Pandemic Programming for Performance Portability:

Coupling Approaches for Next Generation Architectures (CANGA)

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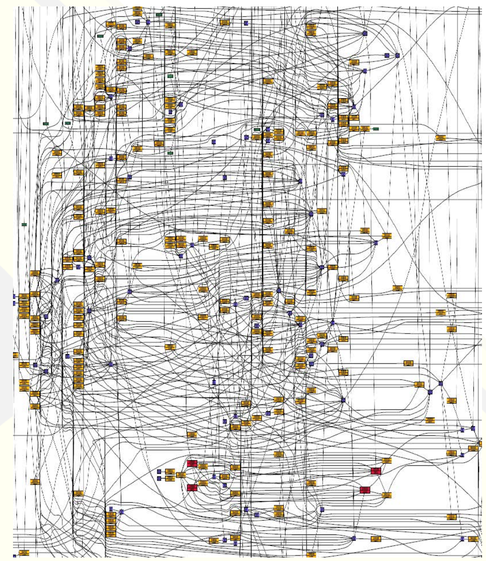
SciDAC Scientific Discovery through Advanced Computing

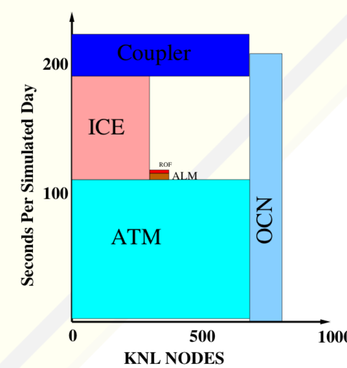
Parallelism Pandemic

- Spread of computational elements increasing
  - Multi-core CPUs
  - GPUs with substantial internal parallelism
- Mutations
  - CPUs, GPUs, FPGAs, Tensor cores, burst buffers
  - configurable, custom (post-K)
- 10k-100k threads/node, variable workloads
- Treatments
  - Directives (OpenMP/OpenACC): R >1
  - Kokkos: R >> 1
    - Portable abstractions through template metaprogramming
    - Emphasis on data layout, indexing, some support tasking
  - 3x - 10x GPU speedups, treats some symptoms (portability, data access)
  - Still can’t get enough oxygen to breathe, esp. strong scaling regime

Social Distancing with Asynchronous Many-Task

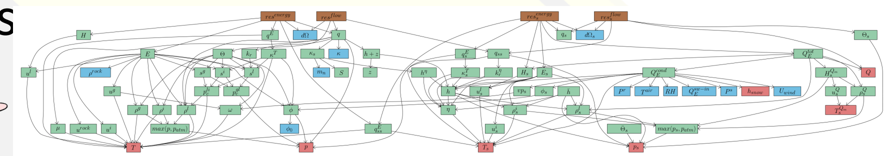
- Federation of tasks
  - Self-isolation: tasks w/ clear interfaces, no side effects
  - Contact tracing: Light-weight runtime creates DAG and schedules work
  - **Legion**, Uintah, HPX, PARSEC, others
- Computing advantages
  - Exposes more parallelism
  - Can automatically load balance
  - Fault tolerance
  - Map tasks to appropriate hardware (I/O, GPU, CPU, etc.)
- Science advantages
  - Managing complexity: to add functionality, add task to task queue
  - Treat models as collection of processes, couple at process level
  - Move away from large monolithic stove-piped components
  - Scale-aware: launch and couple tasks at appropriate time, space scales, enable more flexible time integration (requiring algorithmic change)
  - Include more of overall workflow (e.g. in situ analysis)


Example DAG from S3D combustion

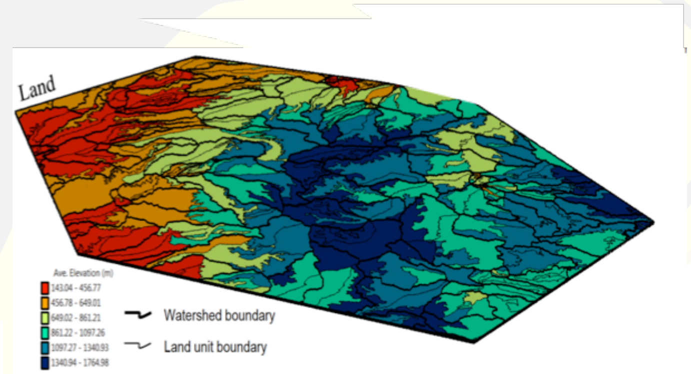


CANGA Project

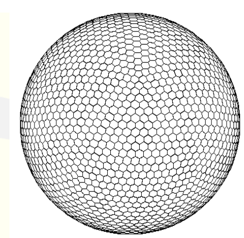
- PIGLET: Prototype Integration of Global models using Legion Execution of Tasks
  - Prototype coupler
  - Task-based components (ocean, ice, land)
  - In situ analysis

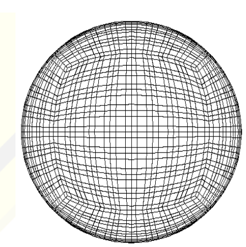


- ROO: Remapping Online-Offline
  - Irregular meshes
  - Property preserving remap
  - Adaptive on-line
  - Meshless remaps (esp. velocity)



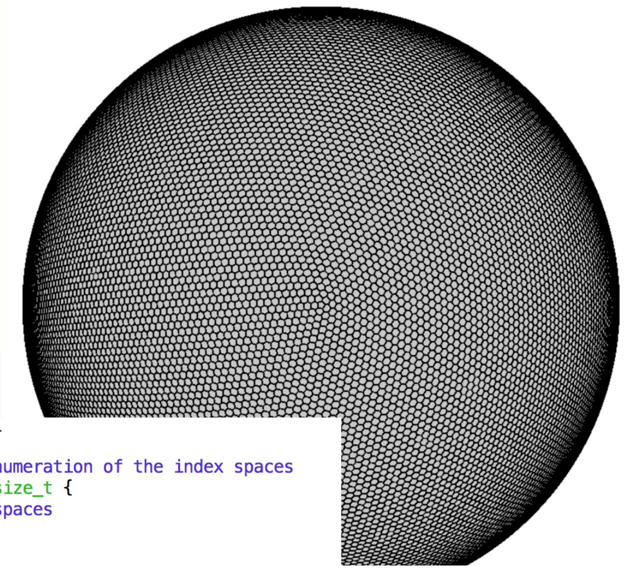
- TIGGER: Time InteGration for Greater E3SM Robustness
  - New time integration approaches
  - Prototype/simple coupled models for testing integration





Legion/FleCSI

- FleCSI: C++ application framework
  - Control, execution, data models
  - Runtime abstractions for AMT
    - MPI, Legion, HPX, Charm++
- Specialization layer (I. Demeshko)
  - Mesh, partitioning
  - Connectivity, owned/shared/halo
  - Performance
- Contact tracing app
  - Register fields
  - Register tasks, with fields, intent (r,w,rw)
- Launch tasks on distributed index space



```
struct index_spaces_t {

  //! The individual enumeration of the index spaces
  enum index_spaces : size_t {
    // the main index spaces
    vertices,
    edges,
    cells,
    // index spaces for connectivity
    vertices_to_edges,
    vertices_to_cells,
    edges_to_vertices,
    edges_to_cells,
    cells_to_vertices,
    cells_to_edges,
    edges_to_edges,
    cells_to_cells,
    //
    // total number of index spaces
    size = cells + 1
  };

  //! Maps an entity dimension to an index space id
  static constexpr size_t entity_map[1][3] = {
    vertices,
    edges,
    cells,
  };
```

