The Effect of Numerics on Trace Gas Transport

A proposed intercomparison test of Atmospheric General Circulation Models

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What limits our ability to forecast ozone recovery?

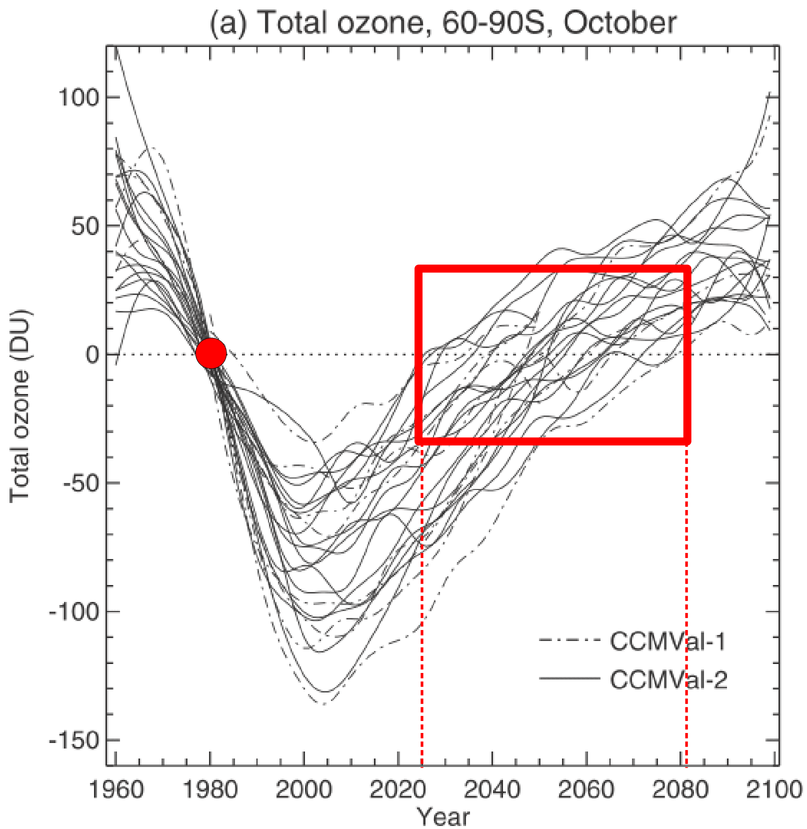

Fig : A spread in Ozone recovery projections (to 1980, pre-Montreal protocol levels) across state-of-the-art chemistry climate models. (A CCMVal study). Figure from Karpechko et al. 2013.

- Is it the Chemistry?

  Or the Dynamics?

  Or is it transport?

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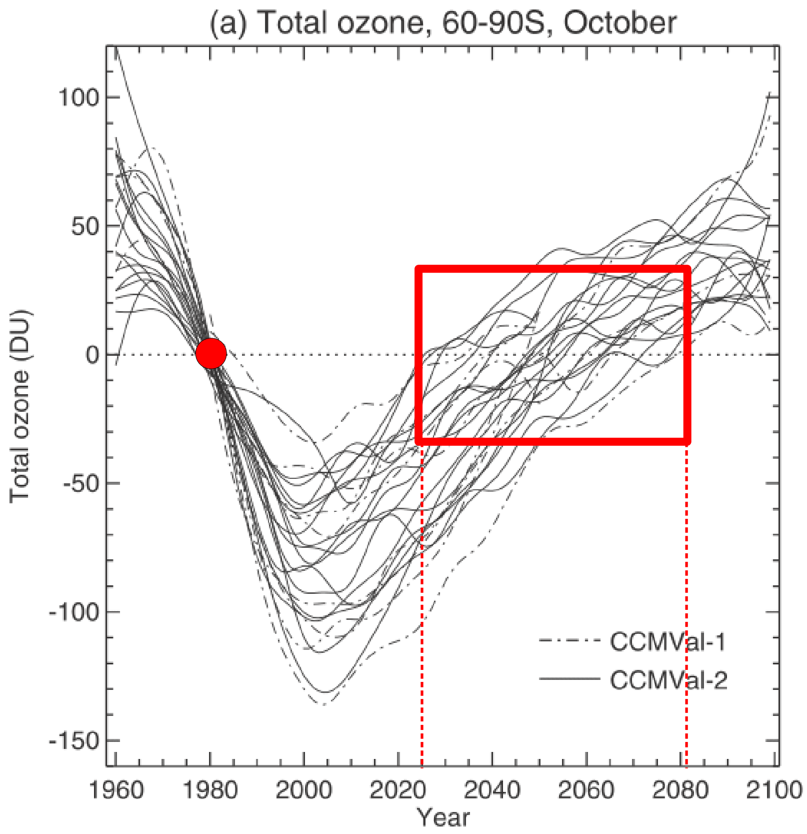

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- Is it the Chemistry?
  Or the Dynamics?
  Or is it transport?
- Strongest correlation between projected Antarctic ozone and polar vortex methane **(a transport diagnostic)** (Karpechko et al. 2013)

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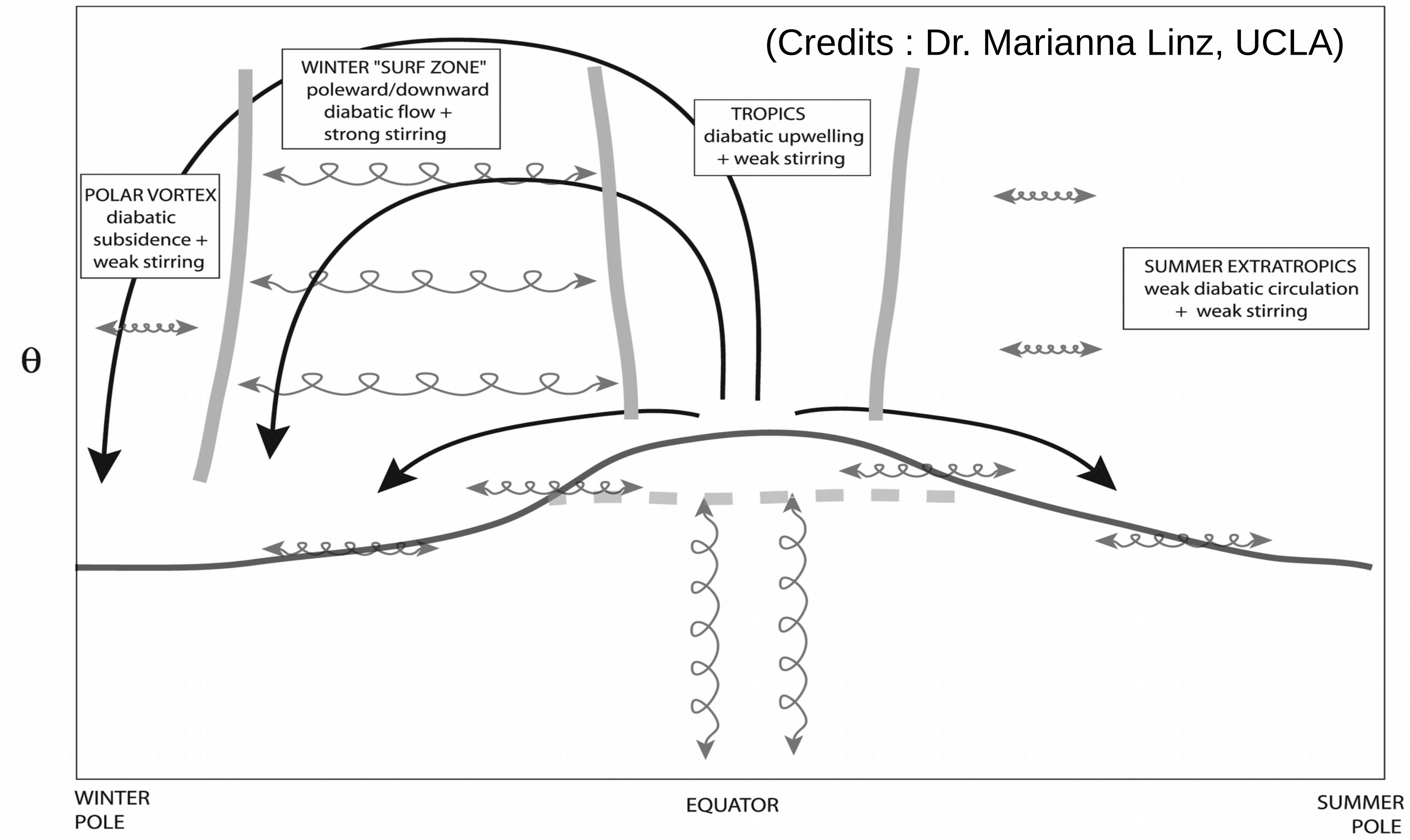
Stratospheric Circulation and Tracer Transport



Factors affecting stratospheric tracer transport in climate models :

1. Resolved circulation (mean Lagrangian mass transport)
2. Isentropic mixing
3. Diffusion (numerical)

Goal of the study

- **Benchmark test :** Propose a “simple” benchmark test to assess transport in dry dynamical cores

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- **Convergence :** Robustness of transport to changes in horizontal and vertical resolution

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- **Numerics :** Study transport in dynamical cores that employ totally different numerical schemes to isolate the role of numerics
- **Convergence :** Robustness of transport to changes in horizontal and vertical resolution
- **No parameterizations :** To exclusively focus on transport and model dynamics

Benchmark Test

Recipe

- **Forcings :** Apply identical temperature (diabatic) forcings across all cores :

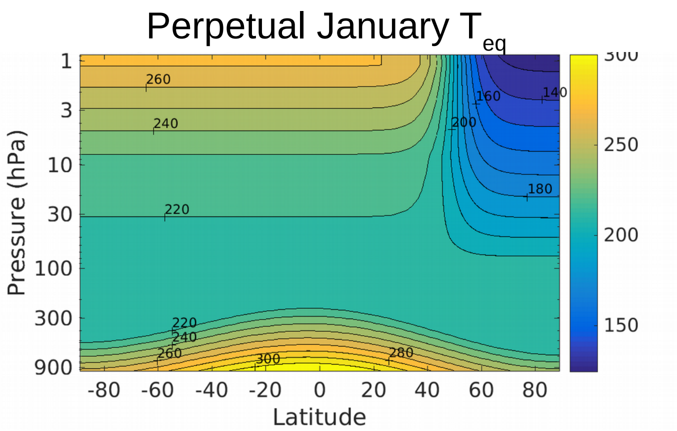
  #1 Newtonian relaxation to equilibrium temperature profile (Held-Suarez Troposphere, Polvani-Kushner Stratosphere)

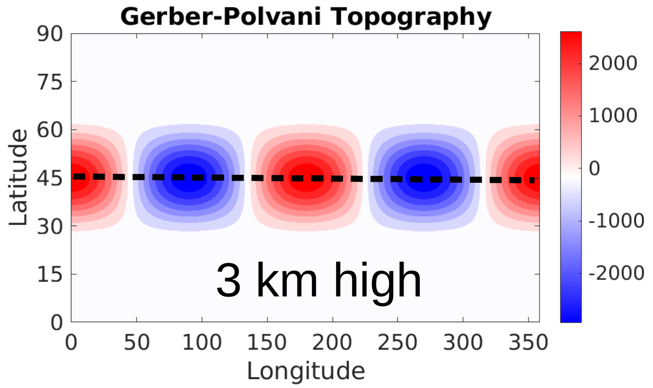
  #2 No seasonal cycle. Perpetual January climatology.

  #3 A 3km high, wave-2 sinusoid (Gerber-Polvani) topography for stratospheric forcing and SSW events.

  #4 Age of air : computed by introducing a linearly increasing clock tracer near the surface (p ≥ 700hPa)

  #5 No parameterizations. Rayleigh drag near surface and stratospheric sponge near the model top.





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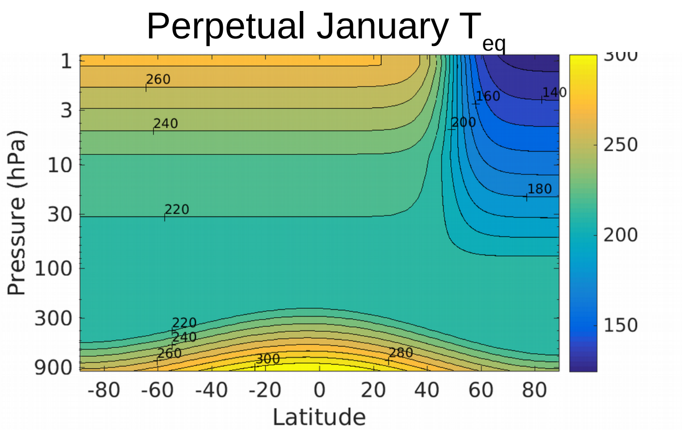
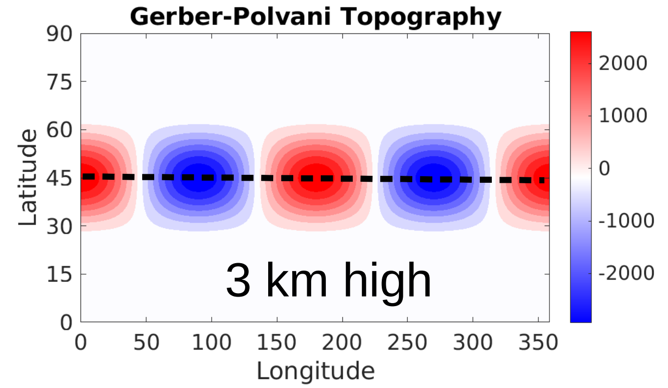
- **Convergence :** Integrate models for ~30 years. Use last 10 years for analysis, with converged age of air.





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Dynamical cores considered for the benchmark test

PS : PSEUDOSPECTRAL (GFDL)

Traditional Lat-Lon grid

CSFV *: CUBED SPHERE*

FINITE VOLUME (GFDL)

(GFDL CM4, fvGFS)

SE : CAM SPECTRAL ELEMENT

Cubed Sphere Grid (4x4 element)

(DOE E3SM)

FV : CAM FINITE VOLUME

Traditional Lat-Lon grid

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Traditional Lat-Lon grid
(NCAR WACCM)

(H)ORIZONTAL AND (V)ERTICAL RESOLUTION

H : T42 (2.8^o x 2.8^o), T85 (1.4^o x 1.4^o)
V : 40 and 80 levels

H : C48 (2^o x 2^o), C90 (1^o x 1^o)
V : 40 and 80 levels

H : NE16 (2^o x 2^o) , NE30 (1^o x 1^o)
V : 40 and 80 levels

H : F19 (2.5^o x 1.9^o), F09 (1.25^o x 0.9^o)
V : 40 and 80 levels

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Age of air to study transport in dynamical cores

- Compare transport using age of air in the stratosphere.

- **Age of air** : Time elapsed since the air was last in contact with the surface.

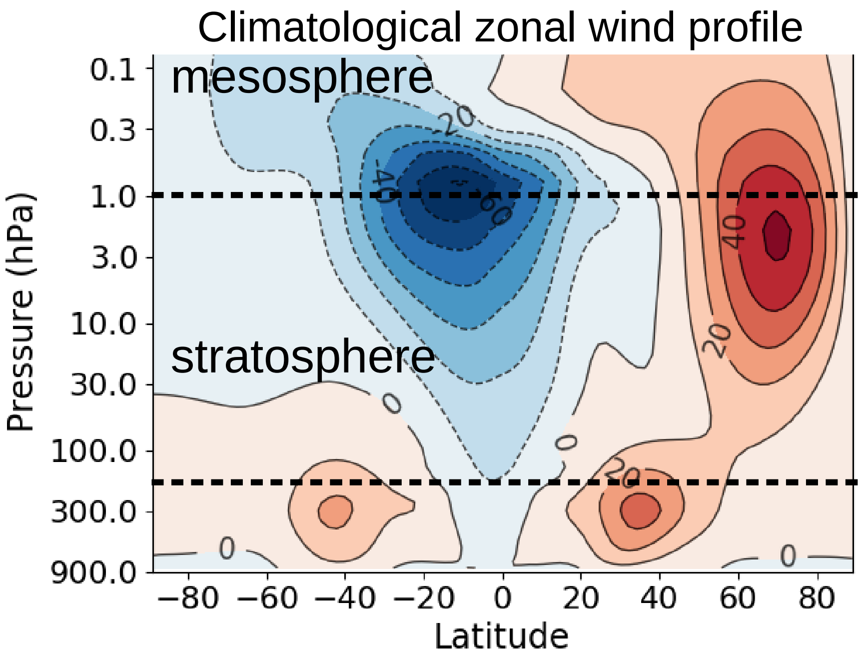
  # independent of model chemistry

  # impacted by both the mean Lagrangian mass transport and isentropic mixing

  # helps connect transport biases to changes in resolved dynamics or numerical biases

Results

Typical Tracer Distribution



Perpetual January climatology

- Midlatitude Jets
- Tropical Easterlies
- Wintertime Polar Vortex

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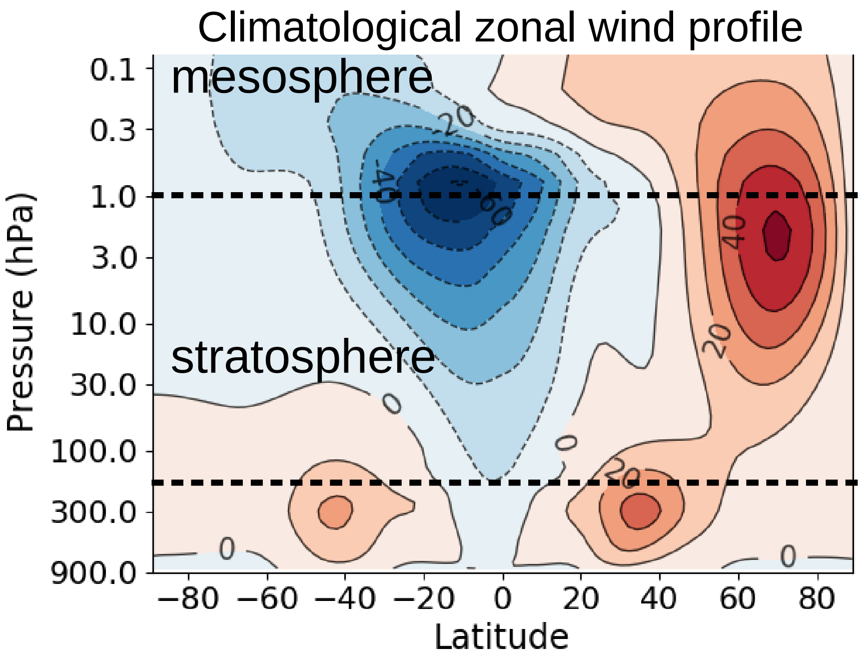

