Impact of Numerics on Stratospheric Transport

Insights from Theory, Idealized and Comprehensive* Models

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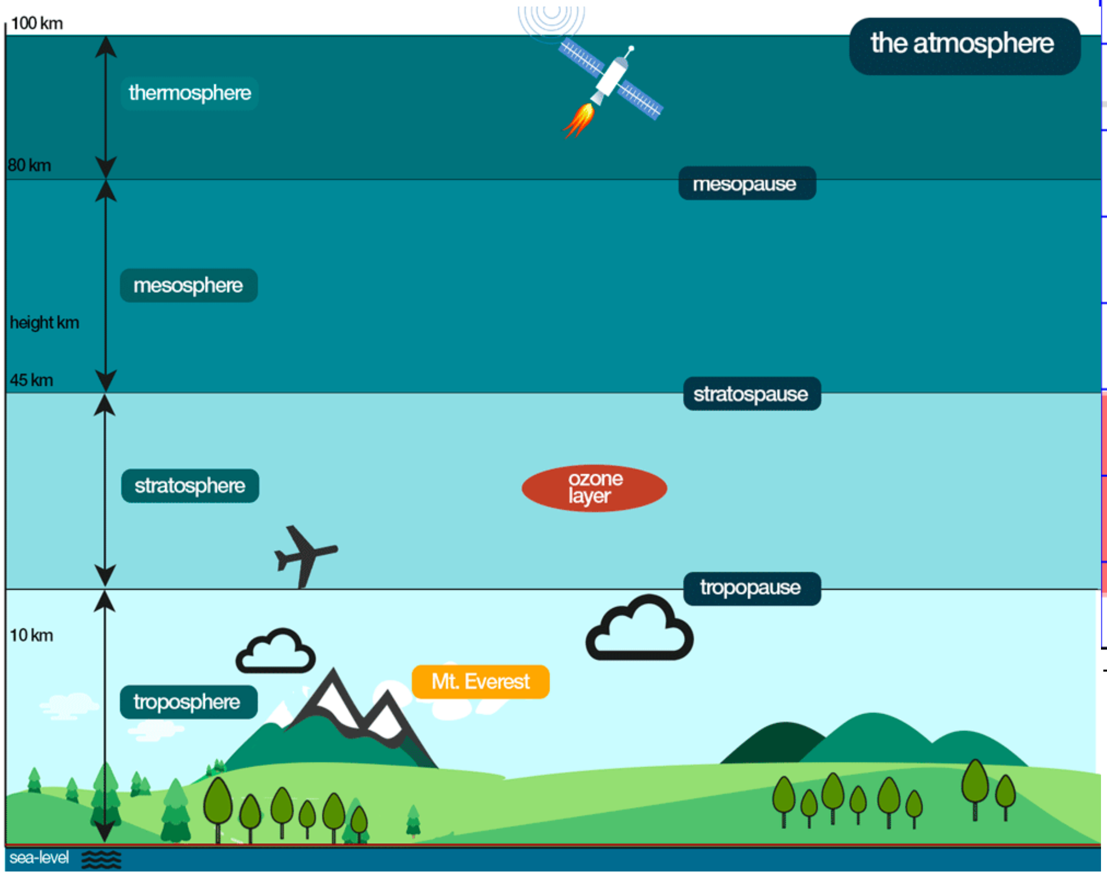
the atmosphere
100 km
80 km
45 km
10 km
height km
thermosphere
mesopause
mesosphere
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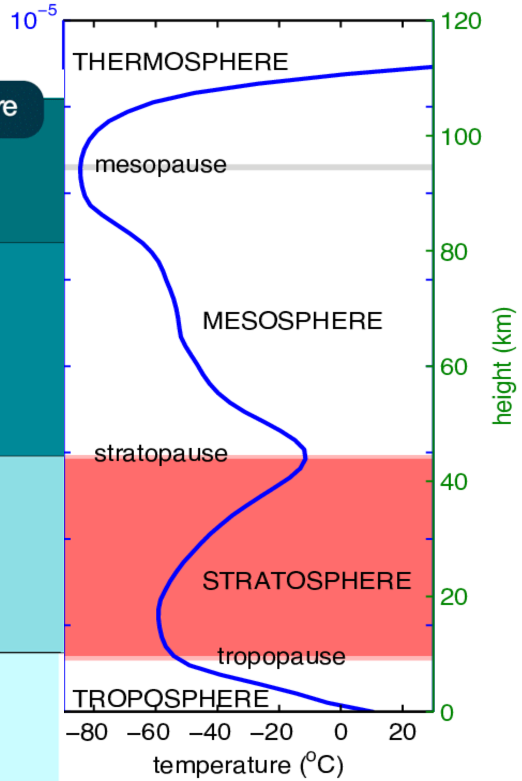
ozone layer
tropopause
troposphere
Mt. Everest
sea-level


THERMOSPHERE
mesopause
MESOSPHERE
stratopause
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10^{-5}
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20
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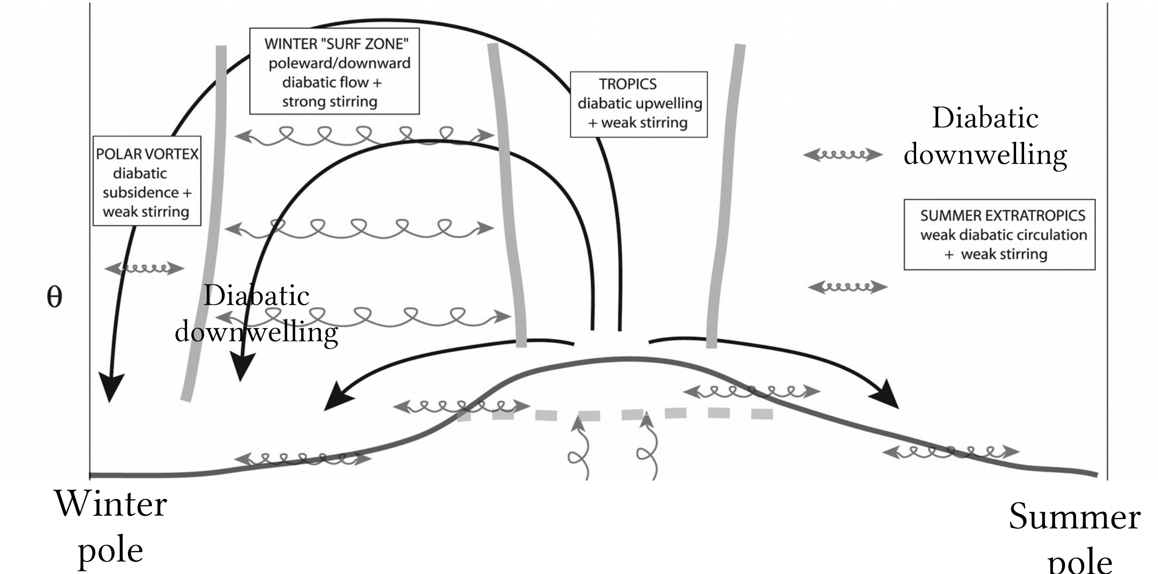
height (km)
−80 −60 −40 −20 0 20
temperature (°C)

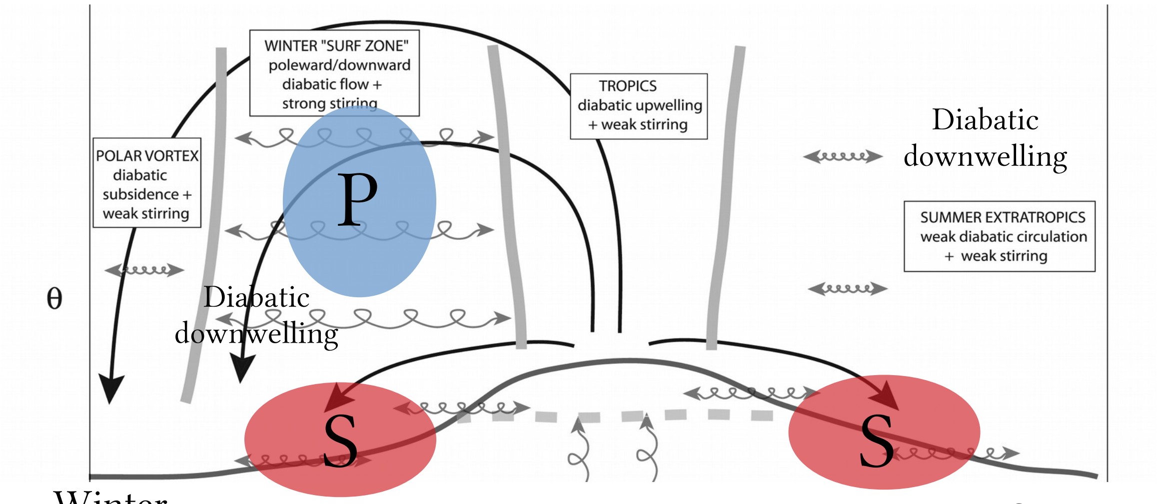
Large-Scale (wave-driven) Circulation of the Stratosphere a.k.a. BDC



(Figure: Marianna Linz)

- Brewer-Dobson Circulation (BDC) is **wave-driven**
- Tropical upwelling, extratropical downwelling of mass

Large-Scale (wave-driven) Circulation of the Stratosphere a.k.a. BDC



Winter pole

Summer pole

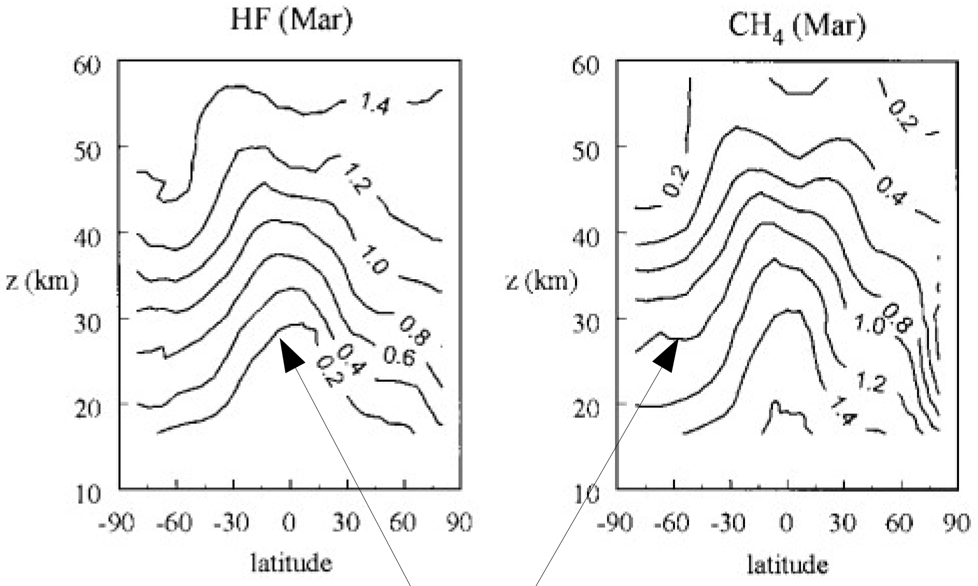
P : planetary-scale wave drag

S : synoptic-scale wave drag

(Figure: Marianna Linz)

- Brewer-Dobson Circulation (BDC) is **wave-driven**
- Tropical upwelling, extratropical downwelling of mass
- Winter midlatitude “surf zone” driven by planetary wave breaking
- Quiescent summer hemisphere

Large-Scale circulation (more so than chemistry) determines trace gas distribution



(Figure: Plumb 2002)

Similar contours for two trace gases **despite** different sources/sinks and opposite gradients

Spread in ozone recovery projections: differences rooted in simulated transport

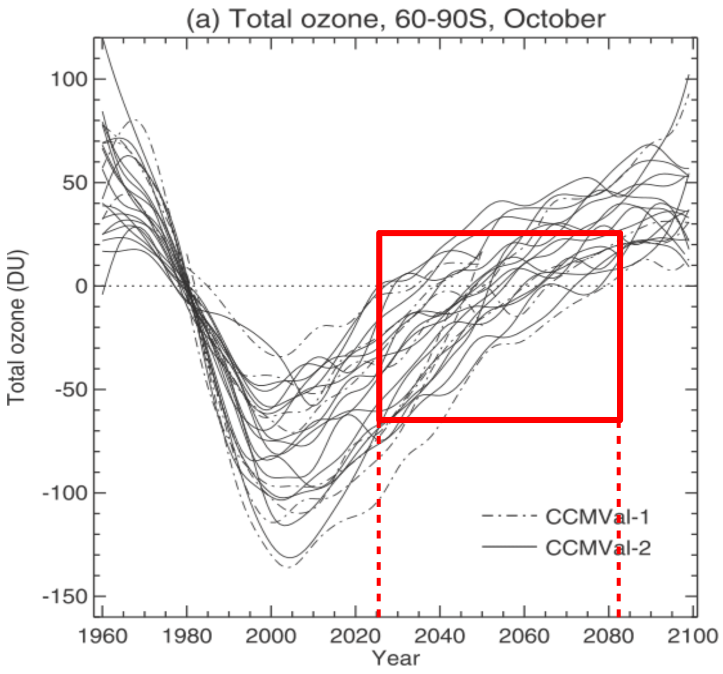
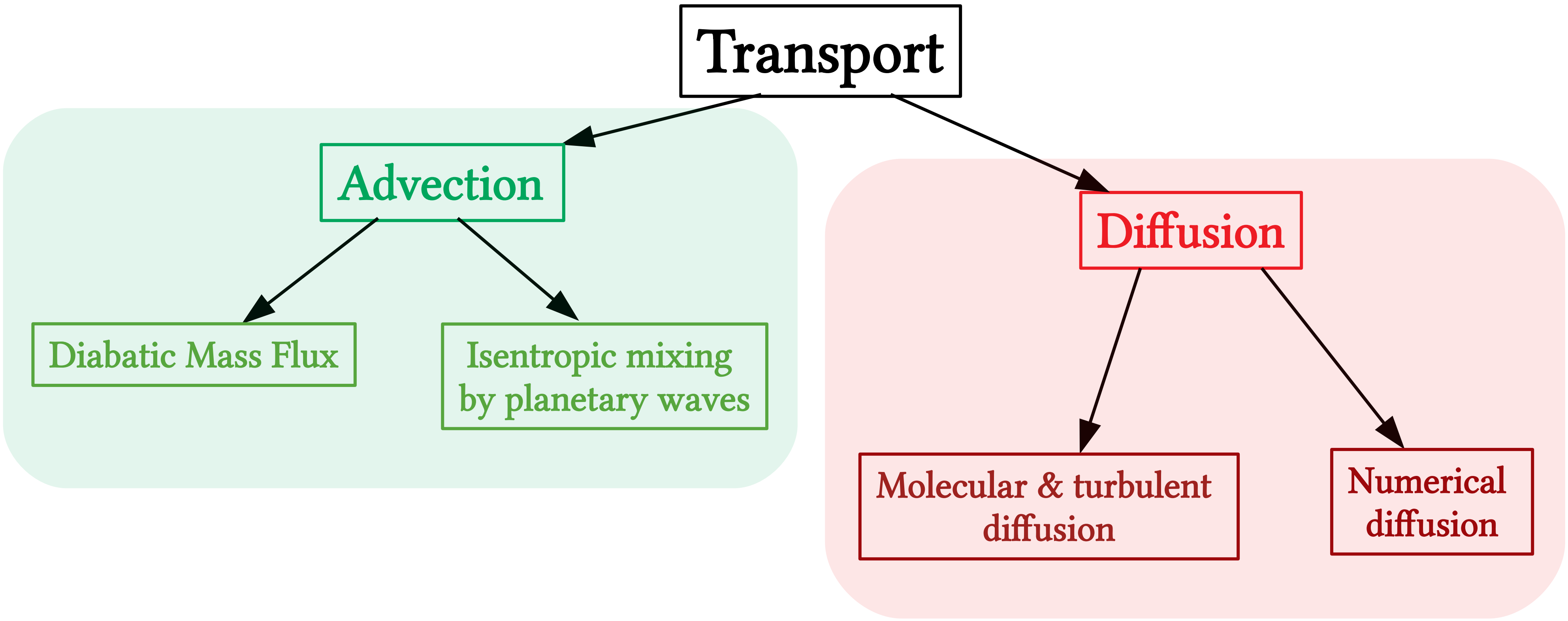


