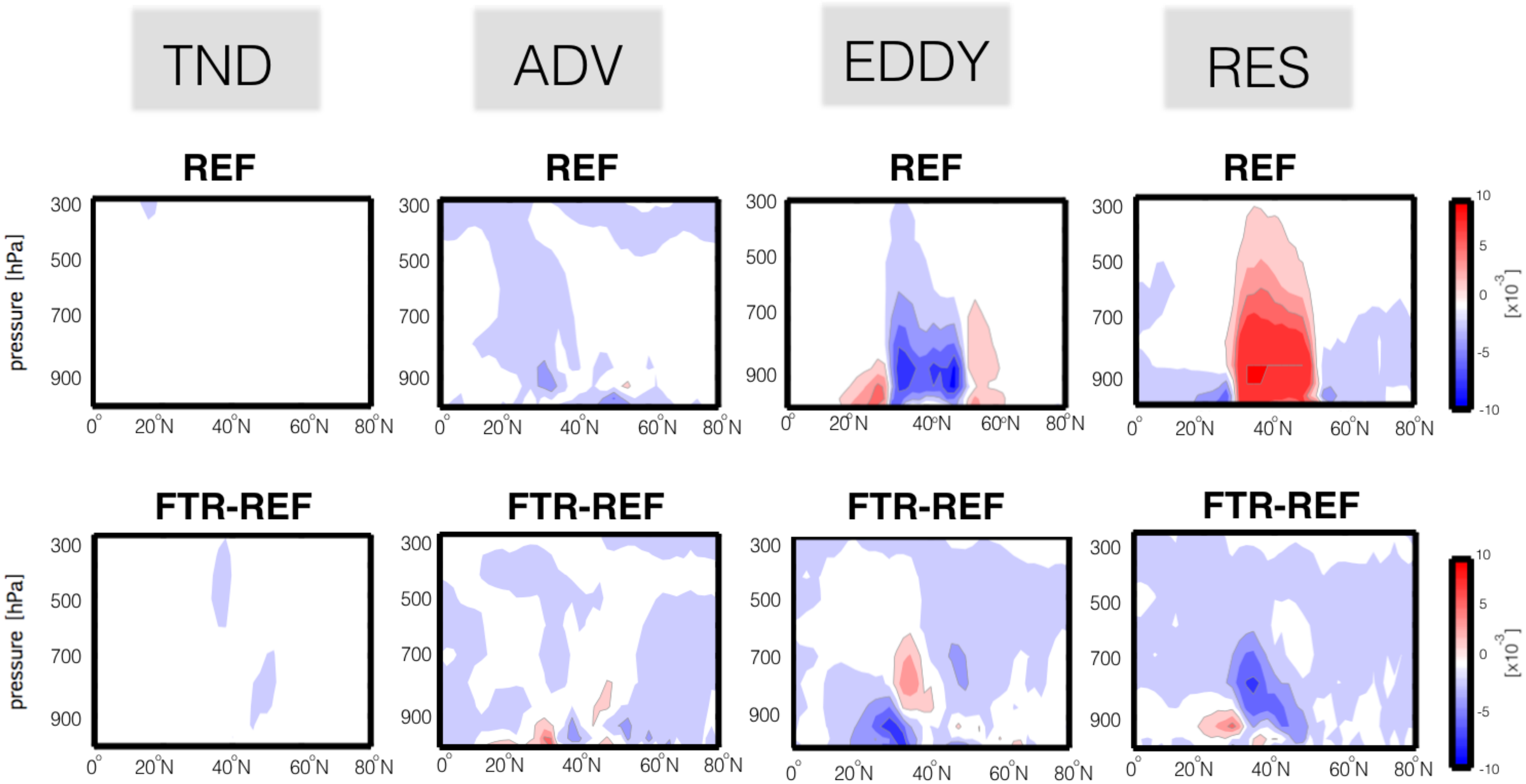
Changes in Transport to the Arctic over the 21st Century



#1 Increased concentrations at the tropopause primarily reflect an increase in tropopause height (*Holzer and Boer (2001), Fang et al. (2011), Doherty et al. (2017), Abalos et al. (2017)).*

#2 Reduced concentrations throughout the troposphere persist.

