# Atmosphere Modeling I: Dynamics


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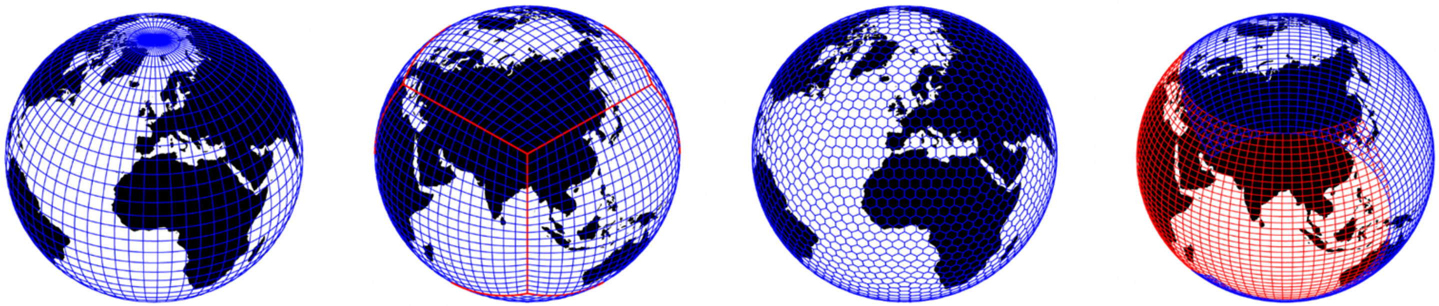
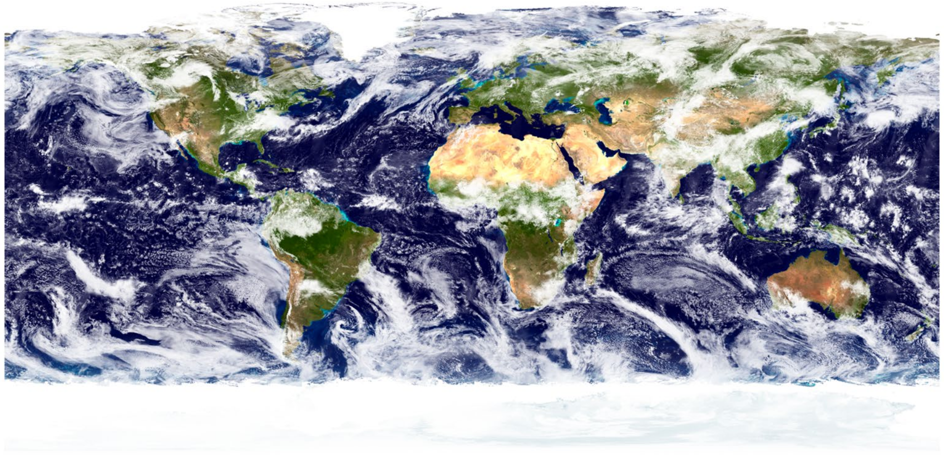


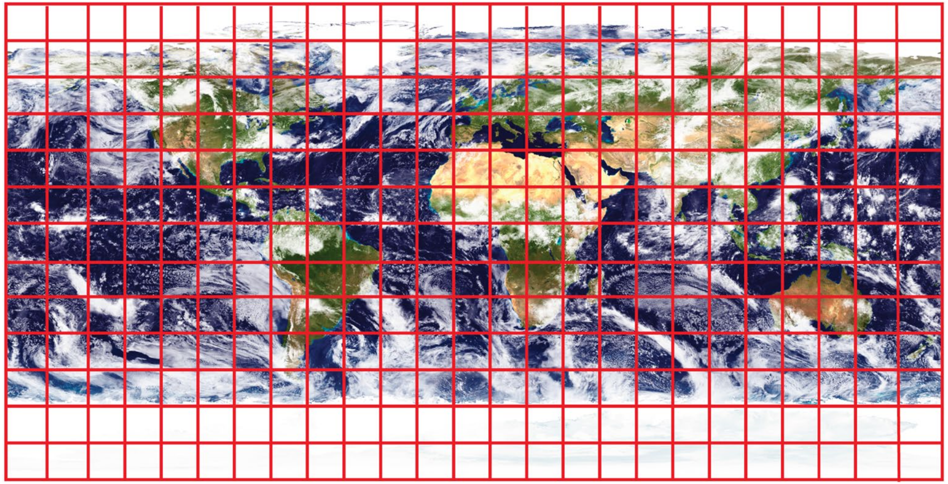
Some figures and slides adapted from Adam Herrington's DCMIP talk

# Domain



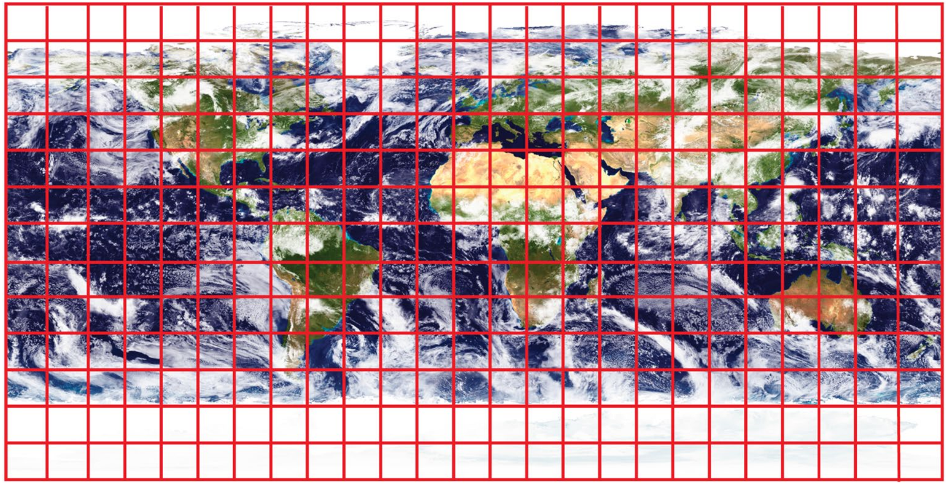
Source: NASA Earth Observatory

# Horizontal computational space



Red lines: regular latitude-longitude grid

# Dynamical core



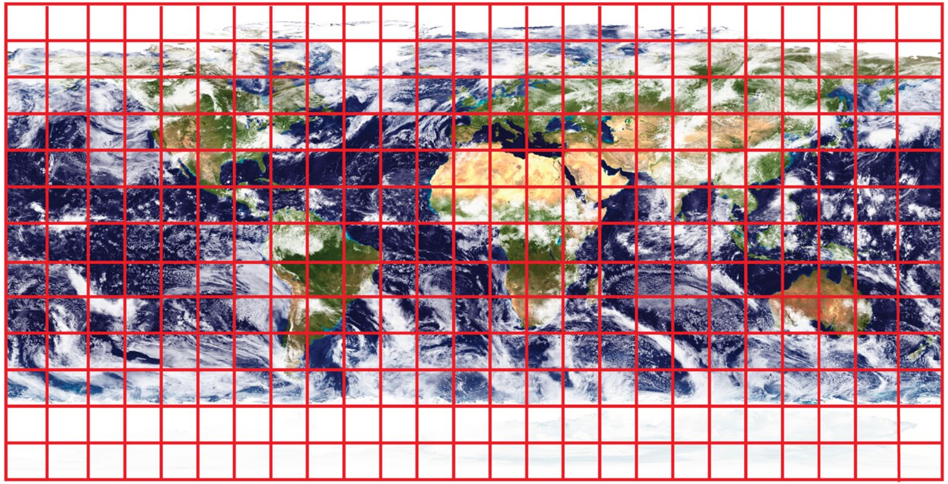
Red lines: regular latitude-longitude grid