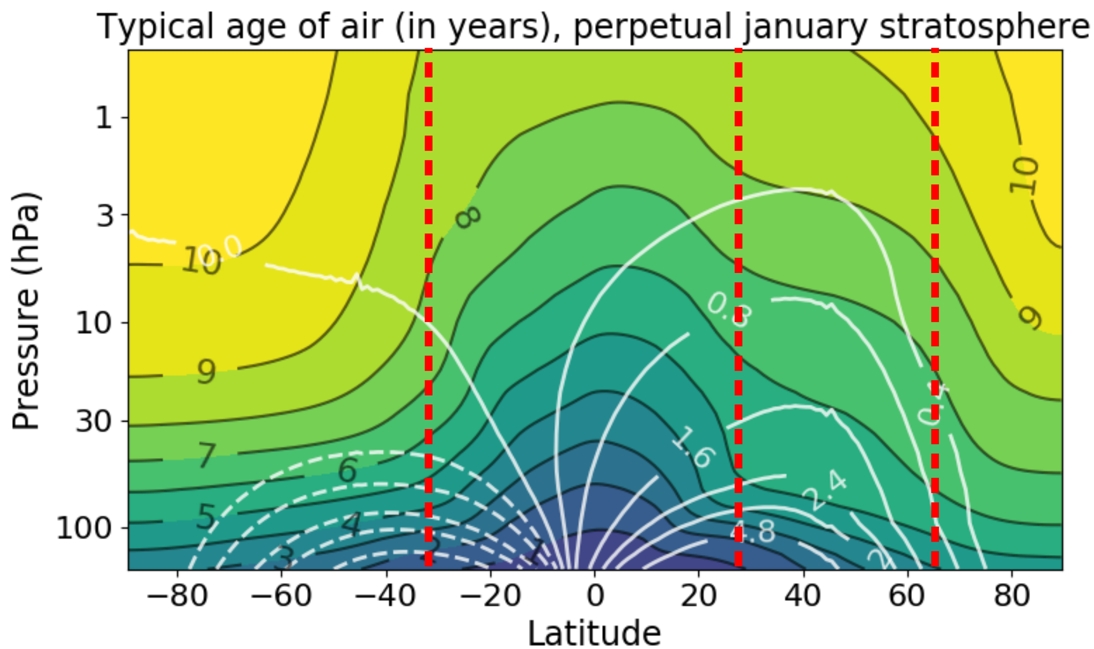

Fig : Mean Lagrangian mass transport in white (10^9 kg/s)

Perpetual January climatology

- Midlatitude jets
- Tropical easterlies
- Wintertime polar vortex

Tracer profile properties

- Youngest in the tropics
- Sharp subtropical and vortex edge gradients
- Flatter contours in midlatitudes

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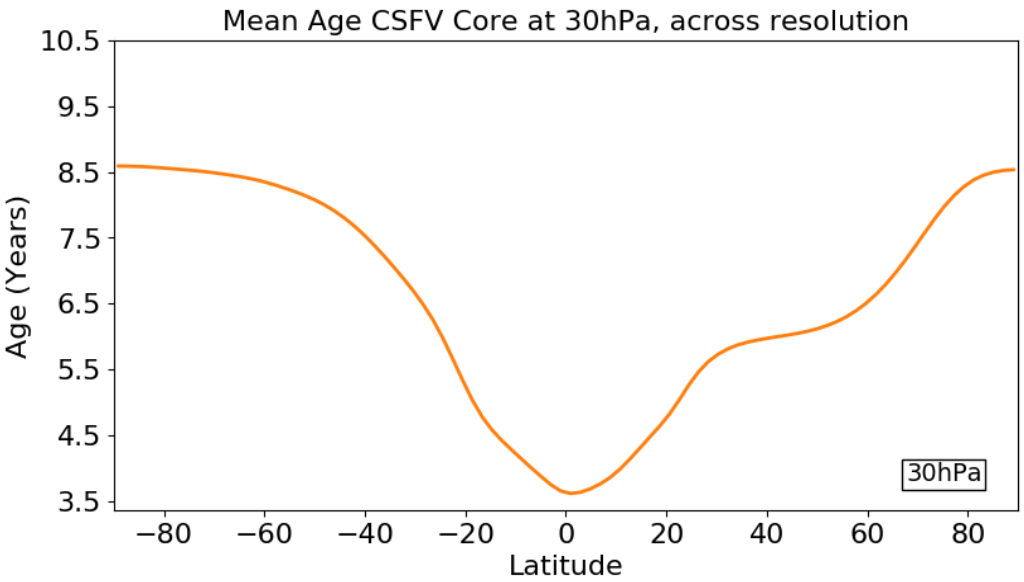
Age of air for CSFV and FV core



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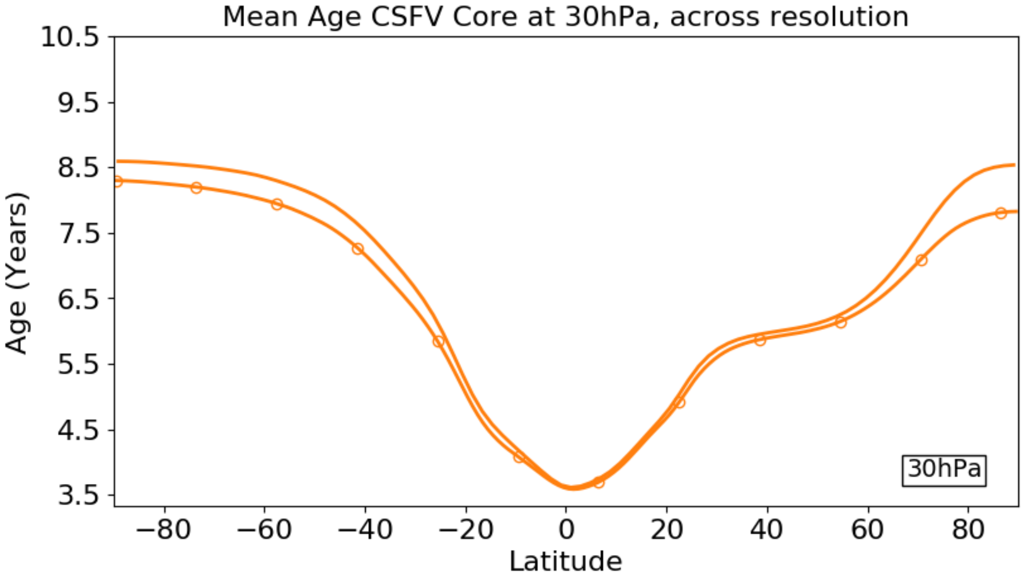

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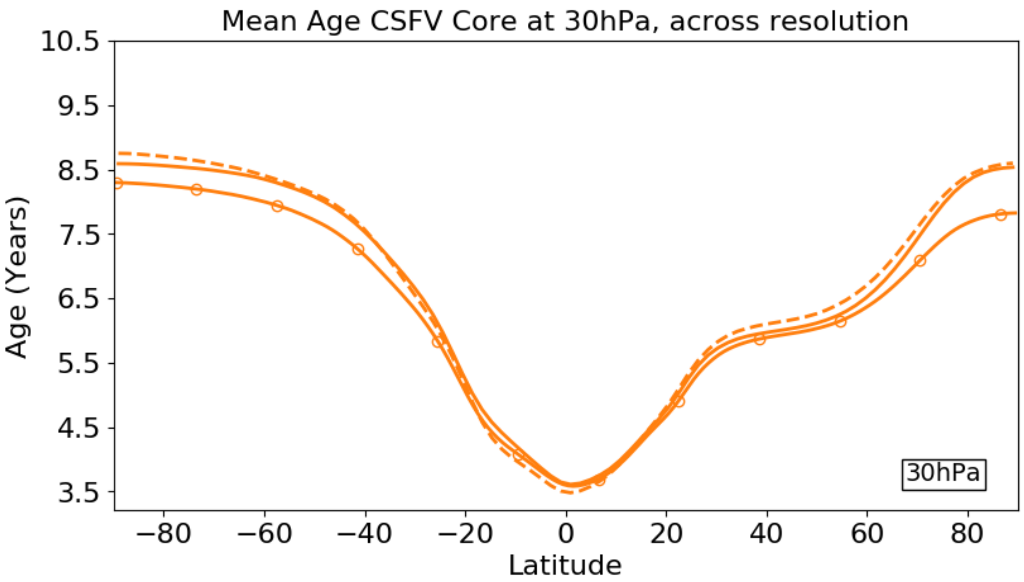

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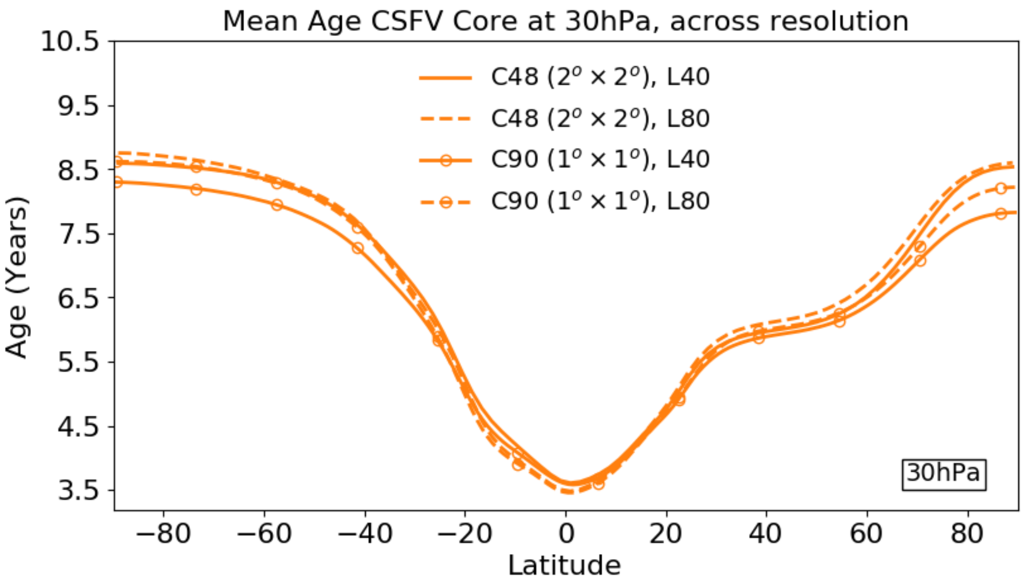

- Transport in cubed sphere finite volume core consistent across different vertical and horizontal resolutions

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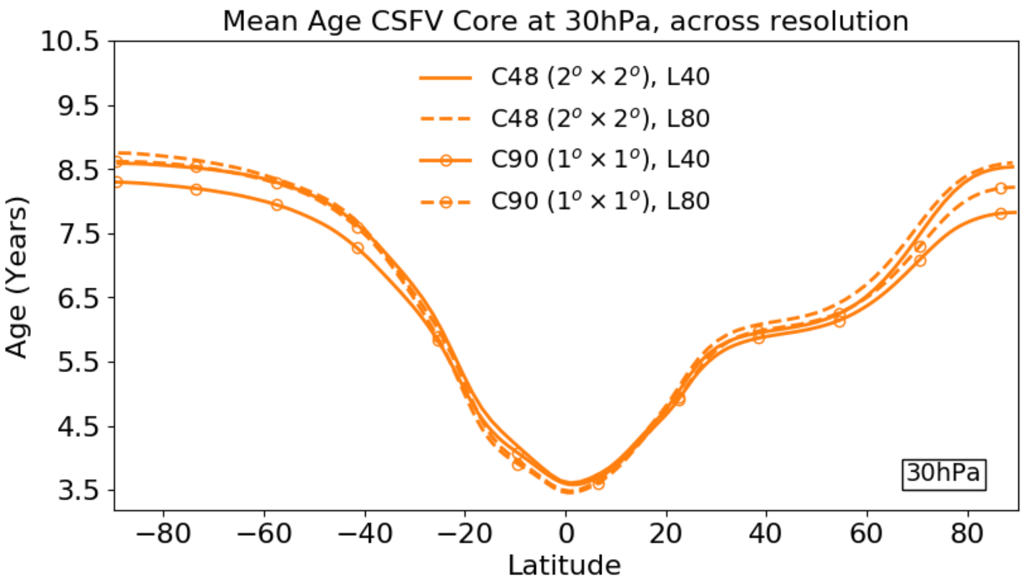

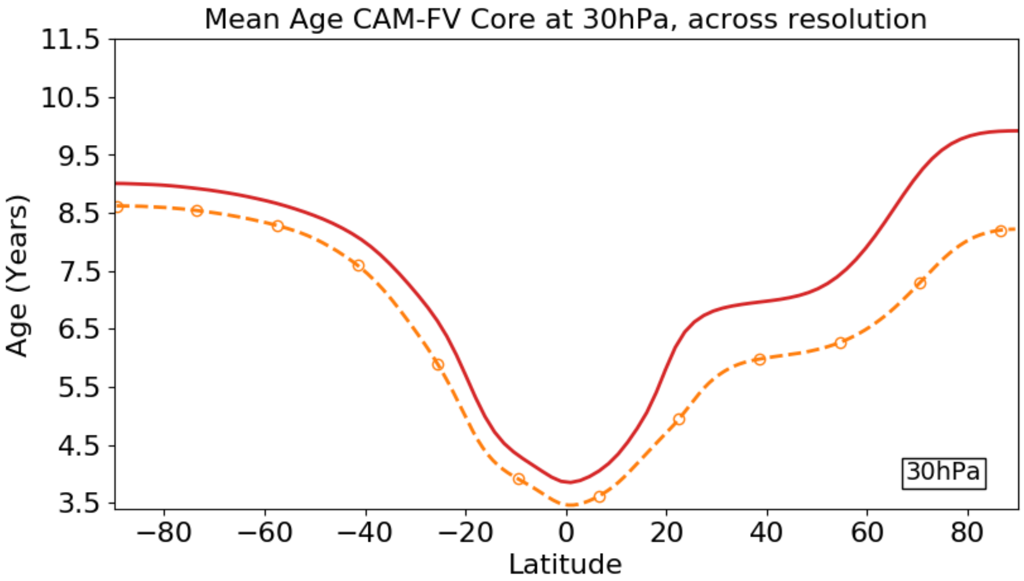

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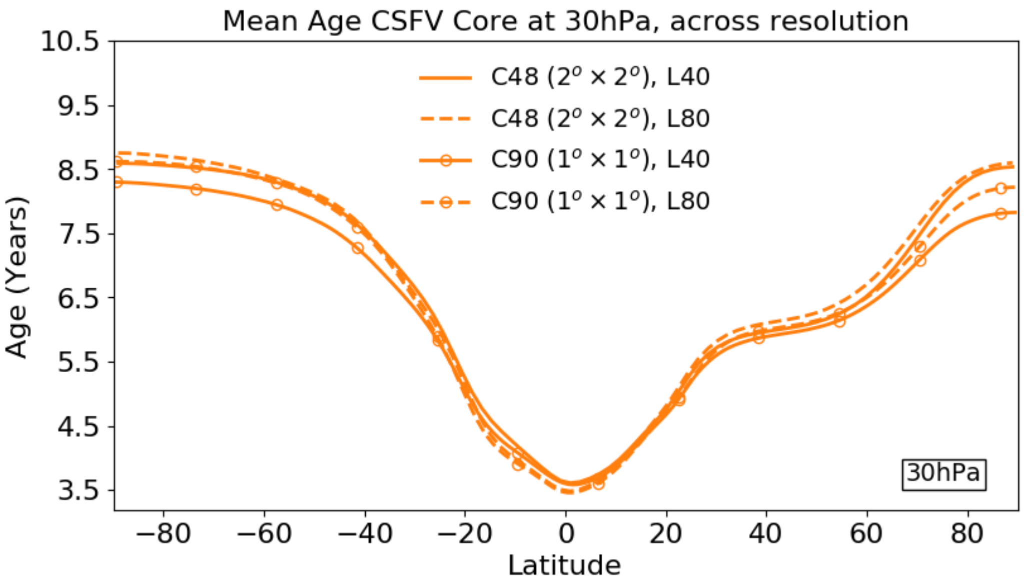