Changes in Transport to the Arctic over the 21st Century

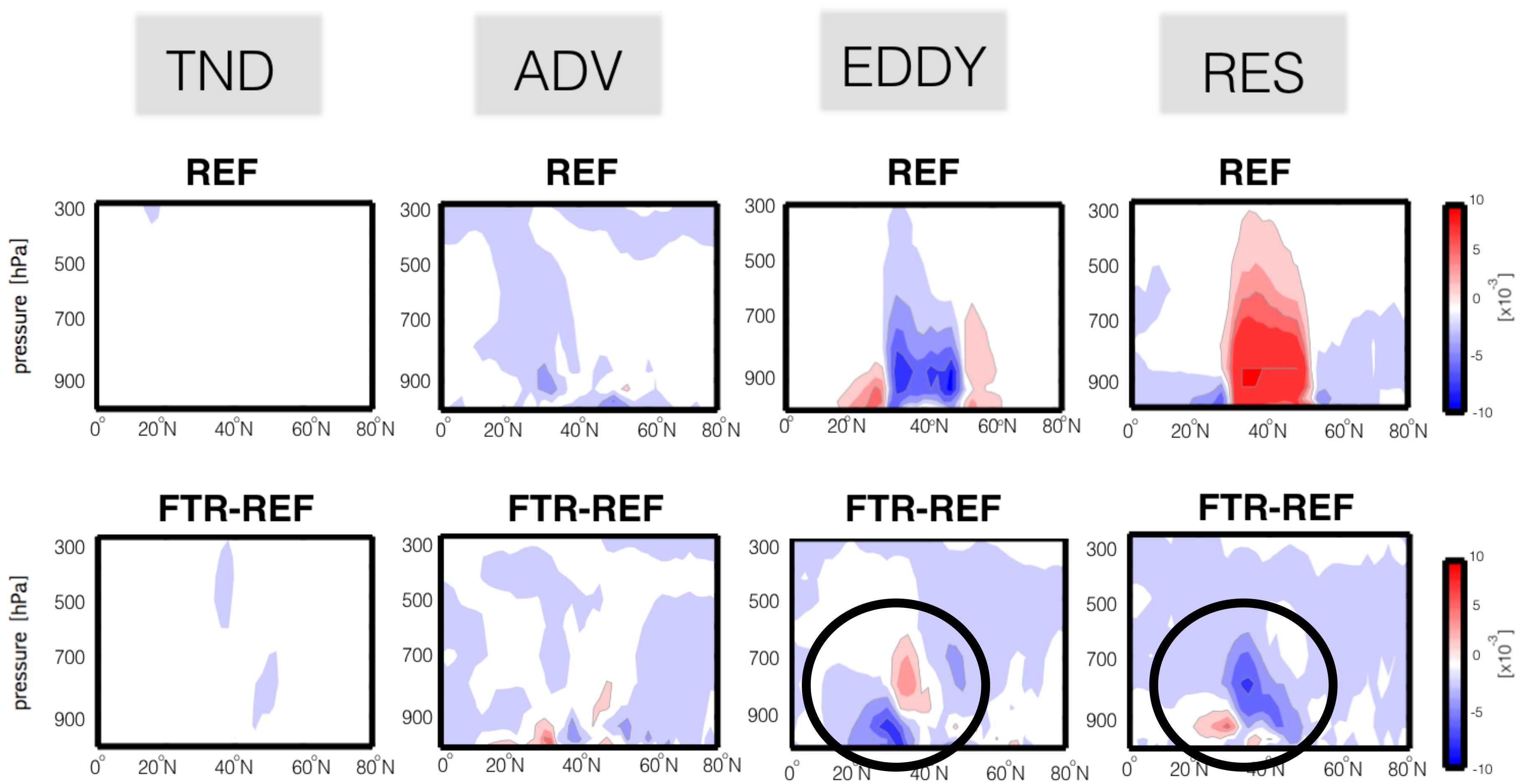


$$\overline{\chi}_t = -\overline{v}^*\overline{\chi}_y - \overline{w}^*\overline{\chi}_z + \nabla \cdot \mathbf{M} + \overline{L} + \overline{X}$$

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.

