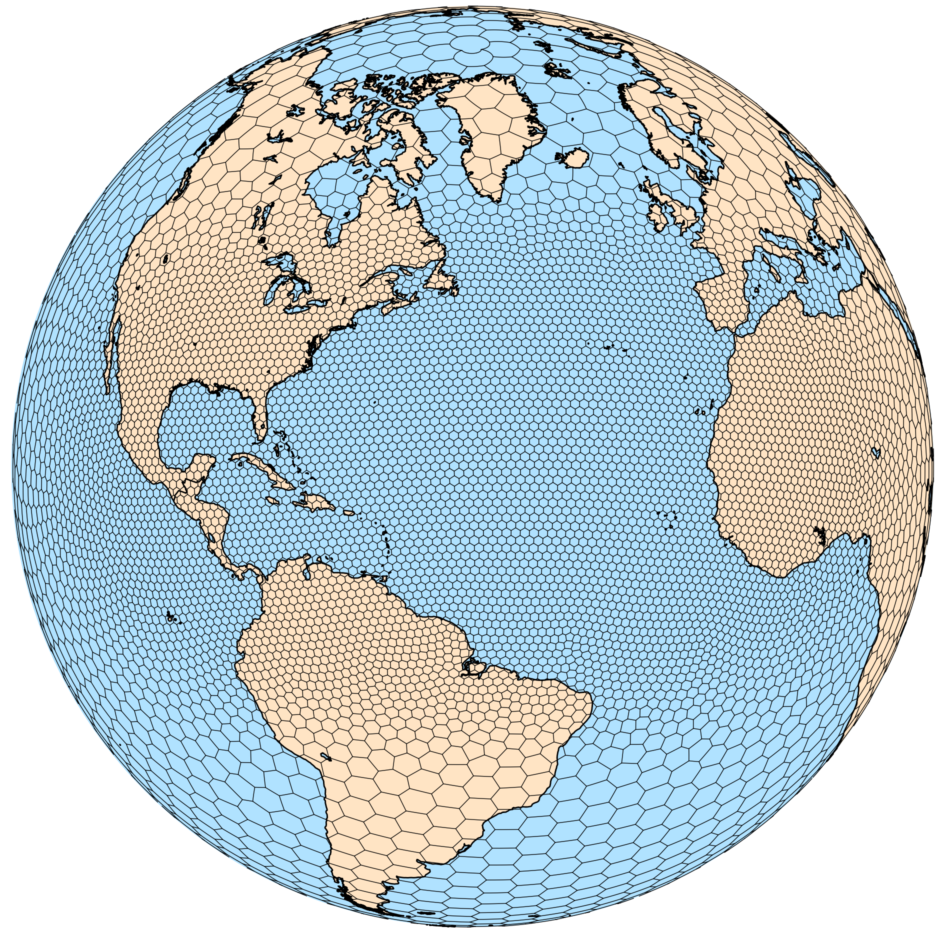
MPAS
Model for Prediction Across Scales

Dynamical Core

- Spatial discretization
  - Transport
  - Filters
  - Namelist parameters
  - References



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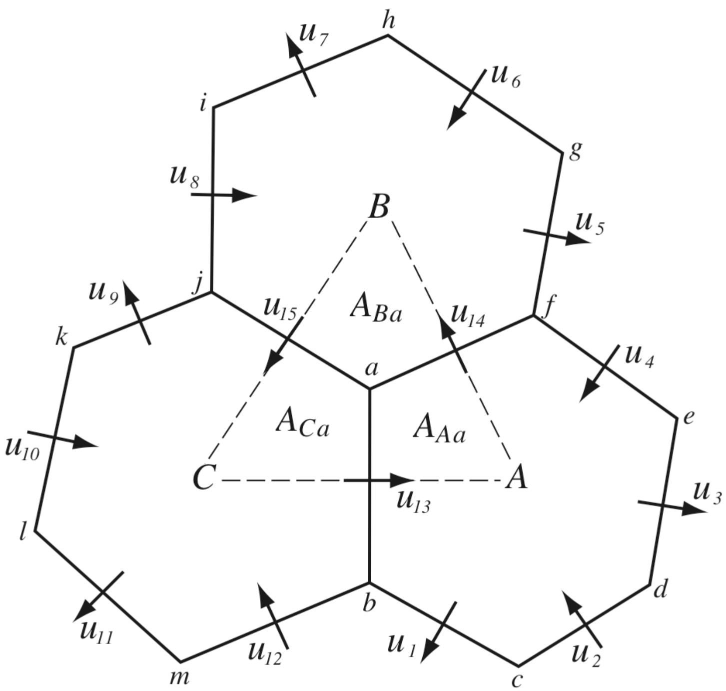
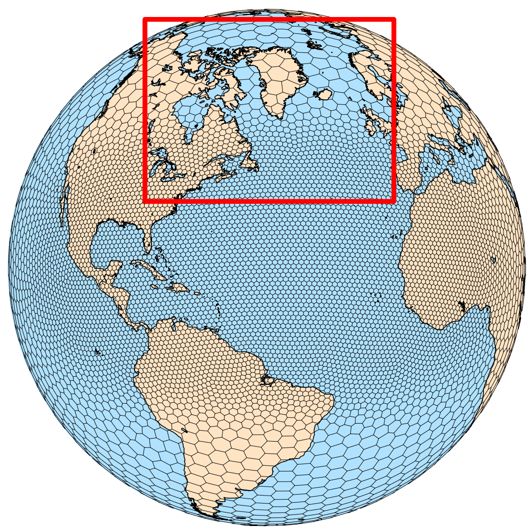
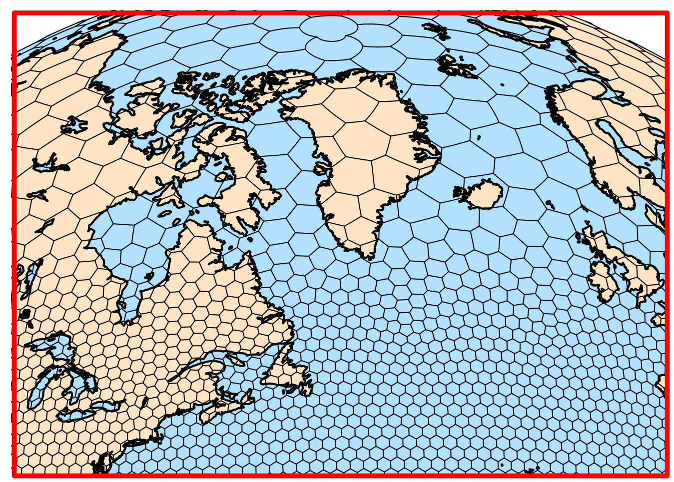
MPAS Horizontal Mesh



Unstructured spherical centroidal Voronoi meshes

- Mostly *hexagons*, some pentagons (5-sided cells) and heptagons (7-sided cells).
- Cell centers are at cell center-of-mass (centroidal).
- Cell edges bisect lines connecting cell centers; perpendicular.
- C-grid staggering of velocities (velocities are perpendicular to cell faces).
- Uniform resolution – traditional icosahedral mesh.





