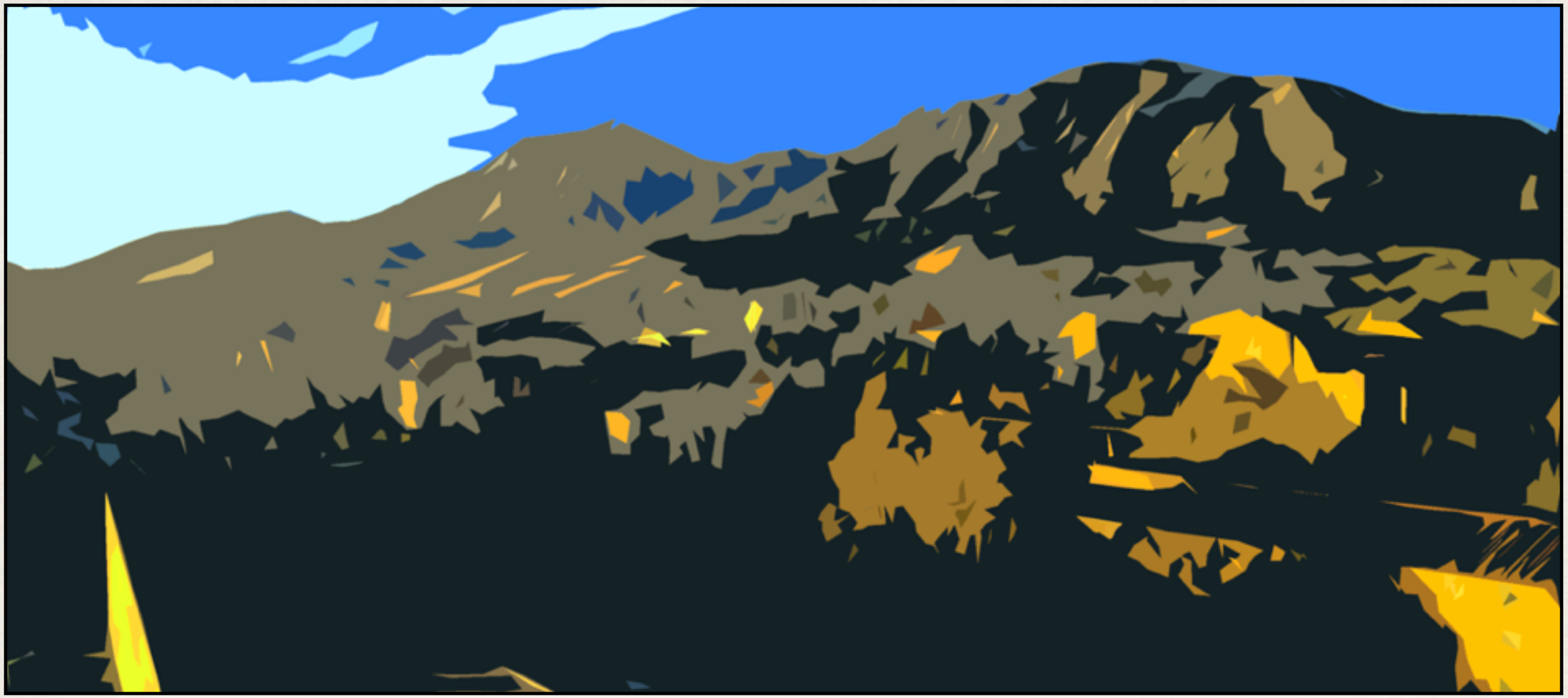

A High-Order Atmospheric Column for Global Climate Modeling

David M. Hall Department of Computer Science, University of Colorado at Boulder

Monday, Dec 14, 2015 3:25-3:40pm AGU 2015 Fall Meeting

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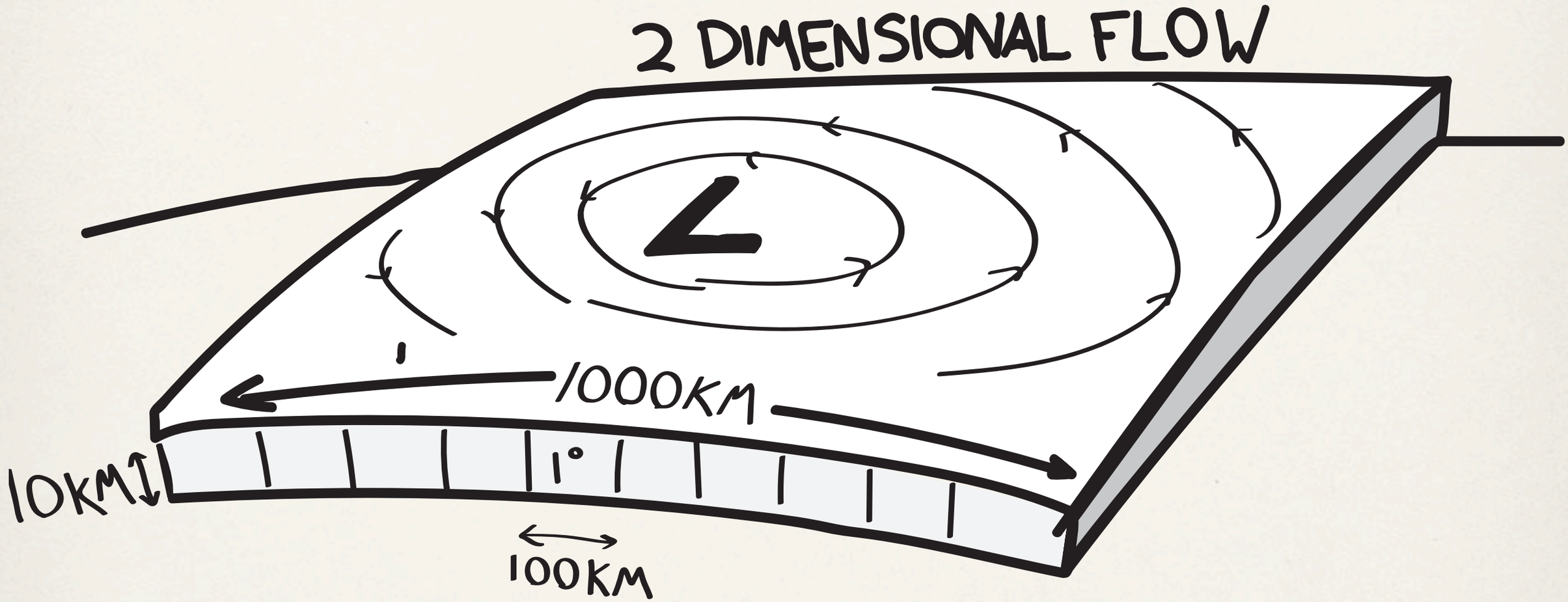
Vertical processes become more important at high resolution

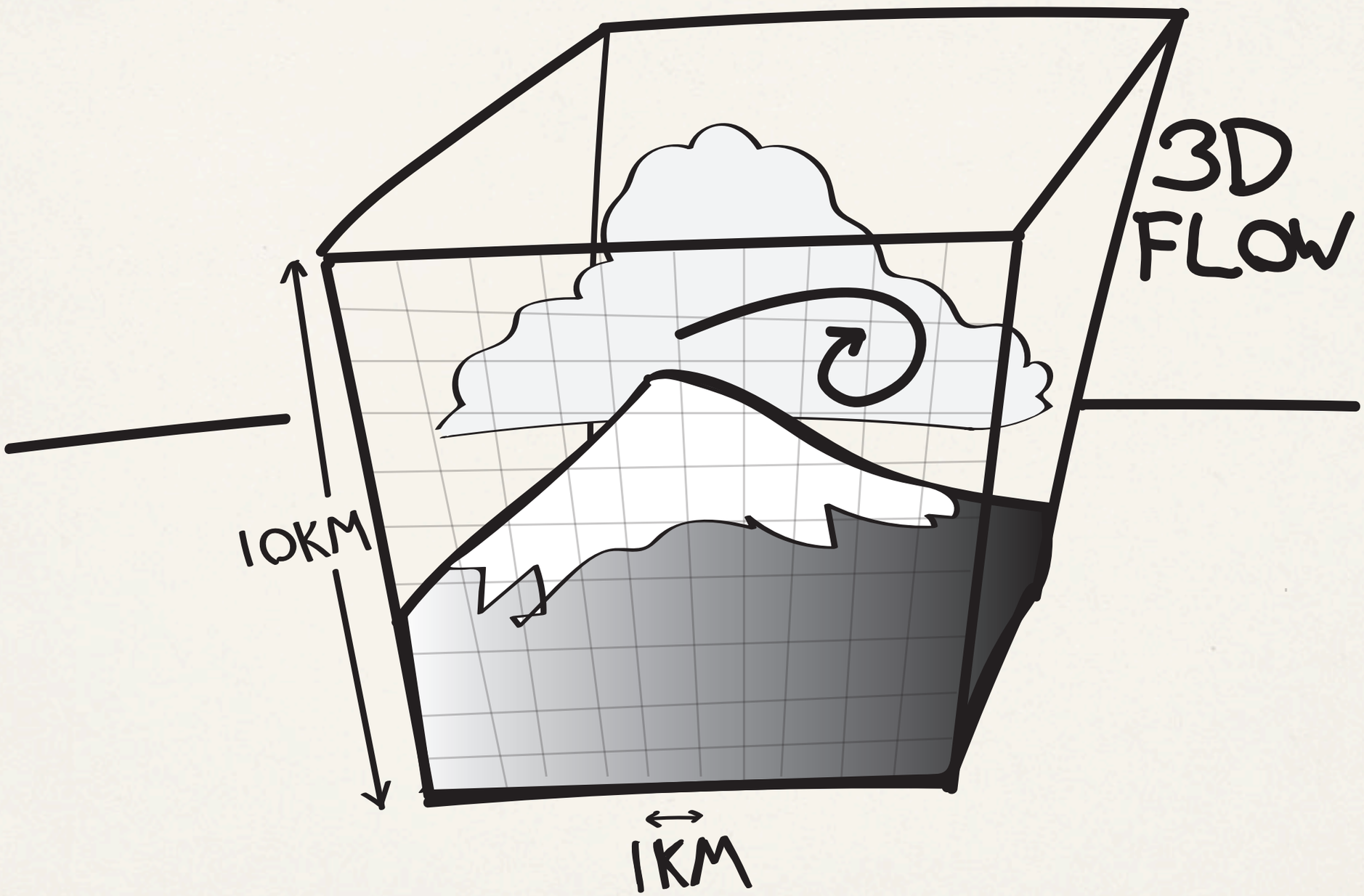
Vertical processes are become increasingly important in the atmospheric dynamical core as global climate simulation resolution is increased.

