Adaptable cloud parameterization:

An early career project on resolution dependence

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DOE BER Advisory Committee Meeting, 26 April 2018

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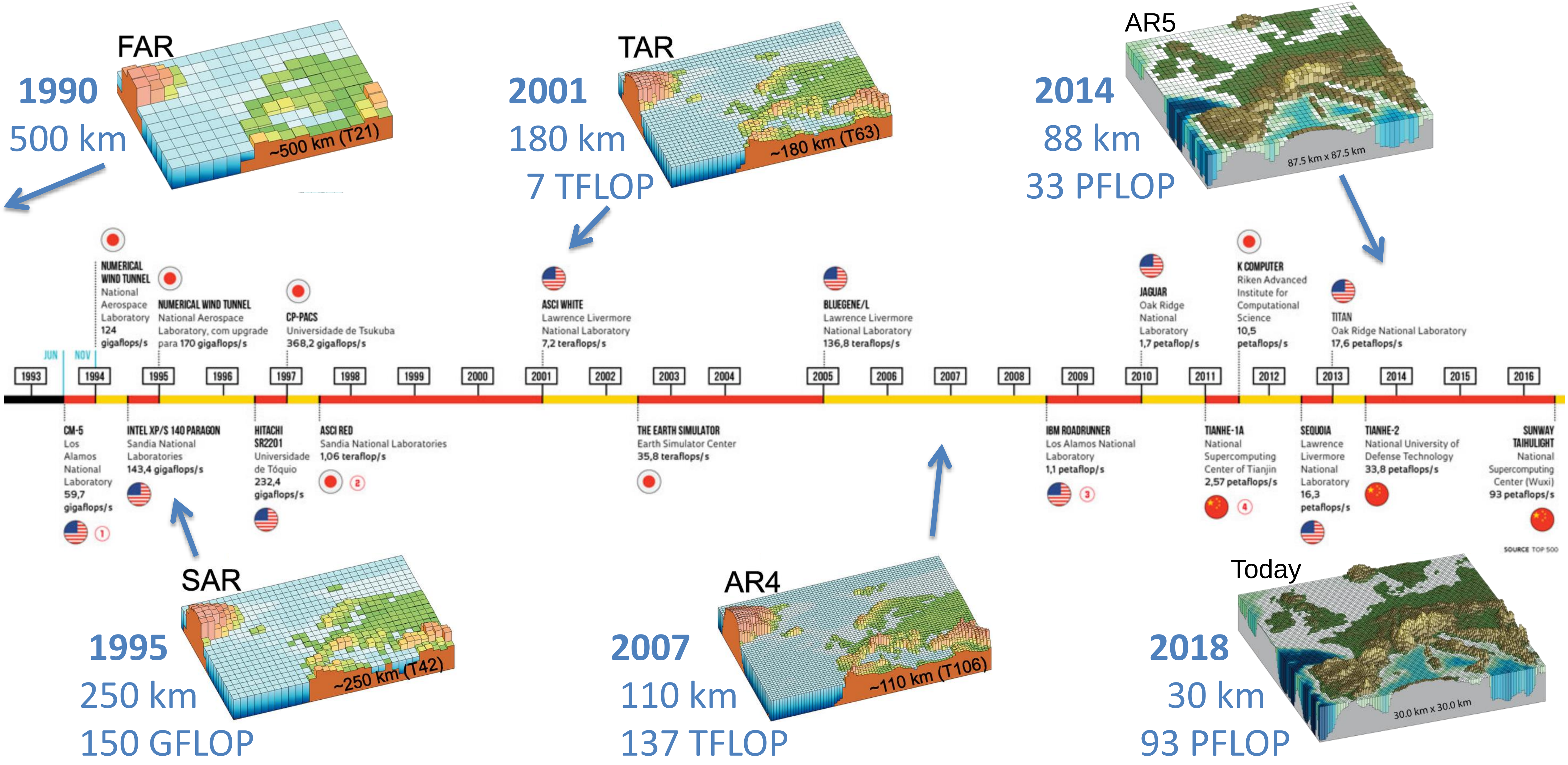
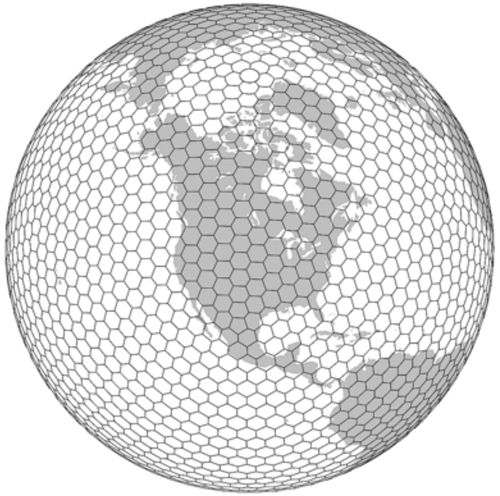


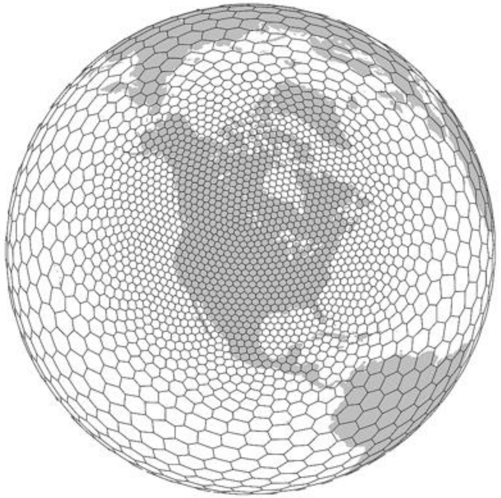
http://revistapesquisa.fapesp.br/en/2017/05/16/speed-test/; AR4; AR5

Resolution / scale awareness

- The model system, as well as its components, should operate correctly when run at different grid spacings

Low Resolution | **High Resolution** | **Multi-Resolution**





- **Resolution awareness:** A resolution aware model should perform better with higher resolution while not unacceptably corrupting coarse regions of the domain