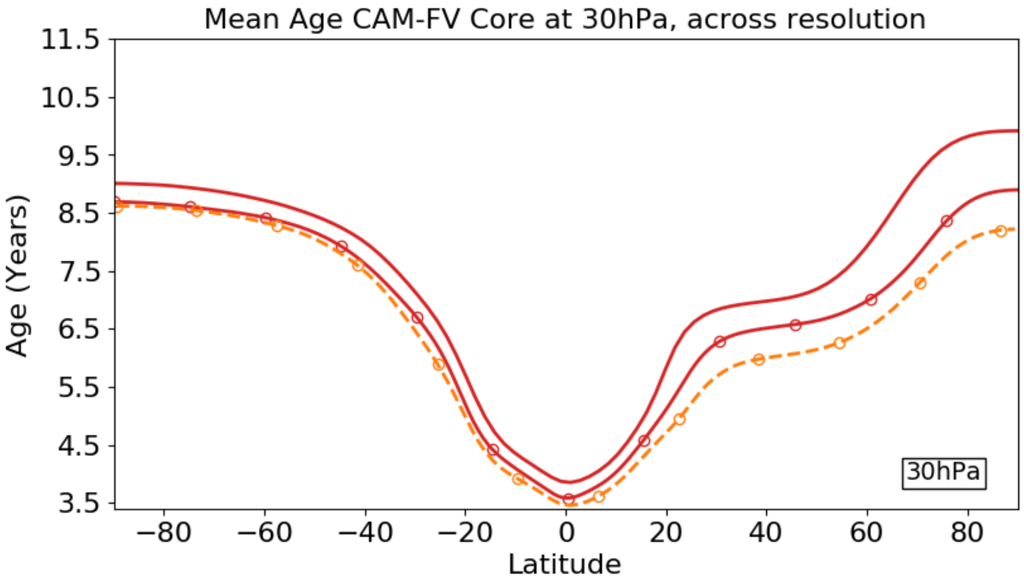

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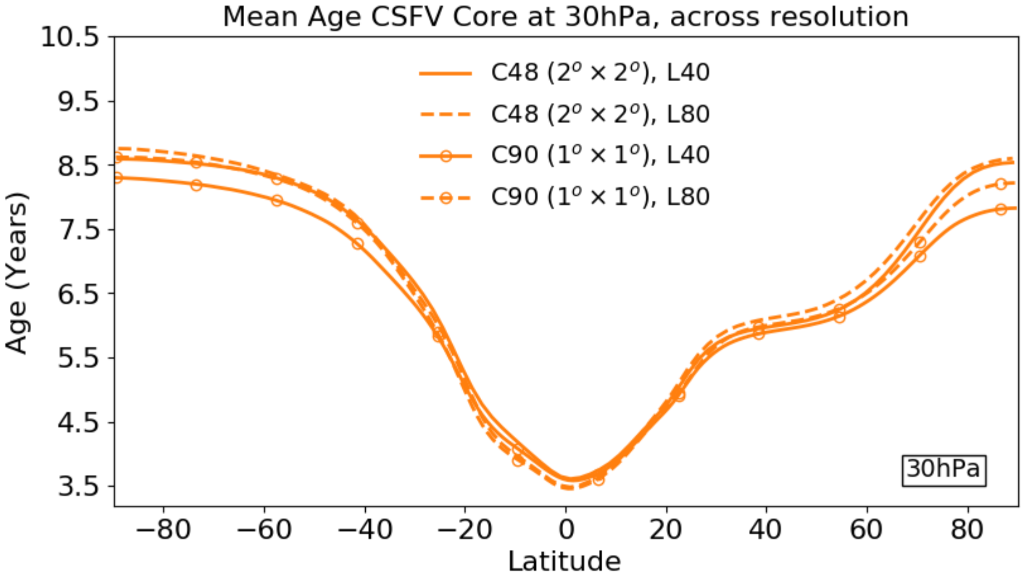

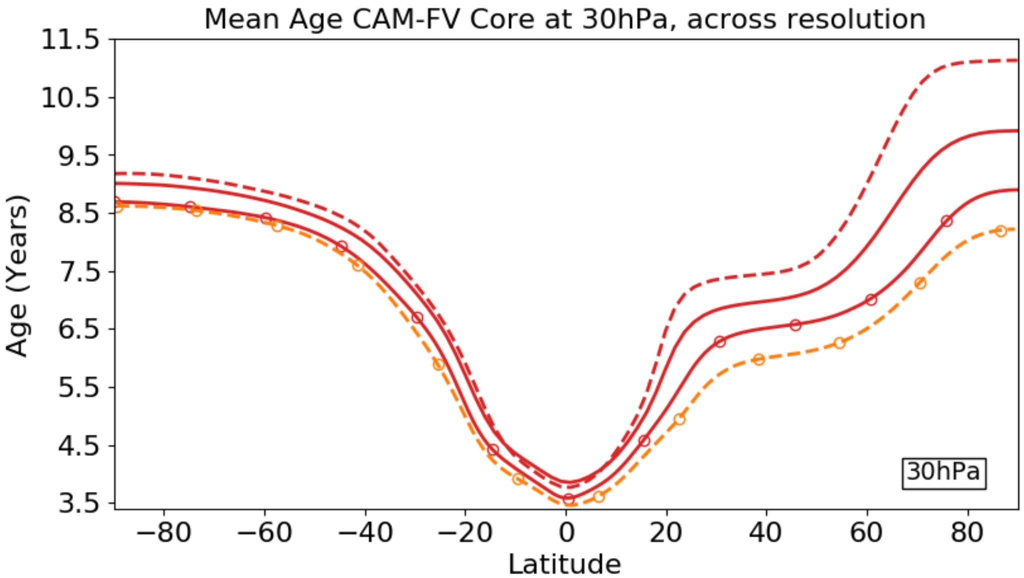

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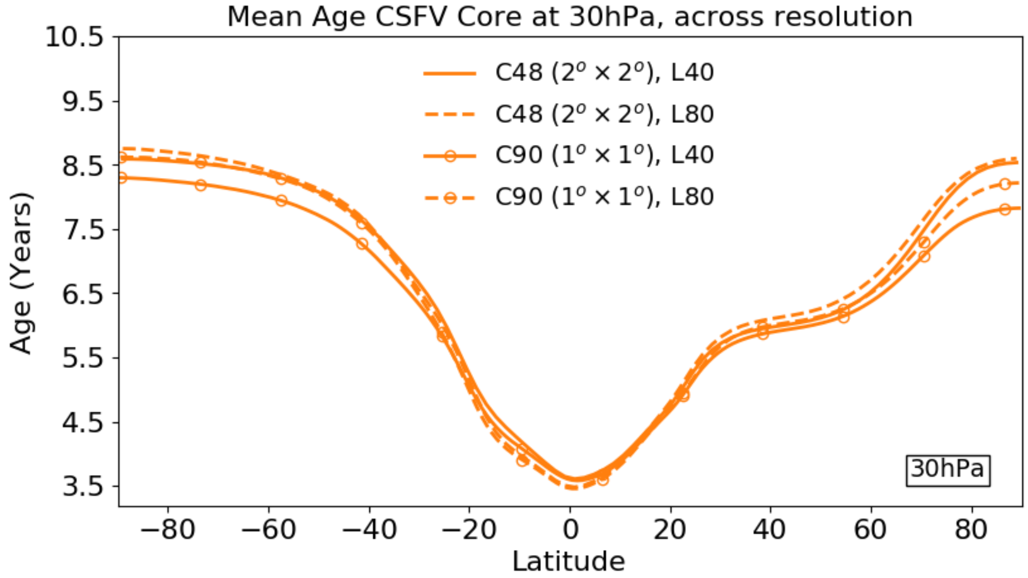

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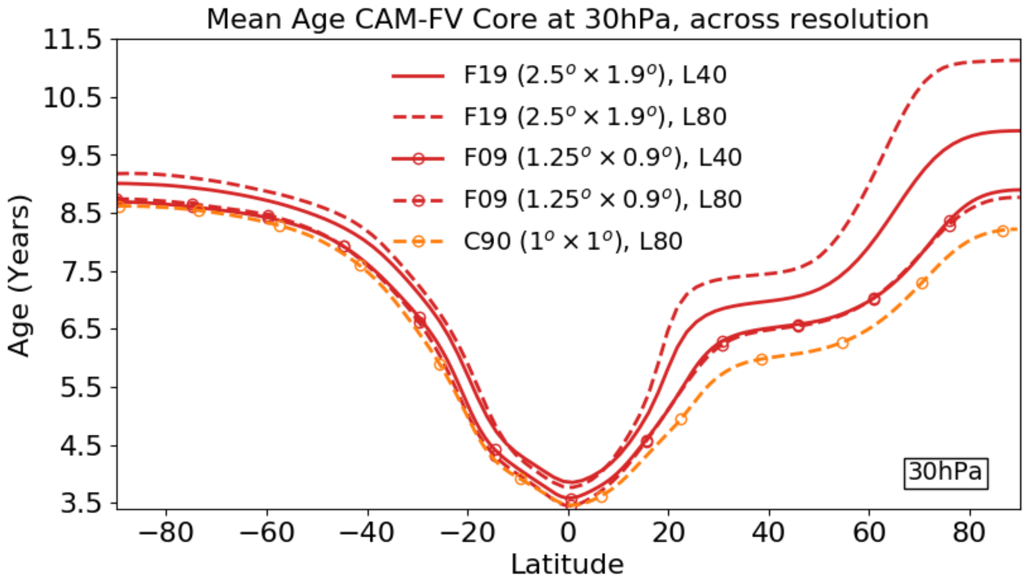

- Transport in CAM finite volume core converges well with increasing horizontal resolution.
- Polar regions not represented well at low horizontal resolutions

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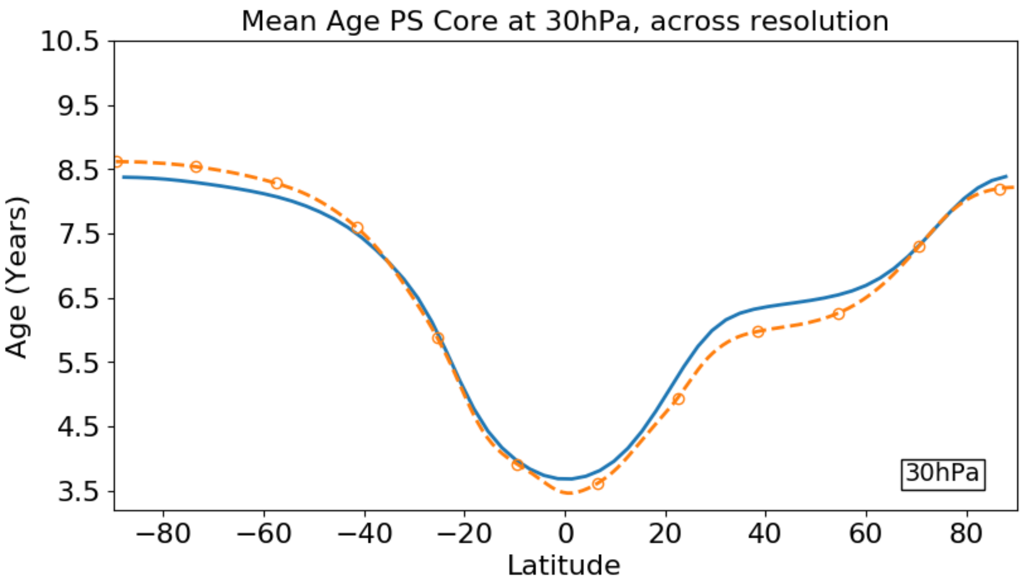
Age of air for PS and SE core



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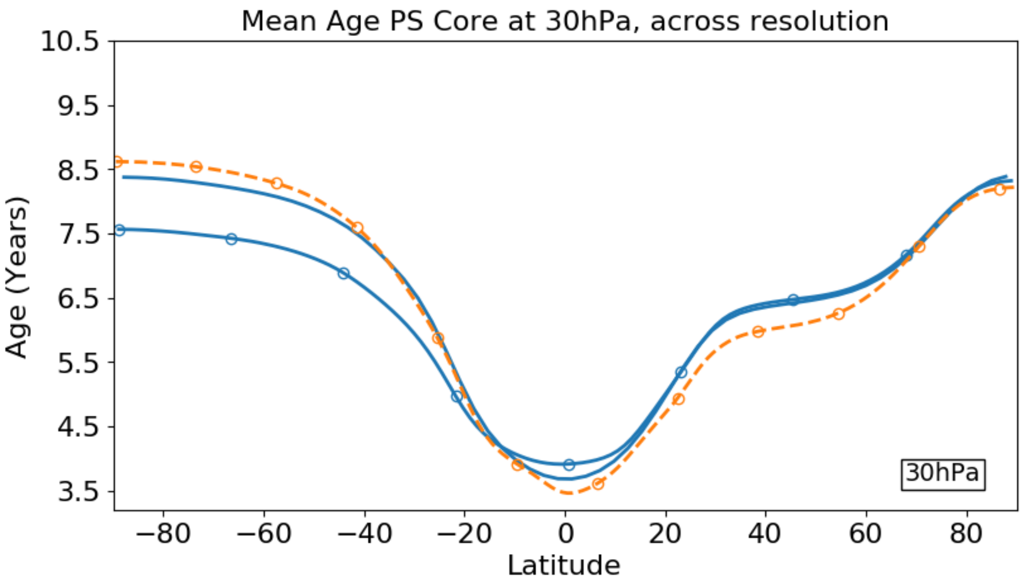

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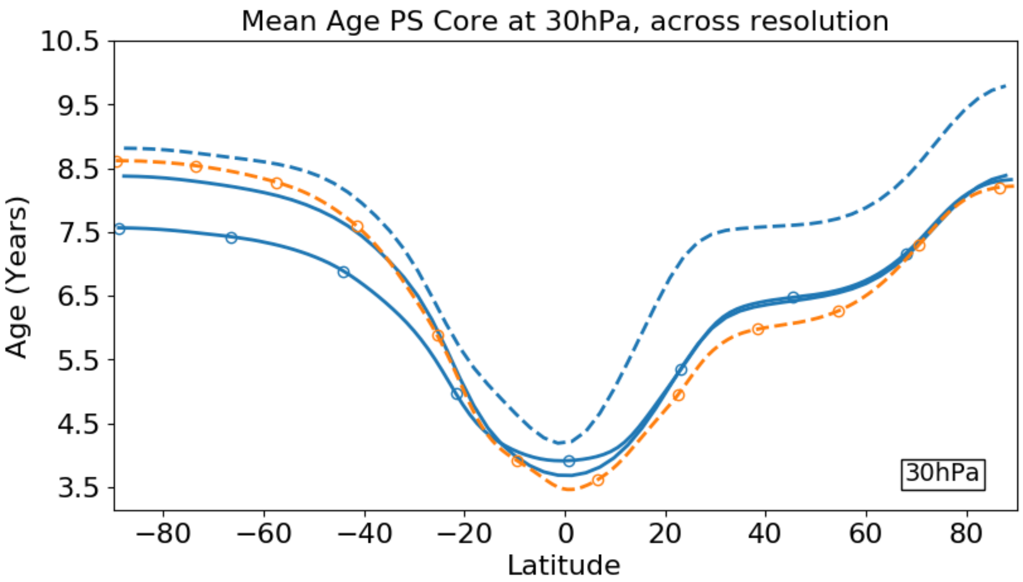

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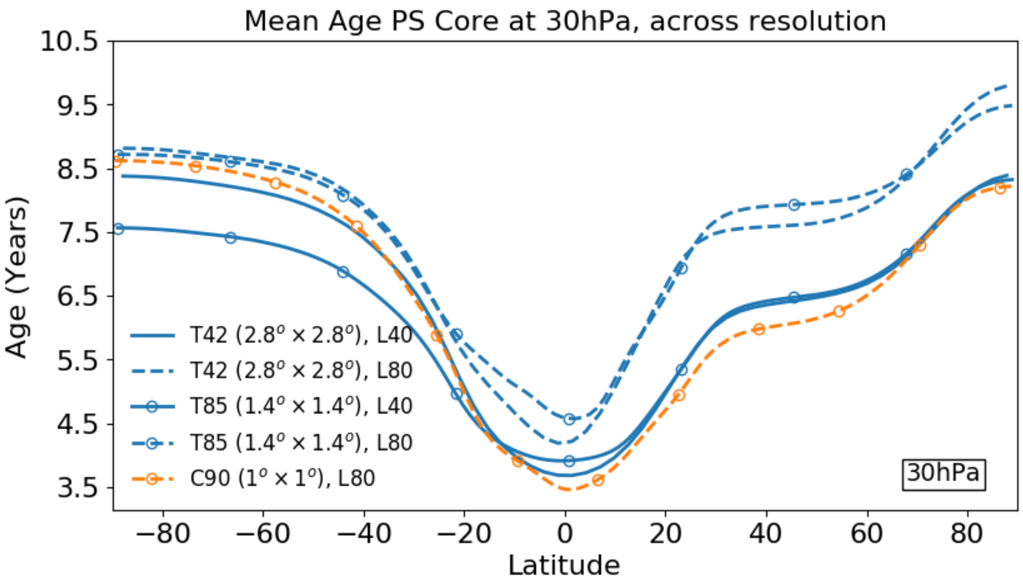

- Drastic changes in transport in the pseudospectral core as vertical resolution in increased.
- Transport very similar to CSFV at moderate vertical resolutions

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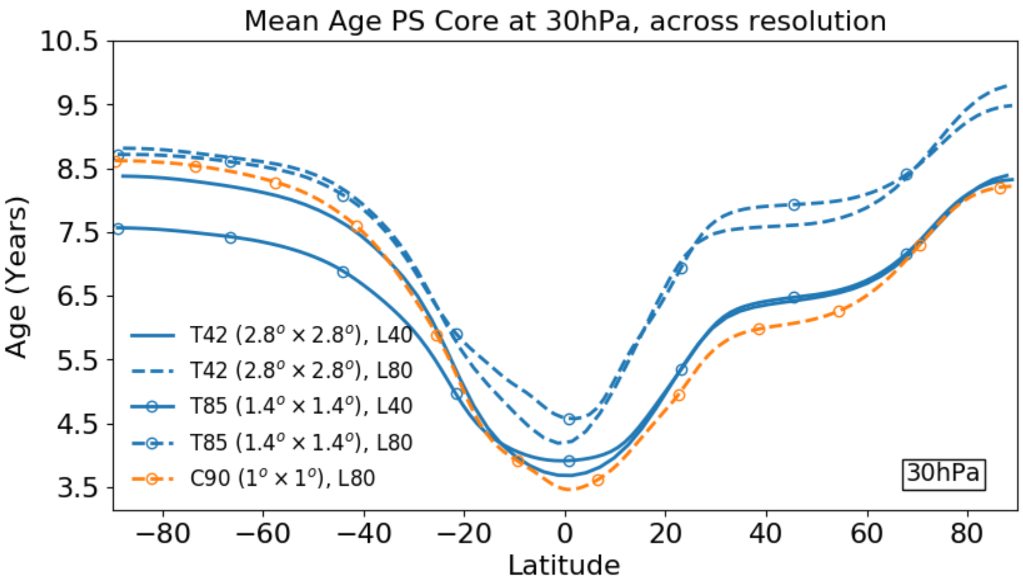

