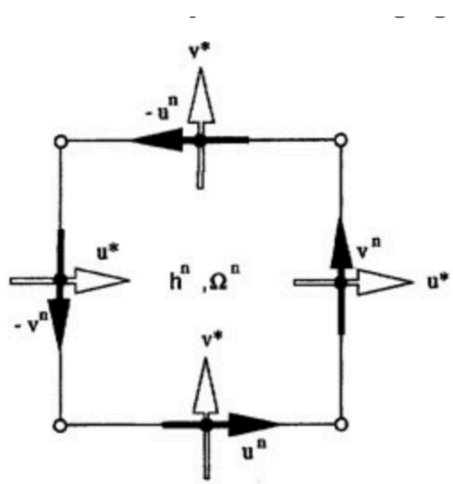
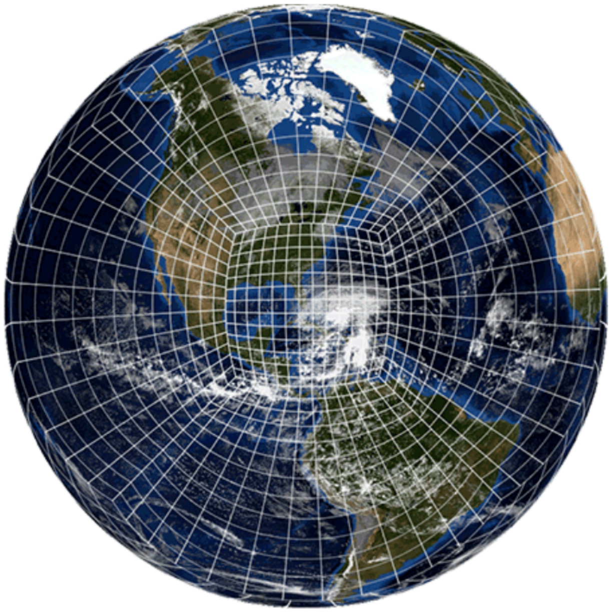
AN INTRODUCTION TO THE FV3 DYNAMICAL CORE

Timothy Chui

Mar. 24, 2020

https://www.gfdl.noaa.gov/fv3/





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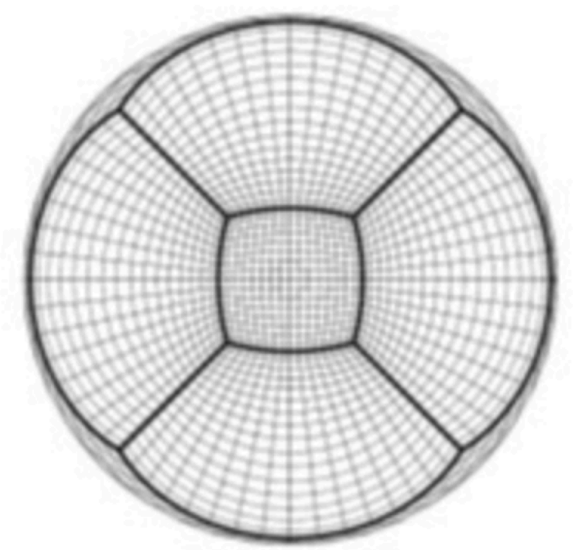
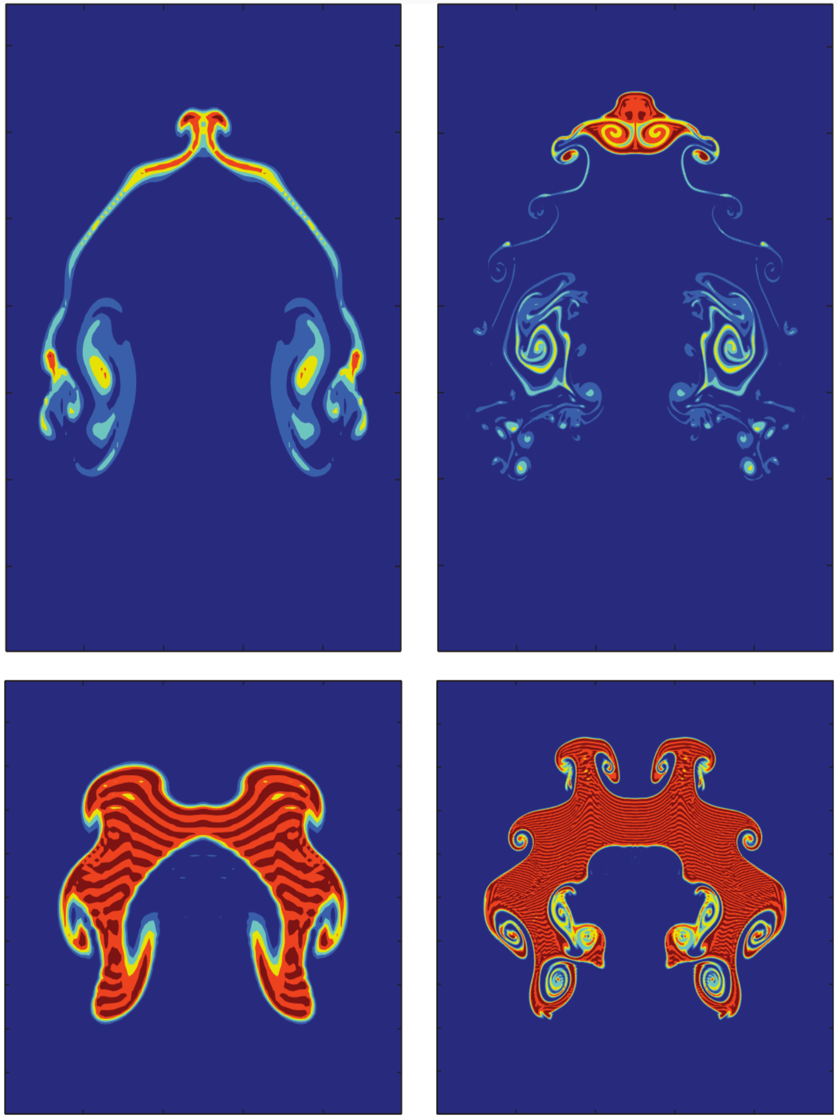


https://www.gfdl.noaa.gov/fv3/fv3-grids/

Overview of FV3

- FV3 = Finite-Volume Cubed-Sphere Dynamical Core
- Developed from 1D/2D FV Core (Lin and Rood 1996)…
- … into a lat-lon model (Lin 2004)…
- …then finally a prototype 3-D cubed-sphere core (Putman and Lin 2007)



Chen et al. (2013)

Overview of FV3

- Developed and maintained by the Geophysical Fluid Dynamics Laboratory (GFDL), under NOAA

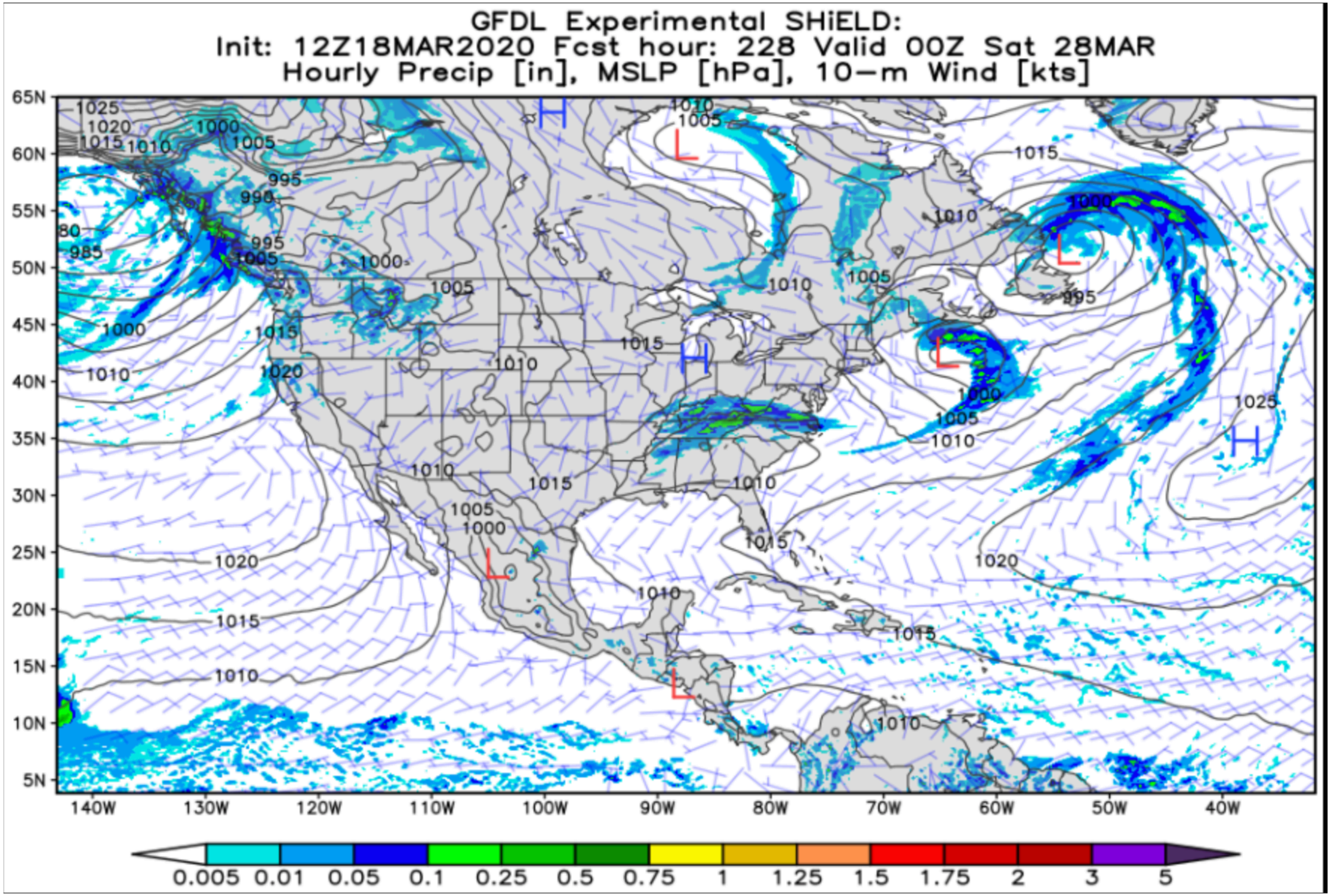
- Replaced the spectral core in the Global Forecast System (GFS) in June 2019

Overview of FV3

Model	Dy-core	Ocean model	Land Model	Physics* Modification from AM2
CM2.0/AM2.0	Arakawa B grid	MOM4	LM2	–
CM2.1/AM2.1	FV	MOM4	LM2	–
ESM2	FV	MOM4/with TOPAZ	LM3	–
CM2.5/FLOR	FV3	MOM5	LM3	–
CM3/AM3	FV3	MOM5	LM3	Donner conv.; Full Chemistry
CM4/AM4/SPEAR	FV3	MOM6	LM4	Double-plume UW conv.; Fast Aerosols; Garner topo drag
ESM4	FV3	MOM6/with COBALT	LM4	Double-plume UW conv.; Full Chemistry; Garner topo drag
HiRAM	FV3 with non-hydro option	–	LM3	UW conv.; GFDL MP
SHiELD (fvGFS)	Non-hydro FV3	Mixed-layer Ocean	NOAH	GFS Physics w/ GFDL MP and other revisions