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MPAS Nonhydrostatic Atmospheric Solver

Equations

- Prognostic equations for coupled variables.
- Generalized height coordinate.
- Horizontally vector-invariant equation set.
- Continuity equation for dry air mass.
- Thermodynamic equation for coupled potential temperature.

Variables: $(U, V, \Omega, \Theta, Q_j) = \tilde{\rho}_d\,(u, v, \omega, \theta, q_j)$ $\qquad \tilde{\rho}_d = \rho_d/\zeta_z$

Vertical coordinate: $z = \zeta + A(\zeta)h_s(x,y,\zeta)$

Prognostic equations:

$$\frac{\partial \mathbf{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\nabla_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \mathbf{z}_H p}{\partial \zeta}\right] - \eta\,\mathbf{k}\times\mathbf{V}_H - \mathbf{v}_H \nabla_\zeta\cdot\mathbf{V} - \frac{\partial \Omega \mathbf{v}_H}{\partial \zeta} - \rho_d \nabla_\zeta K + \mathbf{F}_{V_H}$$

$$\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - (\nabla\cdot\mathbf{v}\,W)_\zeta + F_W$$

$$\frac{\partial \Theta_m}{\partial t} = -(\nabla\cdot\mathbf{V}\,\theta_m)_\zeta + F_{\Theta_m}$$

$$\frac{\partial \tilde{\rho}_d}{\partial t} = -(\nabla\cdot\mathbf{V})_\zeta$$

$$\frac{\partial Q_j}{\partial t} = -(\nabla\cdot\mathbf{V}\,q_j)_\zeta + F_{Q_j}$$

Dry-air flux divergence

Flux divergence

Diagnostics and definitions:

$$\frac{\rho_m}{\rho_d} = 1 + q_v + q_c + q_r + \ldots$$

$$p = p_0\left(\frac{R_d \zeta_z \Theta_m}{p_0}\right)^\gamma \qquad \theta_m = \theta[1 + (R_v/R_d)q_v]$$

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Operators on the Voronoi Mesh
Flux divergence and transport

Transport equation, conservative form:

$$\frac{\partial(\rho\psi)}{\partial t} = -\nabla\cdot\mathbf{V}(\rho\psi)$$

Finite-Volume formulation, Integrate over cell:

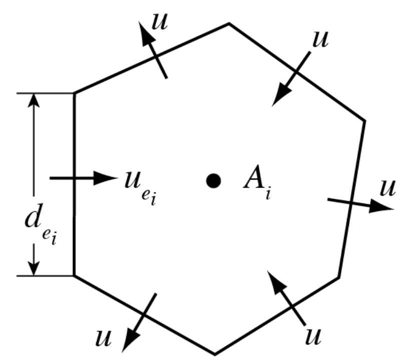
$$\int_D \left[\frac{\partial}{\partial t}(\rho\psi) = -\nabla\cdot\mathbf{V}(\rho\psi)\right] dV$$

Apply divergence theorem:

$$\frac{\partial(\overline{\rho\psi})}{\partial t} = -\frac{1}{V}\int_\Sigma (\rho\psi)\,\mathbf{V}\cdot\mathbf{n}\; d\sigma$$

Discretize in time and space:

$$(\overline{\rho\psi})_i^{t+\Delta t} = (\overline{\rho\psi})_i^{t} - \Delta t\,\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\overline{(\rho\mathbf{V}\cdot\mathbf{n}_{e_i})\psi}$$



Velocity divergence operator is 2nd-order accurate for edge-centered velocities.

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Operators on the Voronoi Mesh
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Apply divergence theorem:

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Discretize in time and space:

$$(\overline{\rho\psi})_i^{t+\Delta t} = (\overline{\rho\psi})_i^t - \Delta t\,\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\,\overline{(\rho\mathbf{V}\cdot\mathbf{n}_{e_i})\psi}$$

In MPAS, the mass flux is a prognostic variables at the cell edge.

Scalar mixing ratios are defined at cell centers. Their definition at the cell edges defines the *transport scheme.*

More generally, a transport scheme defines the temporally and spatially integrated scalar mass flux through the edge over timestep Δt.

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Operators on the Voronoi Mesh
Flux divergence and transport

$$\phi^t \rightarrow \phi^{t+\Delta t}$$

Runge-Kutta time integration

$$\phi^* = \phi^t + \frac{\Delta t}{3} \boxed{RHS(\phi^t)}$$

$$\phi^{**} = \phi^t + \frac{\Delta t}{2} \boxed{RHS(\phi^*)}$$

$$\phi^{t+\Delta t} = \phi^t + \Delta t \boxed{RHS(\phi^{**})}$$

$$(\overline{\rho\psi})_i^{t+\Delta t} = (\overline{\rho\psi})_i^t - \Delta t \boxed{\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\overline{(\rho\mathbf{V}\cdot\mathbf{n}_{e_i})\psi}}$$

