Community Climate System Model

Strategic Plan for the Community Atmosphere Model

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Atmospheric Model Working Group

Overview

The purpose of this plan is to set a roadmap for development of the Community Atmosphere Model (CAM). The plan will implement the infrastructure and knowledge base required to address priority scientific goals and fulfill community modeling requirements. The success of this plan will not constitute a single 'new model' release, but rather a scientific and user infrastructure that has the flexibility to rapidly respond to the continually evolving needs of the scientific community. The plan outlines scientific and community goals, timelines, and a detailed description of component development for achieving the goals.

Imperatives:

- Improve representation of physical processes in CAM
- Add additional scientific functionality (e.g.: microphysics in convection, convectively driven gravity waves)
- Continue a high level of community support and collaboration
- Develop, use and distribute better evaluation tools and metrics

Frontiers:

- High resolution simulations for regional climate prediction
- Develop, integrate and test dynamical cores to support high resolution modeling
- Develop or incorporate physical parameterizations that work across scales from the cloud permitting through mesoscale, to global scale

Science Goals

Future CAM development will build on current successes, as well as attempt to improve the current simulations and use enhanced computational capacity to aim for new goals. Improvement can be measured by (a) more functionality, (b) better computational efficiency, (c) physics improvements and/or (d) bias reduction.

1. Climate simulation and prediction across scales: Traditional grid scales used for climate (on the order of 100 km) are insufficient to resolve or sufficiently constrain process-based representations to generate extreme event probabilities that are critical for impact assessment. High-end computational power now enables climate prediction at the regional (10-25km) and soon local (<10km) scale. These scales, pushing to the hydrostatic limit and below, are necessary to make further progress: (1) for evaluation of processes at the cloud scale (aerosol activation, cloud microphysical and dynamical interactions) that affect regional and global climate sensitivity and drive climate biases and (2) for estimation and assessment of impacts using self consistent models to produce credible statistics of climate variability (e.g.: intensity of precipitation) and extreme events (e.g.: hurricanes) to drive impact assessment models (e.g.: of the hydrological cycle).

A single path toward developing high-resolution capability, both in terms of physical and dynamical process representation, is not clear at present. We will develop a framework for CAM to permit simulation across scales. CAM will continue to perform and investigate high resolution and regional climate modeling on a number of fronts, including highly scalable dynamical core options (e.g., HOMME, MPAS) and fine-scale physical representations.

Capability to perform credible global simulations at 25km (the edge of regional scale) exists now. For the near term (0-2yrs) development will push towards credible climate and short-term forecast simulations down to10 km using a highly scalable dynamical core and investigating sub-column representations for fine-scale moist physics. Beyond 2 years static mesh refinement and across-scale consistent physics representation will form the basis of regional climate modeling capacity.

There is ongoing work with higher vertical resolution versions of the model. We have some specialized versions that people are using, many in the context of WACCM/Chemistry. Testing at high vertical resolution can help identify problems in the physics. Tests of CAM5 up to L80 have been done. Most likely there will be continued exploration of the vertical resolution. L30 will remain the standard for now. If significant bias reduction is possible with higher vertical resolution, it is an option.

It is also expected we will continue to look at the location of the model top, but leave it where it is. WACCM can go much higher.

Maintaining lower resolution capability at 200km (2deg) and 100km (1deg) for the near future is a key community imperative.

2. Expanding frontiers and functionality: CAM5 has cloud-aerosol interactions (aerosol indirect effects). We will continue to improve representation of cloud-aerosol interactions in CAM. We will also continue to understand climate sensitivity and climate feedbacks in the model. Finally, we expect to also make the code compatible with super-parameterization though the Multiscale Modeling Framework (MMF) project. Other potential frontiers to explore include restoring/reviving the ability to track stable isotopes through the hydrologic cycle in the model.

3. Continuous simulation and process improvement: Ongoing activity will further improve simulation fidelity and also address known model and process deficiencies such as:

- Clear-sky long-wave radiation
- Radiative impact of clouds: interactions of aerosols with clouds
- Deficient amount of middle and low clouds in the tropics and subtropics.
- Modes of variability: MJO, diurnal cycle of precipitation, shallow to deep convection transition
- Better simulation of precipitation: means and higher order statistics
- Realistic “weather” statistics

- balanced model with good seasonal means
    - realistic hurricane climatologies in all basins
    - wave transients with the right spectra
    - realistic extreme event distributions

- Good representation of the coupled system and reductions of bias
    - ENSO
    - ITCZ
    - MJO
    - Arctic Climate

Timeline

CAM will continue to have stable 'strategic' model releases. The community requires stable model versions that can be used extensively. However, we envision a need for intermediate releases that are more frequent than the past CAM releases of about every 2-5 years.

Strategic releases imply more complete documentation and scientific evaluation. This is similar to the recent history of model releases. It may be pegged to releases for specific projects (such as IPCC runs).

An intermediate release will be for a stand-alone model that has major new functionality or performance improvement. We expect some interim improvements to CAM5 to be ready soon (1 year after initial release).