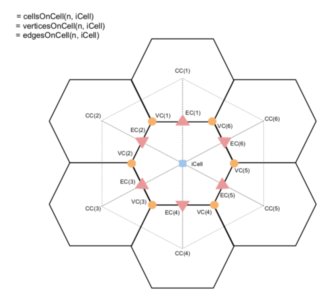
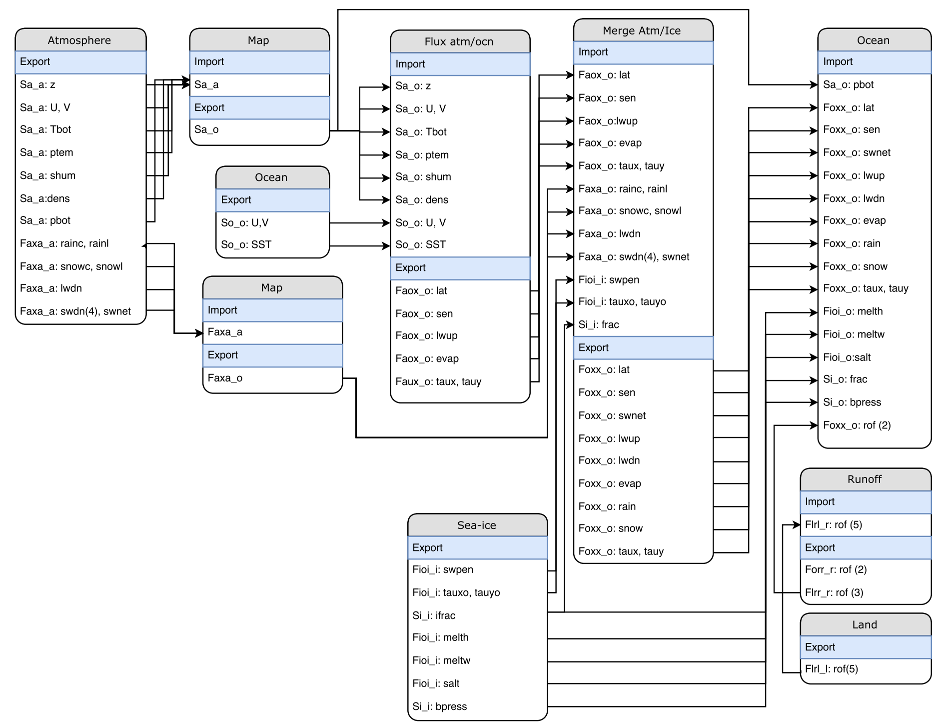


Figure 5.4: Ordering of elements relative to cells.

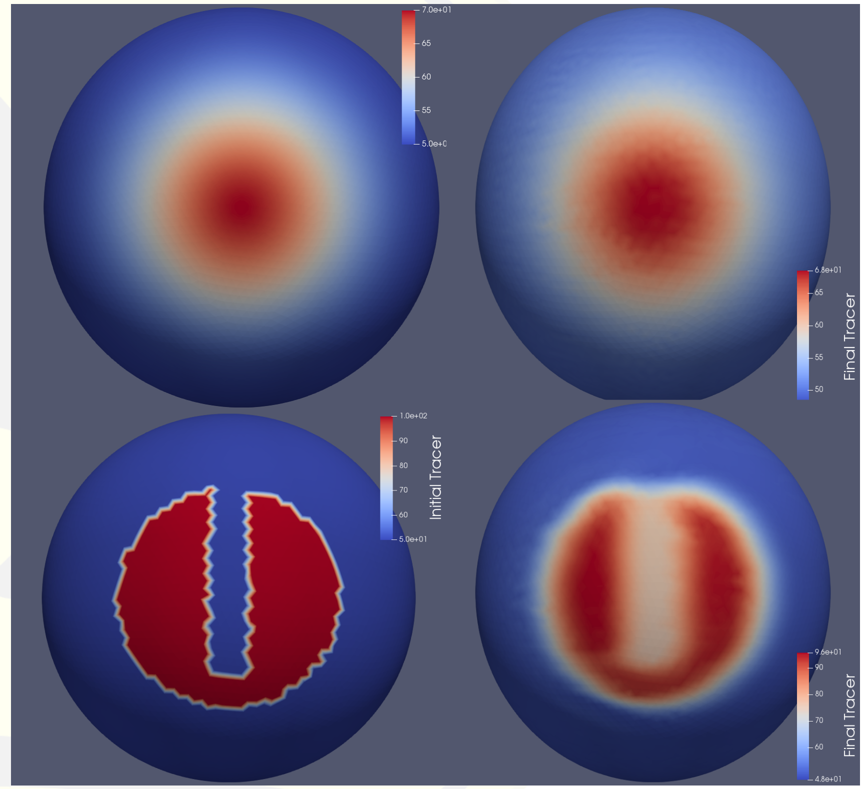
Prototype Coupler

- Start with current coupling
  - Large components
  - Field exchanges slightly simplified
- Interfaces for all functionality
  - Ocean, Atmos, Sea-ice, Land
  - Merging, Remap, Averaging
- Working in FleCSI
- Next steps
  - Awaiting some mesh infrastructure (mult. Meshes)
  - Add more realistic functions, data components
  - Start breaking up large components
    - Evaluate how much parallelism available



Ocean Model (MPAS-O)

- Brian O'Neill, Andrew Reisner
- Started with transport, shallow water
- Now have enough functionality for baroclinic test
  - Testing
- Added parallel I/O capabilities
- ANL: Mukund Raj, Hanqi Guo, Tom Peterka
  - In situ analysis
  - Lagrangian particle tracking
  - Optimizations, predictive load balancing

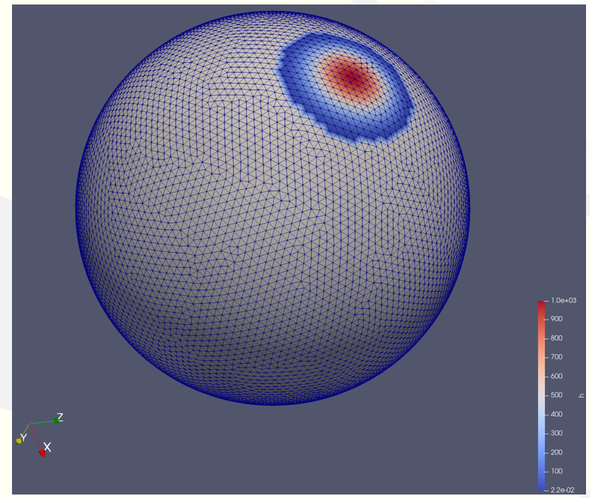


Shallow Water Test Case 1 in FleCSI

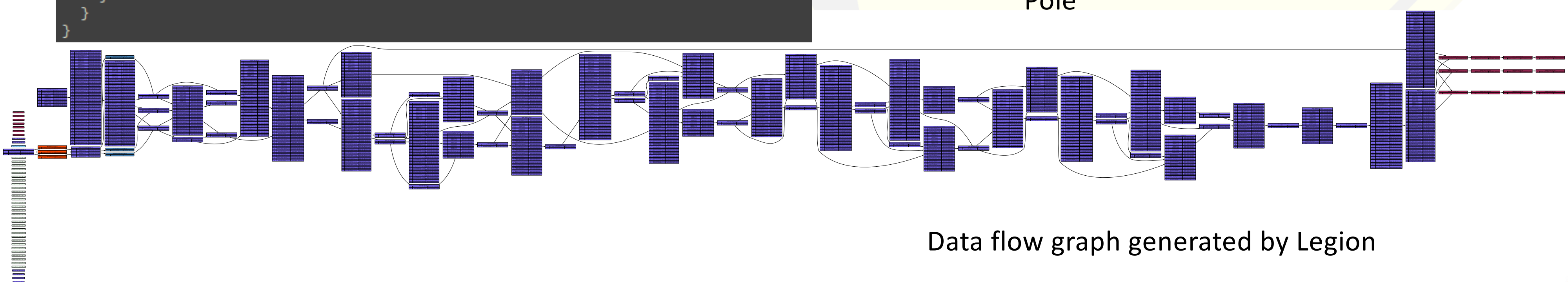
```
// compute height at vertices, pv at vertices, and average pv to edge locations
for (auto v : mesh.vertices()) {
  auto & cells_on_vertex = mesh.cells(v);
  for (std::size_t k = 0; k < nVertLevels; k++) {
    h_vertex(v)[k] = 0.0;
    for (std::size_t i = 0; i < vertexDegree; i++) {
      h_vertex(v)[k] += h(cells_on_vertex[i])[k] * kiteAreasOnVertex(v)[i];
    }
    h_vertex(v)[k] /= areaTriangle(v);

    pv_vertex(v)[k] = (fVertex(v) + vorticity(v)[k]) / h_vertex(v)[k];
  }
}

// compute pv at the edges
for (auto e : mesh.edges()) {
  for (std::size_t k = 0; k < nVertLevels; k++) {
    pv_edge(e)[k] = 0.0;
  }
}
for (auto v : mesh.vertices()) {
  for (auto e : mesh.edges(v)) {
    for (std::size_t k = 0; k < nVertLevels; k++) {
      pv_edge(e)[k] += 0.5 * pv_vertex(v)[k];
    }
  }
}
```