- Grid cell size (dx) defines the resolution of the computational grid (≠ effective resolution!)
- The ***dynamical core*** solves the governing fluid and thermodynamic equations on resolved scales
- The near-grid-scale solutions (e.g., 2*dx waves) are not accurately represented and are removed by implicit and/or explicit numerical filters
- In modeling jargon, the dynamical core is referred to as the ***dycore*** or the ***dynamics***

# Physics parameterizations

See "Atmosphere Modeling II: Parameterizations" talk this PM

Christina McCluskey, Meg Fowler and Ben Stephens



Red lines: regular latitude-longitude grid

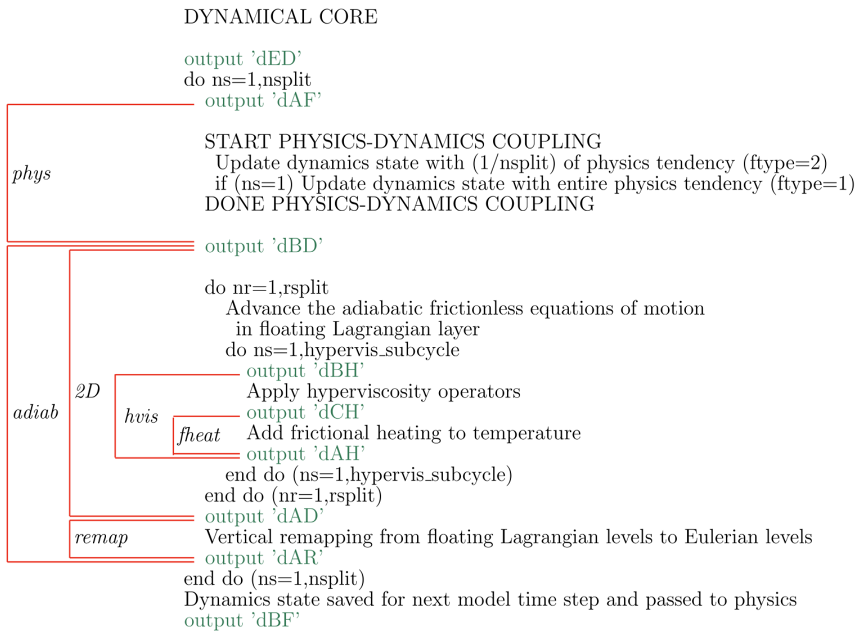
- Many important processes occur at the sub-grid-scale that must be parameterized
- ***Parameterizations*** compute the grid-cell average tendencies due to sub-grid processes in terms of the resolved atmospheric state
- In modeling jargon, parameterizations are referred to as the ***physics***
- Sometimes called ***column physics***, which emphasizes that physics only operate in a column

# Coupling the physics to the dynamics

High-level workflow for coupling the physics to the dynamics:

1. Use the ‘state’ to compute the total tendency of temperature, humidity, winds & tracers from the ‘physics suite’
    - ❑ A physics suite contains multiple physics schemes
    - ❑ The physics schemes may be coupled to one another (sequential update split) or not (parallel split)
1. Apply the physics tendencies as a forcing term to the discretized dycore equations and integrate forward in time
    - ❑ Individual processes are often sub-cycled within the host model time-step
1. Send new prognostic state to (1) and repeat

*coupling to surface components not included




Schematic of a dycore time-step in CAM-SE (Lauritzen and Williamson 2019)

CAM-SE: Community Atmosphere Model w/ Spectral-Element dycore option

# What do we need to represent in a model?

Model: MPAS
Variable: Outgoing Longwave Radiation

# Multi -scale nature of atmospheric dynamics (from Thuburn 2011)

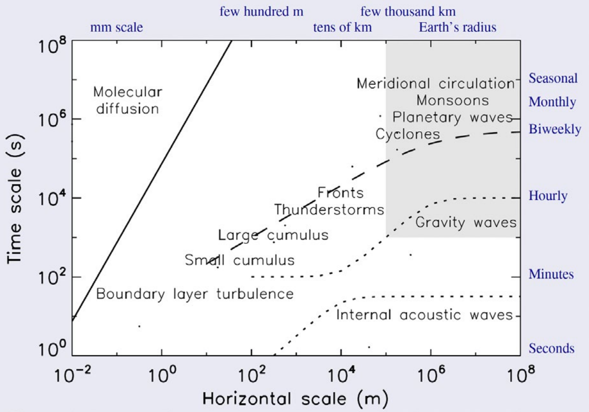
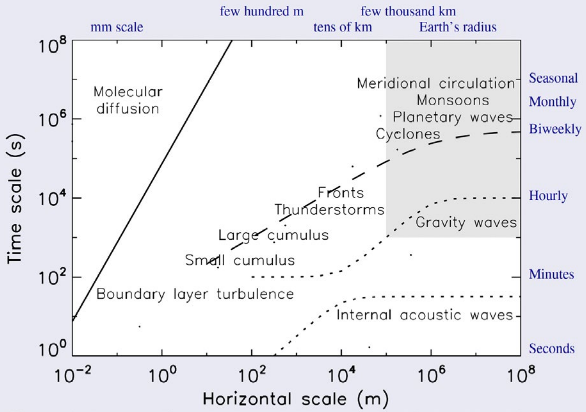



Figure from Thuburn (2011): Schematic depicting the time scales and horizontal scales of a range of atmospheric phenomena.

