The importance of vertical resolution in the free troposphere for modeling intercontinental plumes

Jiawei Zhuang, Daniel J. Jacob, Sebastian D. Eastham

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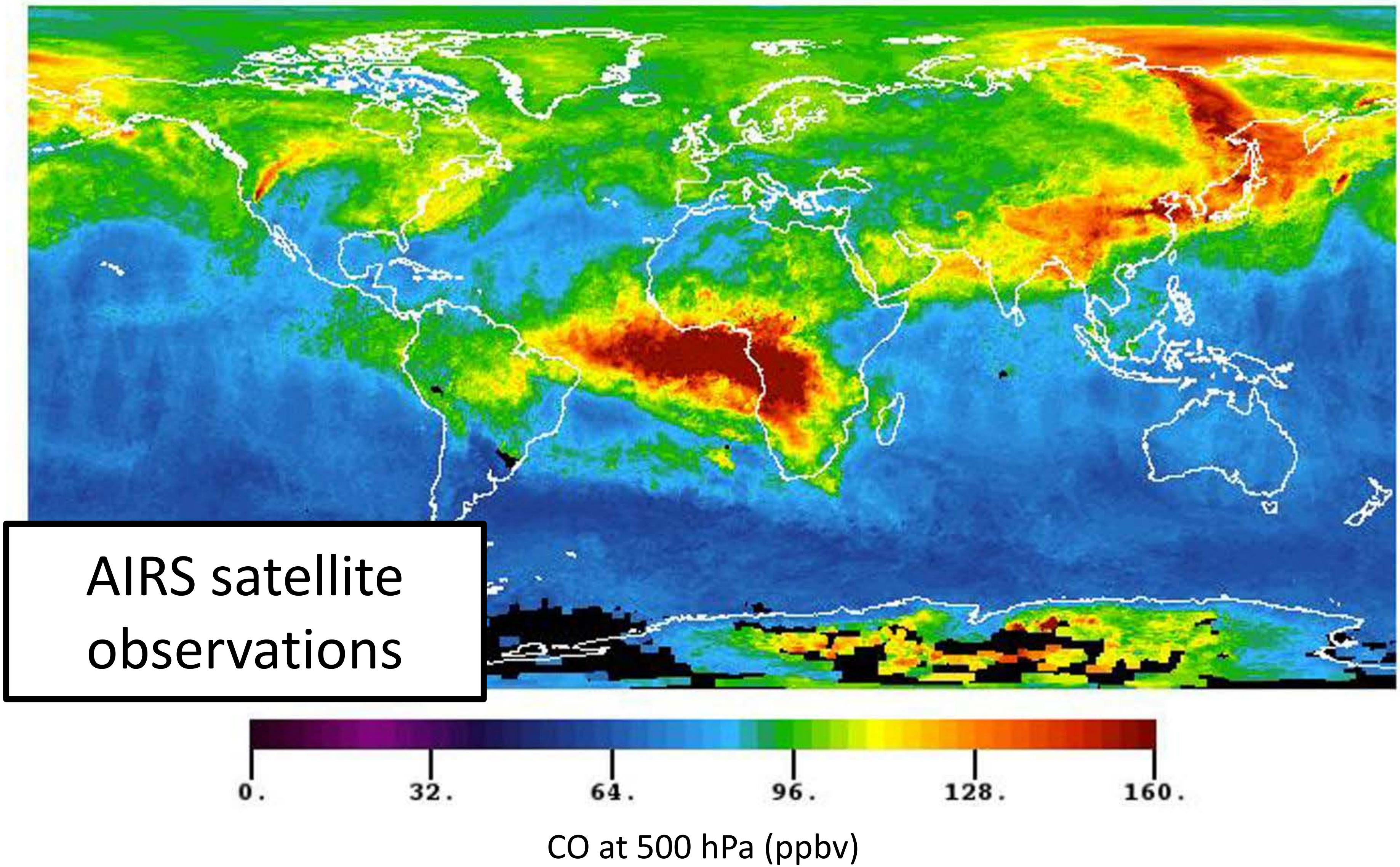
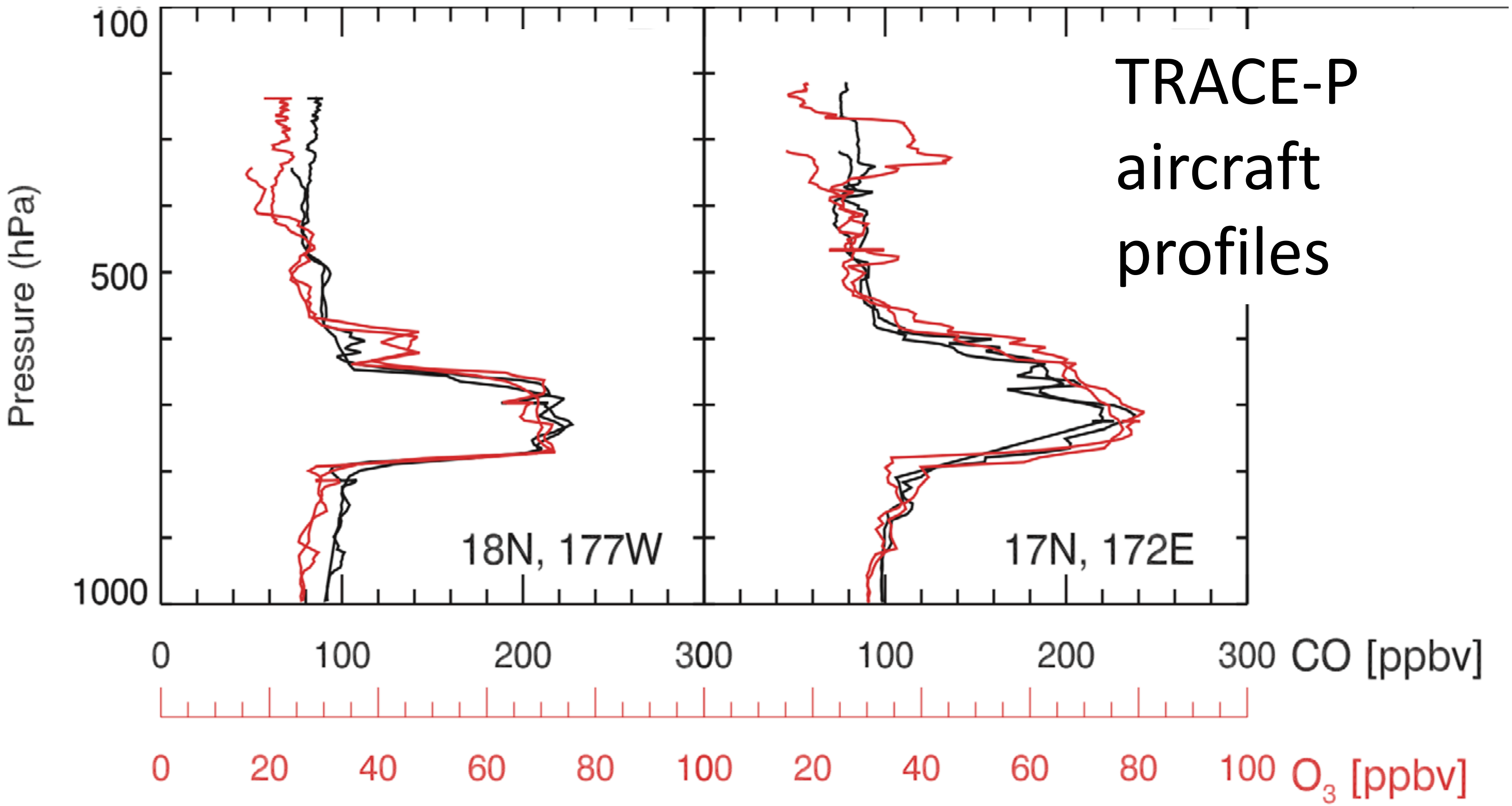
NASA-GEOS model resolution history

