Workshop Summary: Future Physics for Global Atmospheric Models

Workshop Summary (Held June 12-14th, NCAR, Boulder, CO)

Andrew Gettelman, Julio Bacmeister, Vincent Larson, Leo Donner

Introduction

From June 12-14th 2019 the Future Physics for Global Atmospheric Models workshop was held at NCAR in Boulder, Colorado. There were about 45 participants, with about 25 junior scientists and graduate students and 20 experienced scientists from the US and abroad. The workshop was wide ranging, with a goal of understanding what the next steps and opportunities are for the future of physical parameterizations in global atmospheric models for weather and climate.

Speakers were asked to address four questions. 1. What problems in climate (or weather) should we be addressing with future global models? 2. What are the critical uncertainties/challenges in physical parameterizations needed to answer or make progress on these problems? 3. What specific parameterization methods can meet those challenges? 4. What excites and scares you about the next generation of models? Participants were asked to phrase these questions in the context of CESM, the Community Earth System Model.

The discussion started with an overview of the perspective from weather and climate centers (with talks by representatives from NOAA and DOE). The workshop then dedicated sessions and topics to specific classes of parameterizations such as shallow turbulence, deep convection, aerosols and cloud microphysics, and gravity waves and momentum forcing. A final session on 'new approaches' explored ideas beyond traditional uniform global models with deterministic parameterizations.

This document provides a summary of these discussions. Key takeaways are listed first. Then we discuss some notes on the problem of physical parameterization and key issues for weather and climate modeling, then discussion of key issues and next steps for physical parameterization, and ending with new approaches.

Key Takeaways

There were several overall themes that came out of the workshop and deserved highlighting:

- Quantifying uncertainty in physical parameterizations at all scales is critical and should be done with CAM6. This is critical as global models are used for decision support.
- The connective tissue between parameterizations, and between parameterizations and the dynamical core, is a critical part of uncertainty.
- Emerging, highly parallel supercomputer architectures can be exploited either to perform storm-resolving (3-5km) global simulations, to use expensive but parallelizable physics (e.g., subcolumns or superparameterization), or to create large ensembles of simulations.
- There are interesting conceptual differences in approaches to parameterization, especially of turbulence, as well as new conceptual ideas for parameterization (such as

machine learning).

- It was noted that new approaches (machine learning, global storm resolving models at 3km, embedded LES) are not better overall than classical methods for weather or climate (yet).
- Tuning or training of parameterizations against high-quality data is important. Quality data and a good loss function are essential for empirical approaches including neural networks and machine learning, which make few assumptions about the physics of the atmosphere. In traditional parameterizations, tuning can be thwarted by model structural errors, and if not done broadly enough, may limit unified cross-scale approaches.
- In all these areas CESM has an advanced suite of parameterizations and a valuable role to play as a platform for testing new ideas.
- Model development is a social balance between competition and cooperation, and recent examples of cooperative (or collaborative) approaches seem to have advantages over competitions.

With regard to specific parameterizations:

- Key development areas for **cloud microphysics** are rimed ice (graupel and hail) and the ice nucleation process. Unifying microphysics in models (i.e. between convection and stratiform clouds) is also a priority.
- **Deep convection** is at a crossroads as we enter a ‘gray zone’ where we start to resolve mesoscale motions (3-25km). Convection that shuts down gracefully is an approach, prognostic deep convective motions are desirable to resolve convection in the time domain, and consistent convective microphysics is desirable.
- **Shallow turbulence** is being parameterized by a variety of methodologies, including eddy diffusivity mass-flux, high-order closure, and low-order closure. While these three methodologies are beginning to show areas of convergence with each other, each method still shows distinct advantages and disadvantages with respect to, e.g., computational cost, fidelity to the underlying physics, suitability in gray-zone resolutions, and interfacing with microphysics.
- **Gravity wave parameterizations** (GWP), in particular for orographic gravity waves (OGWP), are explicitly parameterizing unresolved motion vs. “subgrid motion”, since topographic BCs are typically smoothed after coarse-graining onto model grids. GWP that explicitly considers cross-grid effects is desirable. In addition, alternatives to the saturation hypothesis for representing wave breakdown should be examined.