Changes in Transport to the Arctic over the 21st Century

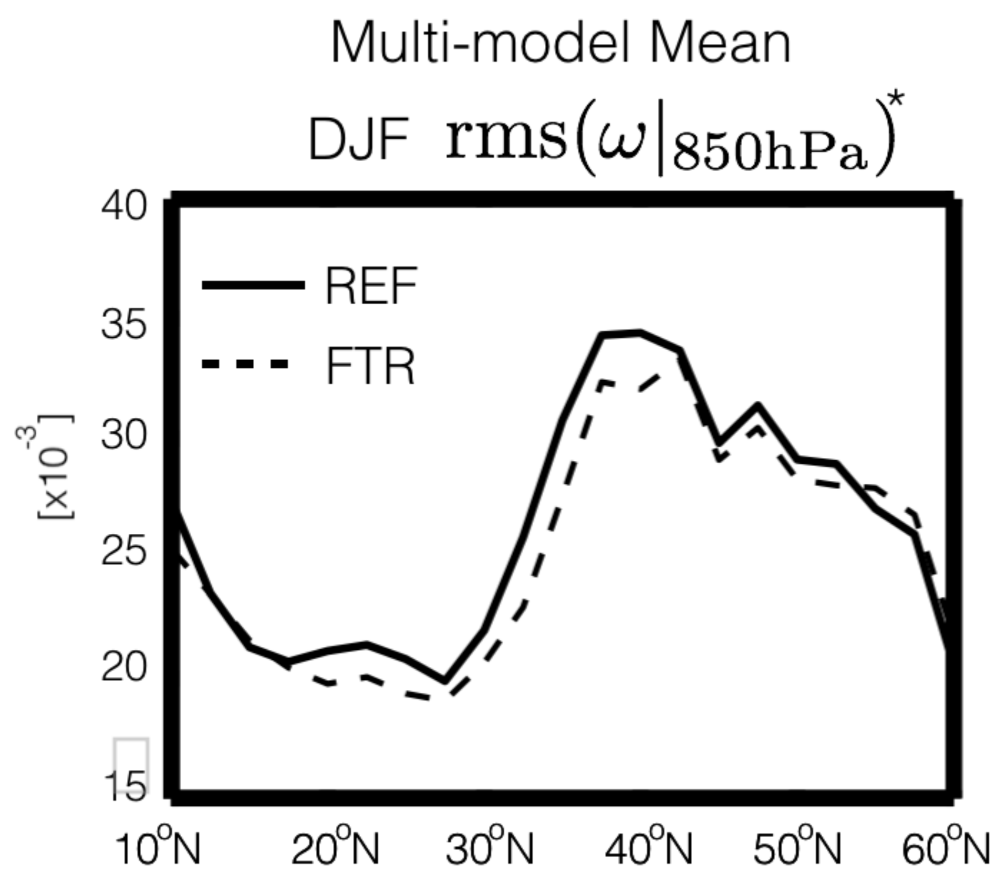


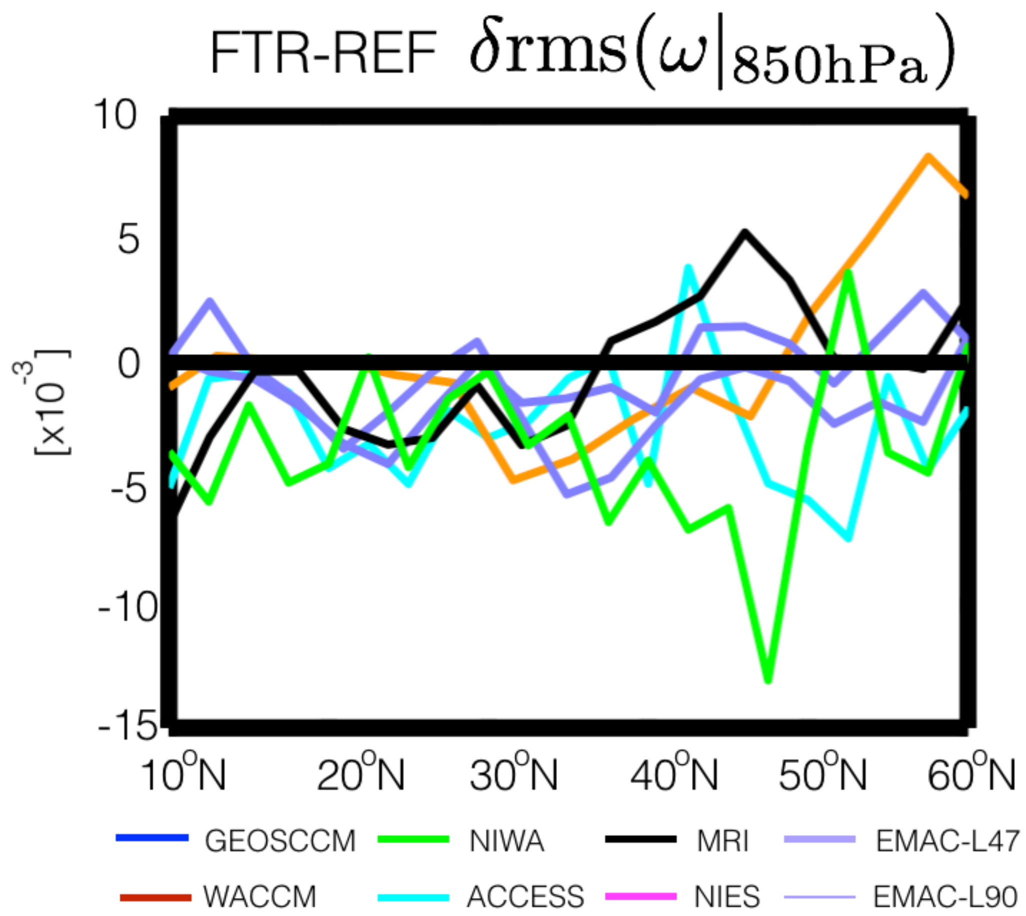
$$\overline{\chi}_t = -\overline{v}^* \overline{\chi}_y - \overline{w}^* \overline{\chi}_z + \nabla \cdot \mathbf{M} + \overline{L} + \overline{X}$$

TND ADV EDDY RES

Changes in budget terms indicate that reduced concentrations of loss tracers are associated with reduced vertical transport by both eddies and convection, not by changes in the mean circulation.

Changes in Transport to the Arctic over the 21st Century





Consist with both reduced convective mass fluxes in the future (*Held and Soden (2006)*) as well as robust decreases in lower tropospheric vertical motion in stationary eddies(*Wills and Schneider, 2016*).

I. Transport to the Arctic

Hindcast (1960-2010) simulations show:

-Large differences in transport to high latitudes among *both* specified-dynamics and free-running simulations.

-Poleward extent of the Hadley Cell controls the poleward transport of tracers emitted only over land, whereas ocean convection matters more for tracers with ocean sources.

-Certain measures of the Hadley Cell are poorly constrained in specified-dynamics simulations, consistent with large differences in meridional transport.

Orbe, C., Yang, H., Waugh, D. W., Zeng, G., Morgenstern, O., Kinnison, D. E. et al. (2018). Large-scale tropospheric transport in the Chemistry-Climate Model Initiative (CCMI) simulations. *Atmospheric Chemistry and Physics*, 18(10), 7217-7235.

Yang, H., Waugh, D. W., Orbe, C., Zeng, G., Morgenstern, O., Kinnison, D. E. et al. (2018). Tracer Transport into the Arctic: Relative Roles of the Midlatitude Jet and the Hadley Cell Edge. *Under Review in Atmospheric Chemistry and Physics Discussions.*

Orbe, C., D. Plummer., Waugh, D. W., Yang H., and CCMI Co-authors, Description of the Specified-Dynamics Experiment in the Chemistry Climate Model Initiative (CCMI) (*In Prep*)

I. Transport to the Arctic

Future (1960-2100) simulations show:

-Consistent increase in transport of NH midlatitude source tracers into the tropopause/lower stratosphere, primarily due to an increase in tropopause height.