Version	Horizontal Resolution	# of Vertical Layers
GEOS1 (~1990)	2°x2.5°	20
GEOS3	1°x1°	48
GEOS4	1°x1.25°	55
GEOS5	0.5°x0.666°	72
GEOS-FP (initially)	0.25°x0.3125°	72
GEOS-FP (now)	~0.13°	72

Intercontinental plumes have a horizontal span of ~1000 km

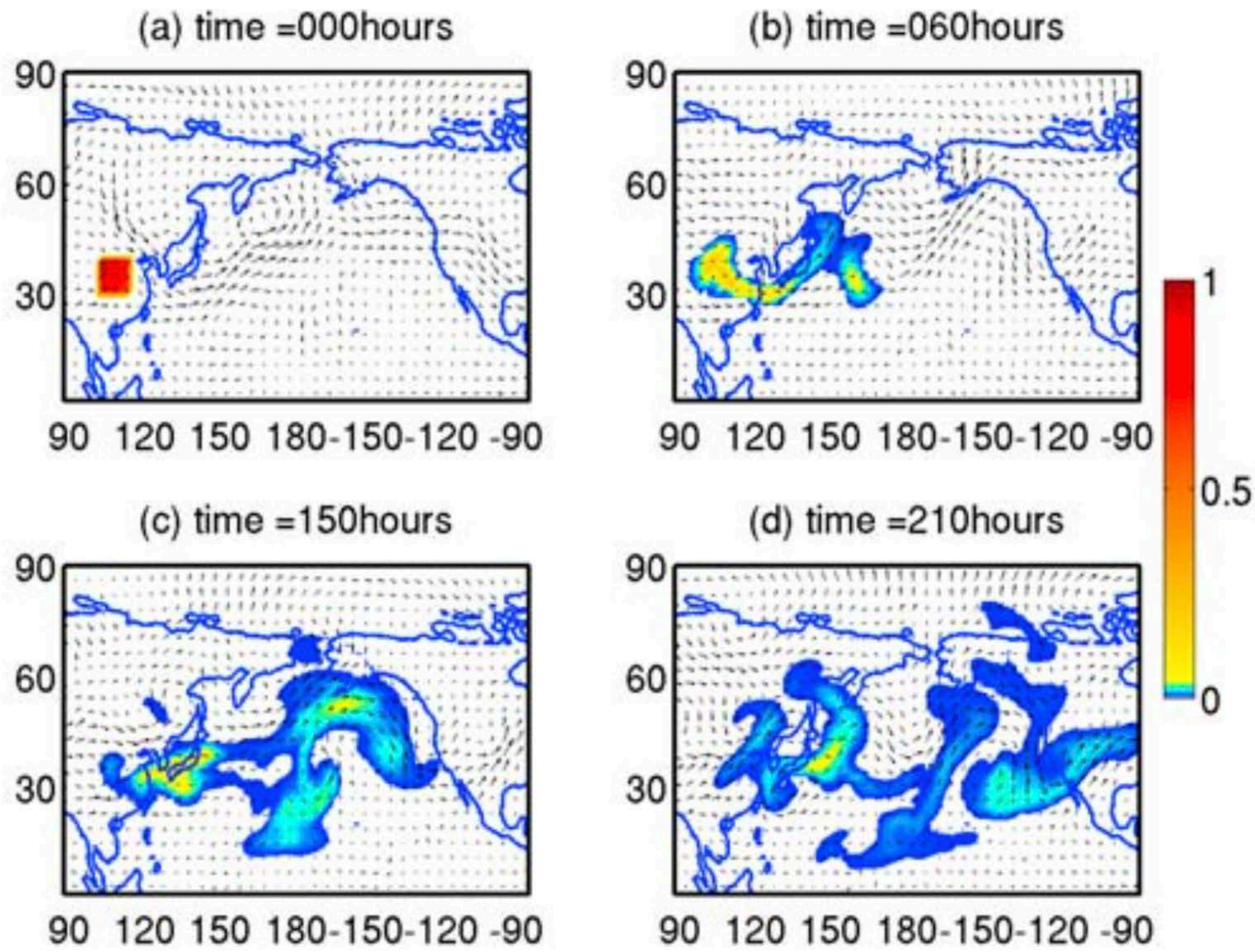


… but only ~1 km thick, poorly resolved by current models with low vertical resolution



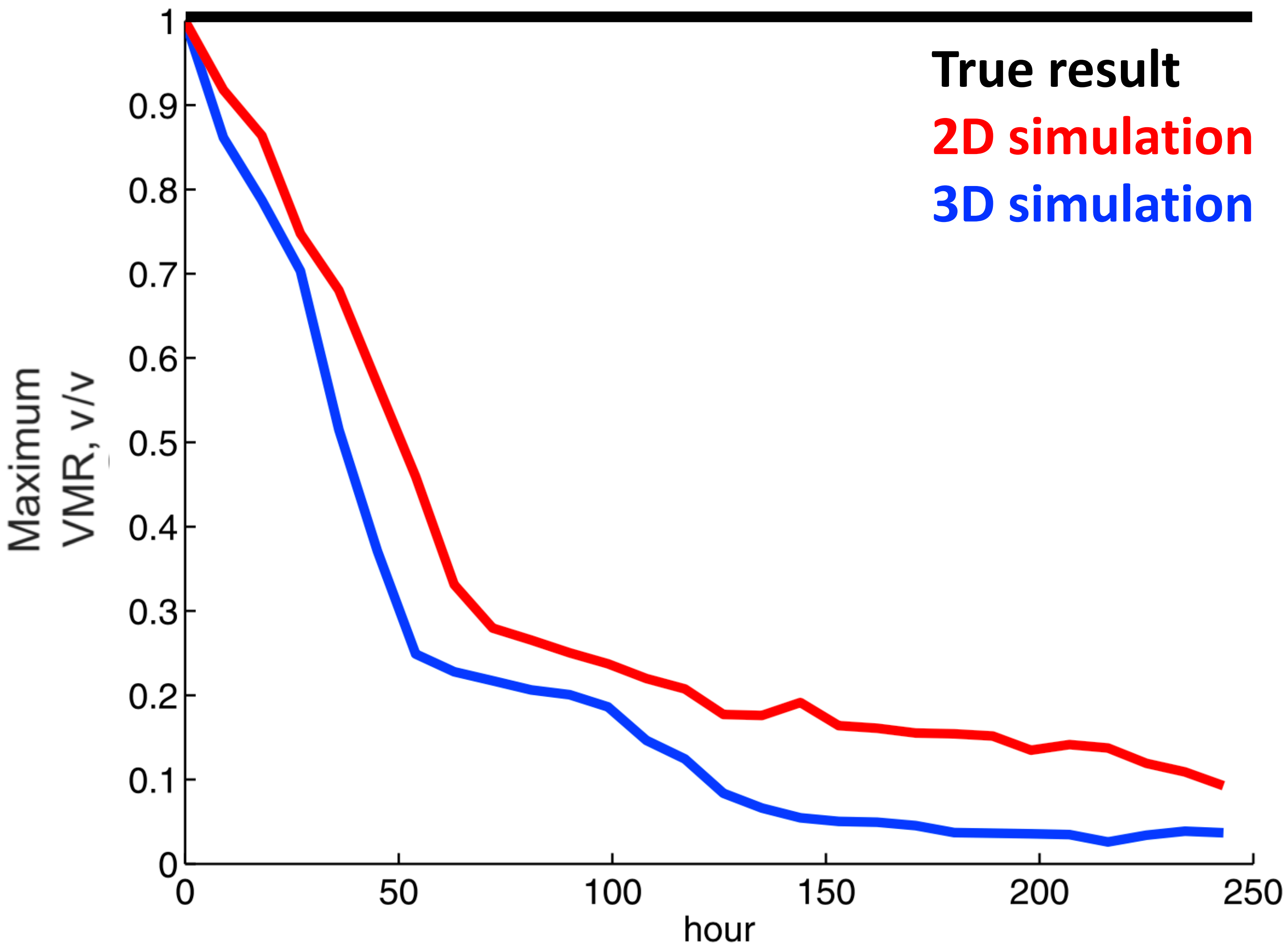
(Heald et al., 2003)