At low resolutions, resolved dynamics are 2D



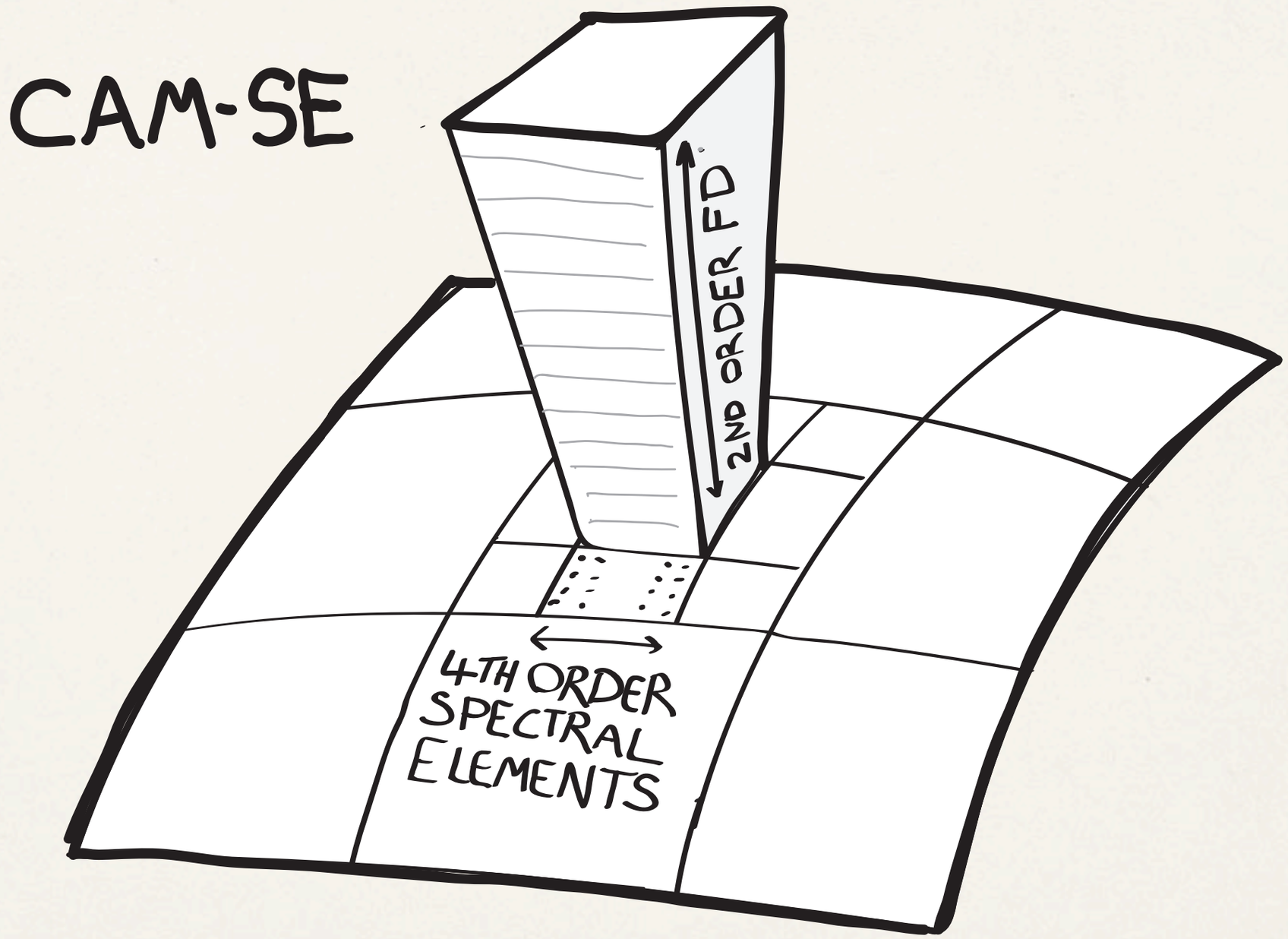
At synoptic resolutions of 1° or coarser, resolved horizontal scales are large with respect to the atmosphere depth, and the simulation is nearly two dimensional, with horizontal processes dominating.

At high resolutions, resolved dynamics are 3D



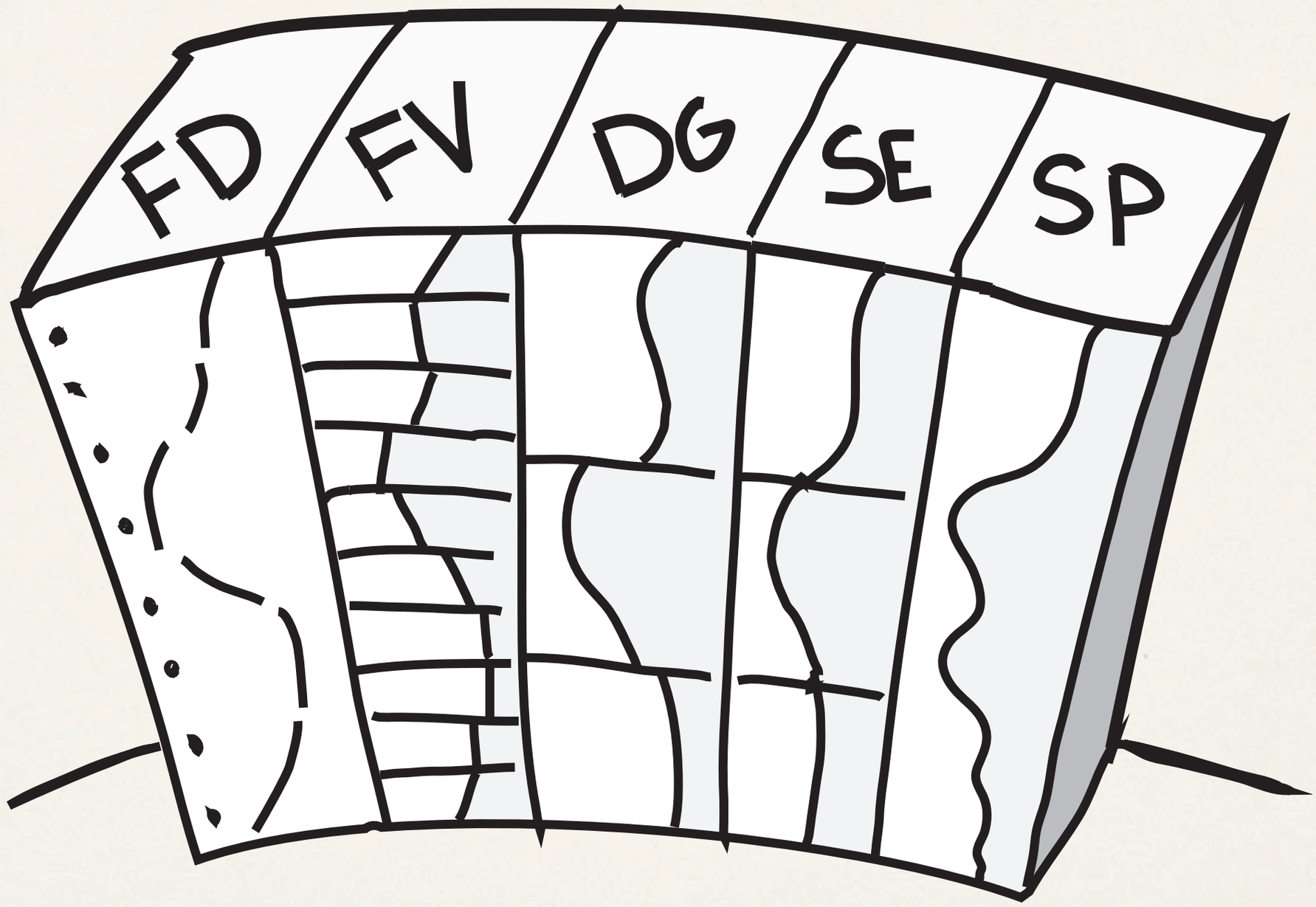
At much higher resolutions, the element aspect ratio approaches 1, and resolved vertical features become as significant as horizontal features. At these resolutions the flow is fully three dimensional.

In CAM-SE, horizontal and vertical representations are split



In CAM-SE, the horizontal and vertical representations are split, with 4th order spectral elements in the horizontal and 2nd order mimetic finite differences in the vertical

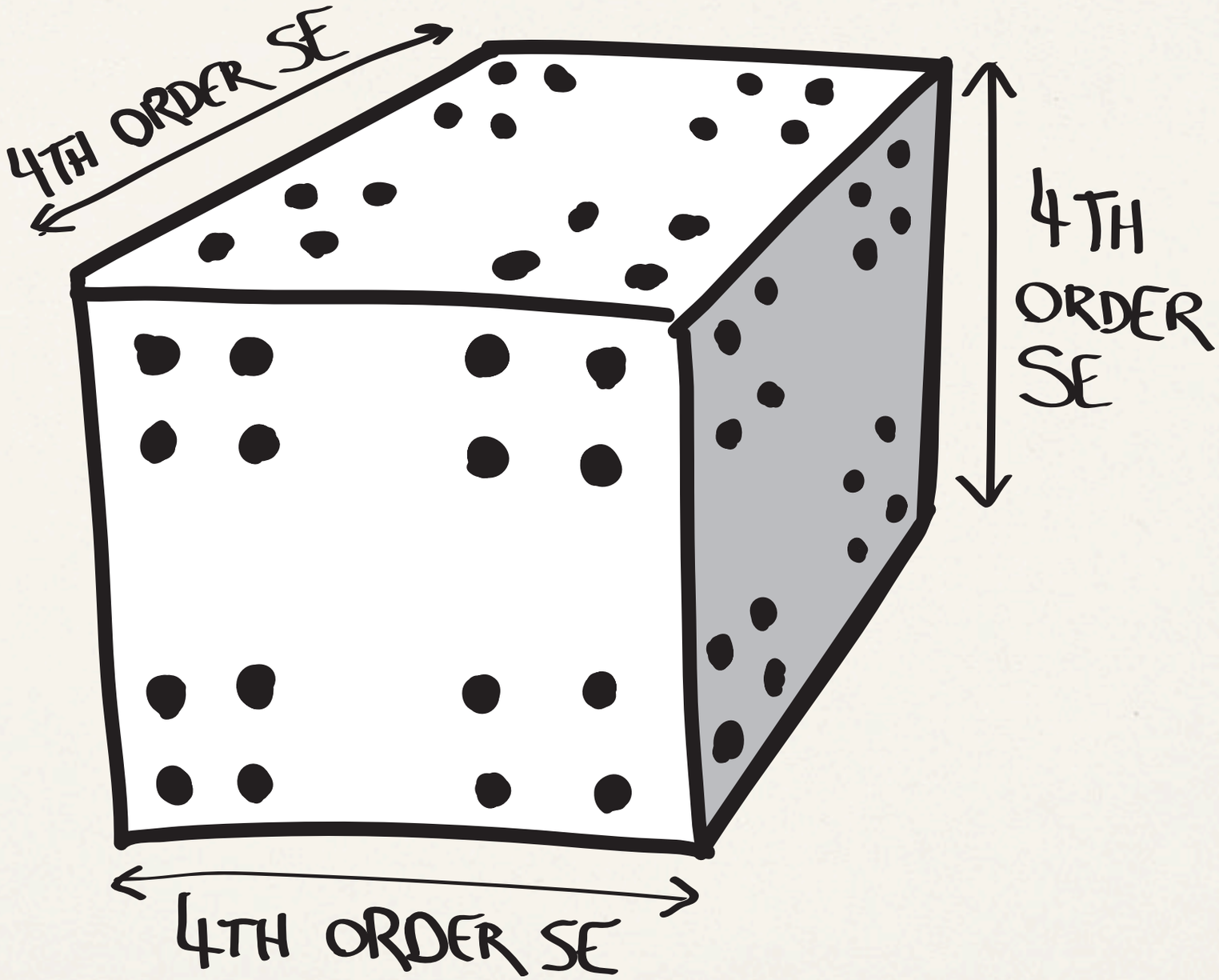
Many vertical representations are possible



However, almost any vertical representation could be used to discretize the column including: finite differences, finite volumes, discontinuous Galerkin, spectral elements, and fully spectral methods.