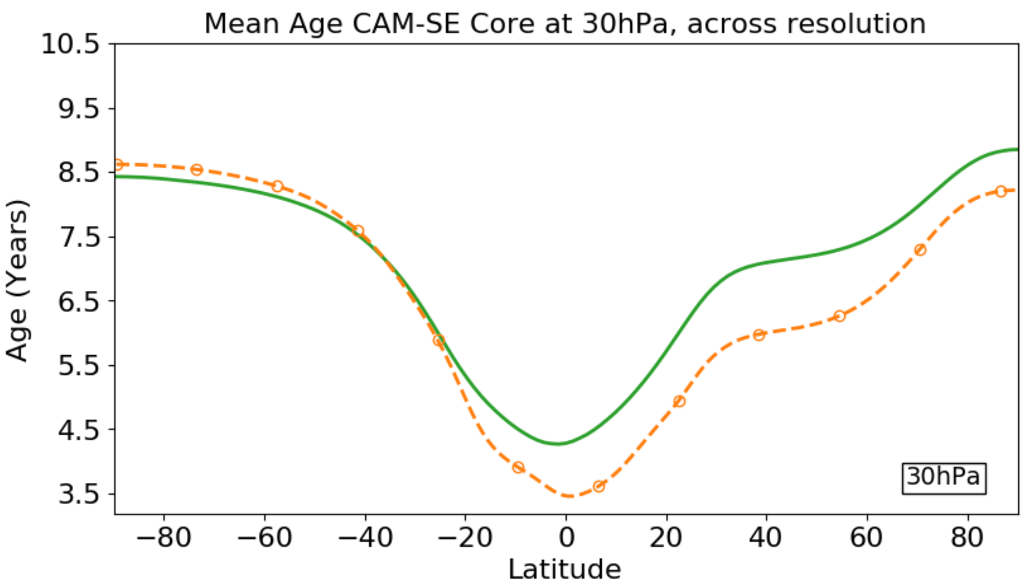

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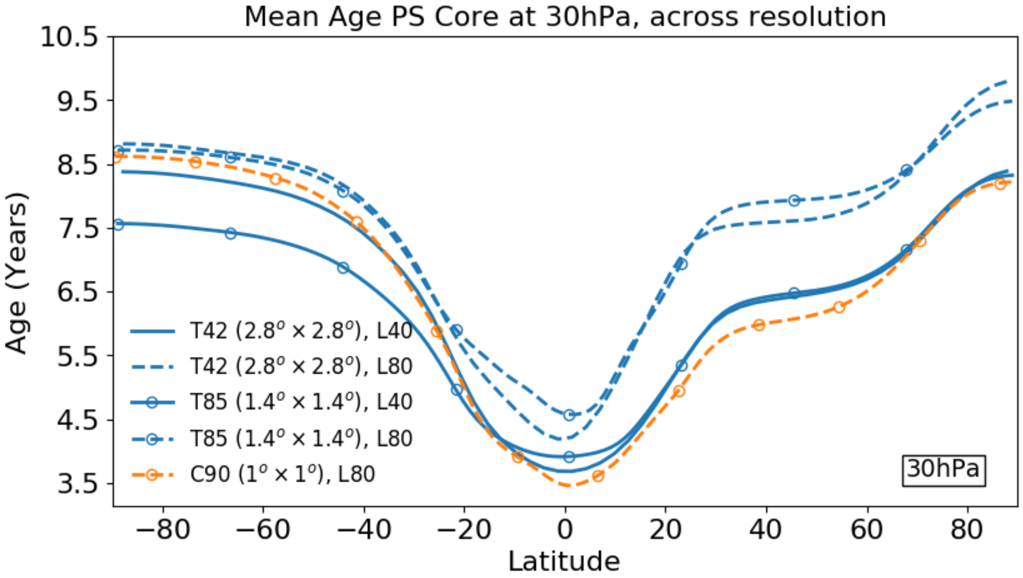

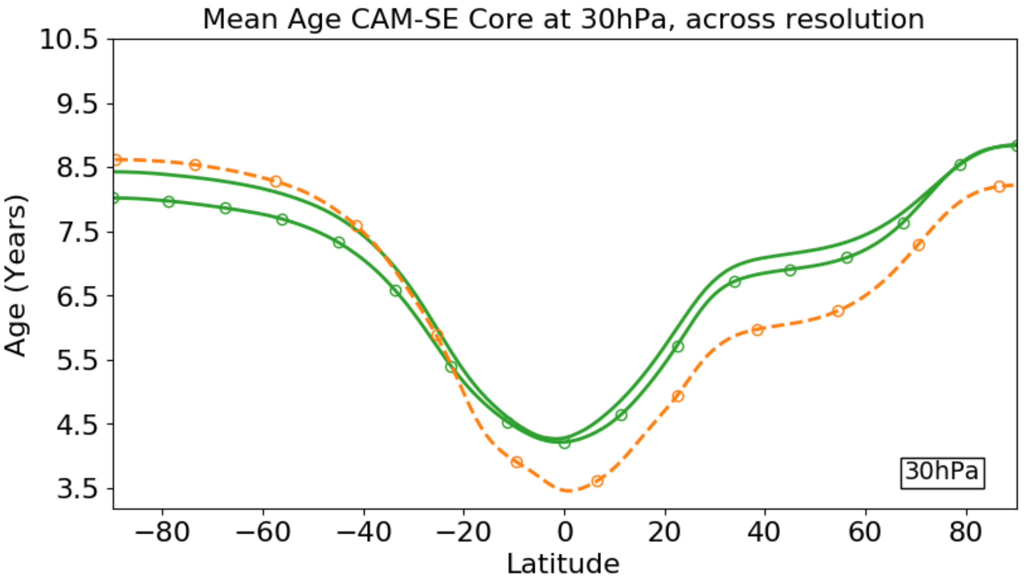

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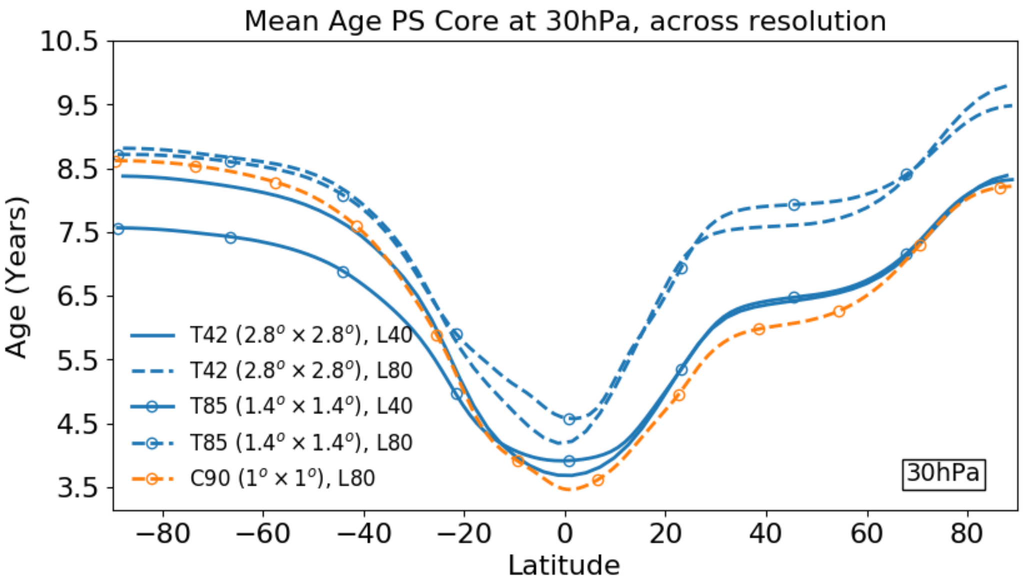

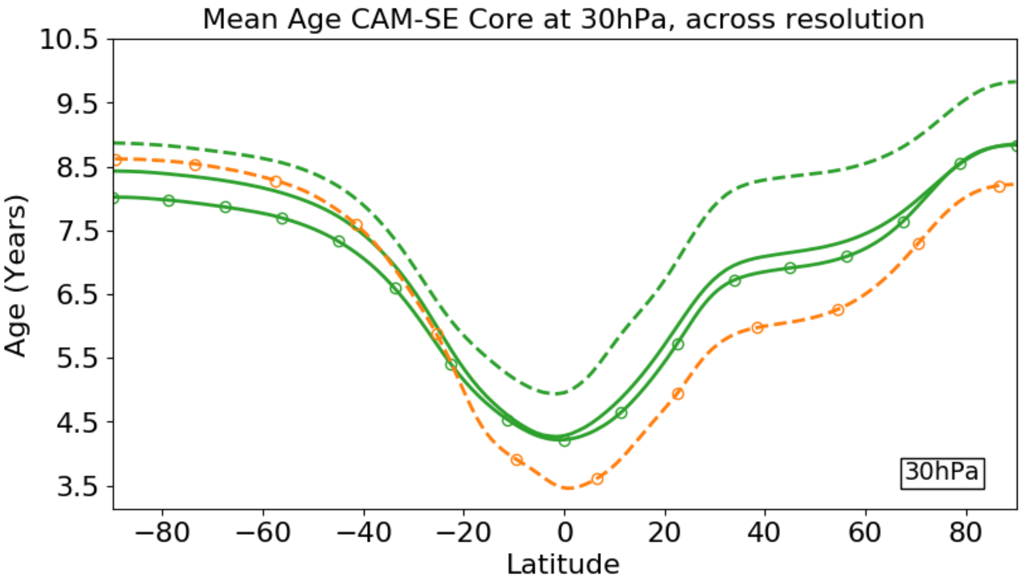

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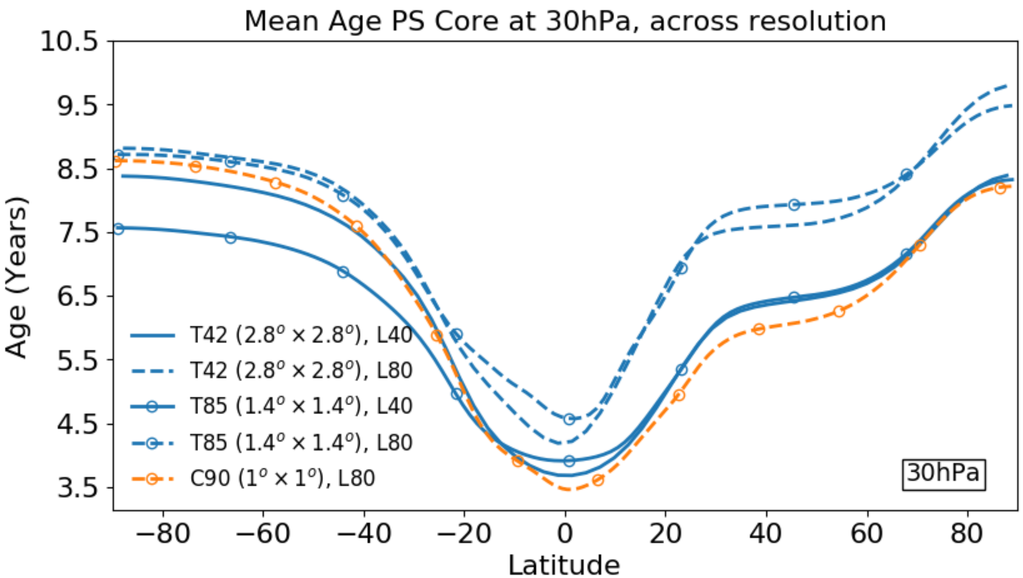

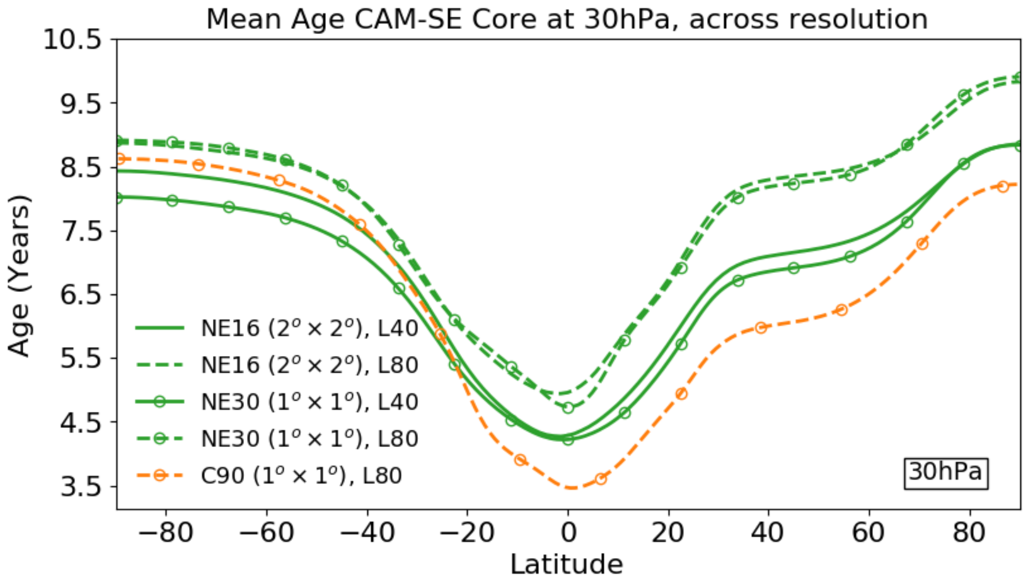

- Drastic changes in transport in the pseudospectral core as vertical resolution in increased.
- Transport very similar to CSFV at moderate vertical resolutions
- Transport in CAM spectral element extremely sensitive to vertical resolution as well.

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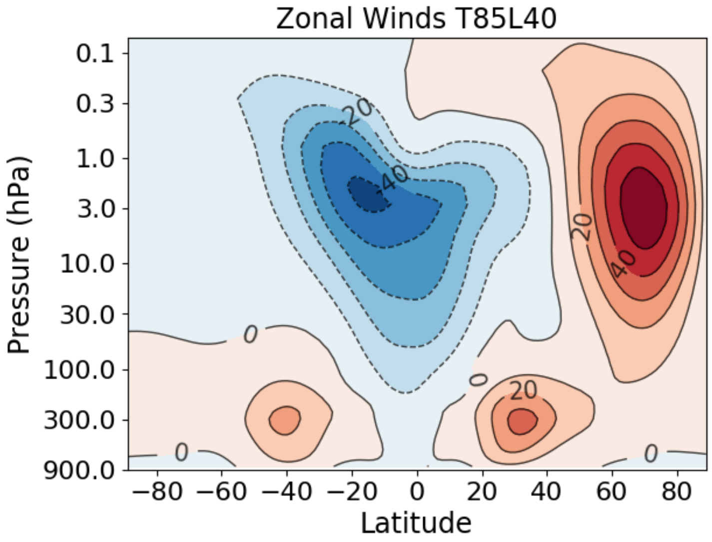
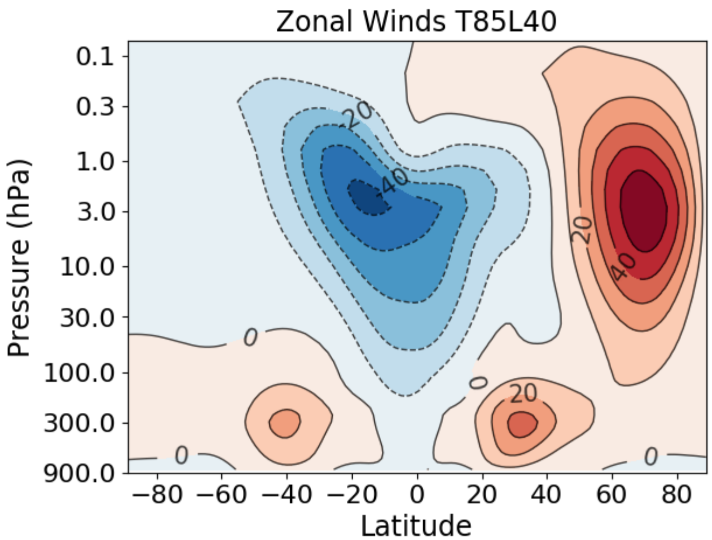
Westerlies in the tropical stratosphere



T85 : 1.4° x 1.4°, 40 vertical

Westerlies in the tropical stratosphere



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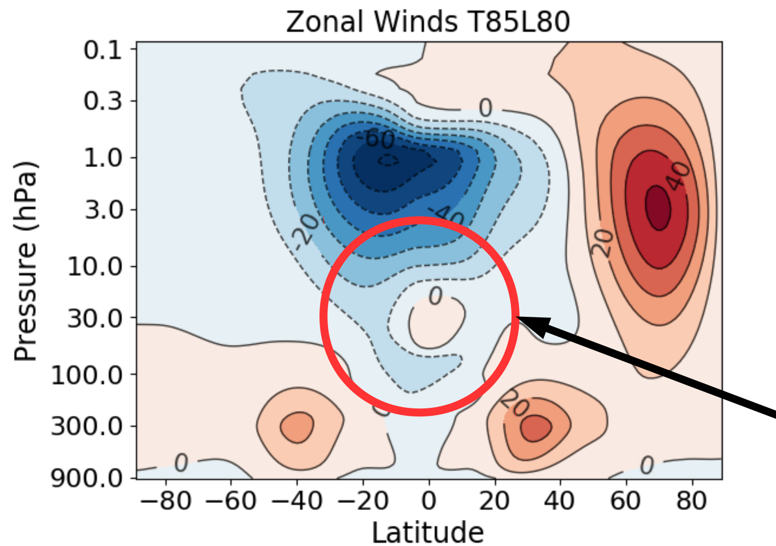

T85 : 1.4^{O} x 1.4^{O}, 80 vertical

Fig : Zonal wind structure for T85L40 and T85L80 runs.

Westerlies develop in tropical stratosphere as vertical resolution is increased

- GFDL’s Pseudospectral and NCAR’s Spectral Element core resolve tropical westerlies as the vertical resolution is increased (from 40 to 80 levels).
- The Finite Volume cores (CSFV and CAM-FV) do not exhibit such westerlies.
- The westerlies are stationary and do not exhibit quasi-periodic oscillations.