- O($10^4$ km): large-scale circulations (Hadley circulation)
- O($10^4$ km): undulations in the jet stream and pressure patterns associated with the largest scale Rossby waves (called *planetary waves*)
- O($10^3$ km): cyclones and anticyclones
- O(10 km): the transition zones between relatively warm and cool air masses can collapse in scale to form fronts with widths of a few tens of km
- O($10^3$ km - 100 m): convection can be organized on a huge range of different scales (tropical intraseasonal oscillations; supercell complexes and squall lines; individual small cumulus clouds formed from turbulent boundary layer eddies)

# Multi-scale nature of atmospheric dynamics (from Thuburn 2011)




- ❑ All phenomena along the dashed line are important for weather and climate, and so need to be represented in numerical models
- ❑ Important phenomena occur at all scales – there is no significant spectral gap! Moreover there are strong interactions between phenomena at different scales, and these interaction need to be represented
- ❑ The lack any spectral gap makes the modeling of weather and climate very challenging

- ❑ O($10^4$ km): large-scale circulations (Hadley circulation)
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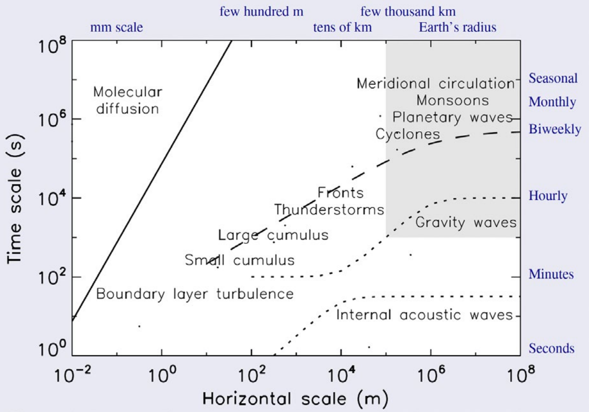


- Two dotted curves correspond to dispersion relations for internal inertio-gravity waves and internal acoustic waves (fast processes)
- these lines lie significantly below the energetically dominant processes on the dashed line
  - they are energetically weak compared to the dominant processes along the dashed curve
  - we do relatively little damage if we distort their propagation
  - the fact that these waves are fast puts constraints on the size of dt (at least for explicit and semi-implicit time-stepping schemes)!

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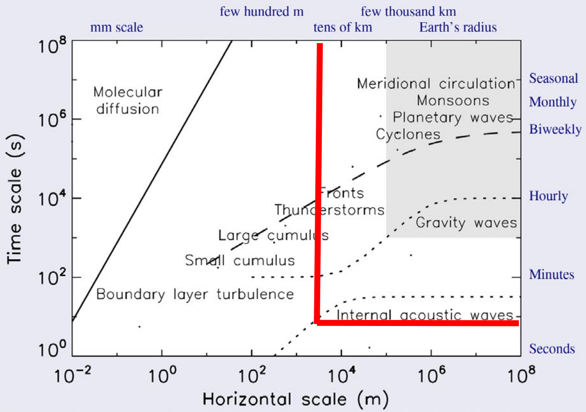


Horizontal Resolution

- the shaded region shows the resolved space/time scales in typical current day climate models (approximately 1˚– 2˚ resolution)
- we develop CAM at 1˚ resolution, but it has been ran down to ~3 km using the MPAS non-hydrostatic dycore
- as the resolution is increased some `large-scale' parameterizations may no longer be necessary (e.g., deep convection) and we might need to redesign some parameterizations that were developed for horizontal resolutions of hundreds of km's

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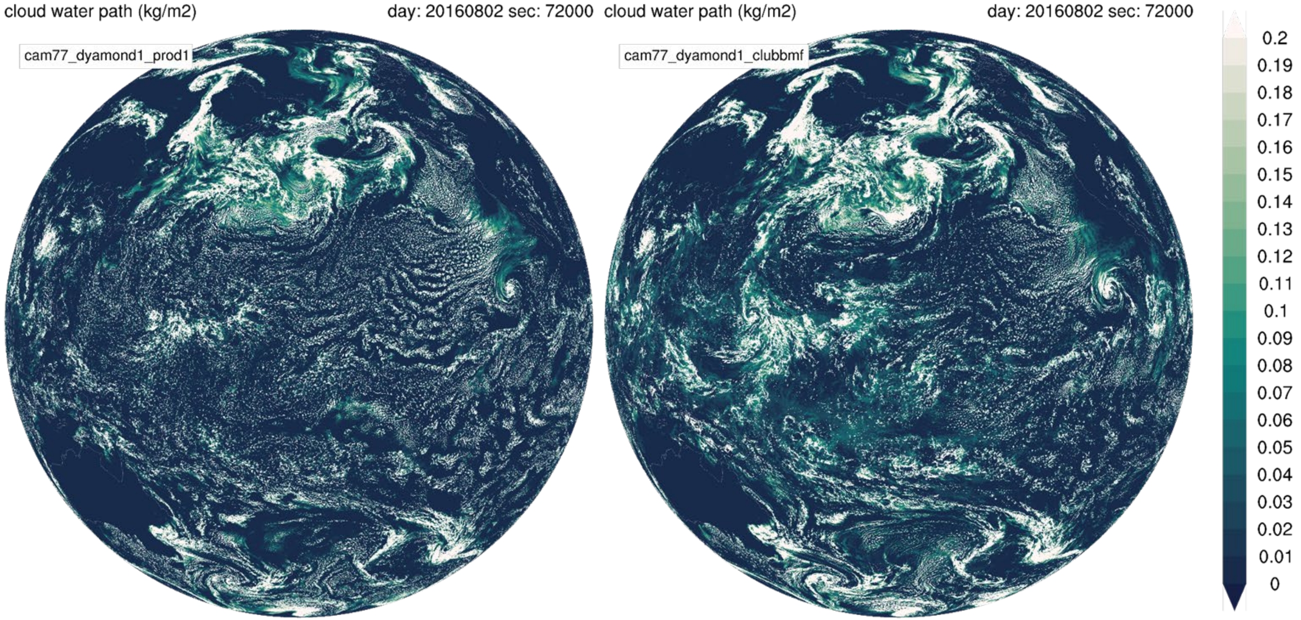
# Do we still need to parameterize cumulus convection at ~3 km grid spacing?

CAM-MPAS simulations (3.75 km grid spacing, 58 vertical levels)

- ❑ With the 'deep convection' scheme off (left), the model struggles to simulate convective transitions (shallow cumulus → congestus → cumulonimbus), and instead produces 'sprinkles' of deep convection in most places
- ❑ Adding parameterized convection (right) produces a more realistic spectrum of cloud types



# Designing a GCM– Scope

What is the scope?

- ❑ NWP? Climate?
- ❑ Meteorological processes:
  - ❑ Planetary waves?
  - ❑ Extratropical storms?
  - ❑ Squall lines?
  - ❑ Tropical cyclones?
  - ❑ Supercells?
- ❑ Chemistry? Stratosphere? Space Weather?