Fig : Model projections of ozone recovery (from Karpechko et al. 2013)

- A **spread of over 60 years** in ozone recovery times among state-of-the-art models.
- Differences correlated strongest with transport, not chemistry (Karpechko et al. 2013)
- Inaccuracies in ozone recovery essentially a transport problem!

Various Processes Influence Stratospheric Transport



Age-of-air: an idealized tracer to assess transport

- Age of air of an air-mass quantifies the time elapsed last surface contact. (Hall and Plumb 1994, Waugh and Hall ‘02)
- **A measure of transport timescales** in the atmosphere
- Age is an idealized tracer with a source in time. **Independent of chemistry/parameterizations, only depends on the tracer advection suite of a model.**

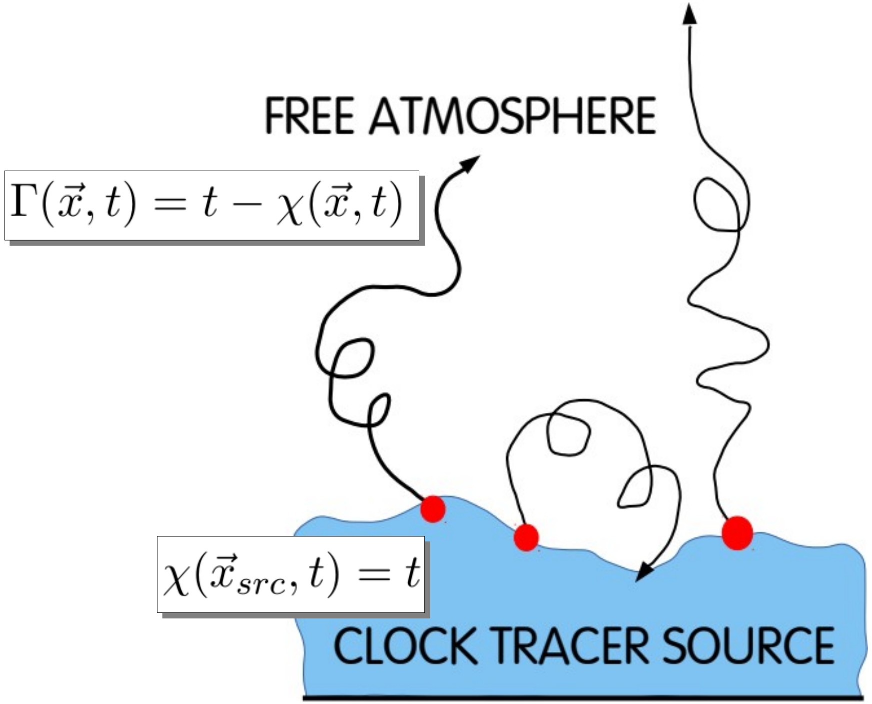
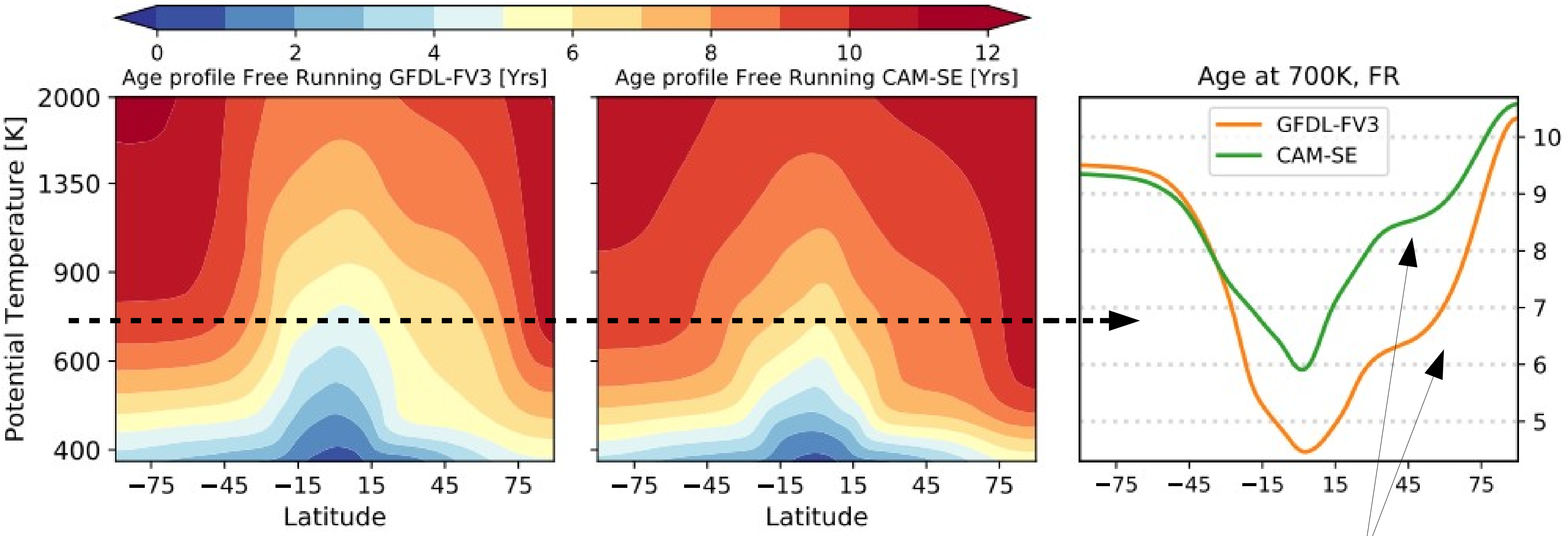


Fig: Computing age in models using clock tracer

Even two of the most modern dynamical cores exhibit very different transport!



FV3

FINITE VOLUME

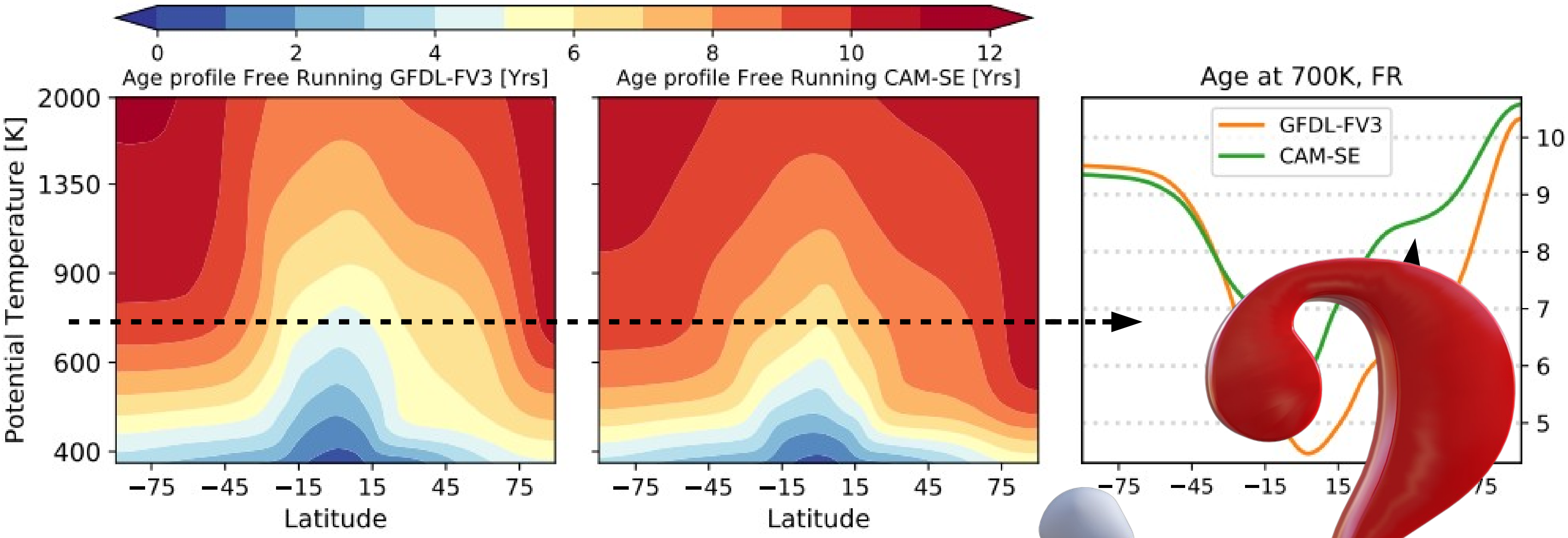
SE

SPECTRAL ELEMENT

Age of air in SE is 40% older than FV3

Transport differences obtained at the “dynamical core level”

Even two of the most modern dynamical cores exhibit very different transport!



FV3
FINITE VOLUME

SE
SPECTRAL ELEMENT

Age [illegible] air in SE is [illegible]% older than FV3

Transport differences obtained at the "dynamical core level"

A transport benchmark test to assess transport in different dynamical cores

A Proposal for the Intercomparison of the Dynamical Cores of Atmospheric General Circulation Models

Isaac M. Held*
and Max J. Suarez**

1994

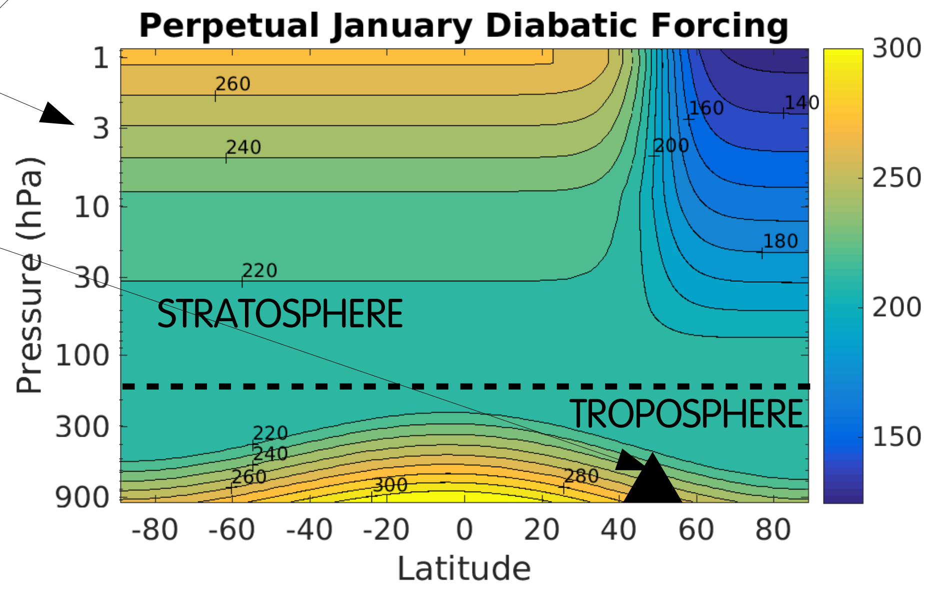
Configuration of the Benchmark test: Dynamics

- We build upon the Held-Suarez benchmark test for model dynamics
- Dynamics: Impose Held-Suarez + Polvani-Kushner type diabatic forcing i.e.,

  + Short-wave heating ⟶ Newtonian relaxation to prescribed temperature profile
  + PBL ⟶ Rayleigh damping
  + GW dissipation ⟶ model sponge
  + Stationary wave forcing ⟶ wave-2 topography

- Focus on large-scale dynamics and transport coupling. **No uncertainty from parameterizations**.