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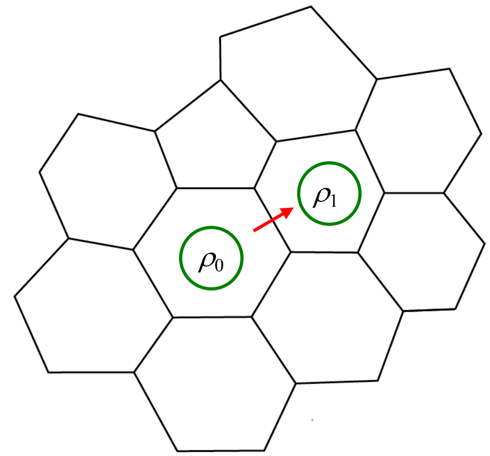
Transport – Unstructured MPAS Mesh

$$
\begin{aligned}
\frac{\partial \mathbf{V}_H}{\partial t} &= -\frac{\rho_d}{\rho_m}\left[\nabla_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \mathbf{z}_H p}{\partial \zeta}\right] - \eta\, \mathbf{k} \times \mathbf{V}_H \\
&\quad - \mathbf{v}_H \nabla_\zeta \cdot \mathbf{V} - \frac{\partial \Omega \mathbf{v}_H}{\partial \zeta} - \rho_d \nabla_\zeta K + \mathbf{F}_{V_H} \\
\frac{\partial W}{\partial t} &= -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - \left(\nabla \cdot \mathbf{v}\, W\right)_\zeta + F_W \\
\frac{\partial \Theta_m}{\partial t} &= -\left(\nabla \cdot \mathbf{V}\, \theta_m\right)_\zeta + F_{\Theta_m} \\
\frac{\partial \tilde{\rho}_d}{\partial t} &= -\left(\nabla \cdot \mathbf{V}\right)_\zeta \\
\frac{\partial Q_j}{\partial t} &= -\left(\nabla \cdot \mathbf{V}\, q_j\right)_\zeta + F_{Q_j}
\end{aligned}
$$

$$\mathbf{V} = \rho \mathbf{v}; \quad \mathbf{v} = (u,\, w)$$



For the horizontal dry-air mass flux, the value of the density ρ_d at a cell face is set equal to the average of the densities from the two cells sharing the face:

$$\rho_{\text{edge}} = (\rho_0+\rho_1)/2, \quad \mathbf{V}_{\text{edge}} = u_e\, (\rho_0+\rho_1)/2$$

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Vertical coordinate: $z = \zeta + A(\zeta) h_s(x, y, \zeta)$

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$$\frac{\partial \mathbf{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\nabla_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \mathbf{z}_H p}{\partial \zeta}\right] - \eta\,\mathbf{k}\times\mathbf{V}_H$$
$$- \mathbf{v}_H \nabla_\zeta \cdot \mathbf{V} - \frac{\partial \Omega \mathbf{v}_H}{\partial \zeta} - \rho_d \nabla_\zeta K + \mathbf{F}_{V_H}$$
$$\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - (\nabla \cdot \mathbf{v}\, W)_\zeta + F_W$$
$$\frac{\partial \Theta_m}{\partial t} = -(\nabla \cdot \mathbf{V}\,\theta_m)_\zeta + F_{\Theta_m}$$
$$\frac{\partial \tilde{\rho}_d}{\partial t} = -(\nabla \cdot \mathbf{V})_\zeta$$
$$\frac{\partial Q_j}{\partial t} = -(\nabla \cdot \mathbf{V}\, q_j)_\zeta + F_{Q_j}$$

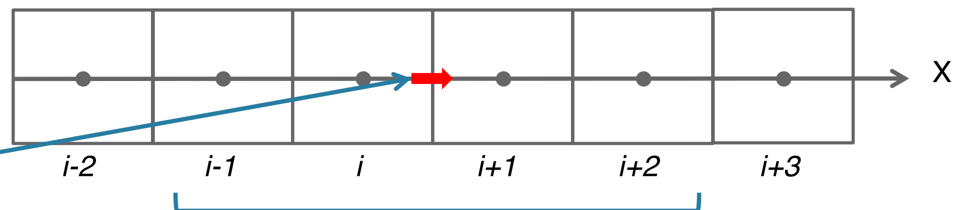
Flux divergence

Diagnostics and definitions:

$$\frac{\rho_m}{\rho_d} = 1 + q_v + q_c + q_r + \ldots$$
$$p = p_0\left(\frac{R_d \zeta_z \Theta_m}{p_0}\right)^\gamma \qquad \theta_m = \theta[1 + (R_v/R_d) q_v]$$

Operators on the Voronoi Mesh
Flux divergence and transport

How do we define the edge mixing ratio on the MPAS unstructured mesh?
First consider a structured mesh - WRF 3rd and 4th-order fluxes



$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}(\psi_{i+1}+\psi_i) - \frac{1}{12}\left(\delta_x^2\psi_{i+1}+\delta_x^2\psi_i\right) + sign(u)\,\frac{\beta}{12}\left(\delta_x^2\psi_{i+1}-\delta_x^2\psi_i\right)\right]$$

(Hundsdorfer et al, 1995; Van Leer, 1985)