My Early Career Project

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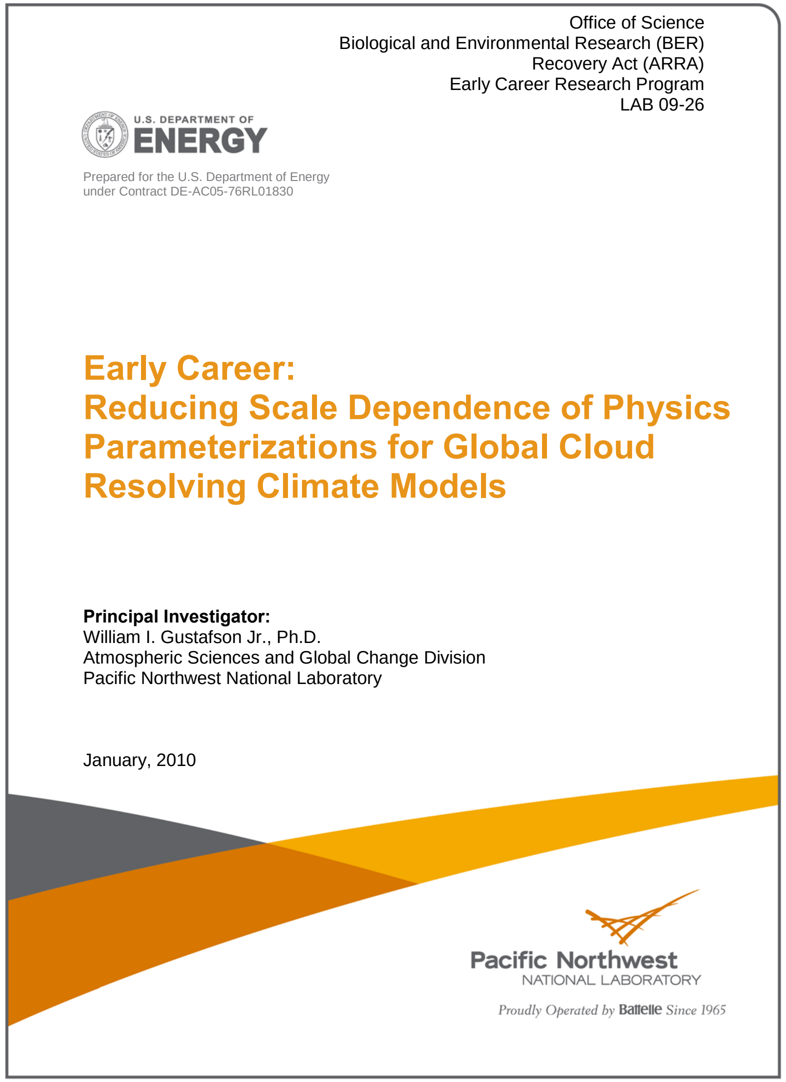
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U.S. DEPARTMENT OF ENERGY

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**Early Career:
Reducing Scale Dependence of Physics Parameterizations for Global Cloud Resolving Climate Models**

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January, 2010

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Overall goal

Reduce the grid-size dependency in atmospheric models so that they can be used across a range of scales for a variety of applications

Project foci

1. Understand the impact of resolution dependence on model system behavior
2. Understand causes of resolution dependence within physics parameterizations and seek mitigation options

Improving resolution awareness & cloud parameterization is central to achieving BERAC's grand challenges

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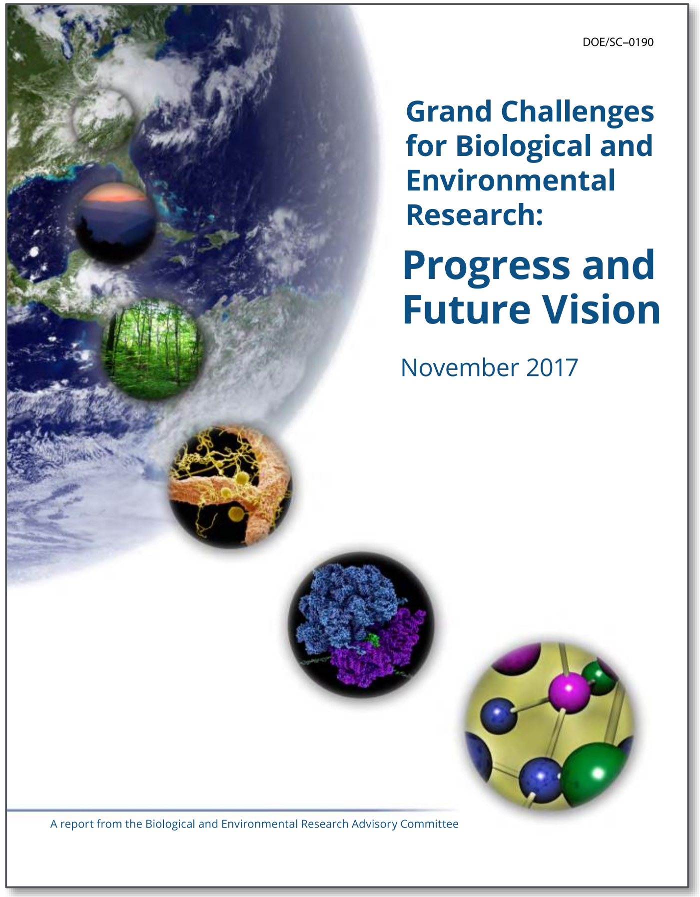
4 of 8 Earth and Environmental Systems Sciences Grand Challenges Directly Impacted by Resolution-Awareness and Cloud Param. Issues

3.1 Advance Earth system modeling… from process-resolving coupled models to reduced-order models to transform understanding… of Earth system behavior at multiple time scales

3.3 Advance... **scale-aware simulation capability** of Earth system feedbacks associated with aerosols and moist processes

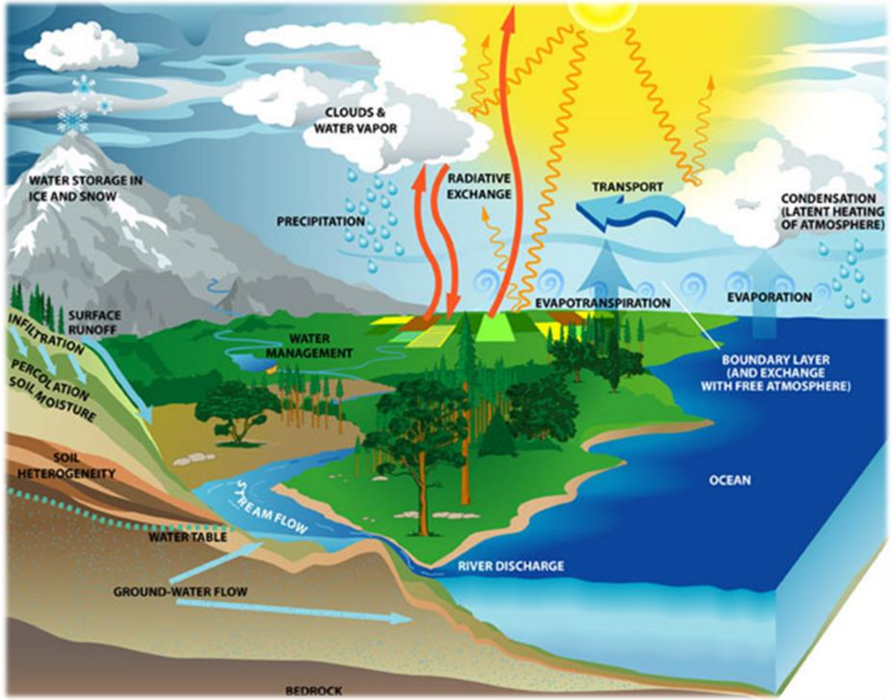
3.5 Characterize, understand, and model the complex, multiscale water cycle processes