These choices constrain the scales that need to be resolved by the dynamical core, which may require different **equation sets** (e.g., non-hydrostatic, deep atmosphere) and prognostic variables

# Designing a GCM: common large-scale model assumptions

The following approximations are made to the compressible Euler equations:

- **spherical geoid**: geopotential $\Phi$ is only a function of radial distance from the center of the Earth $r$: $\Phi = \Phi(r)$ (for planet Earth the true gravitational acceleration is much stronger than the centrifugal force).
  $\Rightarrow$ Effective gravity acts only in radial direction
- **quasi-hydrostatic approximation** (also simply referred to as *hydrostatic approximation*): Involves ignoring the acceleration term in the vertical component of the momentum equations so that it reads:
  $$\rho g = -\frac{\partial p}{\partial z}, \quad (1)$$
  where $g$ gravity, $\rho$ density and $p$ pressure. Good approximation down to horizontal scales greater than approximately $10km$.
- **shallow atmosphere**: a collection of approximations. Coriolis terms involving the horizontal components of $\Omega$ are neglected ($\Omega$ is angular velocity), factors $1/r$ are replaced with $1/a$ where $a$ is the mean radius of the Earth and certain other metric terms are neglected so that the system retains conservation laws for energy and angular momentum.

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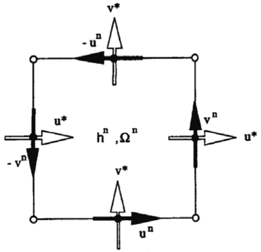
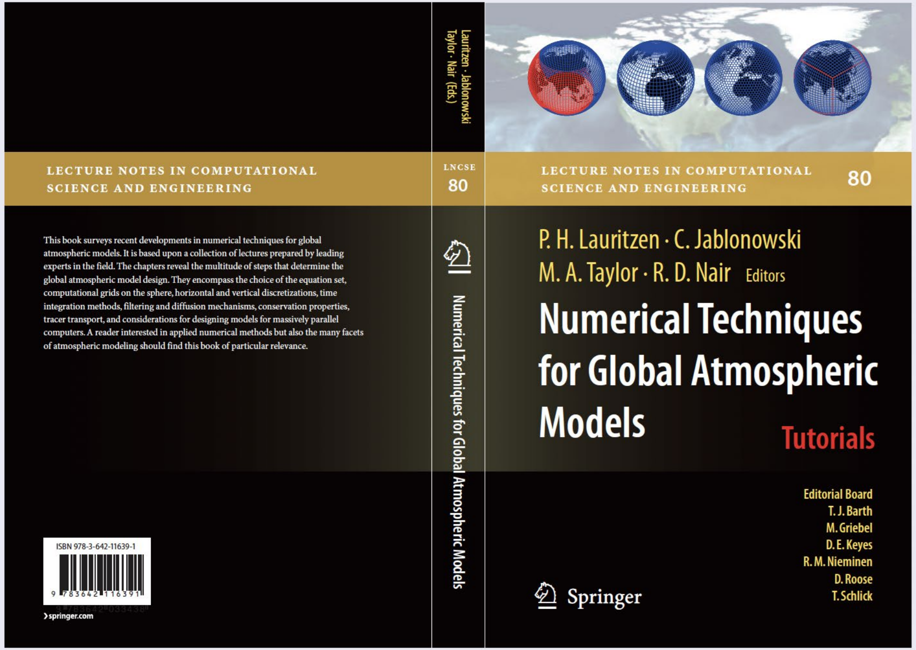
Other dynamical core design considerations:



- Vertical Coordinate
- Grid type, discretization method, order of accuracy, arrangement of variables
- Mass and energy conservation
- Tracer transport properties – shape preservation, preserves linear correlations, scalability

# Interested in numerical methods for global models?




- ❑ Book based on the lectures given at the 2008 NCAR ASP (Advance Study Program) Summer Colloquium
- ❑ 16 Chapters; authors include J.Thuburn, J.Tribbia, D.Durran, T.Ringler, W.Skamarock, R.Rood, J.Dennis, Editors, ….Foreword by D. Randall

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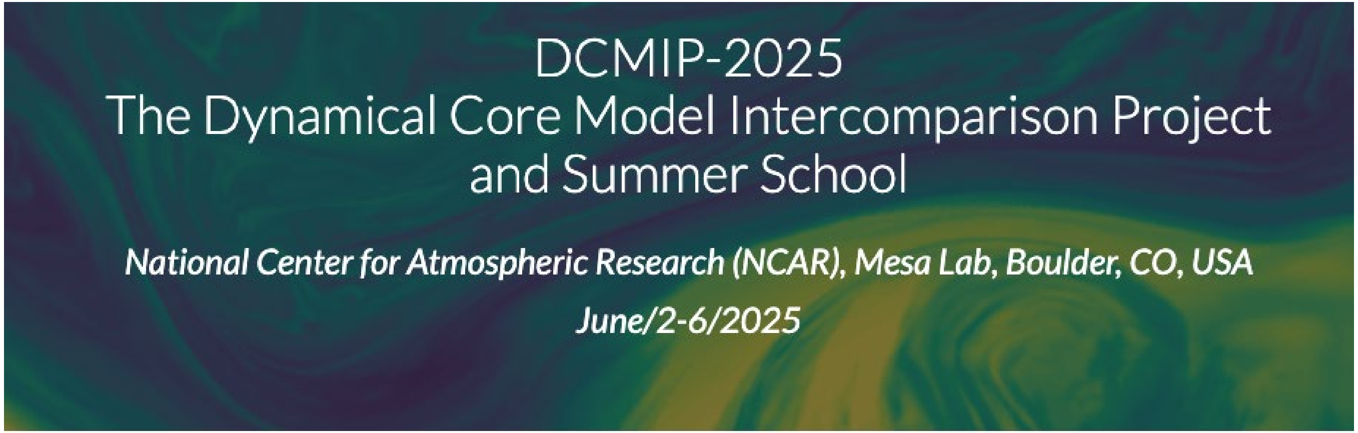
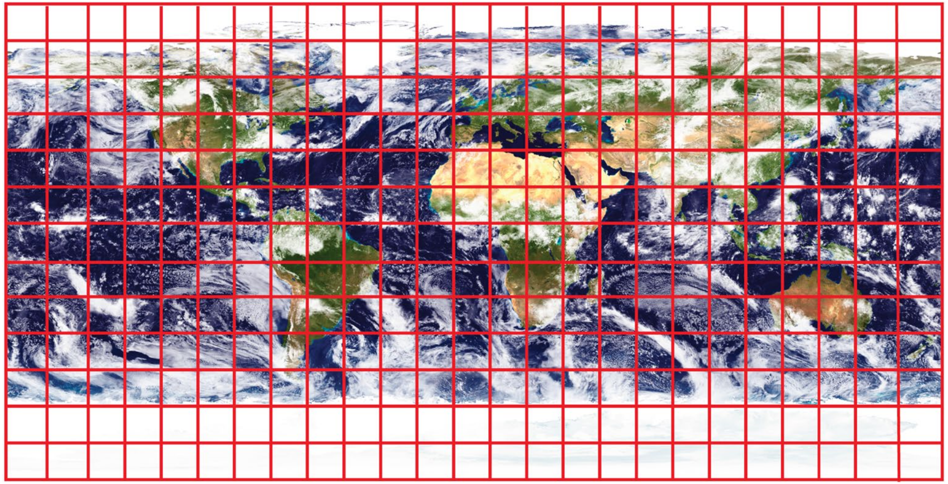



## The DCMIP-2025 Vision

*The DCMIP-2025 summer school surveys the design decisions in atmospheric General Circulation Models (GCMs) with a focus on their dynamical cores and takes a unique look at Machine Learning emulators for GCMs. DCMIP is built upon lectures, hands-on dynamical core & ML modeling projects, shared cyberinfrastructure, and computational tools that utilize the Community Earth System Model (CESM) from NCAR.*

All talks available in dcmip.org and recordings on YouTube!