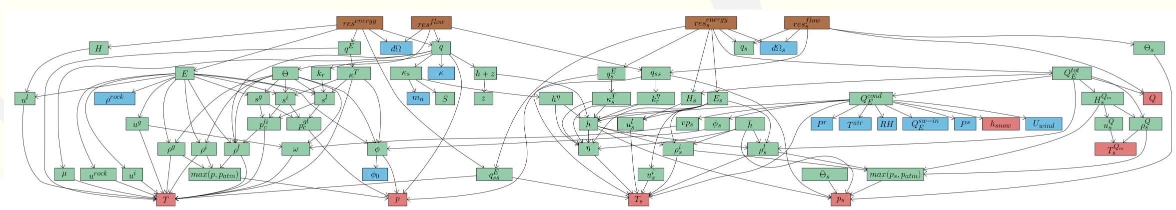
Advection of Cosine Bell over the Pole

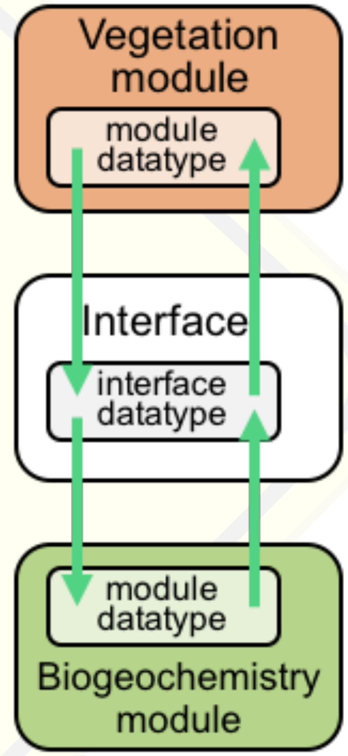


Data flow graph generated by Legion

CANGA – Component Model (Land)

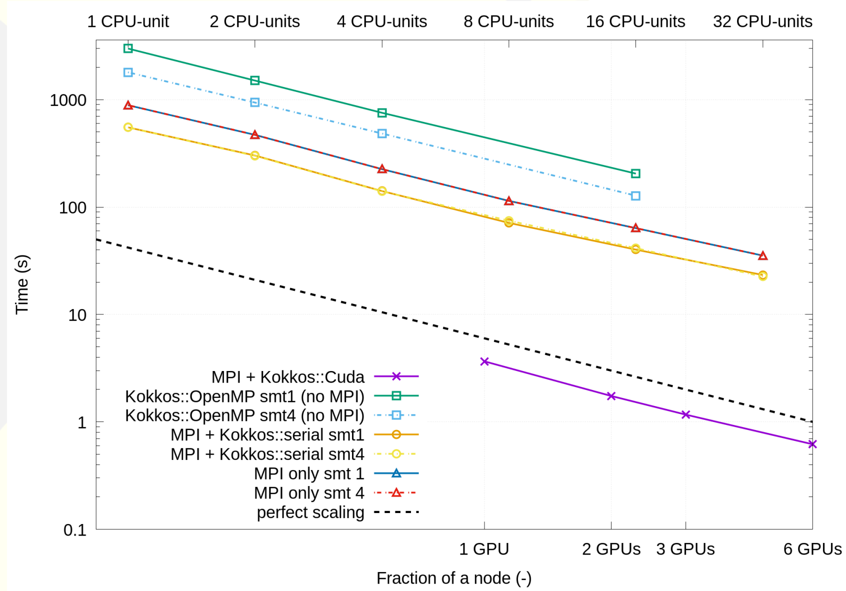
- ORNL: Ethan Coon, Himanshu Pillai, Mario Morales Hernandez
- Continued (arduous) effort to refactor ELM fixed-phenology model into kernels suitable for tasking and/or acceleration.
  - Finished: `CanopyHydrology`
  - Ongoing: `CanopySunFraction` `SurfaceRadiation` `CanopyTemperature` `BareGroundFluxes` `CanopyFluxes`
  - Process:
    - Refactor existing ELM to identify interfaces, ensure correctness of Fortran kernel
    - Implement test harness around kernel in C++, call Fortran kernel
    - Source translator: Fortran kernel → C++ kernel
    - Template C++ kernel on array-type to allow Legion, Kokkos, FleCSI data
- Implemented light-weight layer on Legion for supporting ELM data model.

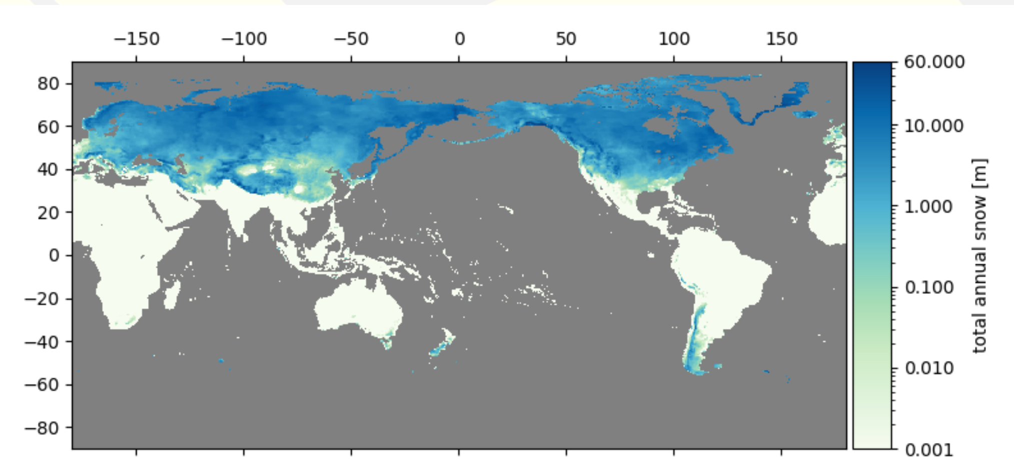




Land Mini-app Performance

- Global application based on CRU forcing at 0.5 degrees
- Executed `CanopyHydrology` on 17 Plant Functional Types across the globe (purposefully load imbalanced)
- Comparing performance of kernels on two nodes of Summit using: Legion, MPI, MPI+Kokkos::OpenMP, MPI+Kokkos::Cuda, Legion+Kokkos::Cuda





[Exploring the Use of Novel Programming Models in Land Surface Models]
Coon, Ethan T ; Elwasif, Wael R ; Pillai, Himanshu ; Thornton, Peter E ; Painter, Scott L; 2019 IEEE/ACM Parallel Applications Workshop, Alternatives To MPI (PAW-ATM), 2019-11, p.1-10

Summary of Task-parallel Work

- Functionality increasing and getting close to realistic code
- Starting to be able to evaluate
  - Performance
  - Ease of use

RNA vaccines (Remapping New Algorithms)

- New features related to Tempest remap
  - Irregular meshes (eg watersheds)
  - MOAB integration
  - Velocity remap and property preservation
- Meshless Remap
  - Remap from native field locations
  - Property preservation
- Adaptive online remap
  - Adapt order of remap based on field properties
  - Discontinuities in fields/domains
- Clinical trials

Tempest and MOAB

- P. Ullrich, Vijay Mehadavan
- Irregular domains complete (v2.0.1, 2018)
- Integration with MOAB
  - Performance at scale
- Bounds preservation (flatten the curve)
  - Clip and Assured Sum (CAAS)
- Property preservation
  - Theoretical limits