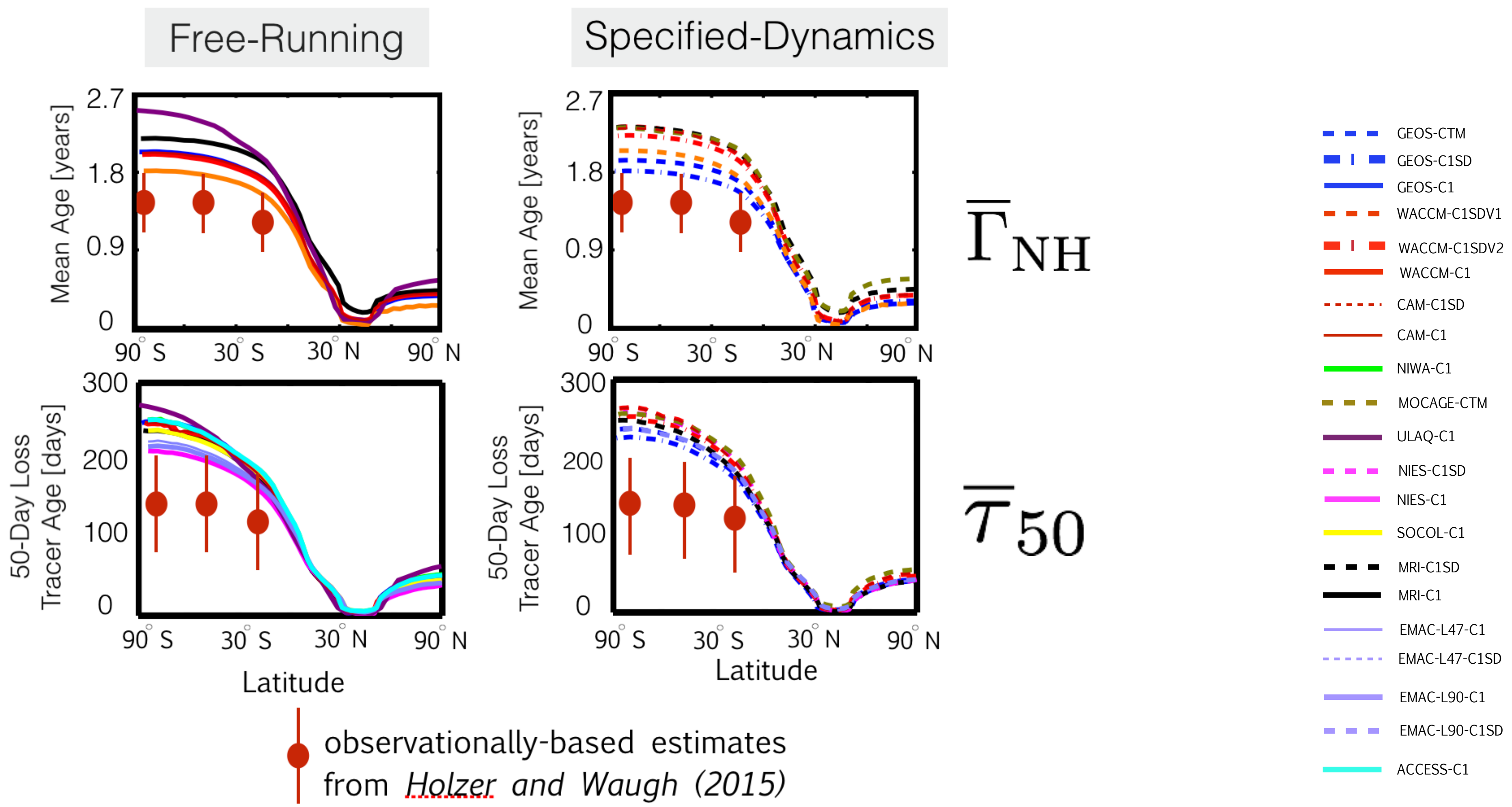
-Reduced vertical transport out of the lower troposphere, consistent with weaker vertical eddies and reduced convective mass fluxes.

Orbe, C., Abalos M., Waugh, D. W., Wang H., et al. Future Projections of Large-scale Tropospheric Transport Changes in the Chemistry-Climate Model Initiative (CCMI) simulations, (*In Prep*).

Interhemispheric Transport

- The differences in interhemispheric transport are also large (30-40%) and no better constrained among the SD simulations (versus FR).

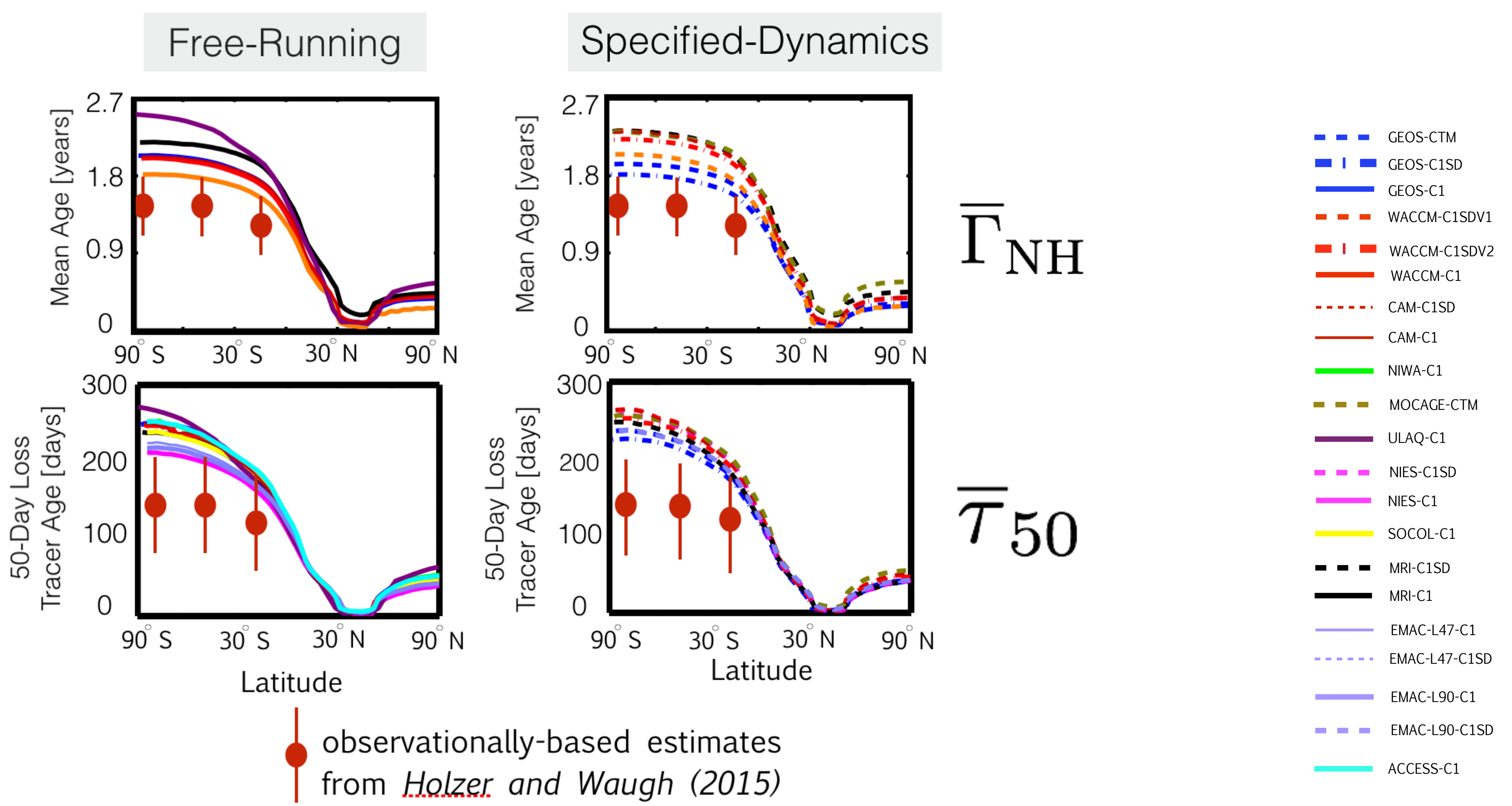
900-1000 mb Annual Mean 50-Day Tracer Ages ($\overline{\tau}_{50}$)
and the NH Midlatitude Mean Age ($\overline{\Gamma}_{NH}$)