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Westerlies in the tropical stratosphere

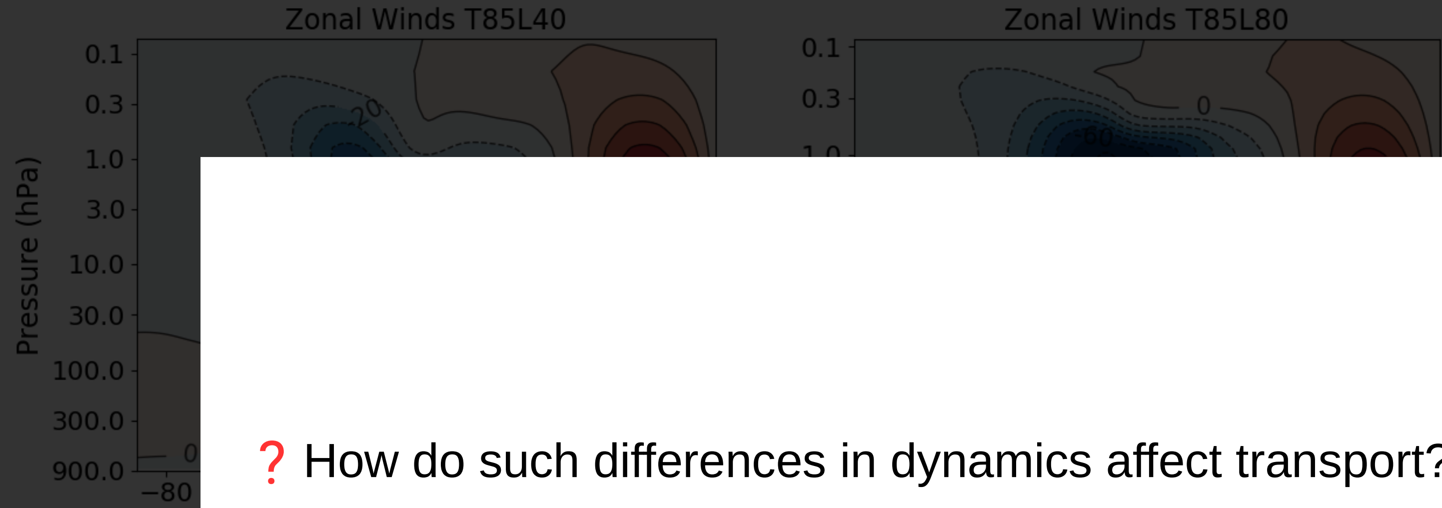

Fig : Zonal wind structure for T85L40 and T85L80

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vertical

eased

T85

Questions

❓ How do such differences in dynamics affect transport?

❓ Can differences in transport be resolved if all models have the same climatology?

- GF

  we

- The Finite Volume cores (CSFV and CAM-FV) do not resolve such westerlies.

- The westerlies are stationary and do not exhibit quasi-periodic oscillations.

How do these differences affect transport?

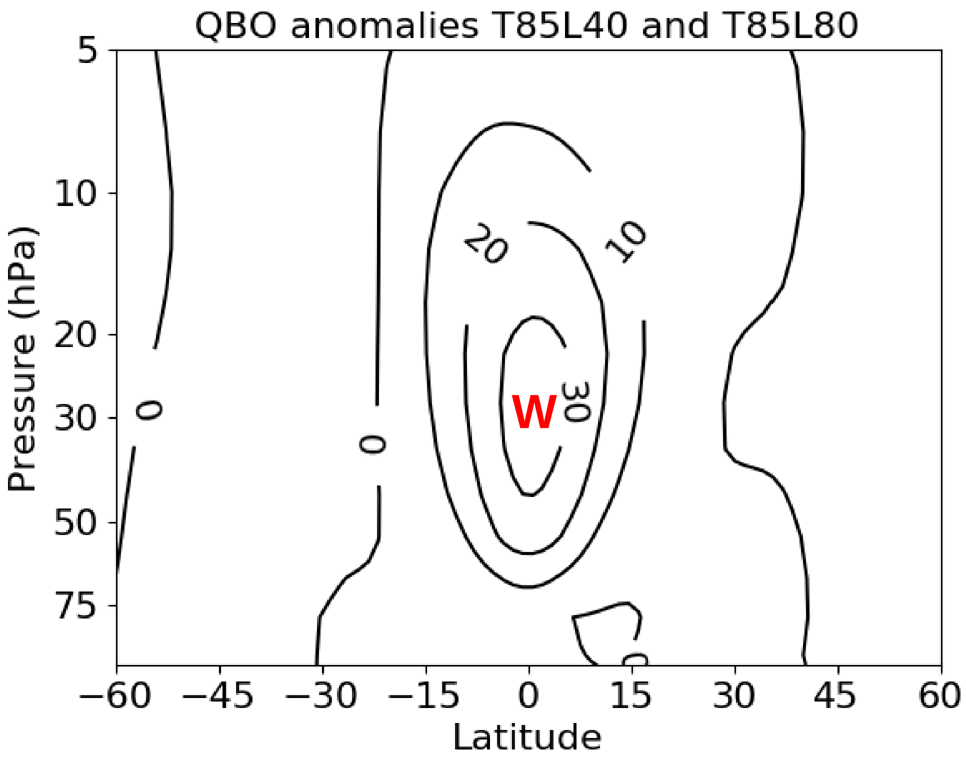

Fig : Wind anomalies T85**L80** – T85**L40.**

in m/s.

- Figure shows wind anomalies between PS core's T85**L80** and T85 **L40** runs**.** Positive wind anomalies associated with a fixed QBO-like development

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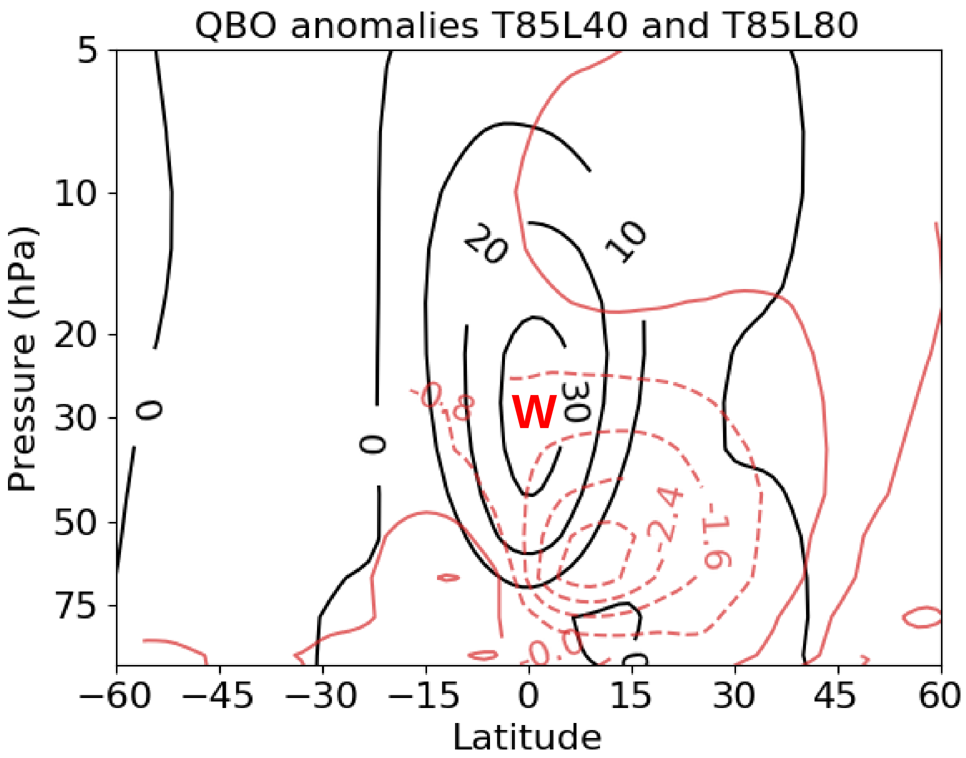

Fig : Wind anomalies (black) T85**L80** – T85**L40** with diabatic circulation anomaly (red)

- Figure shows wind anomalies between PS core's T85**L80** and T85 **L40** runs**.** Positive wind anomalies associated with a fixed QBO-like development
- Westerly wind anomalies induce a downwelling in the tropics
- An anti-clockwise circulation develops in the tropics

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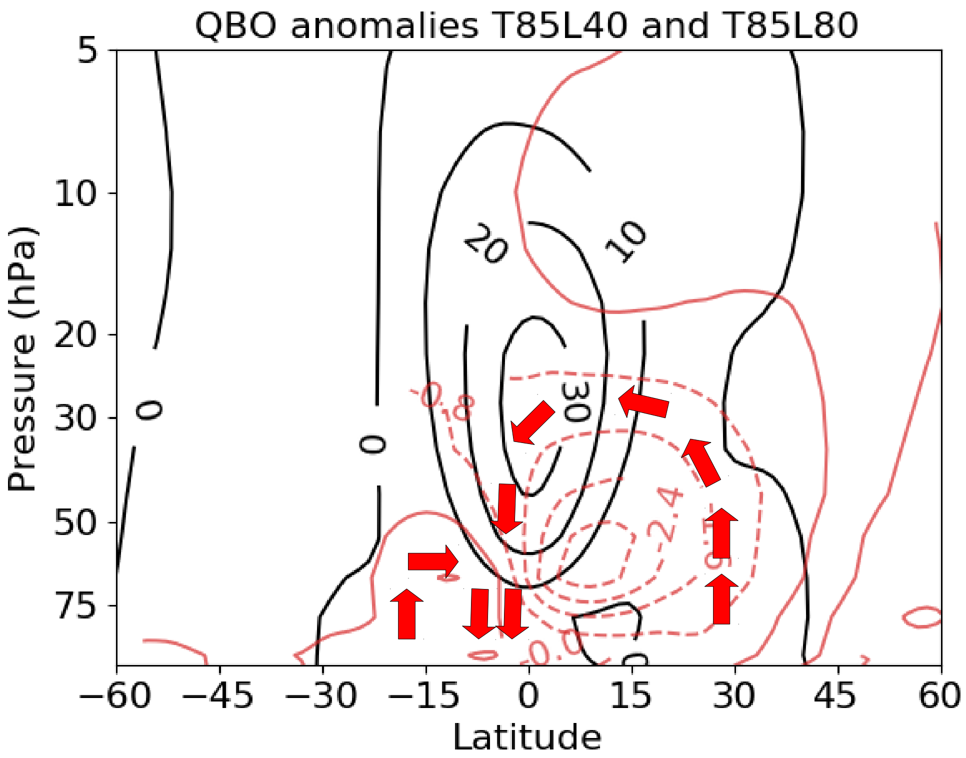

Fig : Wind anomalies (black) T85**L80** – T85**L40** with diabatic circulation anomaly (red) (10^8 kg/s)

- Figure shows wind anomalies between PS core's T85**L80** and T85 **L40** runs**.** Positive wind anomalies associated with a fixed QBO-like development
- Westerly wind anomalies induce a downwelling in the tropics
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What causes this difference in climatology?

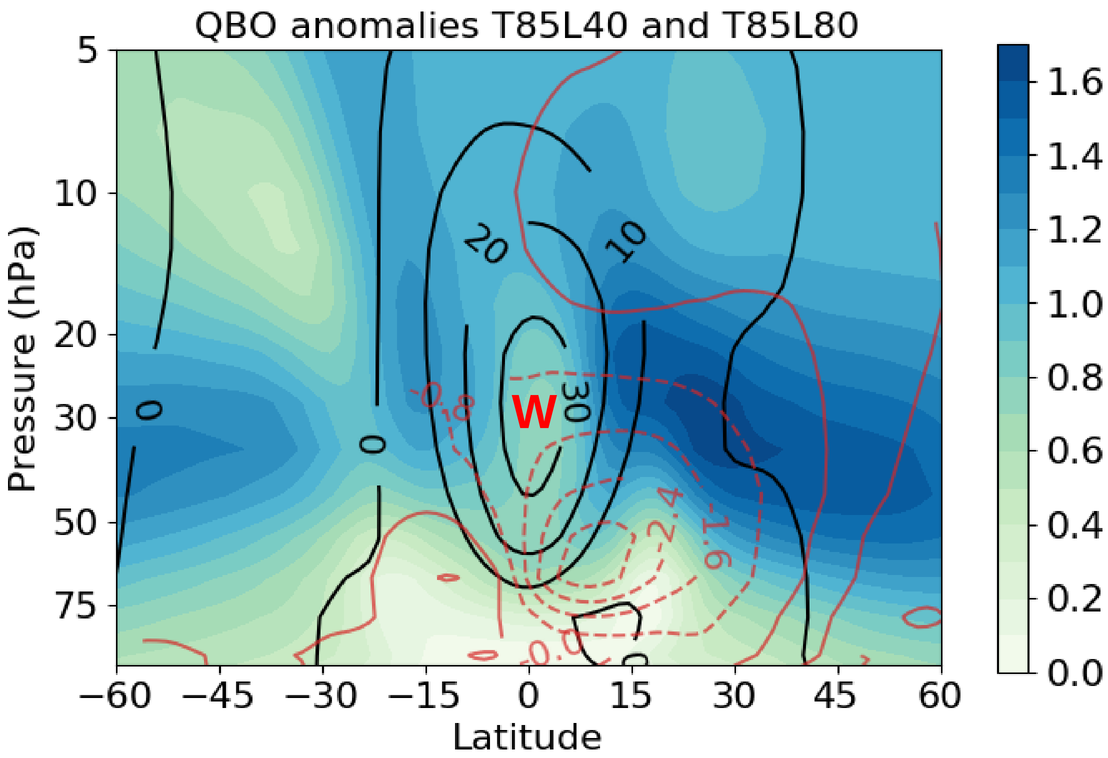


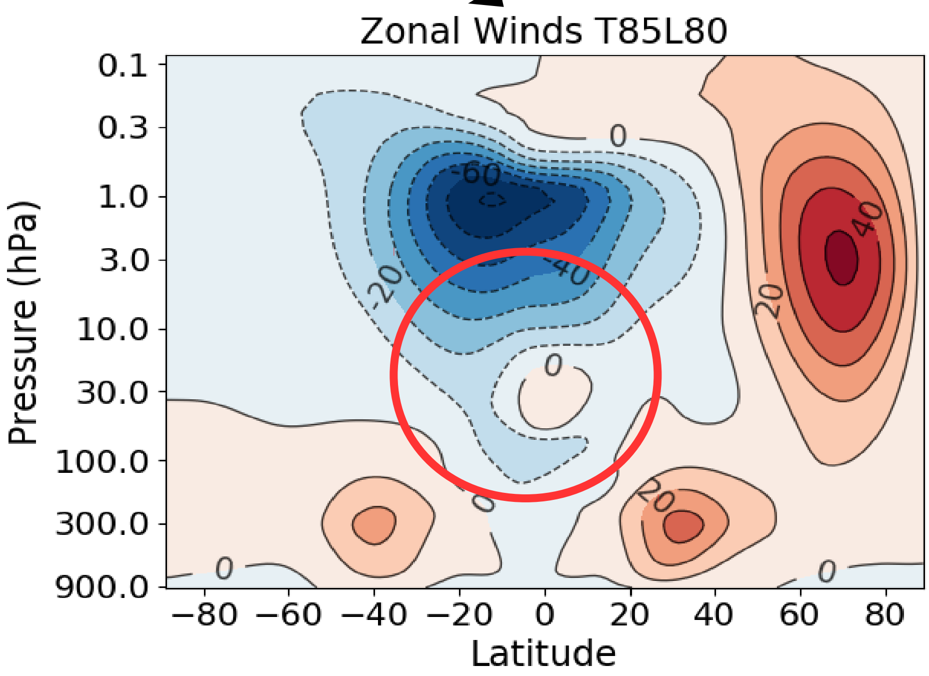
Fig : Age anomaly contours (in color)

T85**L80** – T85**L40.** Units : Years

- The winds influence the mixing of older midlatitude air with younger tropical air by changing the mean meridional transport in the tropics.

Increasing horizontal damping eliminates westerlies

PSEUDOSPECTRAL



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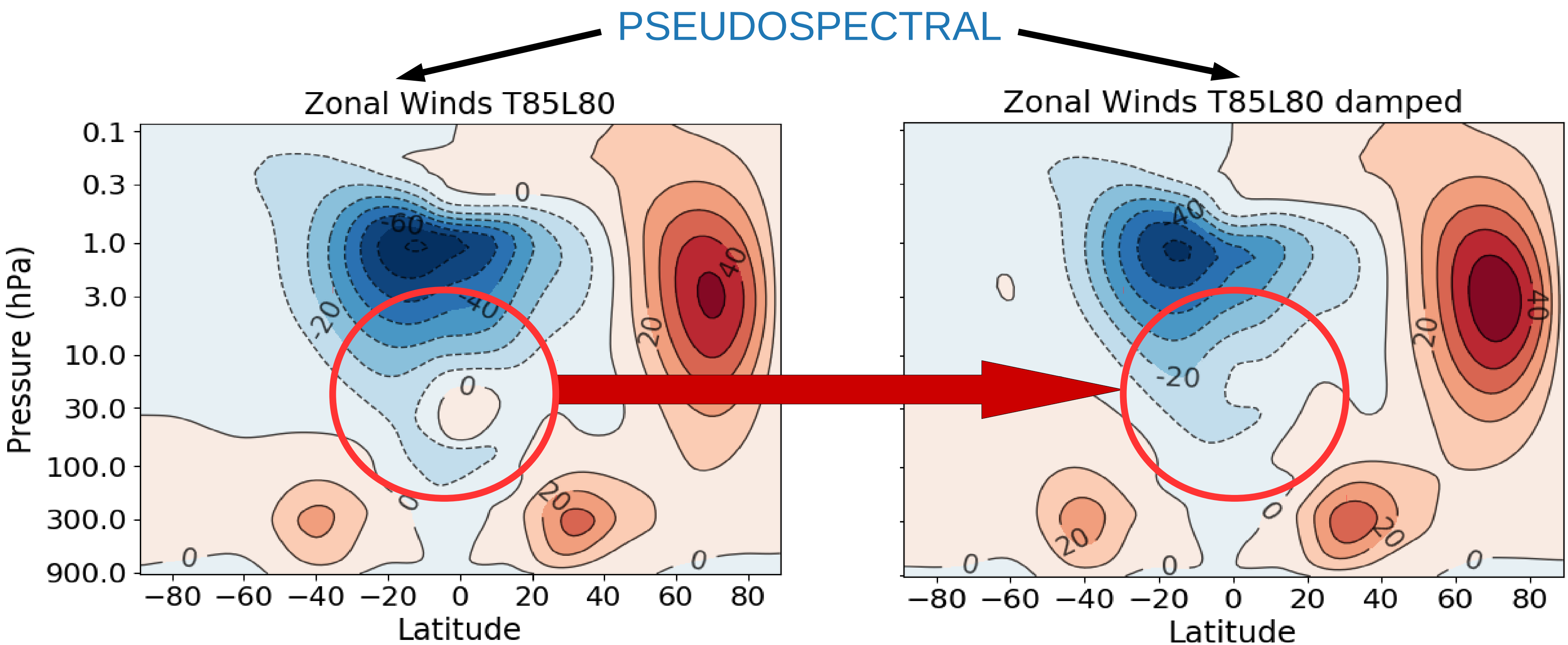
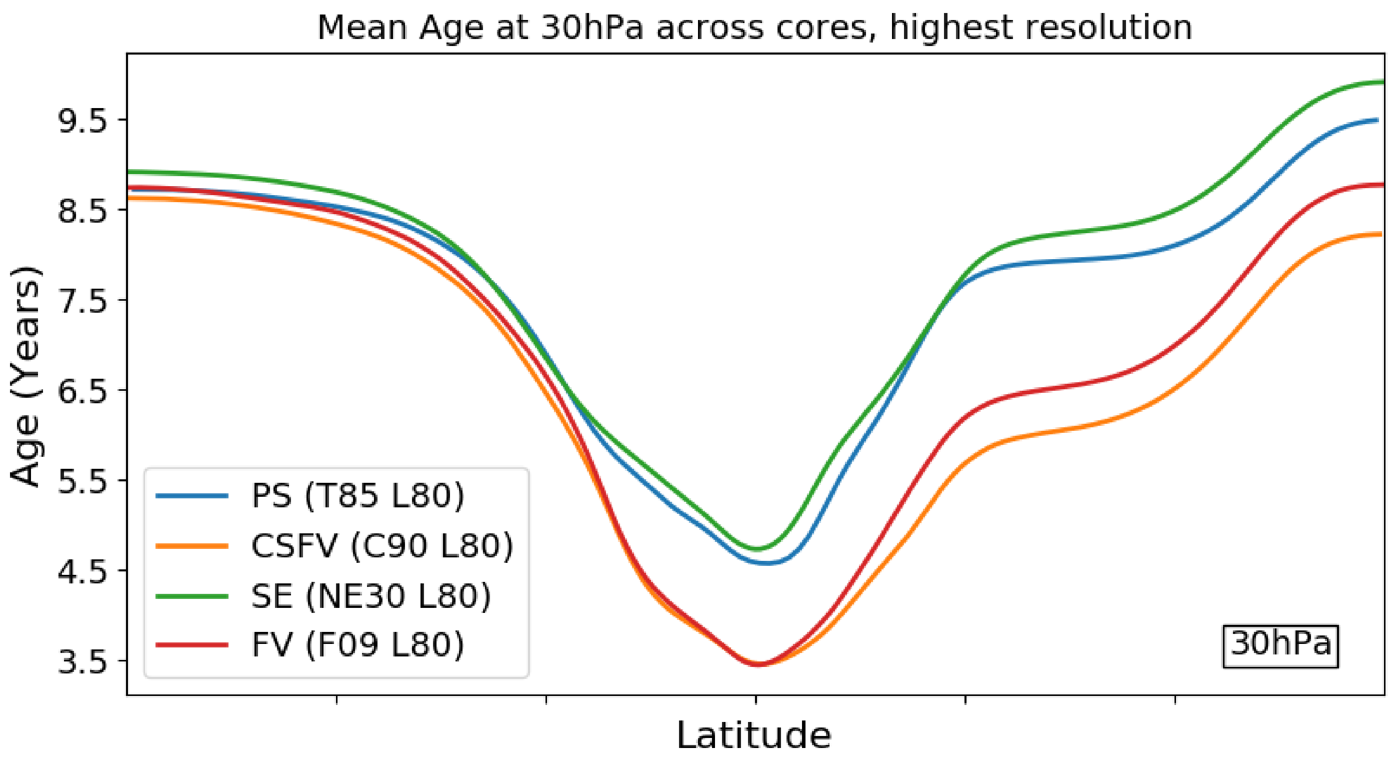