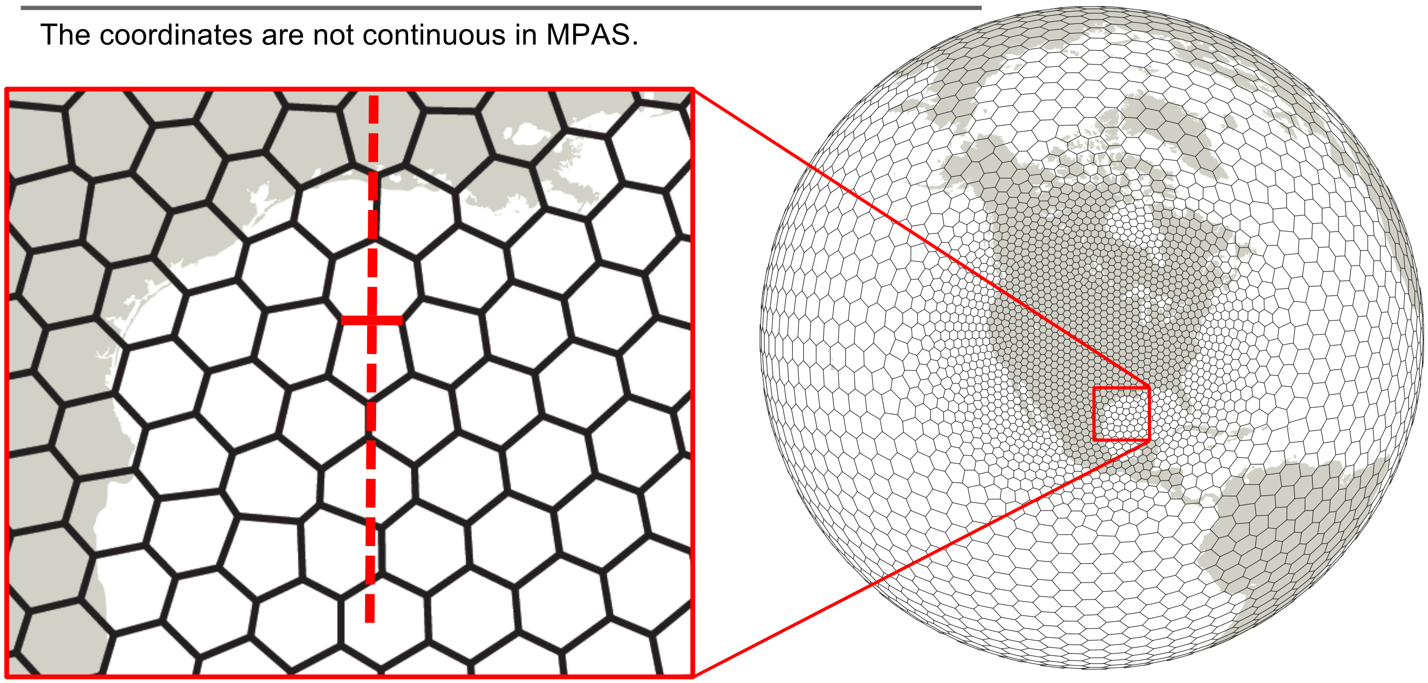
β = 0, fourth-order; β = 1 third order

Operators on the Voronoi Mesh
Flux divergence and transport

3rd and 4th-order WRF fluxes:

$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \frac{1}{12}\left(\delta_x^2\psi_{i+1}+\delta_x^2\psi_i\right) + sign(u)\,\frac{\beta}{12}\left(\delta_x^2\psi_{i+1}-\delta_x^2\psi_i\right)\right]$$

The coordinates are not continuous in MPAS.



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Transport – Unstructured MPAS Mesh

3rd and 4th-order fluxes (e.g. WRF):

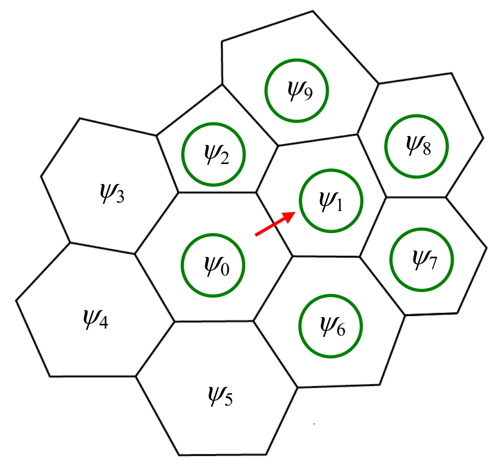
$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \frac{1}{12}\left(\delta_x^2\psi_{i+1}+\delta_x^2\psi_i\right) + sign(u)\,\frac{\beta}{12}\left(\delta_x^2\psi_{i+1}-\delta_x^2\psi_i\right)\right]$$

where $\delta_x^2\psi_i = \psi_{i-1} - 2\psi_i + \psi_{i+1}$ *(Hundsdorfer et al, 1995; Van Leer, 1985)*

Recognizing $\delta_x^2\psi = \Delta x^2\frac{\partial^2\psi}{\partial x^2} + O(\Delta x^4)$ we recast the 3rd and 4th order flux as

$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \Delta x_e^2\frac{1}{12}\left\{\underline{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1}} + \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right.$$
$$\left. + sign(u)\,\Delta x_e^2\frac{\beta}{12}\left\{\underline{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1}} - \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right]$$

where *x* is the direction normal to the cell edge and *i* and *i+1* are cell centers. We use the least-squares-fit polynomial to compute the second derivatives.



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Transport – Unstructured MPAS Mesh

3rd and 4th-order fluxes (e.g. WRF):

$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \frac{1}{12}\left(\delta_x^2\psi_{i+1}+\delta_x^2\psi_i\right) + sign(u)\,\frac{\beta}{12}\left(\delta_x^2\psi_{i+1}-\delta_x^2\psi_i\right)\right]$$

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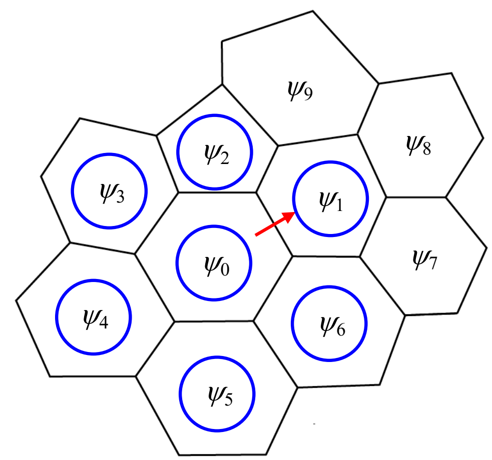
$$\left. + sign(u)\,\Delta x_e^2\frac{\beta}{12}\left\{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1} - \underline{\left(\frac{\partial^2\psi}{\partial x^2}\right)_i}\right\}\right]$$



where *x* is the direction normal to the cell edge and *i* and *i+1* are cell centers. We use the least-squares-fit polynomial to compute the second derivatives.

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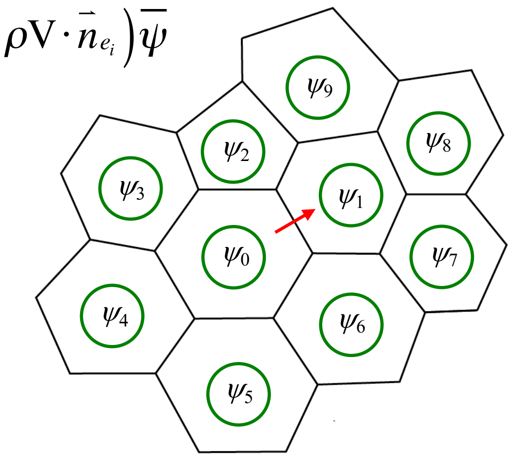
Flux divergence, transport, and Runge-Kutta time integration