Interhemispheric Transport

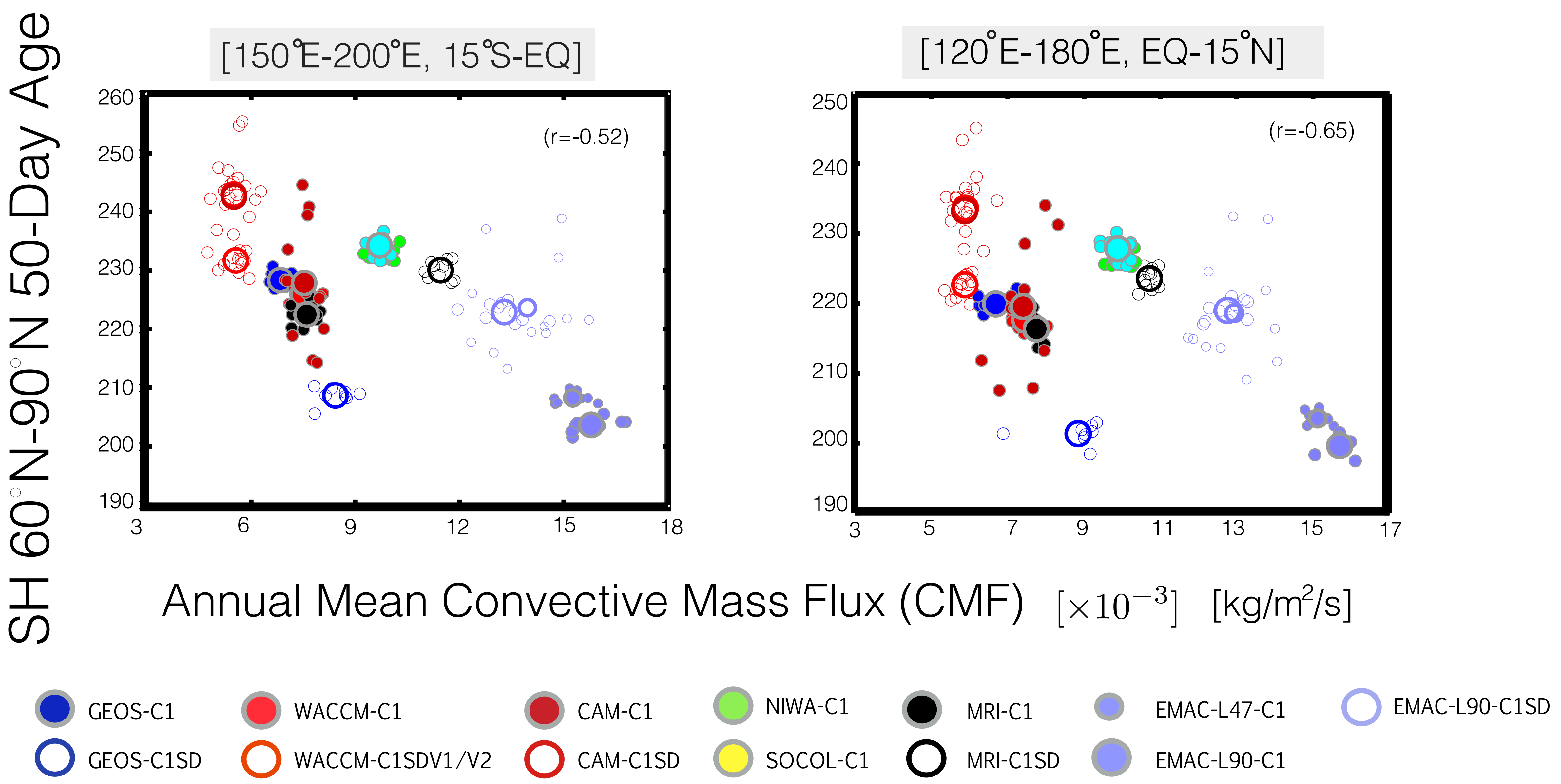
- Sparse observationally-based estimates of the mean age and 50-day tracer age (●) indicate that all models tend to feature too slow transport (*Holzer and Waugh (2015)*).

900-1000 mb Annual Mean 50-Day Tracer Ages ($\overline{\tau}_{50}$)
and the NH Midlatitude Mean Age ($\overline{\Gamma}_{NH}$)