- Diffusion in PS and SE is achieved using explicit, linear, hyperdiffusion
- Increasing horizontal diffusion sufficiently damps the tropical westerlies
- Increasing vertical diffusion does not have much impact

Age of air in damped runs



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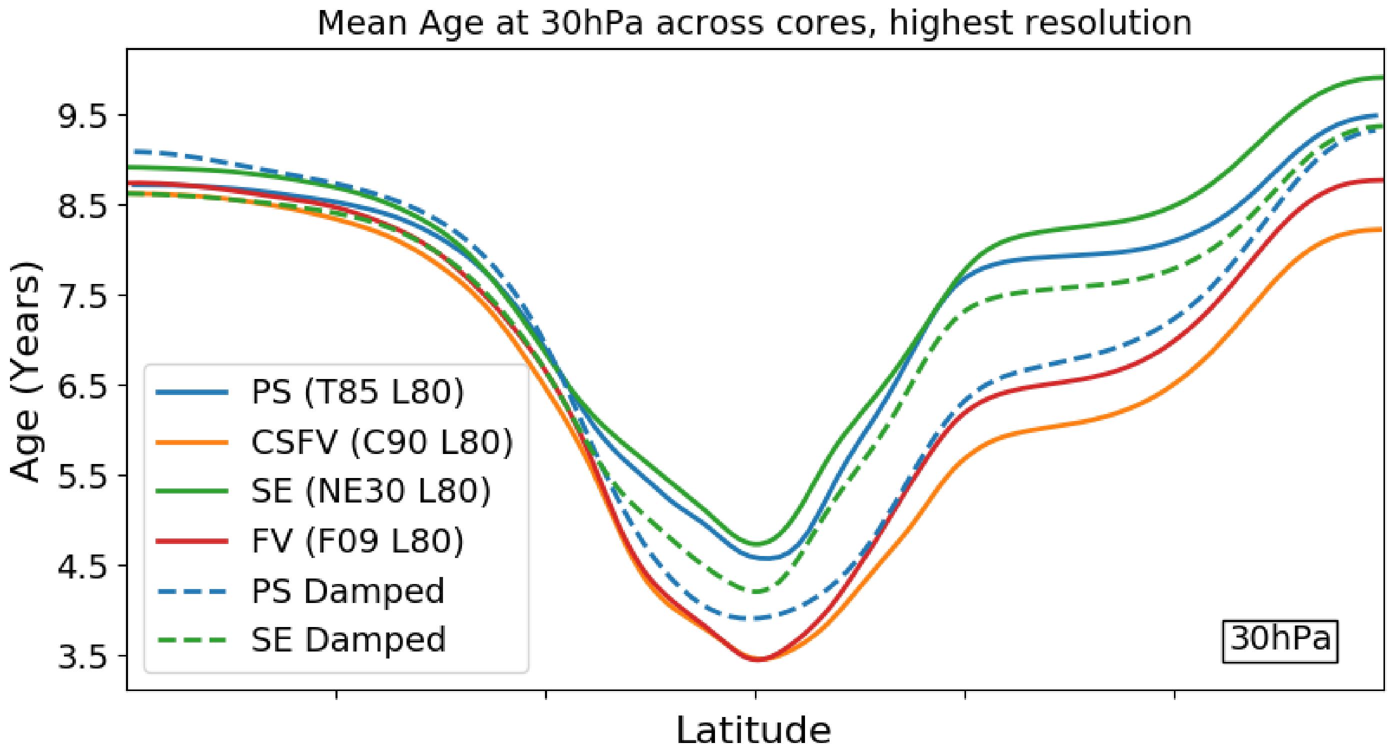

- Damping the tropical westerlies significantly decreases the age in PS and SE cores

- Brings the age in closer agreement with CSFV and FV

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Benchmark Age

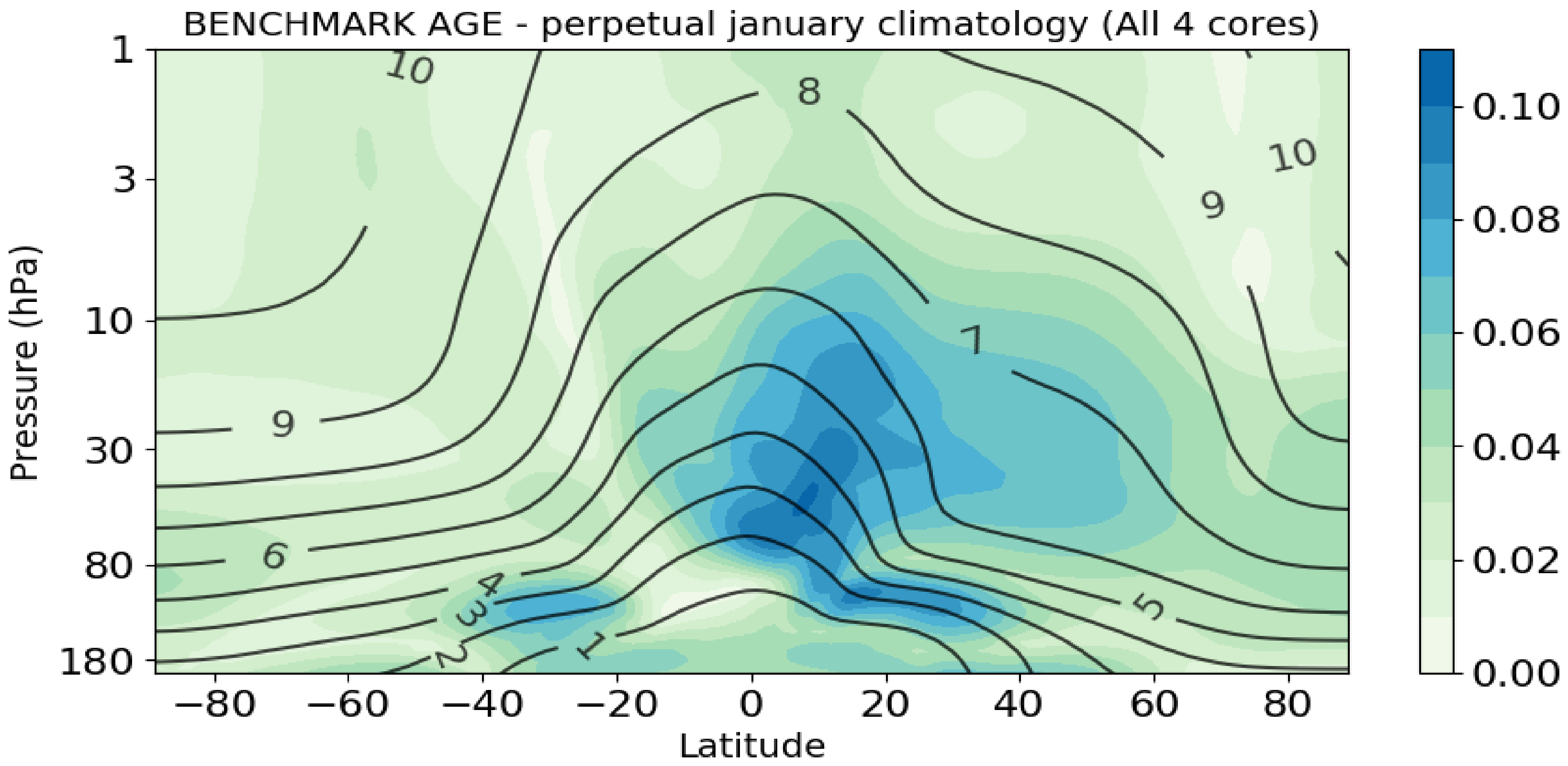

Fig : Age of air (in year) in black contours. *'Fractional'* age deviation across models in color

- Ensemble Mean (highest res) is used to propose a benchmark age of air
- Allows to study transport at climatological time scales subjected to realistic atmospheric transport processes
- An important tool to test dynamical cores and tracer transport schemes

Benchmark Age

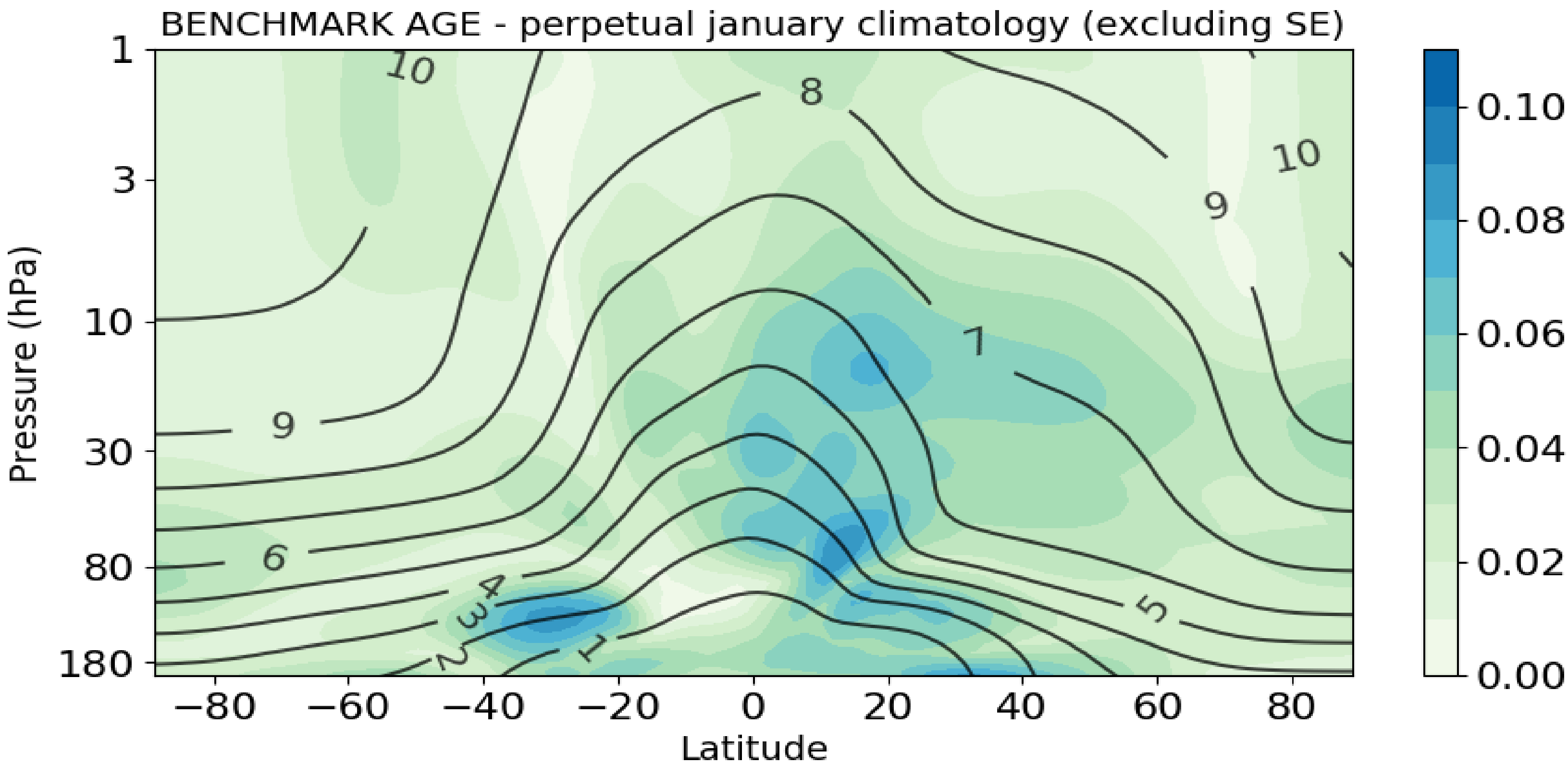

Fig : Age of air (in year) in black contours. *'Fractional'* age deviation across models in color

- Age of air CAM SE dynamical core contributes much to the fractional age deviation

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... In Conclusion

1) A benchmark test to assess tracer transport in dynamical cores has been proposed.

2) 4 very different dynamical cores show convergent behaviour at moderate vertical resolution.

3) At high vertical resolution, the pseudospectral and spectral element (models with spectral convergence) diverge due to development of QBO-like tropical winds.

4) Transport for such high vertical resolutions can be corrected by damping/regularizing the tropical circulation.

Further exploration

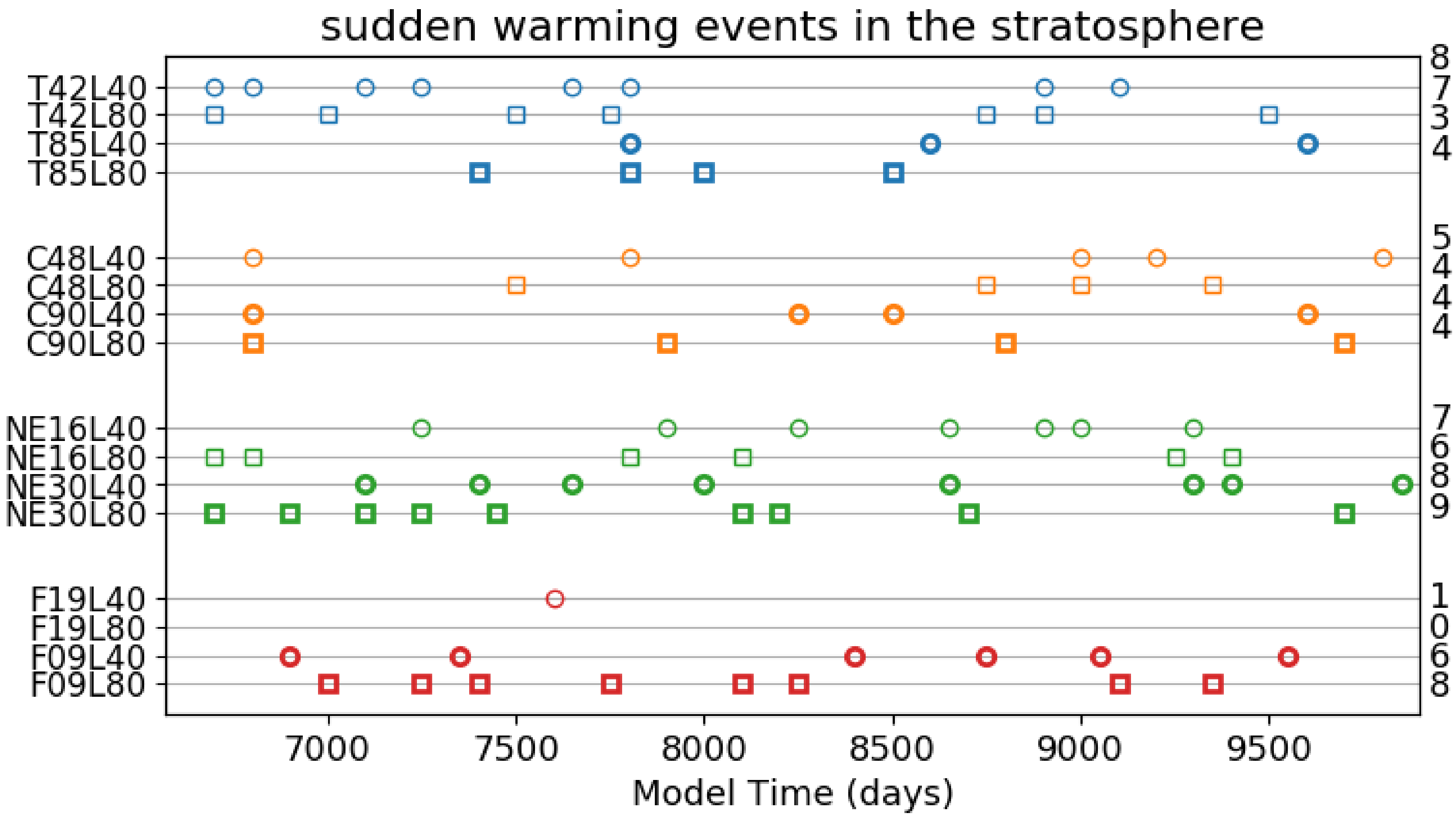
1) Assessing transport using CAM-SE-CSLAM at high resolution (0.25^0 x 0.25^0). Improved coupling between spectral element dynamics and finite volume transport.