Scalar transport equation for cell i: $$\frac{\partial(\rho\psi)_i}{\partial t} = L(\mathrm{V},\rho,\psi) = -\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\left(\rho\mathrm{V}\cdot\vec{n}_{e_i}\right)\overline{\psi}$$



1. Scalar edge-flux value ψ is the weighted sum of cell values from cells that share edge and all their neighbors.
2. Each edge-flux is used to update the two cells that share the edge.
3. Three edge-flux evaluations and cell updates are needed to complete the Runge-Kutta timestep.
4. Weights are pre-computed and stored for use during the integration.

$$(\rho\psi)^* = (\rho\psi)^t + \frac{\Delta t}{3} L(\mathbf{V},\rho,\psi^t)$$

$$(\rho\psi)^{**} = (\rho\psi)^t + \frac{\Delta t}{2} L(\mathbf{V},\rho,\psi^*)$$

$$(\rho\psi)^{t+\Delta t} = (\rho\psi)^t + \Delta t\, L(\mathbf{V},\rho,\psi^{**})$$

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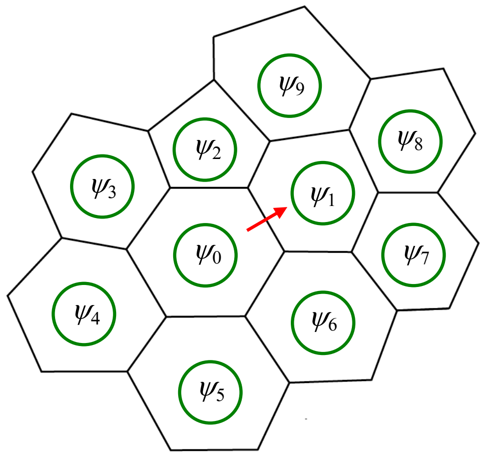
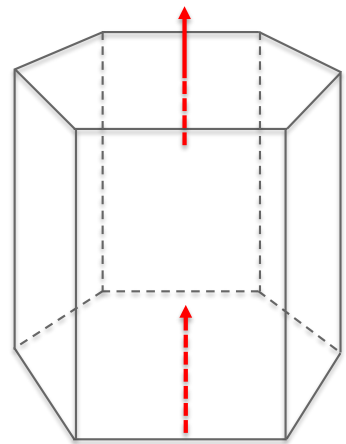
Model for Prediction Across Scales

Flux divergence and transport. Conservation



Horizontal (scalar) mass fluxes



Vertical (scalar) mass fluxes

The mass (or scalar mass) flux on a cell edge (face) is used to update both cells sharing that edge (face), thus mass (and scalar mass) is conserved exactly.

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Model for Prediction Across Scales

Scalar transport: Positive-definite and monotonic renormalization

Scalar update, last RK3 step: $$(\rho\phi)_i^{t+\Delta t} = (\rho\phi)_i^t - \frac{1}{V_i}\sum_{n_{e_i}} \underbrace{A_{e_i}\overline{(\rho\mathbf{V}\cdot\mathbf{n_{e_i}})\phi}}_{\text{fluxes } f_i} \qquad (1)$$

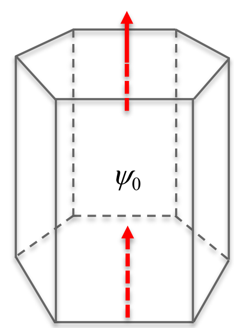
<u>Renormalization</u>

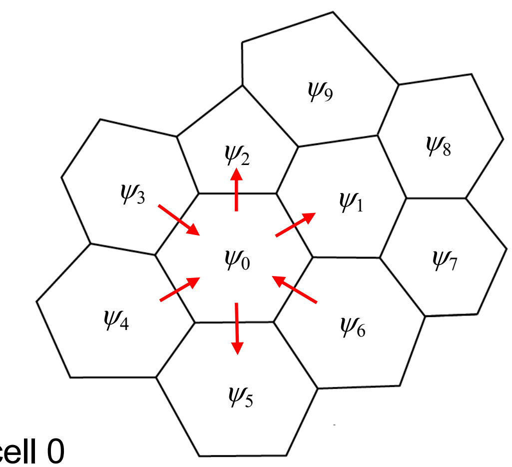
(1) Decompose flux: $f_i = f_i^{upwind} + f_i^c$

(2) Renormalize high-order correction fluxes f_i^c such that solution is positive definite or monotonic:

$f_i^c = R(f_i^c)$

(3) Update scalar equation (1) using $f_i = f_i^{upwind} + R(f_i^c)$





n = 8 in this example, 6 horizontal fluxes and 2 vertical fluxes to update cell 0

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Conservative Transport with RK3 Time Integration: *Examples*

$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \Delta x_e^2 \frac{1}{12}\left\{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1} + \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right.$$
$$\left. + \, sign(u)\, \Delta x_e^2 \frac{\beta}{12}\left\{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1} - \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right]$$

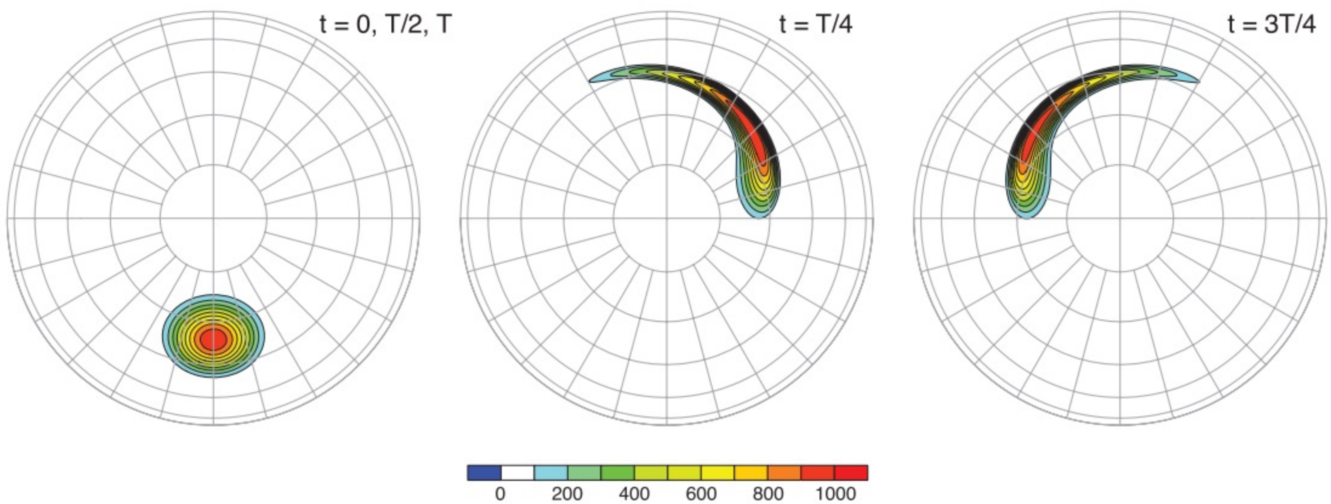

FIG. 5. Exact solution for the Blossey and Durran (deformational flow) test case adapted to the sphere, from Skamarock and Menchaca (2010).