Plumes get diluted far too rapidly due to numerical error



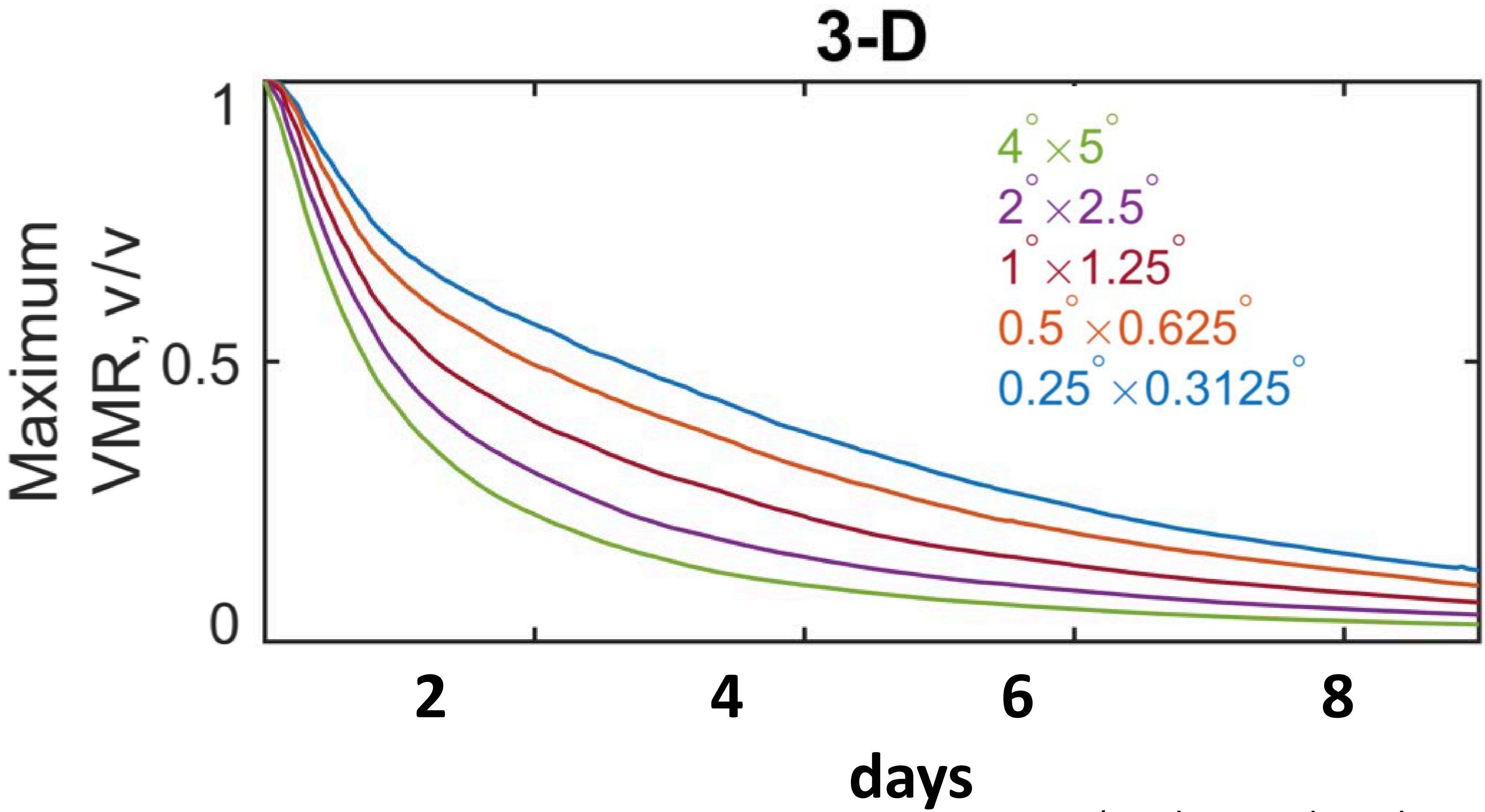
(Rastigejev et al. 2010)