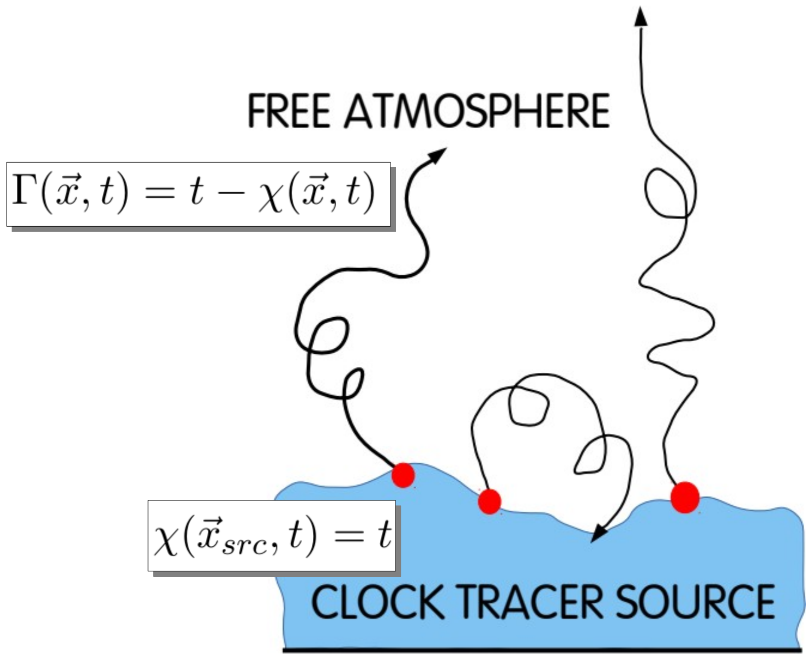
$$\frac{\partial T}{\partial t} = \cdots - k_T(\phi,\sigma)\left[T - T_{eq}(\phi,p)\right]$$



Held-Suarez + Polvani-Kushner (HSPK) setup

Configuration of the Benchmark test: Transport

- Transport: use a **clock tracer** at the surface to compute the age-of-air in idealized models
- Integrate models for 10,000 model days with **no seasonal cycle – perpetual January conditions**
- We call this – the **Free Running (FR) test**

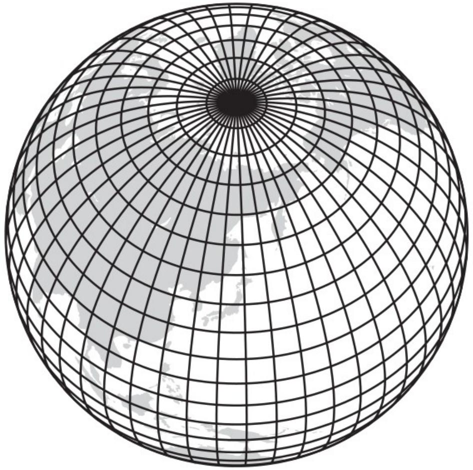


Quantifying transport in models using clock tracer

We benchmark 4 dynamical cores from 2 modeling centers ...

↓ Spectral-methods based	↓ Finite Volume based	
GFDL-PS PSEUDOSPECTRAL	**CAM-FV** CAM FINITE VOLUME	⟵ Traditional cores
CAM-SE CAM SPECTRAL ELEMENT	**GFDL-FV3** CUBED SPHERE FINITE VOLUME	⟵ Modern cores

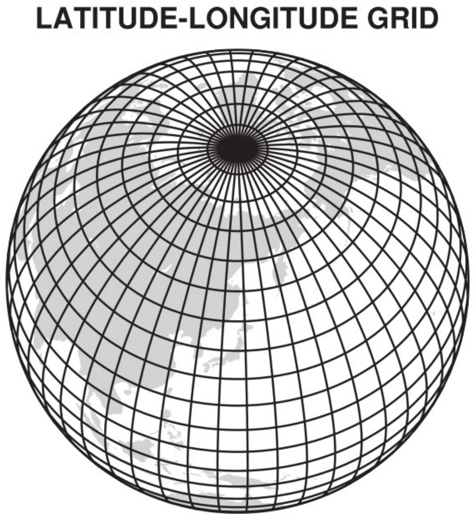
LATITUDE-LONGITUDE GRID



CAM-FV

CAM FINITE VOLUME

Differences in numerical grids



CAM-FV

CAM FINITE VOLUME

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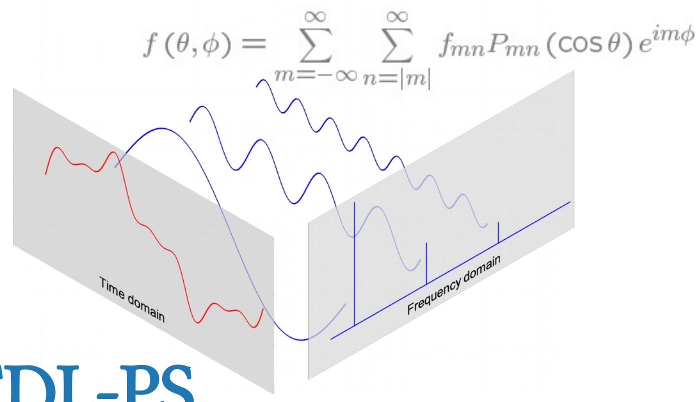
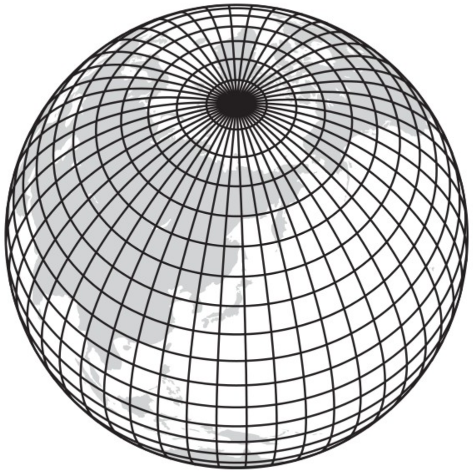


GFDL-PS

PSEUDOSPECTRAL

Differences in numerical grids

LATITUDE-LONGITUDE GRID

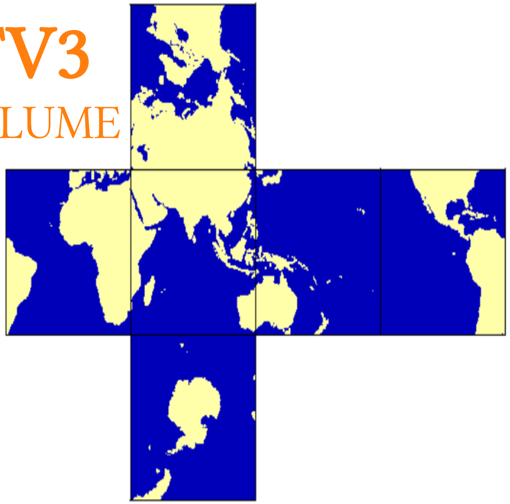


CAM-FV

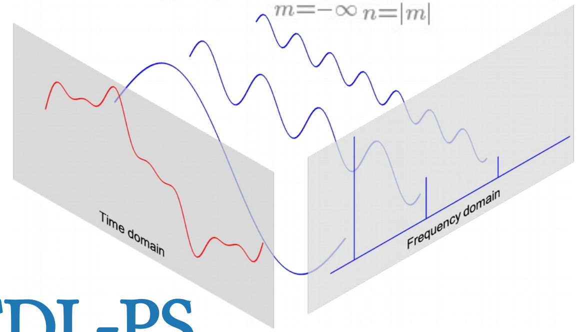
CAM FINITE VOLUME

GFDL-FV3

CUBED SPHERE FINITE VOLUME



$$f(\theta,\phi) = \sum_{m=-\infty}^{\infty} \sum_{n=|m|}^{\infty} f_{mn} P_{mn}(\cos\theta)\, e^{im\phi}$$

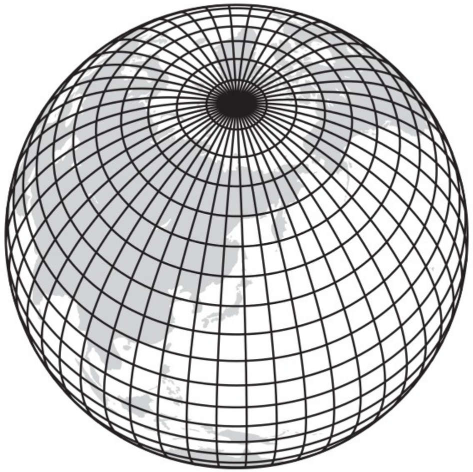


GFDL-PS

PSEUDOSPECTRAL

Differences in numerical grids

LATITUDE-LONGITUDE GRID

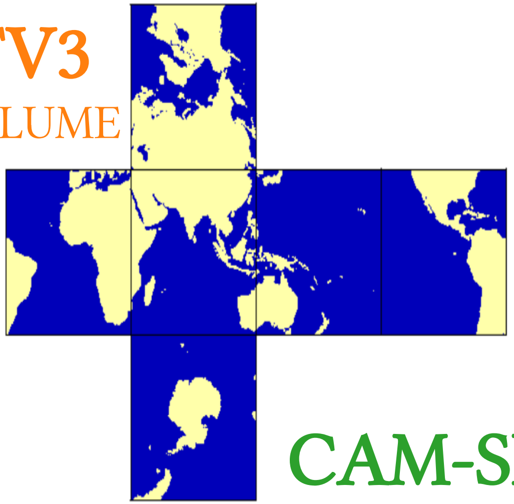


CAM-FV

CAM FINITE VOLUME

GFDL-FV3

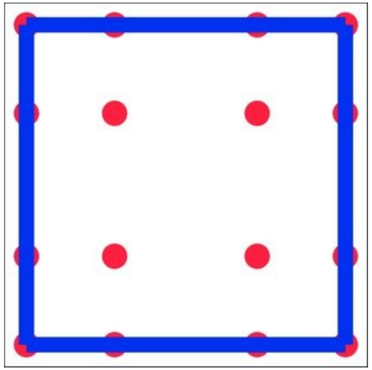
CUBED SPHERE FINITE VOLUME



CAM-SE

CAM SPECTRAL ELEMENT

+



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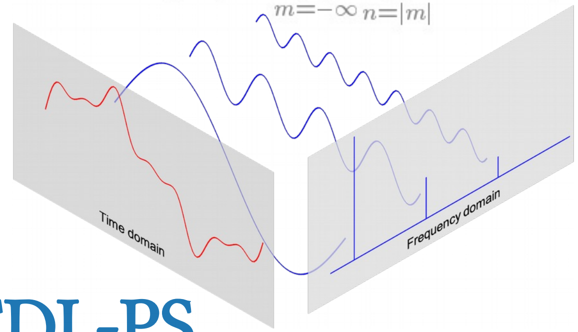
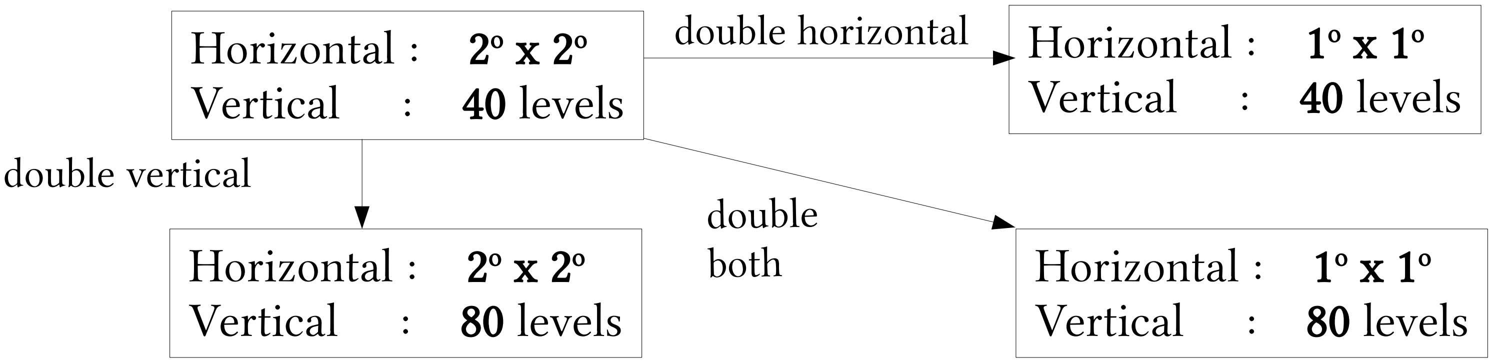


GFDL-PS

PSEUDOSPECTRAL

… and test the sensitivity of simulated transport to grid resolution as well



Million+ core hours on Cheyenne. 60+ terabytes (!) of data.

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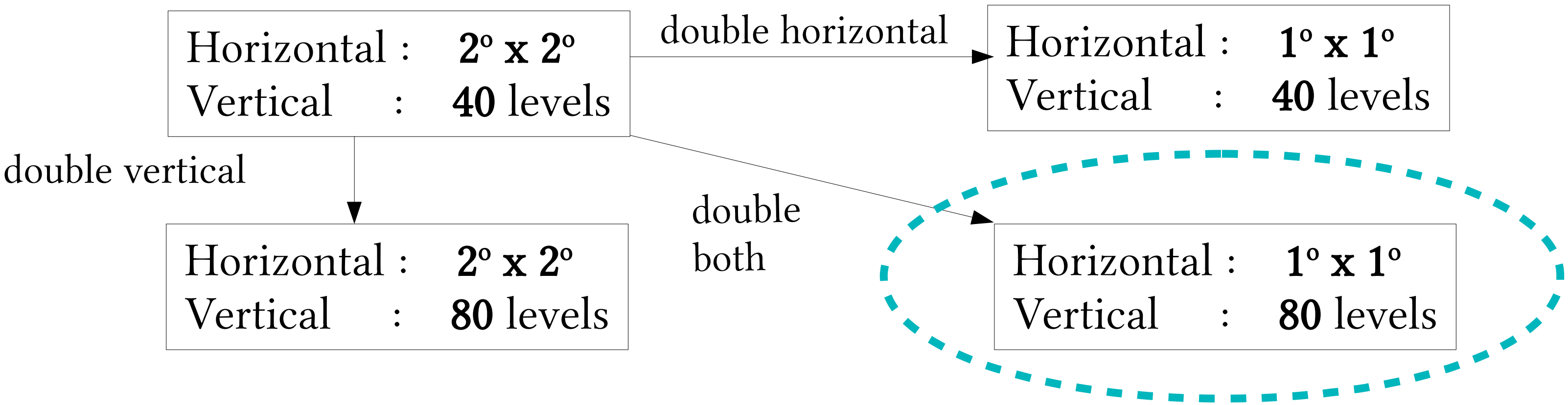