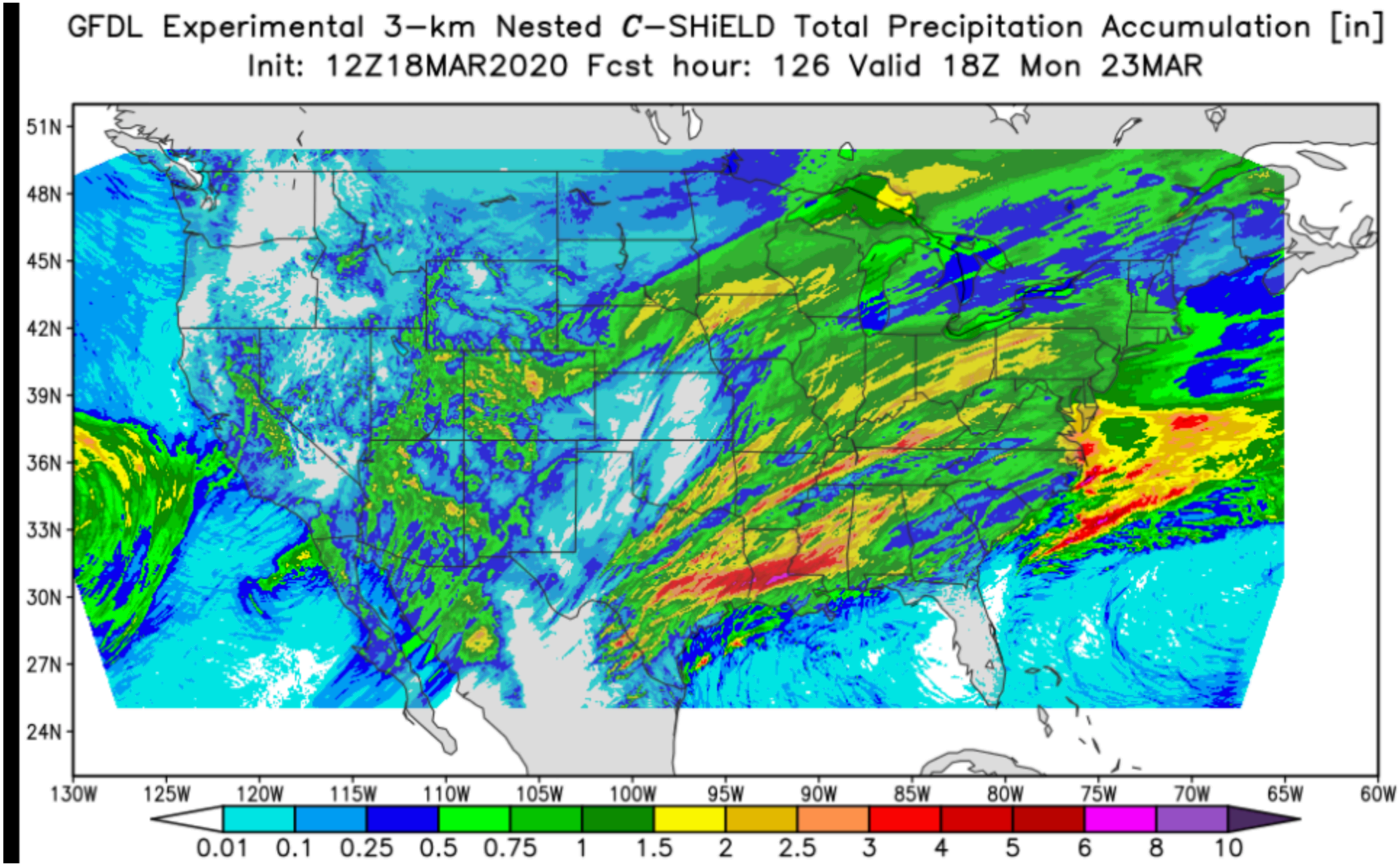
https://www.gfdl.noaa.gov/fv3/fv3-applications/

Overview of FV3



https://fvgfs.gfdl.noaa.gov/fvGFS_products.php?MODEL=2019v15G&YMDH=2020031812&Region=GoM&field=precip_slp_wind

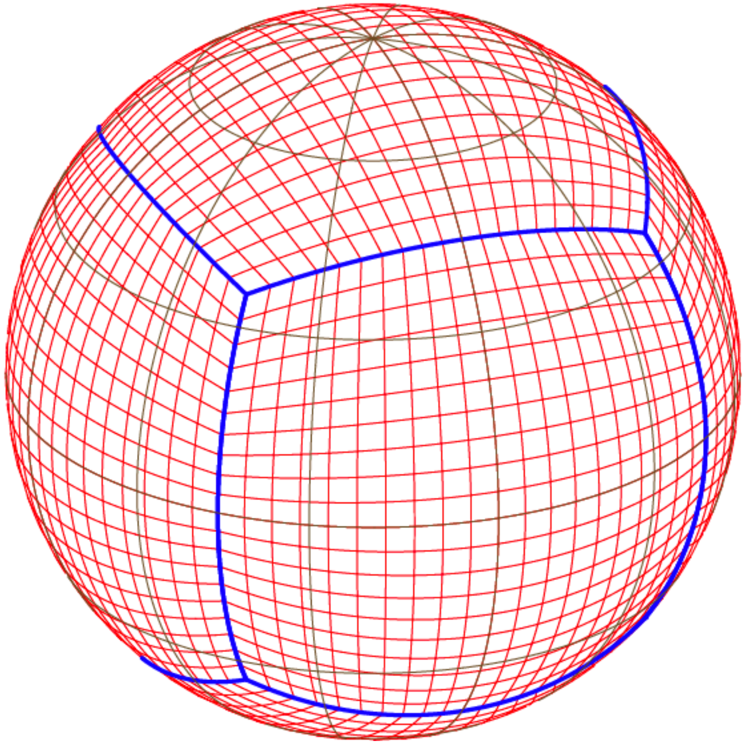
Overview of FV3



https://fvgfs.gfdl.noaa.gov/fvGFS_products.php?MODEL=C-SHiELD_FY2019&YMDH=2020031812&Region=CONUS&field=precip_accum

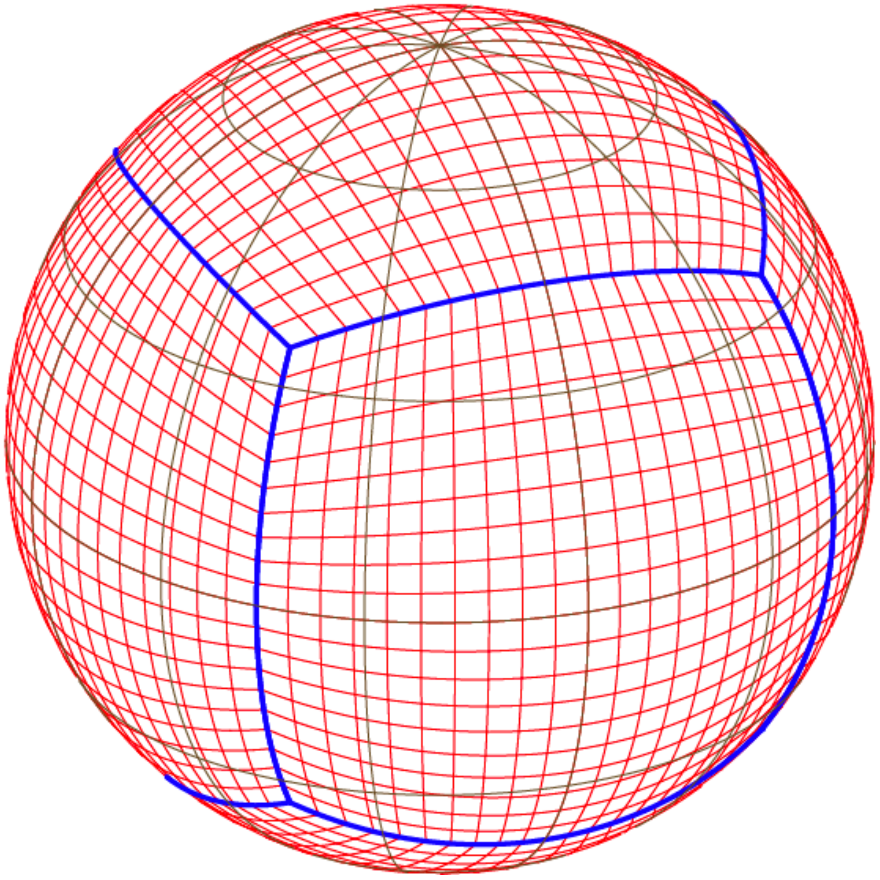
Overview of FV3

- **Philosophy**
  - Based on physical principles
  - Efficient and scalable
- **Mesh**
  - Cubed-sphere
- **Horizontal**
  - Flux-Form Semi-Lagrangian (FFSL)
  - Compressible
  - CD-grid
- **Vertical**
  - Lagrangian
  - Non-hydrostatic
- **Physics**
  - GFS + GFDL MP + YSU PBL



https://www.researchgate.net/figure/The-equiangular-gnomonic-cubed-sphere_fig1_319964216

Cubed-Sphere Mesh



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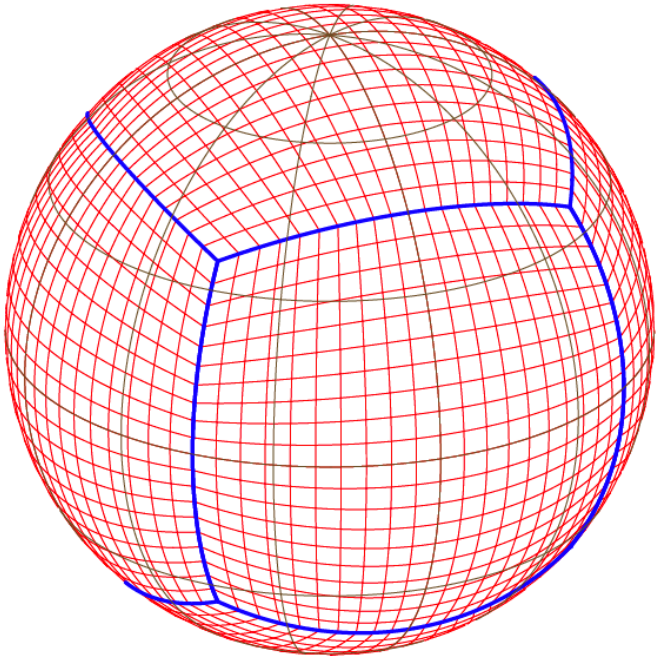
Cubed-Sphere Mesh

Comparison with Geodesic (ICON)/Voronoi (MPAS) Meshes

- Not as uniform (cell shapes/sizes can vary a lot more)
- Easier to apply higher-order FV schemes ("logically rectangular")
- Easier to support nesting



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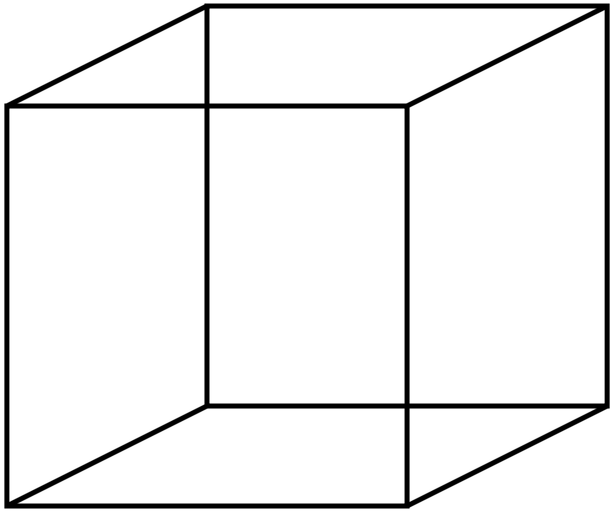

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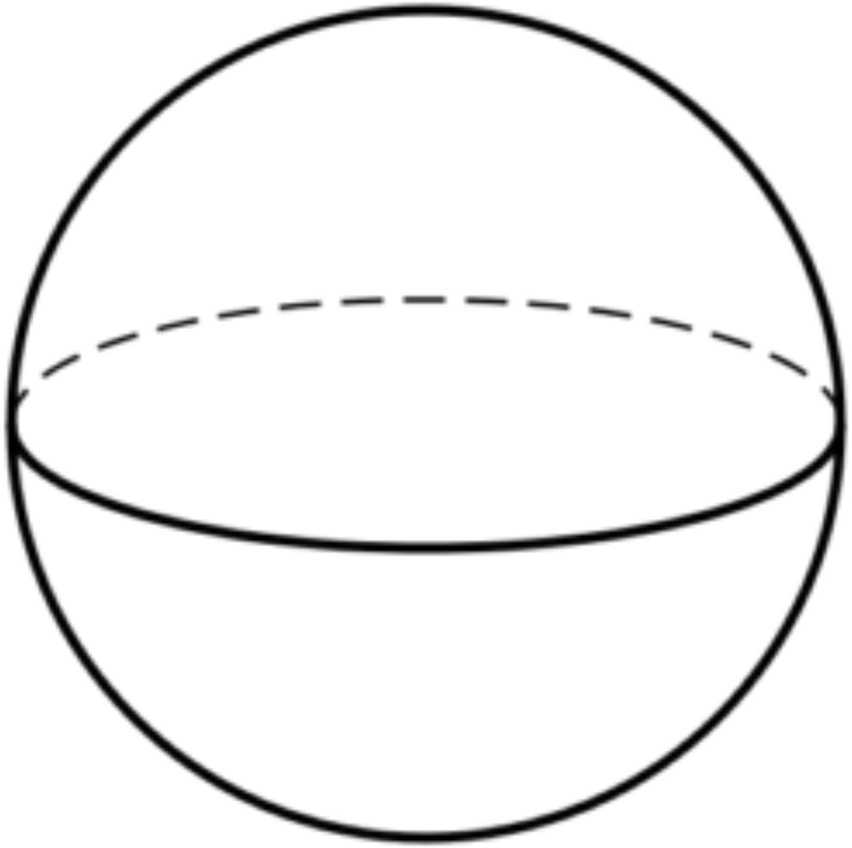