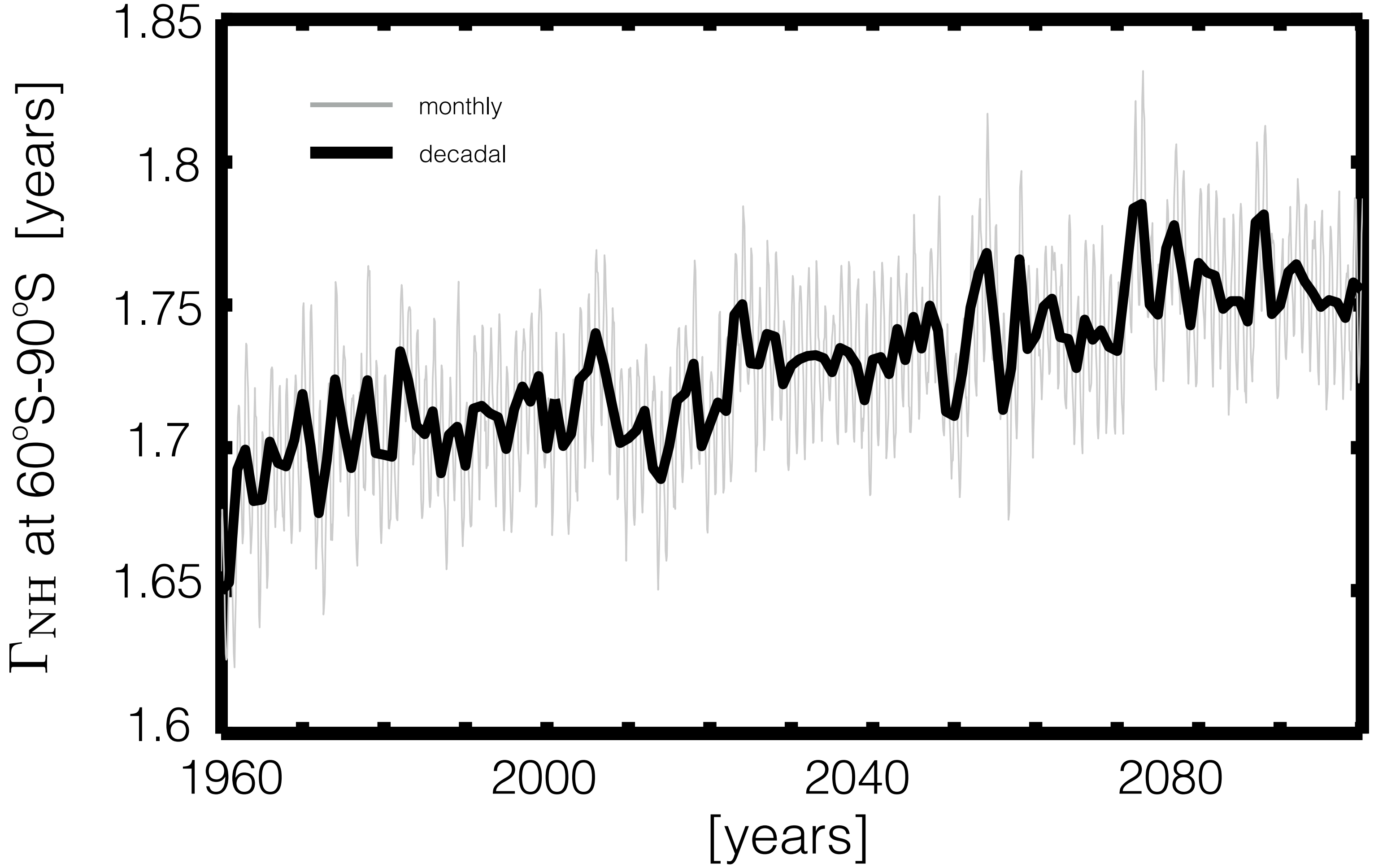
Interhemispheric Transport

- In the annual mean, SH tracer age differences correlate best with differences in (parameterized) convection in the tropics and northern subtropics, particularly over the Pacific Ocean.



Changes in Interhemispheric Transport over the 21st Century

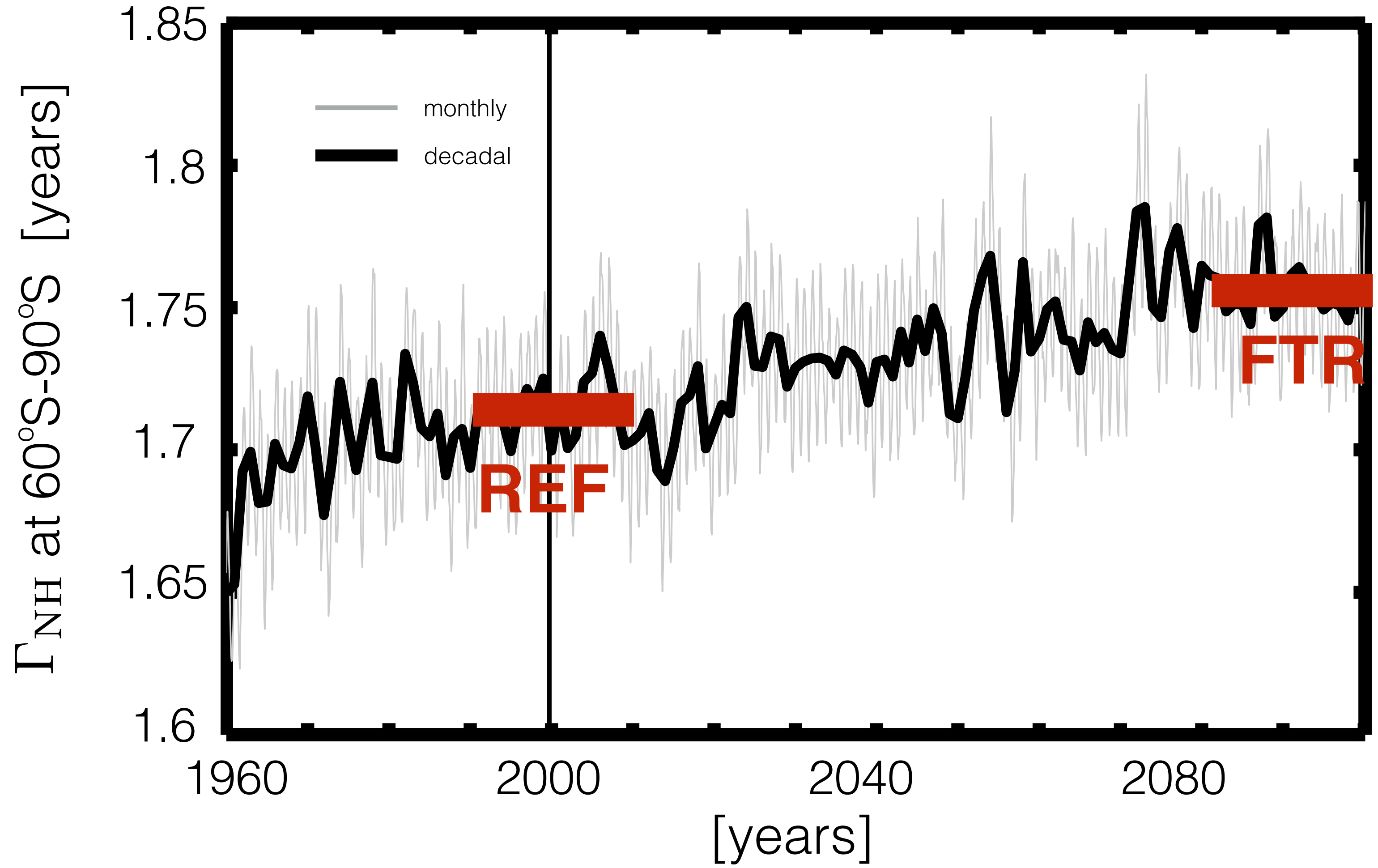
1960-2099 NH Midlatitude
Mean Age over the Southern Pole*