Intermediate CAM releases imply a different standard of release: a model will probably not be required to reproduce the 20^{th} century to be released. AMIP runs and coupled system testing will be done, but the standard for release may not be as comprehensive. These releases will be useful for a subset of the community, such as more active developers. They may also be used as components for 'strategic' releases. Intermediate releases should be no more than once per year. The code should be scientifically traceable, but full documentation need not be rewritten, though our goal will be to update the documentation so that strategic releases are easier.

Metrics and Evaluation

The goals of local model evaluation efforts are twofold. First, we produce diagnostics to ensure that CAM is producing a climate that is consistent with available observations. Second, we use diagnostics to help us understand what controls CAM's mean state and sensitivity to climate perturbations.

The current diagnostic sets for CAM are very valuable for developers and users. They need expanding and upgrading. We will endeavor to keep them current and to develop a better framework for community involvement in contributing diagnostics.

We will continue to use Taylor skill scores as a benchmark for model performance. For reference, the CAM4 release metrics are (a) Taylor skill scores for present day (b) stable 1850 run and (c) 'acceptable' 20^{th} century run.

In the future, we will continue to compare CAM to global observational datasets, incorporating useful new datasets as they become available. In addition, we will expand our evaluation of CAM with metrics that capture important modes of climate variability (e.g., building on what has already been done for ENSO). We will also promote the use of diagnostics that allow us to evaluate key process relationships in CAM through continued use of Single Column Atmosphere Model (SCAM) experiments. We will endeavor to maintain a community version of SCAM and make it easy to add cases. We will also explore a doubly periodic dynamics version that can be used to test physics like a cloud resolving model.

The evaluation of CAM during specific periods of climatic or observational importance (e.g., 2005 Hurricane season, 2007 sea ice loss, response to big volcanic eruptions, big ENSO events, year of tropical convection etc.) is crucial. To ensure that we can compare CAM to observations during specific periods, it will be important to continue nudged, initialized and data assimilation efforts such as CAPT and DART that tie the model to specific observations. As part of this functionality, it is desirable to be able to provide model output along aircraft flight tracks or satellite orbit tracks.

We are interested in expanding diagnostics for:

- Climate sensitivity. For example, can we include target diagnostics that explain inter-model spread in the IPCC climate projections? We could try to inspire research that leads to diagnostics that are useful for understanding climate sensitivity. There are some hints from emerging research that there are useful climate sensitivity metrics based on the mean state (e.g., Boe et al., 2009; others?).

- Aerosol indirect effects. Are there observations that show process relationships or metrics that can help explain the strength of modeled effects?

- Understanding variability and extremes. For example, we need more precipitation frequency and intensity diagnostics for comparison with observations.

- Sophisticated comparison with new observational datasets. e.g., instrument simulator packages such as the COSP simulator for CloudSat, CALIOP, ISCCP etc.

- Metrics measuring model performance at higher frequencies in space and time (this goes with variability and extremes).

- Better stratification of metrics that already exist (easy/hard to improve or calculate), also revisiting the skill score metric priorities.

- More process-oriented observational data such as those from the DOE ARM program.

- Chemical diagnostics that can help in diagnosing simulation biases (e.g.: using ozone hole chemistry to test high latitude model biases)

To help with local efforts, we want to more fully engage with the external research community beyond the core AMP developers. A lot of evaluation/diagnostic work occurs in the university and NASA research worlds. There is also a lot of useful work being done locally at NCAR that we should more fully engage with. Many papers have been published based on the CFMIP archive/CAM3, but has this work influenced development and local evaluation efforts? Although this work occurs on a different timescale and mostly on released model versions, can it inform the development on a day-to-day basis more? Our goal is to better engage the community to keep our diagnostics updated.

Model biases in the standalone CAM may be exposed or amplified in coupled simulations. We should investigate these biases and try to establish standardized cases for model diagnostics of this type of biases.

Examples include the double ITCZ and the stratus clouds off the west coasts of the continents.

Similar problems exist in the interaction of the CAM with the land surface model and the sea-ice model. We should encourage the community to think across the models and across the working groups.

CAM Model Components

Dynamics

Requirements:

1) Scalable to hundreds of thousands of (a million) processors
2) Regionally refinable to allow regional climate studies in contrast to or complementary to nested modeling
3) Conservation of energy and tracer masses
4) Reasonable spectra of kinetic energy, temperature and tracers
5) Economical, i.e. no more expensive than current methods of choice for comparable quality solution.
6) Any dynamical core needs to be ‘accessible’ and easy to maintain in conjunction with the core developers.

Since frictional heating occurs on scales well below the truncation limit, 3) and 4) imply a fixer will most certainly be needed. The fixer should be applied on the parameterization grid since that is where interactions with the other climate system components occur and horizontal re-mappings might affect conservation.