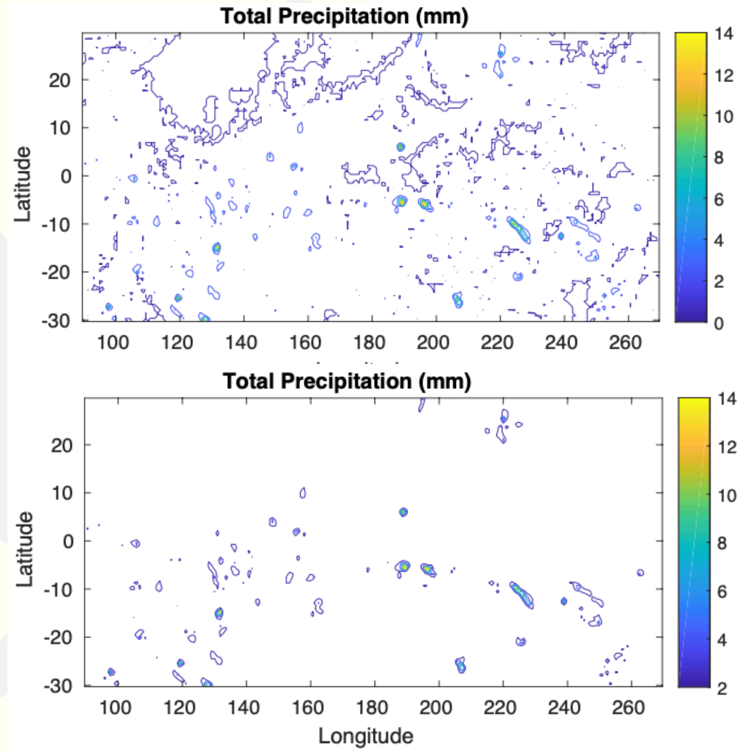
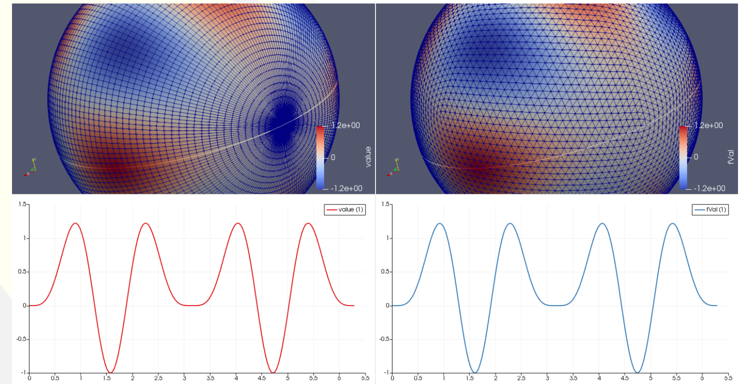


Figure: [Top] Precipitation field without CAAS. [Bottom] Precipitation field with CAAS, now maintaining a zero lower bound on the field.

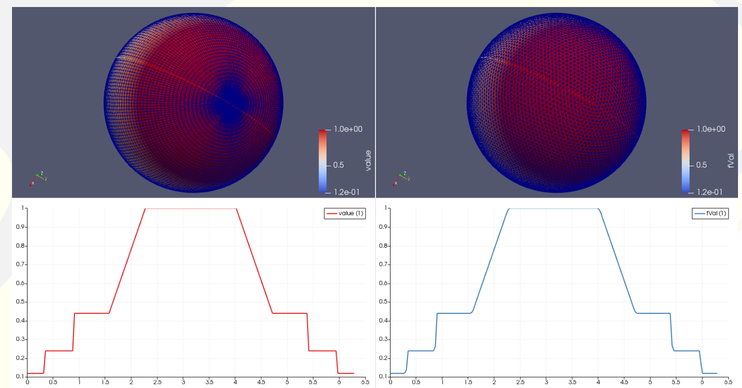
- **V. Mahadevan, I Grindineau, R Jacob, J Sarich.** 2018. Improving climate model coupling through a complete mesh representation: a case study with E3SM (v1) and MOAB (v5.x), Geosci. Model Dev., DOI:10.5194/gmd-2018-280, in press.

Adaptive On-line Remap

- SUNY: Jim Jiao, Yipeng Li (Stony Brook)
- Weighted Least Squares – Essentially Non-Oscillatory (WLS-ENO)
  - High-order accuracy with superconvergence for smooth functions using weighted least squares
  - Techniques for detecting and resolving Gibbs Phenomenon at C^0 and C^1 discontinuities in remap
  - Accurate and robust treatment of pole singularities in latitude-longitude grids
    - Y. Li, Q. Chen, X. Wang, and X. Jiao, WLS-ENO Remap: Superconvergent and Non-Oscillatory Weighted Least Squares Data Transfer on Surfaces, *J. Comput. Phys.*, 2020, under revision.
    - Y. Li, X. Jiao, et al., Adaptive Resolution of Gibbs Phenomenon in High-Order Remapping between Non-Matching Meshes, to be submitted to *J. Comput. Phys.*



Transfer of spherical harmonics from RLL to CVT mesh.



Transfer of discontinuous functions from RLL to CVT mesh.

Meshless Remap

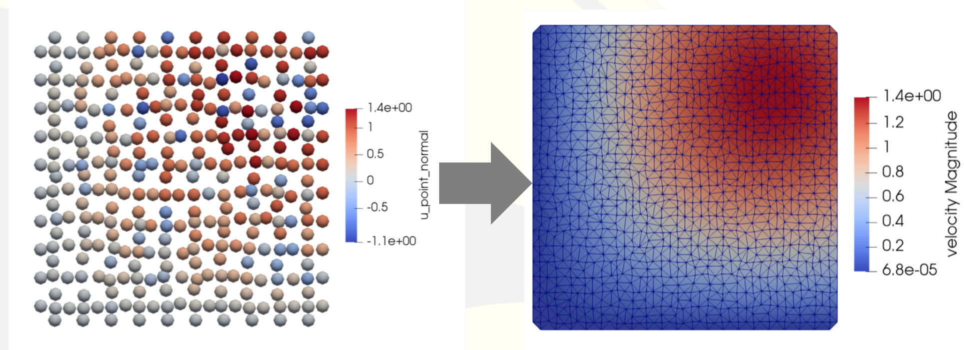
- Paul Kuberry, SNL
- Native field reconstructions for various DOF representations
- Three methods
  - Gen Moving Least Squares (GMLS)
  - GMLS w/ global conservation
  - GMLS + CAAS for local bounds preservation (squash the sombrero)
- Degree of basis (1-4)
- Additional property preservation planned

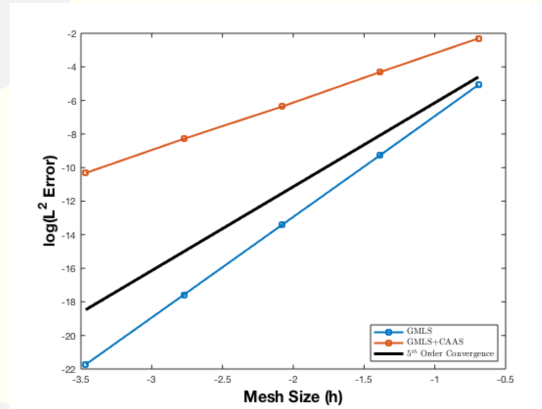
Software release: Compadre Toolkit v. 1.0 DOI: [10.11578/dc.20190411.1](https://doi.org/10.11578/dc.20190411.1)

P. Kuberry, P. Bochev and K. Peterson, A virtual control, mesh-free coupling method for non-coincident interfaces. Proceedings of the ECCM 6/ECFD 7, Glasgow, UK, 2018.

P Kuberry, P Bosler, *Meshless Transfer for Earth System Models via the Compadre Toolkit*. Workshop on Meshfree and Particle Methods: Application and Theory, September 2018, Santa Fe, New Mexico.

Data Transfer from Face Elements (RT) to a nodal finite element basis





Convergence study CubeSphere to ICOS:
Optimal for GMLS
Suboptimal for GMLS+CAAS (investigating)

Clinical Trials: Remap Intercomparison

Black-box Regridding Operators

$R_{S\text{->}T}\, X_S = X_T$

- Conservative, high-order L_2 projection
- Mesh-free, patch-based recovery
- Generalized Moving Least Squares method
- Lagrange-multiplier based optimization schemes

Sampled field on source mesh

Apply Regridding

Remapped field on target mesh

Source mesh

Target mesh

Mesh preprocessing

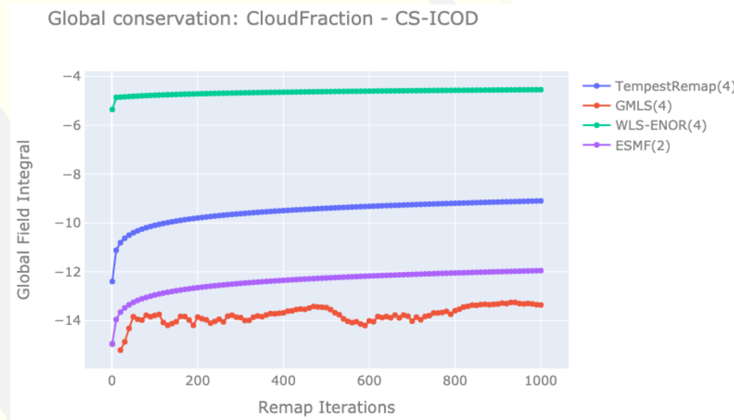
- Cell areas
- Global GLL nodes and Jacobians
- Cell vertex connectivity
- Cell adjacency connectivity