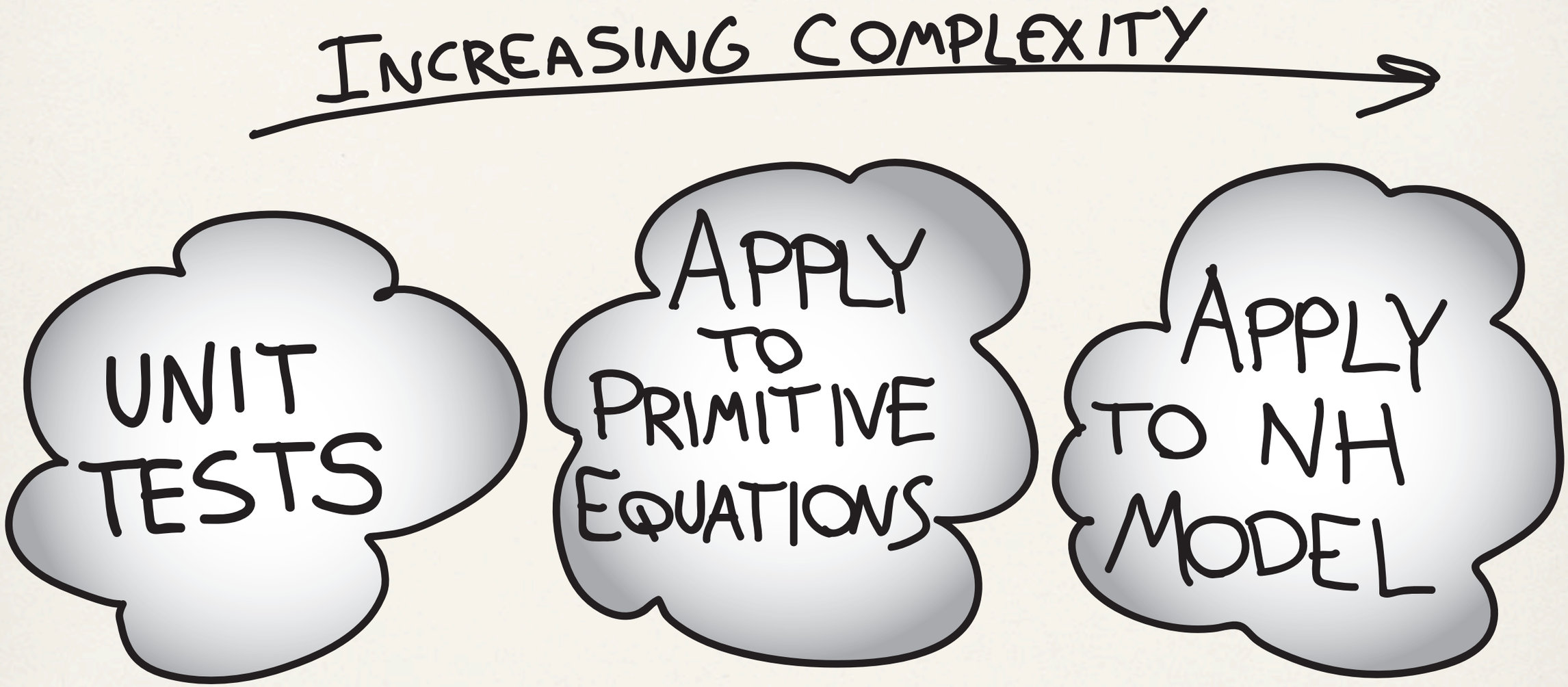
Representations should match at high resolution?

Resolution< 4km/grid cell



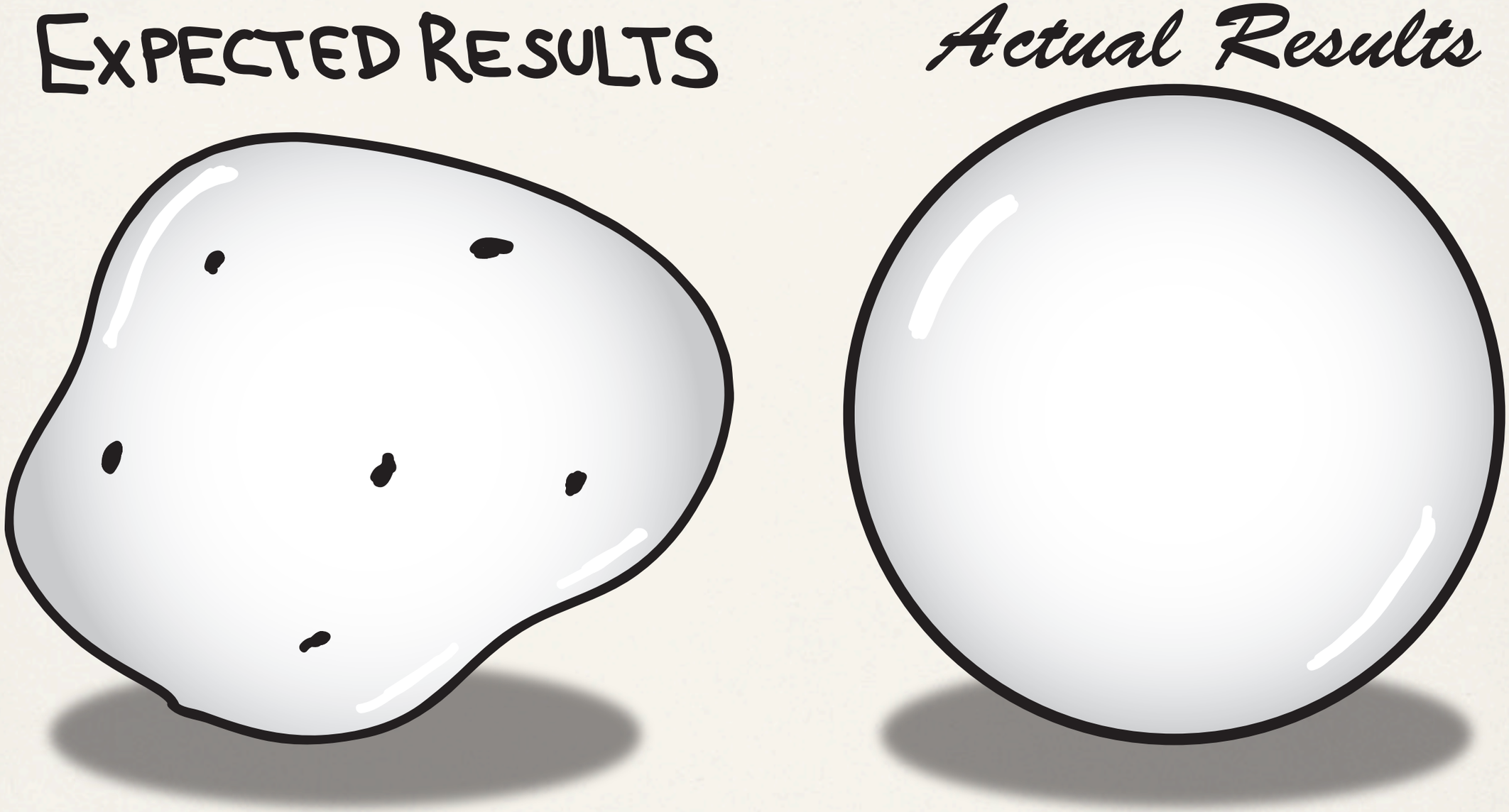
At three dimensional resolutions, with cell sizes around 4km or smaller, we conjecture that it might make sense to use horizontal and vertical representations with similar discretizations and accuracy. Thus we have chosen to investigate the use of CG spectral-elements in the vertical as well.

Testing the new vertical SE operators



To test this conjecture, we built a set of vertical spectral element operators and applied them first to units tests and then to the familiar CAM-SE primitive equation model, in order to verify that they were able to reproduce known results on standard tests.

Vertical SE operators gave better than expected results



To our surprise, the vertical SE operators didn't match those of the FD operators, rather they gave **better** results on a number of standard DCMIP tests. This lead us to consider the notion that the new operators might be of benefit in both the hydrostatic and non-hydrostatic regimes.

Questions that should be answered?

- **What is the impact on solution quality?**
- **What is the relative computational cost?**
- **Can we maintain conservation and monotonicity?**
- **Can we couple it to existing physical parameterizations?**
- **What is the optimal polynomial order?**

Before we can take this notion seriously, we need to quantify the impact of the SE vertical operators on the solution quality and computational cost. We also need to consider whether it can maintain conservation, monotonicity, and if it can be coupled to existing physical parameterizations packages.

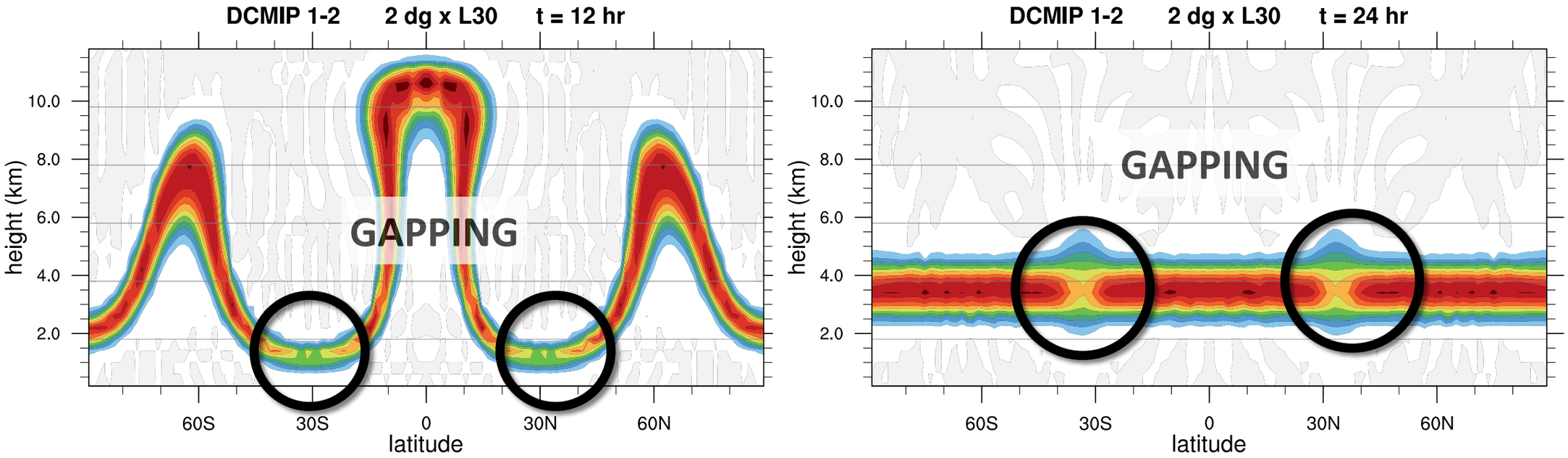
Qualitative Improvements to the CAM-SE Primitive Equation Solutions

Next, let's take a look at some of the qualitative improvements that were observed in tests of the vertical SE discretization