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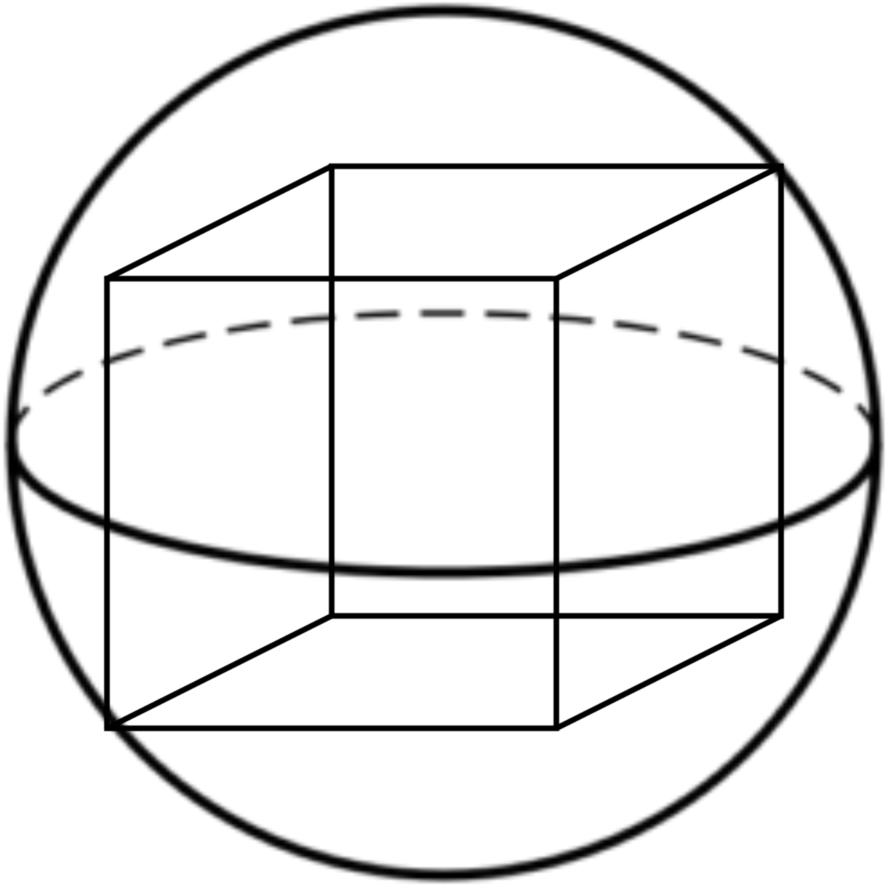
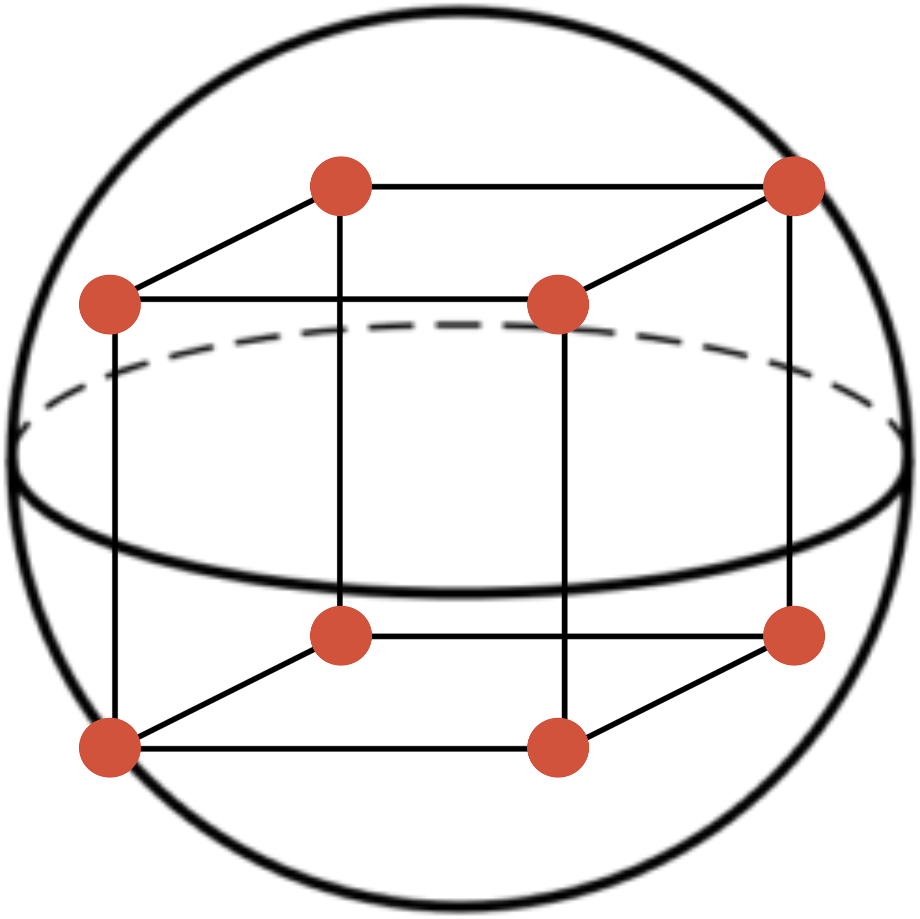


Cubed-Sphere Mesh

- Take a cube, and inscribe it in a sphere
- The vertices of the cube are in contact with the sphere; all other points on the cube are within the sphere
- Goal: map (project) all points of the cube onto the sphere



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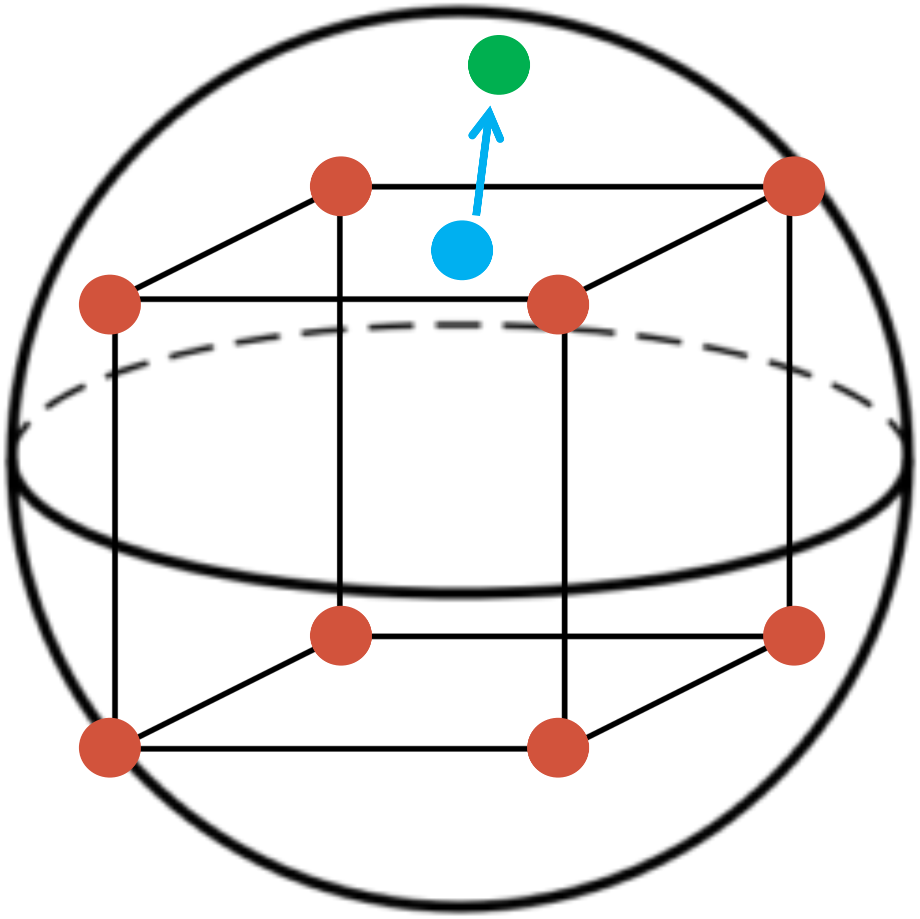

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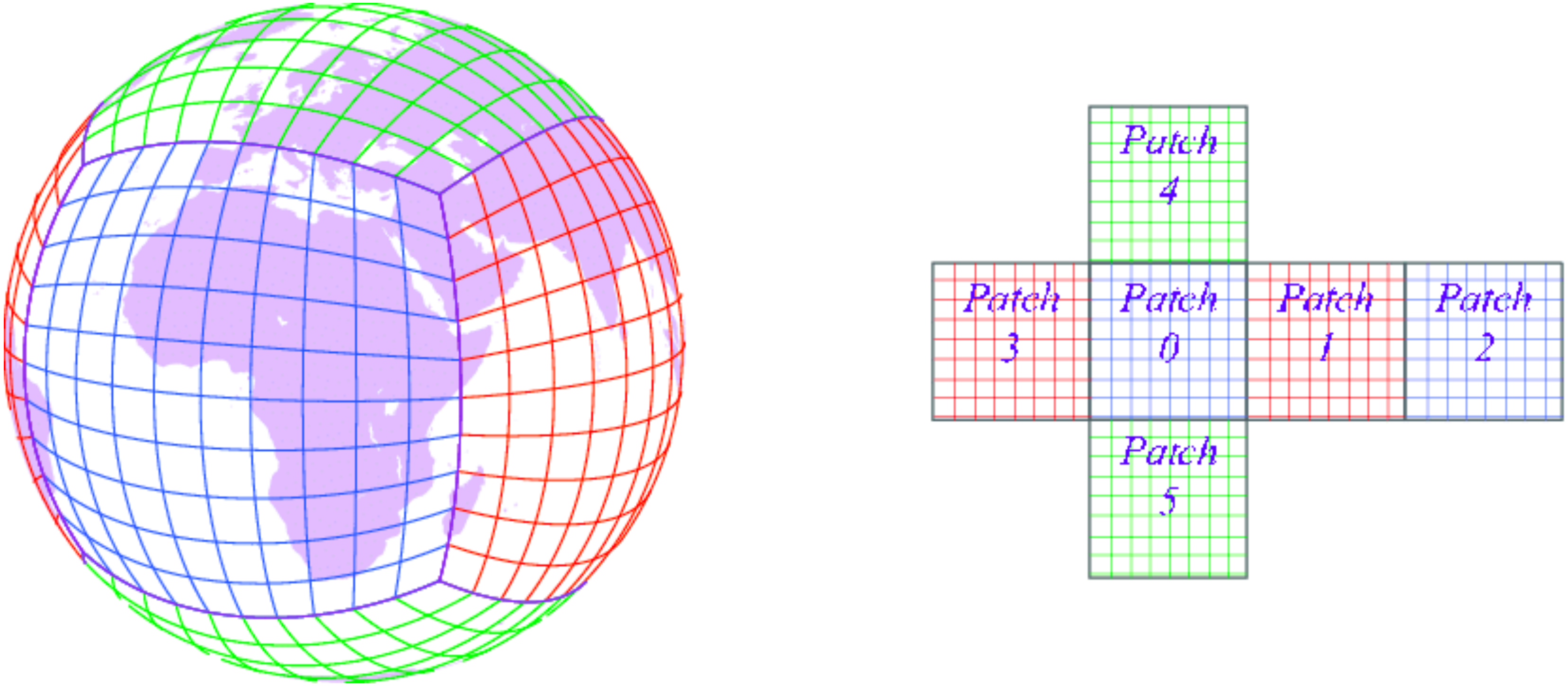

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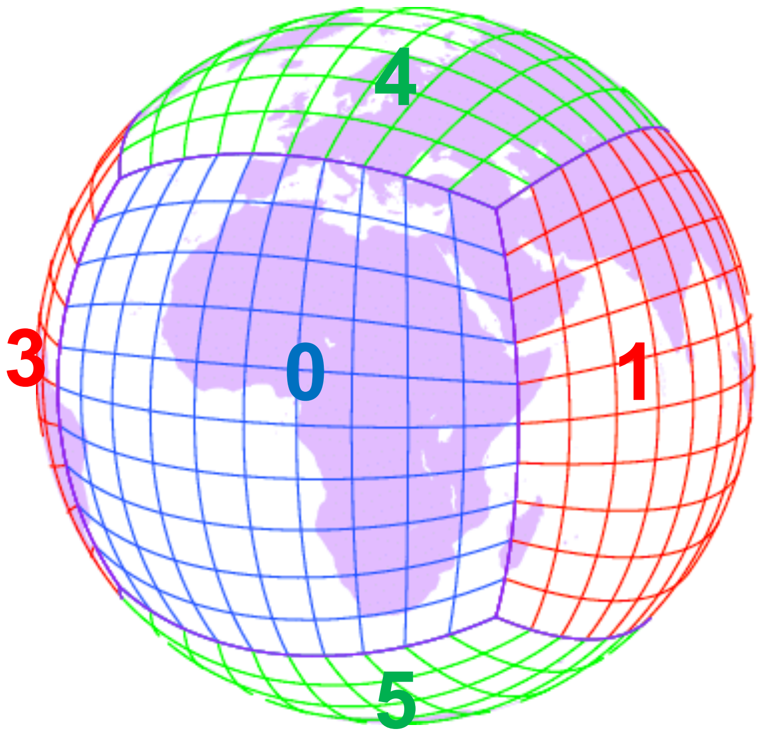