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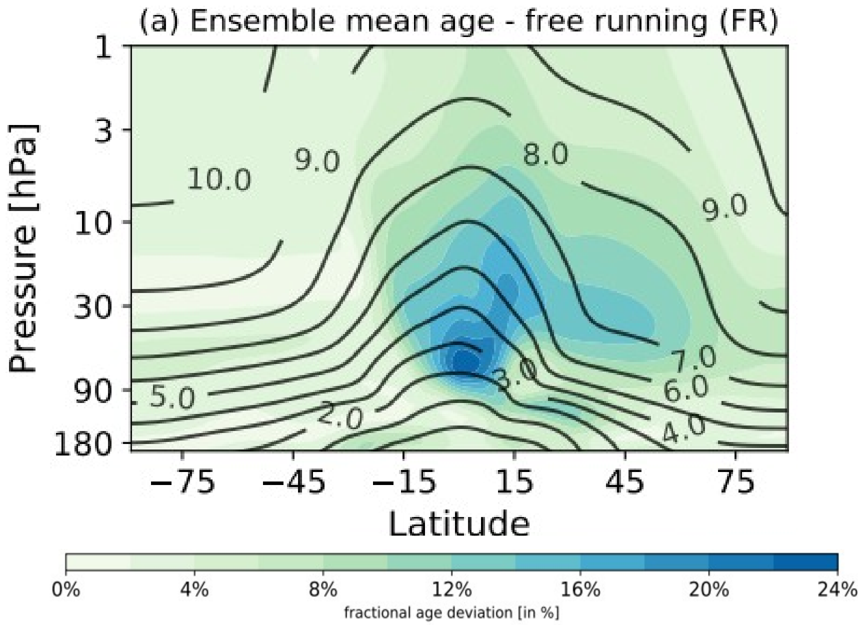
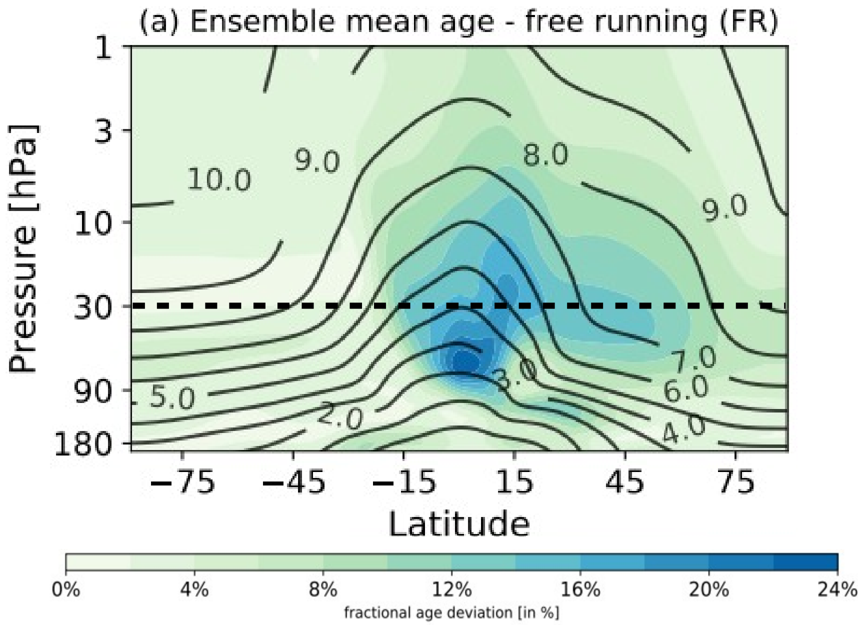
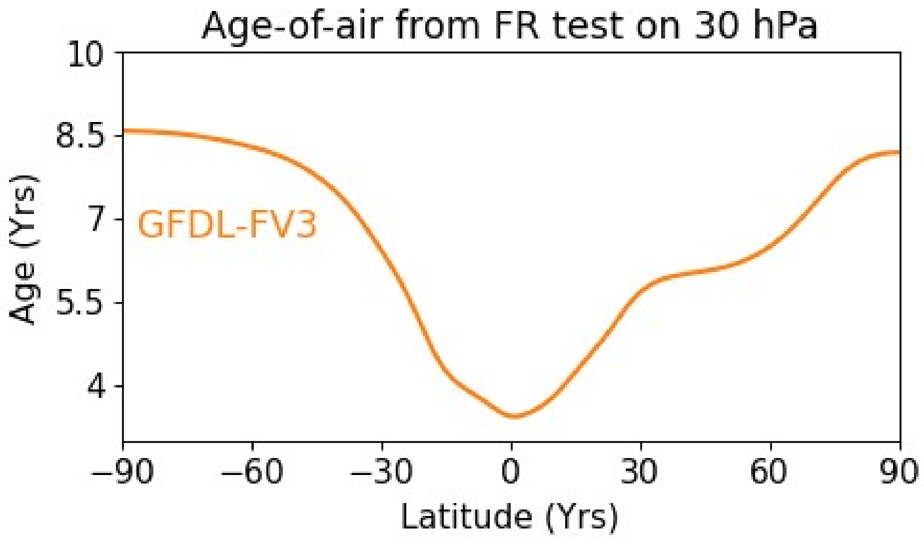
Age-of-air from the Free Running (FR) benchmark test



Intermodel age differences strongest in the tropics

Age-of-air from the Free Running (FR) benchmark test





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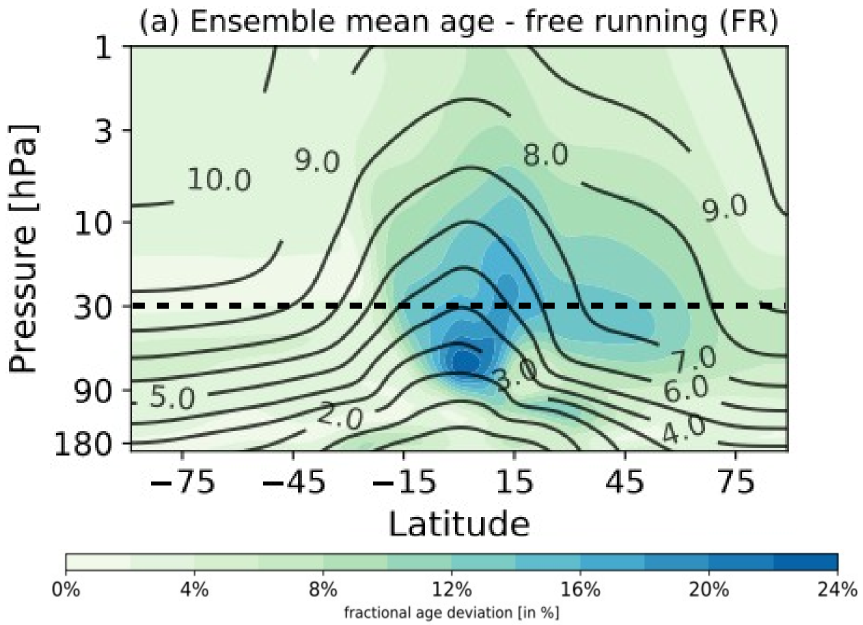

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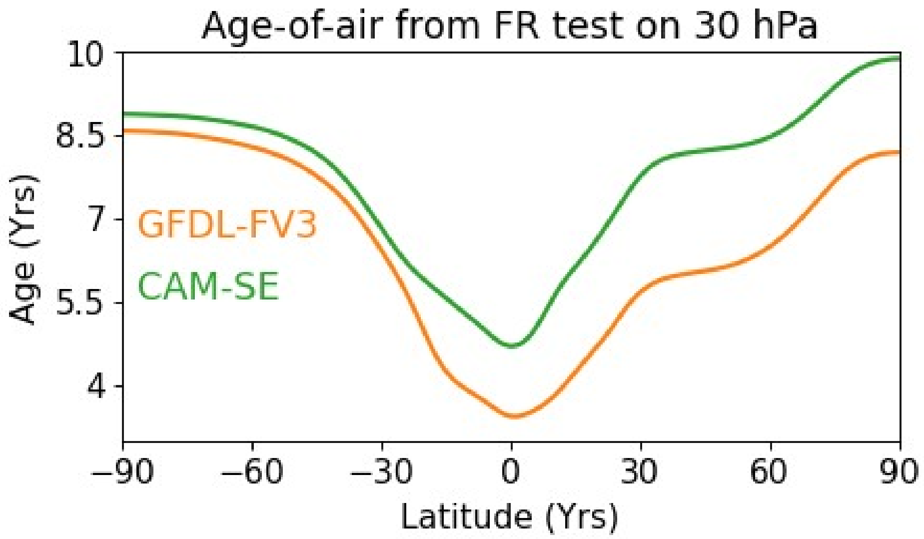
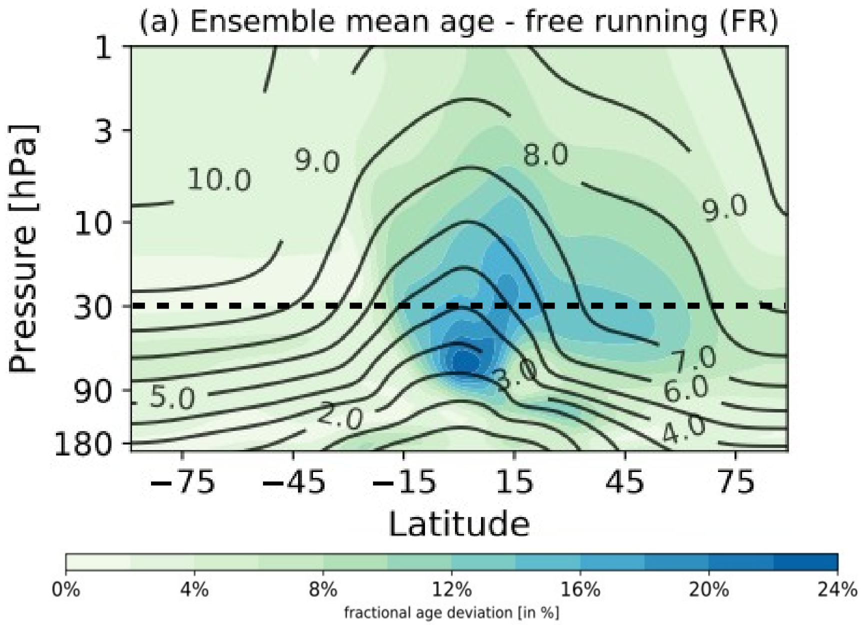
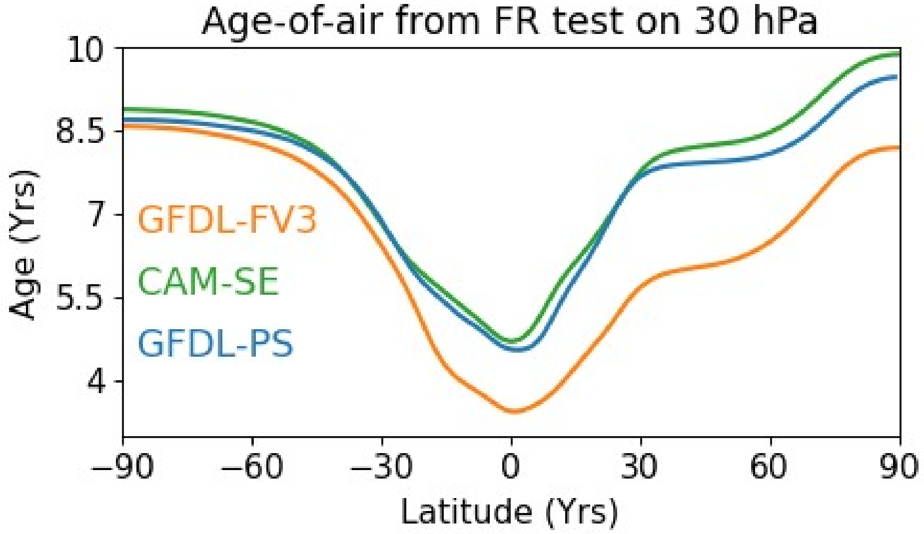


Striking differences in age between GFDL-FV3 and CAM-SE

Age-of-air from the Free Running (FR) benchmark test





Intermodel age differences strongest in the tropics

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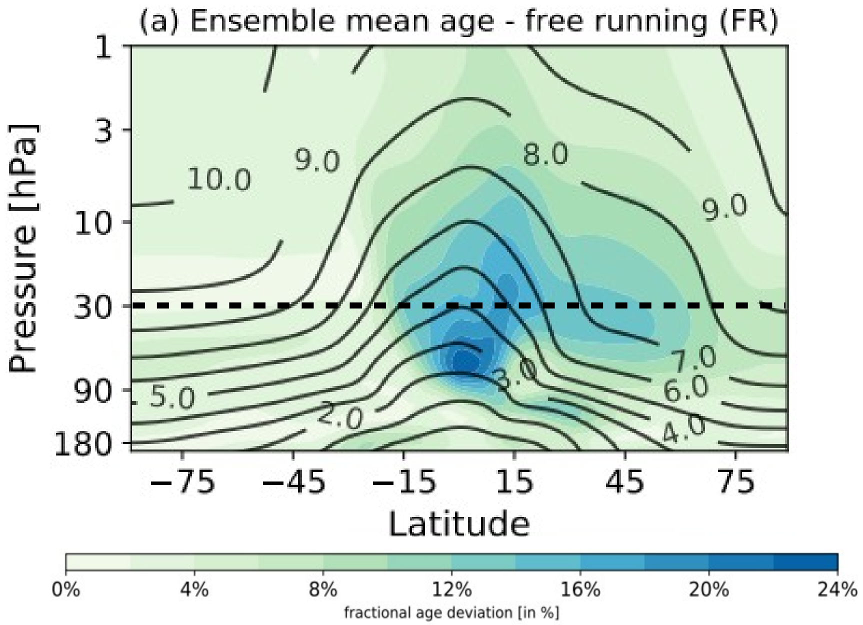
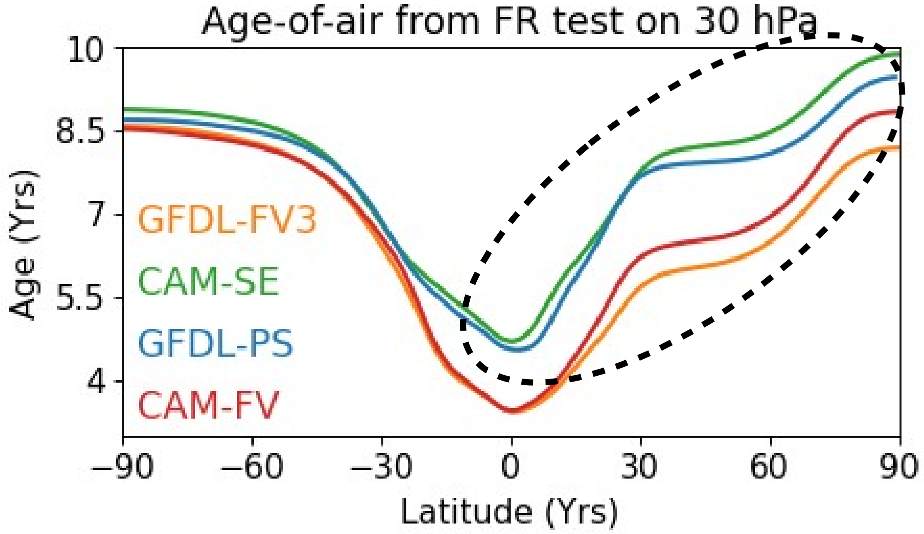
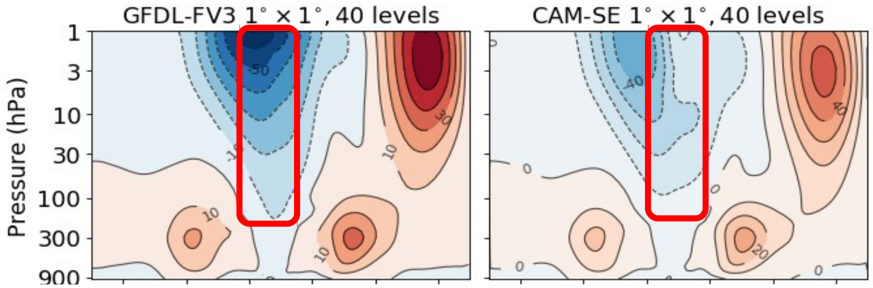