# Dynamical core



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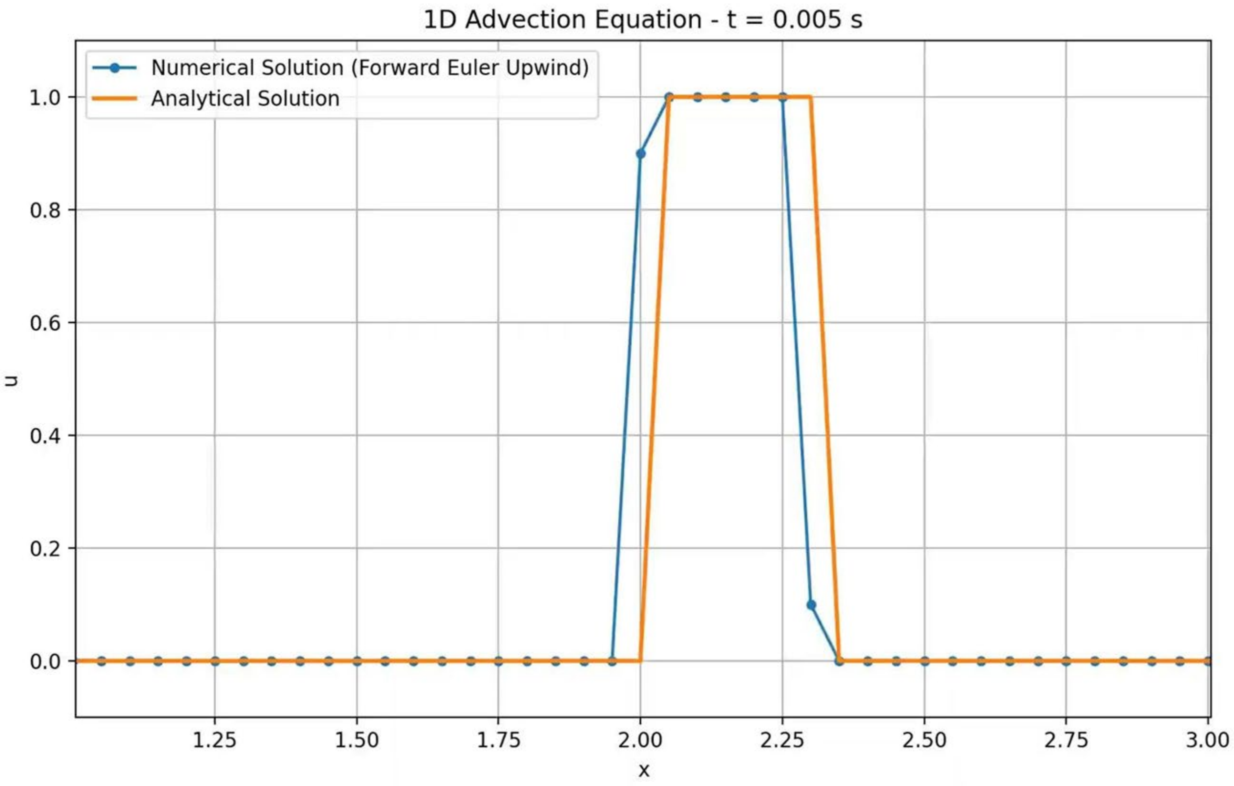
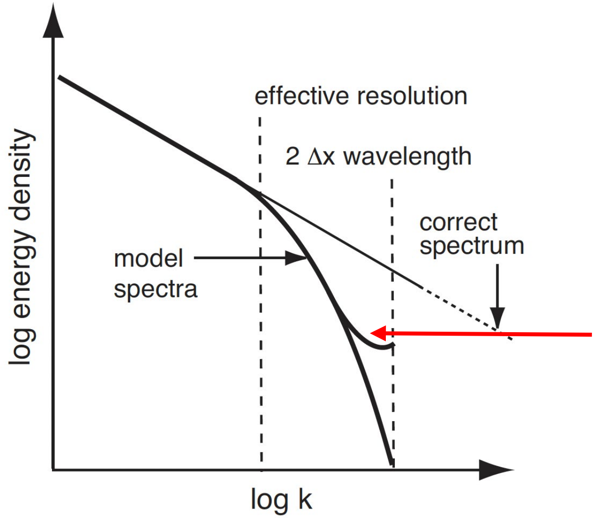
# Numerical errors in the dynamical core



# Effective Resolution: smallest scale ( highest wavenumber $k = k_{eff}$ ) that a model can accurately represent

- ❑ $k_{eff}$ can be assessed analytically for linearized equations (Von Neumann analysis)
- ❑ In a full model, once can assess $k_{eff}$ using the kinetic energy of, e.g., the horizontal wind (see below).

Effective resolution is typically 4-10 times the grid spacing, depending on numerical method




Fall-off in energy at the grid-scale due to scale-selective numerical filters in dycore

Figure from Skamarock (2011): Schematic depicting the possible behavior of spectral tails from model forecasts

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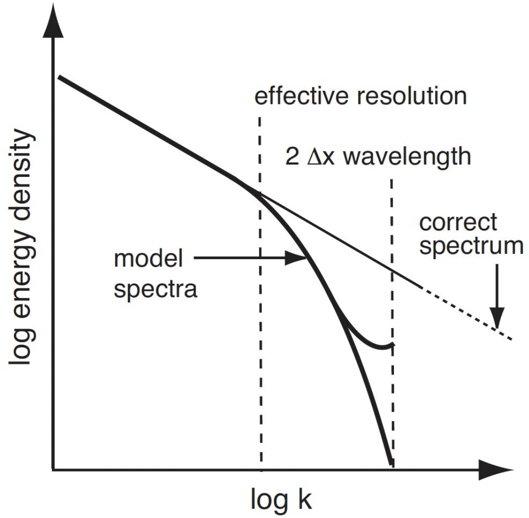