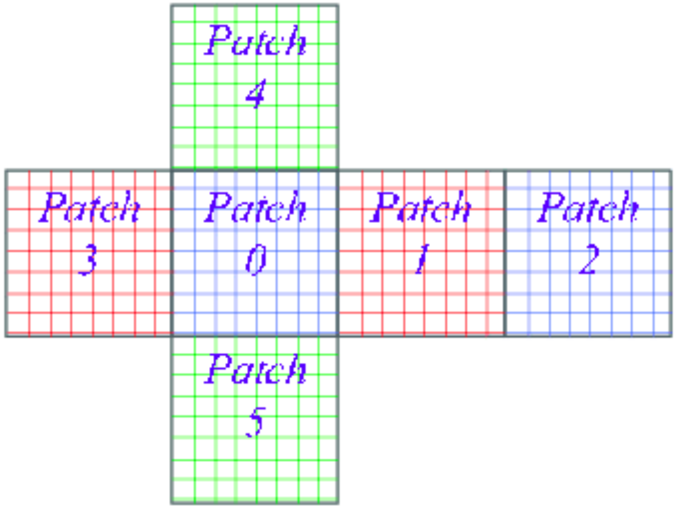

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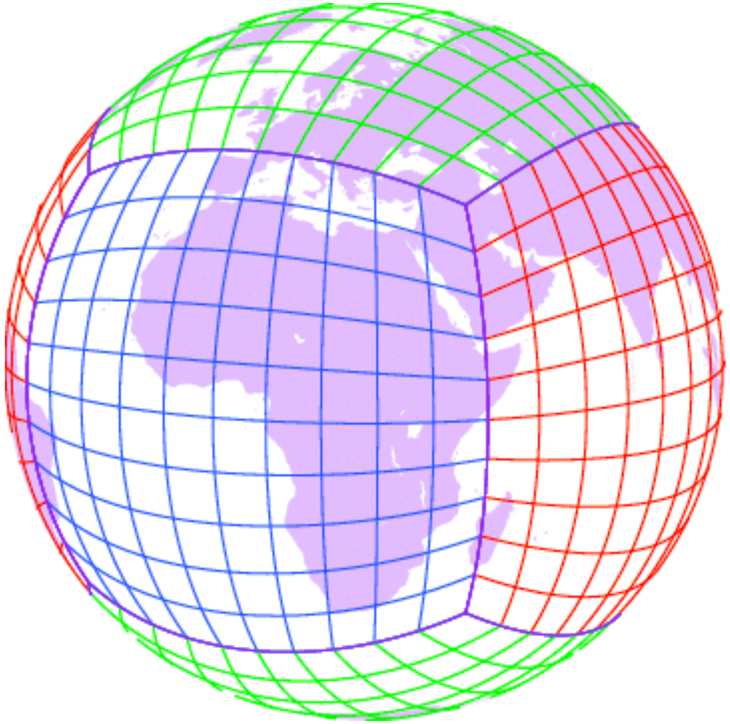


Mesh Descriptions

- Grid label: cM
  - M = # number of points along cubed-sphere edge
  - Total # of cells = M x M x 6
- Grid lengths (θ = latitude, λ = longitude):

$$\delta h = \sqrt{\sin^2\left(\frac{\theta_2 - \theta_1}{2}\right) + \cos\theta_1 \cos\theta_2 \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}$$

Cubed-Sphere Mesh

Cell Descriptions

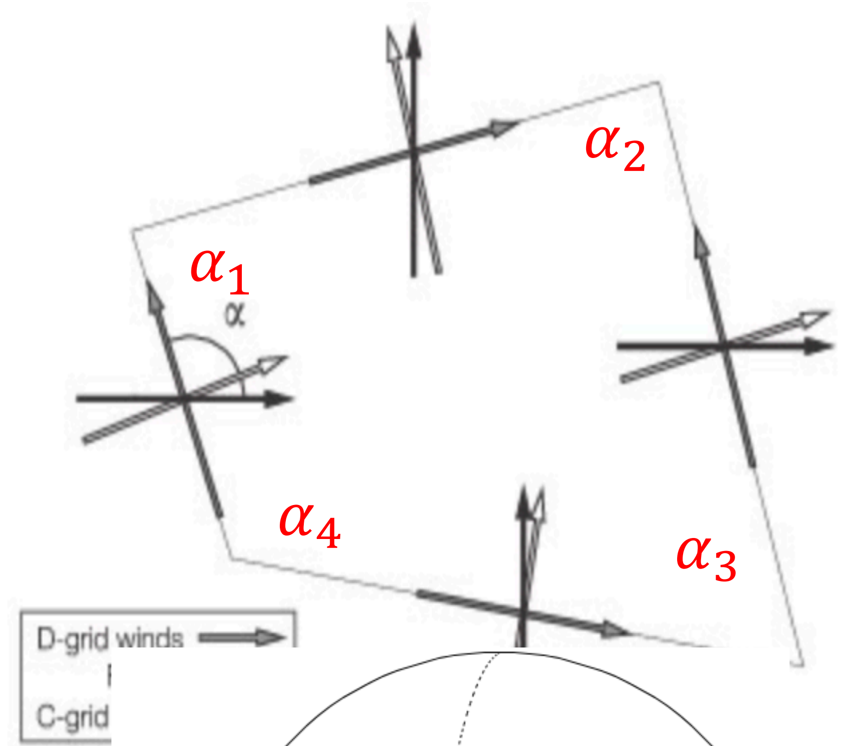
- Geometry defined by locations of vertices

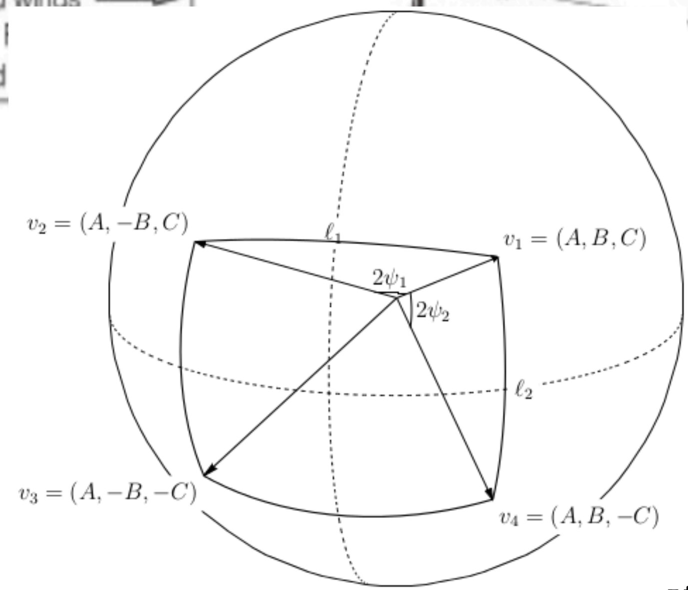
- Edges are great-circle arcs

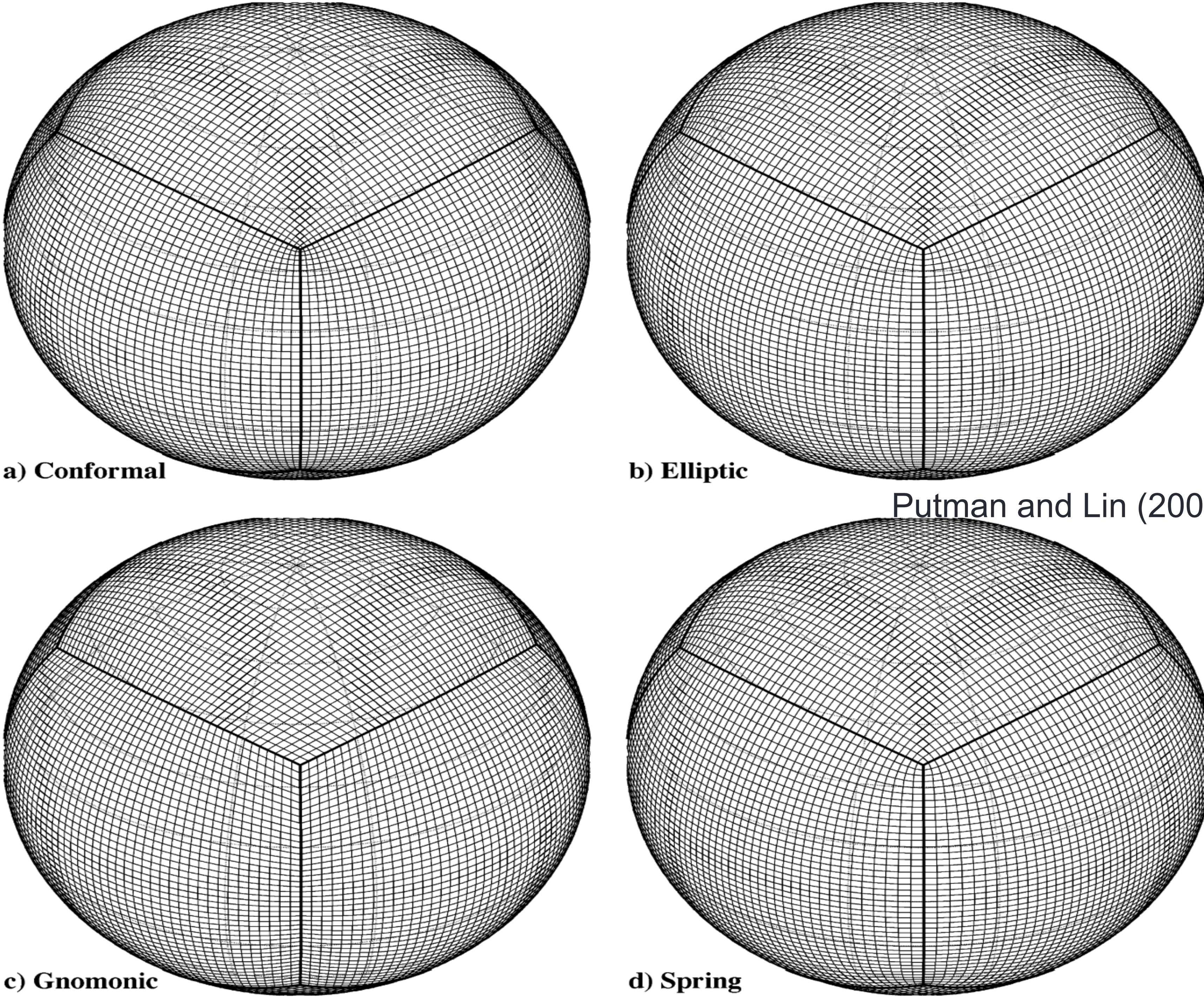
- Cell areas (from spherical excess):

$$\Delta A = R^2[\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 - 2\pi]$$

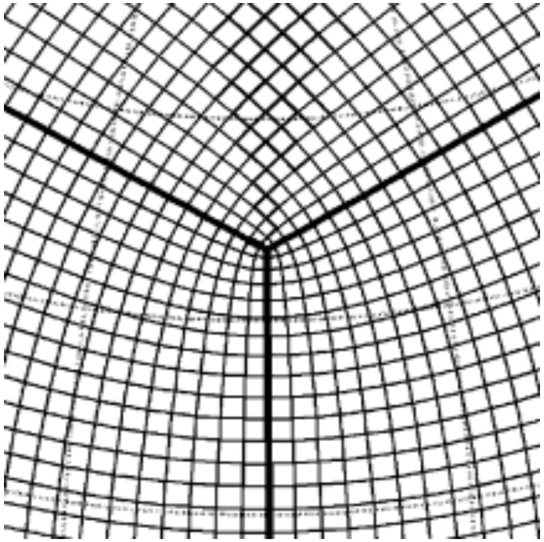
https://math.stackexchange.com/questions/1205927/how-to-calculate-the-area-covered-by-any-spherical-rectangle



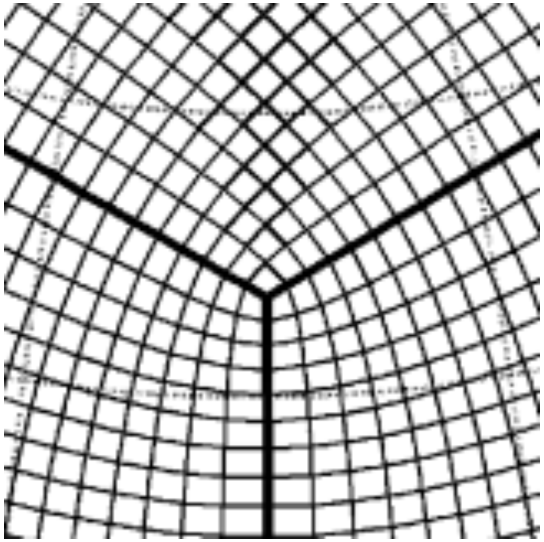




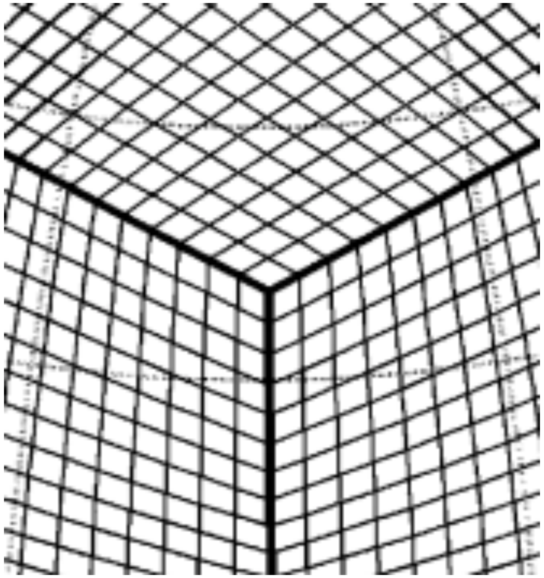
Putman and Lin (2007)