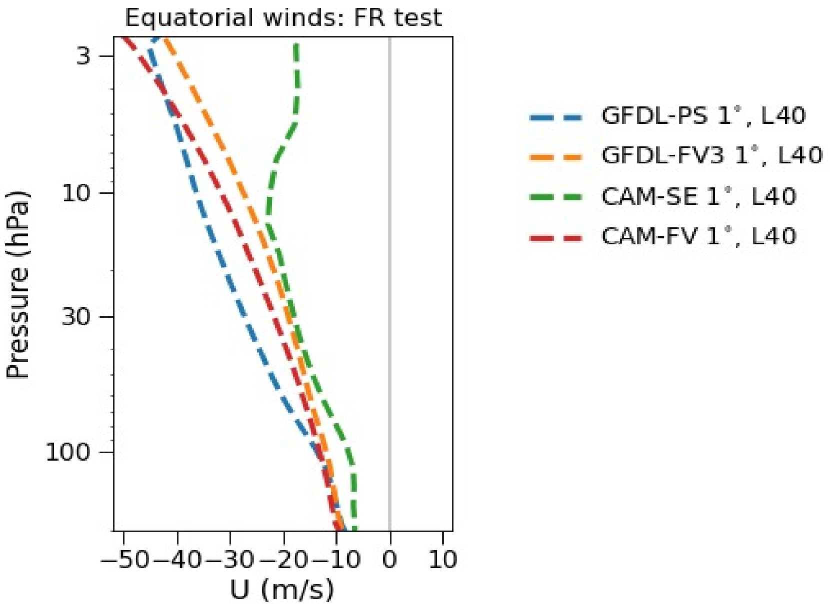
Intermodel age differences strongest in the tropics



Striking differences in age between finite-volume and spectral-based cores

The dynamical cores fail the Held-Suarez test in the stratosphere





- The dynamical cores disagree on the tropical stratospheric winds.
- **Dichotomy** among finite volume (tropical easterly) and spectral-based (tropical westerly) dycores **at high vertical resolution**.
- Differences in tropical dynamics lead to global differences in transport.

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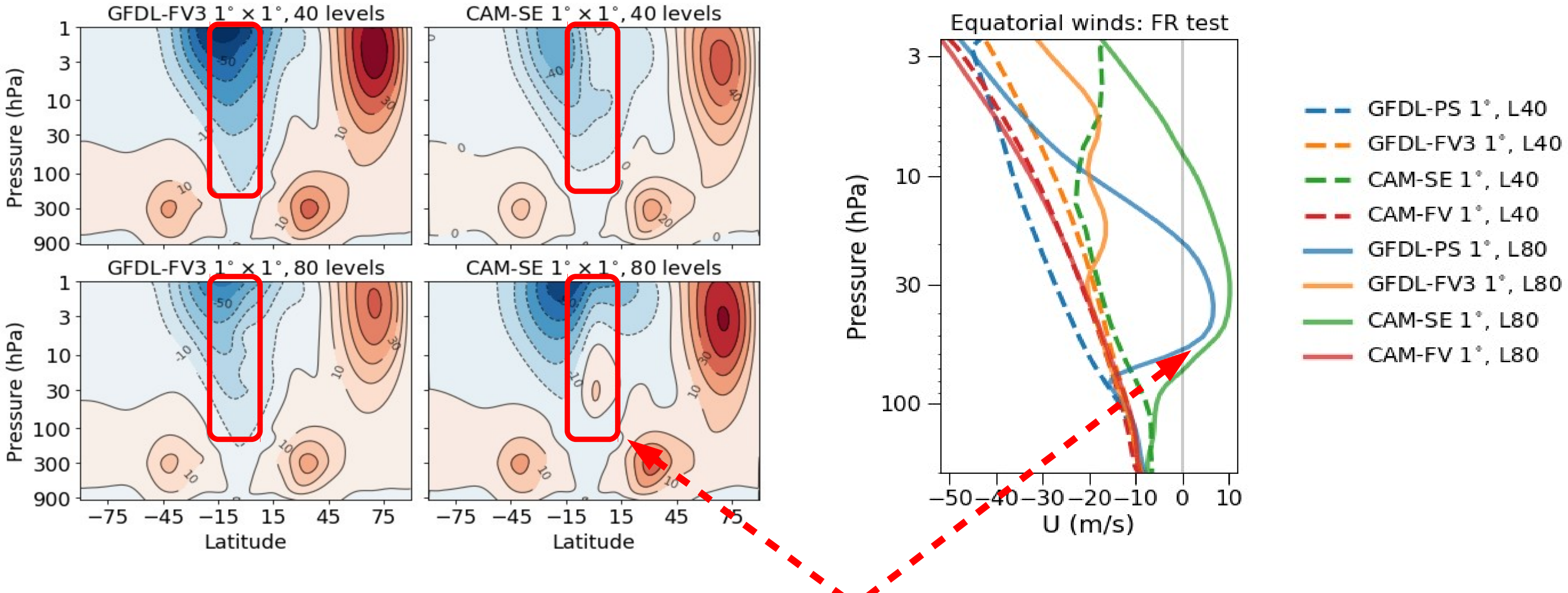

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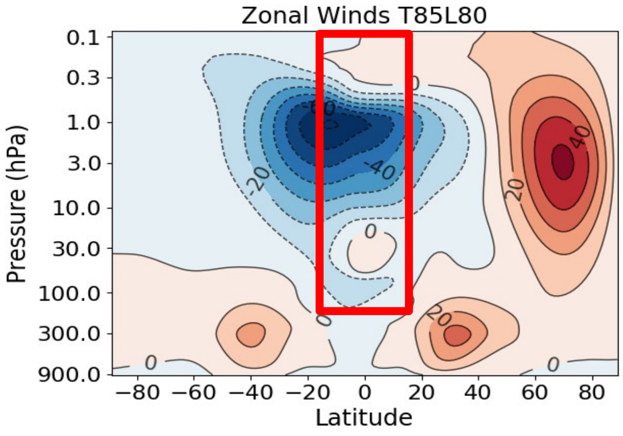
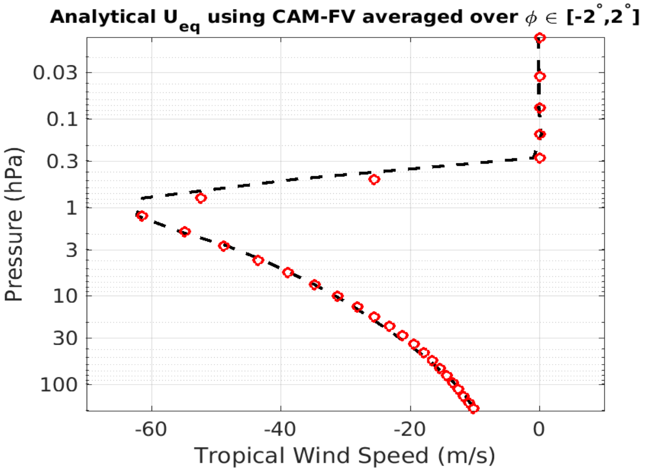
Updating our benchmark test: specifying the tropical winds

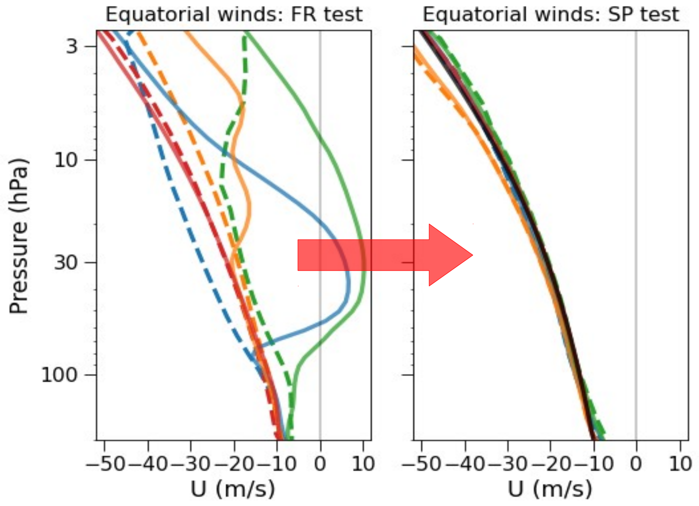


$$u_t(\lambda, \phi, p, t) = -\frac{[u(\lambda, \phi, p, t) - u_{eq}(p)]}{\tau}$$



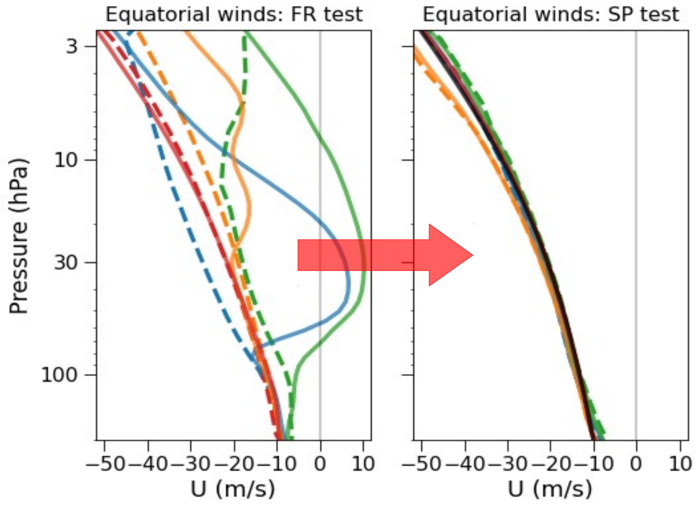
- **Analytical U_{eq}(p) profile:** Specified winds in the tropical stratosphere to compensate for unresolved small-scale processes. Inspired by specified QBO in WACCM.
- Newtonian relaxation to this prescribed easterly wind profile
- We call this - the **Specified (SP) test**

Consistent tropical dynamics under the nudged (SP) benchmark test



- Nudging eliminates tropical wind variance among dynamical cores, and across resolutions

Consistent tropical dynamics under the nudged (SP) benchmark test



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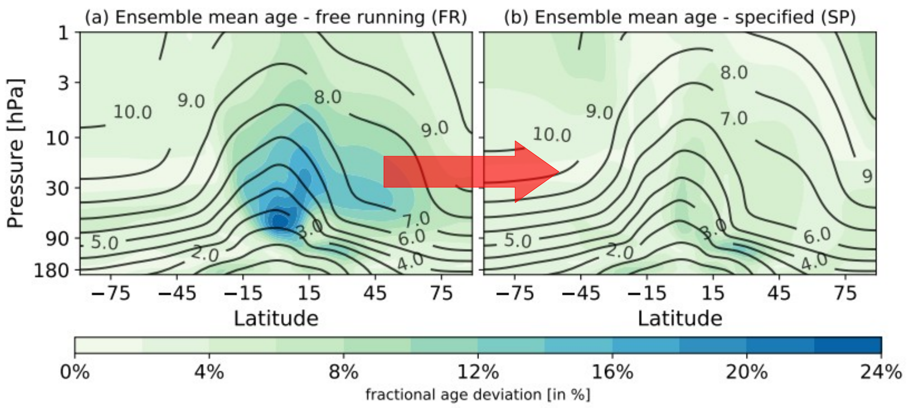
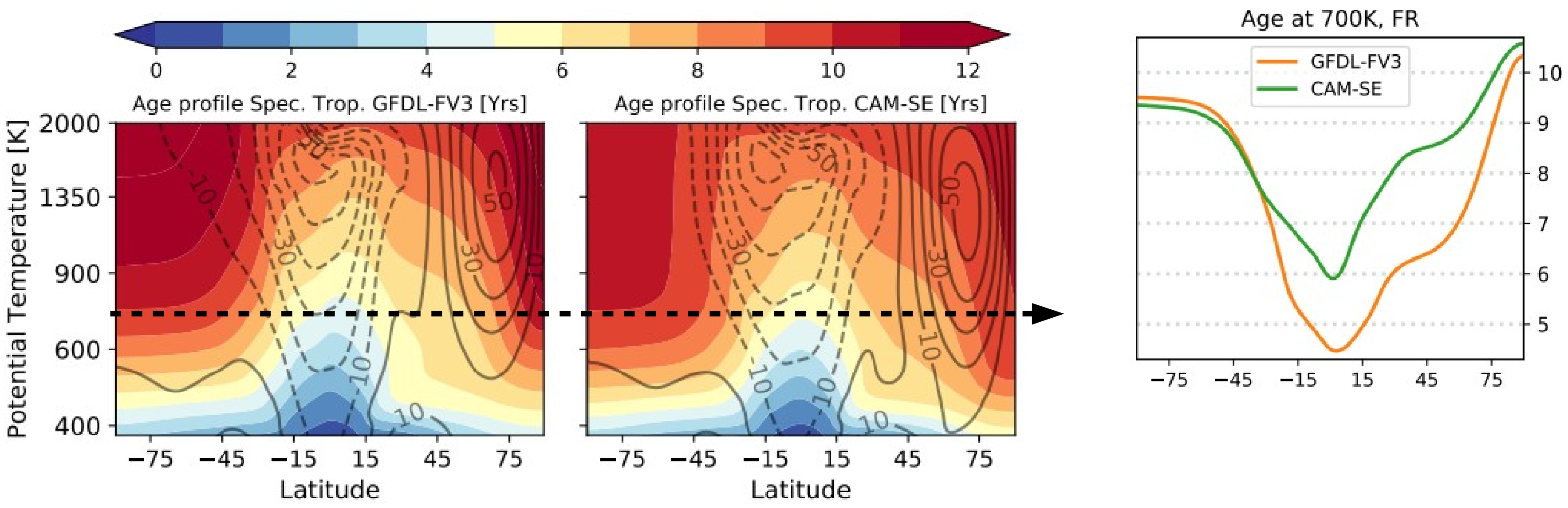


