Multiscale methods for enabling scale-aware capability in CESM:

A SciDAC Climate Application

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with

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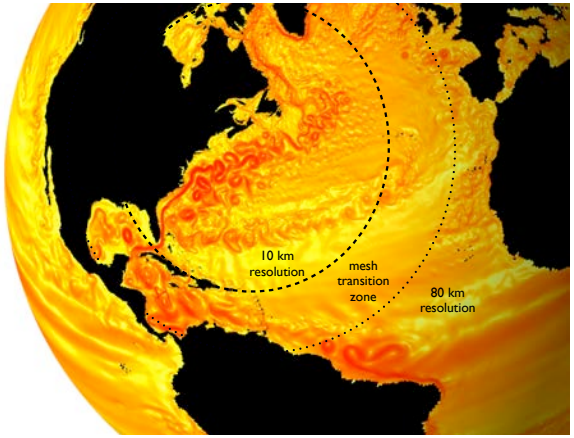
Drivers for the project

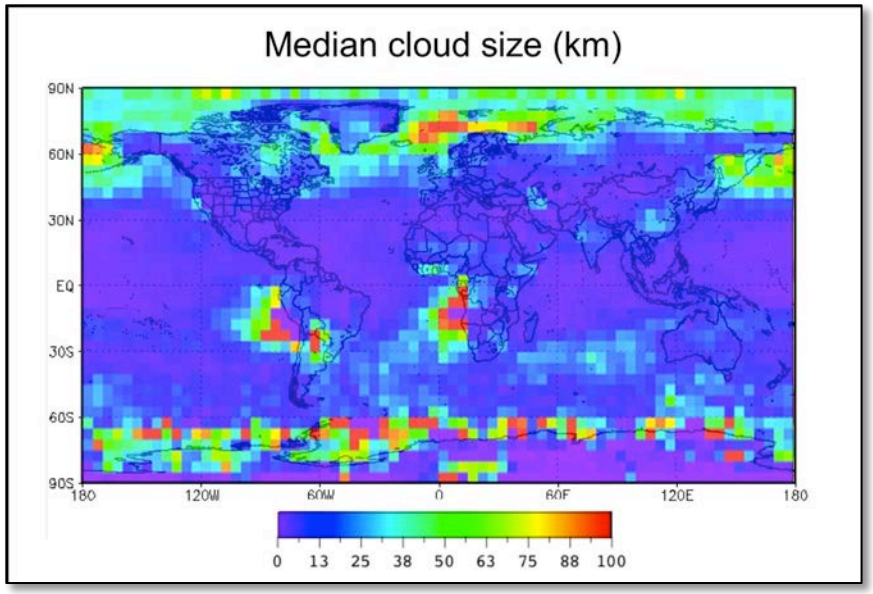
- Many phenomena we want to simulate occur at the very small scales of clouds and ocean eddies.
- Two-way interactions are important for the organization and variability of the climate.
- Given cost of uniform ultra-high resolution, ***statically or dynamically refinable models*** could be a key experimental platform.

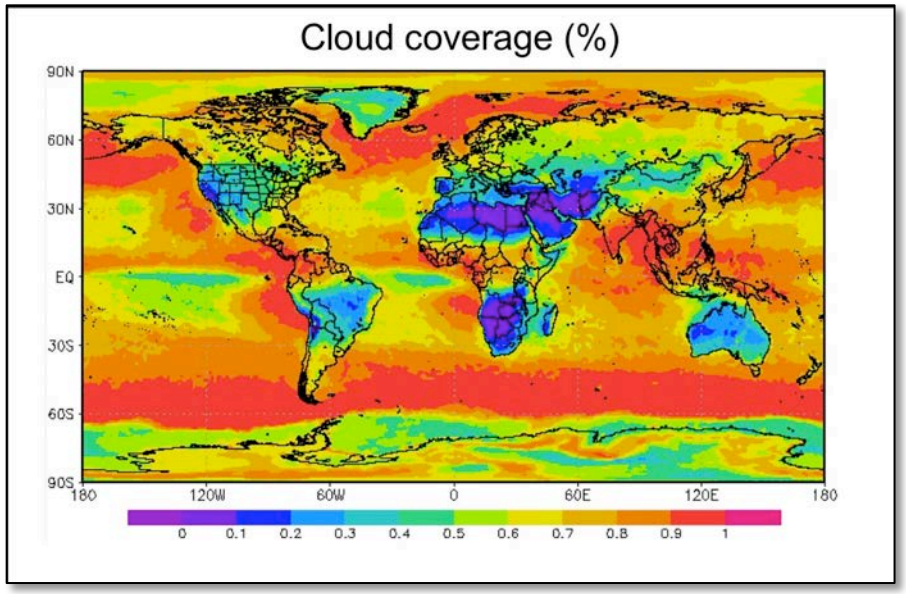


Goals of the project

- Develop, validate, and apply multiscale models of the climate system based upon atmospheric and oceanic components with variable resolution.
- Exploit new variable resolution unstructured grids based on finite element and finite volume formulations developed by DOE.
- Integrate advances in time-stepping methods, grid generation, and automated optimization methods for next-generation computer architectures.

Clouds scales and model resolution





UHR AR5 AR4

Requirements for the next generation of model physics

- Fidelity down to scales of key features of interest: cloud systems and ocean eddies
- Relaxation of usual parameterization assumptions:
  - *Ensembles:* Grid box may contain ~1 system, not >>1
  - *Scale separation:* Time steps and grid resolutions comparable to characteristic time and length scales of systems
  - *Equilibrium:* Due to scale "entanglement", sub-grid physics are not in equilibrium with boundary conditions imposed by resolved fields
  - *No memory:* Sub-grid systems will retain state across steps
  - *Scale awareness:* Physics needs to quasi-invariant to resolution
  - *Determinism:* Physics evolution is inherently stochastic.

Multiscale Team

Principal Investigator:	**Bill Collins**
Science Team Leads:	
• *Atmosphere:*	**Steve Ghan**
• *Ocean:*	**Todd Ringler**
• *Computational Science:*	**Carol Woodward**
• *Multiscale UQ:*	**Don Lucas**
Program managers:	**Dorothy Koch (BER) and Randall Laviolette (ASCR)**
Laboratory Staff and University Pis:	***LANL, LBNL, LLNL, ORNL PNNL, SNL, OSU, NCAR, UCLA, and UWM***

Connections to SciDAC Institutes

There are four SciDAC Institutes:

- **QUEST:** *Quantification of Uncertainty in Extreme Scale Computations*
- **SUPER:** *Institute for Sustained Performance, Energy and Resilience*
- **FastMATH:** *Frameworks, Algorithms and Scalable Technologies for Mathematics*
- **SDAV:** *Scalable Data Management, Analysis, and Visualization*

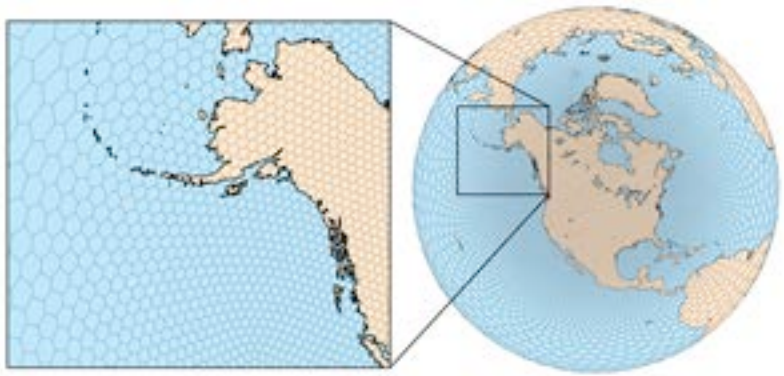
We will interact with 3 of these Institutes via liaisons:

- **QUEST:** Bert Debusschere (SNL)
- **SUPER:** Lenny Oliker and Sam Williams (LBNL)
- **FastMATH:** Carol Woodward (LLNL)
- **Exec Council:** Bill Collins (LBNL)