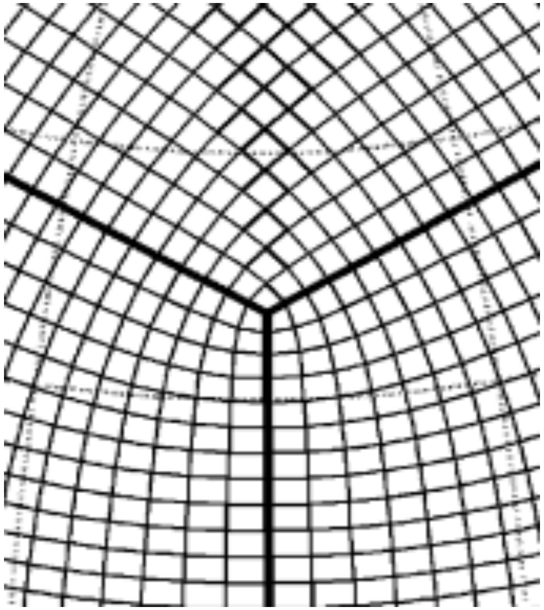
a) Conformal



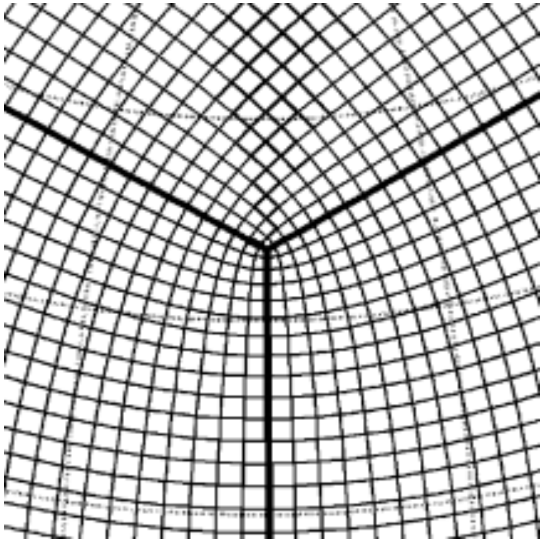
b) Elliptic



c) Gnomonic

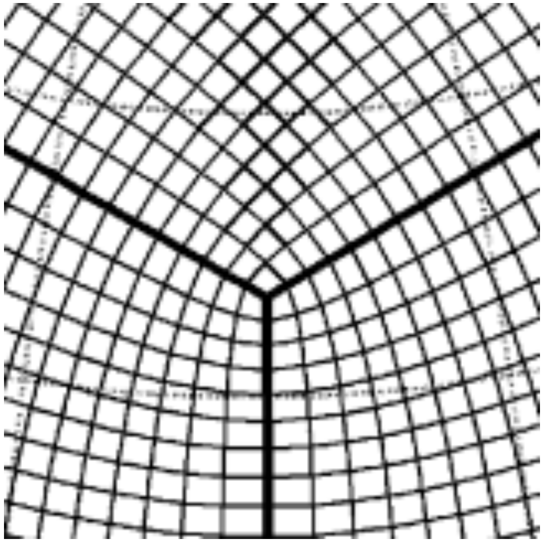


d) Spring



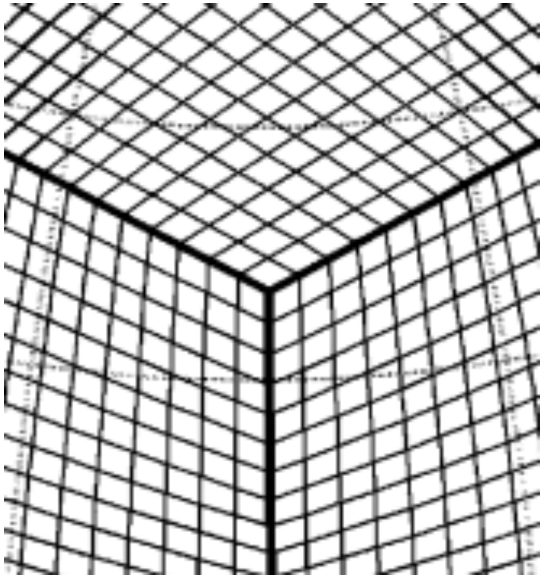
Orthogonal (rectangles have ~90° angles), not Uniform (fast change in shape and size near vertex)

a) Conformal



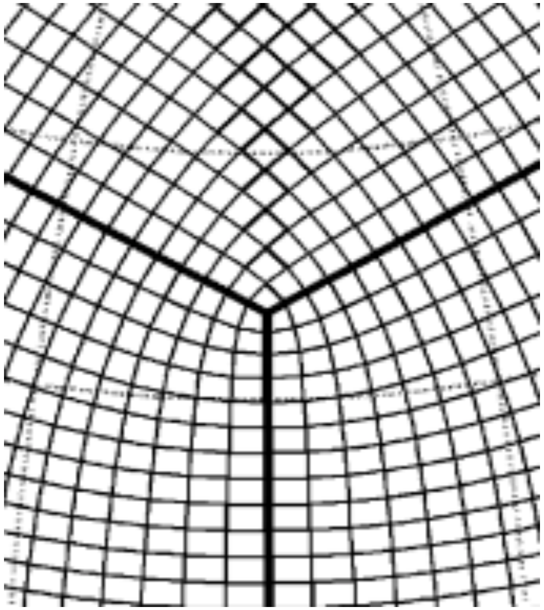
Kinda Orthogonal, Kinda Uniform

b) Elliptic



Not Orthogonal, Uniform

c) Gnomonic



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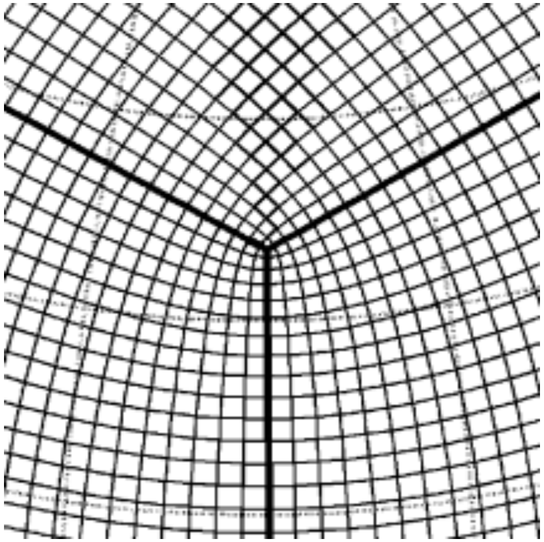

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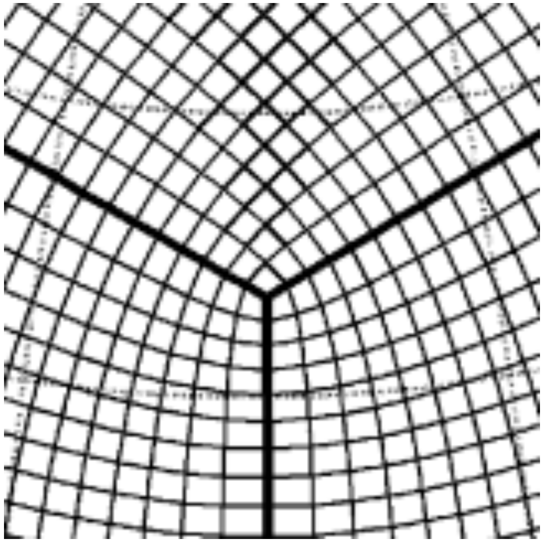

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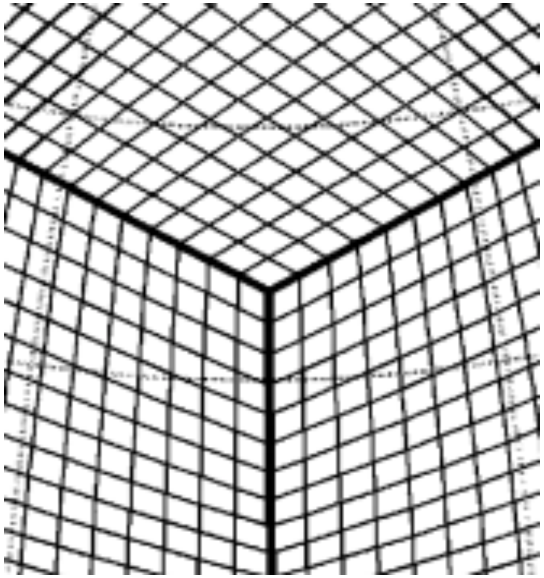
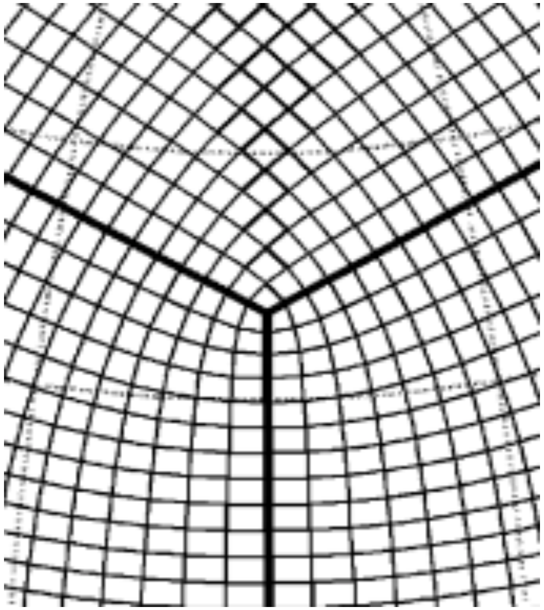