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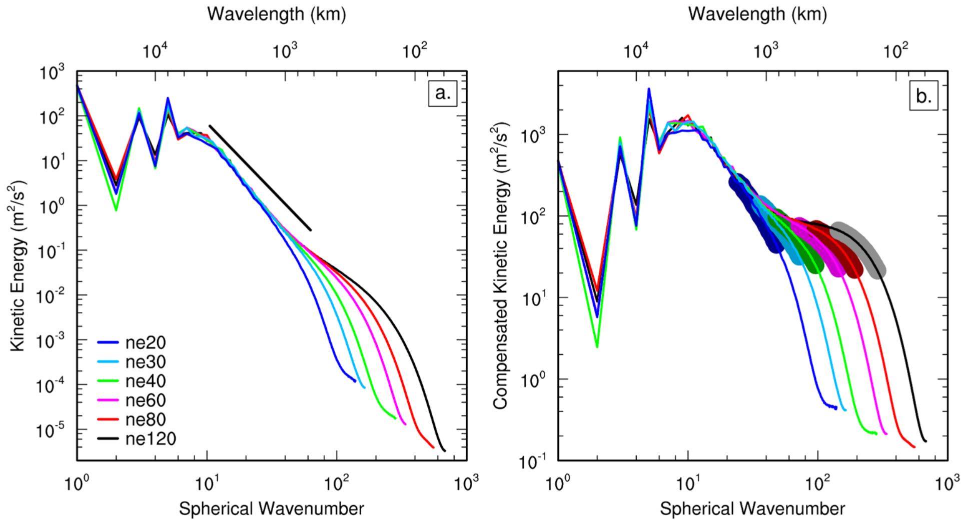


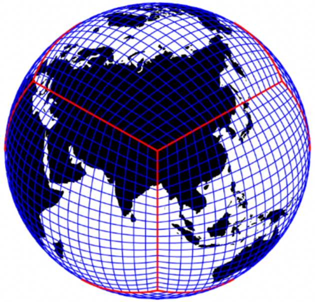

Figure from Herrington and Reed. 2020: Kinetic energy spectrum (left) and compensated kinetic energy spectrum (right) at the 200-hPa level in the simulations

# CAM’s dycores

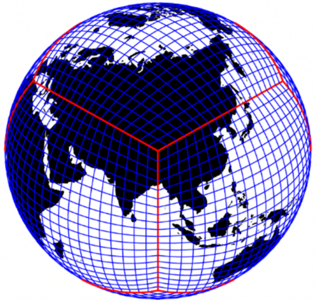
Eulerian Spectral Transform (EUL)

Finite-Volume (FV)

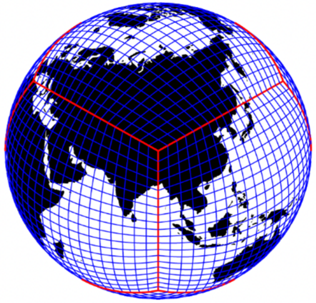
Finite-Volume Cubed-Sphere (FV3)



Spectral-Element CSLAM (SE-CSLAM)



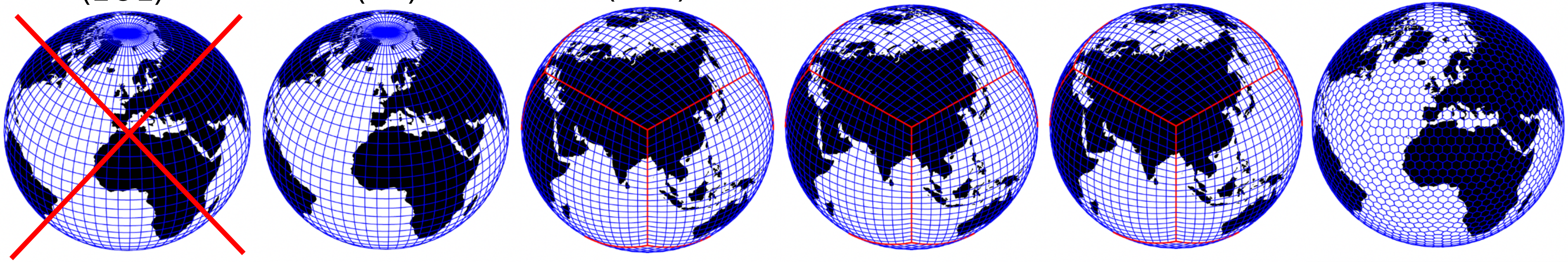
Spectral-Element Non-Hydrostatic (SE-NH)



Model for Prediction Across Scales (MPAS)

# CAM's dycores

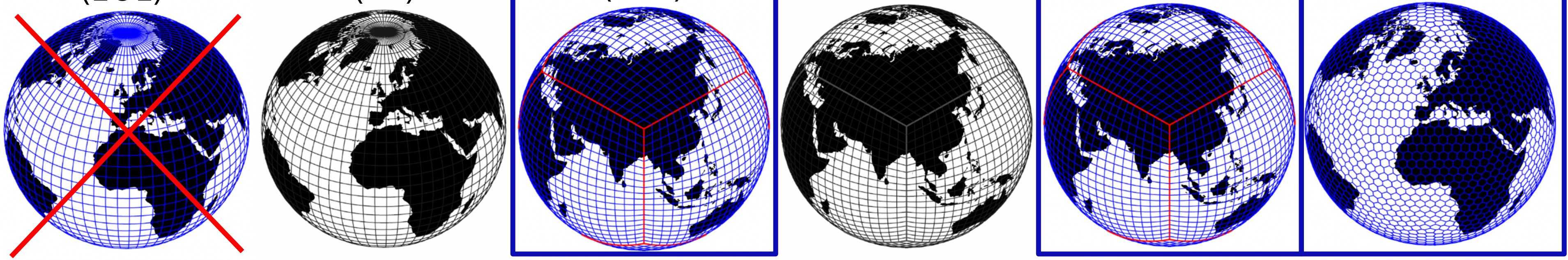
Eulerian Spectral Transform (EUL) | Finite-Volume (FV) | Finite-Volume Cubed-Sphere (FV3) | Spectral-Element CSLAM (SE-CSLAM) | Spectral-Element Non-Hydrostatic (SE-NH) | Model for Prediction Across Scales (MPAS)



The EUL dycore was decommissioned earlier this year

# CAM's non-hydrostatic dycores

| Eulerian Spectral Transform (EUL) | Finite-Volume (FV) | Finite-Volume Cubed-Sphere (FV3) | Spectral-Element CSLAM (SE-CSLAM) | Spectral-Element Non-Hydrostatic (SE-NH) | Model for Prediction Across Scales (MPAS) |
| --- | --- | --- | --- | --- | --- |