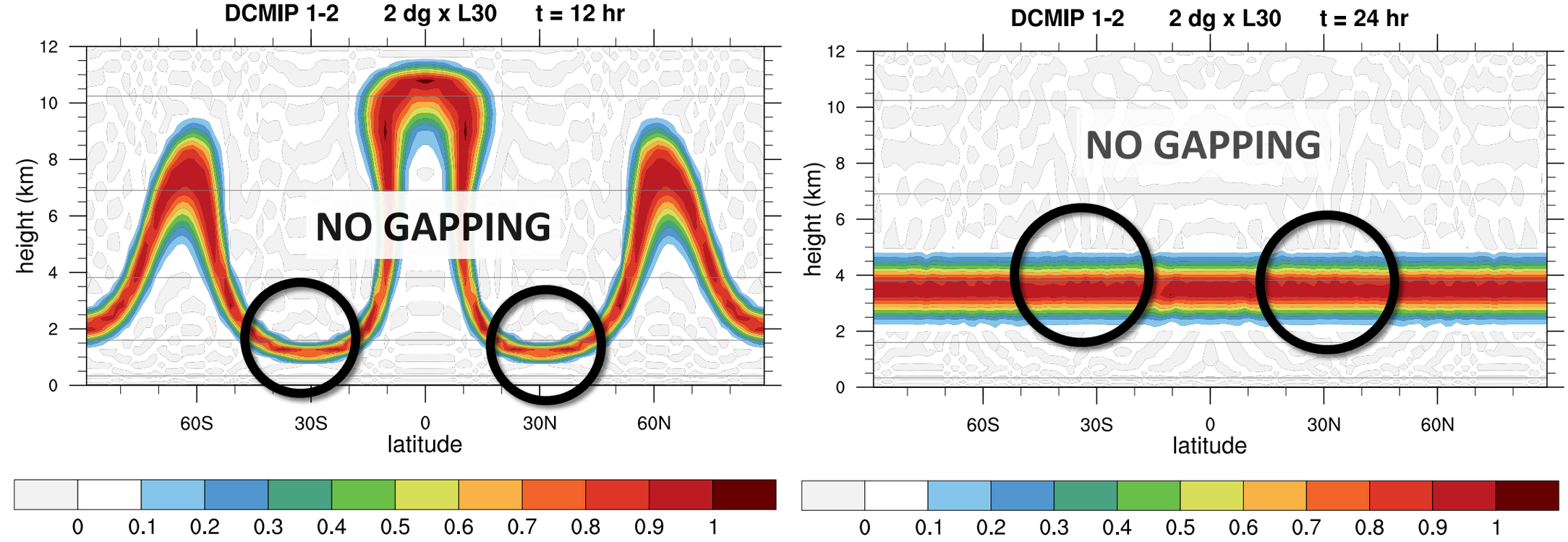
Vertical Tracer Transport: Reduced Gapping

DCMIP 1-2: dt=5 sec, no limiter, no hyperviscosity

Vertical FD

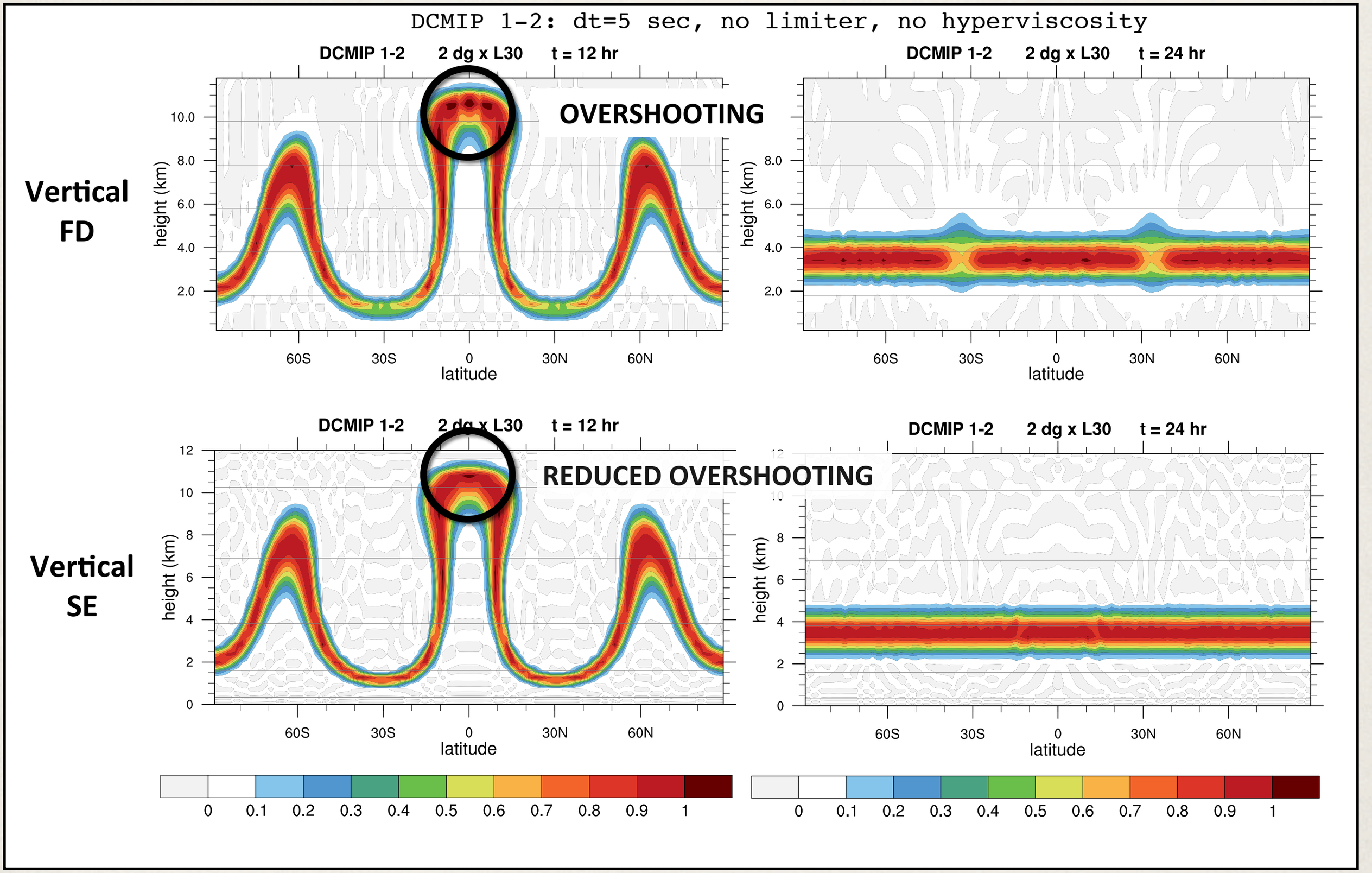


Vertical SE



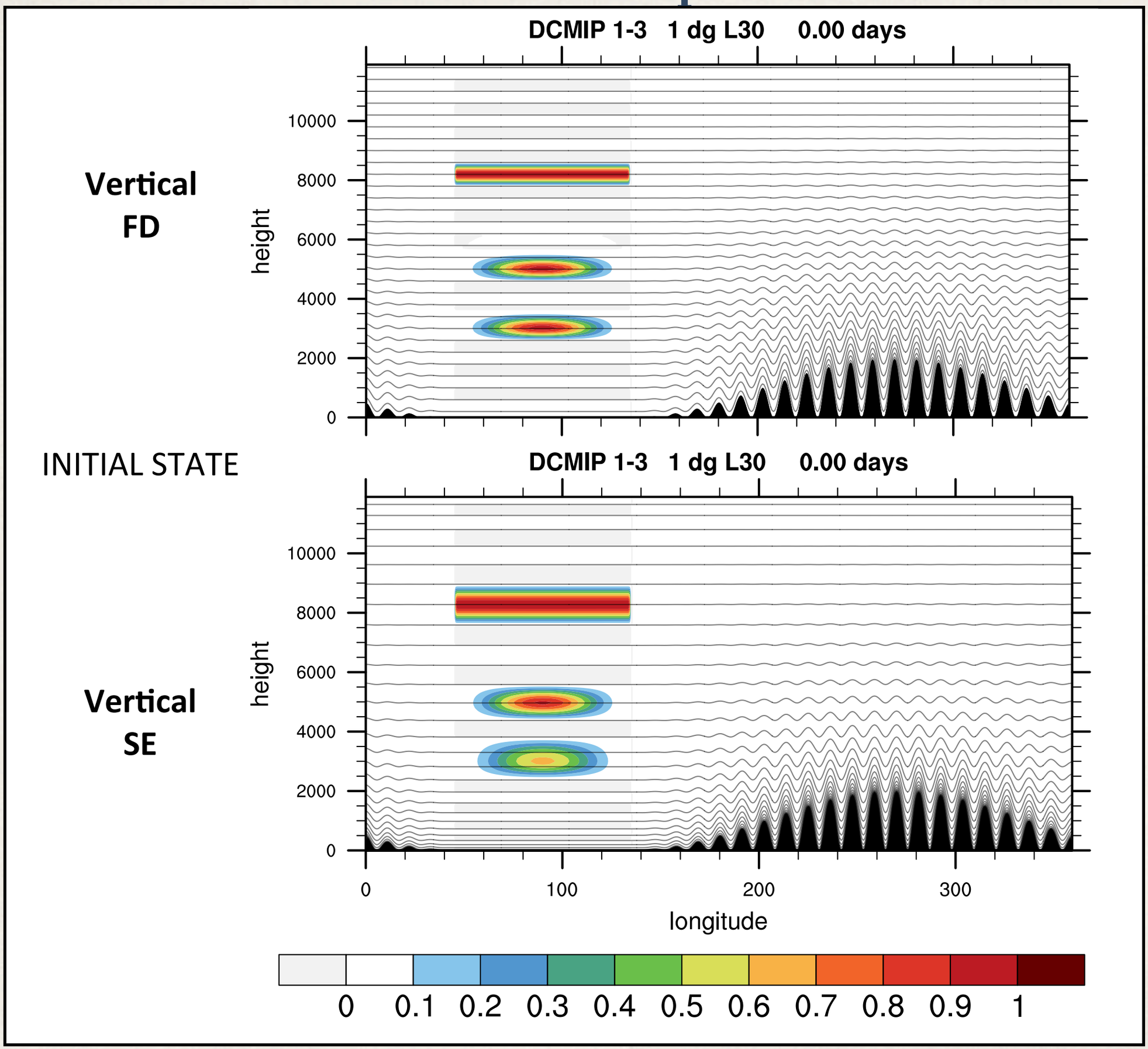
The Hadley-like tracer transport test DCMIP 1-2, showed considerably better results, at the same effective resolution. At 2° horizontal resolution gapping in the final solution was significantly reduced.

Vertical Tracer Transport: Reduced Overshooting



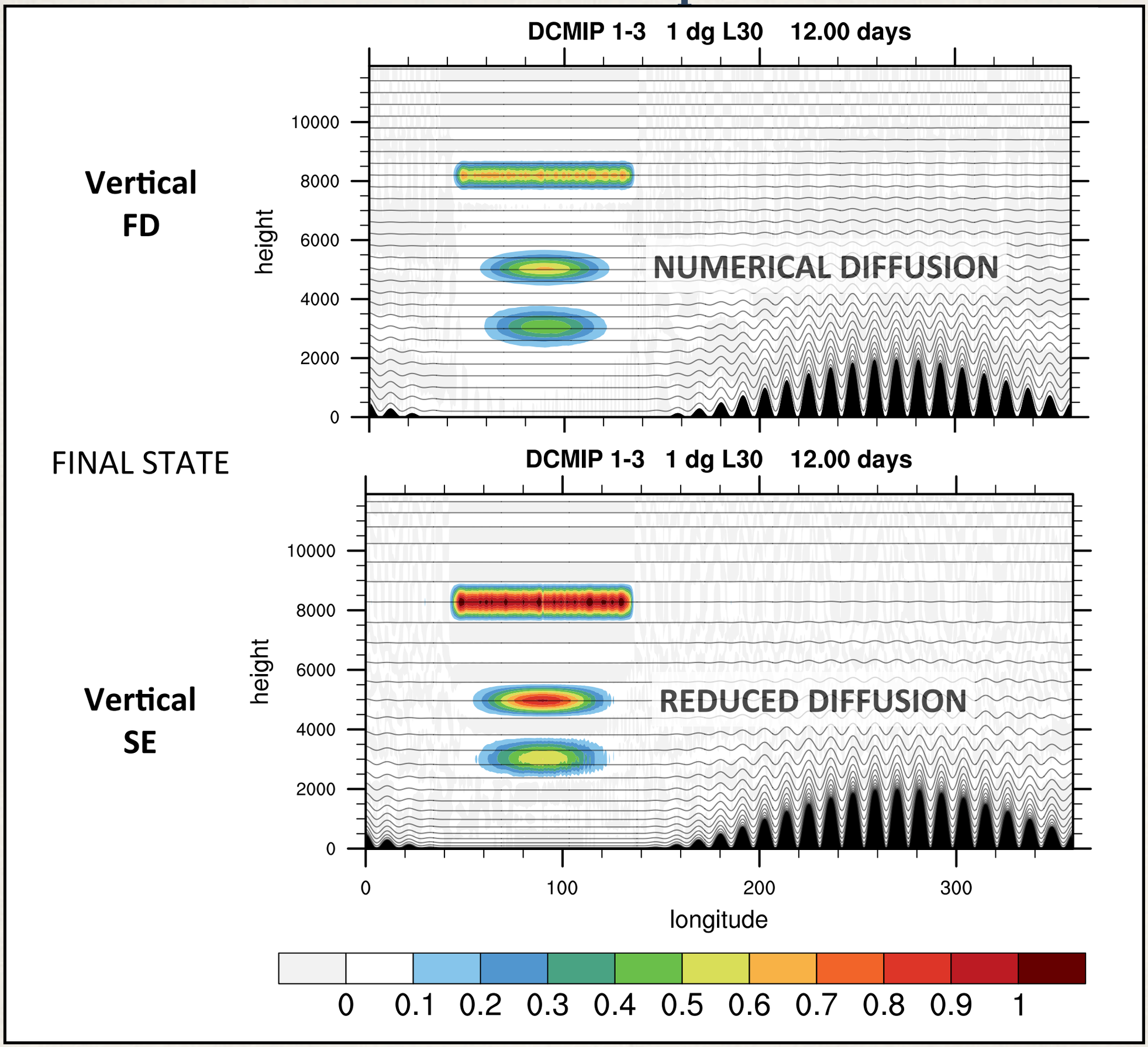
This test also showed reduced tracer overshooting in simulations without a limiter.

