Effect of numerics on transport of trace gases in atmospheric climate models

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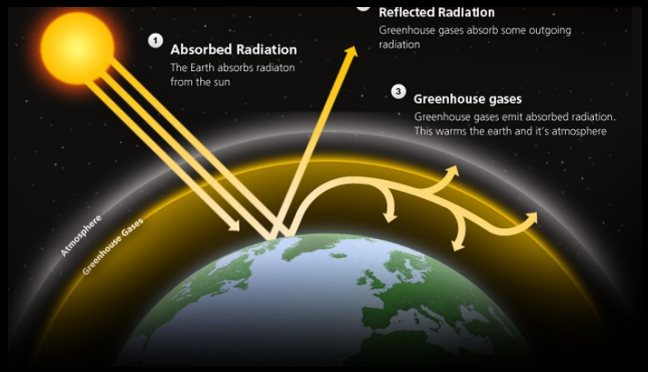
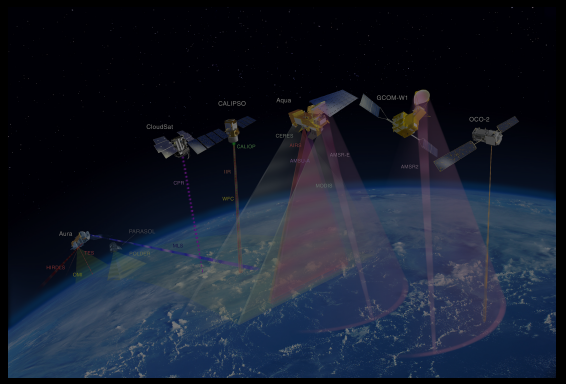
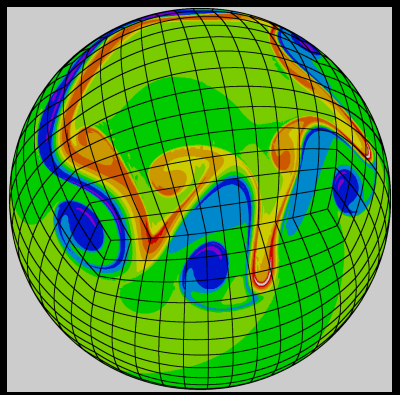


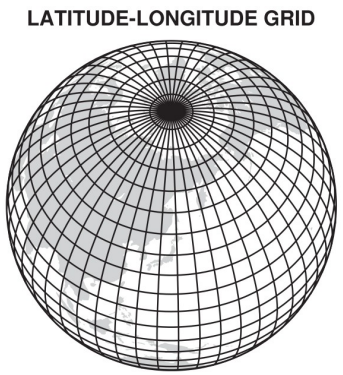


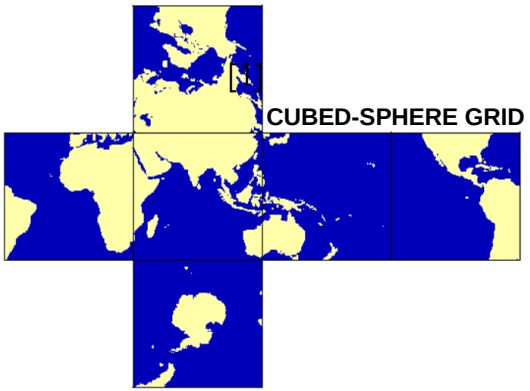


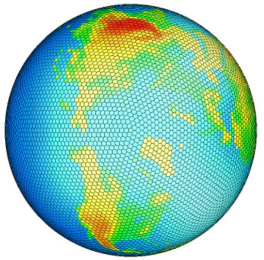
… what on earth is a CLIMATE MODEL ?