c) Gnomonic

Lowest error in idealized advection tests

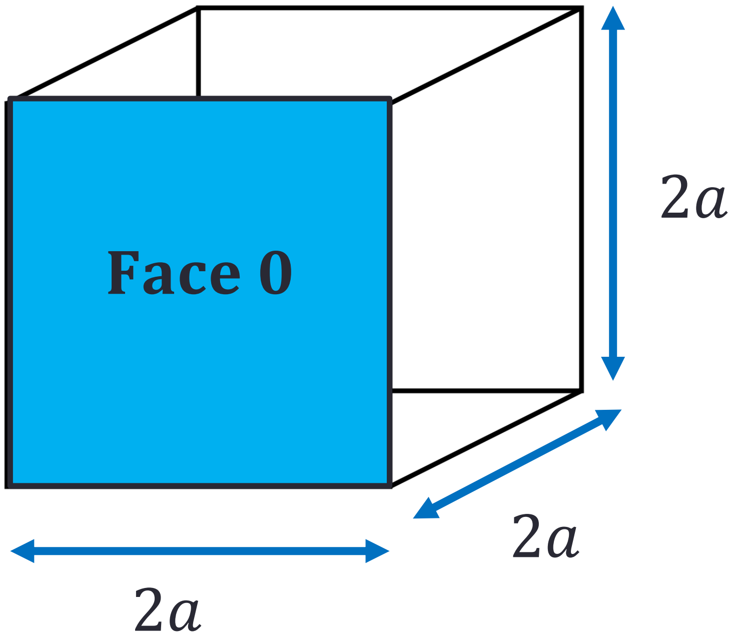


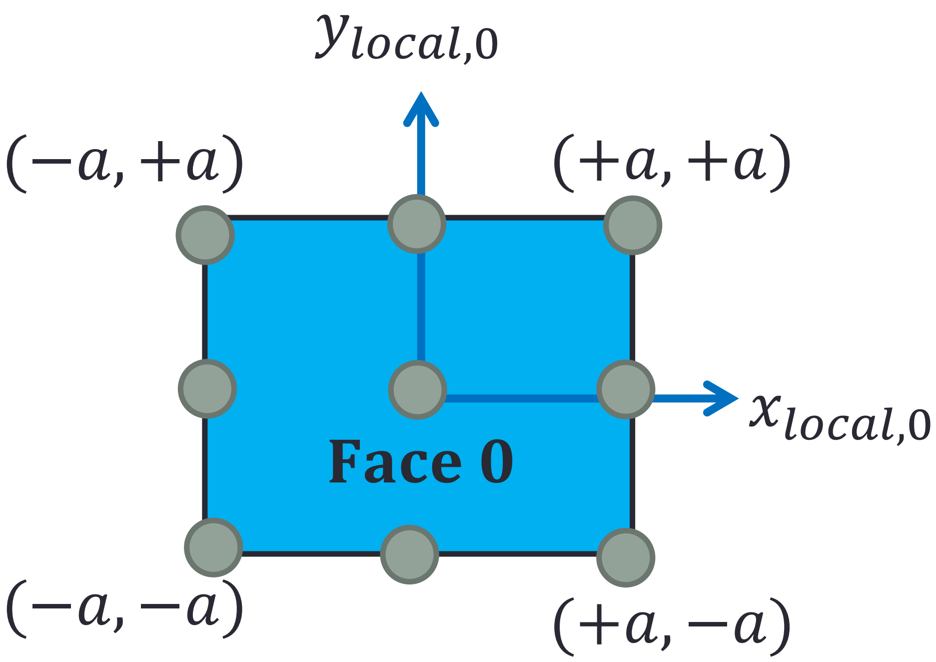
d) Spring

Cubed-Sphere Mesh

Gnomonic

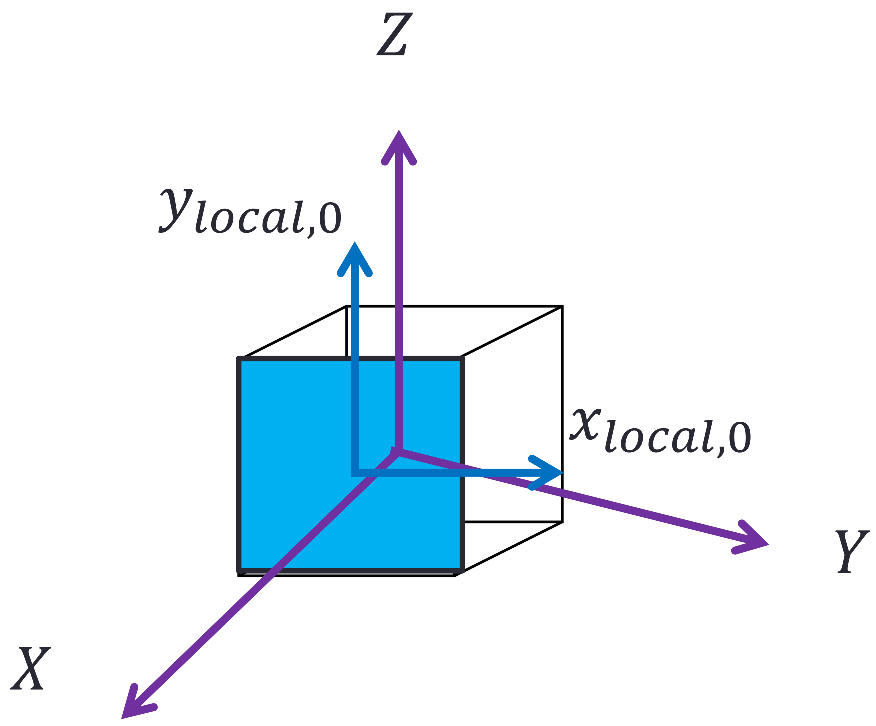
- Gnomonic = expand inscribed cube by projecting points to surface of the sphere





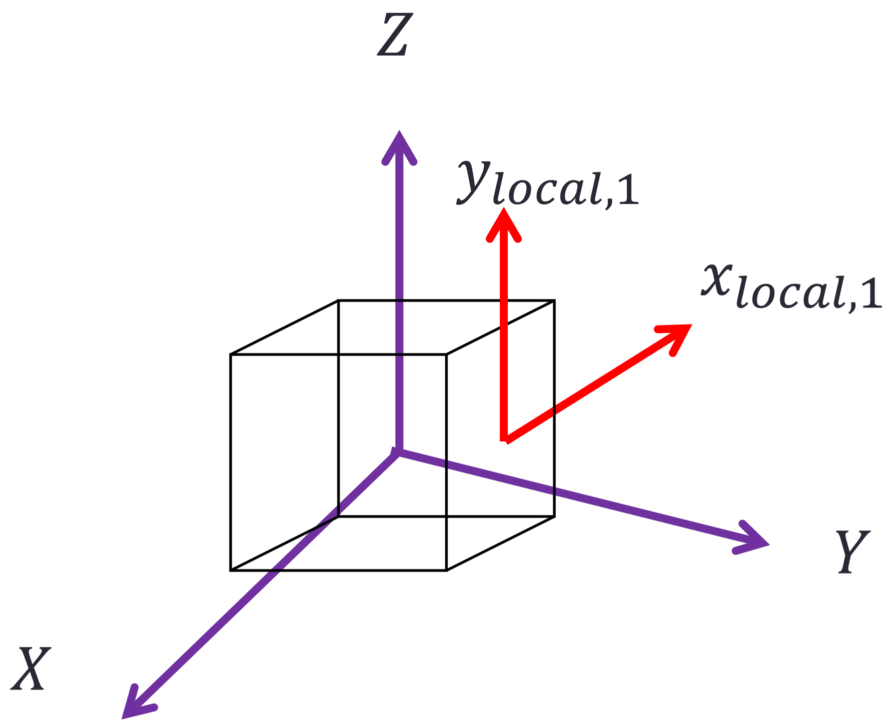
Cubed-Sphere Mesh

Gnomonic



Cubed-Sphere Mesh

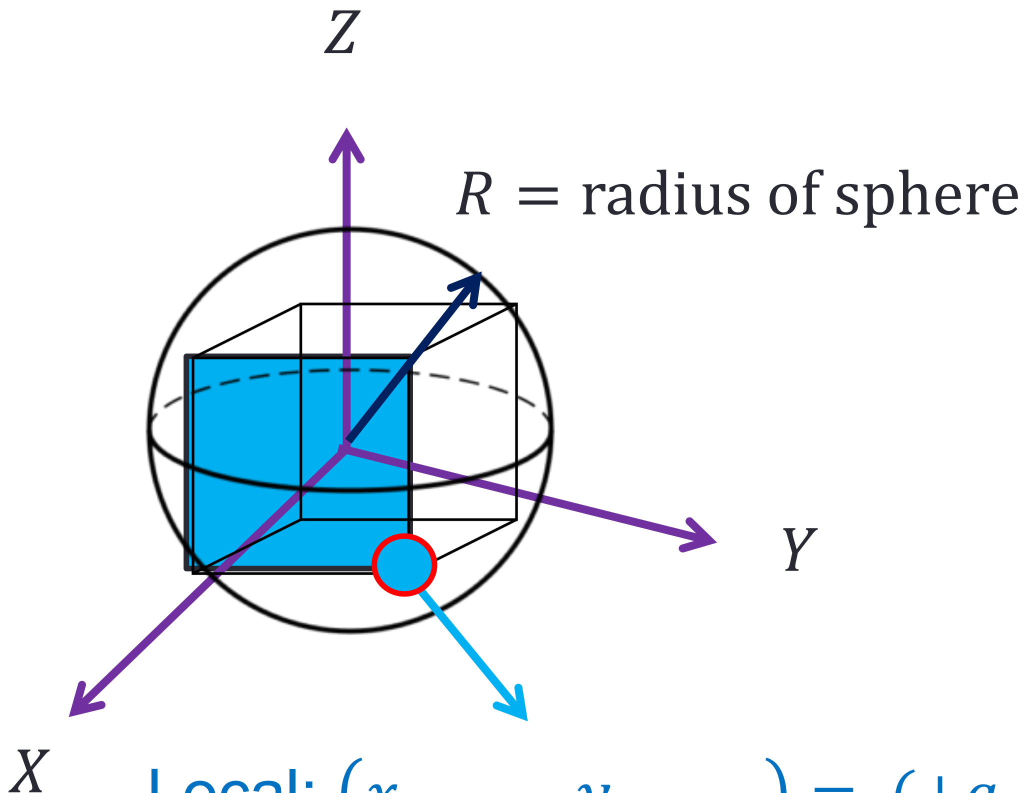
Gnomonic



Cubed-Sphere Mesh

Gnomonic

$$a = \frac{\sqrt{3}}{3} R$$



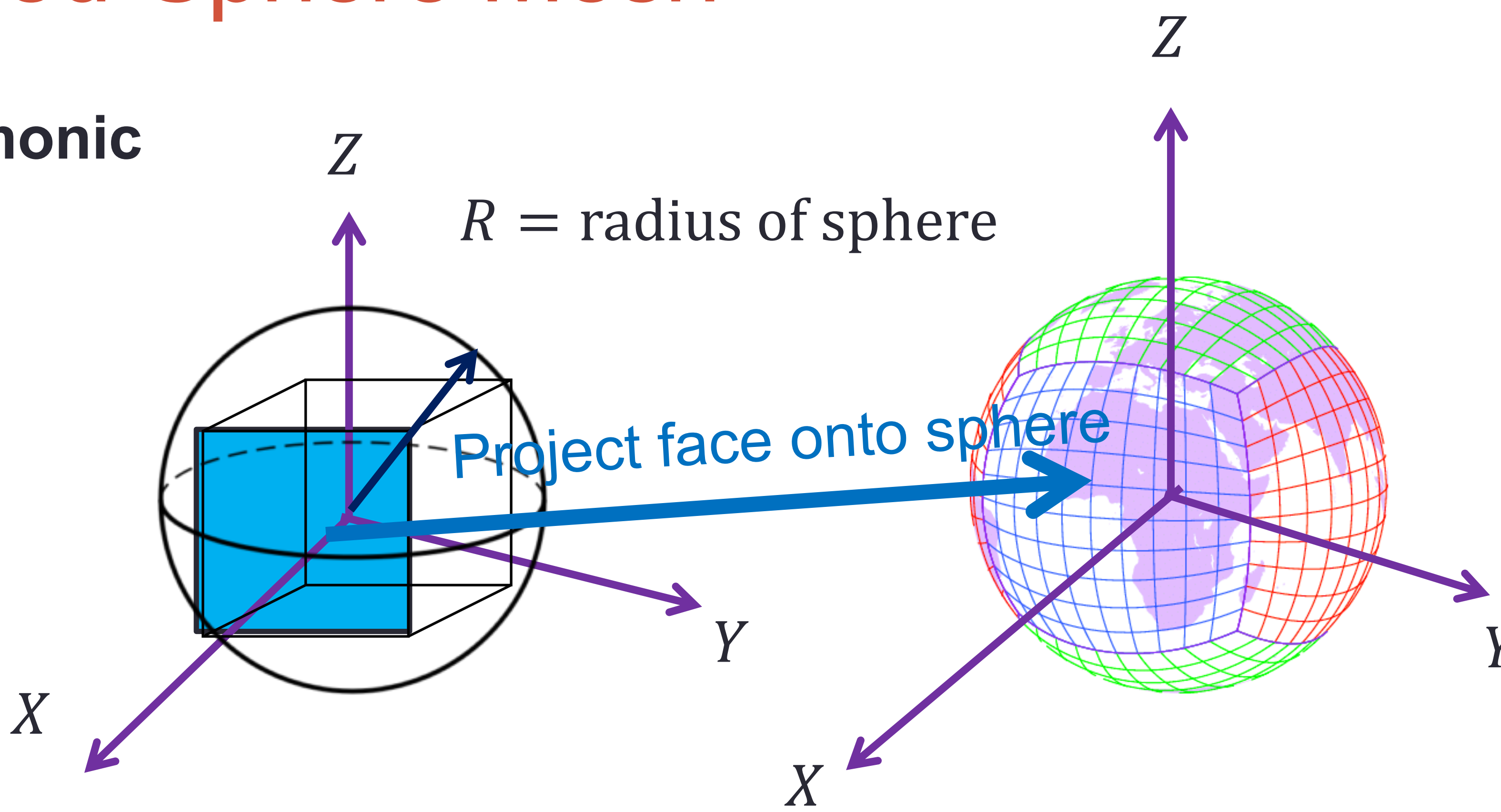
Local: $(x_{local,0}, y_{local,0}) = (+a, -a)$

Global: $(X, Y, Z) = (+a, +a, -a)$

Cubed-Sphere Mesh

Gnomonic

$$a = \frac{\sqrt{3}}{3} R$$



For Face 0, on surface of sphere:

$$(X, Y, Z) = \frac{R}{\sqrt{a^2 + x_{local,0}^2 + y_{local,0}^2}} (+a, x_{local,0}, y_{local,0})$$

Cubed-Sphere Mesh

Equidistant Gnomonic

- Equally space points on the local face to project onto the sphere
  - i.e. 5 points along an edge, located at $-a, -\frac{1}{2}a, 0, +\frac{1}{2}a, +a$