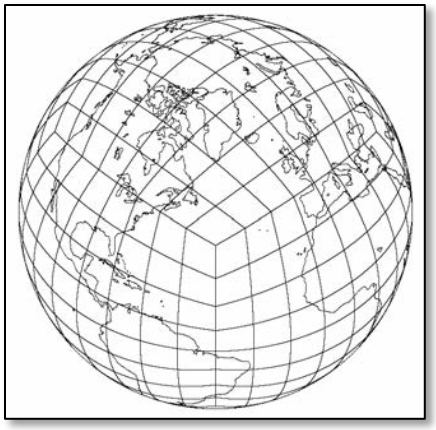
Project Elements

Variable Mesh Dycores

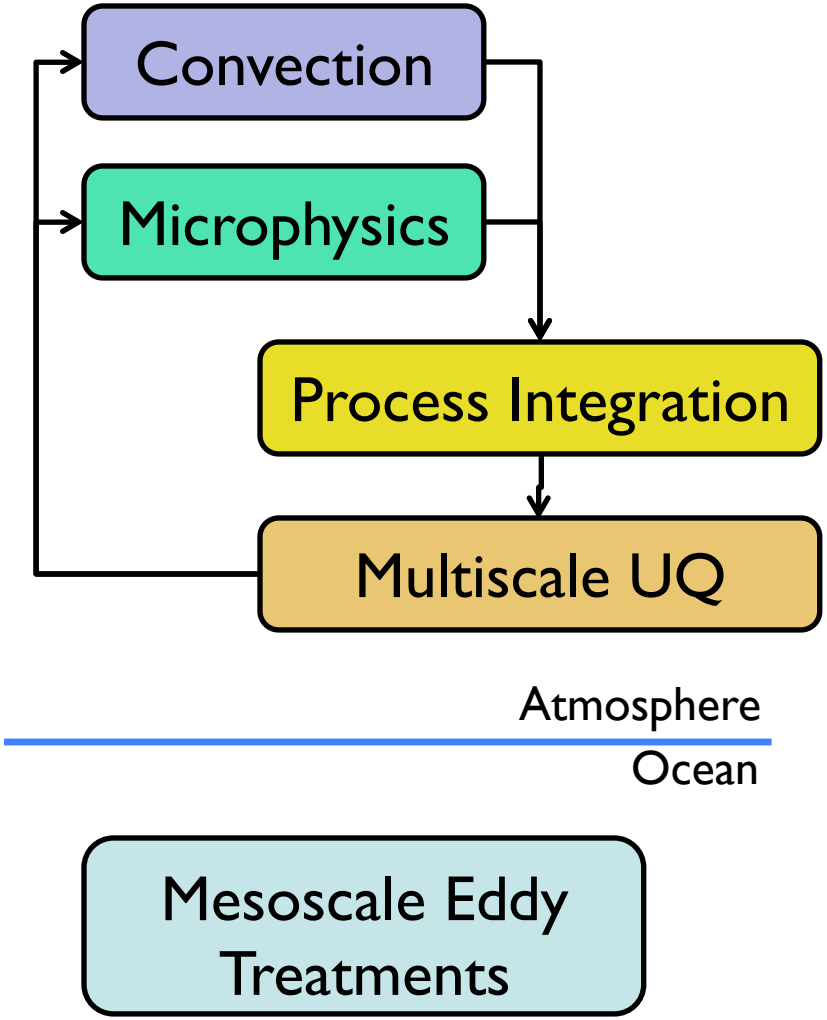
Model for Prediction Across Scales (MPAS)



Spectral Element Dycore



Physics-Dynamics Interface



Specific Task Areas

- **Multiscale modeling of the atmosphere**
  - *Clouds and convection (3 approaches)*
  - *Cloud and aerosol microphysics*
  - *Process integration*
  - *Verification, validation, and UQ*
  - *Experimental tests of the multiscale atmosphere*
- **Development and testing of multiscale ocean**
  - *Multiscale meoscale eddy parameterizations (4 stages)*
  - *Verification, validation, and UQ*
  - *Multiscale coupling of air-sea interactions*
- **Application of the multiscale Earth system model**

MPAS
Model for Prediction Across Scales

Building Global, Multi-Scale Climate System Component Models

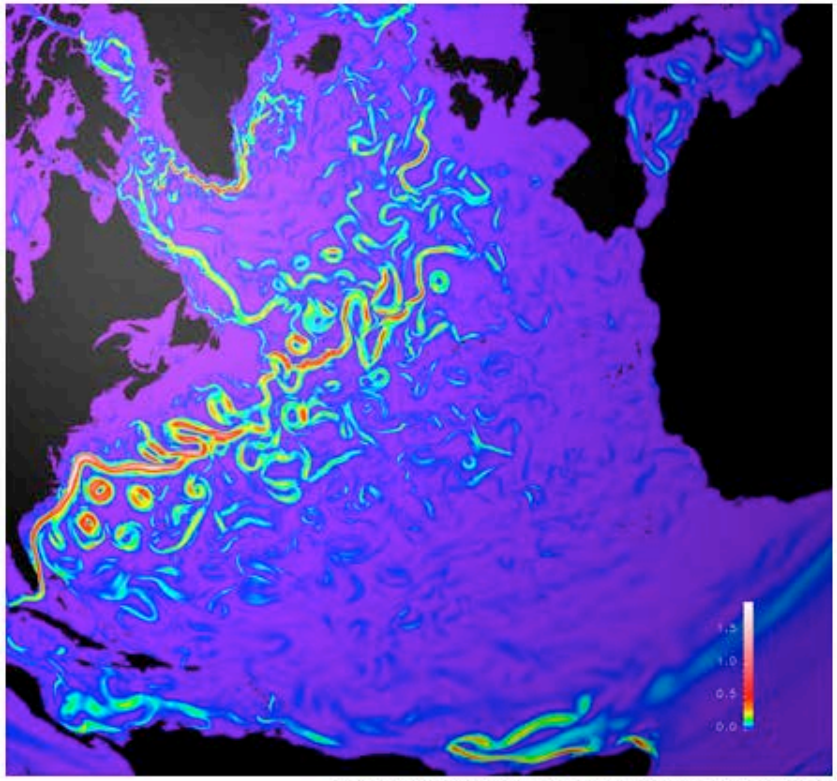
1. MPAS is an unstructured-grid approach to climate system modeling.

2. MPAS supports both quasi-uniform and variable resolution meshing of the sphere using quadrilaterals, triangles or Voronoi tessellations.

3. MPAS is a software framework for the rapid prototyping of single-components of climate system models (atmosphere, ocean, land ice, etc.).

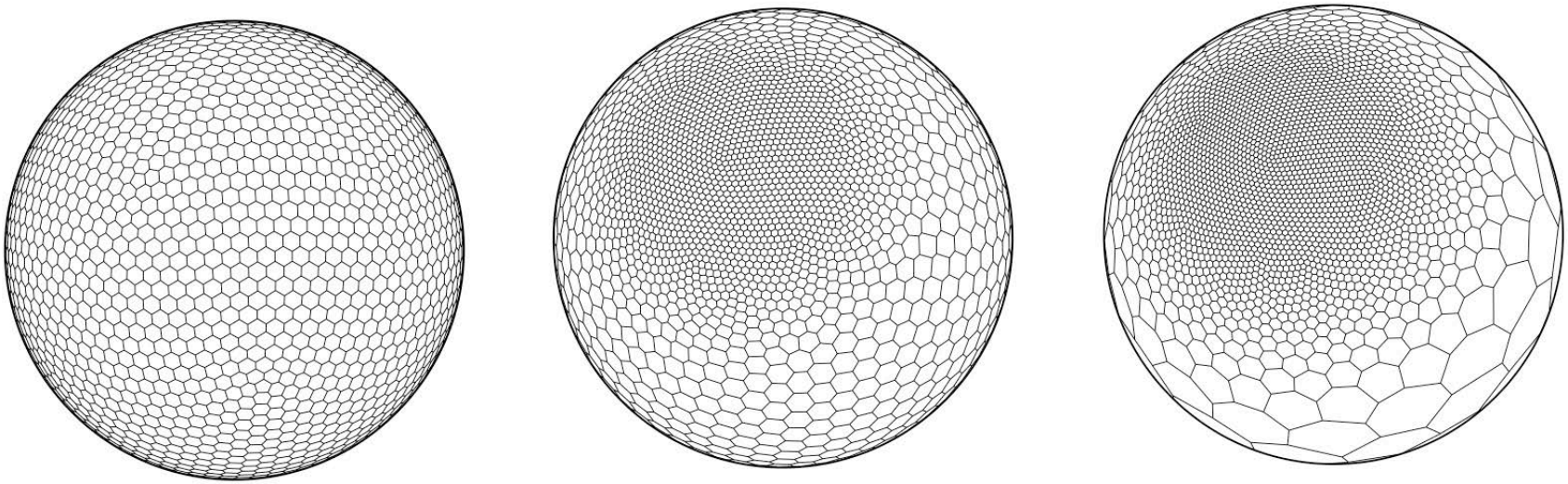
4. MPAS offers the potential to explore regional-scale climate change within the context of global climate system modeling. Multiple high-resolution regions are permitted.

5. MPAS is currently structured as a partnership between NCAR MMM and LANL COSIM, where we intend to distribute our models through open-source, 3rd-party facilities (e.g. Sourceforge).



snapshot of kinetic energy from a global ocean simulation with 7.5 km resolution in the North Atlantic.

Pillar #1: Spherical Centroidal Voronoi Tessellations: Various ways to distribute 2562 nodes on the sphere.



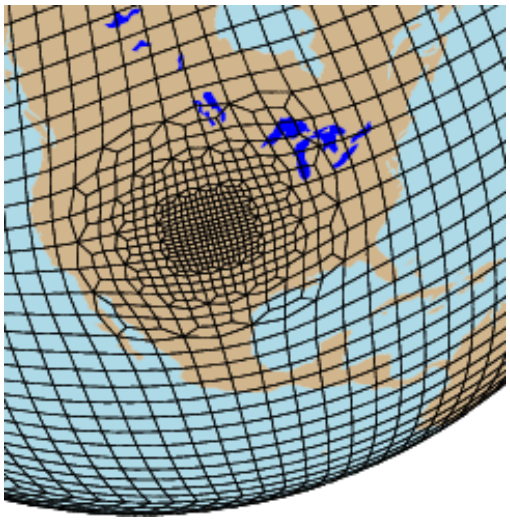
x1 x4 x16

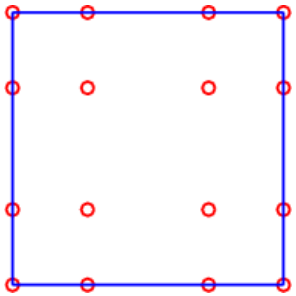
1. The meshes are simple to produce.
2. The local resolution is controlled by a single, user-specified scalar function.
3. We have very precise control over the distribution of local grid resolution.
4. We have mathematical guarantees on the mesh quality.

• Ju, L., T. Ringler and M. Gunzburber, 2010, Voronoi Tessellations and their Application to Climate and Global Modeling, Numerical Techniques for Global Atmospheric Models, Lecture Notes in Computational Science. (pdf).