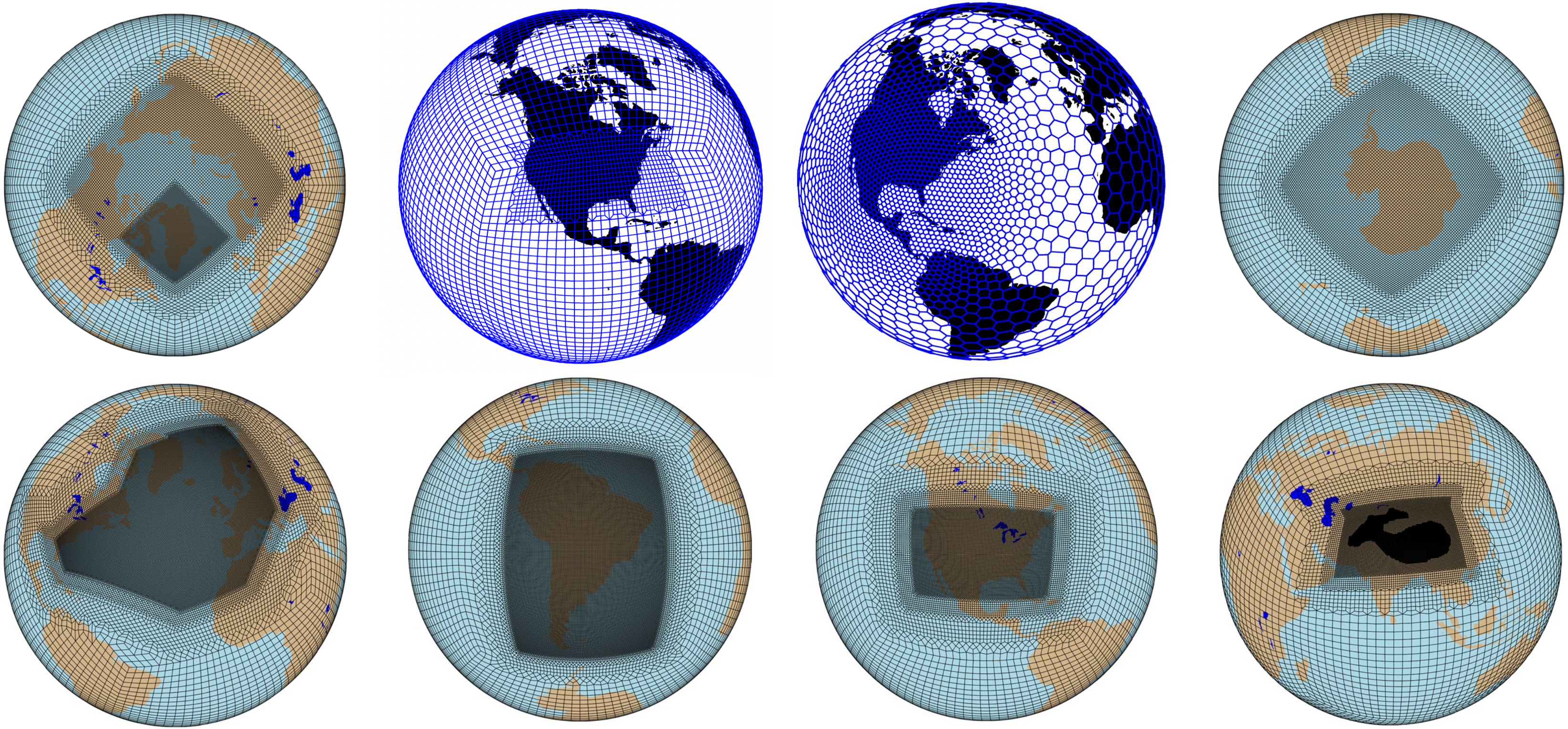


- ❑ CAM has three dycores based on non-hydrostatic equation sets
- ❑ Scale analysis indicates non-hydro req'd for length scales O(10 km) and less (k→m)
  (e.g., Wedi and Smolarkiewicz, 2009)

# Mesh refinement

See Adam Herrington's talk on Friday!

SE, MPAS & FV3 support mesh refinement



# CAM model tops

The vertical extent is from the surface to:

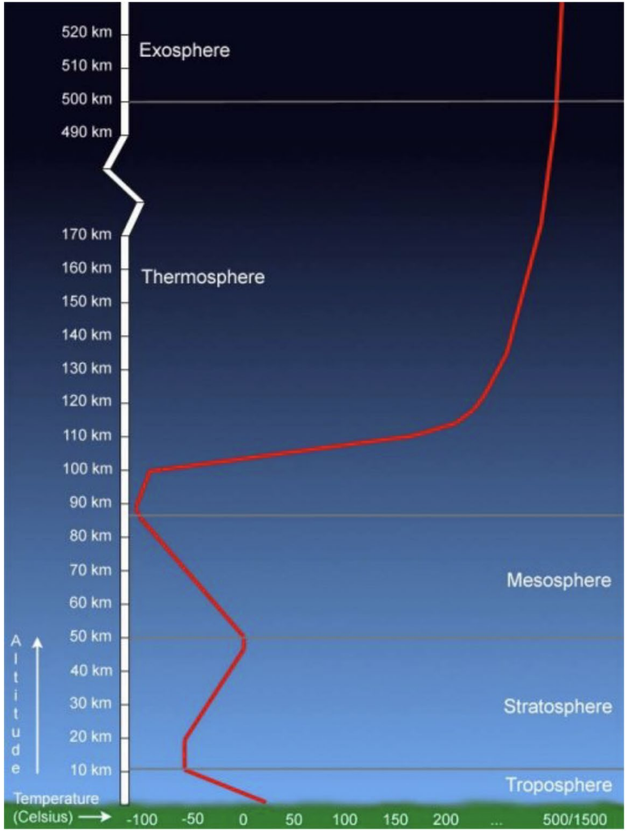
- approximately 42 km / 2 hPa
- approximately 140 km /$10^{-6}$ hPa for WACCM6 (Whole Atmosphere Community Climate Model)
- approximately 600 km / $10^{-9}$ hPa for WACCM-X

Note:

For CAM7 we introduced a mid-top version with 93 vertical levels and model top at 80 km, in addition to a low-top version with 58 levels and 40 km top

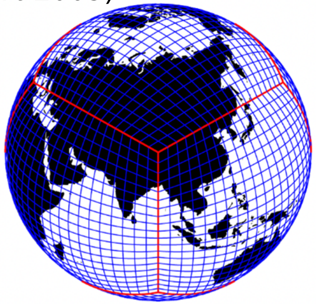
Viscous sponge layer

In practice, GCMs need additional damping in the top few levels of the model to prevent wave reflections off the model top

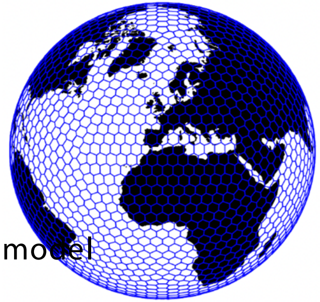


# CAM’s non-hydrostatic dycores

- SE-NH
  - Dynamical core based on HOMME (High-Order Method Modeling Environment; Thomas and Loft 2005)
  - Cubed-sphere tiled with quadrilateral elements; fourth order basis set within each element
  - Reformulated with non-hydrostatic equation set (Taylor et al. 2019)
  - Efficient semi-Lagrangian tracer transport (Bradley et al. 2022)
  - Physics evaluated on separate finite-volume grid (Hannah et al. 2021)
  - Mass conservation to machine precision and good total energy conservation properties