Overall Themes

The key science areas for global models were discussed to set the stage. Weather prediction is extending into sub-seasonal (>10 days) and seasonal (3-6 month) forecasts. That requires coupled models, energy conservation and a host of other considerations that climate models have long had to deal with. Climate prediction is now starting to focus perhaps less on the ‘if’ of climate change, and more on getting to actionable science soon. This requires solving key issues such as shallow cloud responses to climate change, and interactions with aerosols and rain formation. High-resolution information becomes critical to make climate predictions actionable (e.g. representing extremes) and making the models more traceable to physical processes and ultimately observations.

Across several parameterization topics there was an emphasis on quantifying uncertainty in physical parameterizations and climate results of physical parameterizations. CAM6 has an advanced suite of physical parameterizations, and we have not fully tested rigorously how changes to parameters and connections between parameterizations (see below) impact important climate metrics or emergent properties of the simulations. There exist 'uncertainty quantification' methods that could be of use. Several groups identified methods and offered to help. A perturbed parameter ensemble could be developed with CESM2-CAM6 to sample the parameter space of key processes (shallow cloud feedbacks and aerosol-cloud interactions were discussed). This could be made available to the community for analysis, and would be a good test of collaborative work in new areas (uncertainty, big data, machine learning, etc).

Physical parameterizations do not exist in isolation from each other, but need to form a collective whole that works consistently. The set of parameterizations in a model is like the sled dogs in a dog-sled team: complex animals, trained on their own, that then need to be trained together with the right connections between them to get good performance. This has usually been considered explicitly for climate. But tight coupling of schemes can make for less flexible, though more consistent, models. There is a tension between consistency and modularity that needs to be balanced. Another analogy that was used is if you have an old stone wall with irregular stones, a new shiny regular brick won't fit in the wall: modularity works only if all the bricks are the same, and they rarely are. A "unified" approach with fewer and more complex parameterizations has its own challenges with tuning and including general enough physics without being overwhelmed by complexity. It is all a matter of where a model wants to put the complexity: in the physics of a complex, unified scheme, or in the interactions between simple schemes. What is the path forward for CAM and CESM? The focus may be different depending on the use and vision for the model. CAM faces a difficulty of perhaps having a diverse strategic focus. In addition, parameterizations should not exist in isolation from the dynamics. It may be appropriate to move some terms to the 'left hand side' of the equations to allow them to be used and integrated by dynamics. But that sacrifices modularity.

The discussion below on specific parameterization methods will highlight different conceptual approaches to deal with processes that may lie in the 'gray zone'. Gray zones are regions where the basic assumptions used in parameterizations break down, but it is difficult to represent processes explicitly. There are several gray zones, each of a different size. The gray zone for turbulence occurs in shallow clouds at small (<1km) scales, but organized turbulence for deep convection occurs at 1km up to 5km for individual convective cells, and up to 25km for large scale mesoscale convective complexes.

CESM and CAM6 are a wonderful community platform with advanced physical parameterizations. This reflects the success at exchanging ideas and being a platform for ideas. There are also now new ideas for how global climate and even weather solutions can be generated using embedded LES models at different scales (ultra parameterization and super parameterization) and using machine learning emulators from the process to parameterization level. These ideas are not yet mature enough to replace classical parameterization methods, but they are developing rapidly. CESM and CAM should seek to accommodate these efforts to the extent that they do not distract from continuing efforts in classical GCM construction and parameterization theory.

Finally, there are different philosophies and practices of model development. One model is to have rigorous targets and competition between parameterizations and teams. This ‘bake-off’ model has been used particularly in the weather community (we heard examples by NOAA-EMC) where the ‘metrics’ are known and ‘objective’. The ‘bake-off’ approach has also been used in CESM, and at some level in many modeling centers. But for CESM a more collaborative approach to model development may be more appropriate, with collaborative teams of experts working to mitigate specific model biases. The UK MetOffice has recently targeted specific processes for improvement with a cooperative and multidisciplinary focus and has had some success. Climate Process Teams (CPTs) in the U.S. have had some success as well in advancing parameterization (e.g. Higher Order Closure methods) and minimizing model biases in particular areas.