• Ringler, T., L. Ju and M. Gunzburger, 2008, A multiresolution method for climate system modeling: application of spherical centroidal Voronoi tessellations, Ocean Dynamics, 58 (5-6), 475-498. doi:10.1007/s10236-008-0157-2 (link)

Spectral Element Method



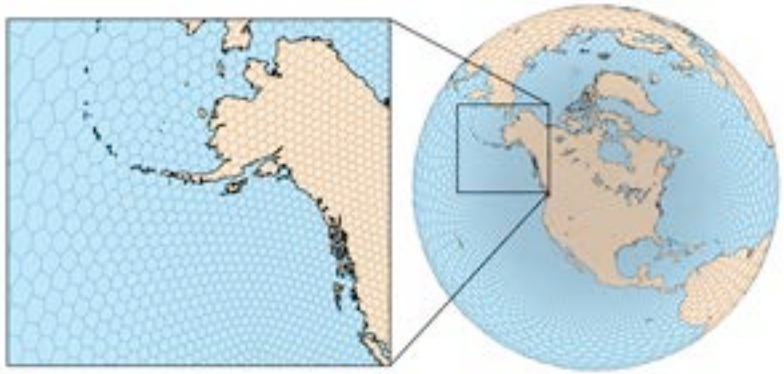


- Spectral Elements: A Continuous Galerkin Finite Element Method
  - Uses finite element grids made of quadrilateral elements
  - Galerkin formulation, with a Gauss-Lobatto quadrature based inner-product
  - Basis/test functions: degree *d* polynomials within each element, continuous across elements

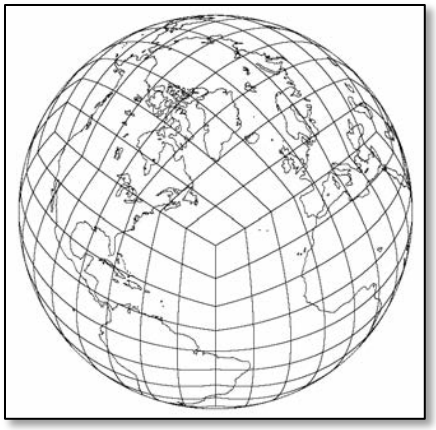
Project Elements

Variable Mesh Dycores

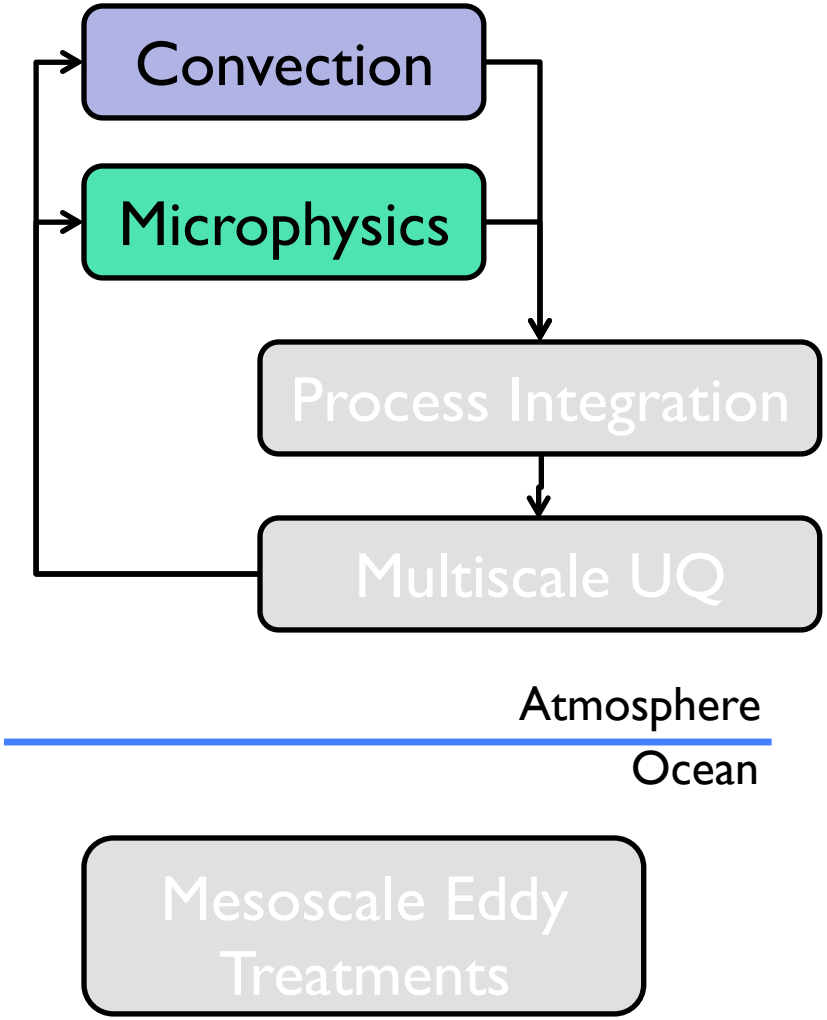
Model for Prediction Across Scales (MPAS)



Spectral Element Dycore



Physics-Dynamics Interface



Current CAM5 Physics

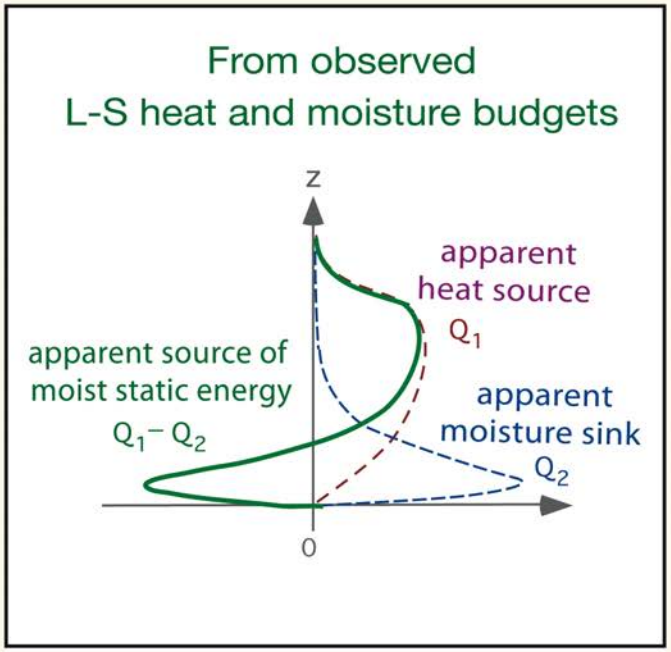
- ~~Boundary Layer (Bretherton)~~
- Deep Convection (ZM)
- ~~Shallow Convection (Park)~~
- ~~Cloud Macrophysics (Park)~~
- Microphysics (MG)
- Radiation
- Aerosols

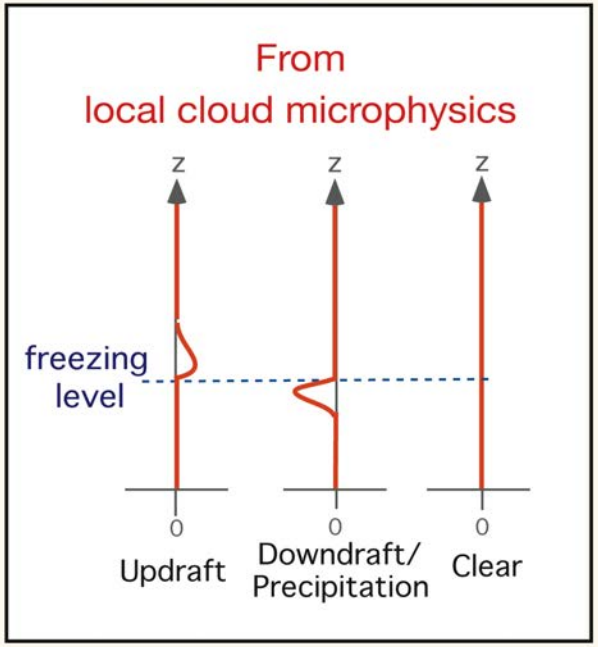
CLUBB

CLUBB

- CLUBB = Cloud Layers Unified By Binormals
- First developed by Golaz et al. (2002), maintained by University of Wisconsin Milwaukee (Vincent Larson's group)
- "Incomplete" third-order turbulence closure (predicting 9 second and third order moments), centered around a trivariate assumed double gaussian PDF
- concurrently undergoing implementation into AM3 as part of CPT initiative
- Should provide unified treatment of PBL and shallow convection
- Goal is for better representation of boundary layer processes and aerosol effects

SCHEMATIC ILLUSTRATION OF MOIST STATIC ENERGY SOURCE UNDER TYPICAL TROPICAL CONDITIONS





GCM-TYPE PROFILE

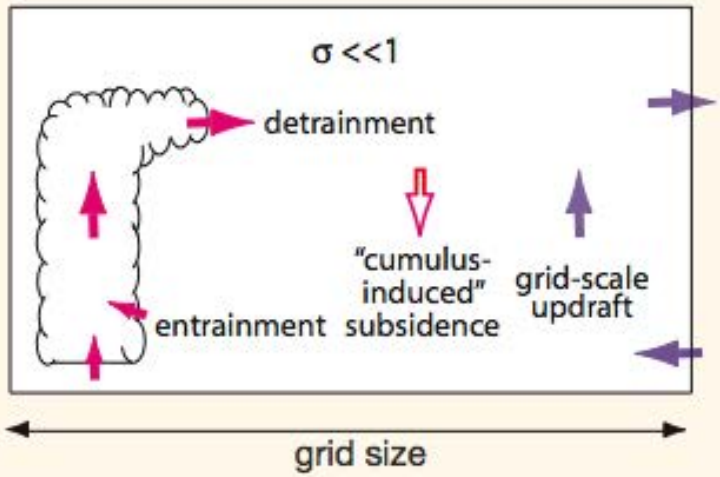
CRM-TYPE PROFILES

Any space/time/ensemble average of the profiles in the right panel does NOT give the profile in the left panel.