Conservative Transport with RK3 Time Integration: *Examples*

$$F(u,\psi)_{i+1/2} = u_{i+1/2}\left[\frac{1}{2}\left(\psi_{i+1}+\psi_i\right) - \Delta x_e^2 \frac{1}{12}\left\{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1} + \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right.$$
$$\left. + \, sign(u)\, \Delta x_e^2 \frac{\beta}{12}\left\{\left(\frac{\partial^2\psi}{\partial x^2}\right)_{i+1} - \left(\frac{\partial^2\psi}{\partial x^2}\right)_i\right\}\right]$$

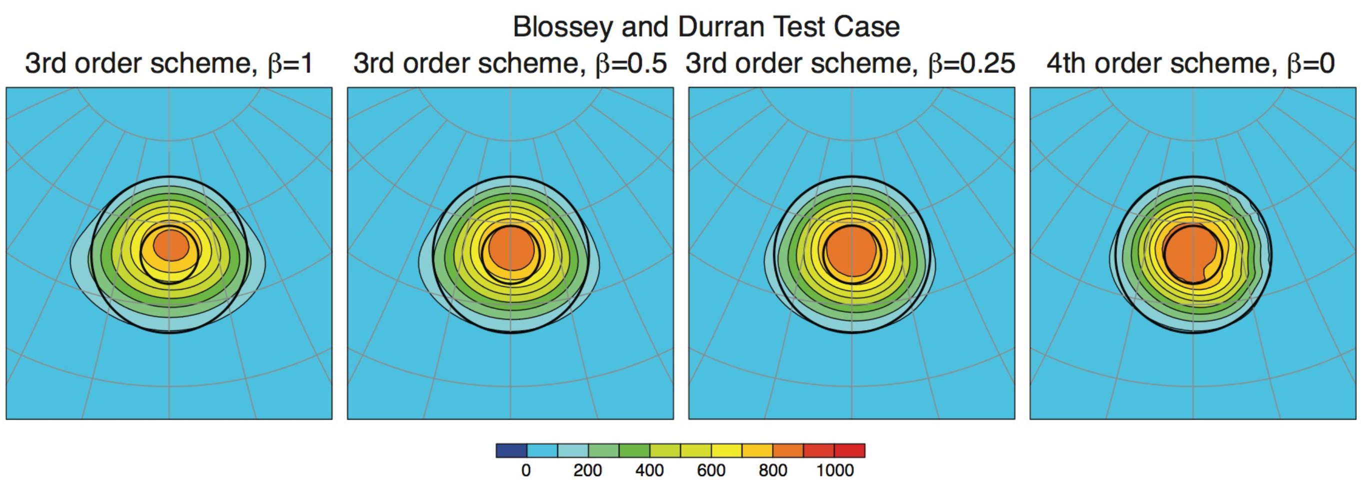

FIG. 7. Deformational flow test case results at time T using (11) with different values of the filter parameter β. The simulations were performed on the 40962-cell grid.

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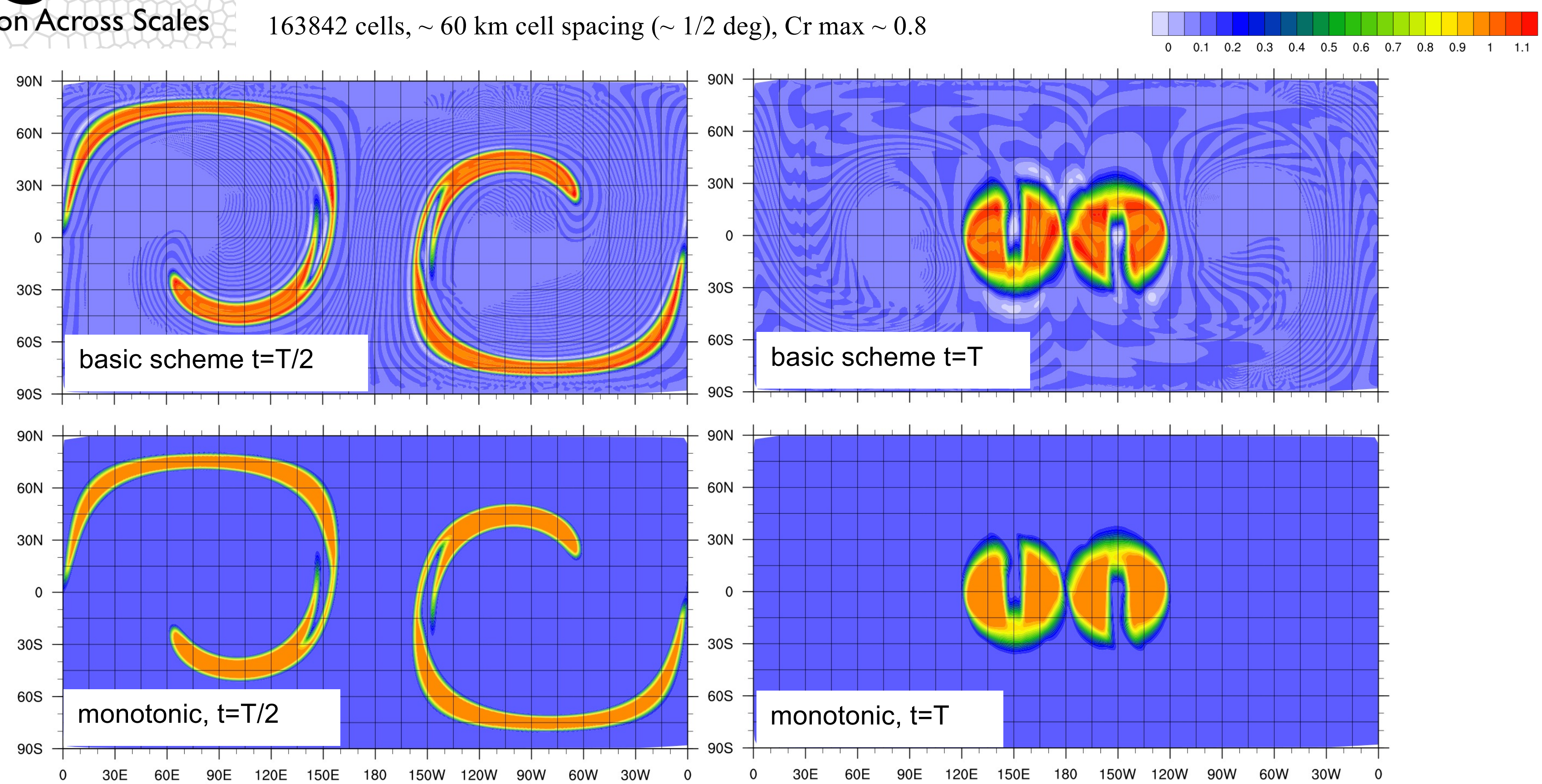
163842 cells, ~ 60 km cell spacing (~ 1/2 deg), Cr max ~ 0.8