The problem of physical parameterization for weather and climate models

Parameterizations of physical processes are designed to represent the impact of processes occurring at scales smaller than the model grid. The 'parameterization problem' in weather and climate models arises from the fact that the magnitude of the sub-grid scale terms is comparable to the grid scale terms, and that critical answers (climate sensitivity, extreme precipitation) depend on the sub-grid terms, which do not have unique formulations. We generally understand the physical laws underlying parameterizations for well defined environments, but the scale mis-matches limit our ability to directly apply process knowledge. Furthermore, the nature of the sub-grid scale terms changes with different scales and different approaches. Different approaches and assumptions, such as those based on statistics or equilibrium, may break down at different (especially smaller) scales (i.e., the assumption of convective updrafts being a small fraction of the grid cell, and subsidence occurs in the same cell). However, the place where the assumptions are invalid is often still too large to fully resolve processes. Hence a ‘gray zone’ exists where physical parameterizations do not work well, but terms are not explicitly resolved.

Climate v. Weather

Weather models seek to define the probabilities for near-term prediction of specific physical states. Model solutions are significantly dependent on initial condition uncertainty. The energy budget is not critical, and the model solutions are dependent on data assimilation strategies, which may guide or limit parameterizations because of a desire for adjoint (inverse) model tools.

Climate models started as exercises in hypothesis testing. Examples include, Can we reproduce the general circulation, and is the planet warming? But now they are being used, like weather models, for decision support or prediction. This puts much higher demands on the models, and on quantifying uncertainty in models. But it is not initial condition uncertainty as in weather modeling, and so that requires a different approach, which is quantification of structural uncertainty.

Computation: Where to put computer time?

For all modeling, computation is a factor. There are three main ways to take advantage of expanding computing power. 1. Resolution can be increased. 2. Physical parameterizations can get more comprehensive (and more expensive), or 3. More ensembles can be performed in order to understand uncertainty. Resolution may entirely change the validity of parameterizations when approaching ‘gray zone’ scales, making changing resolutions not just a matter of making arrays bigger. More complex parameterizations may be harder to understand and evaluate with observations, while ensembles can be difficult to interpret. Both weather and climate prediction have used increased computation to go to finer scales (higher resolution). Weather prediction has typically chosen more ensembles as well, due to the irreducible nature of initial condition uncertainty, while climate prediction has typically chosen to add more comprehensive process representations in the earth system.

Specific Elements in Parameterization

The workshop focused on several different themes for specific parameterization elements. Most of the focus was on clouds, including discussion of deep convective motions, shallow clouds and shallow turbulence in and near the boundary layer, as well as cloud microphysics and aerosols. Also discussed were gravity waves, momentum drag, and momentum fluxes. Several important themes emerged across these areas. This includes the different conceptual methods for parameterization of turbulence. One major category uses ‘Assumed Distributions’, or representing the sub-grid scale with a distribution function. Higher-Order Closure methods like CLUBB, or the Eddy Diffusivity part of EDMF, fall into this category. The second method is a ‘coherent structures’ approach, often the plume-based representation of mass flux deep convective schemes.

Deep Convection

Deep convective motions are often defined using a ‘coherent structures’ approach based on the assumption of one or more updraft plumes, with downdrafts occurring in the grid box. This diagnostic 'mass flux' approach to deep convection has been around for over 40 years (since Arakawa and Schubert 1974), and has held up well for climate models. The problem is that the quasi-equilibrium assumptions of updrafts break down when the updraft area gets to be a significant part of the grid box. This begins a gray zone for updrafts of a few km or so starting at maybe 25km. But explicit resolution of updrafts is difficult. Mid-latitude systems and mesoscale convective complexes may have large updrafts of 1-3 km that can be partially resolved at these grid scales, while tropical updrafts are smaller and potentially more numerous, and more difficult to represent. Below the 5-km scale, deeper convection might be resolved, but a spectrum of more shallow convective elements may not be. 'Storm Resolving' models at 3-5km are 'common' and now forming the basis of 'global storm resolving models' (GSRMs), but it is not clear that they can resolve many deep convective motions. Ideally, a deep convective scheme would possess some sense of 'scale sensitivity' and would shut itself down as the grid scale is reduced or the convective area approaches the grid size, perhaps along the lines of Arakawa and Wu (2013), so that it is not doing much at high resolution. Challenges in representing deep convection also extend to the time domain to represent the initiation and lifecycle of deep convection. Prognostic approaches (which carry information across timesteps) help in this regard.