ASSUMPTION OF SMALL FRACTIONAL CLOUD COVER

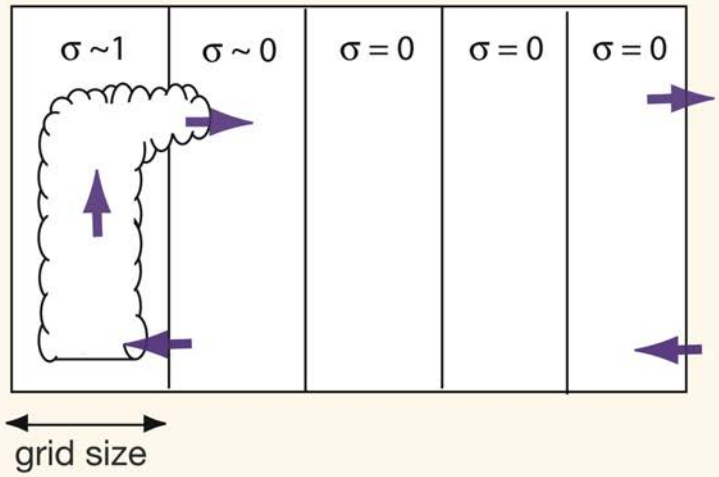
- Specifically, AS assumes $\sigma << 1$, where σ is the fractional area covered by *all convective clouds* in the grid cell.

- Then prediction of grid-scale averages of sensible and latent heat essentially becomes prediction of them in the cloud environment.



But, if cloud occupies the entire grid cell, there is no "environment" within that cell.

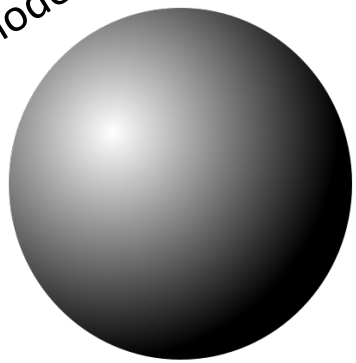
A key to open Route I is eliminating the assumption of $\sigma << 1$.



Bimodal distributioon of σ (Krueger 2002)

The stochastic parcel model

Parcel is modeled as a sphere



A set of ODE's determines the parcel's height, vertical velocity, density, etc.

Two parameters, λ and σ, define entrainment

In time step δt, the probability of a entrainment event is:

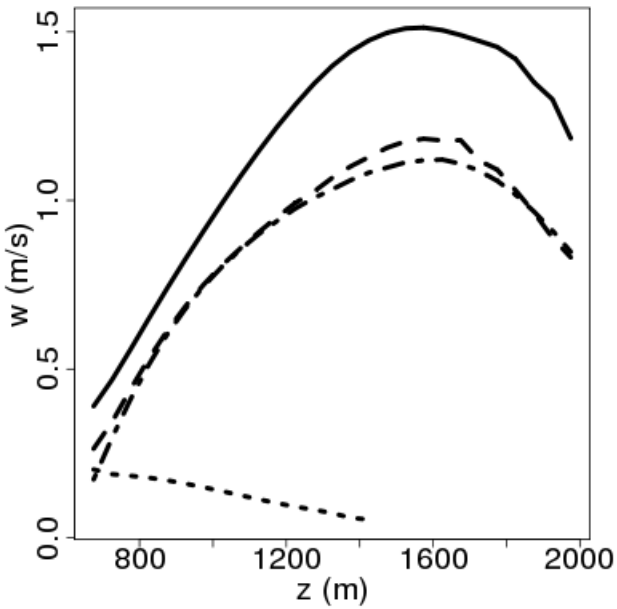
$$P(\text{an entrainment event}) = |w|\delta t/\lambda$$

If there is a mixing event, entrain a fractional amount f:

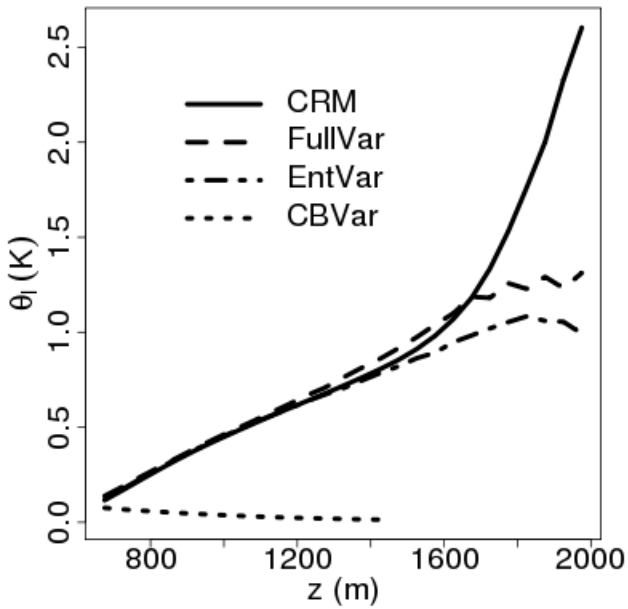
$$P(\text{entrain fraction } f) = \frac{1}{\sigma} e^{-f/\sigma}$$

The stochastic parcel model

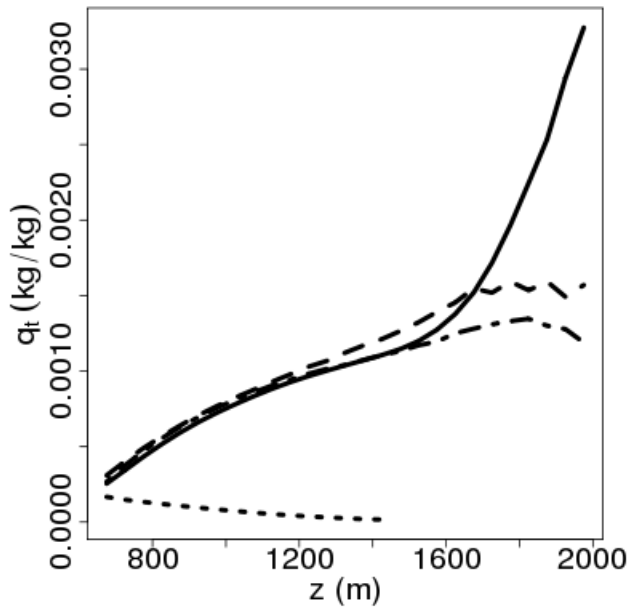
Standard deviations



Vertical velocity



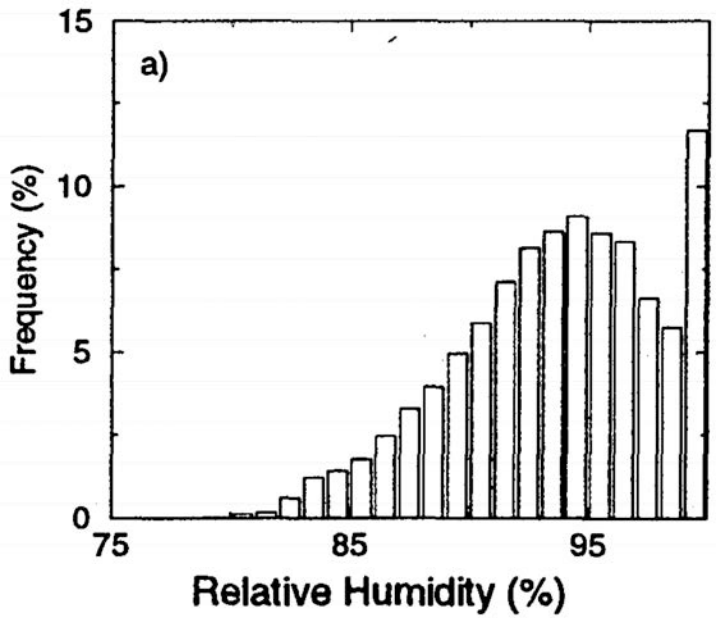
Liquid-water potential temperature



Total water

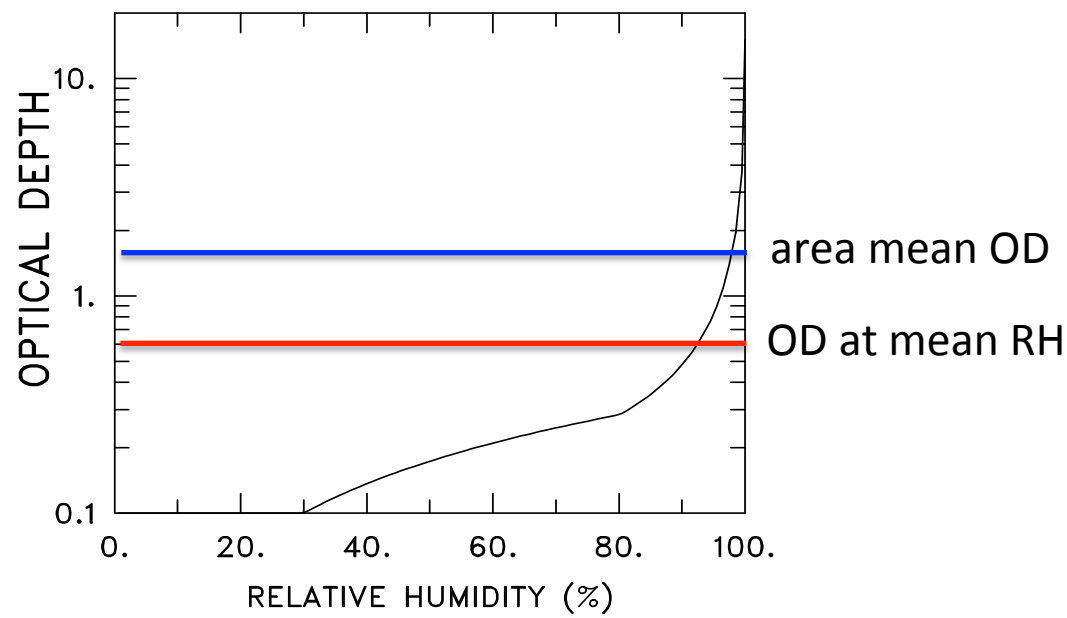
Importance of Subgrid Variability in Aerosol Water Uptake