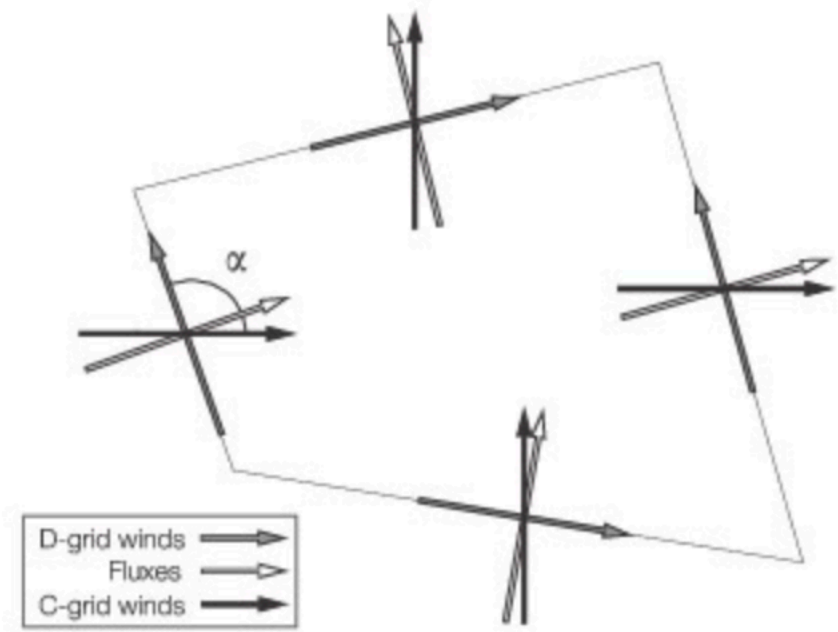
Equiangular Gnomonic

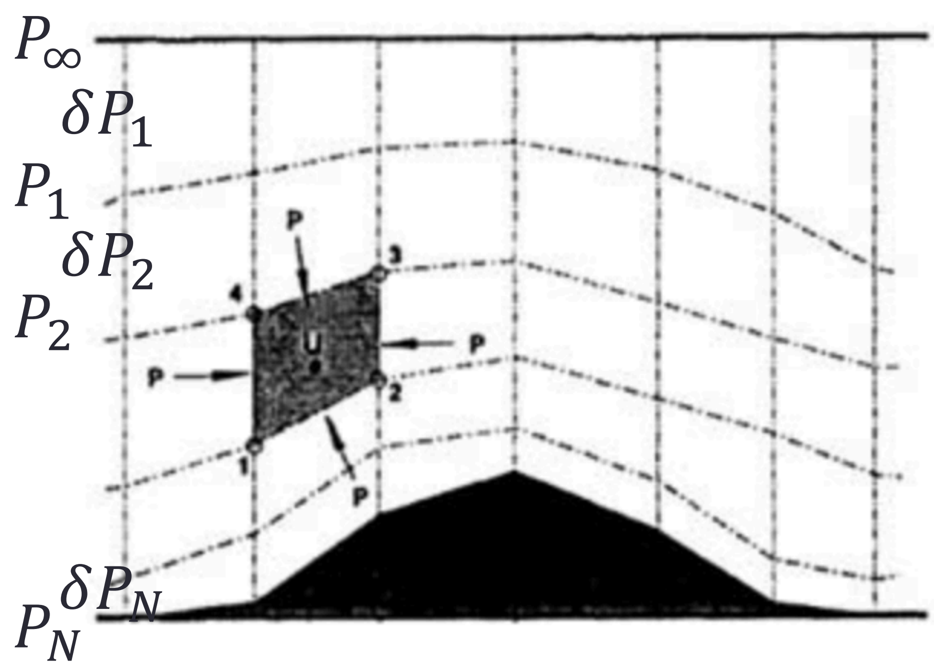
- Space points on the local face according to:

$$x_{local} = a * \tan(x_0)$$
$$y_{local} = a * \tan(y_0)$$

(x_0, y_0) equally range from $\left(-\frac{\pi}{4}, +\frac{\pi}{4}\right)$

FV3 Numerics





Horizontally semi-Lagrangian; CD-staggered grid

Vertically Lagrangian – pressure layers can expand/contract

FV3 Numerics

Horizontal Equations in One Layer

$$\frac{\partial \mathbf{V}}{\partial t} = -\Omega \hat{\mathbf{k}} \times \mathbf{V} - \nabla(\kappa + \nu \nabla^2 D) - \frac{1}{\rho} \nabla p \bigg|_z ,$$

Hor. momentum

$$\frac{\partial \delta p}{\partial t} + \nabla \cdot (\mathbf{V} \delta p) = 0,$$

Hydrostatic pressure thickness ($\propto$ mass of layer)

$$\frac{\partial \delta p \Theta}{\partial t} + \nabla \cdot (\mathbf{V} \delta p \Theta) = 0,$$

Potential temperature (scalar transport)

All scalars are cell-averaged values; all vectors and fluxes are face (edge)-averaged values

FV3 Numerics

Horizontal Equations in One Layer

Pressure

Absolut vort.

Kinetic energy

Divergence

$$\frac{\partial \mathbf{V}}{\partial t} = -\Omega\hat{\mathbf{k}} \times \mathbf{V} - \nabla(\kappa + \nu\nabla^2 D) - \frac{1}{\rho}\nabla p\Big|_z ,$$

Hor. momentum

Div. damping

Density

$$\frac{\partial \delta p}{\partial t} + \nabla \cdot (\mathbf{V}\delta p) = 0,$$

Hydrostatic pressure thickness (∝ mass of layer)

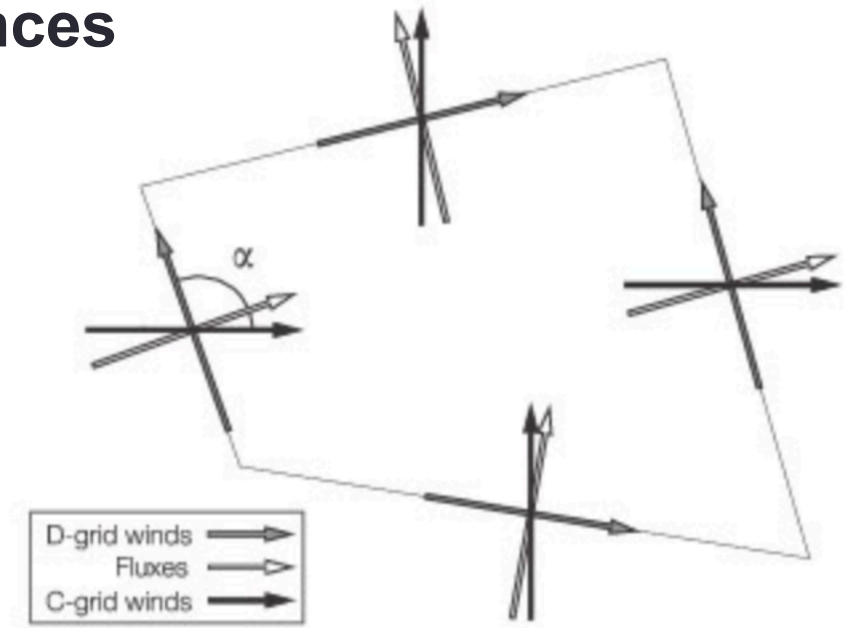
$$\frac{\partial \delta p \Theta}{\partial t} + \nabla \cdot (\mathbf{V}\delta p \Theta) = 0,$$

Potential temperature (scalar transport)

Prescribed **Prognostic variables** **Diagnosed variables**

FV3 Numerics

Flux Divergences

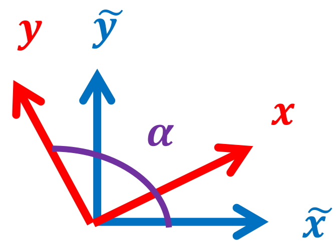


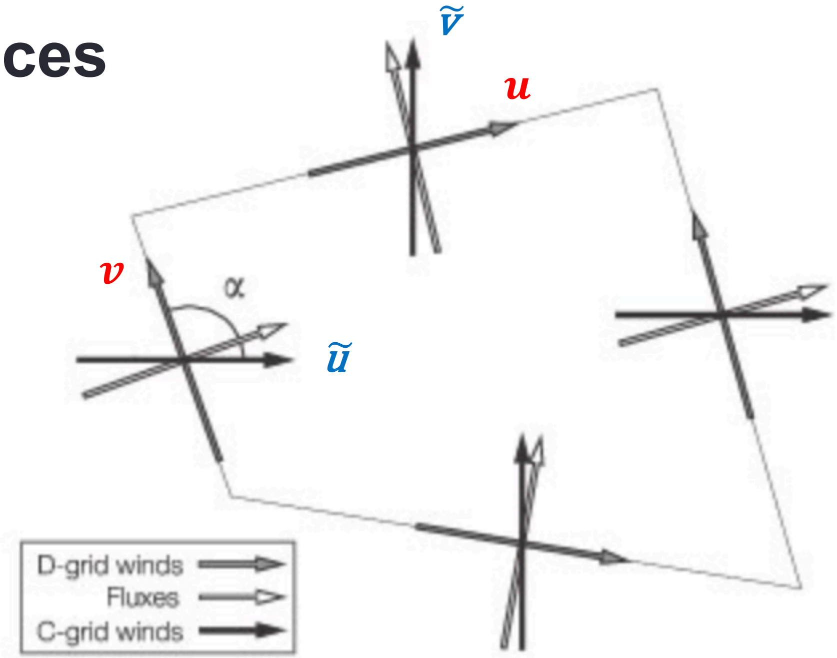
$$F[\widetilde{u^*}, \Delta\tau, \eta] = -\frac{\Delta\tau}{\Delta A}\delta_x[X(\widetilde{u^*}, \Delta\tau, \eta)\Delta y \sin\alpha]$$

$$G[\widetilde{v^*}, \Delta\tau, \eta] = -\frac{\Delta\tau}{\Delta A}\delta_y[Y(\widetilde{v^*}, \Delta\tau, \eta)\Delta x \sin\alpha]$$

FV3 Numerics

Flux Divergences





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FV3 Numerics

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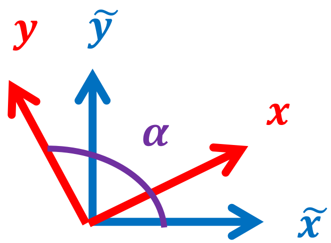

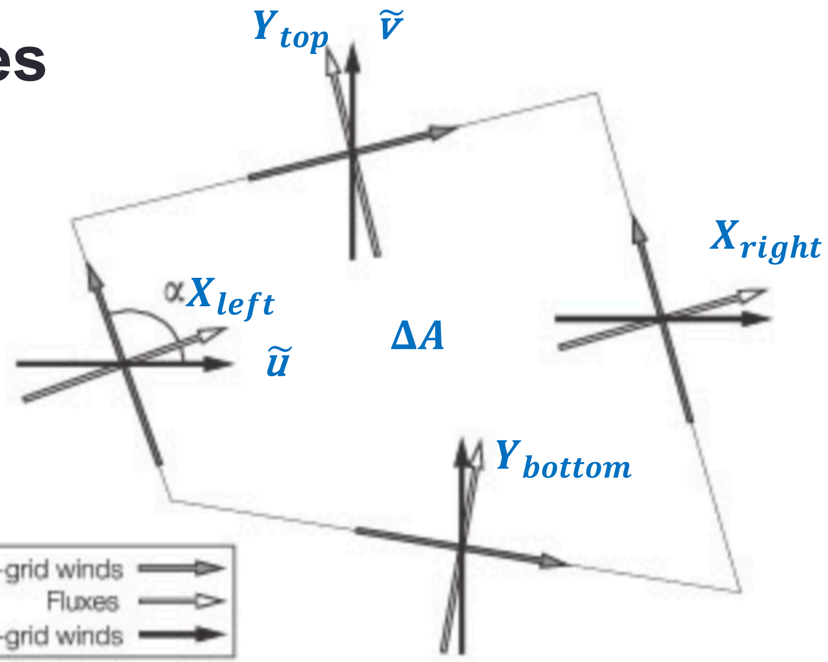

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$$G[\widetilde{v^*}, \Delta\tau, \eta] = -\frac{\Delta\tau}{\Delta A}\delta_y[Y(\widetilde{v^*}, \Delta\tau, \eta)\Delta x \sin\alpha]$$

FV3 Numerics

Discretized Equations

$$\delta p^{n+1} = \delta p^n + F[\widetilde{u^*}, \Delta\tau, \delta p^y] + G[\widetilde{v^*}, \Delta\tau, \delta p^x], \quad (1)$$

$$\Theta^{n+1} = \frac{1}{\delta p^{n+1}} \{\Theta^n \delta p^n + F[x^*, \Delta\tau, \Theta^y] + G[y^*, \Delta\tau, \Theta^x]\}, \quad (2)$$

$$u^{n+1} = u^n + \Delta\tau[Y(\widetilde{v^*}, \Delta\tau, \Omega^x) - \delta_x(\kappa^* - \nu\nabla^2 D) + \widehat{P}_x], \quad (3)$$

$$v^{n+1} = v^n + \Delta\tau[X(\widetilde{u^*}, \Delta\tau, \Omega^y) - \delta_y(\kappa^* - \nu\nabla^2 D) + \widehat{P}_y]. \quad (4)$$