Volume mixing ratio (VMR) should have been preserved by pure advection



(Rastigejev et al. 2010)

Increasing horizontal resolution doesn’t help, because the vertical resolution is too low (~1 km)



(Eastham and Jacob 2017)

Theoretical analysis for why increasing horizontal resolution cannot help

3D advection equation:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = 0$$

*: Assume first-order scheme. High-order schemes degrade to first-order when tracer gradients are sharp.

An Eulerian scheme actually solves **advection-diffusion** equation*:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{u\Delta x}{2}\frac{\partial^2 C}{\partial x^2} + \frac{v\Delta y}{2}\frac{\partial^2 C}{\partial y^2} + \frac{w\Delta z}{2}\frac{\partial^2 C}{\partial z^2}$$

If $\Delta x, \Delta y \rightarrow 0$, accuracy will be limited by vertical resolution

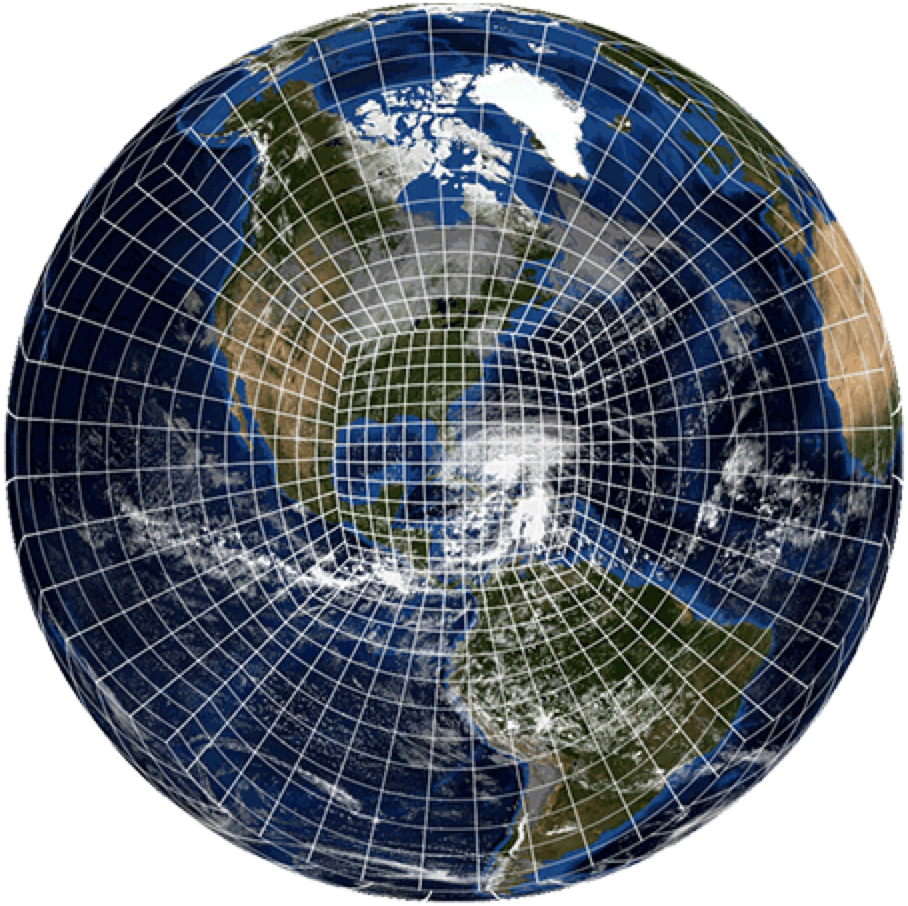
$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{w\Delta z}{2}\frac{\partial^2 C}{\partial z^2}$$