Relative humidity varies substantially within a 160 km cloud-resolving model domain



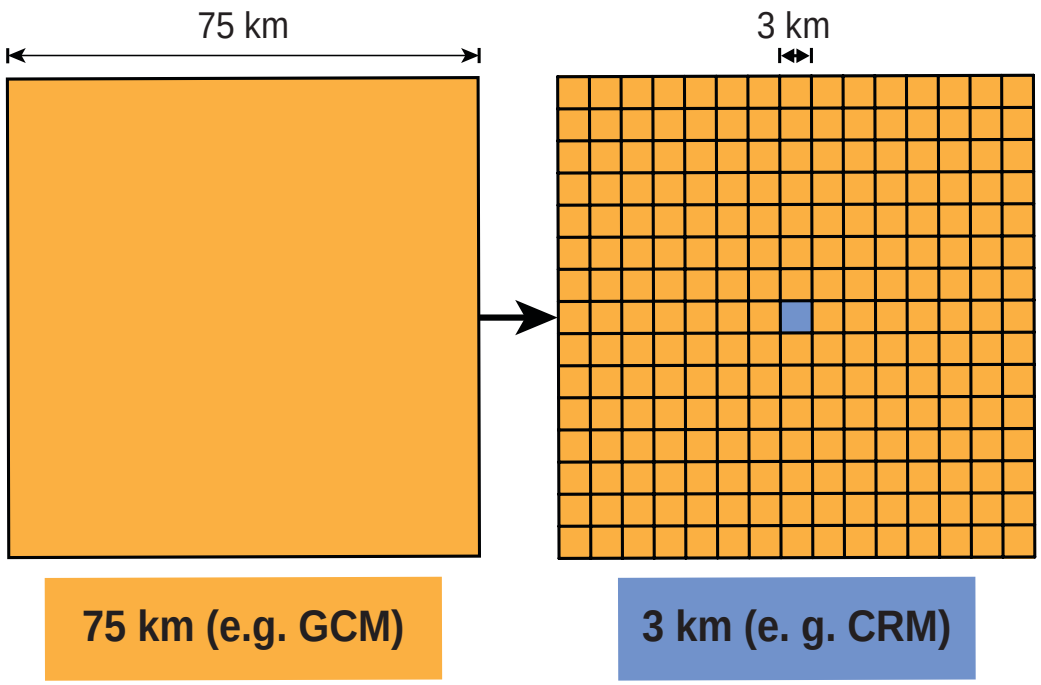
Haywood et al., GRL, 1997

Aerosol optical depth is a highly nonlinear function of relative humidity

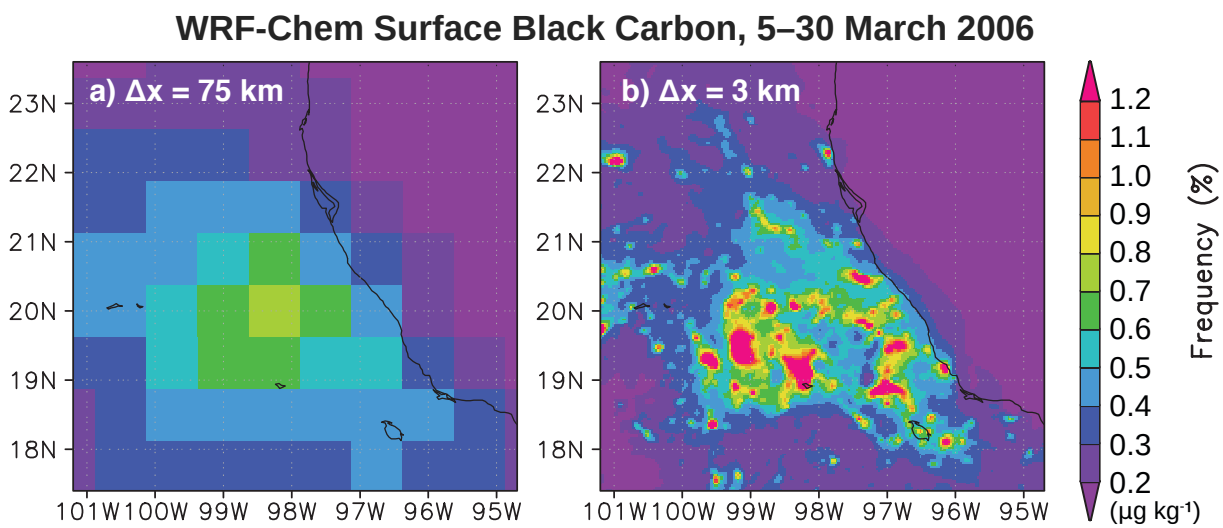


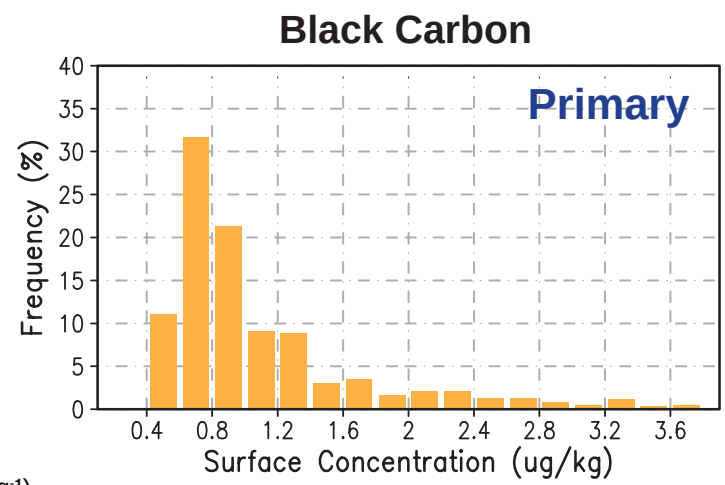
Ghan and Easter., GRL, 1998

Representing Subgrid Aerosol Properties and Processes



PDFs from high-resolution simulations will guide development of a subgrid scheme for aerosols driven by subgrid emissions and the CLUBB subgrid cloud scheme