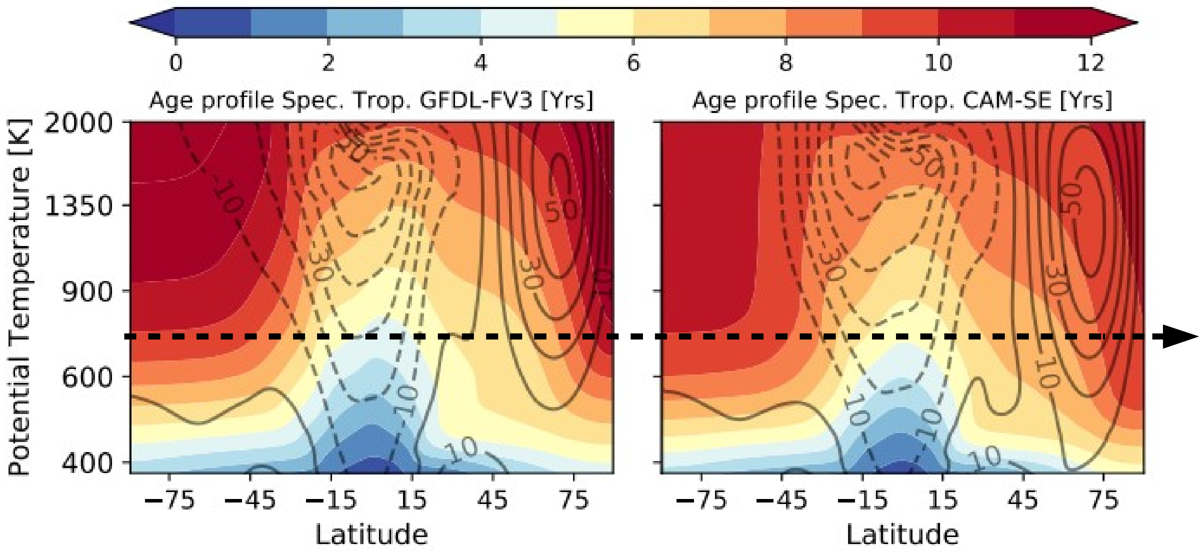
- Reduction in tropical wind variance leads to significant reduction in ensemble age variance

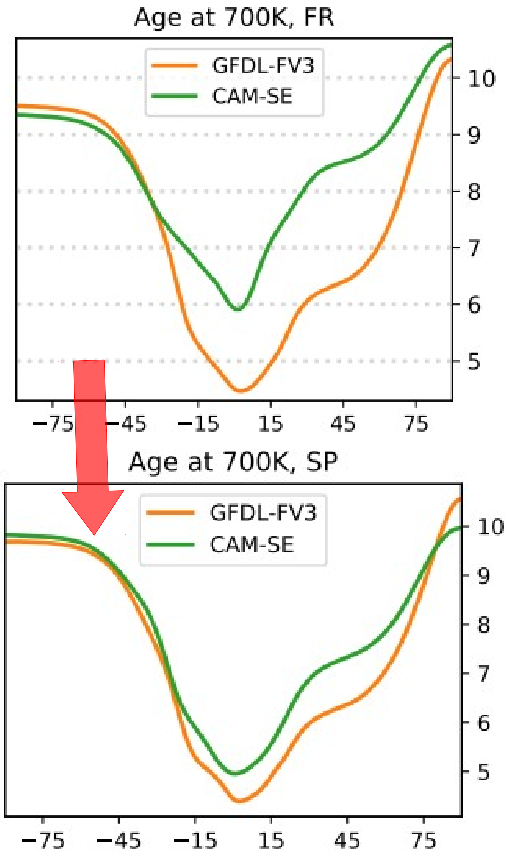
Does constraining the tropical winds resolve the issue?



Constraining tropical winds among models drastically reduces the age difference. Some differences still remain.

Does constraining the tropical winds resolve the issue?



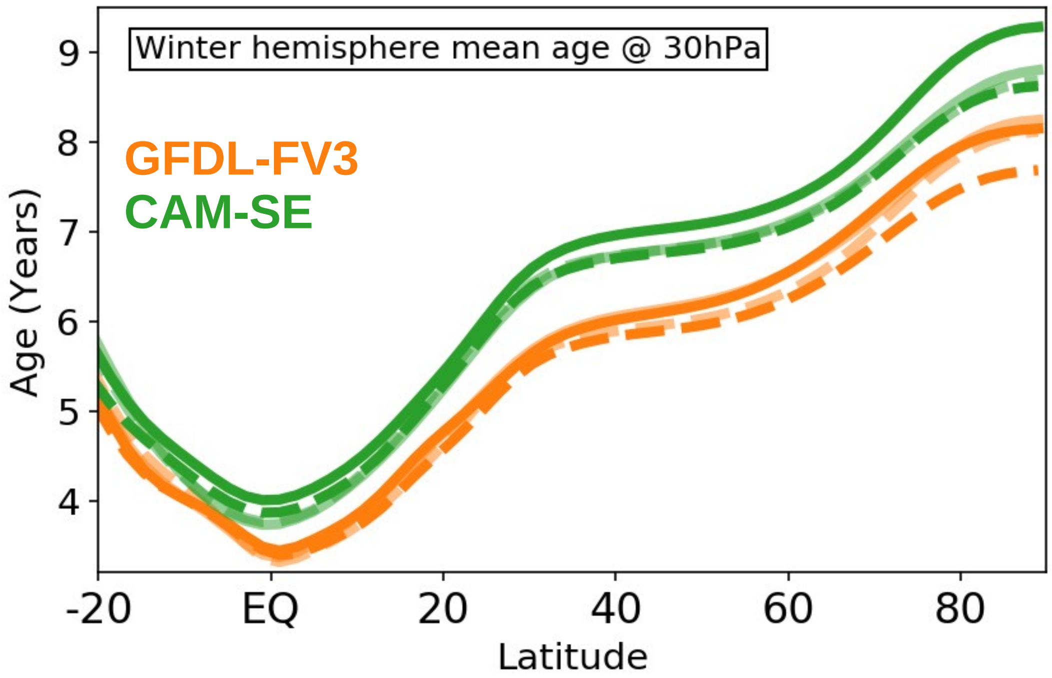


Constraining tropical winds among models drastically reduces the age difference. Some differences still remain.

Models show signs of convergence under the nudged (SP) benchmark test

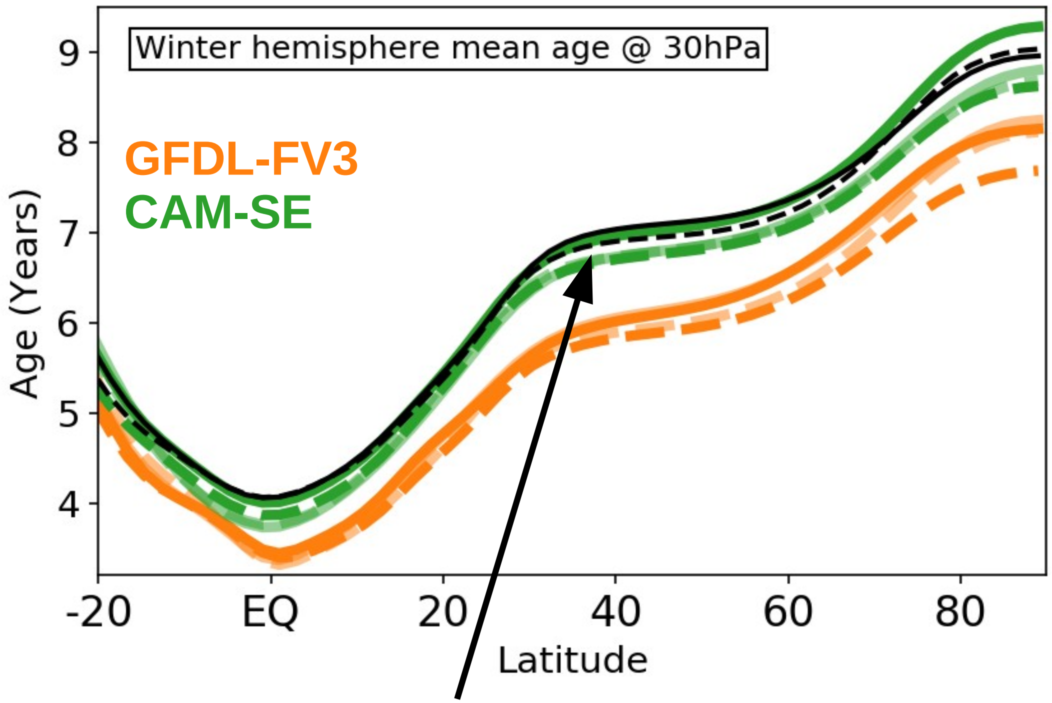
However, the age-of-air in both the models converges to different values

Highlights the strong tropical control of stratospheric transport.



Models show signs of convergence under the nudged (SP) benchmark test

We test the spectral element core at even higher horizontal and vertical resolutions

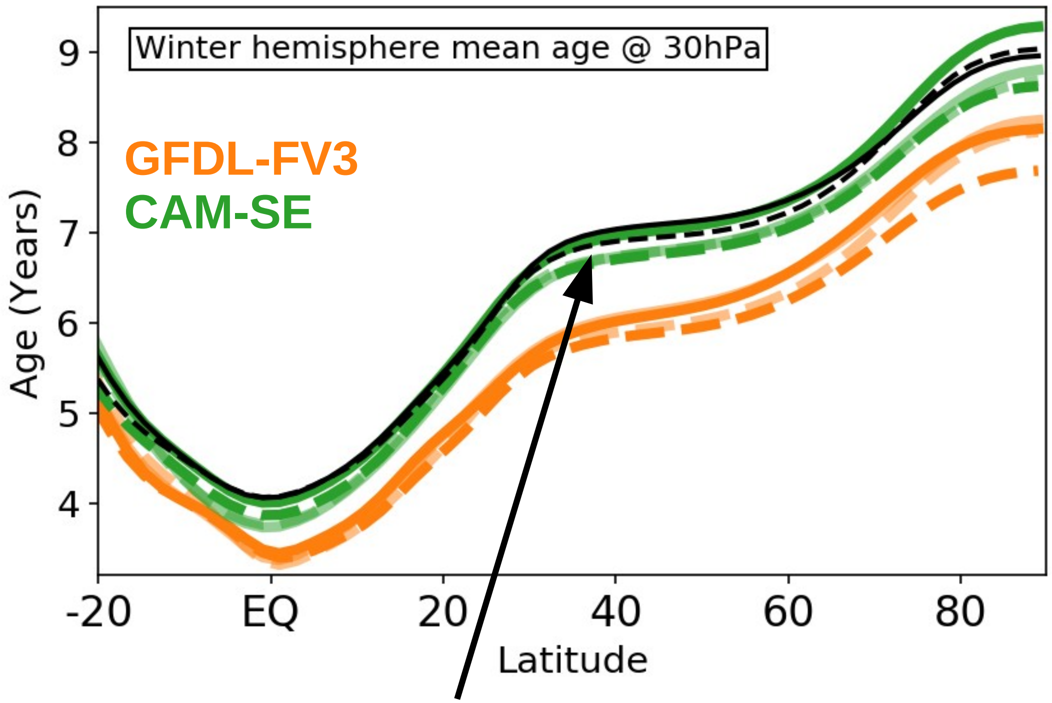


Black curves : HiRes CAM-SE runs
0.5°, L80 (dashed) and 1°, L160 (solid)

Models show signs of convergence under the nudged (SP) benchmark test

We test the spectral element core at even higher horizontal and vertical resolutions

(not shown) Nudging GFDL-FV3 tropical winds to westerlies increases the age throughout the stratosphere.



Black curves : HiRes CAM-SE runs
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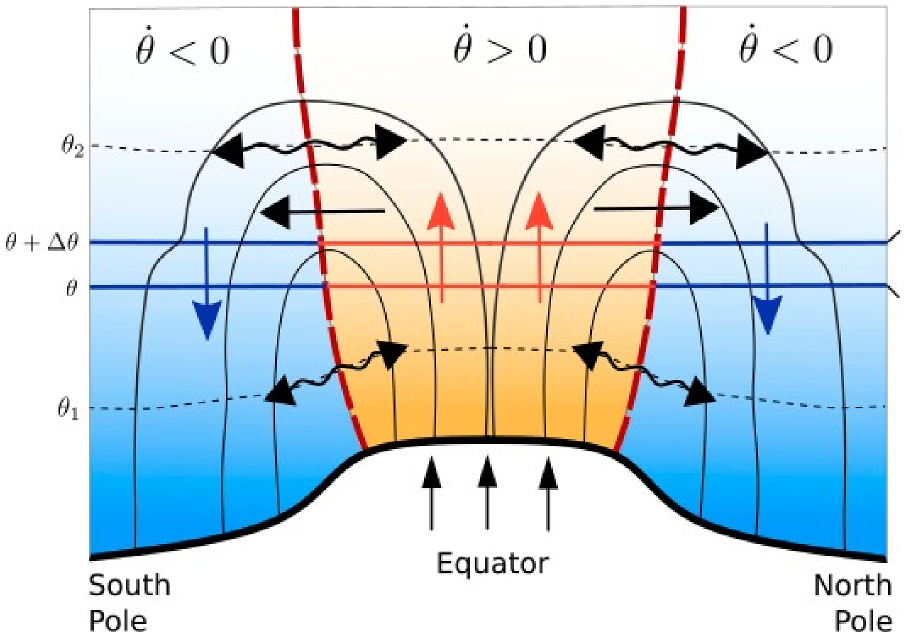
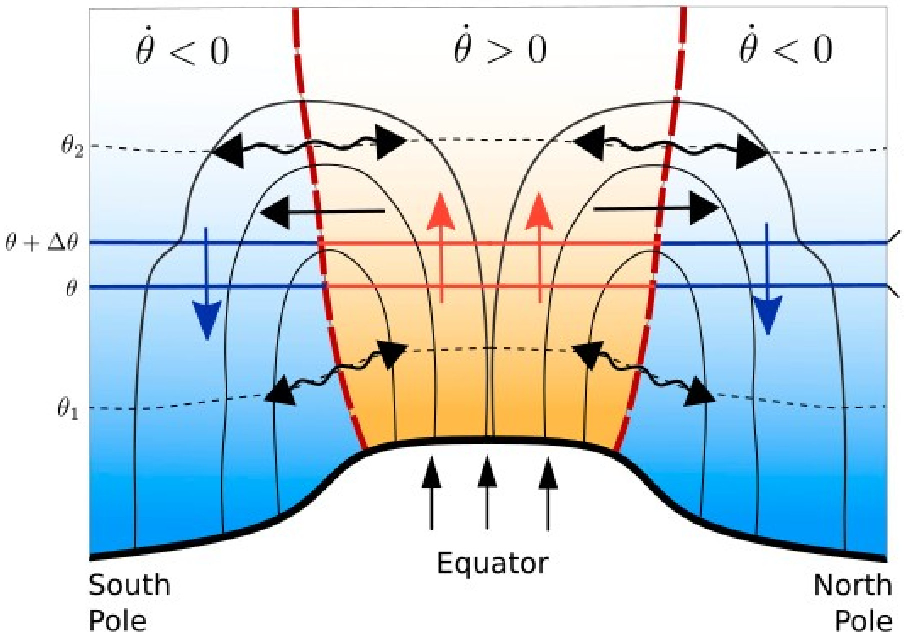
Using Conceptual Transport Models to Understanding Why Tropical Westerlies lead to Higher Age?