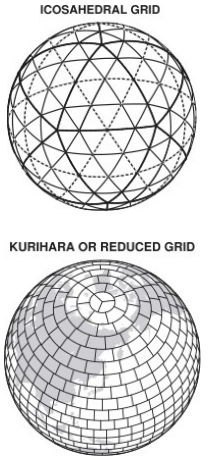
- **Climate model** : a computer model that numerically solves the equations of fluid motion(i.e. a nonlinear system of PDEs) and projects the future conditions (like surface temperature, humidity, precipitation, ice sheet cover etc).

- The kernel of the model is called the **dynamical core**. The equations can be solved using different types of grid.









- Solve using **different numerics**

Pseudospectral Methods
Using Spherical Harmonics. Solved in Wave Space.

Finite Volume Methods
Flux formulation. Reimann Solvers and Flux limiters.

Spectral Element Methods
Weak formulation. Finite Element like. Recently developed at NCAR.

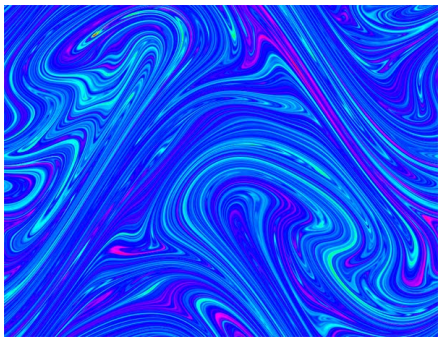
Each different method used to solve the equation can give a slightly different answer. Ensuring consistency and correctness is the main test for a dynamical core

… and what on earth is a TRACER?

- **A (passive) tracer** is any substance, present in small quantities, that moves with the flow without influencing it.
- Atmosphere is like a moving ocean of air. **Atmospheric tracers** include trace gases like Water Vapor, Ozone, Carbon Dioxide, CFCs etc.
- **Why tracers matter ? :** Inaccurate representation of tracers severely affects climate projections from models due to energy imbalance.

Objective : To create a benchmark for 'dynamical cores' of climate models to understand the present state of trace gas transport in the state-of-the-art climate models.

Tracer diffusion in still water



Tracer advected by a turbulent flow

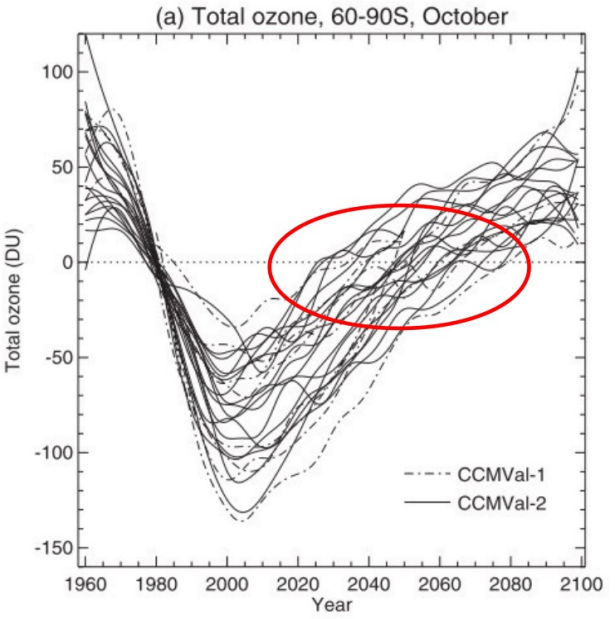
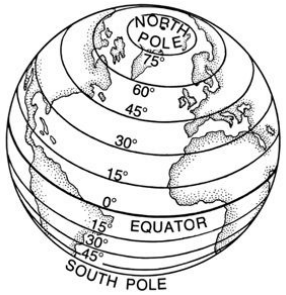
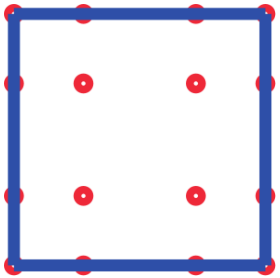