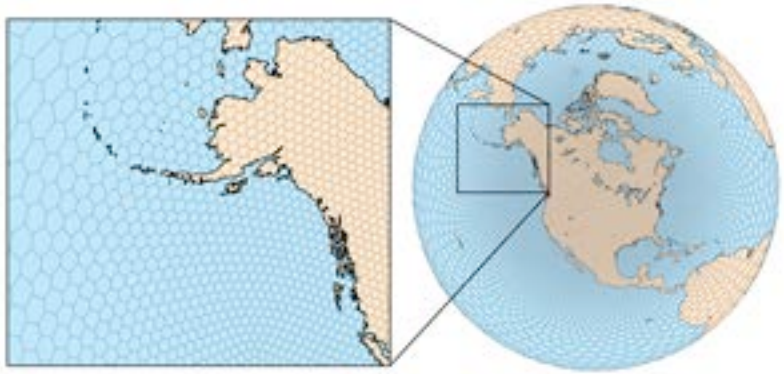




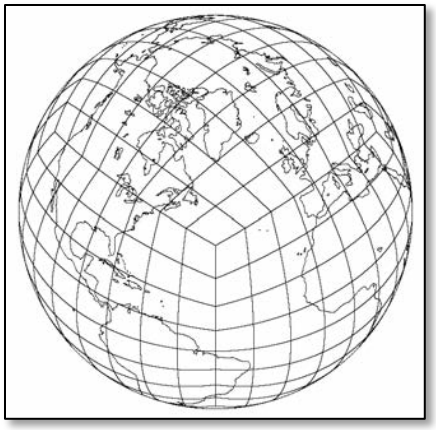
Project Elements

Variable Mesh Dycores

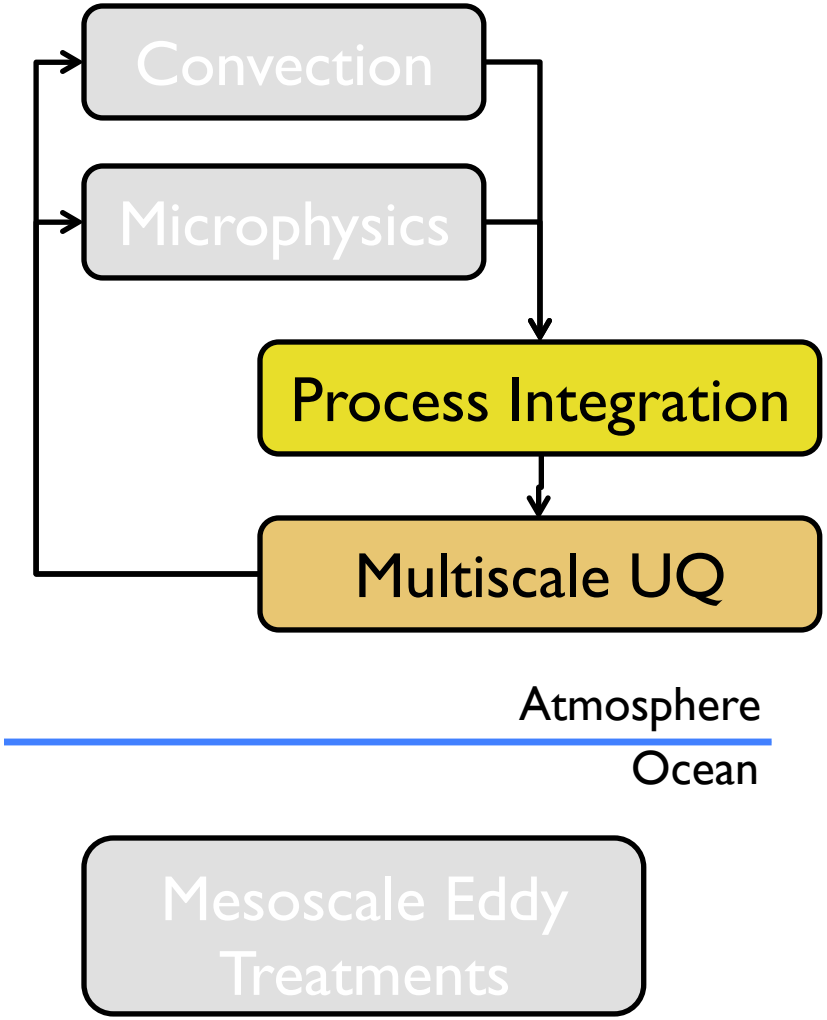
Model for Prediction Across Scales (MPAS)



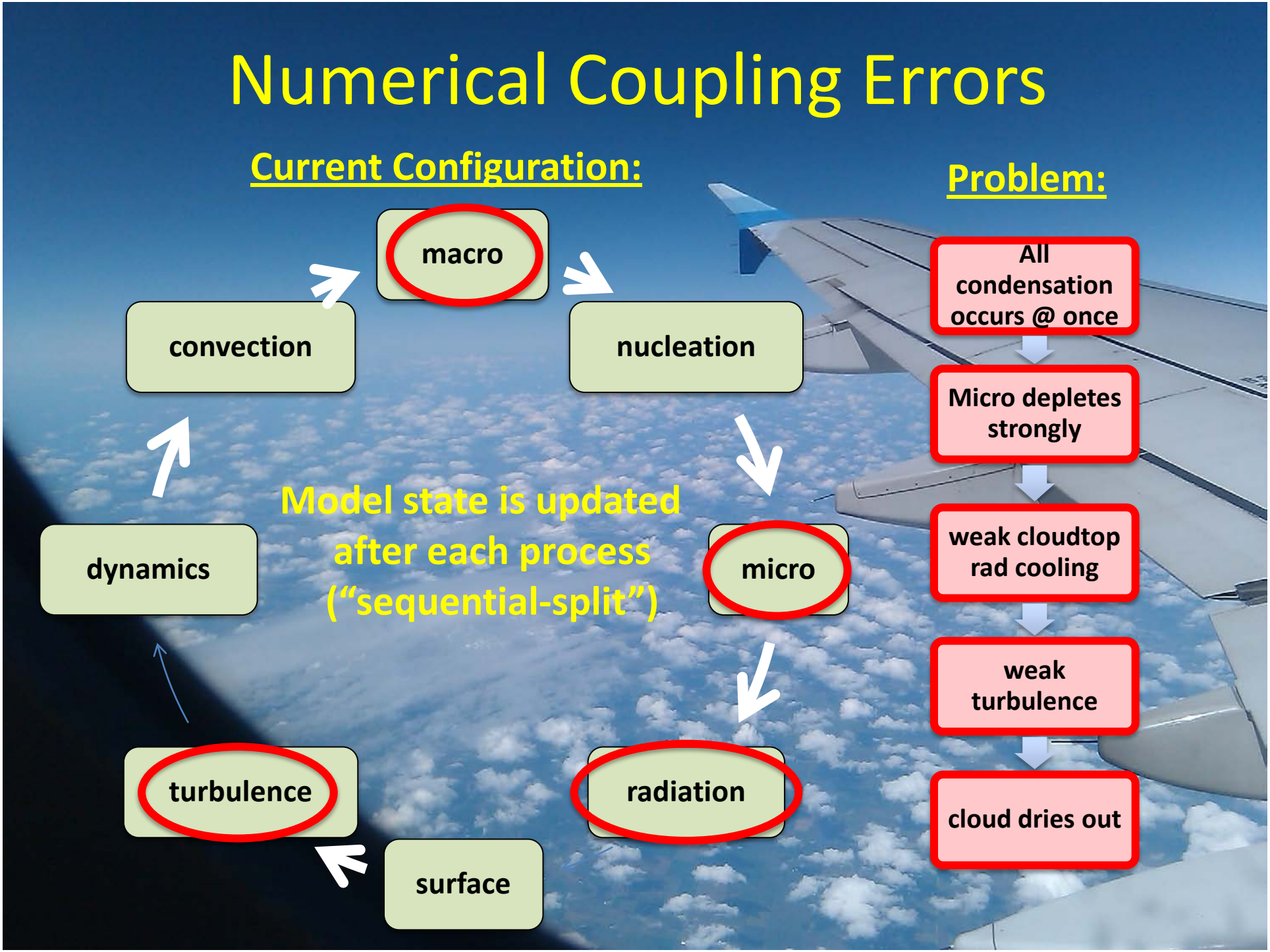
Spectral Element Dycore



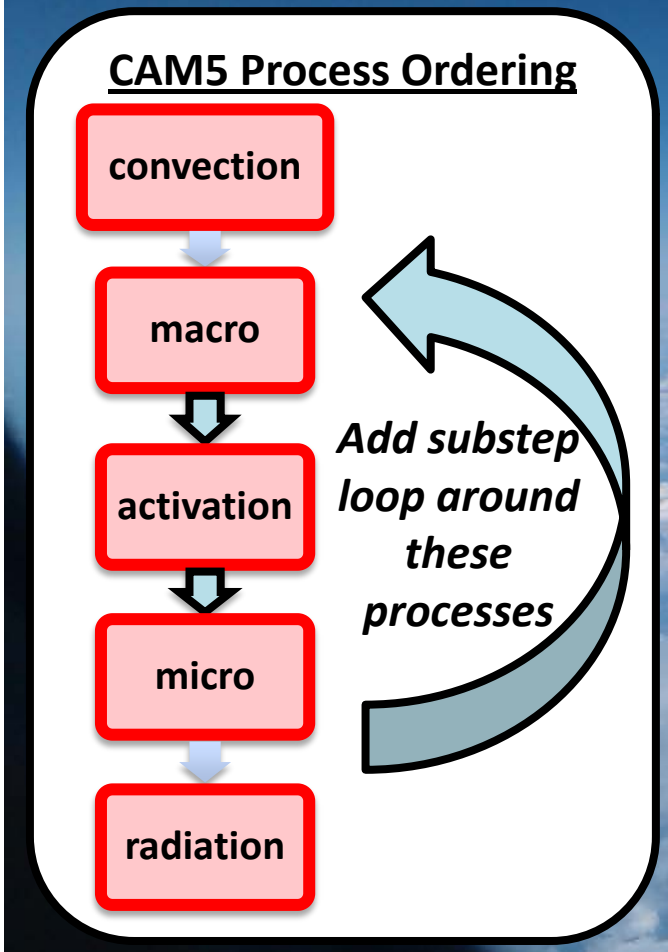
Physics-Dynamics Interface



Numerical Coupling Errors



Convergence Test for Coupling Error



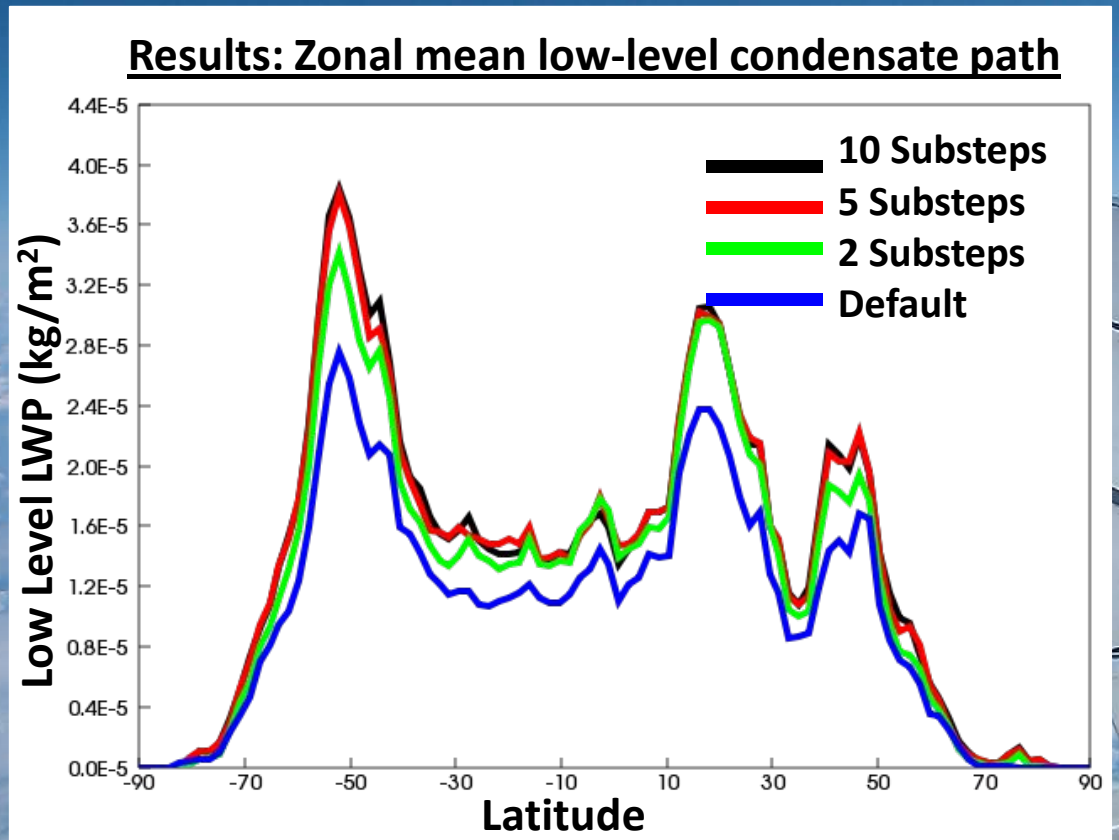


Fig: Zonal-mean LWP below ~820 mb from last 3 days of 5 day cam5_1_16 2° run

- Coupling @ 20 min dt (default) ⇒ LWP too low
- 10 min coupling (2 substeps) appears sufficient