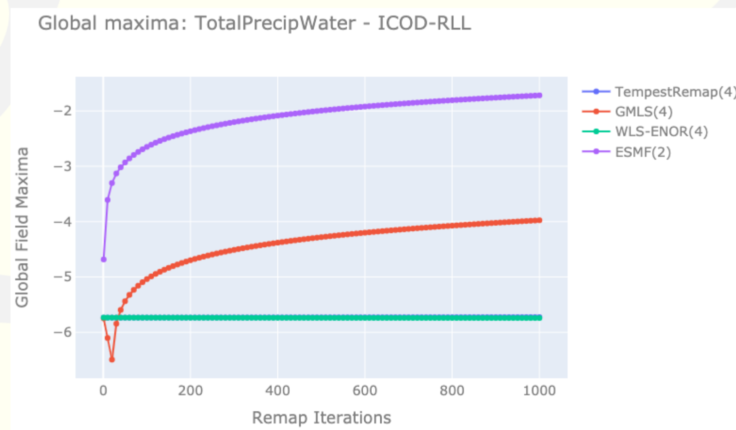
Metrics computations (Python implementation)

- Global integrals (FV and SE type)
- Scalar gradient SE type (direct differentiation over Legendre basis)
- Scalar gradient FV type Barth & Jespersen, 1989 (strategy 3)
- Common metrics implemented in Python:
  - Conservation, accuracy, locality, global and local extrema preservation, and accuracy on gradient of remapped field.
- Manuscript detailing metrics and comparing FV-FV remap schemes

Clinical Trials: Remap Intercomparison

- Analytic Fields
  - Spherical harmonic truncations of observed fields
  - Allows for error, order of convergence
- All methods included
- Metrics
  - Issues with sampling, convergence
  - Sometimes sensitive to metric calc itself
- Compliance with mask orders
  - Ocean, ice meshes wear a mask





Time Integration

- New time integration schemes and analysis
  - Goal of consistent, accurate schemes with no iteration of components
  - Bulk-IFR, ImEx, Heterogeneous
  - SNL, ANL/OSU groups
- Simpler prototype coupled systems
  - Advection, diffusion equations
  - Coupling using bulk formulae at interface
- Analysis of existing E3SM coupling

Ocean-Atmosphere Coupling

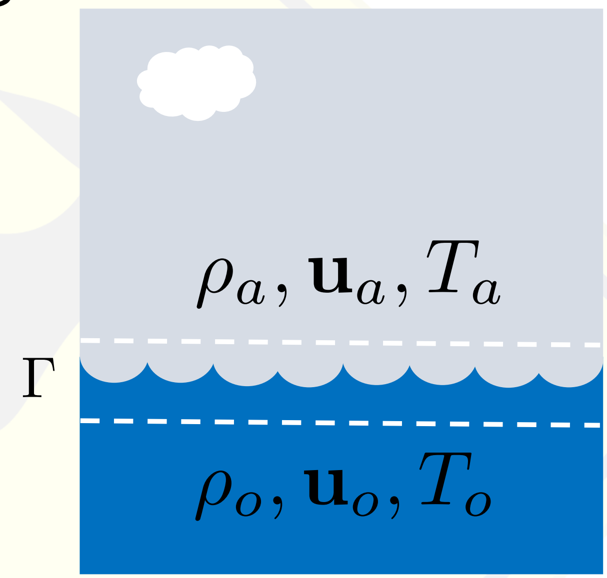
- Consider partial differential equations for atmosphere and ocean circulation with state variables velocity and temperature
- Ocean-atmosphere fluxes are defined by a parameterization of the surface layers: “bulk” formulation
- Coupling conditions

$$\rho_a \nu_a \frac{\partial \mathbf{u}_a}{\partial z} = \rho_o \nu_o \frac{\partial \mathbf{u}_o}{\partial z} = \boldsymbol{\tau} \quad \text{on } \Gamma$$

$$\rho_a K_a \frac{\partial T_a}{\partial z} = \rho_o K_o \frac{\partial T_o}{\partial z} = Q_{net} \quad \text{on } \Gamma$$

$$\boldsymbol{\tau} = \rho_a C_\tau \|[\![\mathbf{u}]\!]\| [\![\mathbf{u}]\!] \qquad Q_{net} = \mathcal{R} + \rho_a C_Q \|[\![\mathbf{u}]\!]\| [\![T]\!]$$

Lemarié, Blayo, Debreu (2015) *Proc. Comp. Sci.*; M. Gross, *et al.* (2018) *MWR*



Velocity and temperature jump at interface

$$[\![\mathbf{u}]\!] = \mathbf{u}_a - \mathbf{u}_o \quad \text{on } \Gamma$$

$$[\![T]\!] = T_a - T_o \quad \text{on } \Gamma$$

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SNL: New time integration approaches

- K. Petersen, C. Sockwell, P. Kuberry, P. Bochev
- New synchronous partitioned scheme for ocean-atmosphere, based on a fully discrete monolithic coupled equations, has been developed and tested on simple 2D tracer equations (paper submitted)
- Investigate consistency of coupling – time integrator
- Flexibility in choice of time-step size and integrator
- Derive Unified framework for taxonomy of couplers
- Improve efficiency of Schur Complement: Investigate dual Lagrange multiplier methods and preconditioners

Atmosphere/ocean tracer

$$\dot{T}_a + \frac{\partial}{\partial x}(u_a T_a) = \frac{\partial}{\partial z} K_a \frac{\partial T_a}{\partial z}$$

$$K_a \frac{\partial T_a}{\partial z} = K_o \frac{\partial T_o}{\partial z} = \alpha(T_a - T_o) \qquad \Gamma$$

$$\dot{T}_o + \frac{\partial}{\partial x}(u_o T_o) = \frac{\partial}{\partial z} K_o \frac{\partial T_o}{\partial z}$$

Non-Iterative Methods for Ocean-Atmosphere Coupling

Bulk Interface Flux Recovery (Bulk-IFR) Coupling Method:
- Approximates interface flux of **monolithic system**
- **Schur complement** method
- Approximates flux at **current time-step** t_{n+1}
- Subsystems solved **independently** with flux as BC

Pros:
- Flux conservation
- Stability
- Consistent time discretization
- Decoupled components
- Heterogeneous time discretization

Cons:
- Schur complement is expensive (future research)

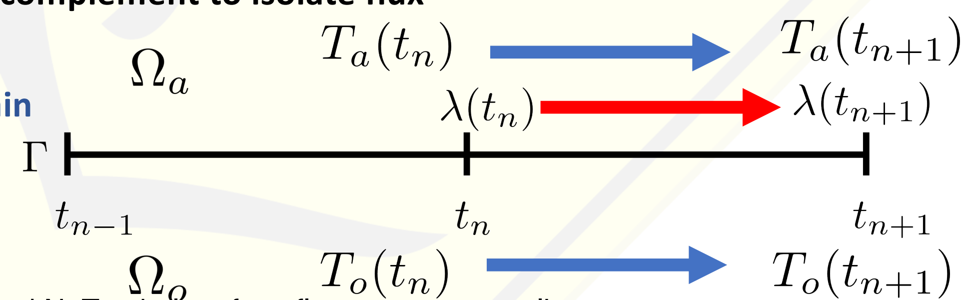
- **Step 1: Define flux as auxiliary variable**

$$\lambda = K_a \frac{\partial T_a}{\partial z} = -K_o \frac{\partial T_o}{\partial z} = \alpha(T_a - T_o)$$

- **Step 2: Define Discrete monolithic system at time t_{n+1}**

$$\begin{bmatrix} M_a & 0 & \Delta t G_{a,\gamma}^T \\ 0 & M_o & -\Delta t G_{o,\gamma}^T \\ \alpha G_{a,\gamma} & -\alpha G_{o,\gamma} & -M_\gamma \end{bmatrix} \begin{bmatrix} T_a^{n+1} \\ T_o^{n+1} \\ \lambda \end{bmatrix} = \begin{bmatrix} \Delta t f_a(T_a^n) \\ \Delta t f_o(T_o^n) \\ 0 \end{bmatrix}$$

- **Step 3: Schur complement to isolate interface DoFs**
- **Step 4: Additional Schur complement to isolate flux**
- **Step 5: Solve for flux**
- **Step 6: Update subdomain solutions independently with flux boundary conditions**



K. C. Sockwell, K. Peterson, P. Kuberry, P. Bochev, and N. Trask. Interface flux recovery coupling method for the ocean–atmosphere system. Results in Applied Mathematics, 8:100110, 2020.

TIGGER Task (SNL): Bulk-IFR results on simplified ocean-atmosphere tracer testcase

2D domain (Horizontal (x) and Vertical (y)) with small sinusoidal forcing in Atmosphere. Advection in vertical direction, diffusion in vertical. Coupling only in vertical direction.