2) Effect of regularizing/relaxing the QBO-like winds (instead of damping) on transport.

References

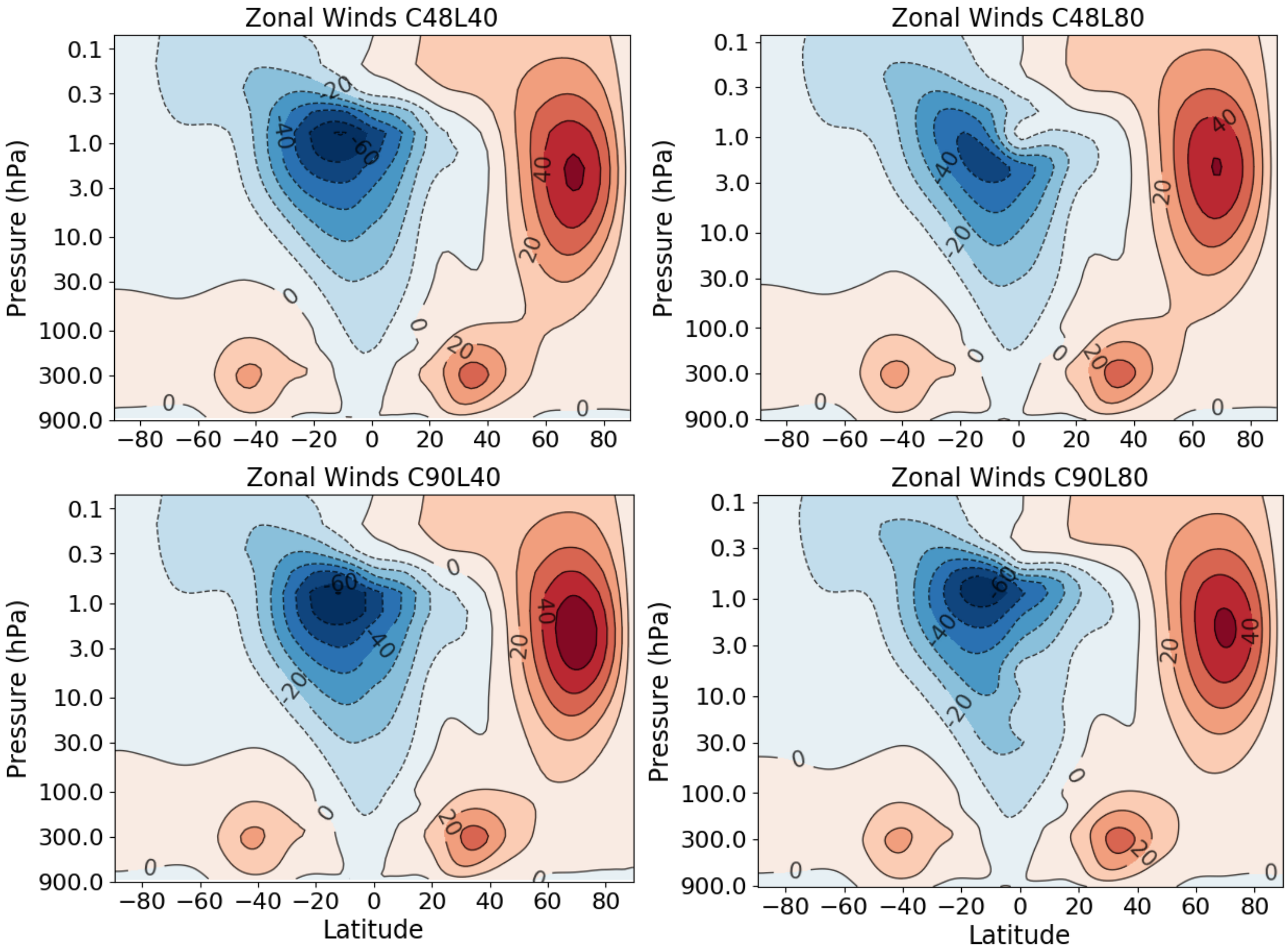
- Gupta, Aman, Edwin P. Gerber, and Peter H. Lauritzen : *Numerical impacts on tracer transport : A proposed intercomparison test of Atmospheric General Circulation Models*, Quart. J. Roy. Meteor. Soc. In preparation.
- Gupta, Aman, Edwin P. Gerber, and Peter H. Lauritzen : *Numerical impacts on tracer transport : Understanding biases in dynamical cores with the leaky pipe framework*, Quart. J. Roy. Meteor. Soc. In preparation.
- Karpechko, A.Y., D. Maraun, and V. Eyring, 2013 : *Improving Antarctic Total Ozone Projections by a Process-Oriented Multiple Diagnostic Ensemble Regression*. J. Atmos. Sci., **70**, 39593976

Supplementary plots



Resolved Climatology : CSFV Core

C48 : 2° x 2°, 40 vertical — C48 : 2° x 2°, 80 vertical



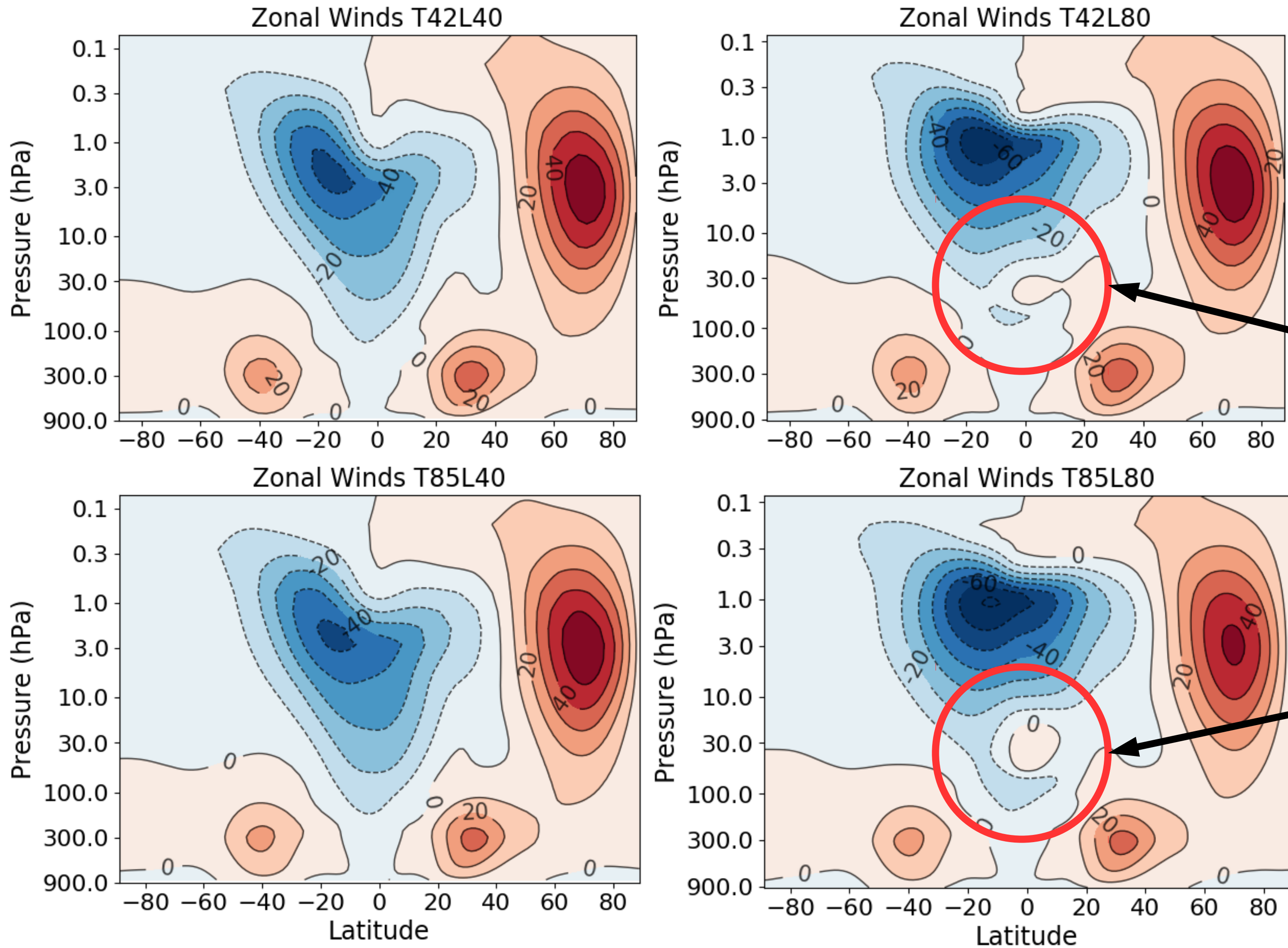
C90 : 1° x 1°, 40 vertical — C90 : 1° x 1°, 80 vertical

Fig : Zonal Wind structure across 4 CSFV runs with different resolutions

Resolved Climatology : Pseudospectral (PS) Core

T42 : 2.8° x 2.8°, 40 vertical

T42 : 2.8° x 2.8°, 80 vertical



T85 : 1.4° x 1.4°, 40 vertical

T85 : 1.4° x 1.4°, 80 vertical

Fig : Zonal Wind structure across 4 PS runs with different resolutions

Westerlies develop in lower tropical stratosphere as vertical resolution is increased

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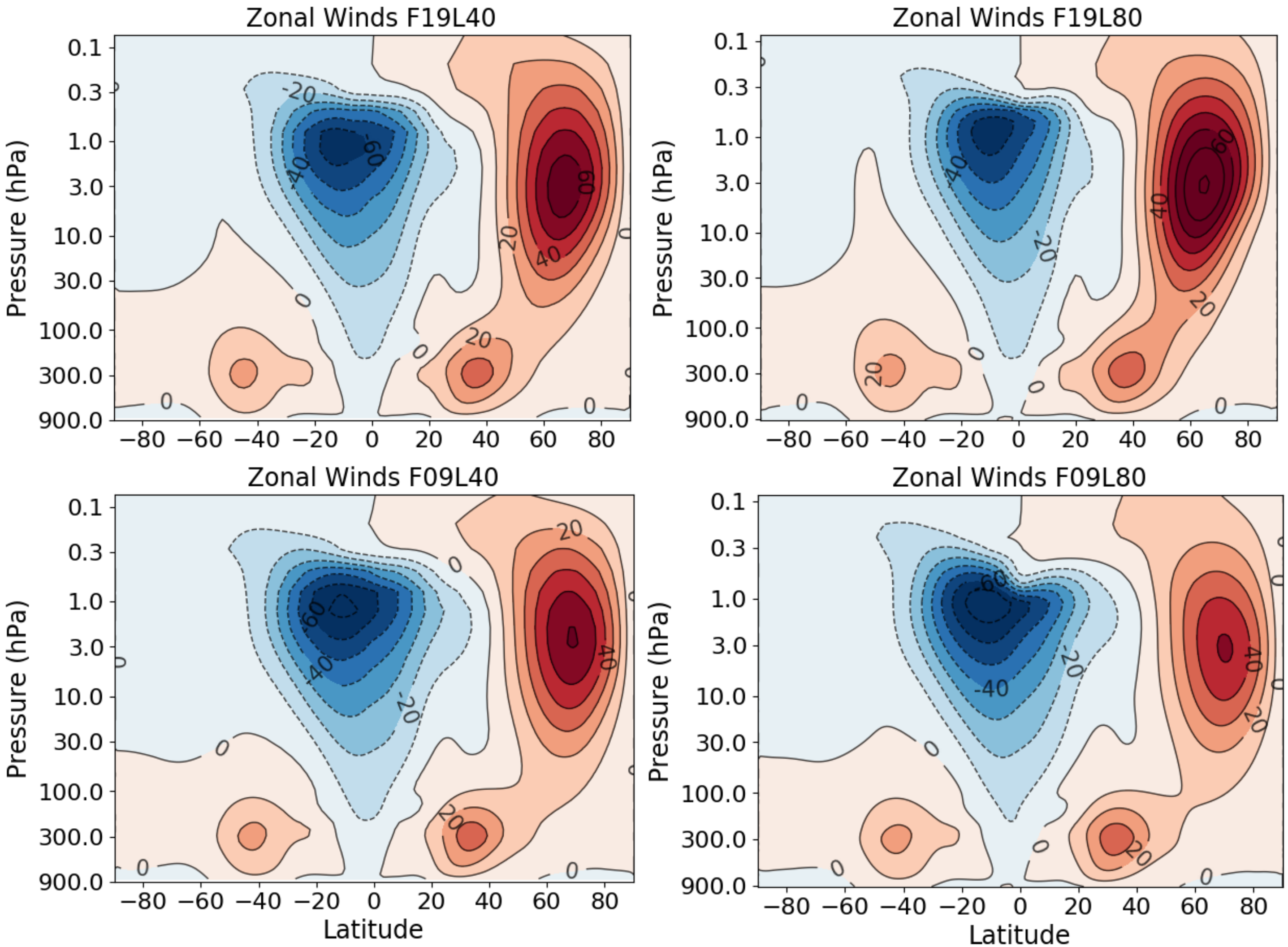
Resolved Climatology : Finite Volume (FV) Core

F19 : 2.5^{o} x 1.9^{o}, 40 vertical   F19 : 2.5^{o} x 1.9^{o}, 80 vertical



F09 : 1.25^{o} x 0.9^{o}, 40 vertical   F09 : 1.25^{o} x 0.9^{o}, 80 vertical

Fig : Zonal Wind structure across 4 FV runs with different resolutions

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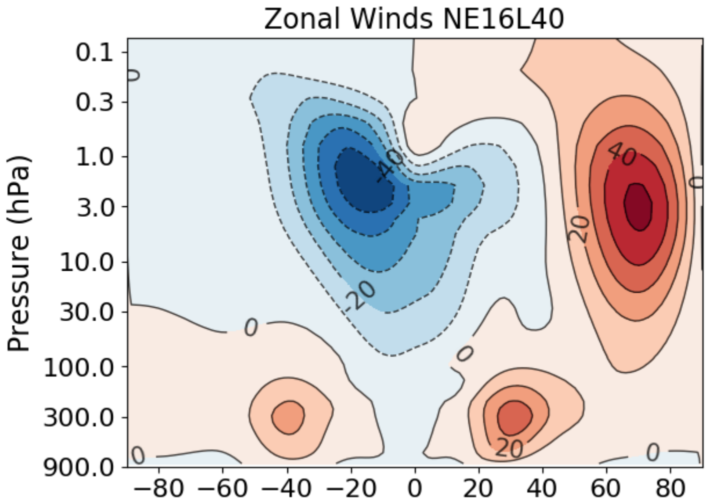
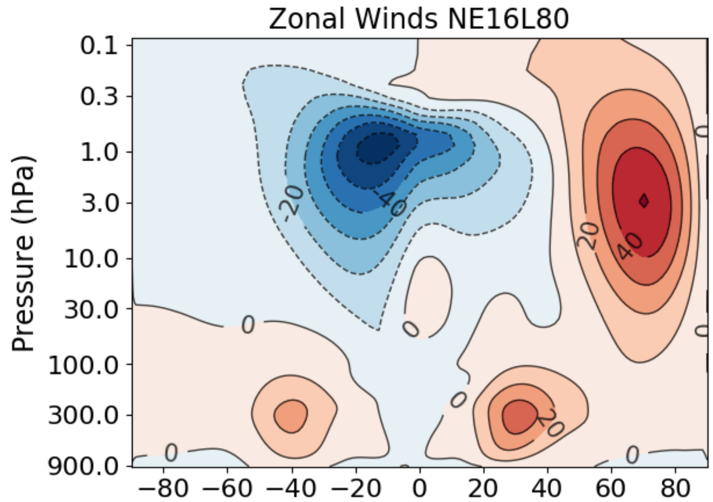
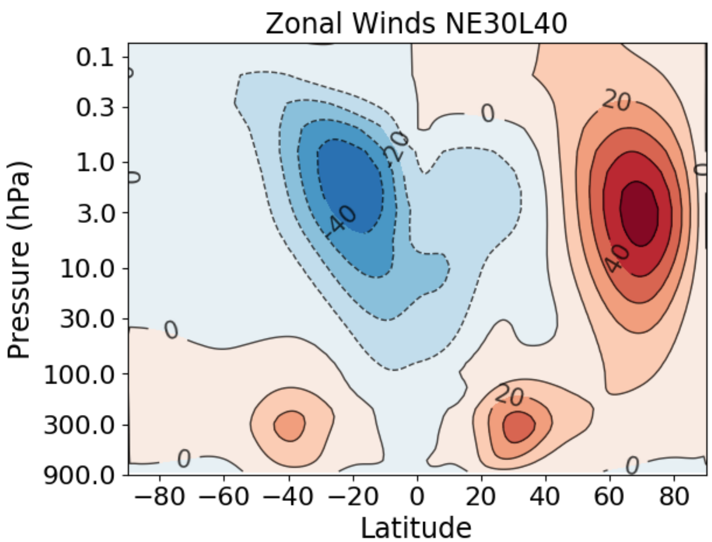
Resolved Climatology : Spectral Element (SE) Core