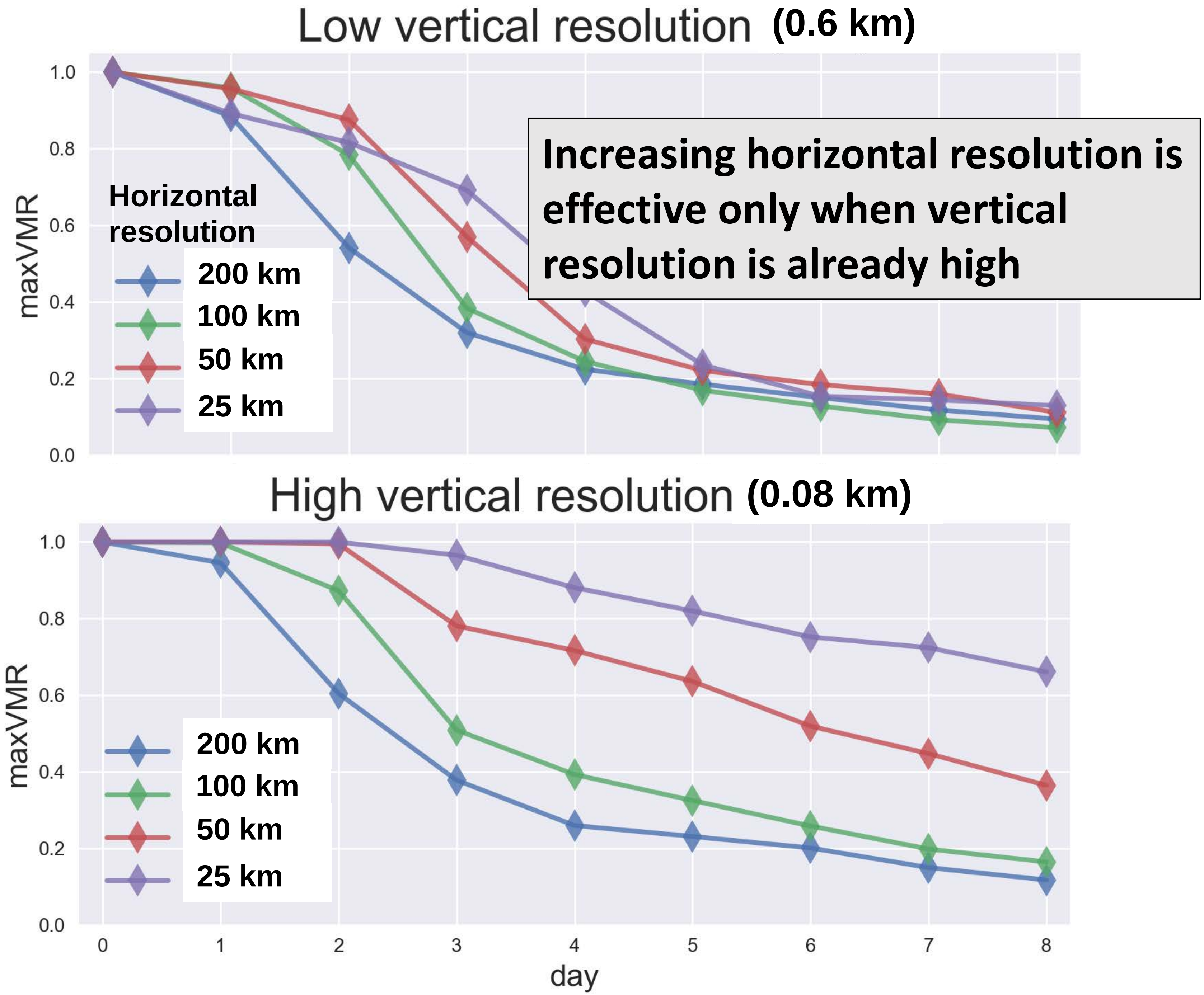
Use the GFDL-FV3 dynamical core to push horizontal and vertical resolutions to the limit

- GFDL-FV3 uses the cubed-sphere grid, to avoid polar singularity and allow efficient execution on massively parallel machines