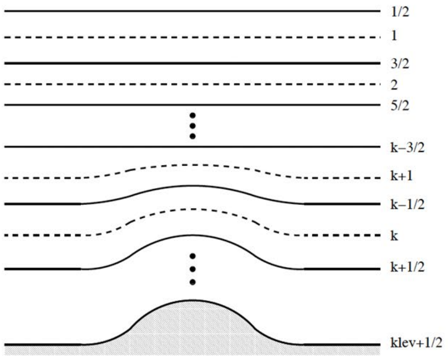


- FV3
  - Cubed-sphere version of FV
  - Flux-form semi-Lagrangian advection on staggered ‘CD’ grid (Lin and Rood 1997)
  - https://www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/
- MPAS
  - Centroidal Voronoi tessellation of the sphere (hexagons)
  - Finite-volume discretization on staggered C-grid
  - Fully compressible non-hydrostatic discretization similar to Weather Research Forecast (WRF) model (Skamarock and Klemp 2009)
  - Height-based terrain-following vertical coordinate (Klemp 2011)
  - Coupled to CAM physics’ pressure-based vertical coordinate (Huang et al. 2022)



# Vertical coordinate: hybrid sigma ($\sigma = p/p_s$)-pressure (p) coordinate

- FV, FV3, SE use a hybrid sigma-pressure vertical coordinate ($\boldsymbol{\eta}$)




*Sigma layers at the bottom (following terrain) with isobaric (pressure) layers aloft.*

- Pressure at model level interfaces:

$$p_{k+½} = A_{k+½}\, p_0 + B_{k+½}\, p_s$$

- where $p_s$ is the surface pressure, $p_0$ is a reference pressure, and $A_{k+½}$ and $B_{k+½}$ are hybrid coefficients (in model code: hyai and hybi). Similarly for model level mid-points.

Note. The vertical index is 1 at the model top, and *klev* at the surface

# Vertically Lagrangian floating coordinate (Lin 2004)

- FV, FV3, SE use a Lagrangian ('floating') vertical coordinate such that

$$\frac{d\xi}{dt} = 0,$$

i.e., vertical surfaces are material surfaces (no flow across them)

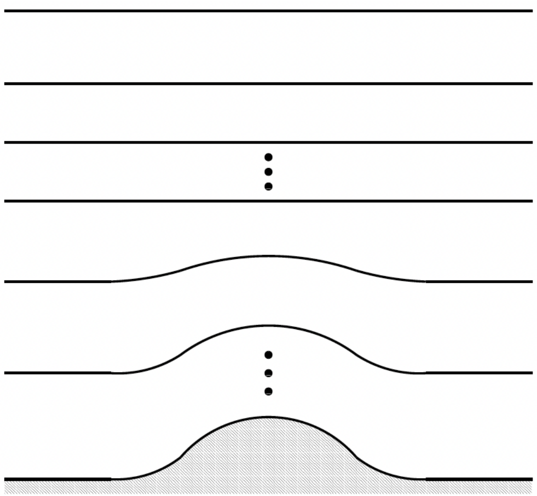


Figure shows 'usual' hybrid $\sigma - p$ vertical coordinate $\eta(p_s, p)$ (where $p_s$ is surface pressure):

- $\eta(p_s, p)$ is a monotonic function of $p$.
- $\eta(p_s, p_s) = 1$
- $\eta(p_s, 0) = 0$
- $\eta(p_s, p_{top}) = \eta_{top}$.

Boundary conditions are:

- $\frac{d\eta(p_s, p_s)}{dt} = 0$
- $\frac{d\eta(p_s, p_{top})}{dt} = \omega(p_{top}) = 0$

($\omega$ is vertical velocity in pressure coordinates)

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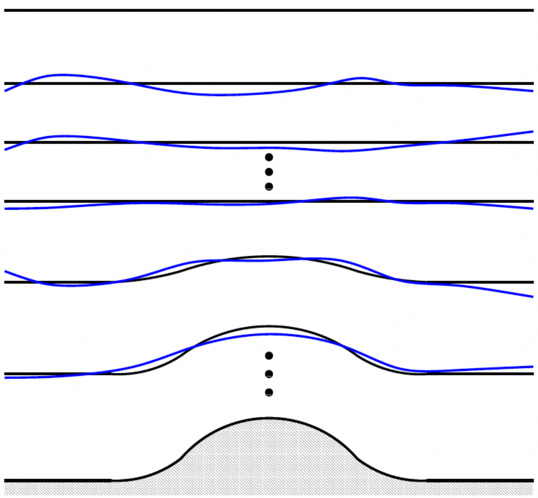


Figure:

- set $\xi = \eta$ at time $t_{start}$ (black lines).
- for $t > t_{start}$ the vertical levels deform as they move with the flow (blue lines).
- to avoid excessive deformation of the vertical levels (non-uniform vertical resolution) the prognostic variables defined in the Lagrangian layers $\xi$ are periodically remapped (= conservative interpolation) back to the Eulerian reference coordinates $\eta$ (more on this later).

**Why use floating Lagrangian vertical coordinates?** Vertical advection terms disappear (3D model becomes 'stacked shallow-water models'; only 2D numerical methods are needed)

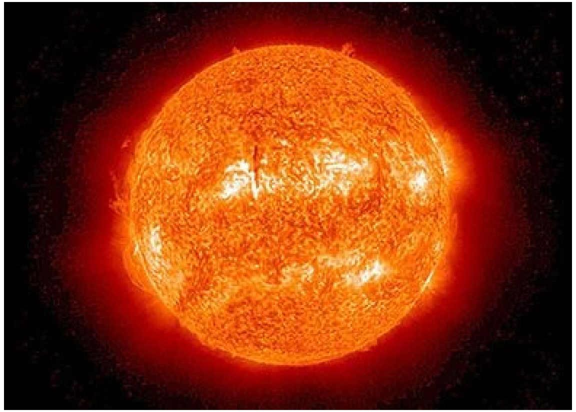
# What's in a physics suite?

See "Atmosphere Modeling II: Parameterizations" talk this PM

Christina McCluskey, Meg Fowler and Ben Stephens

A physics suite contains several processes:

- ❏ Radiation
- ❏ PBL scheme (turbulent fluxes, surface drag)
- ❏ PBL form drag due to sub-grid orography
- ❏ Gravity-wave drag (convection, orography)
- ❏ Cumulus convection (separate schemes for shallow and deep convection)
- ❏ *Stratiform macro- and micro-physics
- ❏ Aerosol physics
- ❏ Chemistry



The specific choice of processes represented, and what scheme is used to represent a process depends on the scope of the model

*Performs the saturation adjustment, which is instantaneous and therefore the fastest process in the model. Historically, the state after the saturation adjustment is considered to be the most realistic atmospheric state in the time-loop.