Multi-scale Uncertainty Quantification of CESM

Need

- Understand CESM sensitivities and uncertainties at all resolution
- "Stabilize" CESM output as resolution is varied

Approach

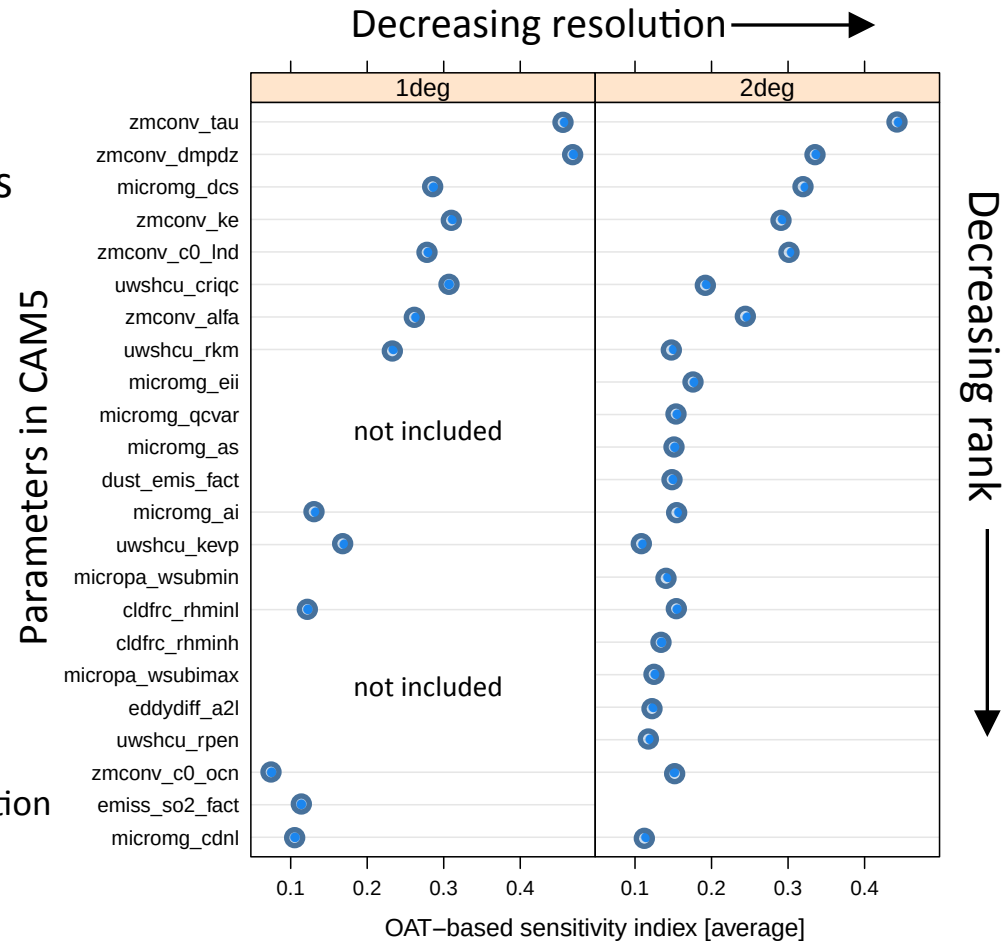
- Bayesian hierarchical, multi- fidelity surrogate modeling
  - Goh et al.,(2012), *arXiv:1208.2716v1*
  - Qian et al., (2008), *Technomet.*
- Hi-res approximated with lo-res and discrepancies for parameters **p**

$$Y_{hi}(\mathbf{p}) = Y_{lo}(\mathbf{p}) + d_{hi\text{-}lo}(\mathbf{p}) + d_{hi\text{-}obs}(\mathbf{p}) + e$$

hi-res output | lo-res output | resolution discrepancy | observation discrepancy | observation error

Benefits

- Characterize uncertainties/sensitivities of hi-res model using cheaper lo-res simulations
- Common model calibration across scales



Above: *The rank order of important parameters in CAM5 is highly correlated at different model resolutions (image courtesy of CSSEF)*

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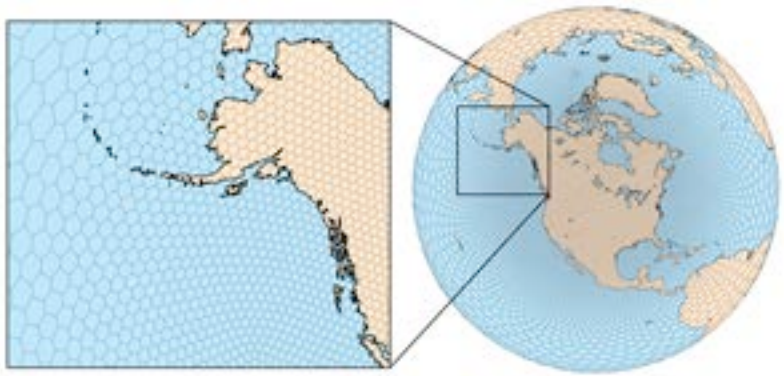

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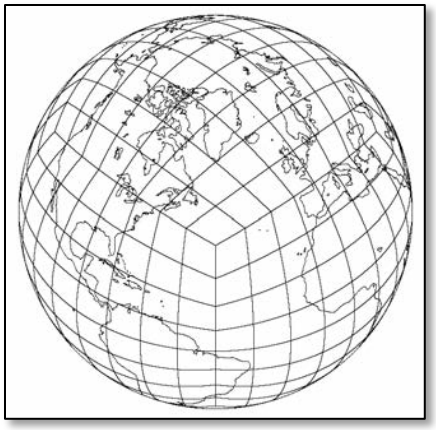

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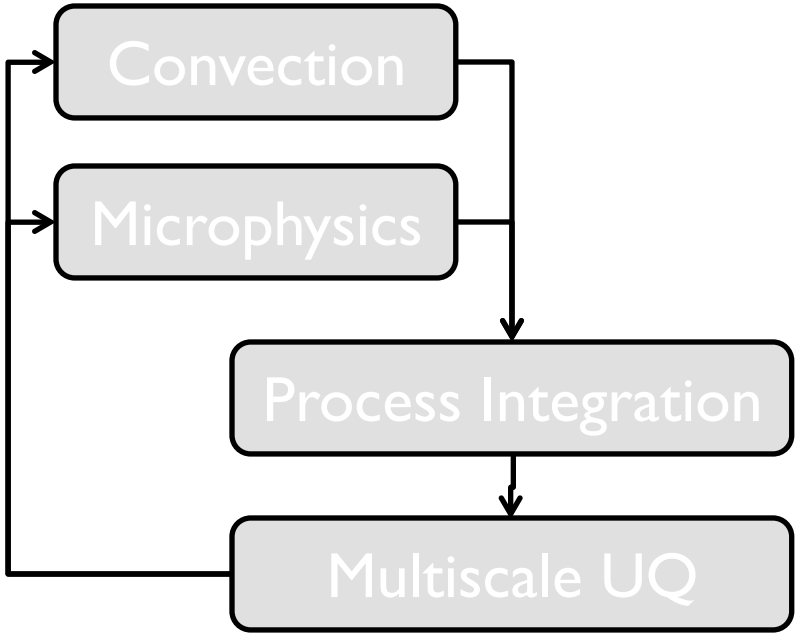