- **Used as the advection module in GCHP**

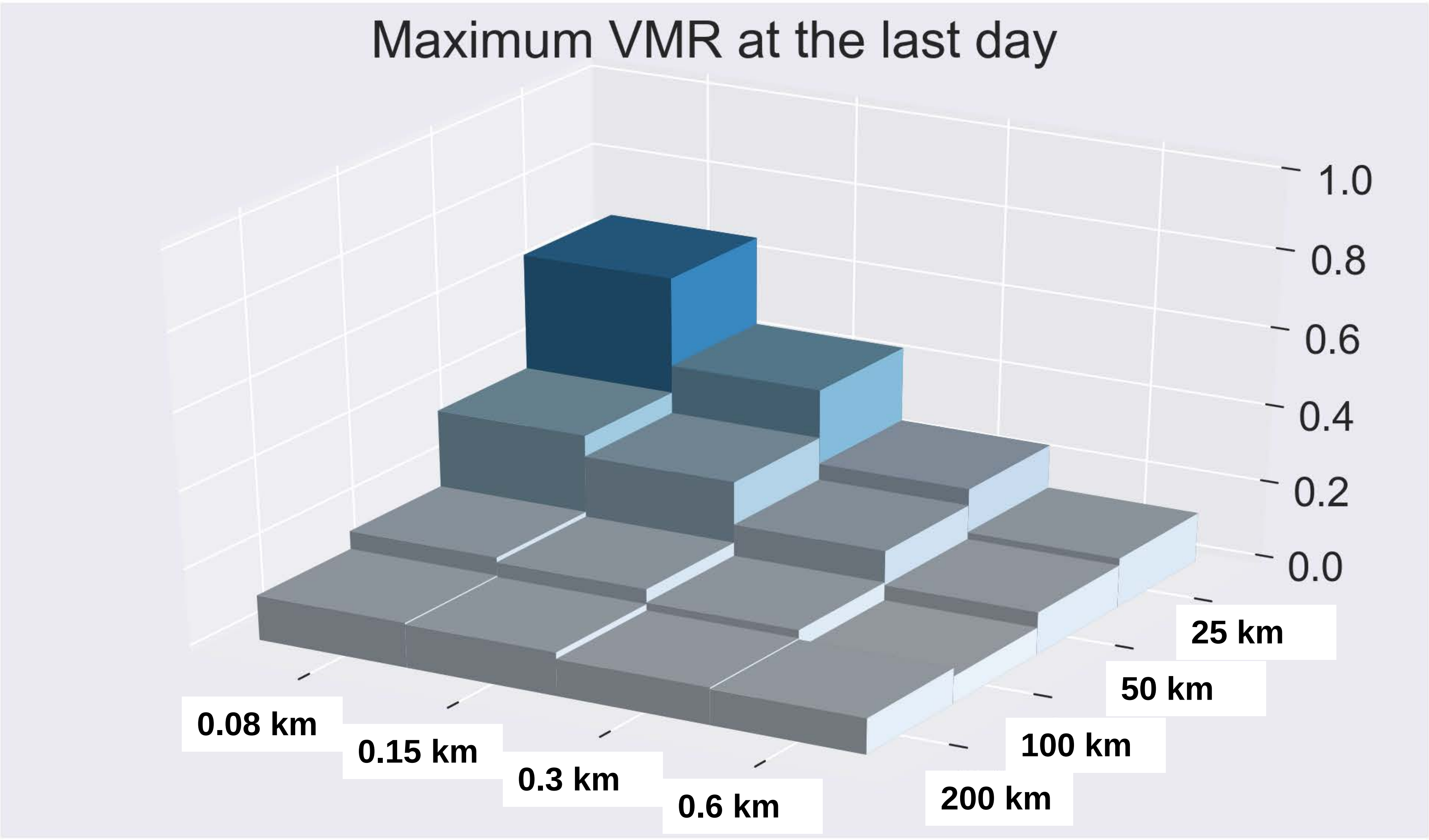
- Implemented in many other models including GEOS-5, CESM, and NCEP-GFS



