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?

- Is it the Chemistry?
- Or the Dynamics?
- Or is it transport?

**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.
What limits our ability to forecast ozone recovery?

- 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
- **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 ($p \geq 700\text{hPa}$)

  **#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.
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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**(H)ORIZONTAL AND (V)ERTICAL RESOLUTION**

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

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

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

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

Fig: Mean Lagrangian mass transport in white (10⁸ kg/s)
Age of air for CSFV and FV core

Mean Age CSFV Core at 30hPa, across resolution

Age (Years)

Latitude

30hPa
Age of air for CSFV and FV core

Mean Age CSFV Core at 30hPa, across resolution
Age of air for CSFV and FV core
Age of air for **CSFV** and **FV** core

- Transport in cubed sphere finite volume core consistent across different vertical and horizontal resolutions
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Age of air for **CSFV** and **FV** core

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

- Transport in CAM finite volume core converges well with increasing horizontal resolution.

- Polar regions not represented well at low horizontal resolutions
Age of air for **PS** and **SE** core

Mean Age PS Core at 30hPa, across resolution
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Drastic changes in transport in the pseudospectral core as vertical resolution is increased.

Transport very similar to CSFV at moderate vertical resolutions

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Transport very similar to CSFV at moderate vertical resolutions.

Transport in CAM spectral element extremely sensitive to vertical resolution as well.
Westerlies in the tropical stratosphere

T85 : 1.4° x 1.4°, 40 vertical
Westerlies in the tropical stratosphere

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.
Westerlies in the tropical stratosphere

The westerlies develop in lower 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 resolve such westerlies.
- The westerlies are stationary and do not exhibit quasi-periodic oscillations.

Questions

? How do such differences in dynamics affect transport?

? Can differences in transport be resolved if all models have the same climatology?
How do these differences affect transport?

- Figure shows wind anomalies between PS core’s T85L80 and T85L40 runs. Positive wind anomalies associated with a fixed QBO-like development.

**Fig**: Wind anomalies T85L80 – T85L40. in m/s.
How do these differences affect transport?

- Figure shows wind anomalies between PS core's T85L80 and T85L40 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.

**Fig**: Wind anomalies (black) T85L80 – T85L40 with diabatic circulation anomaly (red).
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- An anti-clockwise circulation develops in the tropics

**Fig:** Wind anomalies (black) T85 L80 – T85 L40 with diabatic circulation anomaly (red) \((10^8 \text{ kg/s})\)
What causes this difference in climatology?

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

**Fig**: Age anomaly contours (in color)

T85L80 – T85L40. Units: Years
Increasing horizontal damping eliminates westerlies

PSEUDOSPECTRAL

Zonal Winds T85L80

Pressure (hPa)

Latitude
Increasing horizontal damping eliminates westerlies

- 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

Mean Age at 30hPa across cores, highest resolution

Latitude

Age (Years)

PS (T85 L80)
CSFV (C90 L80)
SE (NE30 L80)
FV (F09 L80)
- Damping the tropical westerlies significantly decreases the age in PS and SE cores

- Brings the age in closer agreement with CSFV and FV
Benchmark Age

- 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

Fig: Age of air (in year) in black contours. ‘Fractional’ age deviation across models in color
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- Age of air CAM SE dynamical core contributes much to the fractional age deviation
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° x 0.25°). 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


Supplementary plots

sudden warming events in the stratosphere

Model Time (days)
Resolved Climatology: CSFV Core

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.
Resolved Climatology: Finite Volume (FV) Core

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

- **F19:** $2.5^\circ \times 1.9^\circ$, 40 vertical
  - Zonal Winds F19L40

- **F19:** $2.5^\circ \times 1.9^\circ$, 80 vertical
  - Zonal Winds F19L80

- **F09:** $1.25^\circ \times 0.9^\circ$, 40 vertical
  - Zonal Winds F09L40

- **F09:** $1.25^\circ \times 0.9^\circ$, 80 vertical
  - Zonal Winds F09L80
Resolved Climatology: Spectral Element (SE) Core

NE16 : 2° x 2°, 40 vertical

NE30 : 1° x 1°, 40 vertical

NE16 : 2° x 2°, 80 vertical

NE30 : 1° x 1°, 80 vertical

Fig: Zonal Wind structure across 4 SE runs with different resolutions
Transport in CSFV core robust to changes in vertical and horizontal resolutions.
Age in CAM Finite Volume (FV) core

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

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
Strikingly different age for 80 level runs. As much as 20% increase in age.

Age in Pseudospectral core sensitive to the vertical resolution used:

- **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
Age in Spectral Element (SE) core

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

**NE16 NP4 L40:**
- $2^\circ \times 2^\circ$
- 40 vertical levels

**NE16 NP4 L80:**
- $2^\circ \times 2^\circ$
- 80 vertical levels

**NE30 NP4 L40:**
- $1^\circ \times 1^\circ$
- 40 vertical levels

**NE30 NP4 L80:**
- $1^\circ \times 1^\circ$
- 80 vertical levels