Convective Microphysics

There was more agreement that cloud microphysics should be integrated with deep convective motions. Microphysical processes such as condensation heating, riming, and evaporation in downdrafts can drive convective and ultimately mesoscale motions, and are important to represent consistently. Such calculations would need an updraft scale vertical velocity (which can be provided by some mass flux schemes), and ideally would use a microphysical parameterization consistent with the stratiform microphysics. CAM might be a good example, as the Song and Zhang (2011) version of the MG (Morrison and Gettelman 2008) microphysics is available in CAM6 for the ZM (Zhang and McFarlane 1996) deep convective scheme.

Dynamical Core Integration of terms

There was also discussion of integrating convective motions in the dynamical core, allowing the dynamical core to treat advective components currently included in physics routines, e.g., convective updrafts and downdrafts. This might have the benefits of being able to move downdrafts into an adjacent grid box from the updraft, which would happen with large updraft area. It was noted that as ECMWF is getting to 5km scales, they are starting to do this.

Shallow Turbulence

Shallow turbulence, ranging from shallow convection to stratocumulus and stratus cloud decks in the Planetary Boundary Layer (PBL), is a smaller scale problem than deep convection, and is often now treated with assumed distributions of subgrid-scale variability. These methods are also used to treat stable and dry convective PBLs. Interestingly, the gray zone for shallow turbulence is much finer, with eddies on the order of 10-100m, and hence even a 1-3km horizontal resolution model should parameterize shallow turbulence. Two advanced classes were discussed. Higher-Order Closure (such as CLUBB) is one such example, while the Eddy Diffusivity portion of Eddy Diffusivity Mass Flux (EDMF) schemes is another. CLUBB was thought to be a good path forward as it parameterizes several cloud regimes in a unified way, and is consistently linked with cloud microphysics in those regimes. EDMF is able to unify all types of PBL mixing including shallow convection and strato-cumulus turbulence by combining the ED assumed distribution (for turbulence) with a coherent structures mass-flux approach (for convection). We need to parameterize both the small eddies with ED and the PBL-scale ones with MF. There was some discussion of how much CLUBB could be used in addition to do vertically coherent motion of deep convection, and this unification is an obvious path forward for CAM at high resolution, and maybe even variable resolution.

Cloud Microphysics & Aerosols

A session of the workshop was devoted to cloud microphysics and aerosols. It was widely agreed that bulk 2-moment microphysics schemes such as Morrison-Gettelman (MG: Gettelman and Morrison 2015) are a solid path forward for the future. Coupling between cloud microphysics and shallow turbulence (macrophysics) should be close, and CAM has a good prognostic coupling between CLUBB and the MG microphysics. Modal aerosol schemes (also with 2 moments per size class, e.g. MAM4 or MAM7) also work well for most aspects of weather and climate simulations except for detailed chemical reactions where more involved treatments may be desired.

Several key problems were identified for future work. One is the continued importance of the warm rain formation process (called ‘autoconversion’ in bulk schemes) and how it is altered by the presence of Cloud Condensation Nuclei (CCN) from activated aerosols. The formation of rain, or the delayed formation of rain, from increased cloud drop number, and the resulting feedbacks or ‘buffers’ on the cloud microphysical system are critical for constraining aerosol-cloud-interactions and their effective radiative forcing (ERF_aci), leading to large uncertainties in climate sensitivity estimates. The other critical uncertainty identified on the weather scale (but important for climate at high latitudes) is the mixed-phase regime at temperatures between freezing (273K) and the homogenous freezing limit for ice (-35 to -40˚C). In this region, supercooled liquid water exists, regulated by ice nucleating particles (INP) and the riming process. INP are critical for determining freezing in supercooled liquid clouds, which alter their lifetime and radiative properties substantially. Riming is vital for understanding severe precipitation and hail/graupel, which may also drive storm dynamics. For both of these factors, vertical velocities in clouds are important for describing the activation and subsequent evolution of clouds. It was noted that NCAR (Thompson, Morrison, Gettelman) is working on a more unified 2-moment cloud microphysics scheme that is intended to work across scales from weather to climate by representing rimed ice and ice nucleating particles, and unifying the ice and snow treatment. This is expected to be ready for the next version of CAM.

Cloud microphysics and aerosols were one key area where uncertainty quantification stood out as being critical. Since critical problems of aerosol forcing and cloud feedback related to cloud microphysical (and turbulence) processes, linking cloud processes and the emergent properties of the system is critical. This might best be done with model sensitivity experiments using a rigorous uncertainty quantification method. Several approaches exist, and they were discussed. The time seems ripe for a large community uncertainty quantification effort with CAM6.