NE16 : 2^{o} x 2^{o}, 40 vertical

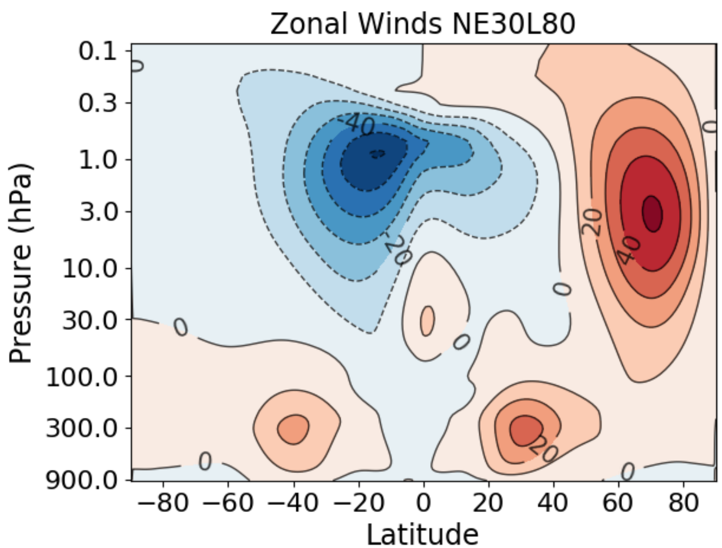


NE16 : 2^{o} x 2^{o}, 80 vertical





NE30 : 1^{o} x 1^{o}, 40 vertical



NE30 : 1^{o} x 1^{o}, 80 vertical

Fig : Zonal Wind structure across 4 SE runs with different resolutions

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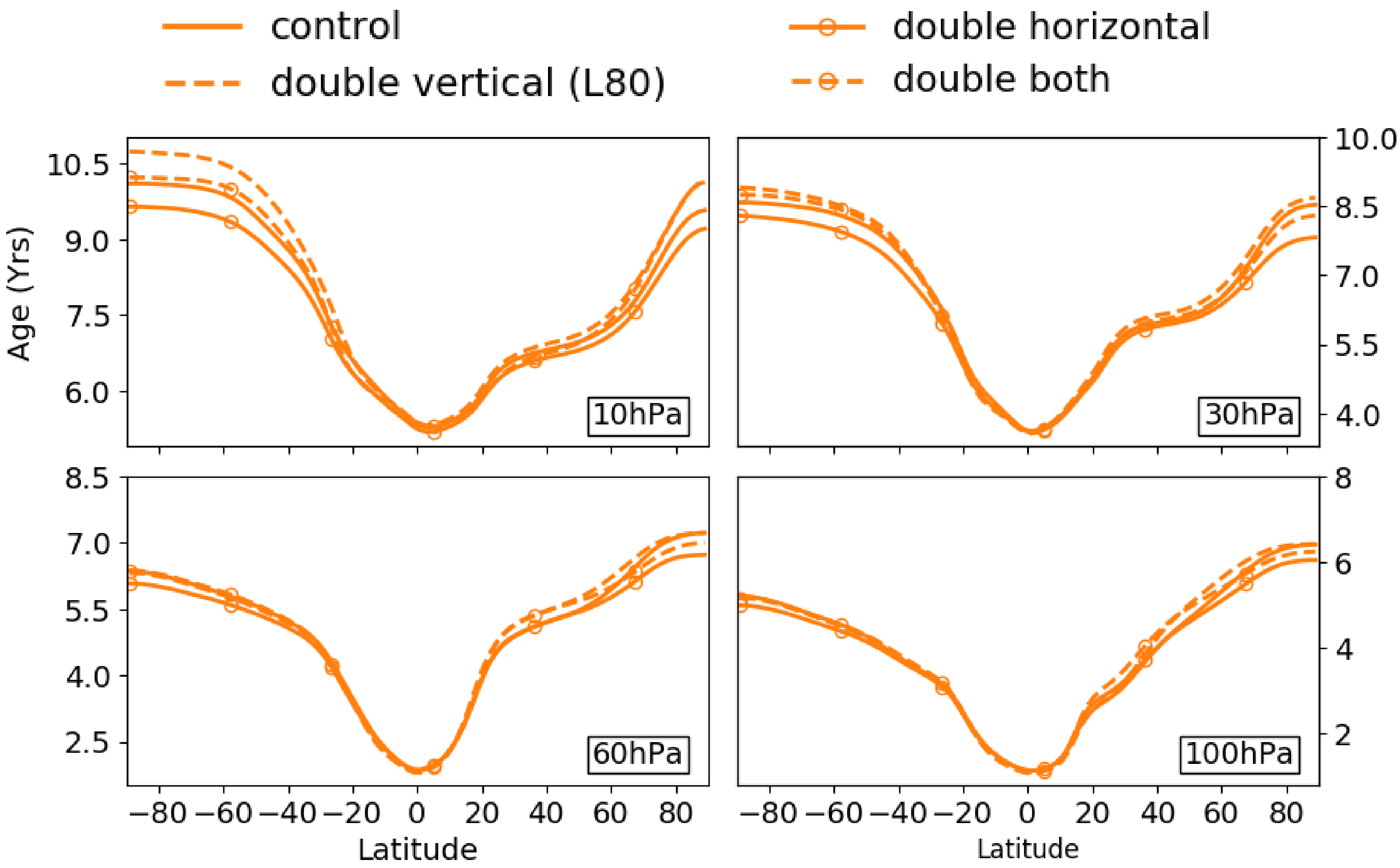
Age in Cubed Sphere Finite Volume (CSFV) core



C48 L40 :

$2^o \times 2^o$

40 vertical levels

C48 L80 :

$2^o \times 2^o$

80 vertical levels

C90 L40 :

$1^o \times 1^o$

40 vertical levels

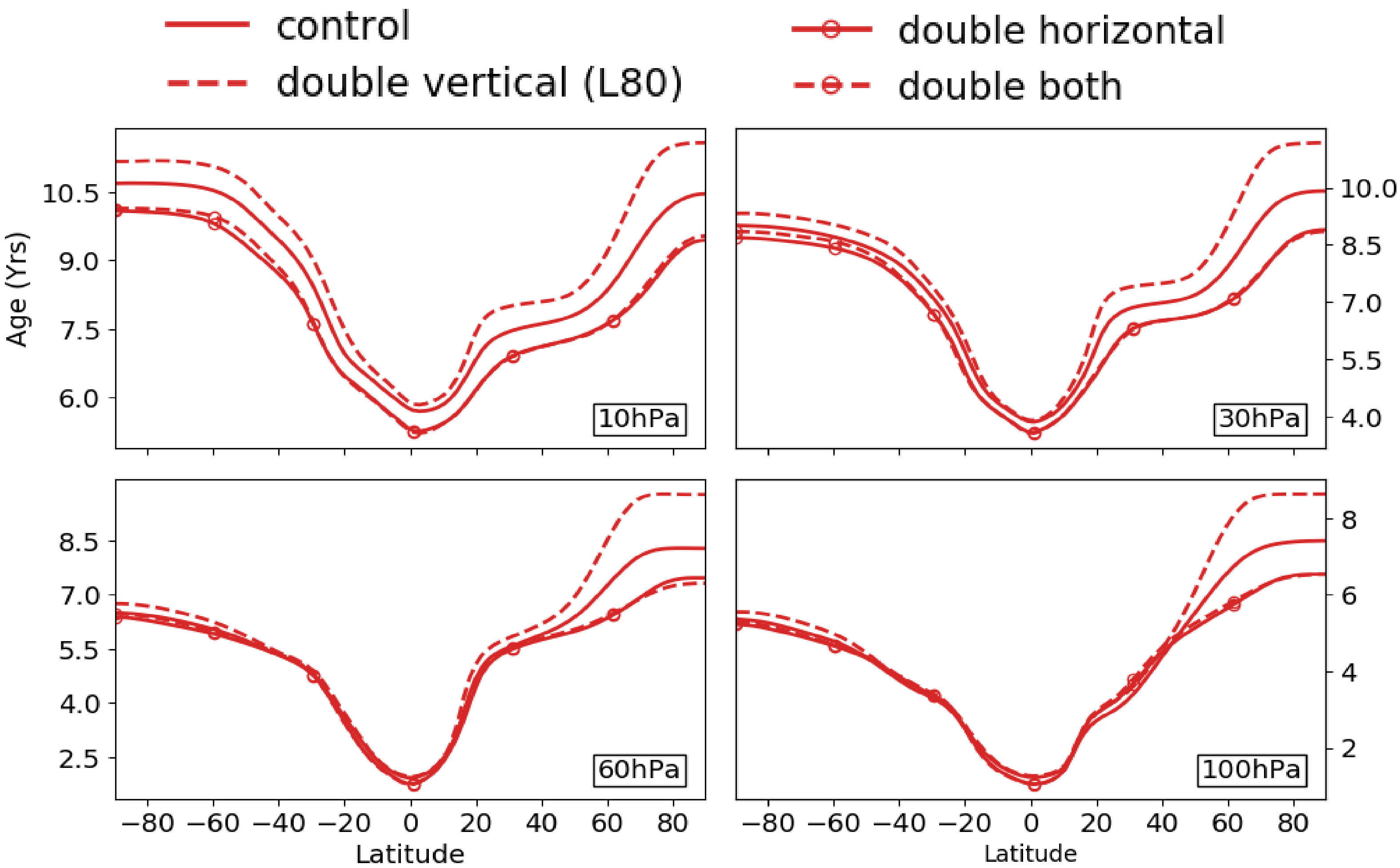
C90 L80 :

$1^o \times 1^o$

80 vertical levels

- Transport in CSFV core robust to changes in vertical and horizontal resolutions.

Age in CAM Finite Volume (FV) core



F19 L40 :

2.5° x 1.9°

40 vertical levels

F19 L80 :

2.5° x 1.9°

80 vertical levels

F09 L40 :

1.25° x 0.9°

40 vertical levels

F09 L80 :

1.25° x 0.9°

80 vertical levels

- Transport in FV core improves with horizontal resolution
- Biases in vortex regions
- Little or no sudden warming events observed for low horizontal resolution runs

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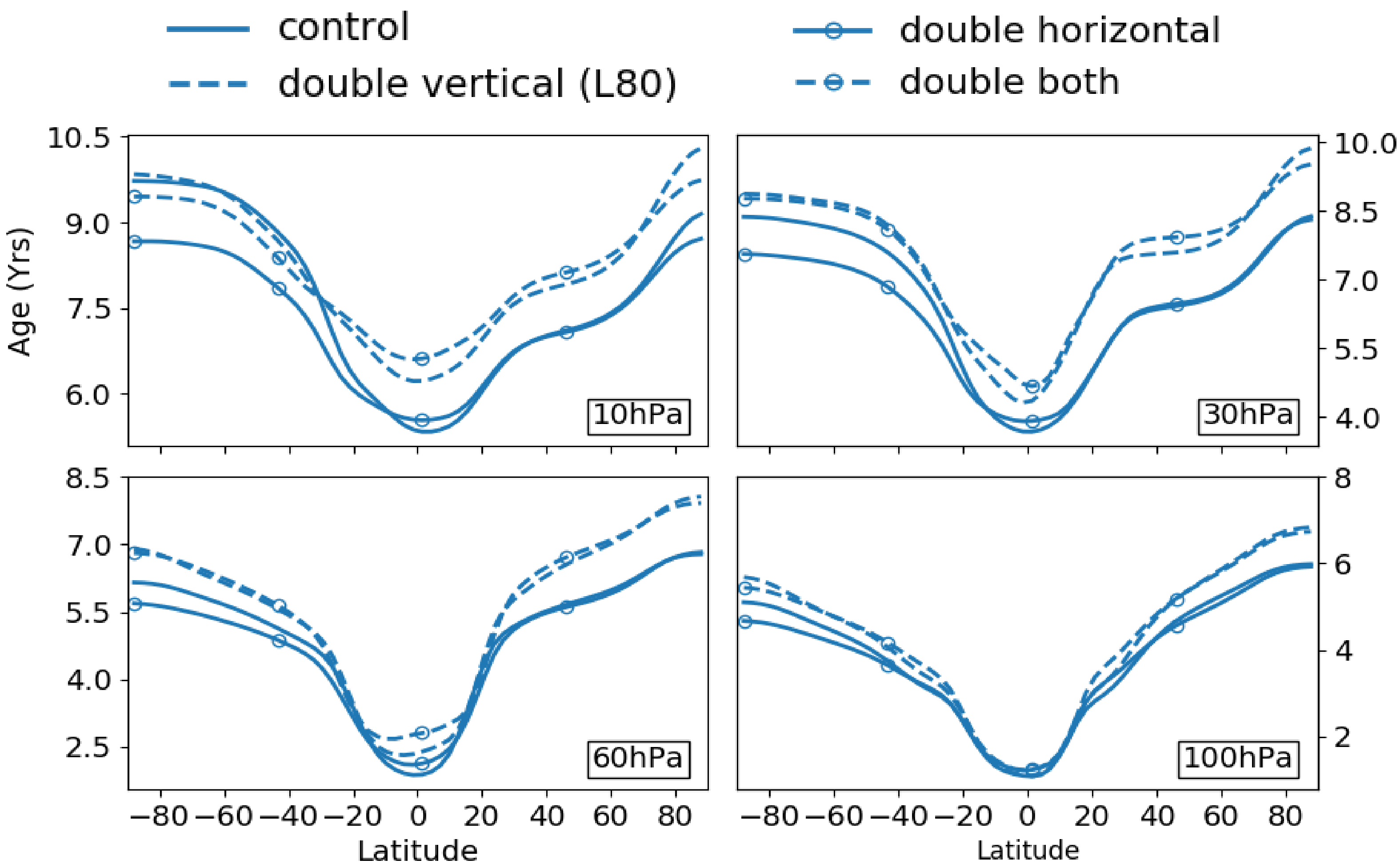
Age in Pseudospectral (PS) core



T42 L40 :

2.8° x 2.8°

40 vertical levels

T42 L80 :

2.8° x 2.8°

80 vertical levels

T85 L40 :

1.4° x 1.4°

40 vertical levels

T85 L80 :

1.4° x 1.4°

80 vertical levels

- Strikingly different age for 80 level runs. As much as 20% increase in age.
- Age in Pseudospectral core sensitive to the vertical resolution used

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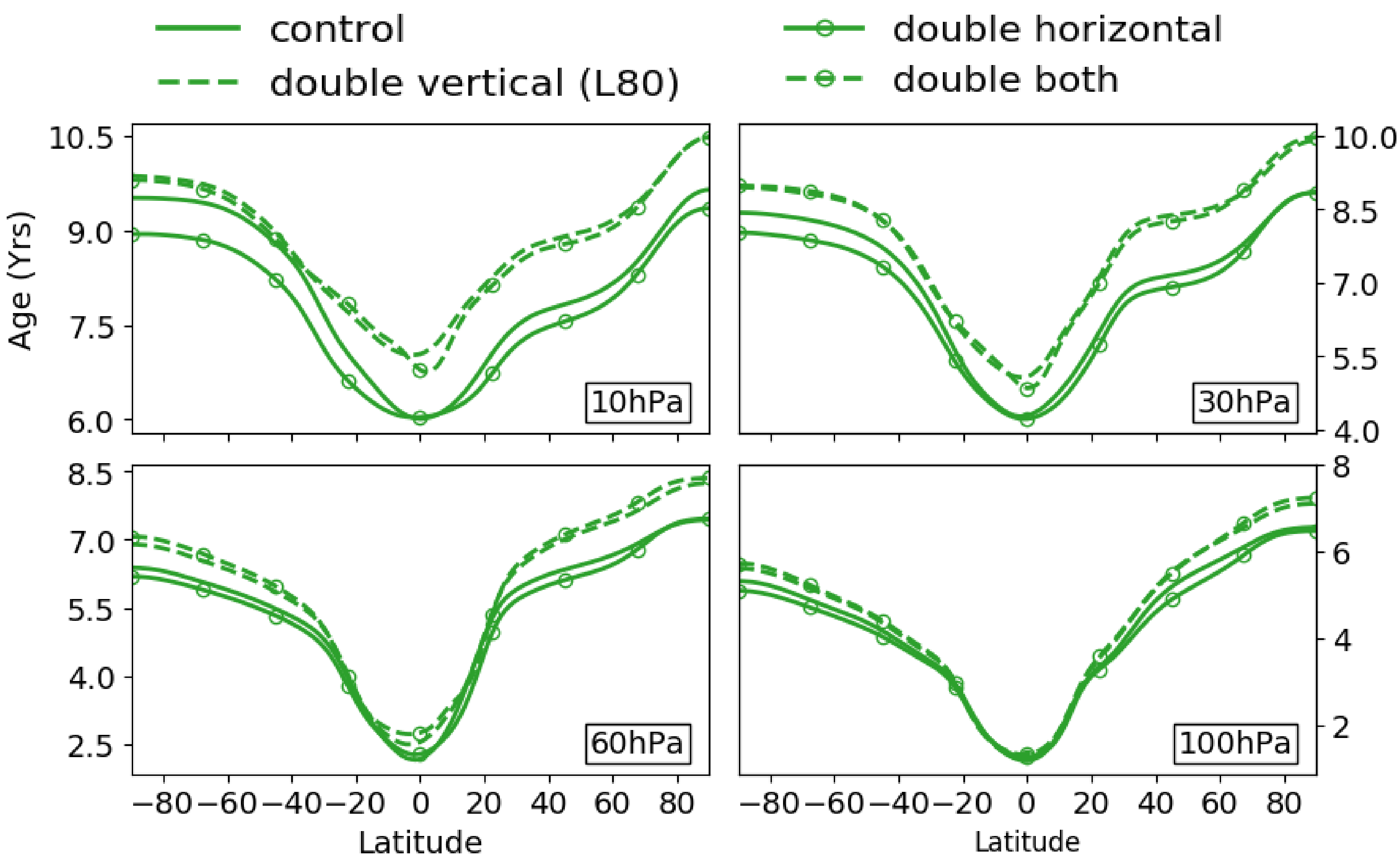
Age in Spectral Element (SE) core



NE16 NP4 L40 :

$2^o \times 2^o$

40 vertical levels

NE16 NP4 L80 :

$2^o \times 2^o$

80 vertical levels

NE30 NP4 L40 :

$1^o \times 1^o$

40 vertical levels

NE30 NP4 L80 :

$1^o \times 1^o$

80 vertical levels

- Again, extreme sensitivity of transport to vertical resolution used
- Behaviour similar to the pseudospectral (PS) core

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