Horizontal tracer transport: Reduced Diffusion



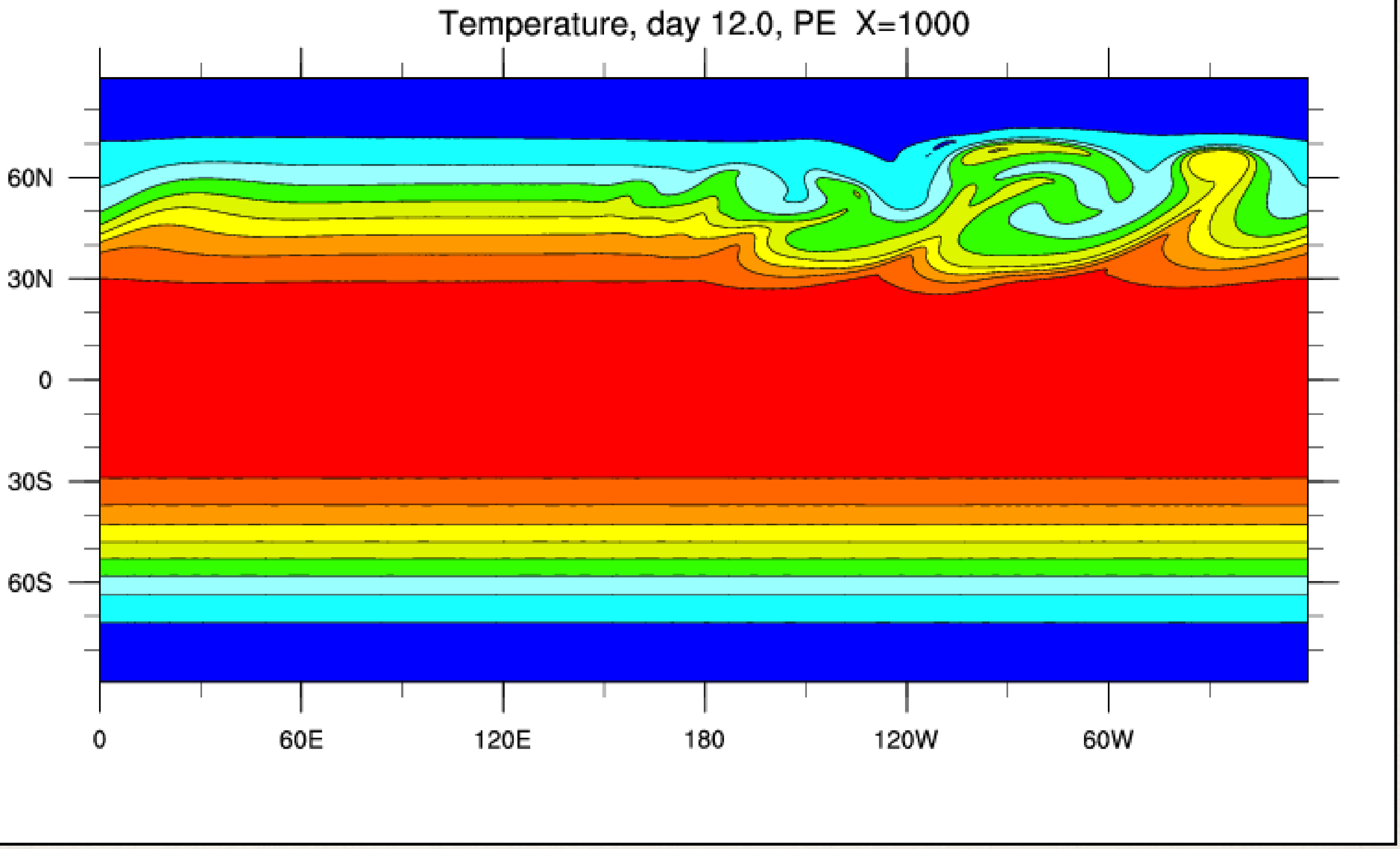
Horizontal advection of thin tracer clouds showed considerably less diffusion when using the vertical SE operators

Horizontal tracer transport: Reduced Diffusion



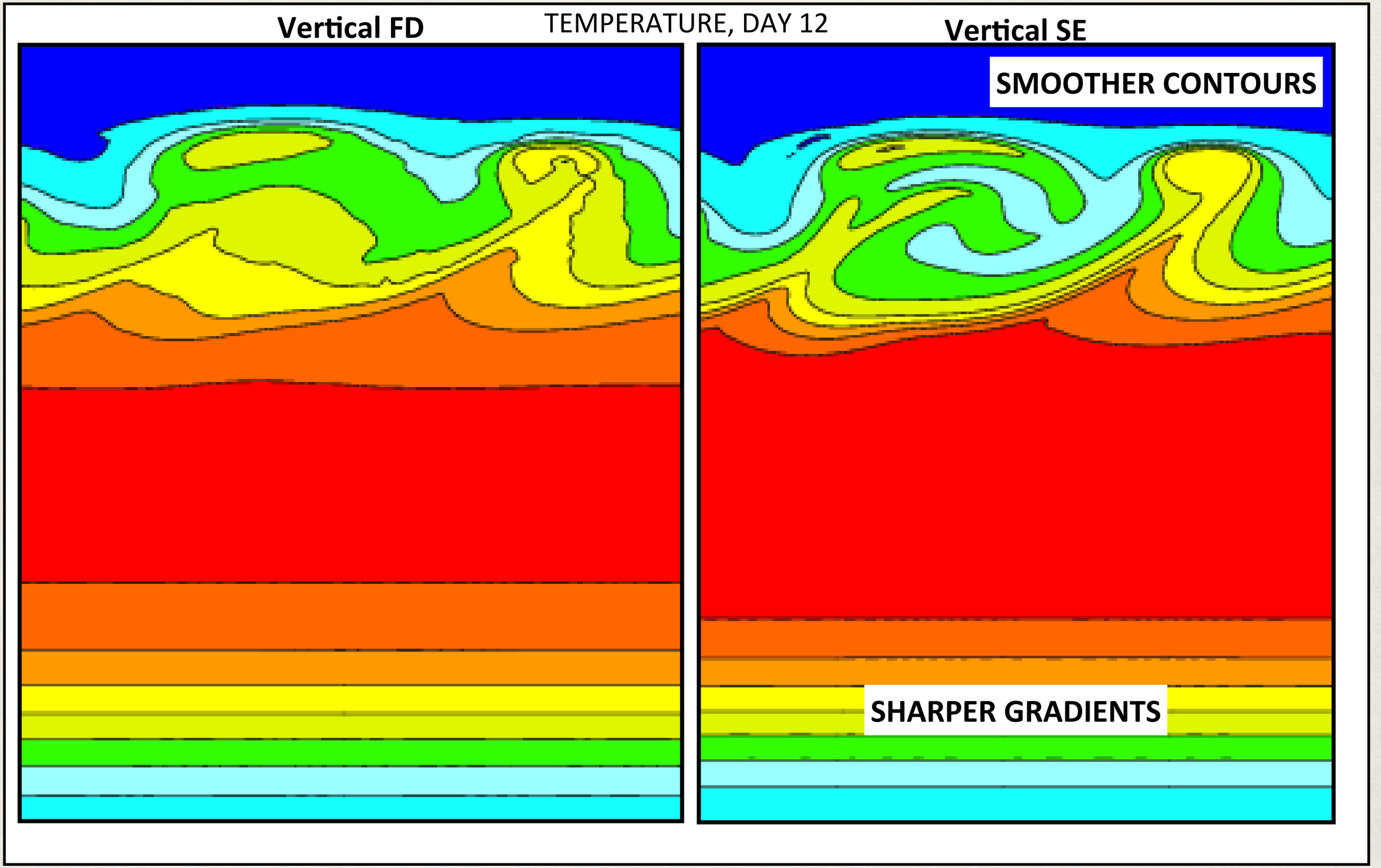
Horizontal advection of thin tracer clouds showed considerably less diffusion when using the vertical SE operators

Dry Baroclinic Instability Test: Smoother Contours



Improvements were also seen in the quality of the baroclinic instability test, although the velocity flow is primarily horizontal at these scales.