3.8 …address the level of confidence and identify emergent constraints for the range of model projections



Origins of resolution non-awareness

- Solutions to create resolution awareness require targeting specific parts of the model



http://www.usgcrp.gov

Atmos. physics parameterizations

1. **Convective clouds**
2. Stratus / cloud microphysics
3. Turbulence
4. Radiation
5. Surface (essentially fluxes)
6. Land/soil

Two primary types of issues for improving parameterizations

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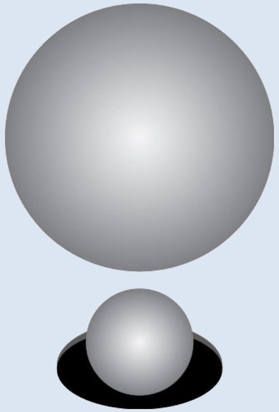
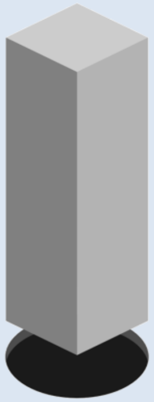


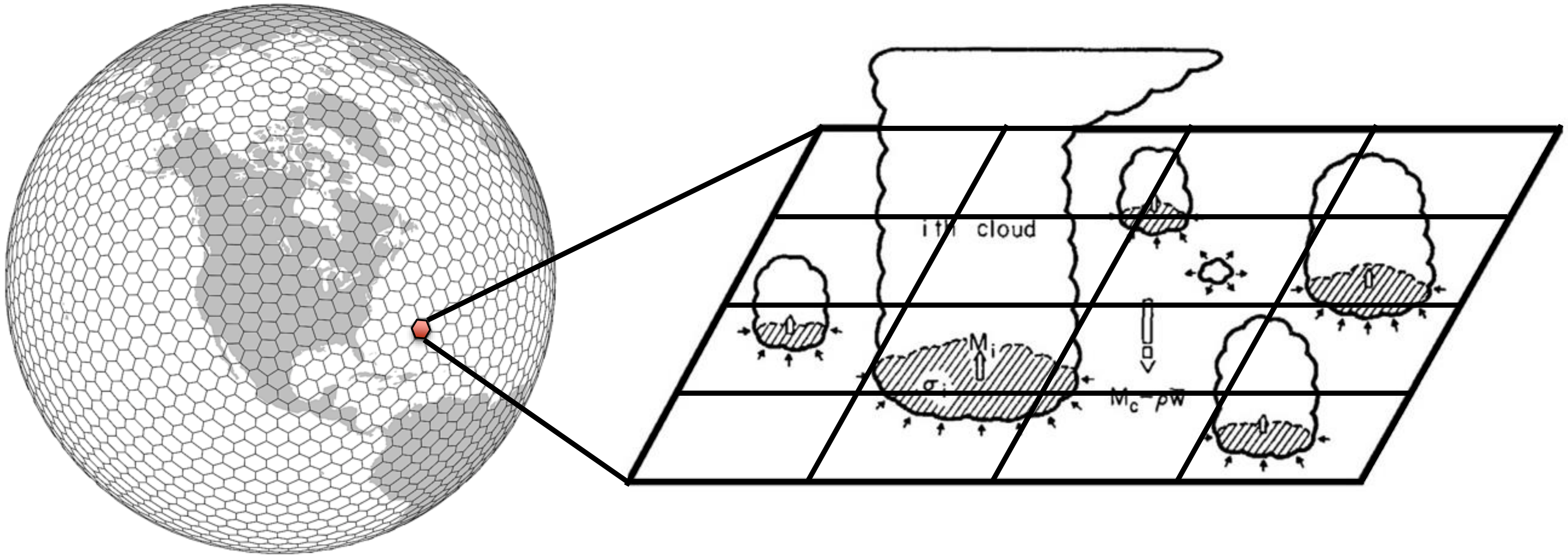
1. Resolution-specific assumptions that need to be handled within the parameterization



2. Systematic errors due to missing processes and/or fundamentally flawed methodologies

Cloud gray zone for convective parameterization

- Convective cloud parameterizations are designed to mix away instabilities that involve moist processes
- Cloud populations, coupling between cloud and the environment, and grid size: a classic multiscale problem
- Common to assume a population of clouds exists within a given grid column

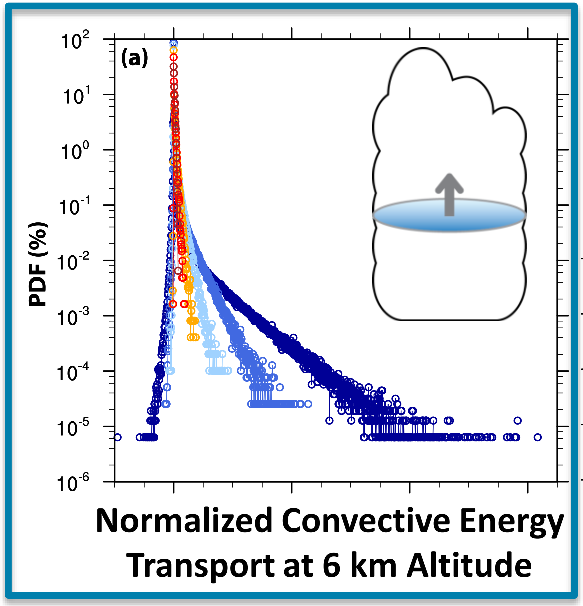


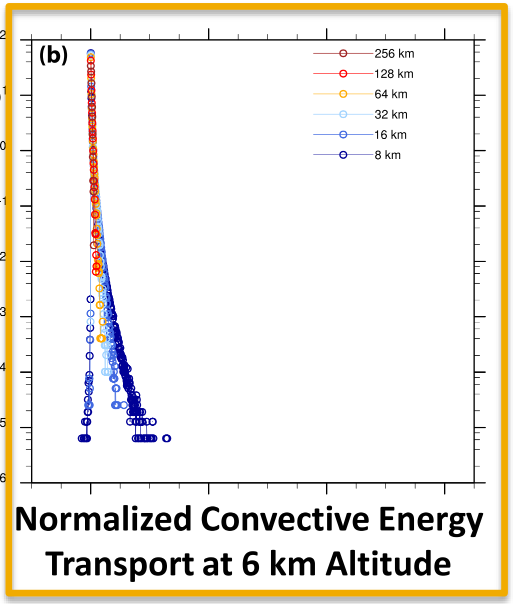
Cloud schematic: Arakawa & Schubert (1974)