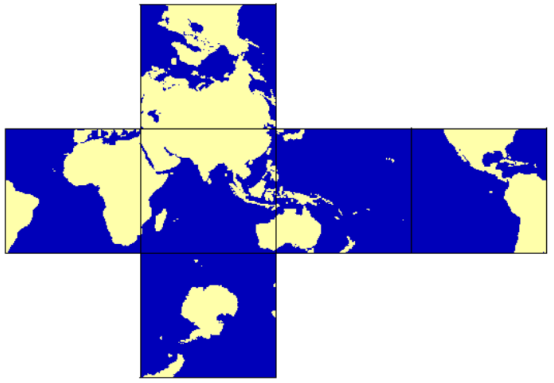
Fig : Ozone recovery times (to Montreal Protocol Levels) as projected by state-of-the-art climate models. From Karpechko et. al. 2013 [1]

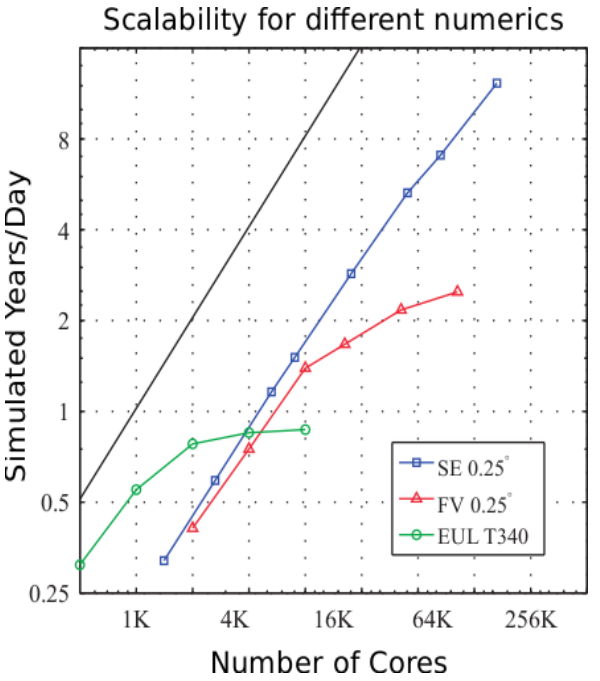
fundamental role of HPC

- **Computationally very expensive** : Practically impossible without the gift of HPC.
- **Grid type can strongly influence scalability** : each grid(rectilinear or unstructured) is intelligently discretized to minimize inter-core communication
- 

Latitude-longitude grid for pseudospectral dynamical core


A 3x3 element inside a cubed sphere cell for spectral element dynamical core


The sphere projected onto 6 sides of the cube for cubed-sphere finite volume dynamical core

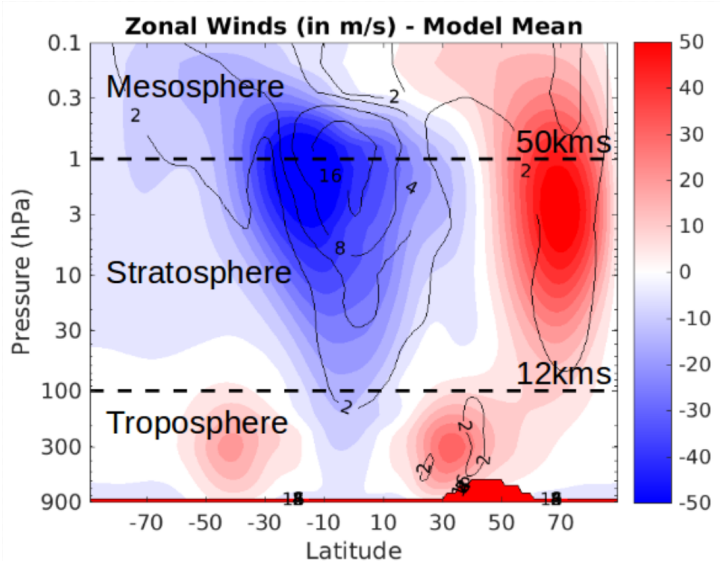


- Weather and storm forecasters need to beat the clock. Speed is important.
- **Cost of this study :** For this (relatively simpler study), ~0.3 million CPU hours burnt, ~20 TBs of data generated, 1 innocent PhD student.