Configuring the dynamics

Transport

namelist.atmosphere

```
&nhyd_model
    config_time_integration_order = 2
    config_dt = 720.0
    config_start_time = '2010-10-23_00:00:00'
    config_run_duration = '5_00:00:00'
    config_split_dynamics_transport = true
    config_number_of_sub_steps = 2
    config_dynamics_split_steps = 3
    config_horiz_mixing = '2d_smagorinsky'
    config_visc4_2dsmag = 0.05
    config_scalar_advection = true
    config_monotonic = true
    config_coef_3rd_order = 0.25
    config_epssm = 0.1
    config_smdiv = 0.1
/
```

Upwind coefficient (0 <-> 1),
> 0 increases damping.
= 0, 4^{th} order scheme,
> 0, 3^{rd} order scheme.

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Operators on the Voronoi Mesh
Resolved and turbulent transport

$$\frac{\partial(\rho\phi)}{\partial t} = \underline{-\nabla \cdot \mathbf{V}\phi}$$

Transport by the resolved flow

$$= \underline{\nabla \cdot (\rho K \nabla \phi)}$$

Turbulent transport, e.g. Smagorinsky

K is an eddy viscosity (m^2/s)

$$= \underline{-\nabla \cdot (\rho \nu_4 \nabla(\nabla \cdot \nabla \phi))}$$

4^{th}-order filter cast as a turbulent transport

ν_4 is a hyperviscosity (m^4/s)

MPAS
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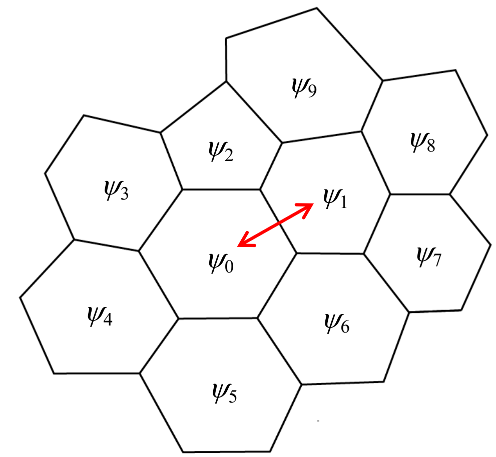
Operators on the Voronoi Mesh
Resolved and turbulent transport

continuous operators		discrete operators
$\nabla \cdot \mathbf{V}\phi$	$\longrightarrow$	$\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\overline{(\mathbf{V}\cdot\mathbf{n_{e_i}})\phi}$
$\nabla \cdot (\rho K \nabla \phi)$	$\longrightarrow$	$\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\overline{\rho K}(\mathbf{n}_{e_i}\cdot\nabla\phi)$
$\nabla \cdot (\rho\, \nu_4 \nabla(\nabla \cdot \nabla \phi))$	$\longrightarrow$	$\frac{1}{A_i}\sum_{n_{e_i}} d_{e_i}\overline{\rho \nu_4}\left(\mathbf{n}_{e_i}\cdot\nabla\left[\frac{1}{A_j}\sum_{n_{e_j}} d_{e_j}(\mathbf{n}_{e_j}\cdot\nabla\phi)\right]\right)$



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Operators on the Voronoi Mesh

Filters for horizontal momentum

2nd order filter

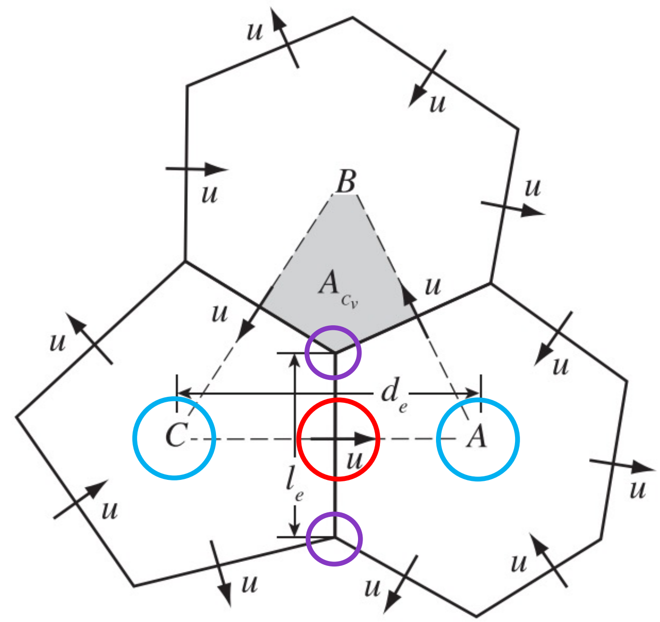
$$\frac{\partial u_i}{\partial t} = \cdots + K_u \nabla^2 u_i$$

$$\nabla^2 u_i = \frac{\partial}{\partial x_i} \nabla_\zeta \cdot \mathbf{v} - \frac{\partial \eta}{\partial x_j}$$

$$\nabla^2 u_i = \frac{\partial}{\partial x_i} \nabla_\zeta \cdot \mathbf{v} - \frac{\partial}{\partial x_j} [\mathbf{k} \cdot (\nabla \times \mathbf{v})]$$

discrete form in MPAS.