Dry Baroclinic Instability Test: Smoother Contours

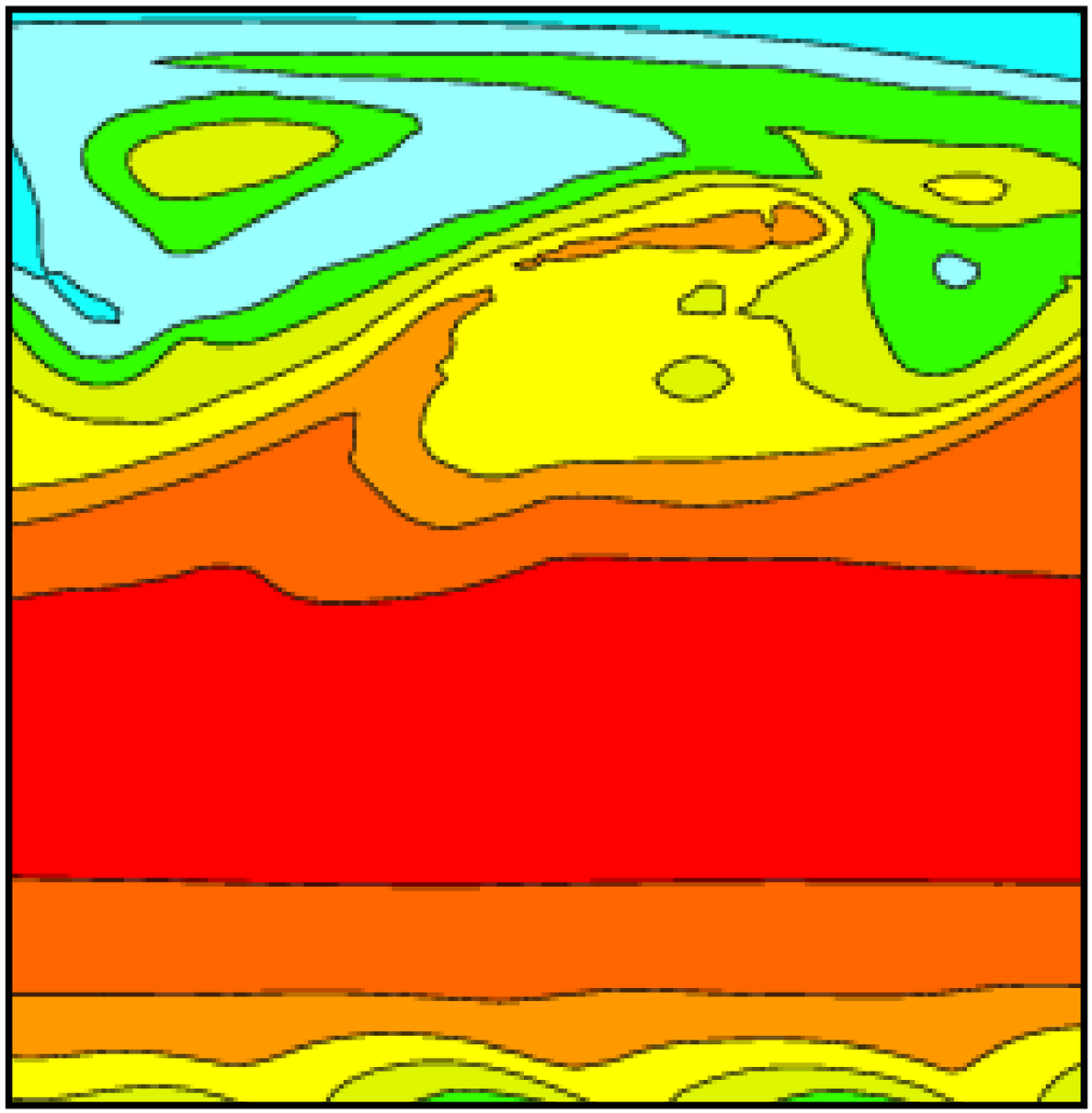


Smoother contours and sharper gradients were observed with the vertical SE operators, although both simulations were conducted at the same resolution.

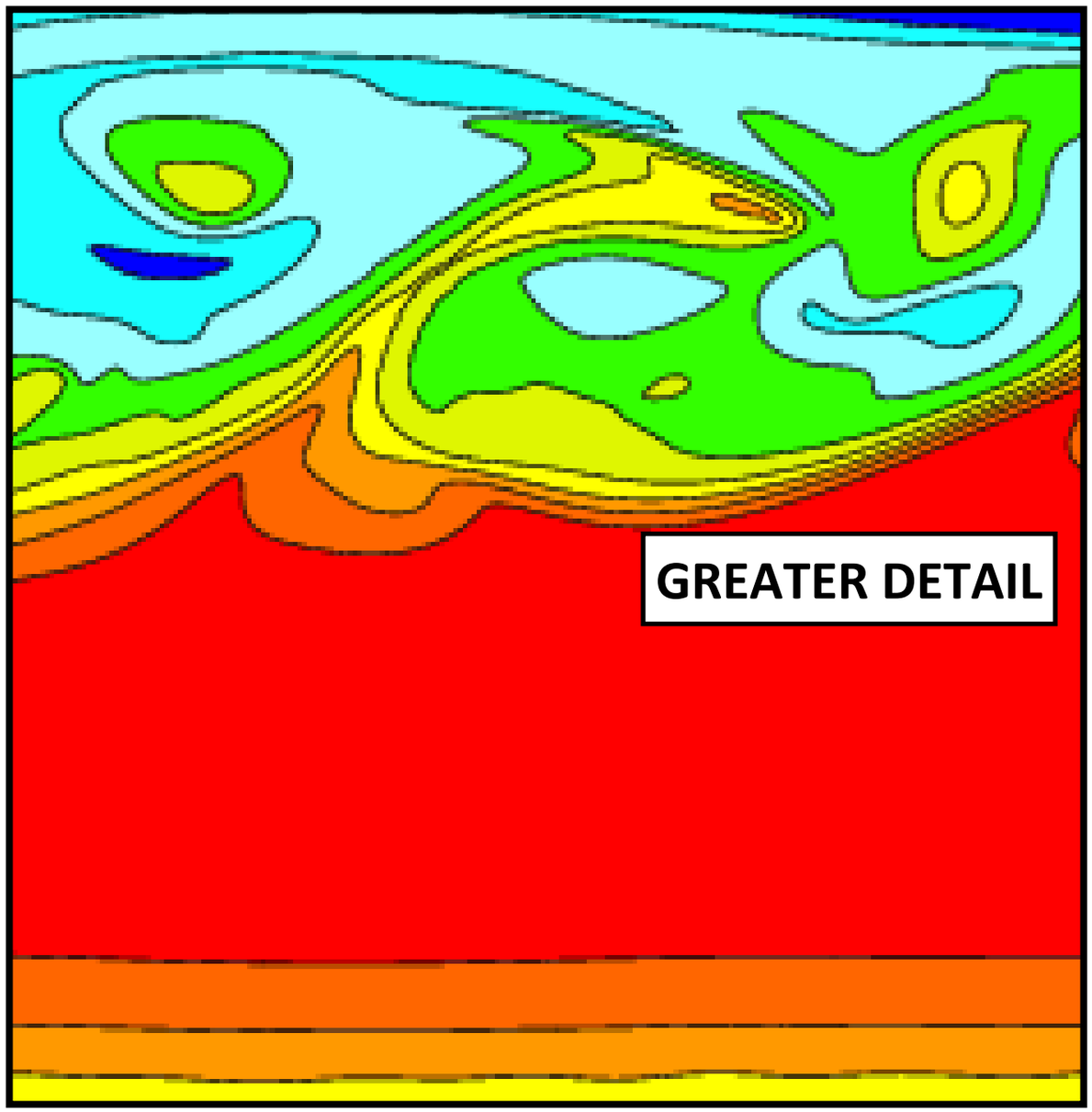
Dry Baroclinic Instability Test: Greater Detail

TEMPERATURE, DAY 22

Vertical FD

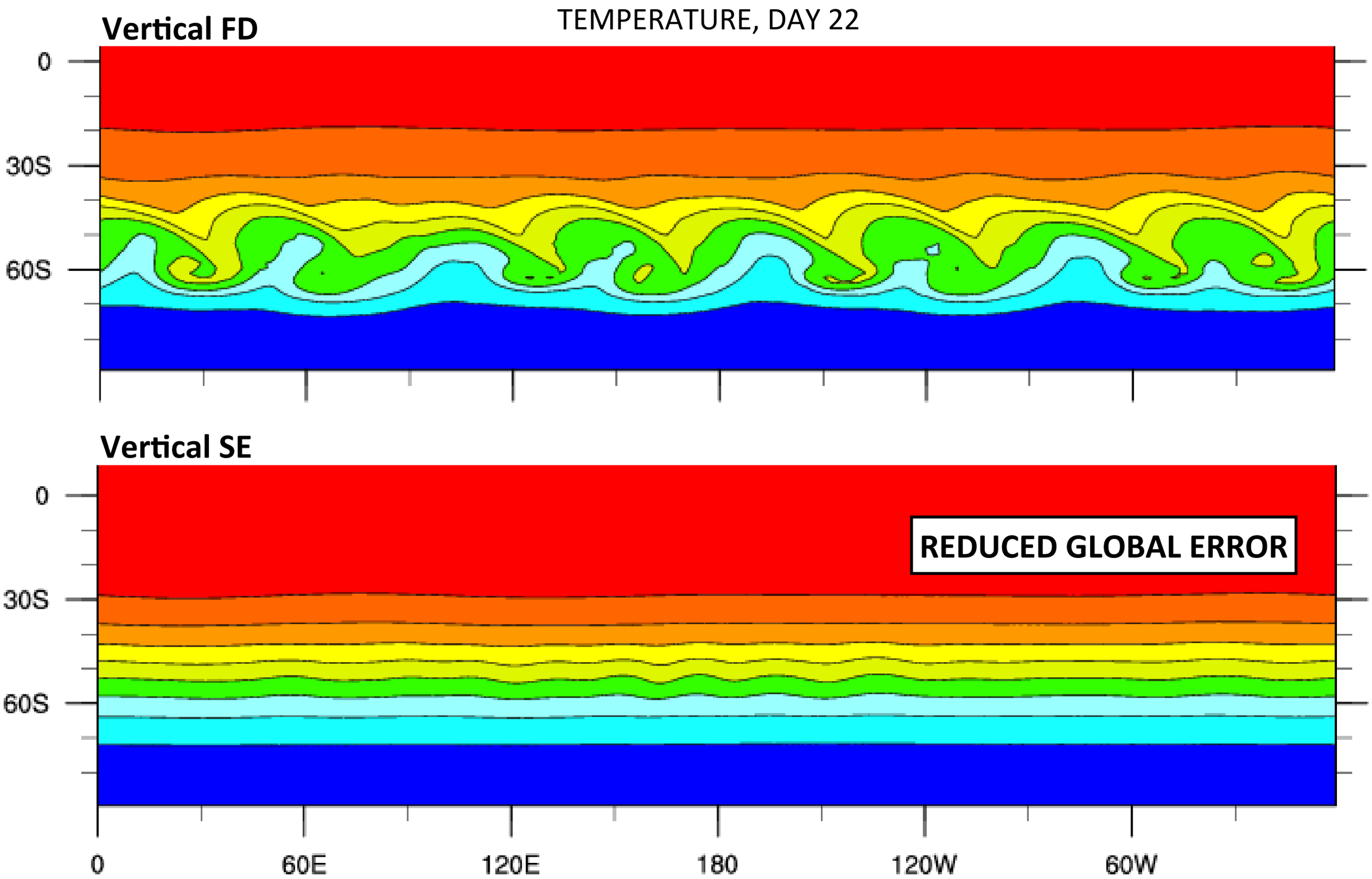


Vertical SE



In many regions, the vertical SE solution exhibited greater detail, almost as if it were performed at a higher overall resolution.