Manufactured Solution is oscillation about reference Temperature

$$T_a = \frac{A}{2n\pi K_a}(y-a)^2 \cos(n\pi(x-ut)) + T_{\text{ref}}$$

$$T_o = \frac{B}{n\pi K_o}(y-b)\cos(n\pi(x-ut)) + T_{\text{ref}}$$

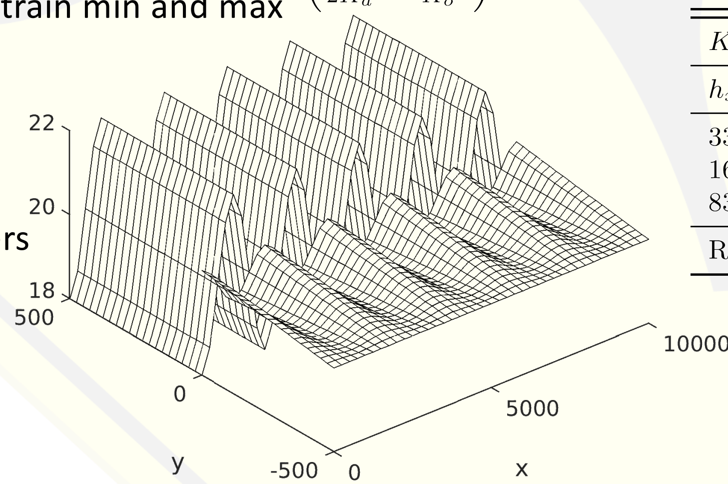
Bulk Condition implies:

$$\alpha = -\frac{Aa}{\left(\frac{a^2 A}{2K_a} + \frac{B}{K_o} b\right)}$$

Constants a and b constrain min and max

Figure: Temp in Celsius

Domain in meters



$K_o = 0.1\ \mathrm{m^2s^{-1}}$	$K_a = 2\ \mathrm{m^2s^{-1}}$	α = 4e-4		
h_x	h_y	Δt	L_2	H_1 SN
333	33.3	1.06	5.059e-03	2.967e-01
166	16.6	0.52	1.216e-03	1.488e-01
83.3	8.33	0.26	2.923e-04	7.458e-02
Rate	-	-	2.057	0.997
$K_o = 10\ \mathrm{m^2s^{-1}}$	$K_a = 200\ \mathrm{m^2s^{-1}}$	α= 4e-2		
h_x	h_y	Δt	L_2	H_1 SN
333	33.3	0.277	4.718e-03	2.993e-01
166	16.6	0.069	1.261e-03	1.547e-01
83.3	8.33	0.017	4.124e-04	8.085e-02
Rate	-	-	2.057	0.997

Table 1: Errors for small and large diffusivities

Consistency in coupling methods

New research direction focusing on achieving consistent in time couplings

- The accuracy of the monolithic system can be spoiled by inconsistent coupling
- IFR coupling can viewed as providing an implicit approximation to the flux: consistency requires an **implicit scheme**
- Direct coupling can viewed as providing an explicit approximation to the flux: consistency requires an **explicit scheme**
- Research question: What to do when mixing implicit and explicit?

Example: choice of a specific coupling approach ”locks” in place a consistency requirement for the time integration scheme:

Method	Coupling	L^2	H^1
FE	Direct	2.815e-15	6.879e-13
FE	IFR	1.336e-4	2.992e-2
BE	Direct	9.689e-5	1.763e-2
BE	IFR	2.818e-15	6.862e-13

Table 1: Relative L^2 and H^1 errors for the simple forward (FE) and backward (BE) Euler comparison with each type of coupling (direct and IFR).

Heterogeneous Asynchronous Time Integrator (HATI)

- Coupler should allow each component to choose time-step size.
  This leads to **Asynchronous time integrator**.

- Combine with flexible choice of time-integrator leads to:
  Heterogeneous Asynchronous Time Integrator (HATI)

- On going collaboration with Jeff Conners (Uconn).
  Space-time approach to allow for asynchronous time steps.
  Time-DG approach allows for many time-discretizations
  to fall into Bulk-IFR framework

- Goal: Flexible HATI integrator in Bulk-IFR coupling framework
  1. Flexible choice in time discretizations (IMEX, Multi-rate)
  2. Flexible choice in time-step size and coupling windows
  3. HATI coupling method is conservative and stable

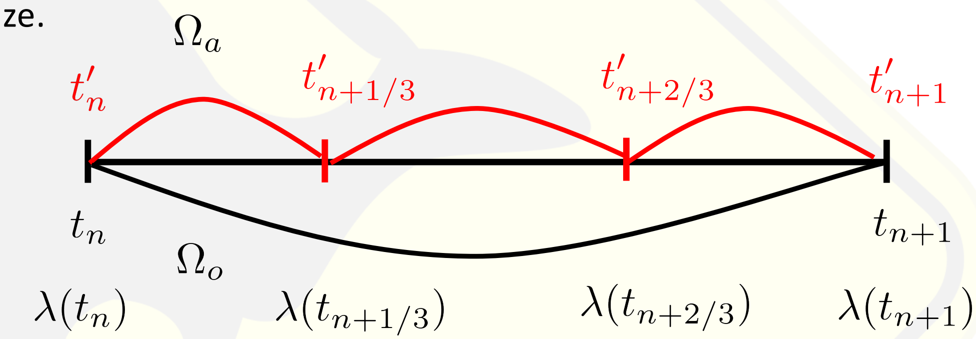


Figure: Time steps for each model over coupling window

ANL: Coupling two Navier-Stokes systems

- Shinhoo Kang, Hong Zhang, Emil Constantinescu
- Impermeable boundary (rigid lid)

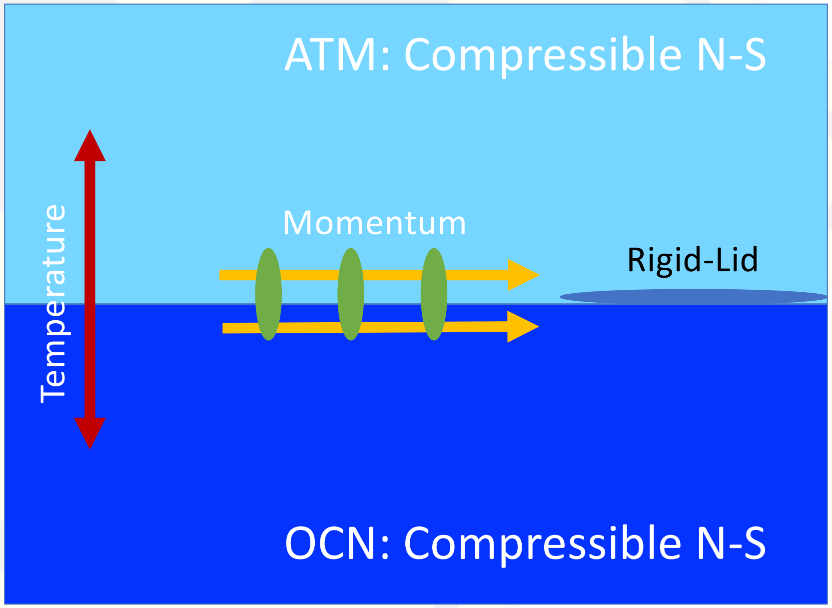
$$(\mathbf{u} \cdot \boldsymbol{n} = \mathbf{0})$$

- Continuity of horizontal momentum

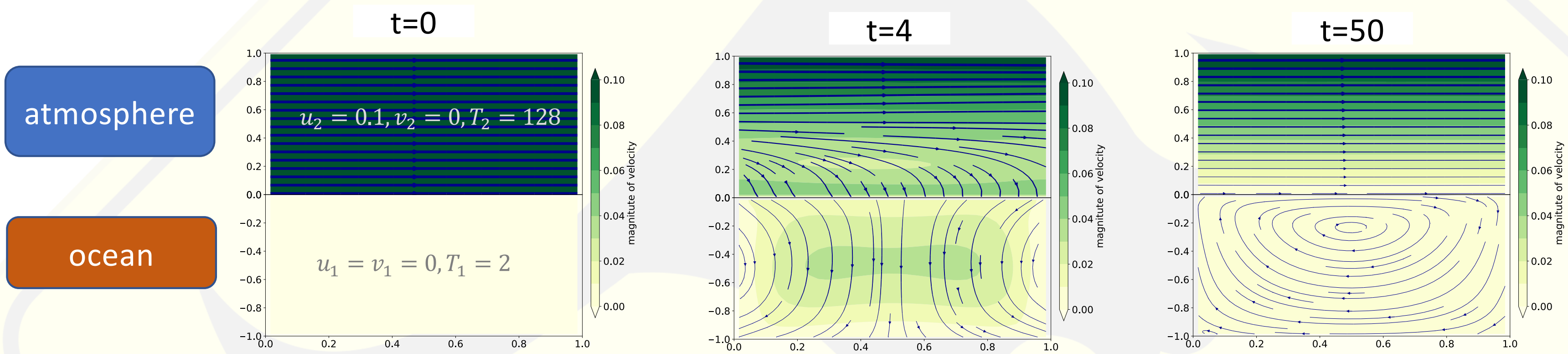
$$\mu_1 \frac{\partial u_1}{\partial y} = \mu_2 \frac{\partial u_2}{\partial y} = b_u(u_2 - u_1)$$