η is the vertical vorticity



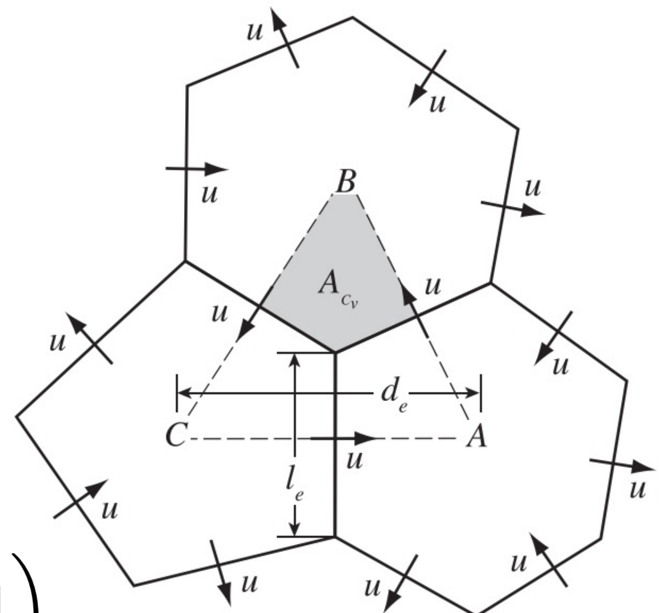
Operators on the Voronoi Mesh
Filters for horizontal momentum

4th order filter

$$\frac{\partial u_i}{\partial t} = \cdots - \nu_4^u \nabla^4 u_i$$

$$\nabla^4 u_i = \nabla^2 \left(\nabla^2 u_i\right)$$

$$\nabla^4 u_i = \frac{\partial}{\partial x_i} \nabla_\zeta \cdot \nabla^2 u_i - \frac{\partial}{\partial x_j} \left[\mathbf{k} \cdot (\nabla \times \nabla^2 u_i)\right]$$



In MPAS

$$\frac{\delta u_i}{\delta t} = -\nu_4 \left(\gamma_u \frac{\partial}{\partial x_i} \nabla_\zeta \cdot \nabla^2 u_i - \frac{\partial}{\partial x_j} \left[\mathbf{k} \cdot (\nabla \times \nabla^2 u_i)\right]\right)$$

MPAS
Model for Prediction Across Scales

Configuring the dynamics

Dissipation

namelist.atmosphere

```
&nhyd_model
    config_time_integration_order = 2
    config_dt = 720.0
    config_start_time = '2010-10-23_00:00:00'
    config_run_duration = '5_00:00:00'
    config_split_dynamics_transport = true
    config_number_of_sub_steps = 2
    config_dynamics_split_steps = 3
    config_horiz_mixing = '2d_smagorinsky'
    config_visc4_2dsmag = 0.05
    config_scalar_advection = true
    config_monotonic = true
    config_coef_3rd_order = 0.25
    config_epssm = 0.1
    config_smdiv = 0.1
/
```

υ_4 $(m^4/s) = \Delta x^3$ x config_visc4_2dsmag

The dissipation options are not applied to the scalar integration. MPAS V8 relies on the monotonic limiter to filter the scalars. We anticipate activating these options for scalars in a future release

Alternately "2d_fixed"

4^{th} order background filter coef, used with 2d_smagorinsky

Configuring the dynamics

Dissipation

namelist.atmosphere

```
&nhyd_model
    config_time_integration_order = 2
    config_dt = 720.0
    config_start_time = '2010-10-23_00:00:00'
    config_run_duration = '5_00:00:00'
    config_split_dynamics_transport = true
    config_number_of_sub_steps = 2
    config_dynamics_split_steps = 3
    config_horiz_mixing = '2d_smagorinsky'
    config_visc4_2dsmag = 0.05
    config_scalar_advection = true
    config_monotonic = true
    config_coef_3rd_order = 0.25
    config_epssm = 0.1
    config_smdiv = 0.1
    config_del4u_div_factor = 10.
/
```

υ_4 *(m⁴/s)* = Δx^3 *x config_visc4_2dsmag*

The dissipation options are not applied to the scalar integration. MPAS V8 relies on the monotonic limiter to filter the scalars. We anticipate activating these options for scalars in a future release

For the horizontal momentum:

$\upsilon_{4,D}$ *(m⁴/s)* = υ_4 *x config_del4u_div_factor*

Hidden in the MPAS V8 namelist.atmosphere

config_del4u_div_factor = 10 (default)

Configuring the dynamics
Dissipation

namelist.atmosphere

```
&nhyd_model
    config_h_mom_eddy_visc2 = 0
    config_h_mom_eddy_visc4 = 0
    config_v_mom_eddy_visc2 = 0
    config_h_theta_eddy_visc2 = 0
    config_h_theta_eddy_visc4 = 0
    config_v_theta_eddy_visc2 = 0
    config_horiz_mixing = "2d_fixed"
```

fixed viscosity (m^2s^{-1})

Fixed hyper-viscosity (m^4s^{-1})

Hidden in the MPAS V8 namelist.atmosphere

The dissipation options are not applied to the scalar integration. MPAS V8 relies on the monotonic limiter to filter the scalars.

2d_fixed option is used primarily in idealized cases.

MPAS
Model for Prediction Across Scales

Spatial Discretization in MPAS
references

Dynamics

Skamarock, W. C, J. B. Klemp, M. G. Duda, L. Fowler, S.-H. Park, and T. D. Ringler, 2012: A Multi-scale Nonhydrostatic Atmospheric Model Using Centroidal Voronoi Tesselations and C-Grid Staggering. Mon. Wea. Rev., 140, 30903105. doi:10.1175/MWR-D-11-00215.1

Transport

Skamarock, W. C. and A. Gassmann, 2011: Conservative Transport Schemes for Spherical Geodesic Grids: High-Order Flux Operators for ODE-Based Time Integration. Mon. Wea. Rev., 139, 2562-2575, doi:10.1175/MWR-D-10-05056.1