FV3 Numerics

Workflow

1.) Compute half-time step (n + ½) $\widetilde{u}^*$ (* = time-averaged value) and $\widetilde{v}^*$ (**C-grid** winds, for fluxes) using vorticity and kinetic energy fluxes from time step n

2.) Also compute PGF at n + ½

$$v^{n+1} = v^n + \Delta\tau[X(\widetilde{u^*}, \Delta\tau, \Omega^y) - \delta_y(\kappa^* - \nu\nabla^2 D) + \widehat{P}_y]. \quad (4)$$

FV3 Numerics

Workflow

3.) Compute full-time step (*n* + *1*) variables on the **D-grid** using the **C-grid** values computed at *n* + ½

$$\delta p^{n+1} = \delta p^{n} + F[\widetilde{u^*}, \Delta\tau, \delta p^{y}] + G[\widetilde{v^*}, \Delta\tau, \delta p^{x}], \quad (1)$$

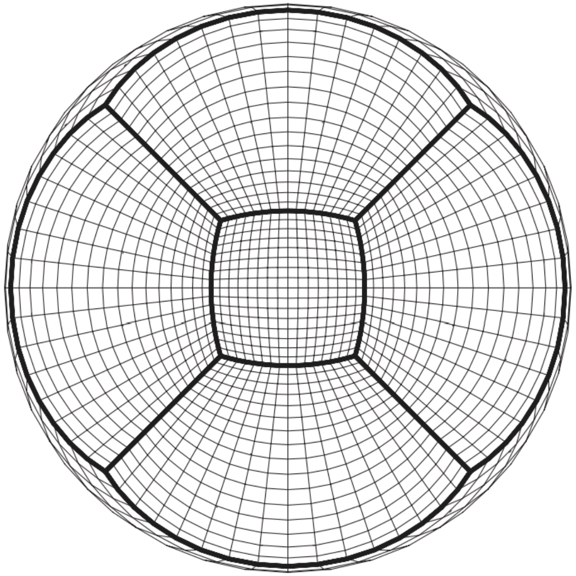
$$\Theta^{n+1} = \frac{1}{\delta p^{n+1}}\{\Theta^{n}\delta p^{n} + F[x^*, \Delta\tau, \Theta^{y}] + G[y^*, \Delta\tau, \Theta^{x}]\}, \quad (2)$$

$$u^{n+1} = u^{n} + \Delta\tau[Y(\widetilde{v^*}, \Delta\tau, \Omega^{x}) - \delta_x(\kappa^* - \nu\nabla^2 D) + \widehat{P}_x], \quad (3)$$

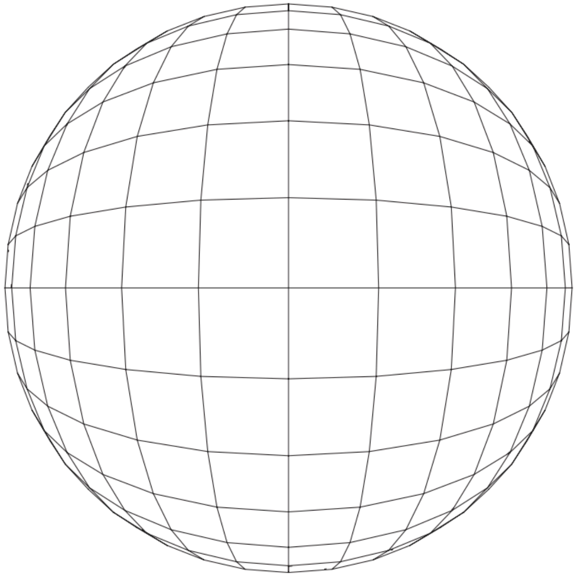
$$v^{n+1} = v^{n} + \Delta\tau[X(\widetilde{u^*}, \Delta\tau, \Omega^{y}) - \delta_y(\kappa^* - \nu\nabla^2 D) + \widehat{P}_y]. \quad (4)$$

FV3 Mesh Refinement

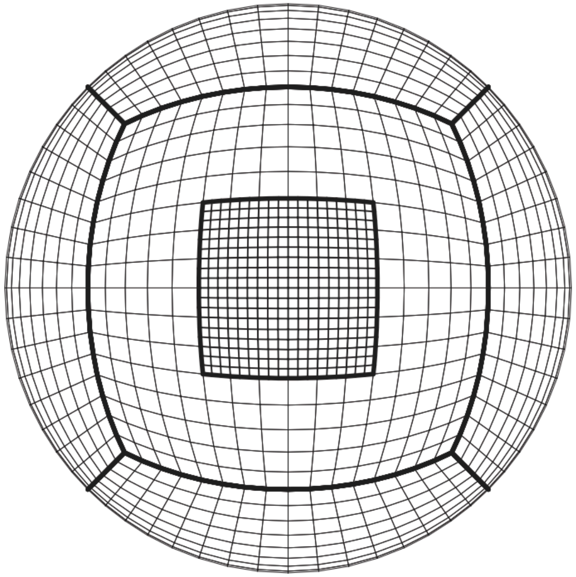
Harris and Lin (2013)



3x stretched-grid refinement from uniform



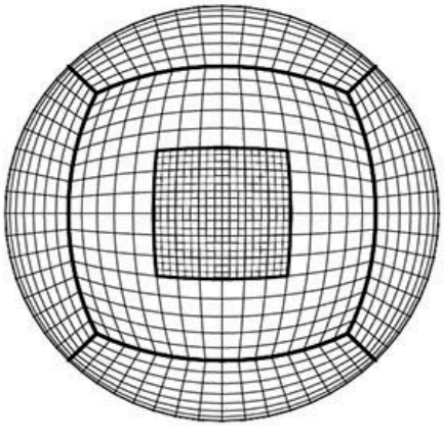
Opposite side of stretched-grid



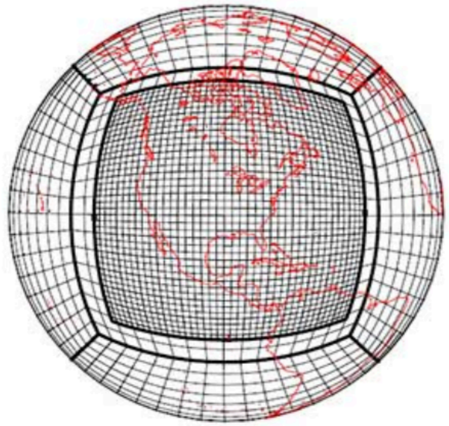
3x nesting ratio from coarse grid (nest/parent **run concurrently; dedicated procs**)

FV3 Mesh Refinement

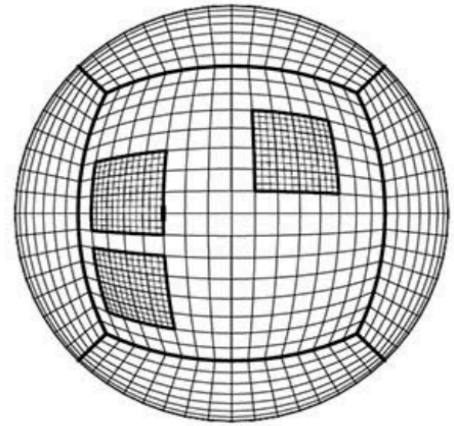
https://www.gfdl.noaa.gov/fv3/fv3-grids/



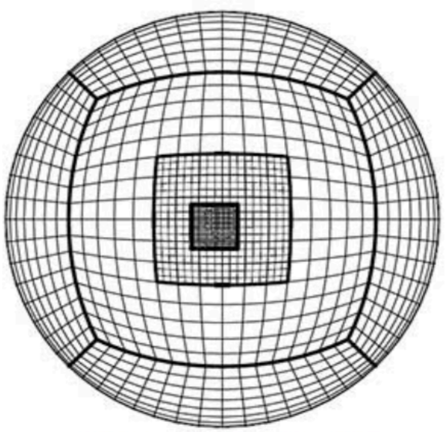
3:1 nested grid



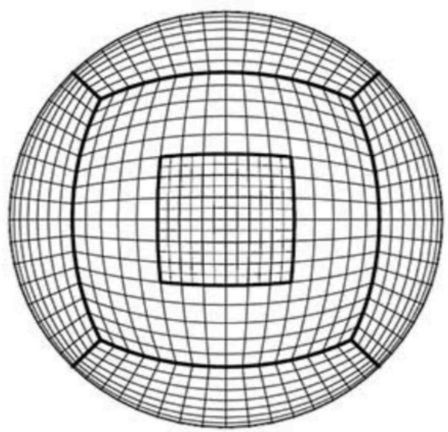
Large nest for RCMs



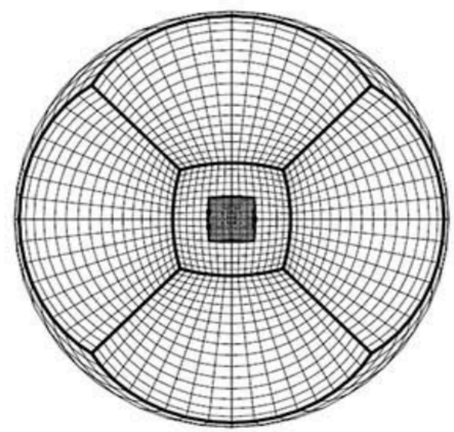
Multiple nests



Telescoping nests



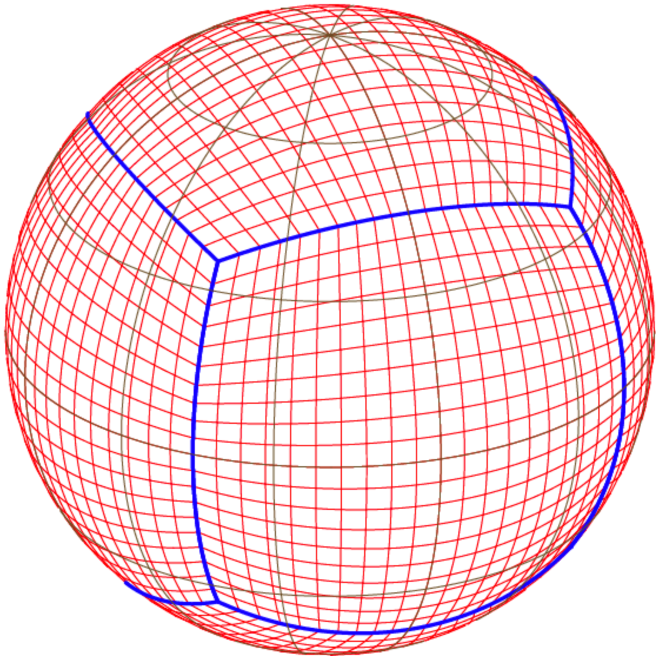
2:1 nested grid



Nest in stretched grid

Summary

- FV3 is a sophisticated **finite-volume global model** on a **CD-gridded, cubed-sphere mesh** that took 20+ years to develop
- Now used for operational weather forecasting and research weather/climate simulations
- Supports **stretched-grids** and **nesting**
- Moving towards community development



https://www.researchgate.net/figure/The-equiangular-gnomonic-cubed-sphere_fig1_319964216

References

FV3 Documentation and References

Disclaimer: We have made every effort to ensure that the information here is as accurate, complete, and as up-to-date as possible. However, due to the *very* rapid pace of FV3 dynamical core and FV3-powered model development these documents may not always reflect the current state of FV3 capabilities. Often, the code itself is the best description of the current capabilities and the available options, which due to limited space cannot all be described in full detail here. **We strongly recommend anyone who wishes to understand FV3 in more detail to read and study the articles linked below.** Contact GFDL FV3 Dycore support or GFDL SHiELD/fvGFS model support for assistance and more information.

https://www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/

Key Journal Articles (many now open access):

- Lin, Chao, Sud, and Walker, 1994: Van Leer transport scheme
- Lin and Rood 1996: FV advection scheme
- Lin and Rood 1997: FV lat-lon shallow-water model
- Lin 1997: FV pressure-gradient force formulation
- Lin 2004: The latitude-longitude FV core
- Putman and Lin 2007: FV3 cubed-sphere advection
- Zhao, Held, and Lin, 2012: Divergence damping and tropical cyclones
- X. Chen, Lin, and coauthors, 2013: A nonhydrostatic finite-volume algorithm
- J.-H. Chen and Lin, 2013: Seasonal hurricane prediction with GFDL Microphysics
- Harris and Lin, 2013: FV3 global-to-regional nesting
- Harris, Lin, and Tu, 2016: FV3 stretched-grid regional refinement
- Lin, Harris, X. Chen, Yao, and Chai, 2017: Nonlinear colliding modons idealized test
- J.-H. Chen, X. Chen, Lin, Magnusson, Bender, Zhou, and Rees, 2018: Initialization from ECMWF analyses
- Zhou, Lin, J.-H. Chen, Harris, X. Chen, and Rees, 2019: Convective-scale prediction with GFDL Microphysics

Documentation articles:

- Diffusion_operators (June 2018)
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