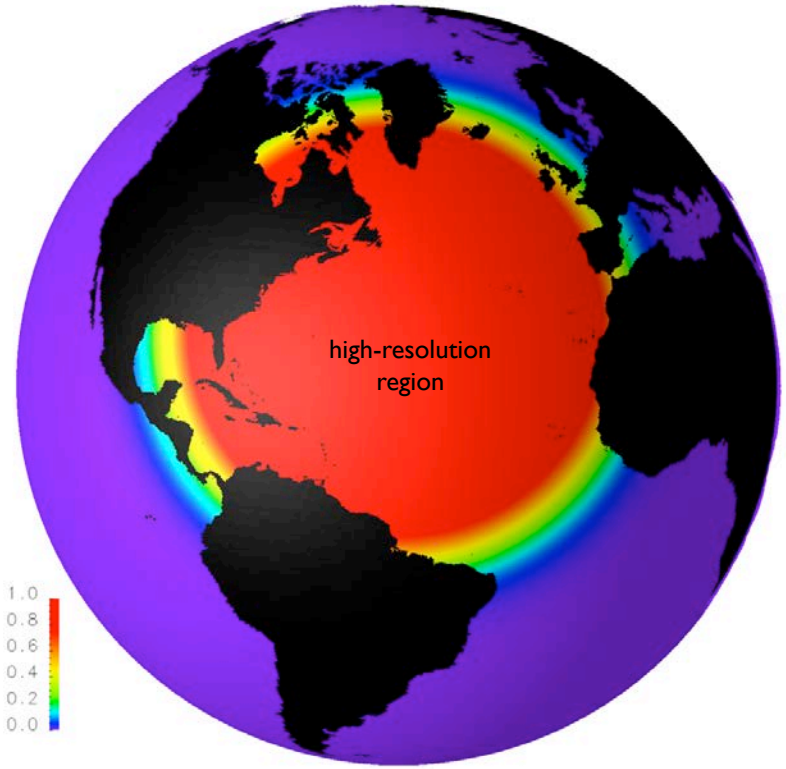
Atmosphere

Ocean

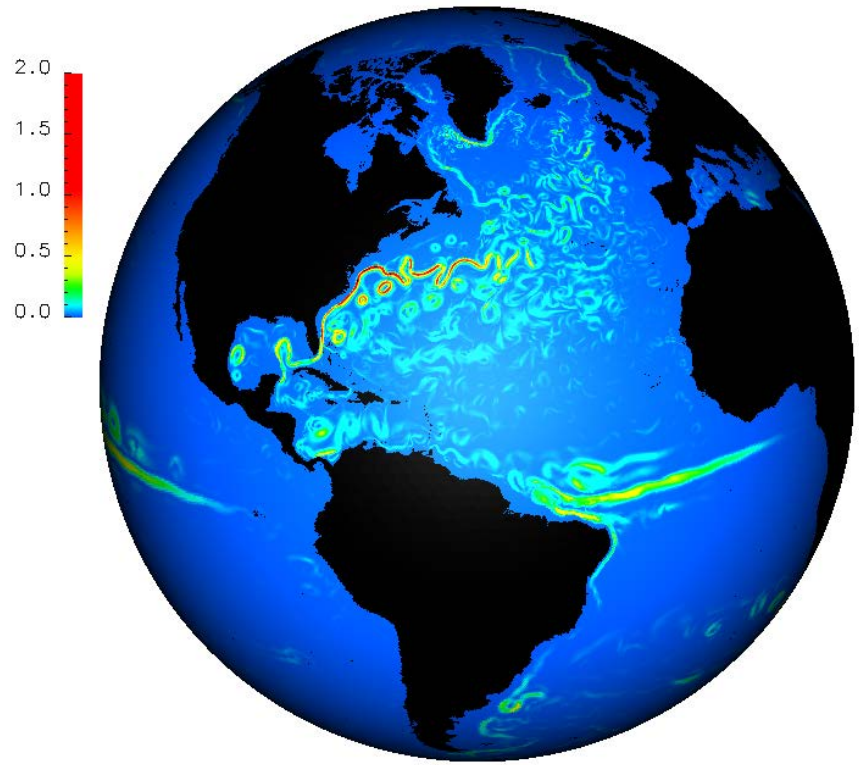
Mesoscale Eddy Treatments

MPAS-Ocean offers a route to multiscale simulation of the global ocean system.

Global ocean simulation containing both eddy-permitting and non-eddying resolutions



Snapshot of kinetic energy: 7.5 km resolution in North Atlantic and 40 km resolution elsewhere.



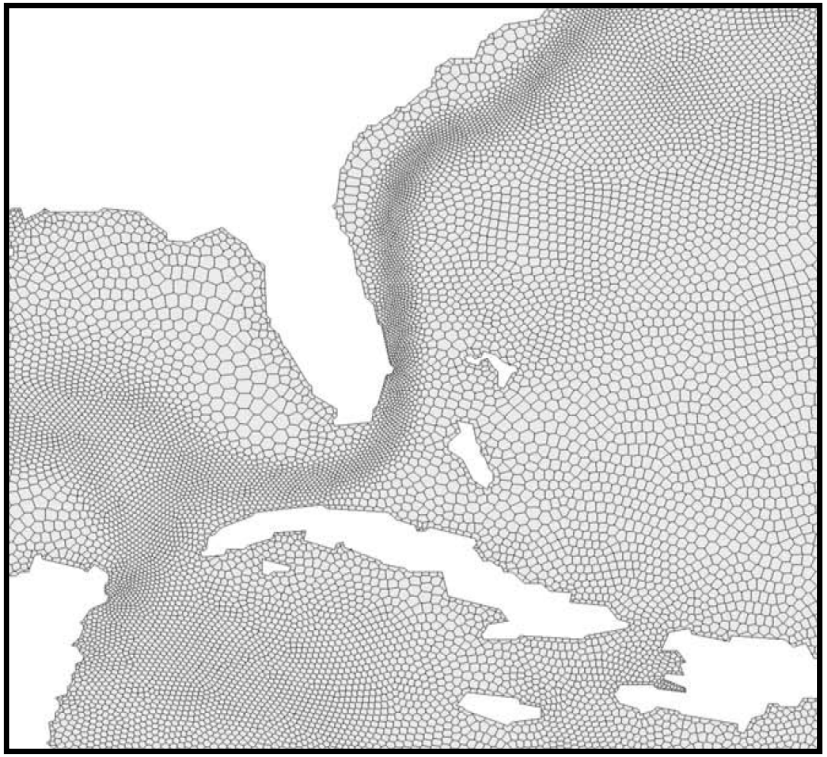
We resolve mesoscale eddies in the high-resolution region, but not in the low-resolution region.

The challenge of mesoscale eddy closure within a multiscale ocean modeling system.

Our goal is to create an ocean modeling system that seamlessly transitions between eddy permitting regions and non-eddy permitting regions.

Numerous empirical models exist for how the eddy closure parameter should depend on the resolved ocean state, but we lack theoretical guidance.

While short-term "engineering" solutions are possible, the full potential of multiscale MPAS-O can not be realized until robust closures are obtained.



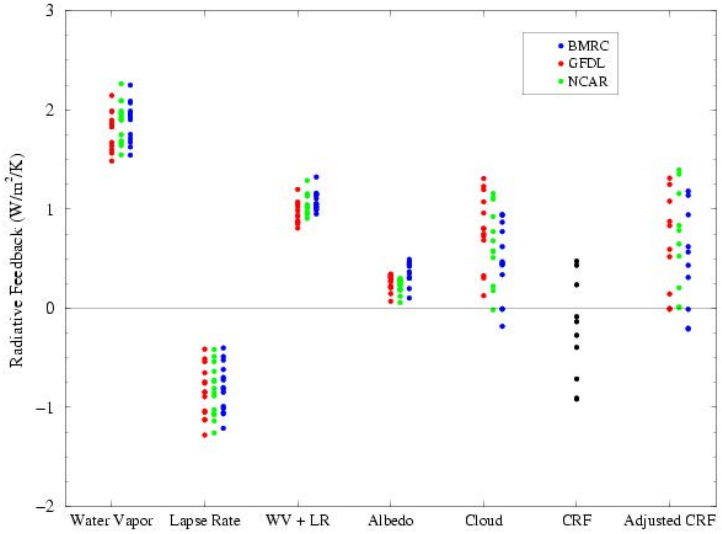
Simulations that attempt to support highly heterogeneous distributions of grid-scale will require robust closure methods for parameterizing mesoscale eddies.

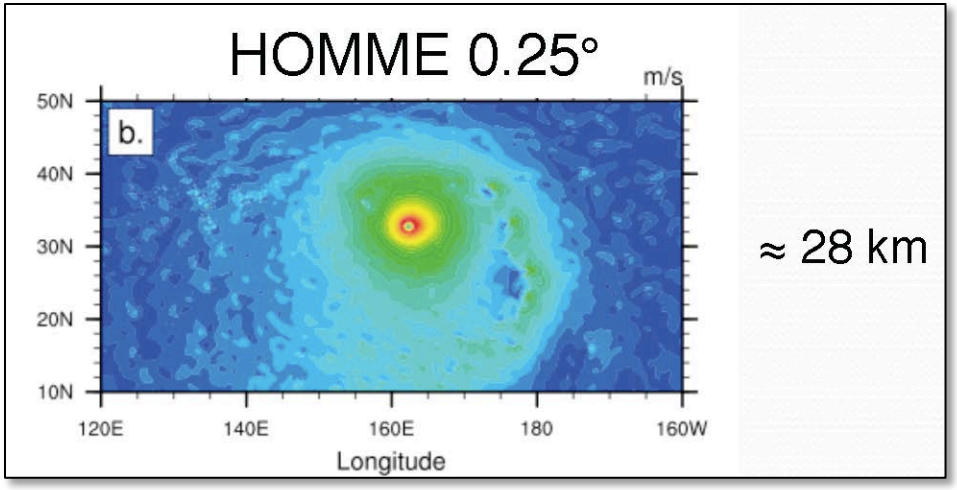
Proposed development path for of multiscale MPAS-O

Work Plan	Anticipated Outcomes
(2012) Implement baseline Gent-McWilliams closure into MPAS-O	Viable quasi-uniform global ocean model suitable for climate change studies.
(2013) Evaluate existing candidates for multiscale closure of mesoscale eddies in idealized settings.	Scientific publications.
(2014) Evaluate best performer(s) in global, multiscale ocean simulations.	Viable multiscale, global ocean model suitable for climate change studies.
(2015) Build new and/or improve existing multiscale closures.	Improved multiscale ocean simulations and scientific publications.

Grand challenge simulations

1. Scale dependence and uncertainty in cloud feedbacks
2. Multiscale ocean-atmosphere interactions in warmer climates





Questions?