Have to pick apart the parameterizations to understand resolution dependence

Derived from Cloud-Resolving Model

Offline Zhang-McFarlane Prediction





Benchmark Simulation as Proxy for Reality

Parameterized Result

- Use cloud-resolving models as a benchmark for system behavior

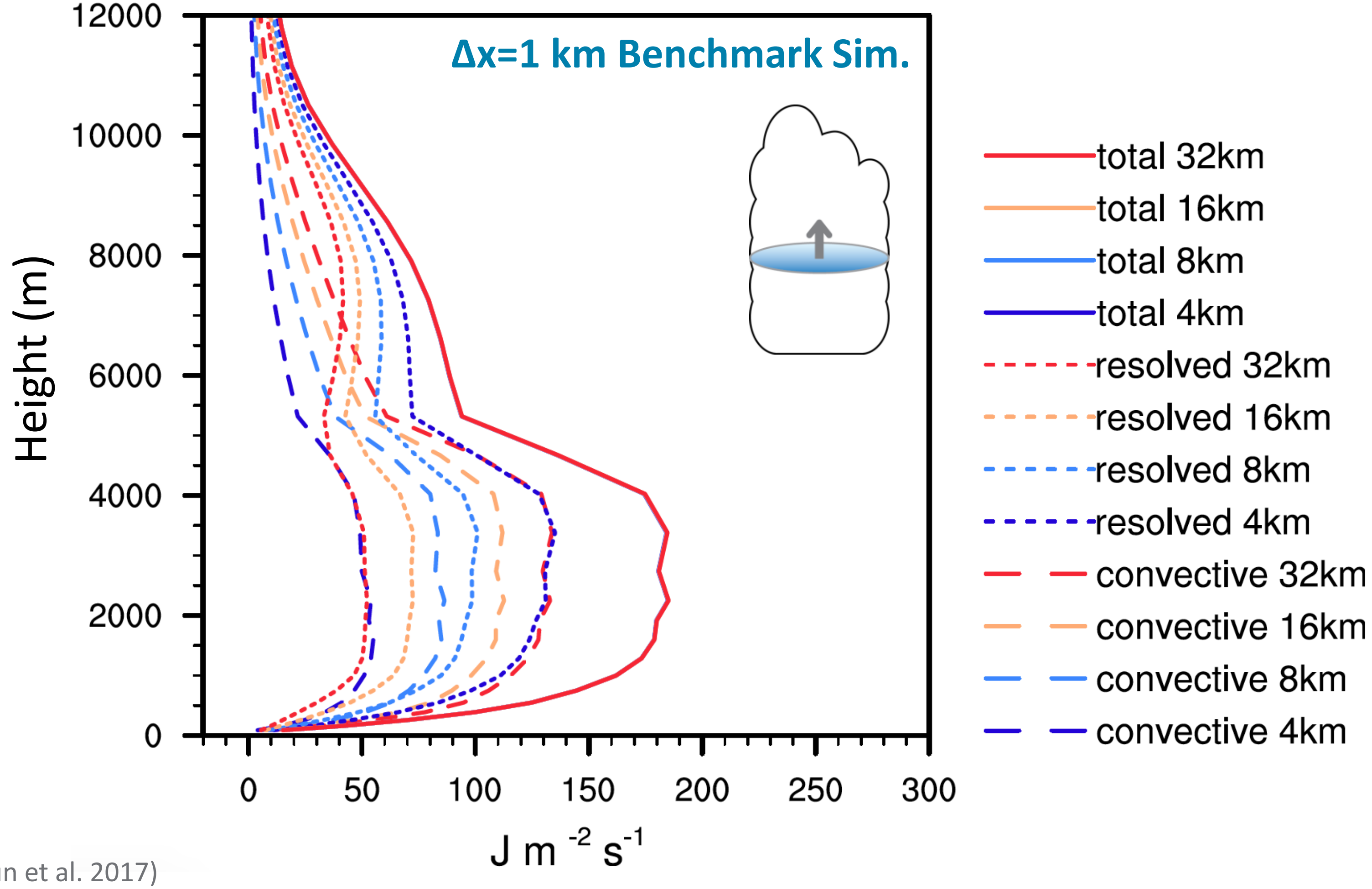
Probability Distributions of
Subgrid Vertical Moist Static Energy Flux

Coarse ESM	o	256 km
	o	128 km
	o	64 km
	o	32 km
	o	16 km
Weather Model	o	8 km

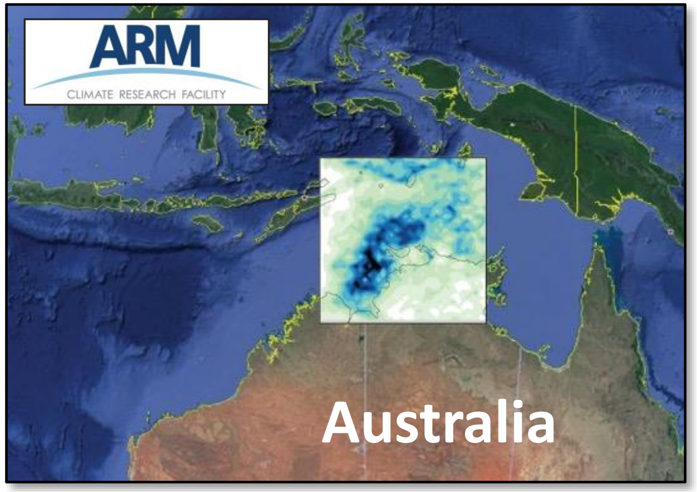
(Xiao, Gustafson, Hagos, Wu, & Wan 2015)