Using the theoretical “leaky pipe” model to estimate midlatitude wave-induced mixing



Full three-dimensional model transport

Using the theoretical "leaky pipe" model to estimate midlatitude wave-induced mixing



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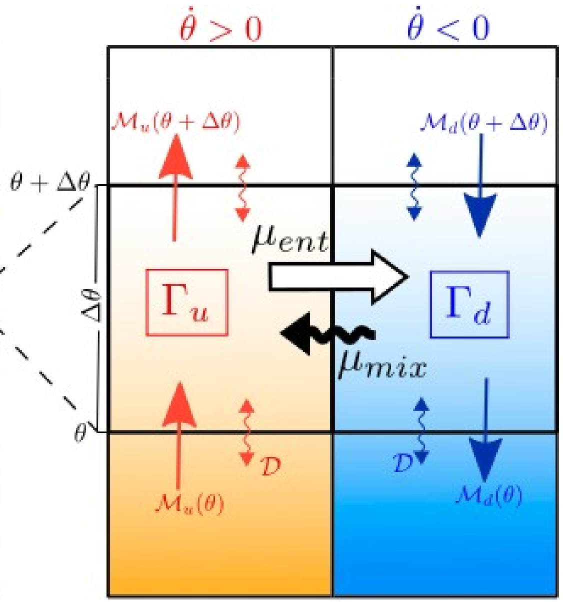
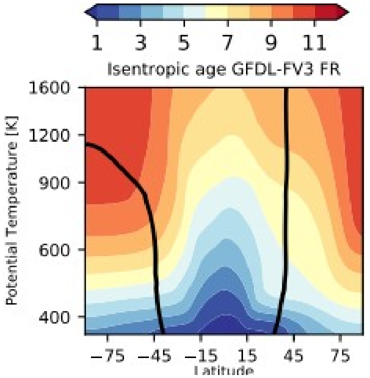


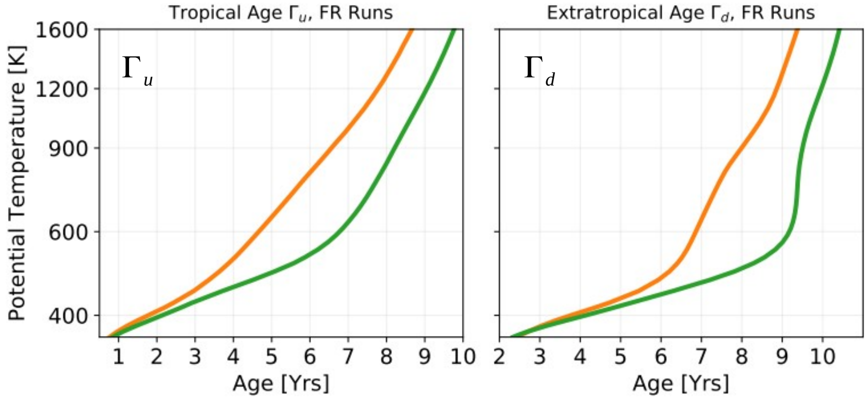
Transport as exchange between tropical and extratropical "pipes"

Using theory to estimate mixing flux



Dimensional reduction from full model age

Mass-flux weighted ages



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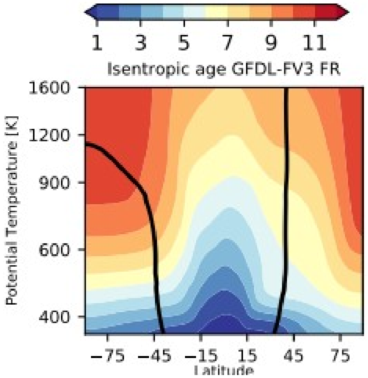
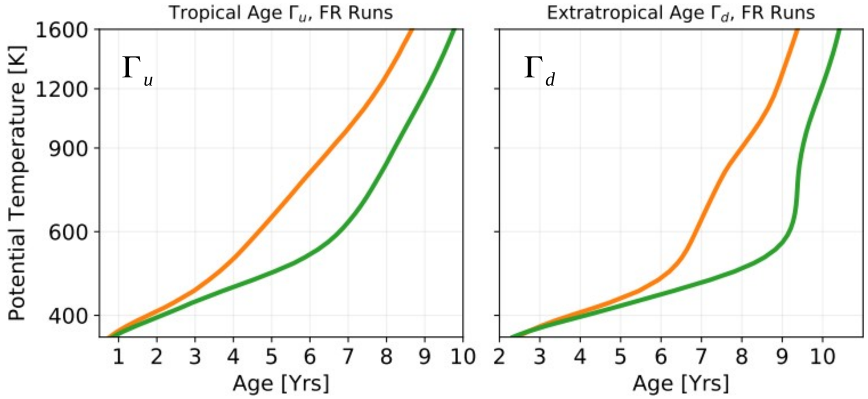


Dimensional reduction from full model age

Mass-flux weighted ages



In the no-diffusion limit, the vertical gradient of the average tropical age allows quantifying the mixing fluxes across the subtropical barrier (Linz et al. 2021)

Mixing equation :

$$\frac{\partial \Gamma_u}{\partial \theta} = \frac{\sigma}{\mathcal{M}} + \frac{\mu_{mix} \Delta\Gamma}{\mathcal{M}}$$

Advection term

Mixing term

$\mathcal{M}(\theta)$: diabatic mass flux

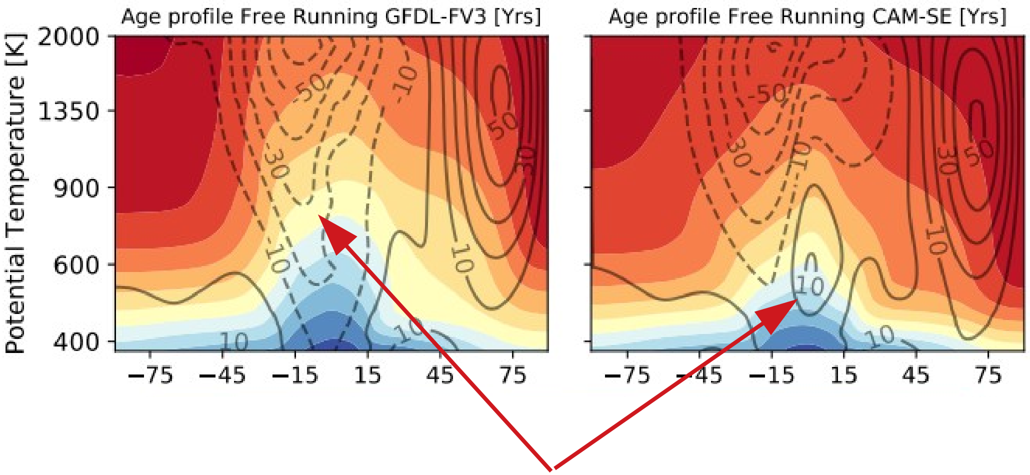
$\sigma(\theta)$: horizontally avgd density

$\mu_{mix}(\theta)$: ET $\rightarrow$ T mixing flux

$\Delta\Gamma(\theta) = \Gamma_d(\theta) - \Gamma_u(\theta)$

Tropical Westerlies Induce Enhanced Tropical-Extratropical Trace Gas Mixing

$$\frac{\partial \Gamma_u}{\partial \theta} = \frac{\sigma}{\mathcal{M}} + \frac{\mu_{mix} \Delta\Gamma}{\mathcal{M}}$$



- The tropical winds in the two models have different phases. Akin to different phases of the QBO.

- Westerlies induce more mixing between the two regions by allowing the midlatitude mixing fluxes to percolate deeper into the tropics

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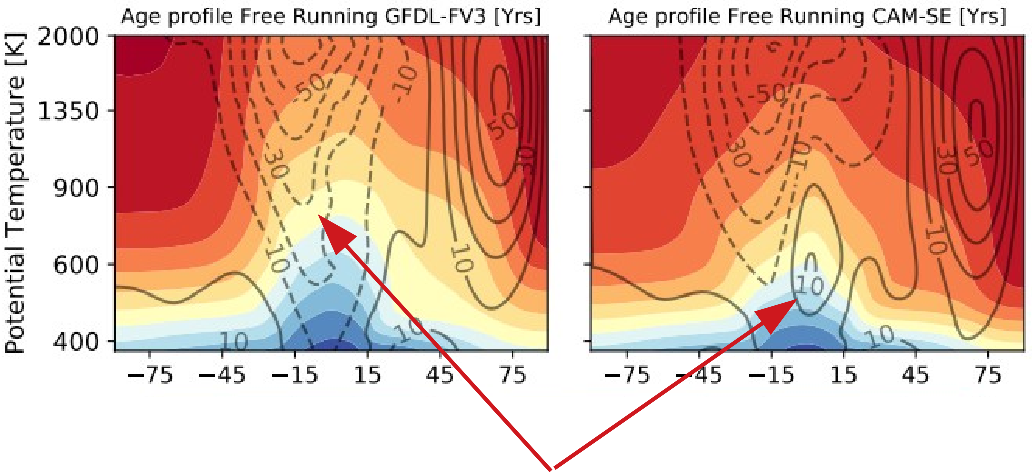

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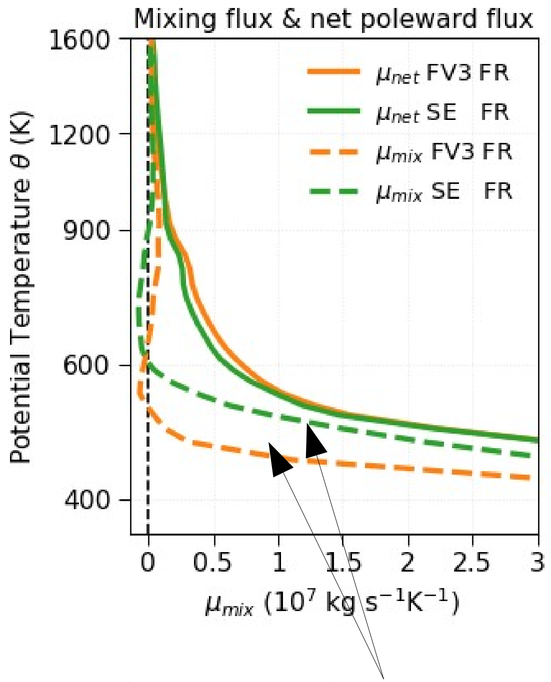
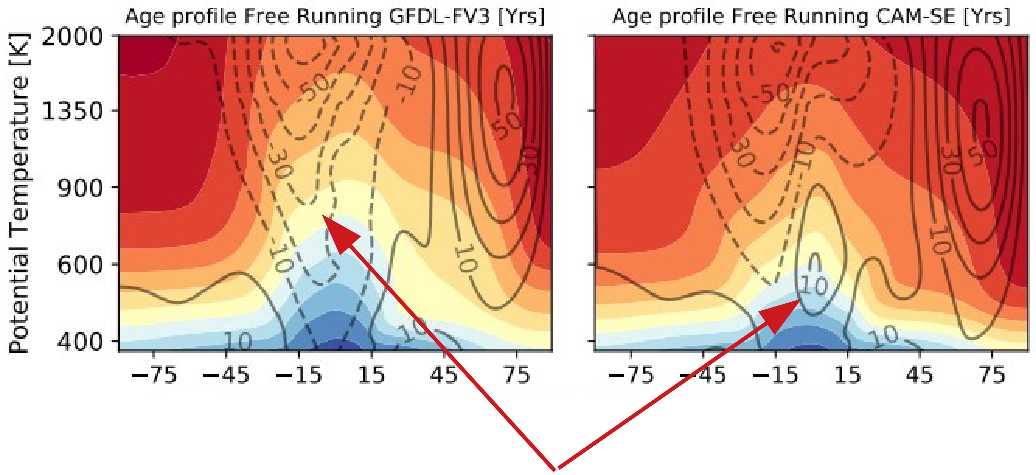
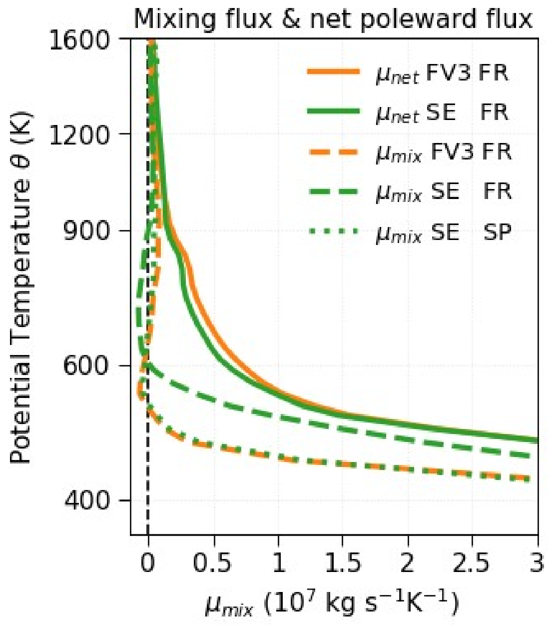