- Continuity of heat flux

$$\kappa_1 \frac{\partial T_1}{\partial y} = \kappa_2 \frac{\partial T_2}{\partial y} = b_T(T_2 - T_1)$$

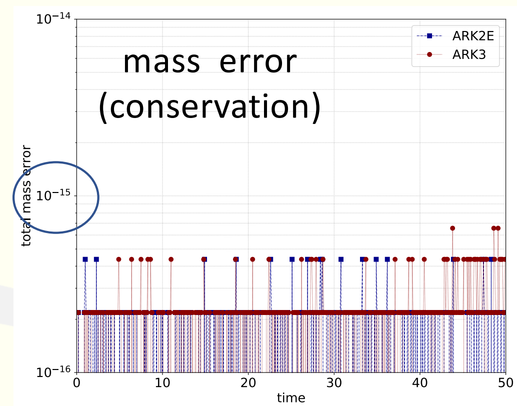


ANL: Implicit-Explicit (IMEX) Coupling



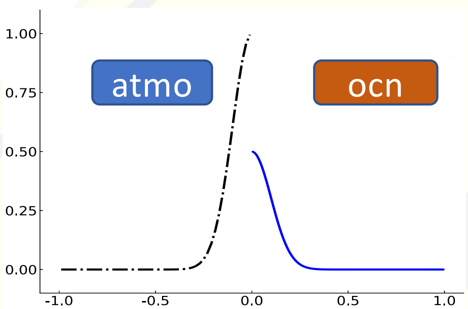
Two coupled compressible Navier-Stokes systems

- Integrate nonstiff system (ocean) explicitly and integrate stiff system (atmosphere) implicitly.
- Exchange the horizontal momentum and the heat flux across interface data under rigid-lid assumption (zero normal velocity) at every stage.
- Total mass is conserved
- High-order IMEX methods
- First-order finite volume method (interface consistency), developing high-order

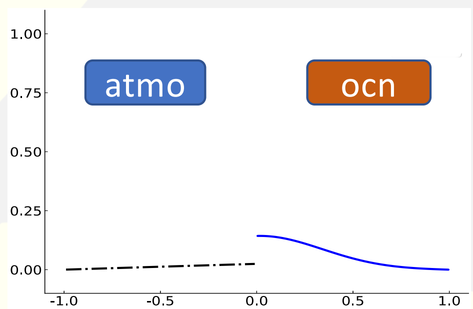


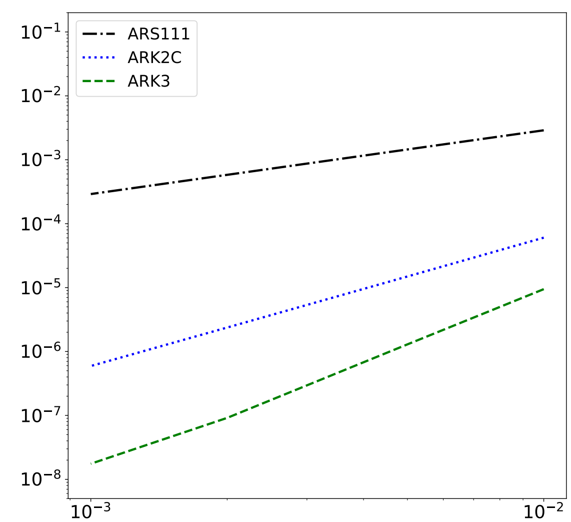
Implicit-Explicit (IMEX) Coupling method

T=0



T=1





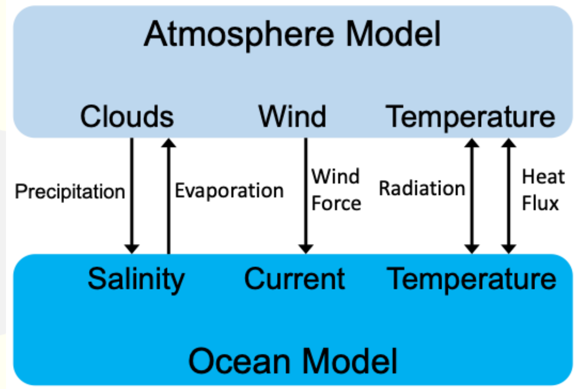
Temporal Convergence study for coupled diffusion eq.

- Achieves 1st and 2nd order convergence rates for ARS111 and ARK2.
- ARK3 is closed to third-order convergence rates above 1e-7 error levels.
- 2nd order central FD method is used for spatial discretization.
- Stiff system (atmosphere) is treated implicitly,
  whereas nonstiff system (ocean) is explicitly dealt with.
  Two orders of magnitude difference is observed in Courant numbers.

dt	$Cr_{d_1}(Cr_{d_2})$	ARS111		ARK2C		ARK3	
		error	order	error	order	error	order
0.010	100.0 (0.16)	2.892e-03	–	6.042e-05	–	9.452e-06	–
0.005	50.0 (0.08)	1.450e-03	0.996	1.492e-05	2.018	1.293e-06	2.870
0.002	20.0 (0.03)	5.812e-04	0.998	2.372e-06	2.007	9.149e-08	2.890
0.001	10.0 (0.02)	2.908e-04	0.999	5.927e-07	2.001	1.753e-08	2.384

TIGGER: Coupling Stability Analysis

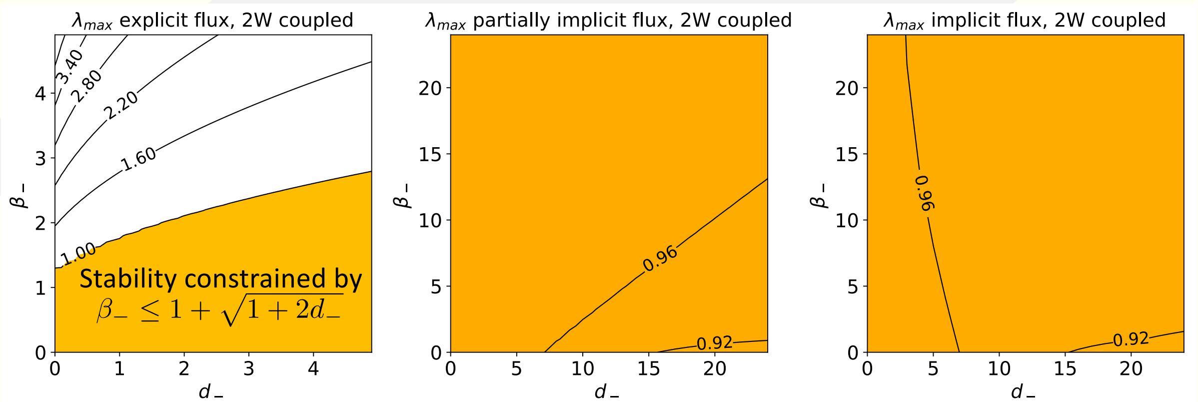
- SNL: Nikki Plakowski, Paul Kuberry
  - Eigenvalue analysis of IFR
  - Noisy, inconclusive
- ANL: H. Zhang, Z. Liu, E. Constantinescu, R. Jacob
  - Normal mode analysis
  - Established stability theory for one-way and two-way coupled systems with bulk interface conditions. (paper published)



$$
\begin{aligned}
\frac{\partial u_1(t,x)}{\partial t} &= F_1(t,u_1(t,x),u_2(t,x)) && \text{in } [t_0,t_f]\times\mathcal{D}_1\\
\frac{\partial u_2(t,x)}{\partial t} &= F_2(t,u_1(t,x),u_2(t,x)) && \text{in } [t_0,t_f]\times\mathcal{D}_2\\
0 &= G_{12}(u_1(t,x),u_2(t,x)) && \text{on } [t_0,t_f]\times(\mathcal{D}_1\cap\mathcal{D}_2)
\end{aligned}
$$