Sources of vertical transport in a real-world simulation

Vertical Energy Transport at Different Scales



Case Study from ARM Campaign



Color=Scale

Coarse

Fine

Pattern=Component

Solid=Total

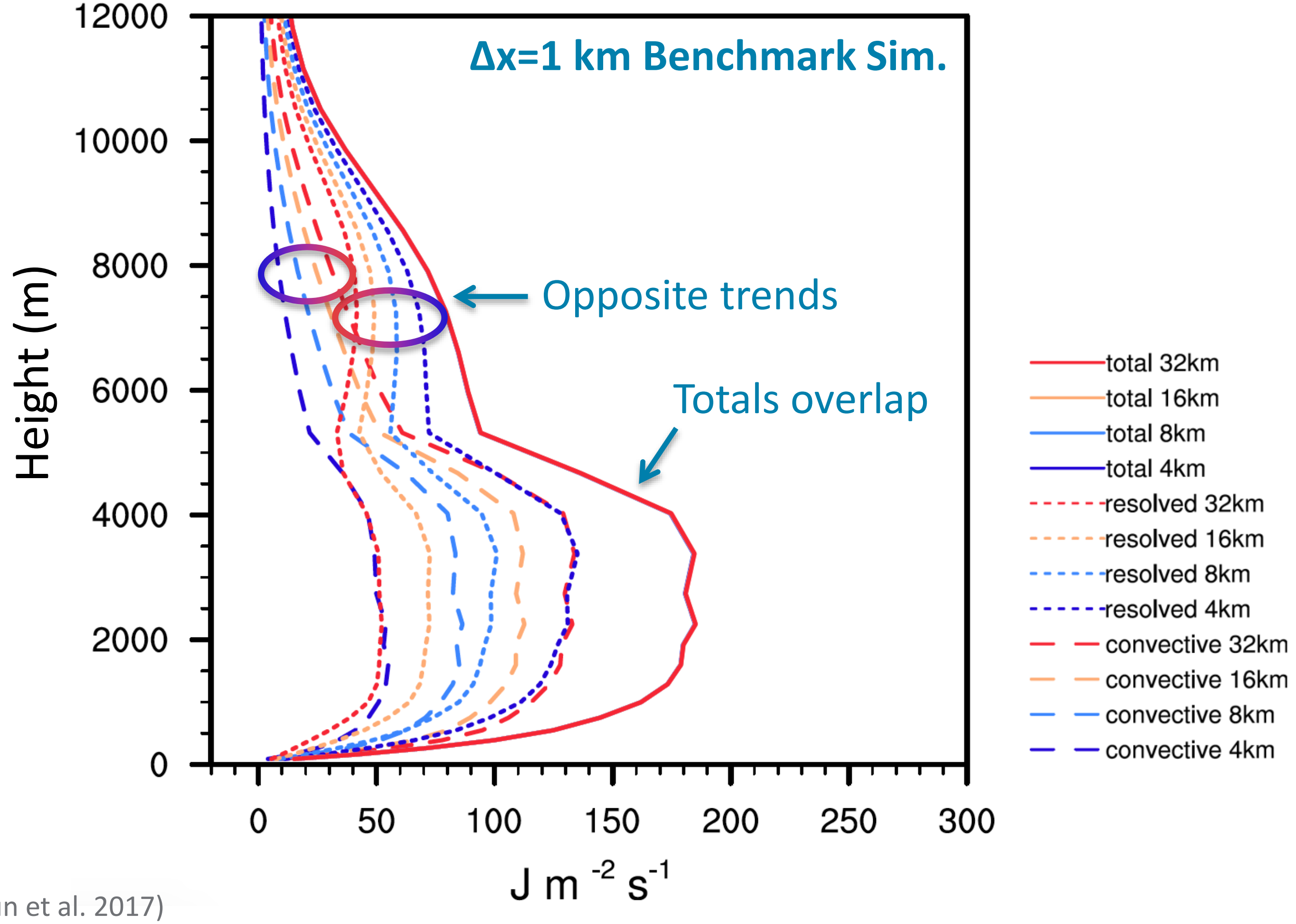
Short Dash=Resolved

Long Dash=Convective

(Yun et al. 2017)

What we should see for the resolution dependence

Vertical Energy Transport at Different Scales



- **Desired behavior**
  - Total transport should not change with resolution
  - Resolved transport should increase with increasing resolution
  - Parameterized convective transport should decrease with increasing resolution

Color=Scale
Coarse
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Pattern=Component
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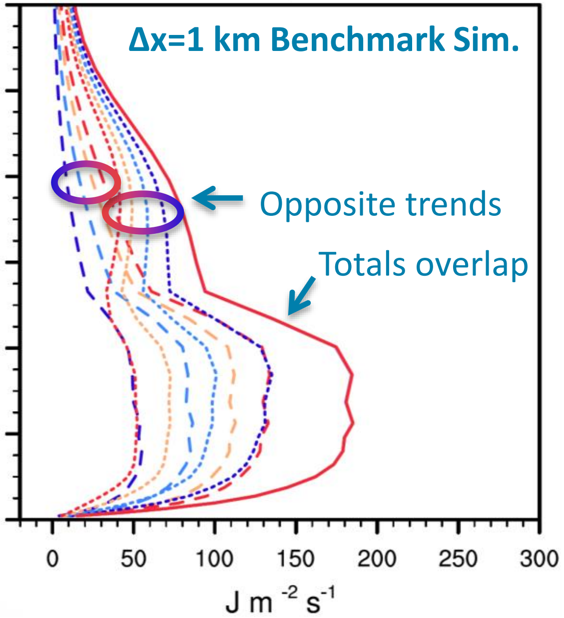
(Yun et al. 2017)

Resolution dependence of parameterized transport opposite of desired within the gray zone

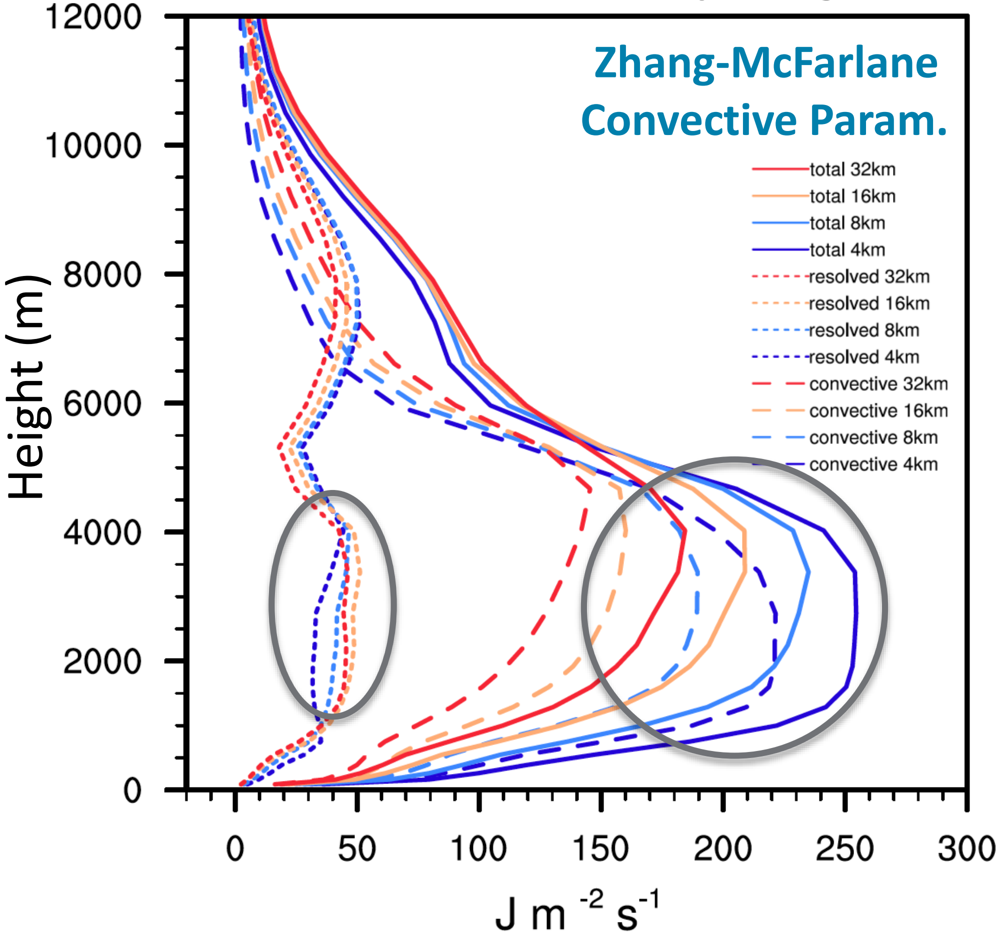
- **Desired behavior**
  - Total transport should not change with resolution
  - Resolved transport should increase with increasing resolution
  - Parameterized convective transport should decrease with increasing resolution