Higher mixing flux in CAM-SE as compared to GFDL-FV3

Tropical Westerlies Induce Enhanced Tropical-Extratropical Trace Gas Mixing



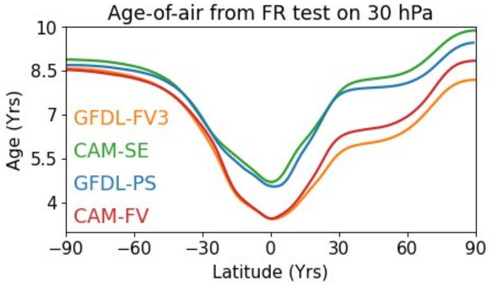
$$\frac{\partial \Gamma_u}{\partial \theta} = \frac{\sigma}{\mathcal{M}} + \frac{\mu_{mix} \Delta\Gamma}{\mathcal{M}}$$

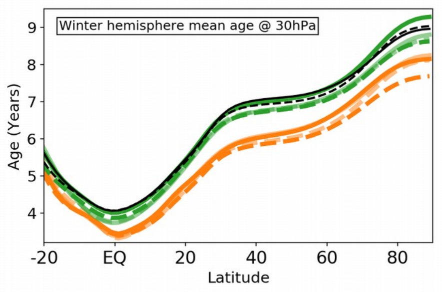


- The tropical winds in the two models have different phases. Akin to different phases of the QBO.
- Westerlies induce more mixing between the two regions by allowing the midlatitude mixing fluxes to percolate deeper into the tropics

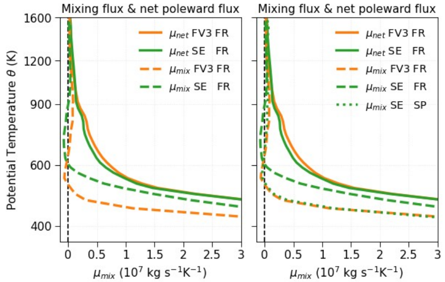
Summary

Model numerics strongly influence the transport-dynamics coupling: finite-volume cores develop tropical easterlies while the spectral cores develop tropical westerlies (the FR test). Tropical differences strongly impact transport throughout the stratosphere, with age in CAM-SE being upto 40% older than in GFDL-FV3.





Constraining tropical winds, through nudging significantly reduces model age differences (the SP test). The models begin to show signs of convergence, although towards different values.



Equatorward shift in Rossby critical lines by a westerly jet enhances mixing of older midlatitude age and younger tropical air, increasing mean residence times of trace gases throughout the winter hemisphere.

References

- Gupta, Aman, Edwin P. Gerber, and Peter H. Lauritzen (2020): "**Numerical impacts on tracer transport: A proposed intercomparison test of Atmospheric General Circulation Models**", Quart. J. Roy. Meteor. Soc.

- Gupta, Aman, Edwin P. Gerber, R. Alan Plumb, and Peter H. Lauritzen (2021): "**Numerical impacts on tracer transport: Diagnosing the influence of dynamical core formulation and resolution on stratospheric transport**", J. Atmos. Sci.,

- Linz, Marianna, R. Alan Plumb, Aman Gupta, and Edwin P. Gerber (2021) : "**Stratospheric adiabatic mixing rate derived from the vertical age gradient**", J. Geophys. Res.: Atmospheres

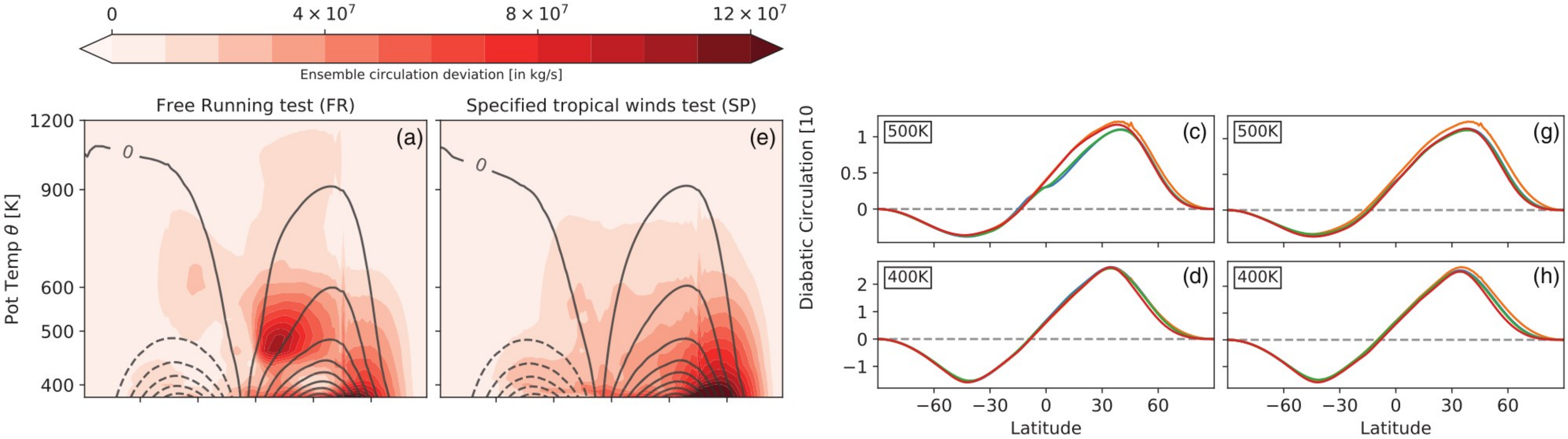
Supplementary Plots

Numerical Schemes

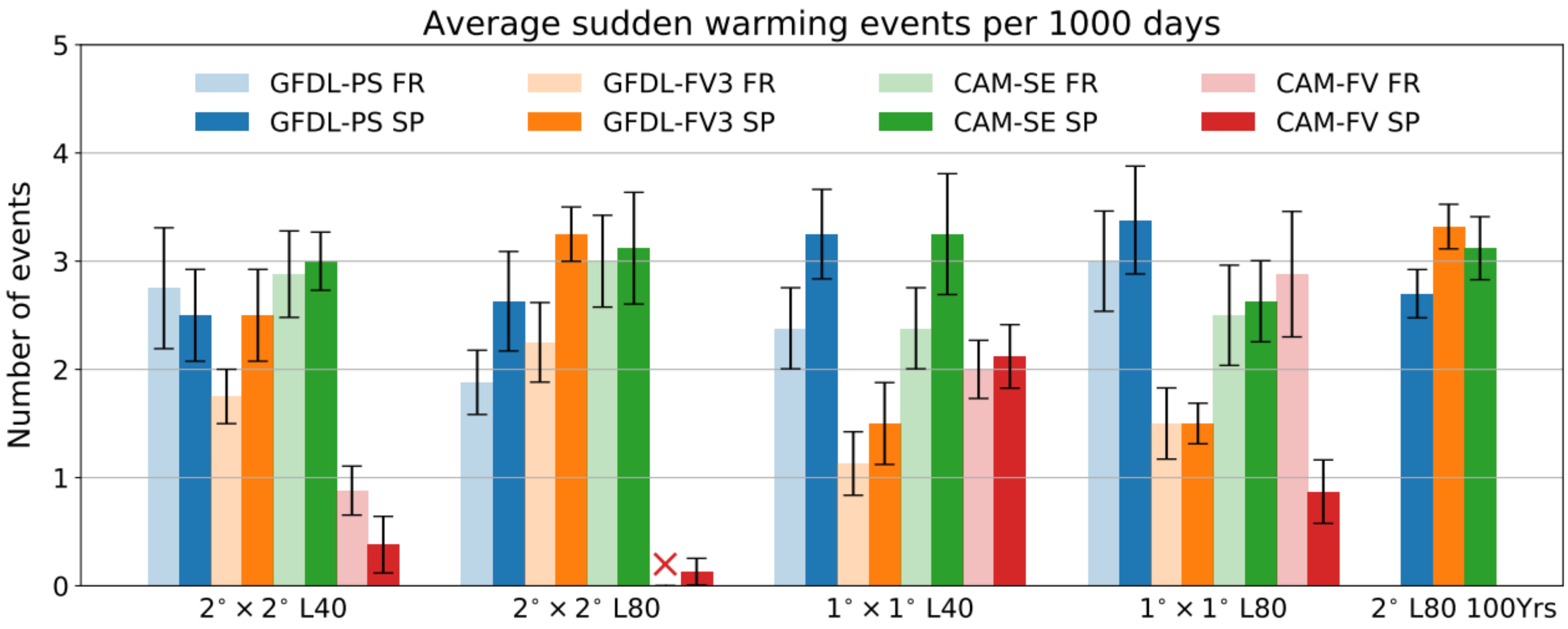
TABLE A1 Horizontal and vertical tracer advection schemes employed by the four dynamical cores considered in the study

Numerics	Horizontal tracer advection	Vertical tracer advection
GFDL–**P**seudo**s**pectral	Default Spectral Scheme	Piecewise Parabolic Method (Colella and Woodward, 1984)
GFDL–Cubed-Sphere **F**inite-**V**olume (GFDL-FV3)	Positive Definite Scheme as in Lin and Rood (1996) with Huynh constraint	Lin (2004) Vertically Lagrangian scheme. Remapping by monotonic and conservative cubic splines.
CAM–**S**pectral **E**lement	Spectral Elements	Lin (2004) Vertically Lagrangian scheme. PPM vertical remapping with mirroring at boundaries.
CAM–**F**inite-**V**olume	*Enhanced* Piecewise Parabolic Method (PPM) (Colella and Woodward, 1984; Carpenter *et al.*, 1990)	*Enhanced* Piecewise Parabolic Method (PPM) (Colella and Woodward, 1984; Carpenter *et al.*, 1990)

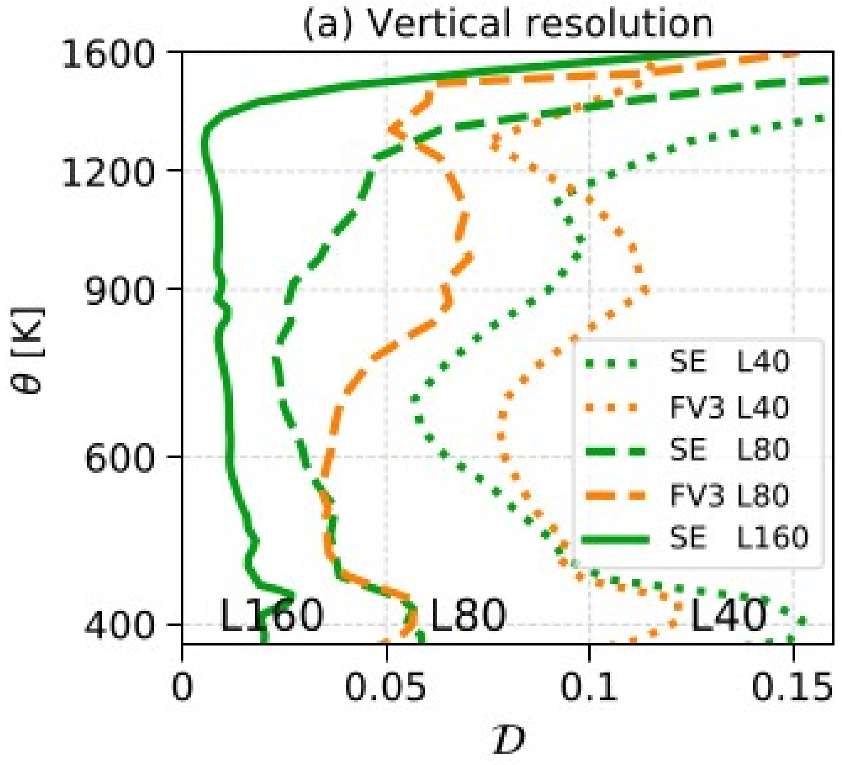
Intermodel Spread in Diabatic Circulation



SSW Frequency

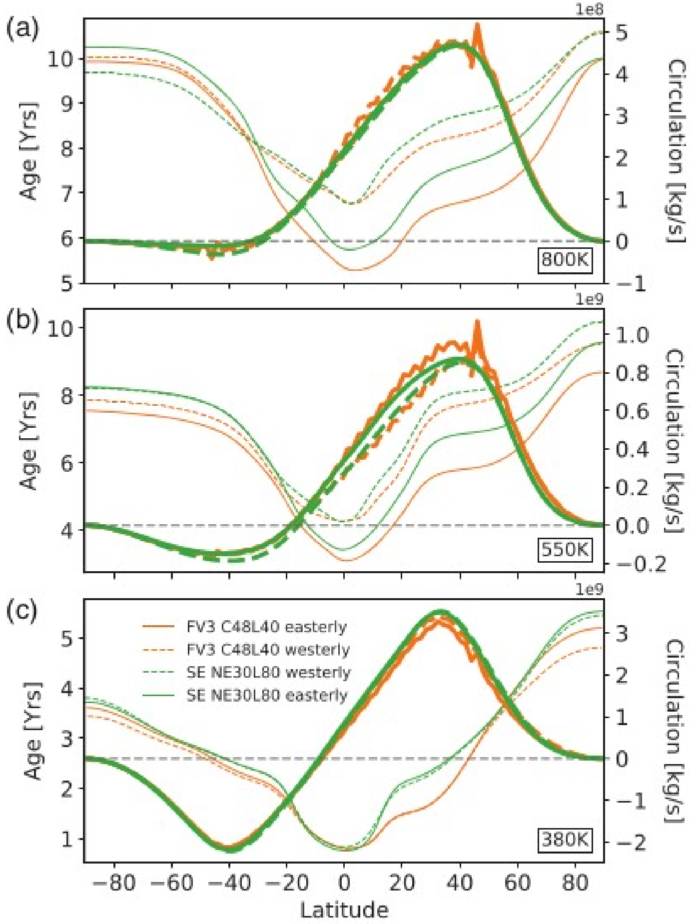


Contribution from Vertical Diffusion



$$\mathcal{D} = \frac{\frac{\Gamma_u + \Gamma_d}{2}\left(\frac{M}{\Delta\Gamma} - \mathcal{M}\right)}{\mathcal{M}_u\Gamma_u + \mathcal{M}_d\Gamma_d}.$$

Imposing a tropical westerly jet in the GFDL-FV3 model



Imposing a tropical westerly jet in the GFDL-FV3 model