- Some models project slower (5-10%) interhemispheric transport, consistent with previous studies (*Holzer and Boer (2001)).*

Changes in Interhemispheric Transport over the 21st Century

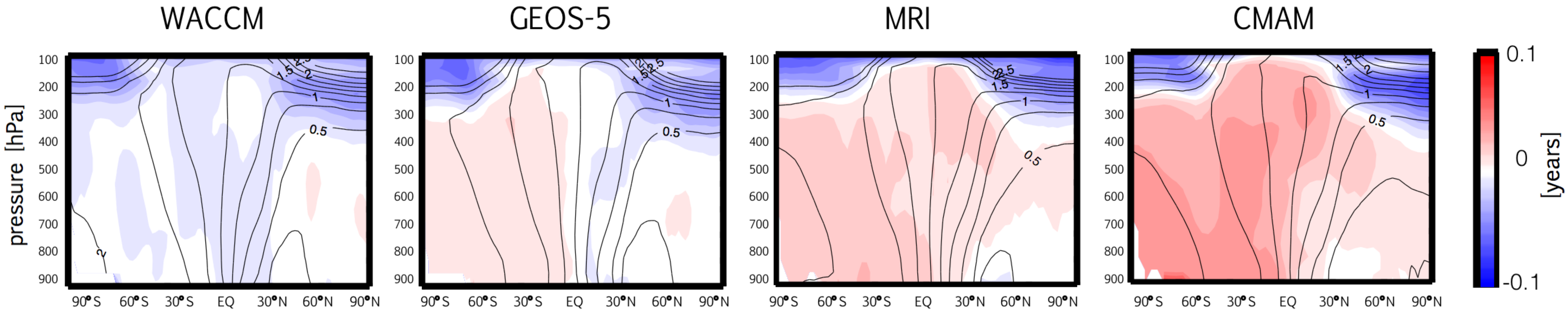
1960-2099 NH Midlatitude
Mean Age over the Southern Pole*



- Some models project slower (5-10%) interhemispheric transport, consistent with previous studies (*Holzer and Boer (2001)*).

Changes in Interhemispheric Transport over the 21st Century

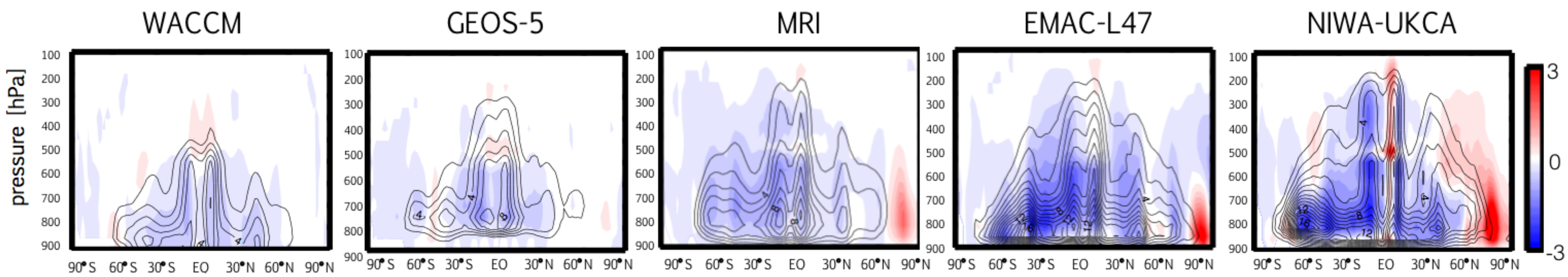
FTR-REF* Changes in Northern Midlatitude Mean Age (Γ_{NH})



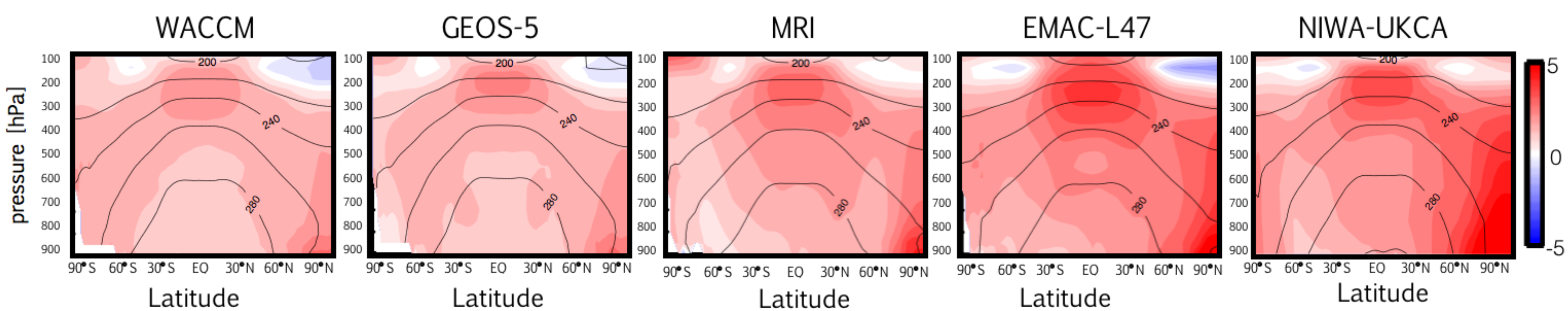
Lack of agreement among models, however, with some showing stronger responses than others.