- **Zhang-McFarlane parameterized behavior**
  - Total transport increases with resolution
  - Resolved transport almost constant
  - Convective transport increases with resolution

Vertical Energy Transport at Different Scales



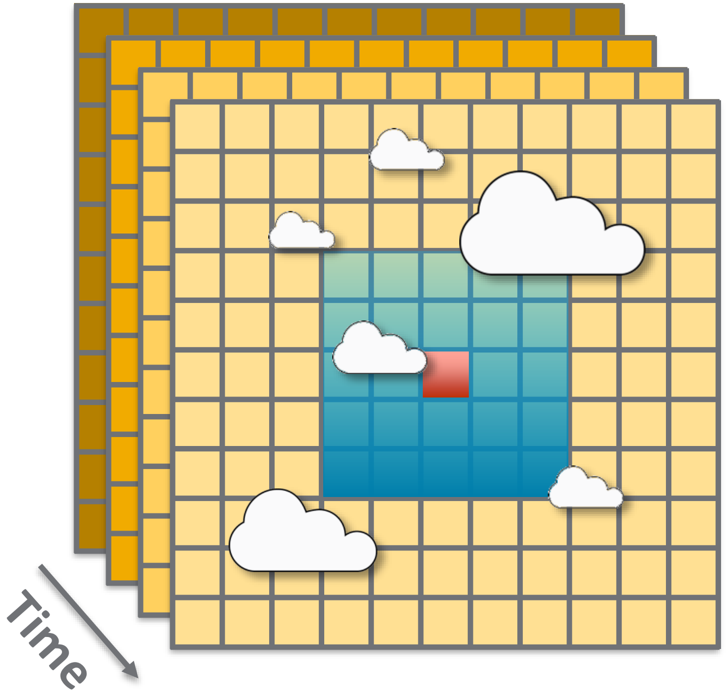
Vertical Energy Transport at Different Grid Spacings



(Yun et al. 2017)

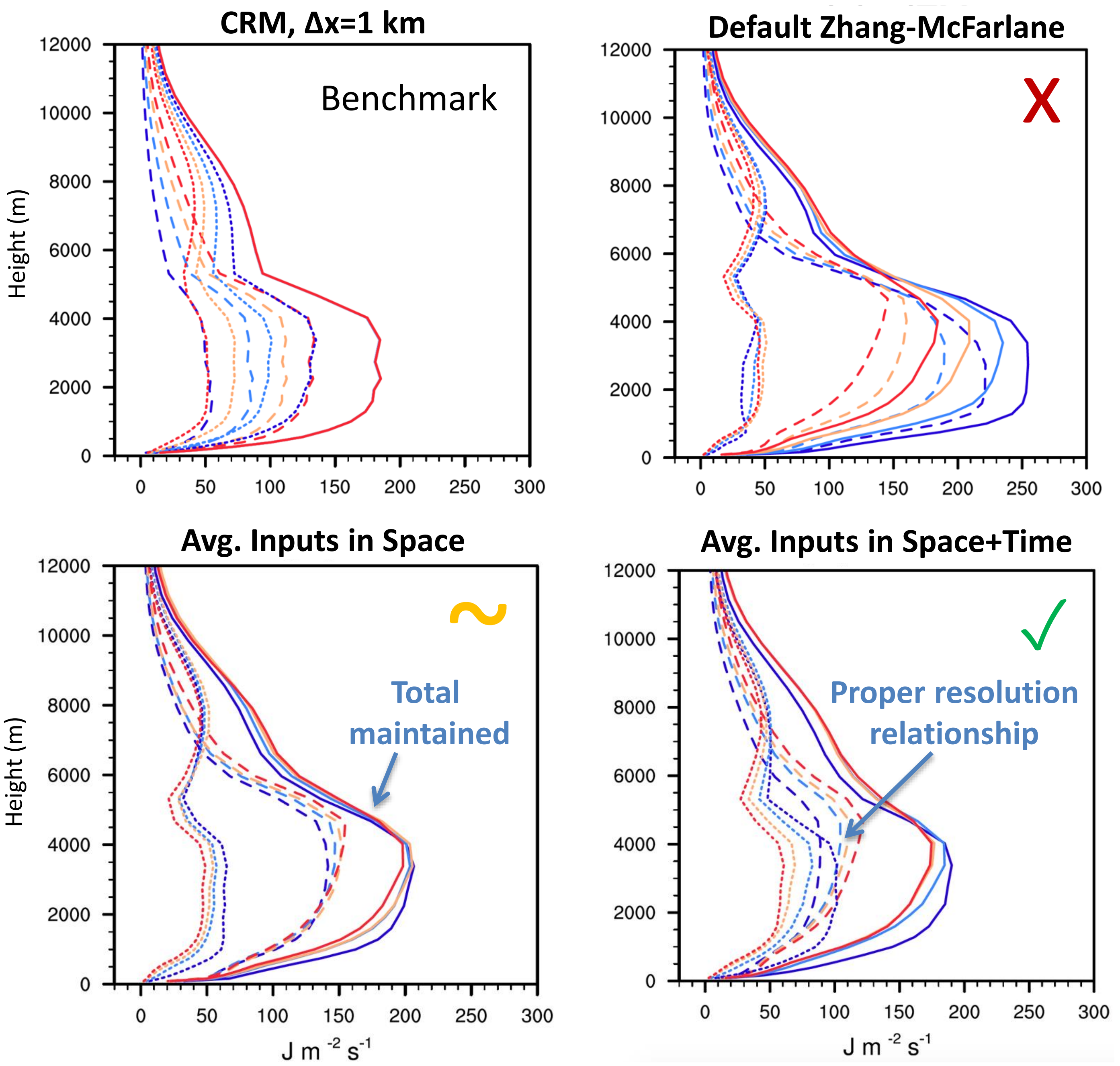
Remedy the resolution dependence problem by applying the Z-M closure assumption over a representative sample size