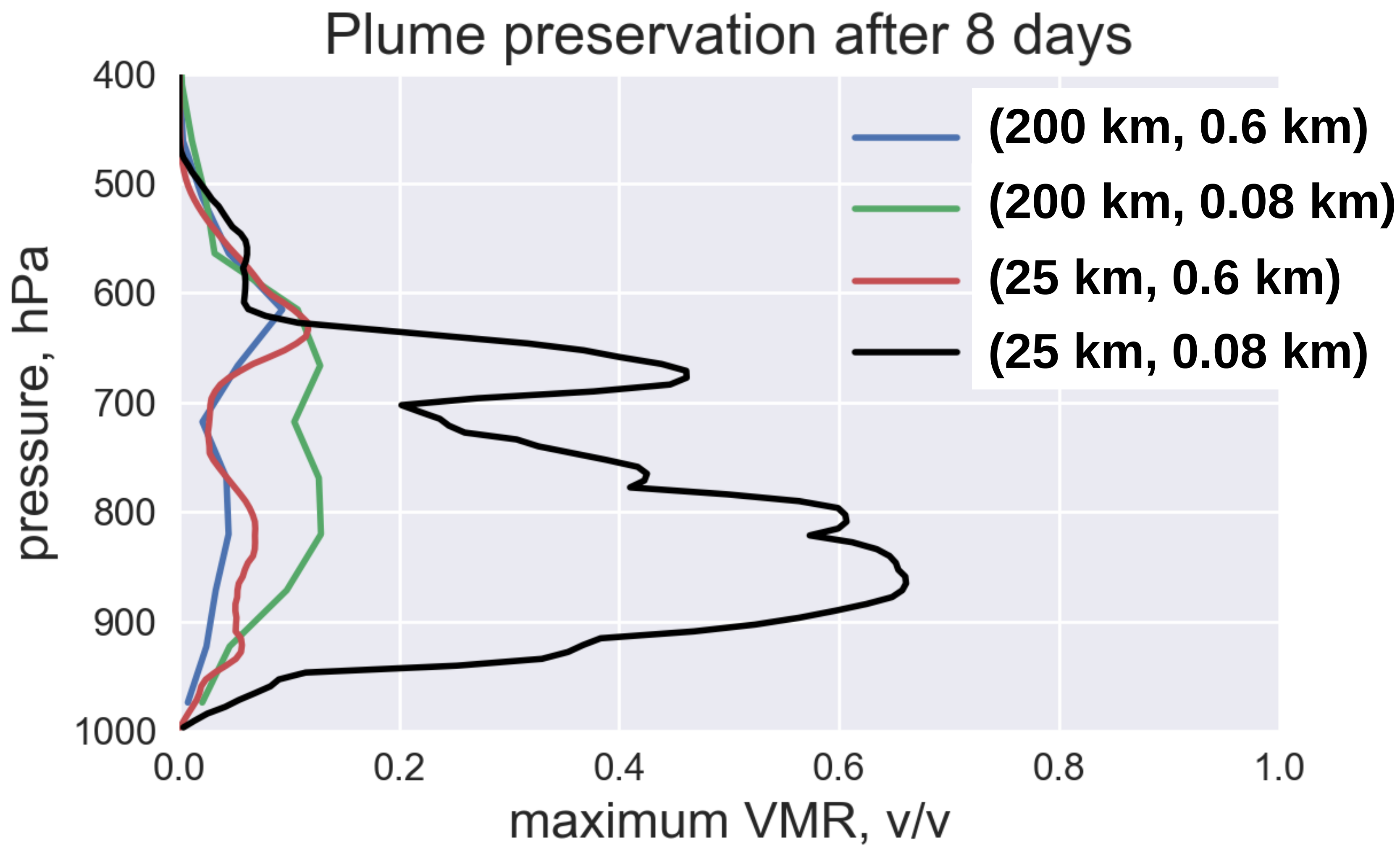


Low vertical resolution (0.6 km)
Increasing horizontal resolution is effective only when vertical resolution is already high
Horizontal resolution
200 km
100 km
50 km
25 km
maxVMR
1.0
0.8
0.6
0.4
0.2
0.0
High vertical resolution (0.08 km)
200 km
100 km
50 km
25 km
maxVMR
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
day

Significant co-benefit from horizontal and vertical grid refinements



A combination of high horizontal and high vertical resolutions brings the vertical profile closer to typical aircraft observations



Optimal resolution ratio under computing power constraint

$$\left[\frac{\boldsymbol{\Delta x}}{\boldsymbol{\Delta z}}\right]_{\boldsymbol{optimal}} = \frac{\boldsymbol{w}}{\boldsymbol{u}}\left(\frac{\boldsymbol{L}}{\boldsymbol{H}}\right)^{\mathbf{2}} \sim \mathbf{1000}$$

u: horizontal wind speed, ~10 m/s

w: vertical wind speed, ~0.01 m/s

L: horizontal extent of plume, ~1000 km

H: vertical extent of plume, ~1 km

Extreme case 1: $\boldsymbol{w = 0}$, i.e. degrades to 2D transport

$\left[\frac{\Delta x}{\Delta z}\right]_{optimal} = 0$, no requirement on vertical resolution.

Extreme case 2: H$\rightarrow \mathbf{0}$, i.e. infinitely thin plume

$\left[\frac{\Delta x}{\Delta z}\right]_{optimal} \rightarrow \infty$, need infinitely high vertical resolution.

Optimal resolution ratio based on atmospheric dynamics

To resolve fronts, the optimal resolution ratio should be:

$$\left(\frac{\Delta x}{\Delta z}\right)_{opt} = \frac{1}{s} \sim 100$$

(Pecnick and Keyser 1989)

s : the frontal slope, ~ 0.01

To resolve quasi-geostrophic flows, the ratio should be:

$$\left(\frac{\Delta x}{\Delta z}\right)_{opt} = \frac{N}{f} \sim 100$$

(Lindzen and Fox-Rabinovitz 1989)

N: the Brunt–Väisälä frequency ~ 10^{-2} rad/s

f : the Coriolis parameter, ~ 10^{-4} rad/s

Summary & future works

- **Plume transport simulation** requires a much higher vertical resolution than **meteorology simulation**.
- Vertical resolution in current models should be increased by **10-fold** to reach optimal configuration.
- Strong **co-benefit** from horizontal and vertical grid refinements.

▪ Need to test higher vertical resolution in GEOS-Chem by vertically interpolating metfields.