Model Response

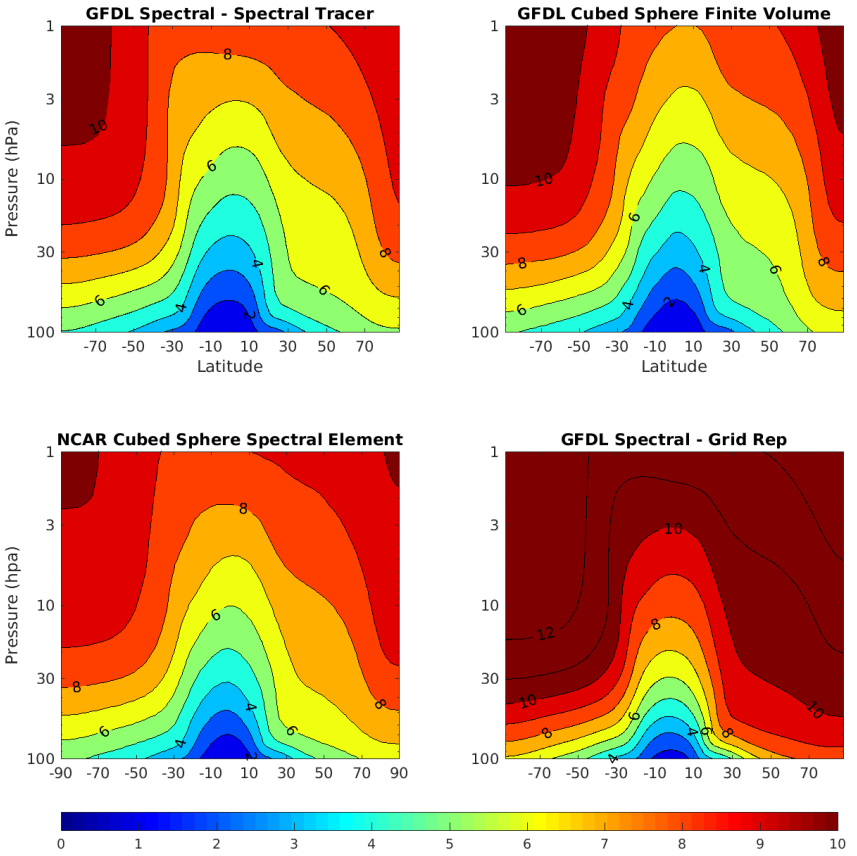
Setup : We force 3 state-of-the-art dynamical cores with different numerics and grids with identical temperature and tracer forcings and study steady state tracer distributions. No chemistry was used!!! Yet, the mean residence times of age were computed mathematically using an idealized tracer.

Fig : Mean steady state winds(in color) with superimposed standard deviations



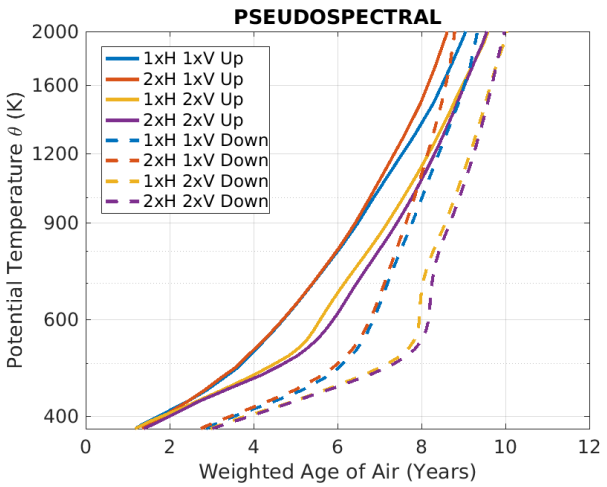
The models have similar winds yet very different tracer distributions. Understanding and resolving these differences is important.