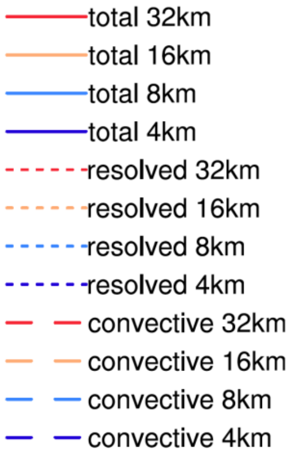
- The "quasi-equilibrium assumption" requires an area large enough to hold a cloud population
- Within the gray zone, "local" information is insufficient to properly inform the parameterization
- So, use a larger time and/or spatial sample more appropriate for the scheme's assumptions



Achieving proper resolution dependence

- Alternative sampling regions for closure calculations
  - Spatial averaging = 90 km box
  - Space+time avg. = 90 km box + 10 min.
- Better sampling recovers a constant total transport
- Resolution dependence now has correct sign

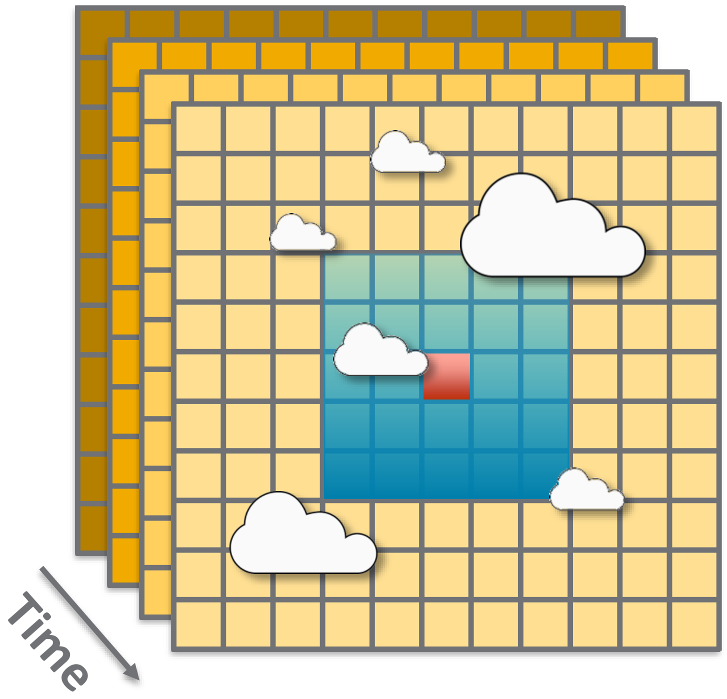




(Yun et al. 2017)

Resolution awareness can be achieved

- Targeted solutions enabling resolution awareness can be developed if we understand the sources of grid dependencies
  - We have encouraging results based on a rather simple approach
  - Maintaining scale-appropriate inputs to Zhang-McFarlane turn it from a "resolution sensitive" parameterization to one with the right resolution tendencies
- Averaging the closure over areas larger than the resolved scale naturally implies a smoothing of the solution
  - Adding variability via stochastics can retrieve the natural variability
  - Requires ensembles, which is a different way of thinking than when using a deterministic simulation



Systematic errors lead to optimization compromises

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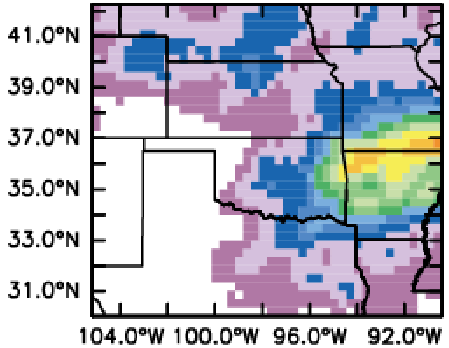
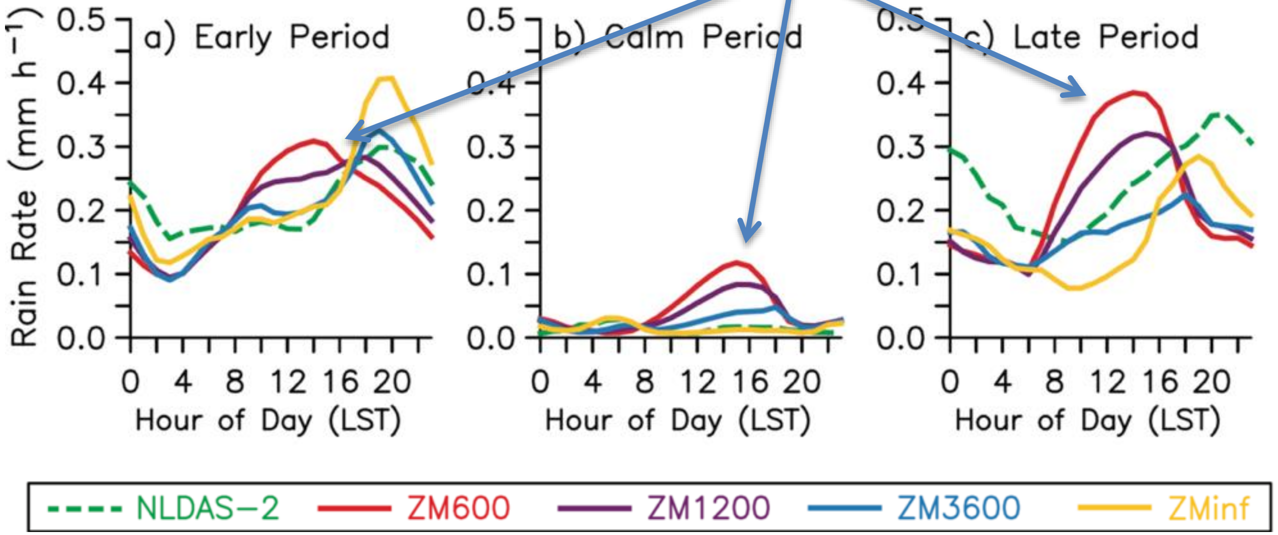
- The convective timescale, τ, controls how quickly convection can impact the environment
  - A timestep and grid spacing dependent parameter in the Zhang-McFarlane deep convection param.
- Trade-off: fast acting convection parameterization correctly simulates amount but disrupts the diurnal cycle

Accumulated Rain
ARM MC3E Campaign



Erroneous afternoon peaks for short τ's



(Gustafson et al. 2014)