TIGGER: Stability Analysis of Interface Conditions in Ocean-Atmosphere Coupling

- Performed **normal mode** stability analysis for two interface conditions and a variety of flux coupling schemes
- Established novel **CFL-like** stability condition that involves the bulk coefficient
- Provided numerical tools to identify instability

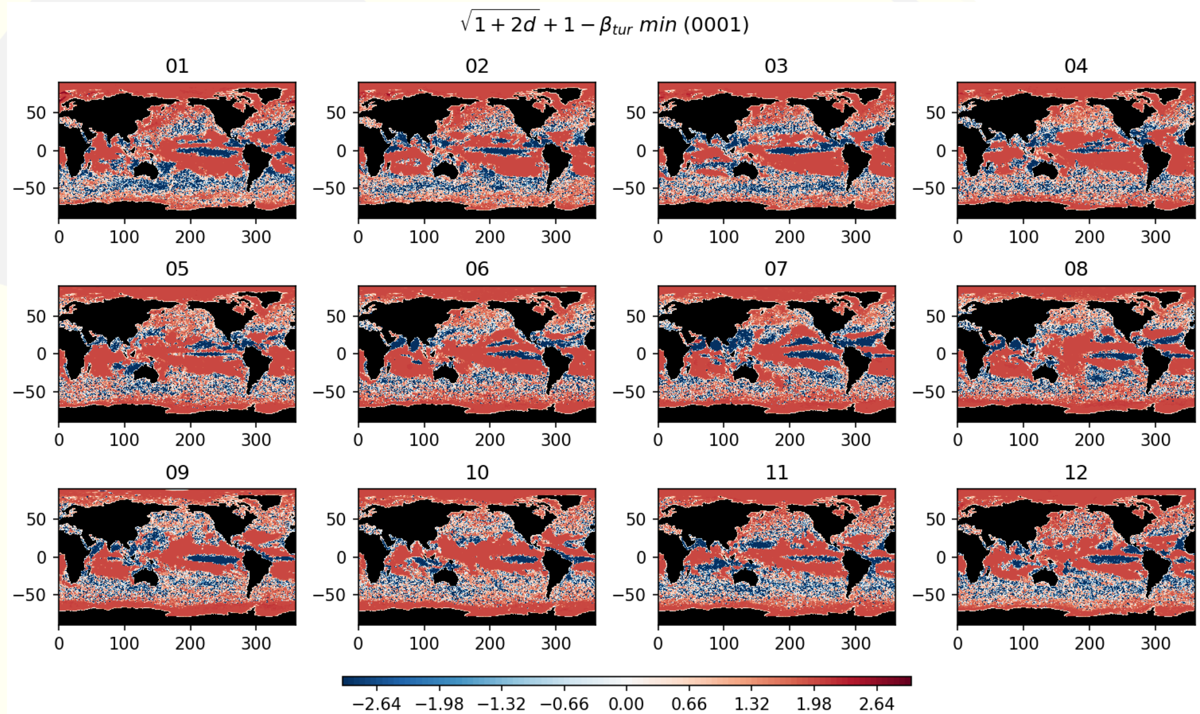


- **Hong Zhang**, **Zhengyu Liu, Emil Constantinescu, Robert Jacob,** Stability Analysis of Interface Conditions for Ocean-Atmosphere Coupling, 2019, submitted
- **Hong Zhang,** Stable time integration for coupled ocean-atmosphere models. SIAM Conference on Computational Science and Engineering, LANS Seminar, Argonne National Laboratory, November, 2019

Stability Analysis of Atmosphere-Ocean Coupling in E3SM

Analyzing and identifying regions of potential unstable coupling using the theoretical CFL-like condition

- Plot showing the minimum of the parameter. Negative value (blue) suggests potential instability during the 1-yr simulation.
- Instability appears in regions with small diffusivity and large coupling coefficient
- Significant seasonal variability: caused by that of both coupling coefficient and diffusivity

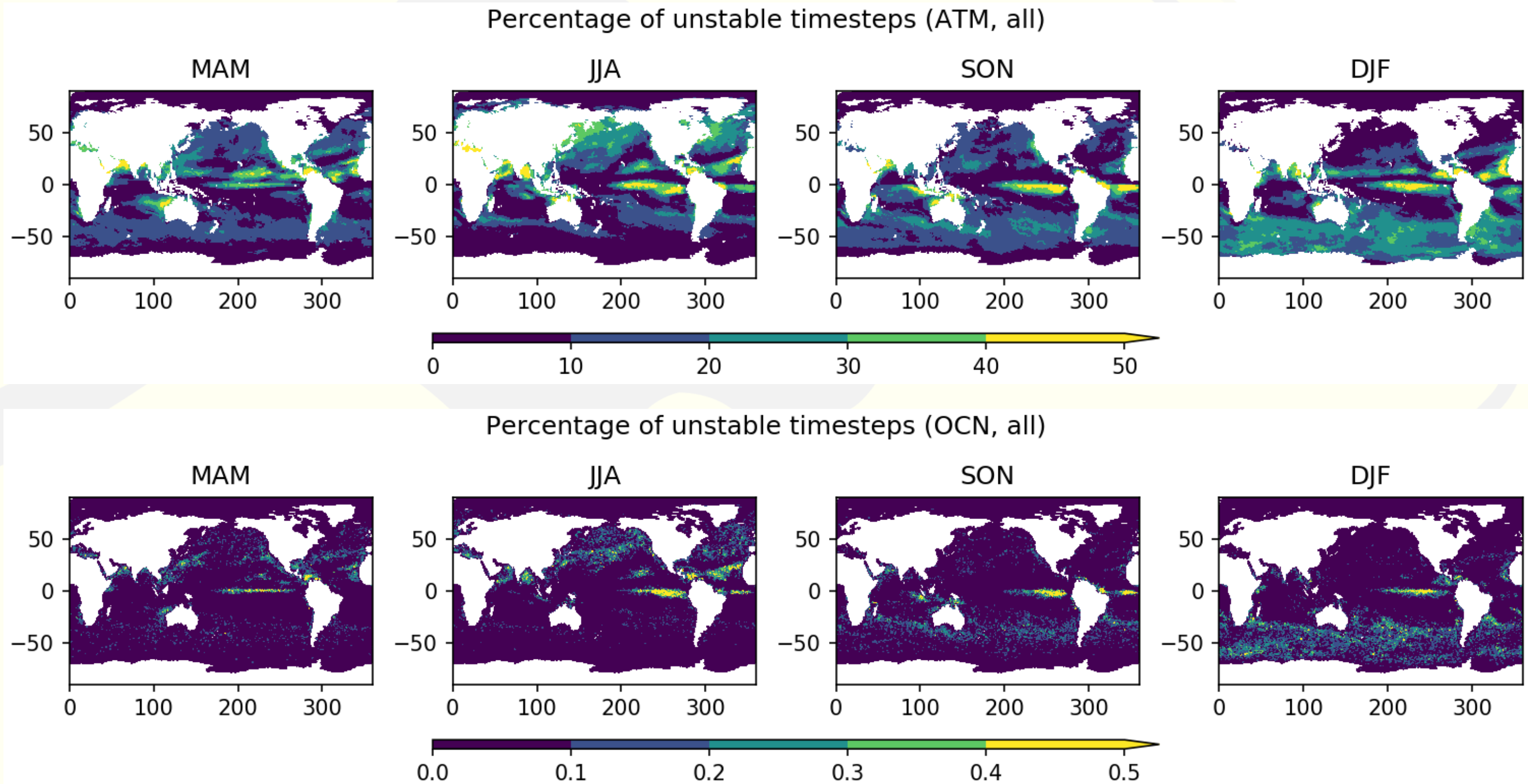


Monthly minimum of $\sqrt{1+2d}+1-\beta$ for the ocean calculated from 1-yr simulation of E3SM

Potential instability with analytical criterion

$$\sqrt{1+2d}+1-\beta<0$$

- Ocean instability timesteps are mostly due to individual events.
- Much more frequent for the atmosphere
  - Midlatitudes: strong seasonality (from both diffusivity and coupling coefficient)
  - Equatorial cold tongue



Summary

- Developing new methods for coupling
  - Improved consistency, accuracy, robustness
  - Work to improve efficiency
- Developing improved understanding of coupled system
  - Stability of coupling
  - Consistency of algorithms across coupled system
  - Classifying approaches