Changes in Interhemispheric Transport over the 21st Century

FTR-REF* Convective Mass Flux Changes (CMF: 10^{-3} kg/m^2/s)



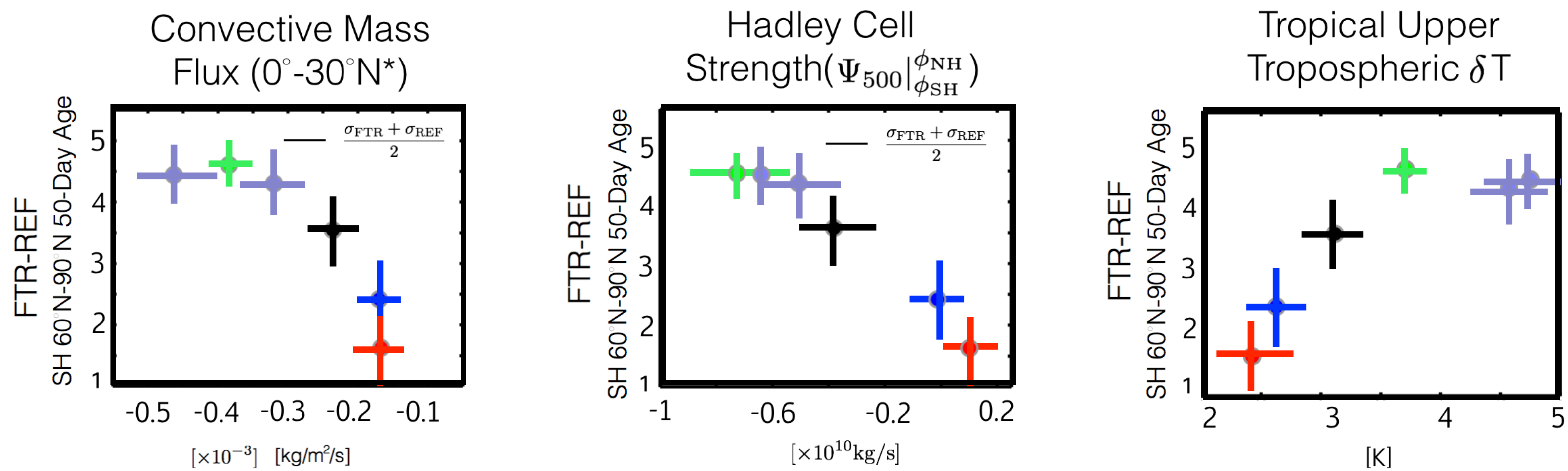
FTR-REF* Temperature Changes [K]



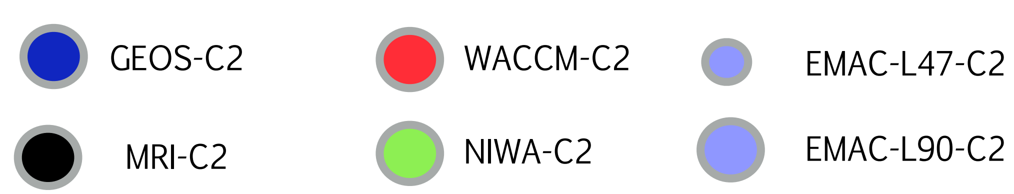
*2080-2100 - 1990-2010

Changes in interhemispheric transport are correlated with changes in convective mass fluxes and the amount of upper tropospheric tropical warming.

Changes in Interhemispheric Transport over the 21st Century



Changes in interhemispheric transport are correlated with changes in convective mass fluxes and the amount of upper tropospheric tropical warming.



(Orbe, Abalos et al. In Prep)

II. Interhemispheric Transport

Hindcast (1960-2010) simulations show:

-Large differences in interhemispheric transport among *both* specified-dynamics and free-running simulations.

-Strength of (sub)tropical convection is positively correlated with differences in the efficiency of interhemispheric transport among models.

Orbe, C., Yang, H., Waugh, D. W., Zeng, G., Morgenstern, O., Kinnison, D. E. et al. (2018). Large-scale tropospheric transport in the Chemistry-Climate Model Initiative (CCMI) simulations. *Atmospheric Chemistry and Physics, 18(10), 7217-7235.*

Orbe, C., Plummer D., Waugh, D. W., Yang H., and CCMI Co-authors, Description of the Specified-Dynamics Experiment in the Chemistry Climate Model Initiative (CCMI) (*In Prep*)

II. Interhemispheric Transport

Future (1960-2100) simulations show:

-Weaker (~5-10%) interhemispheric transport by the end of the 21st century, although some models show no significant changes.

-Interhemispheric transport response is correlated with changes in the strength of lower tropospheric convection and the amount of upper tropospheric tropical warming.

Orbe, C., Abalos M., Waugh, D. W., Wang H., et al. Future Projections of Large-scale Tropospheric Transport Changes in the Chemistry-Climate Model Initiative (CCMI) simulations. (*In Prep*).

Relevant Publications

Published:

Orbe, C., Yang, H., Waugh, D. W., Zeng, G., Morgenstern, O., Kinnison, D. E. et al. (2018). Large-scale tropospheric transport in the Chemistry-Climate Model Initiative (CCMI) simulations. *Atmospheric Chemistry and Physics,* 18(10), 7217-7235.

Wu, X., Yang, H., Waugh, D.W., Orbe, C., Tilmes, S., and Lamarque J.F., “Spatial and Temporal Variability of Interhemispheric Transport Times,” Atmospheric Chemistry and Physics 18.10 (2018): 7439-7452.

In Prep/Under Review:

Yang, H., Waugh, D. W., Orbe, C., Zeng, G., Morgenstern, O., Kinnison, D. E. et al. (2018). Tracer Transport into the Arctic: Relative Roles of the Midlatitude Jet and the Hadley Cell Edge. (*Under Review in Atmospheric Chemistry and Physics Discussions.)*

Orbe, C., Plummer D., Waugh, D. W., Yang H., et al., Description of the Specified-Dynamics Experiment in the Chemistry Climate Model Initiative (CCMI) (*In Prep*)

Orbe, C., Abalos M., Waugh, D. W., Wang H., et al. Future Projections of Large-scale Tropospheric Transport in the Chemistry-Climate Model Initiative (CCMI) simulations. (*In Prep*).