Models poorly simulate mesoscale convective systems (MCSs) & cloud organization

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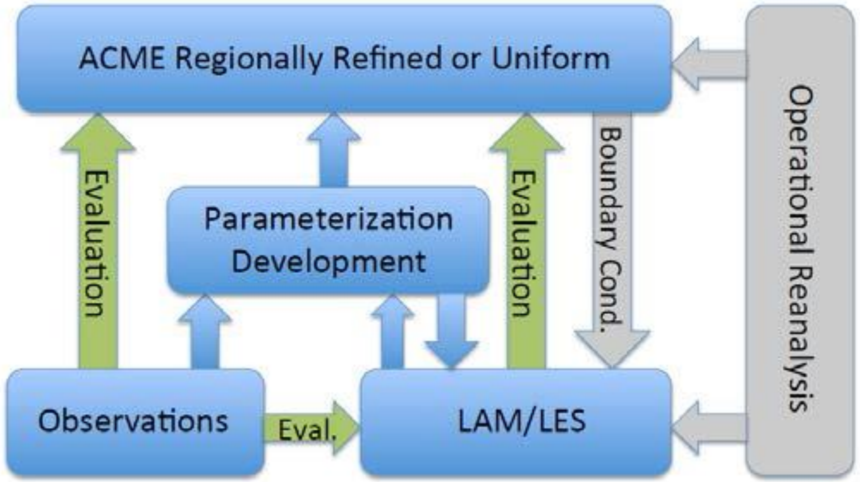
- Issues with MCSs believed to be a primary cause of poorly simulated diurnal cycle over the US

- MCSs are the focus of our *Climate Model Development and Validation MCS project (CMDV-MCS)* aimed at improving the DOE Energy Exascale Earth System Model (E3SM)
  - Add deep convection to the CLUBB scheme so it handles boundary layer turbulence, shallow clouds, and deep convection
  - Develop a functioning Quasi-3D Multiscale Modeling Framework (Q3DMMF) model
  - Address issues of stratiform-convective partitioning and multi-phase clouds through targeting microphysics

CMDV-MCS Strategy



Making observations more impactful through high-res. modeling

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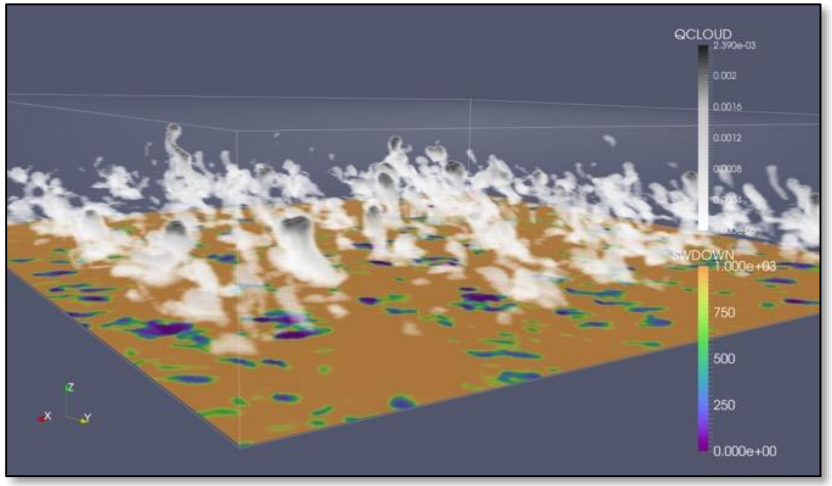
Large-Eddy Simulation Symbiotic Simulation and Observation (LASSO) Product for the DOE ARM Facility

- Produces routine large-eddy simulations to add value to ARM's observations
  - Enables robust parameterization development through a library of cases as opposed to a small number of "well behaved" scenarios
  - Bridges the scale gap between observations and parameterized models
- Currently focused on shallow convection at the Southern Great Plains Observatory in Oklahoma



How to move forward with improving convective parameterizations to enable adaptable atmos. modeling

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- **Resolution awareness:** the ability to adapt to the resolution being used and converge to a more accurate solution
- **Stochastics:** proper variability is important for many applications and is part of handling resolution awareness—implies moving toward using ensembles
- **Capturing non-local processes:** convective organization must be incorporated to account for semi-resolved dynamics (sometimes referred to as memory)
- **New mathematical approaches for multiscale problems:** cloud param. is an ill-founded mathematical dilemma in need of new methodologies

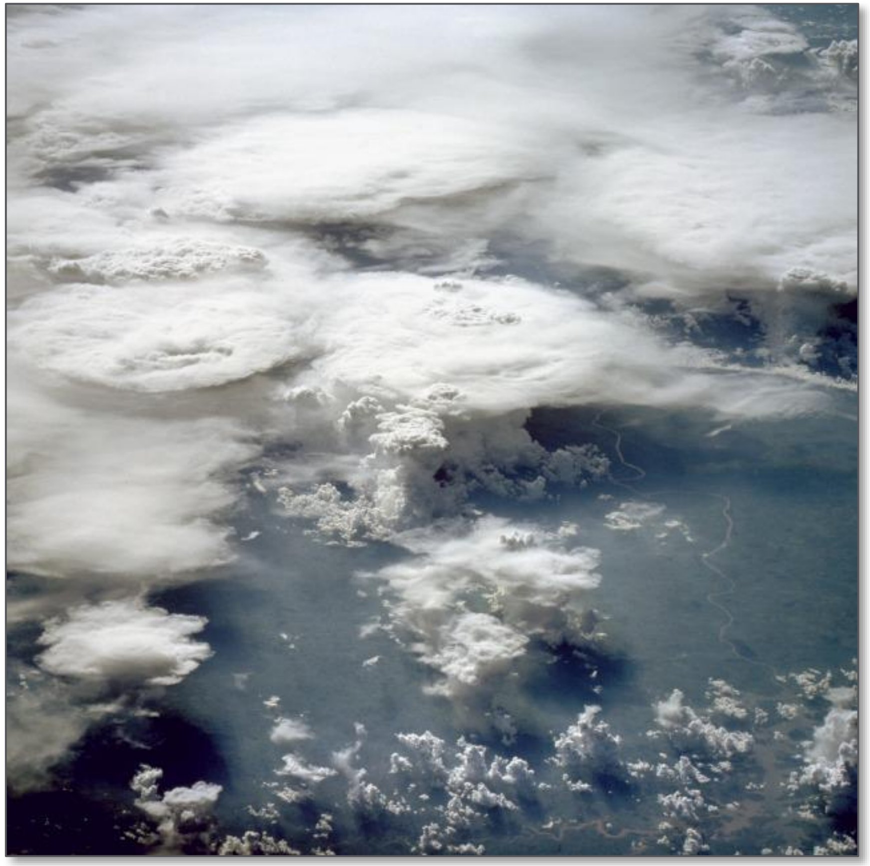

Photo: NASA