Gravity Waves

Gravity Wave drag Parameterizations (GWP) need to parameterize generation, propagation and dissipation of gravity waves. Gravity wave sources include orography (mountain waves) and, in high-top (above the stratopause) models, sources may also include convection, frontal dynamics and shear. The orographic source is inherently "scale-aware" in that forcing for orographic GWP naturally decreases as more and more topography is explicitly resolved. An interesting wrinkle in the case of orographic GWP is that the schemes are explicitly representing unresolved motion rather than true subgrid motion (since the topography itself generating the waves is not resolved). This is a consequence of the fact that topographic boundary conditions for dycores are almost always smoothed after coarse-graining to the model's grid. Among other things this implies that horizontal scales of parameterized waves can be comparable to the grid length in the simulation. This along with the well-observed horizontal propagation of gravity waves may mean that GWP is ripe for extensions that incorporate horizontal communication across grid boxes, which does not occur in current schemes.

Propagation and dissipation models for gravity wave schemes, in particular those employed in orographic schemes, have not evolved significantly since the 1980's. Current schemes use a simple WKB, 2D hydrostatic approximation for wave propagation, and assume a simple balance between wave dissipation and turbulence production to diagnose wave dissipation and its resulting drag. High resolution simulations show that both assumptions are clearly inadequate. A promising path forward may be to incorporate gravity wave energy and action as prognostic variables that can be transported in the model dycore.

Unification of Parameterizations

A number of threads above highlight that 'unification' of parameterizations to work consistently across regimes (and scales), and between parameterizations (like microphysics and condensation), is a key area. Unification of moist turbulence – encompassing PBL, shallow, and deep convection – is a key topic. This is something that has been discussed for a long time, but only recently (mostly with CLUBB and EDMF) have we been attempting unified parameterizations in practice. CAM is at the forefront of thinking in this area with CLUBB.

Consistency between parameterizations (the ‘connective tissue’ discussed earlier) is also another important aspect. This often comes up in ensuring that radiative properties of clouds and aerosols are consistent with their physical treatment (which CAM has done for liquid and aerosols, but not for ice).

Non-Traditional Methods

The workshop ended with discussions of less traditional formulations of weather and climate models, including high-resolution climate prediction, Global Storm Resolving Models (GSRMs), different types of machine learning, and multi-scale modeling using LES to represent clouds. None of these methods is quite mature enough to replace ‘classical’ methods of parameterization and coupling to dynamical cores, but all are being explored. CESM and the CAM community should participate in and encourage these efforts. They may prove useful for understanding critical uncertainties in weather and climate prediction, even if they do not fully replace ‘classical’ current approaches to parameterization.

Advances are still occurring slowly in weather prediction models, which have to evolve incrementally. ECMWF will be running a global hydrostatic 5-km ensemble forecast in 2025. NOAA in the U.S. continues to advance, but faces challenges with a wide range of stakeholders. In general, much of the discussion around operational systems uses current global uniform meshes. But without operational constraints, many key climate and weather phenomena can be understood using refined mesh approaches to target high resolution in specific regimes.

High Resolution ‘Storm Scale’ Models

High resolution global climate prediction is however moving forward, driven by a desire to directly simulate extreme weather events and how they might evolve under climate change. DOE is focusing its ‘SCREAM’ efforts (E3SMv3/4) on high-resolution simulations with few physical parameterizations (simplified higher order closure or SHOC and complex ‘P3’ microphysics), and re-coding the model for GPUs. There is a lot of work on Global Storm Resolving Models (GSRMS): GSRMs run usually using mesoscale model microphysics from 2-7 km. Initial results do not look that different between 2 and 7 km. It may be that 7km is good enough, or that scales below 2 km are necessary. Physical parameterizations built for lower resolutions seem to work okay at these higher resolutions. Non-hydrostatic effects do not seem to be a problem, but participants thought at the 2-3km scale it might matter. There are lots of opportunities and synergies for CESM to get involved with this work, and CESM-CAM should be enabled to do simulations (either uniform or refined mesh) at these scales. They are useful for testing, evaluation and extreme events, and CAM6 physics of CLUBB and MG is well suited for this work. Global climate models at resolutions on the order of a kilometer to a few kilometers without advanced treatment of sub-grid turbulence struggle to simulate low-cloud systems, which are critical in determining climate sensitivity and to simulating global shortwave and longwave radiative fluxes.