Dry Baroclinic Instability Test: Reduced Numerical Error

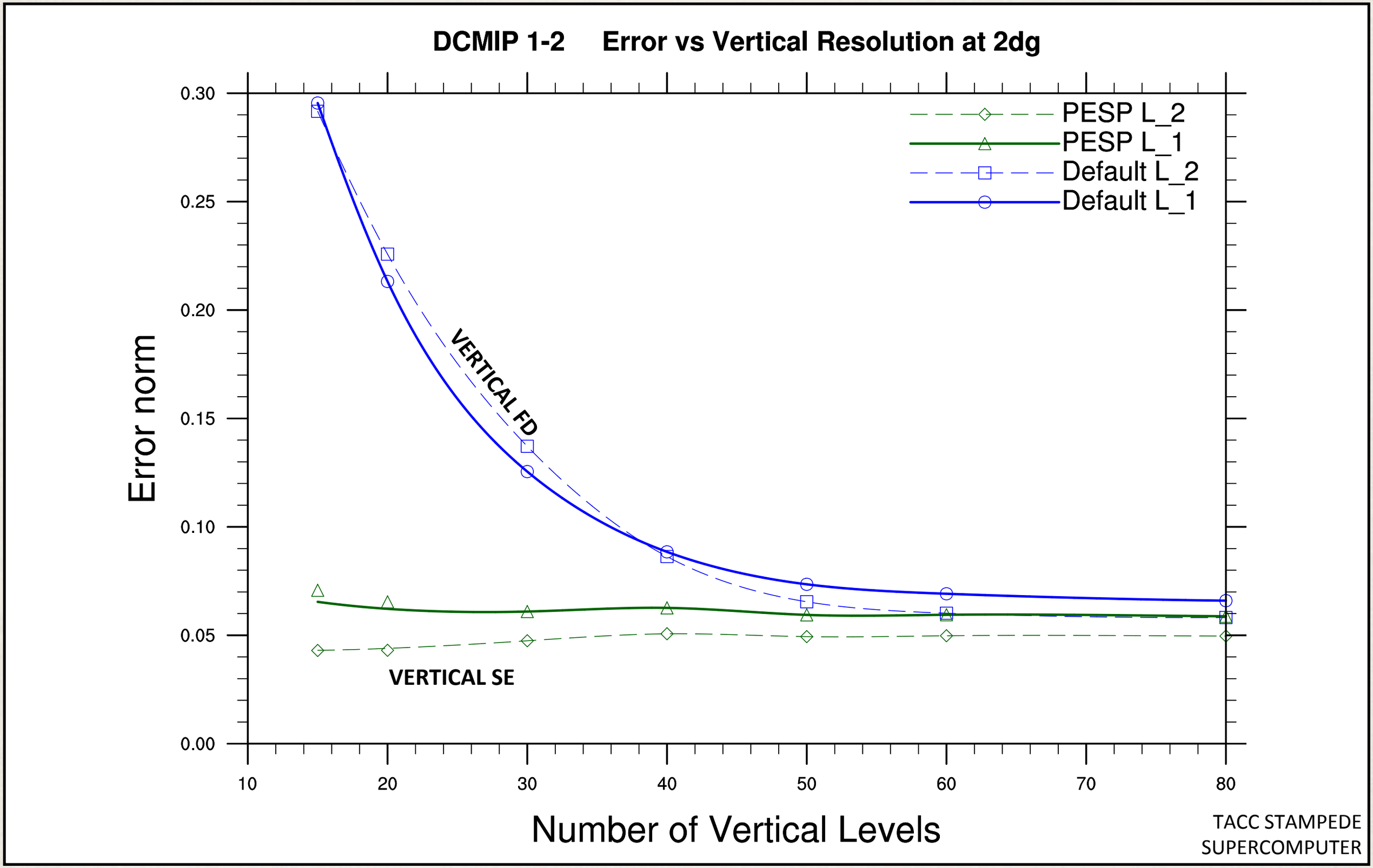


It also produced a delay in the onset of the southern instability, indicating globally reduced numerical error.

Quantitative Improvements

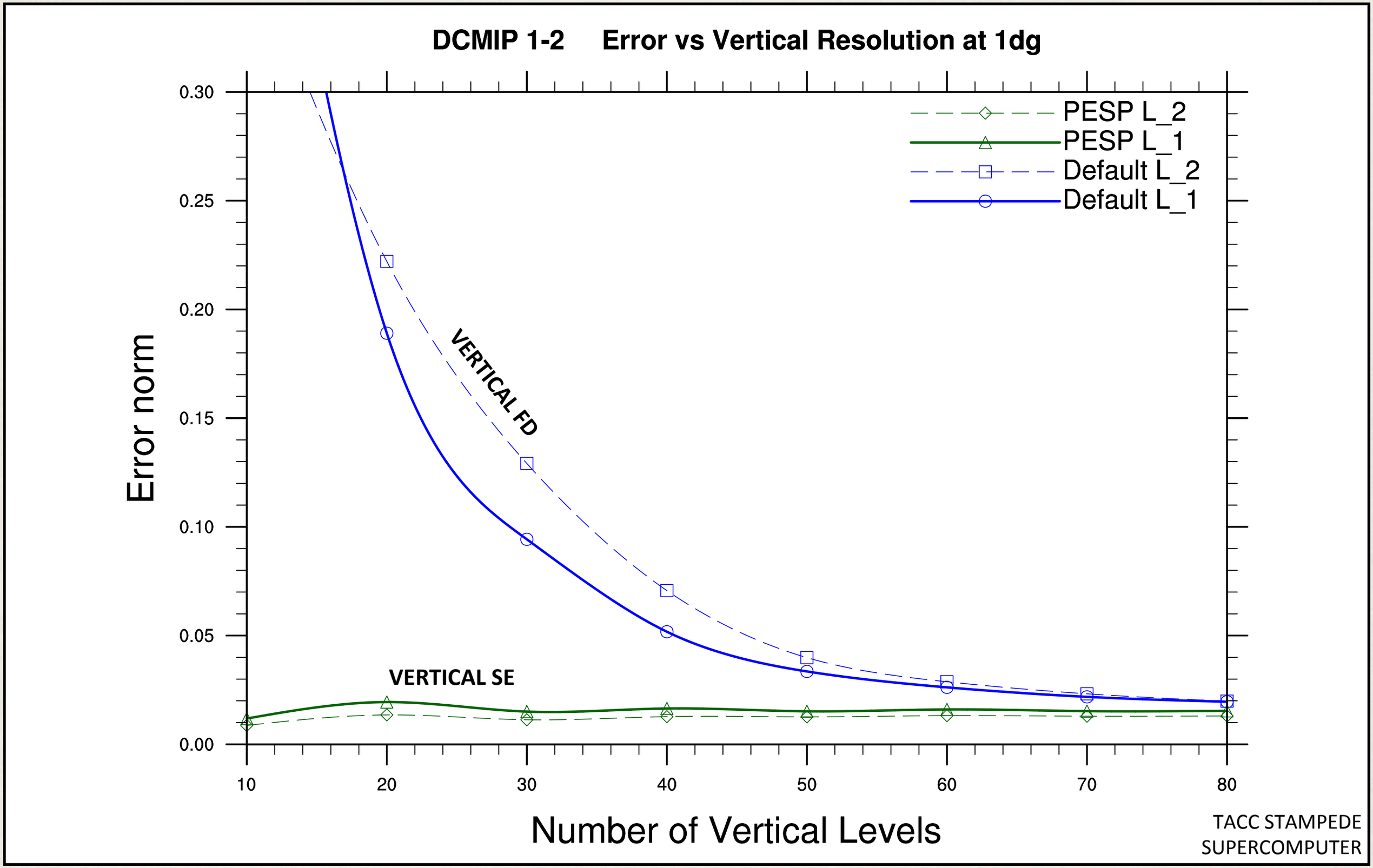
We can make these observations more precise by measuring the error norms where possible

Tracer Transport Error Norms at 2° Resolution



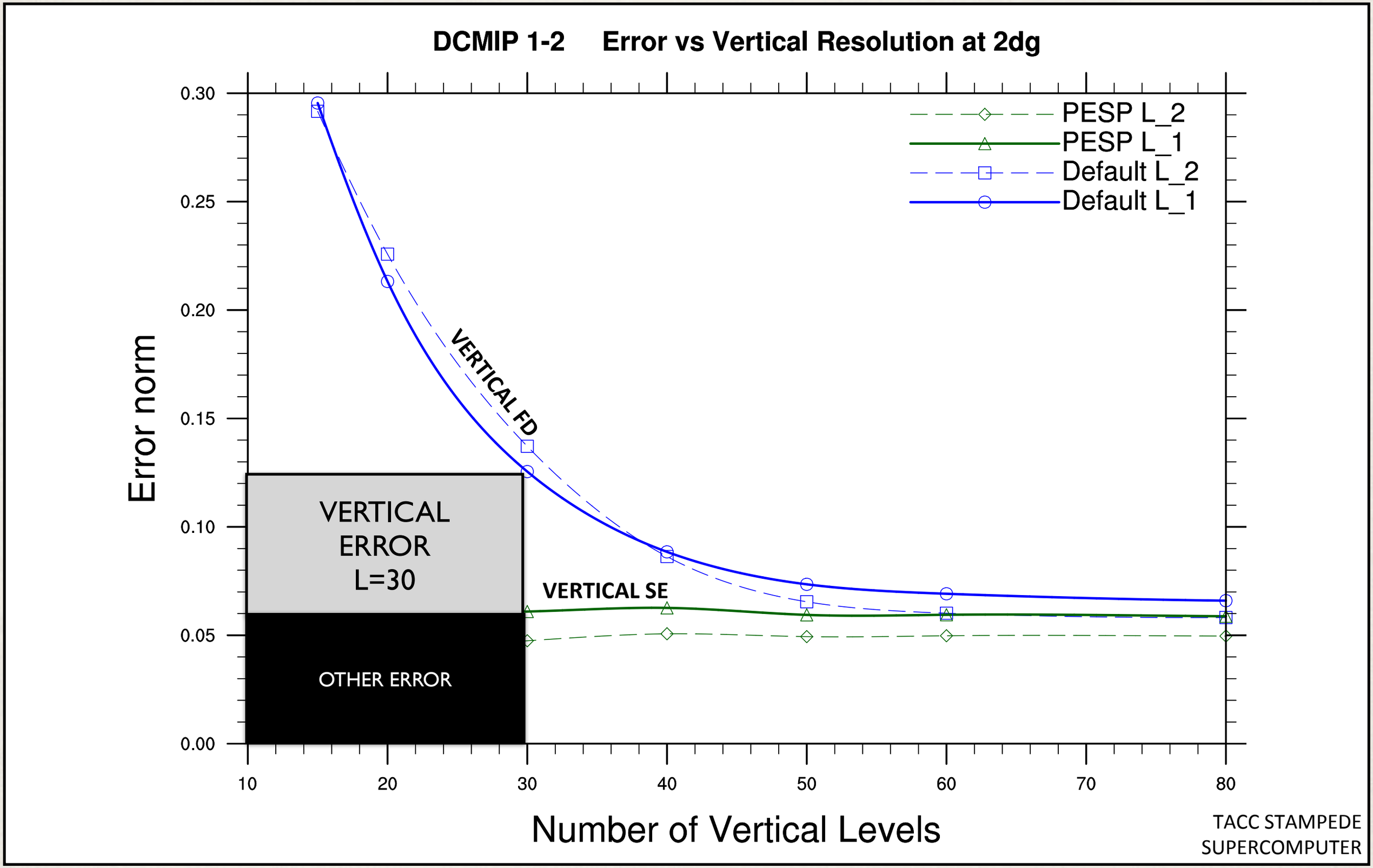
The vertical SE tracer transport solver produced smaller error norms than the default scheme regardless of the number of vertical levels used.