Fig : Mean age for 3 different dynamical cores. Bottom right figure shows age using a finite volume advection scheme in a pseudospectral core

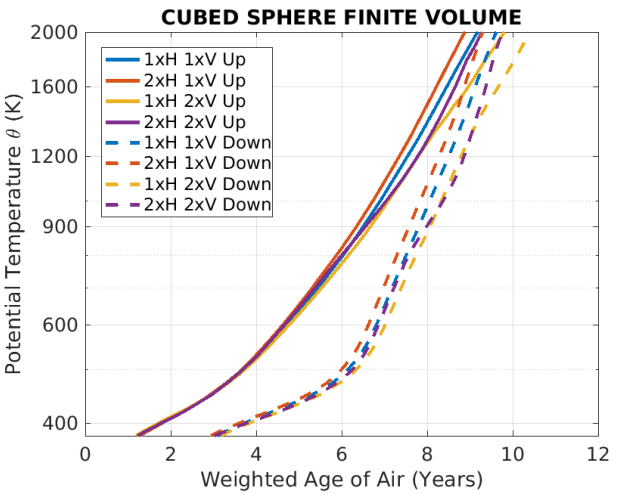


Convergence trends

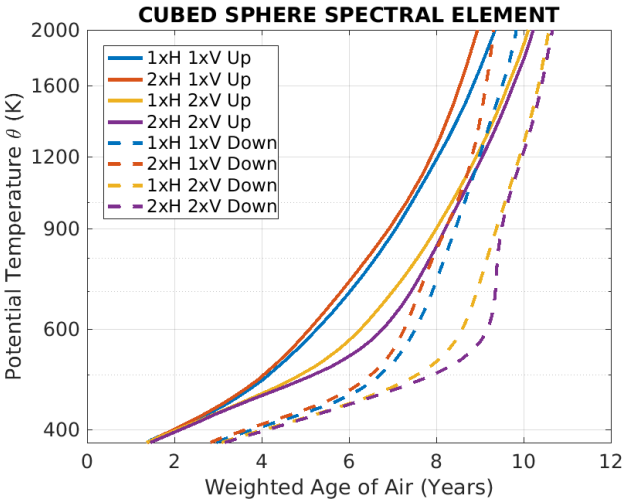
Developed at Princeton-GFDL



Developed at Princeton-GFDL



Developed at NCAR (CAM Model)



Huge spread across resolutions. **Spread minimum for Cubed Sphere Finite Volume dynamical core.**
No signs of convergence for Pseudospectral and Spectral Element cores.

1) Despite similar winds distributions, model disagree on tracer transport. Moreover, 2 out of 3 models in this study show no signs of convergence. Cubed Sphere finite volume has promising tracer transport [2] .

2) The differences can be attributed to numerical dissipation, inertial instabilities and different wave breaking and mixing in these models in the stratosphere. [3]

References

1) Karpechko, A. Yu., J. Perlwitz, and E. Manzini (2014), **A model study of tropospheric impacts of the Arctic ozone depletion** 2011, J. Geophys. Res. Atmos., 119, 7999–8014, doi:10.1002/2013JD021350.

2) (In Preparation) A Gupta, E Gerber, **Numerical impacts on Tracer Transport: A proposed intercomparison test of Atmospheric General Circulation Models**; Quarterly Journal of the Royal Meteorological Society

3) (In Preparation) A Gupta, E Gerber, **Numerical Impacts on Tracer Transport: Understanding biases in dynamical cores with the leaky pipe framework**; Quarterly Journal of the Royal Meteorological Society