Refined Mesh Modeling

There was a great deal of discussion of refined mesh modeling. Such models have high horizontal resolution over one (or several) regions of the globe. They can be a cost-effective way of simulating fine scales, with costs an order of magnitude or more less expensive than uniform high-resolution models. Regional climate models are rapidly evolving into these models. It provides a logical pathway for understanding extreme events, as well as testing and evaluating physical parameterizations against observations. CESM through the Spectral Element (SE) dynamical core has this capability now. There are benefits in making it easier to configure and more widely available to the community. It's not clear whether variable resolution can answer some questions, like longer term climate models (ENSO) or even tropical cyclone evolution, particularly at the basin scale. But for many applications for weather and climate, refined mesh global models may be a workhorse tool.

Machine Learning

Machine learning is simply a new and complex method for emulation, or ultimately regression, to relate a core set of variables to key missing variables. Many groups are exploring whether machine learning emulation approaches will work for geophysical modeling. There are three main areas where modeling may benefit from these approaches. First, machine learning can be used for replacing parts or all of traditional parameterizations that might be too expensive to run in a global model, or with observational training data. Some examples were given, such as replacing the autoconversion process for warm rain formation with a more detailed model treatment. Second, emulators for sub-grid scale models can be used, such as emulating a LES code in a large scale GCM. Finally, machine learning can be used for optimizing parameters in parameterizations. None of these approaches is yet mature enough to replace traditional methods. There are still important limitations such as the bounds of extrapolation from training data and conservation laws that need careful treatment and assessment. It is likely that machine learning will find a place in a hierarchy of model methods, but not totally replace current methods.

Embedded Cloud Resolving (CRM) and Large-Eddy Simulation (LES)

Large-Eddy Simulations typically have a scale of <100m in the horizontal, and have few sub-grid parameterizations. Cloud Resolving Models (CRMs) are coarser scale (1km) but also have few sub-grid parameterizations. Condensation and convection are often done explicitly in LES and CRMs. Such models are often microphysics, radiation and dynamics, and are limited area. These models are very good for testing and developing parameterizations. CRMs have also been embedded in global models to replace cloud and turbulence schemes, as superparameterization (2D CRM) or ultra-parameterization (3D CRM). Super and ultra-parameterization suffer from problems consistently connecting reduced size CRM simulations to global grids. Furthermore, CRM or LES may not be ‘truth’ in many cases where processes are not certain, such as for cold clouds below the freezing level. There is a ‘new’ LES model at NCAR (Fast Eddy), which is solely built for GPU computation. That may not be widely usable on many platforms.

Integration of Physics and Dynamics

There was an interesting discussion of integration of the physics and dynamics at the workshop. At some scale, it might be useful to put dynamical terms from physics like downdrafts and momentum into the dynamical core. The benefit would be integrating physics and dynamics, and using more advanced numerical methods for the physics terms. But this might reveal more structural biases. It seems like there are certain cases where it might be useful. For example ECMWF is considering putting more terms into the dynamics for ~5km simulations in the future.

Summary

A number of paths forward were identified for CAM development of physical parameterizations. Understanding and quantifying parameter uncertainty in CAM6 is a critical exercise for NCAR and the community. Some further advances in cloud microphysics towards the mixed phase (ice nucleation, rimed ice) are important for weather and climate extremes. Continued exploration of deep convection parameterization is useful. One approach may be for CLUBB to go deep (i.e. shut off deep convection). EDMF is also capable of being used for deep convection. Another approach is to use a more ‘scale aware’ convective scheme to adjust itself with resolution. Microphysics should be unified across cloud schemes in CESM.

There are several other broad messages. Focused collaboration (CPT-type approaches) seem to promise more sustained progress and better use of human capital than competition. There are trade-offs between modularity and consistency that CESM will soon need to address: does CAM become more modular, or more integrated. More integrated would allow CAM to push integration with dynamical cores and physics, which may not be possible for modular code. CESM and CAM should push regional modeling with refined meshes, and prepare for global storm resolving (3-7km) simulations. Machine learning approaches should be used as necessary when they are well defined, behaved and perform similarly or better than classical methods at reduced computational cost. CAM should consider better and more integrated use of LES for parameterization development and evaluation (perhaps by enabling ways to run key CAM physics with LES scales and turbulence), and consider how such scales can inform larger scale efforts.