Tracer Transport Error Norms at 1° Resolution



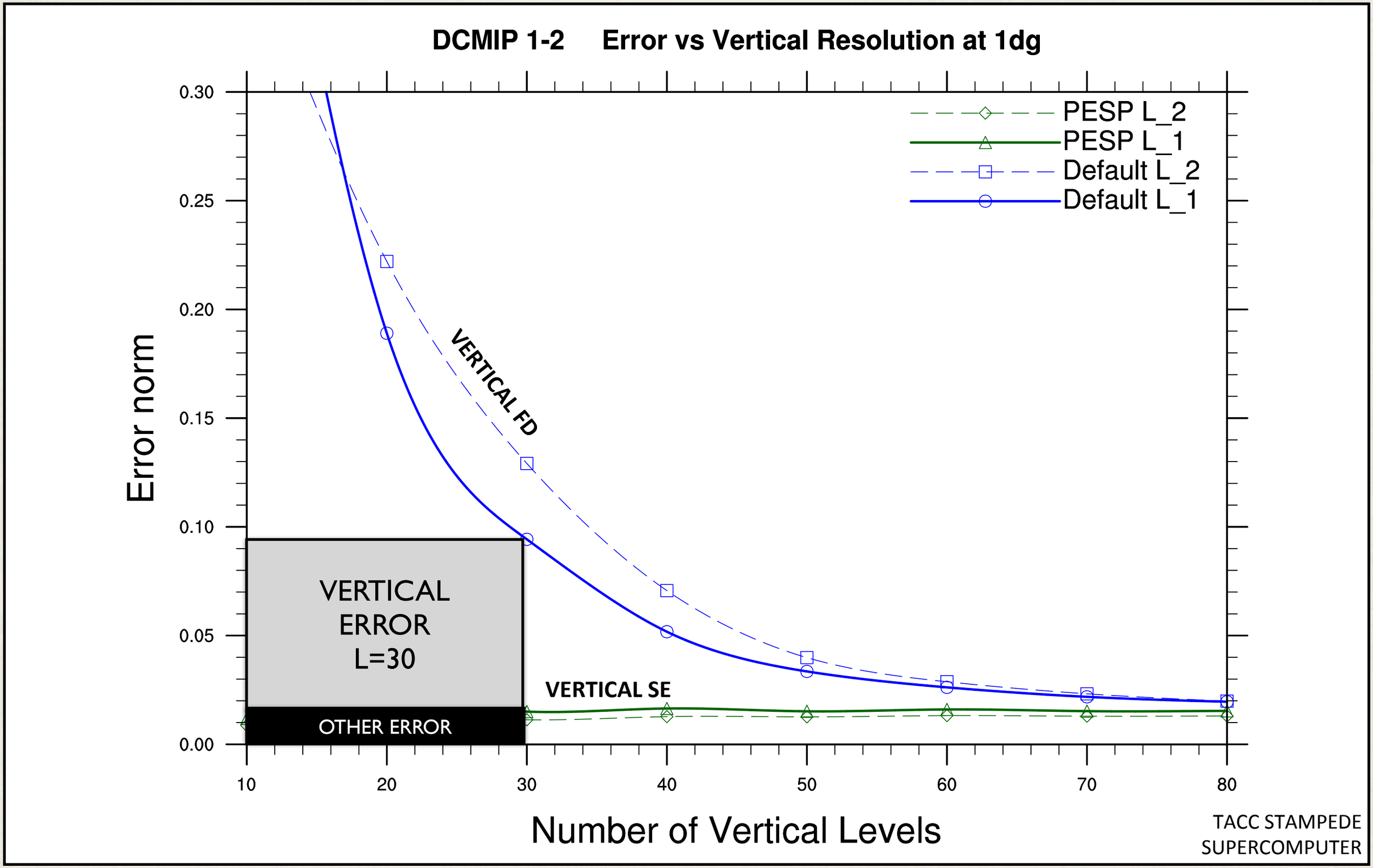
Increasing the horizontal resolution from 2° to 1° reduces the horizontal error contributions, but the vertical contribution is nearly the same.

Tracer Transport Error Norms at 2° Resolution



At 2° the vertical FD error is comparable in magnitude to the other sources of error in the solution.

Tracer Transport Error Norms at 1° Resolution

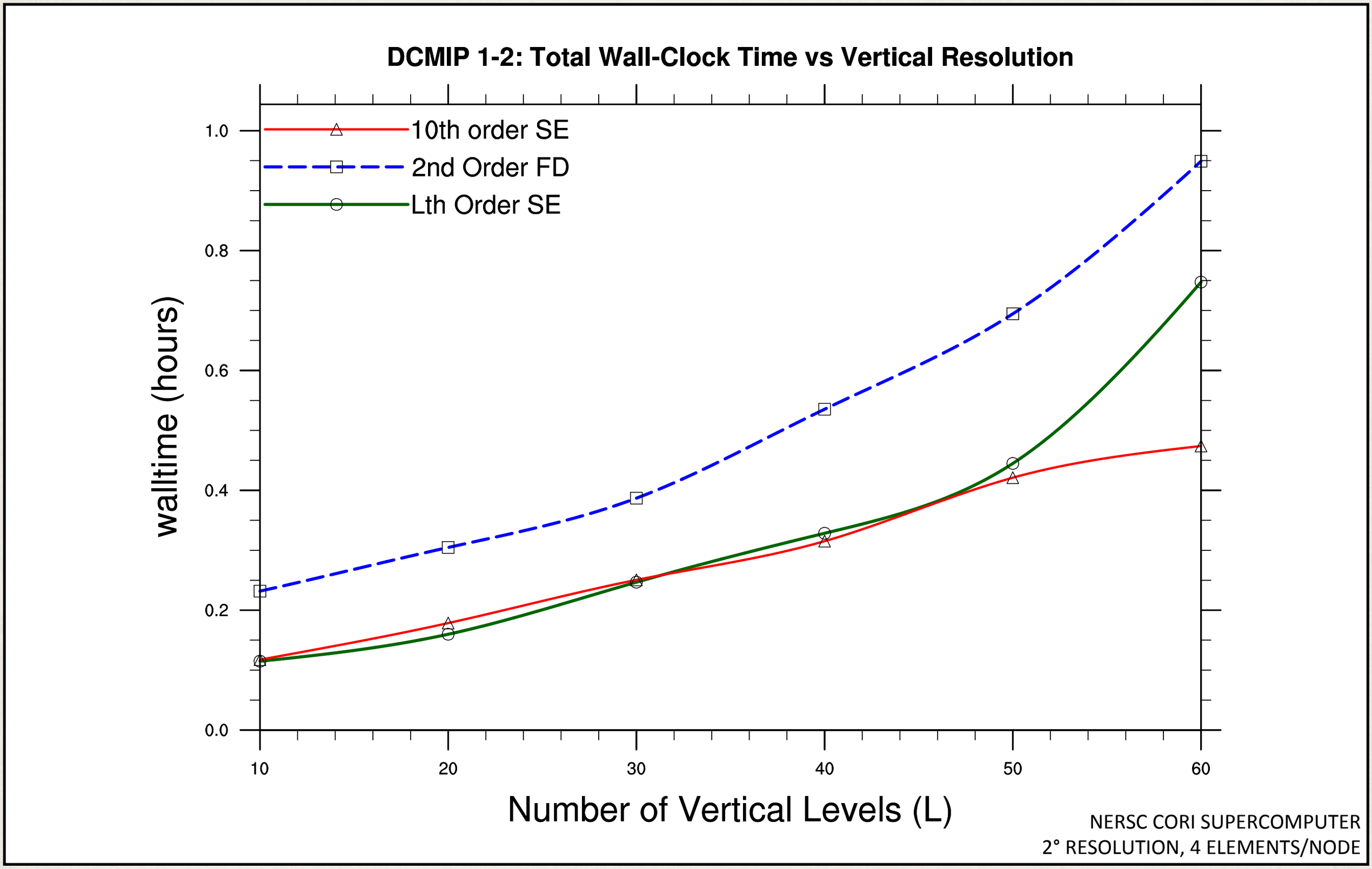


At 1° resolution and finer, the vertical FD error contribution dominates the solution, whereas the vertical SE error remains negligible.

Performance Comparison

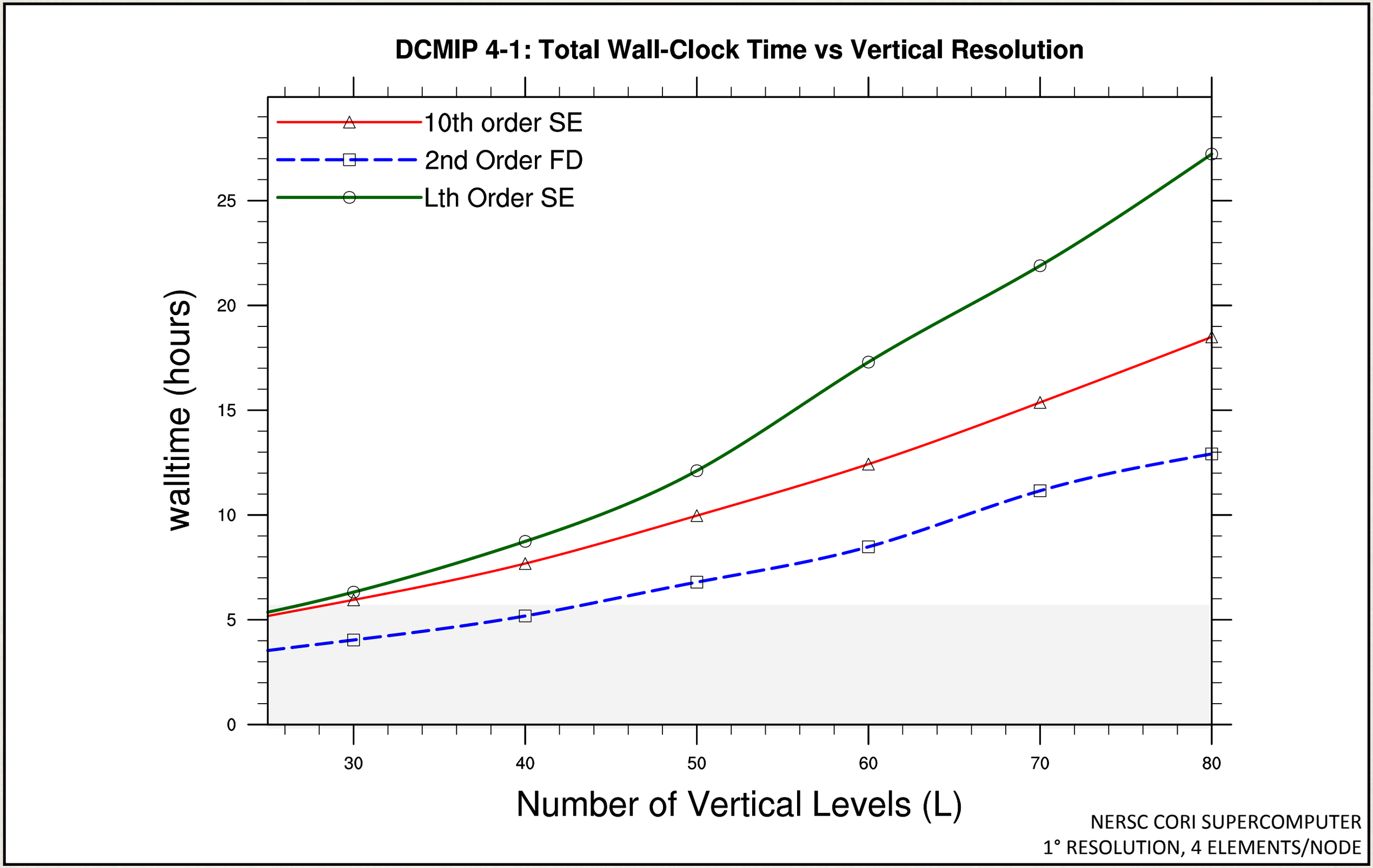
So we have seen that many results are improved with high-order operators,
but what is the performance cost?

Tracer Transport Performance: twice as fast



Performance of the SE Eulerian advection was found roughly twice as fast as the default Lagragian SE advection solver.

Full Model Performance: 50% slower



The SE model with 10th order polynomials was consistently about 50% more expensive than the FD solver. But 30 SE levels gives far greater accurate than 45 FD levels, making SE the less expensive for fixed accuracy.

Conclusions

- **Quality of Vertical SE > FD for all DCMIP test cases, at equal resolution**
- **Vertical SE Eulerian Tracer Transport twice as faster as default method**
- **Vertical SE Prim Eqn. solver is more accurate than FD at fixed cost**
- **Vertical SE potentially better suited to scale-aware parameterizations**
- **Vertical SE potentially better suited to variable-resolution**
- **Q: Can we maintain conservation and monotonicity?**
- **Q: Can we couple it to existing physical parameterizations?**
- **Q: What is its impact on coupled model climatology?**
- **Q: How much could we optimize for speed?**

Funding provided by the DOE

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DE-SC00006959 A Petascale Nonhydrostatic Atmospheric Dynamical Core in the HOMME Framework
DE-SC0014449 A Nonhydrostatic Variable Resolution Atmosphere Model in ACME