Dynamical Core

CAM will likely use a new global dynamical core, not the current FV core. A option already available in CAM is the HOMME spectral element dynamical core defined on a cubed-sphere grid. Another option that is expected to be available in the CAM framework will be the hydrostatic version of MPAS developed by Skamarock (MMM), Klemp (MMM) and Ringler (LANL). There are DOE-efforts to integrate MPAS into CAM. This dynamical core is based on the icosahedral spherical grid. The MPAS group is developing the hydrostatic core as a step towards a full non-hydrostatic core with static mesh-refinement. A third option will be the FV Cubed Sphere core being tested in the GEOS model at NASA.

If other dynamical cores are integrated into the current CAM framework they should be considered on their merits based on a rigorous test suite. For example, there has been some work with the EULAG stretched non-hydrostatic core coupled with CAM physics. Consideration of a dynamical core requires a comparable simulation as defined by standard test cases, aqua-planet simulations and earth-like simulations using identical parameterization representations

The requirement for non-hydrostatic dynamics is small until grid spacing goes well below 10km. It is not envisaged that in the time frame of this plan that CAM will need a non-hydrostatic grid, but many of the new cores have this option.

Several aspects of the physical parameterizations could be improved to better interface with the dynamics:

- Total energy is not treated consistently in CAM. It should be.
- There are still A and B pressure coefficient dependencies on the physics side in CAM. The CAM physics should be versatile in the sense that any vertical coordinate should be accommodated in CAM without having to modify physics routines.
- Open science issues include: Pressure could be kept constant during the physics updates. A cleaner way of including the effect of moisture on the pressure field could be implemented. Other water variables could be included in the pressure as we move towards higher resolution. All mixing ratios could be based on dry air instead of the mix of dry and wet that we are using now. We need to assess whether this is important before putting a significant effort into the infrastructure.
- The Single Column Model (SCAM) should use the same dynamic core (i.e., vertical advection) as CAM.
- Develop a capability for a doubly periodic dynamics driver for idealized experiments (e.g. like a CRM).

Gravity Waves

At resolution of 0.5 – 1 degrees, gravity waves will continue to be parameterized. Current schemes will have to be reformulated– especially if we go down to 0.1 degrees, which will be borderline for resolving some sources.

At 0.1deg (10km) we could potentially resolve most GWs. However we won't be resolving their sources and they will obey nonhydrostatic dynamics, so the GWs won't be what they are in the real world. This is in particular an issue for convection - until the convective towers themselves are resolved (at ~ 1km resolution), the GWs produced won't be what they should be - the GWs respond to the forcing so if the scales (spatial and temporal) of the resolved forcing are larger than in reality, the GWs will also be not quite right. Fronts are generally resolved quite well at ~ 10km, so for that source 0.1 deg CAM might be acceptable for a first guess.

As model resolution increases a good fraction of orographic GW may be reasonably resolved, but convective GW will likely continue to be misrepresented due to the problems in both resolved and parameterized convective heating. Existing high-resolution runs and analyses, e.g. MERRA, also show lots of variability that is not clearly tied to either convection or orography – and not to fronts (at least not surface fronts). Is this something we have been missing? Is it wrong?

Another question that arises in connection with GWP as well as other physics at high resolutions, is whether it is a problem to localize their effects in single columns or single time steps.

Moist Physics

Requirements: Parameterization suite:

1) Conservation of energy and tracer masses
2) Tracer mass changes included in atmospheric continuity equation
3) Option to provide either updated states (time split) or forcing terms (process split) to dynamical core.

Sub-Columns

Requirements:

- Consistent treatment of moisture variability from vapor through condensate (clouds) to precipitation and radiation.

A sub-column generator would provide an estimate of sub-grid variability. By permitting uniform sub-columns, we could better drive physics parameterizations at different resolutions. Carefully treating sub-grid variability across the range of relevant scales is the only sensible way to make the parameterizations scale-independent, which is the key for the seamless prediction across scales in both mesoscale and global models. It would also allow us to implement physical parameterizations driven by explicit dynamics (vertical velocities) into CAM in a more physically consistent and robust way.

Sub-columns also ensure better consistency where non-linear threshold effects are important and variability at the sub-grid scale is large. This is particularly true for radiative transfer and chemistry.

The overall desire is to extend the climate preserving energy and mass balance framework into ‘cloud permitting’ scales typical of mesoscale models. Currently there are several different sets of physical parameterizations (‘physics’) used in NCAR community models, specifically the Weather Research and Forecast (WRF) mesoscale model and CCSM/CAM. To a large extent, these parameterization sets have been developed independently, but in several cases there exist parallel developments and similar frameworks (for example for cloud microphysics).

The steps to achieve this seamless prediction are several. They include (a) software engineering and model architecture issues, (b) deriving numerical solutions/methods for solving the sub-grid physics in a computationally feasible way and (c) determining actual sub-grid distribution functions and their horizontal and vertical correlations through observations and high-resolution cloud models. These larger tasks (especially c) are activities for the parameterization community as a whole. The sub-grid columns information would likely be retained across model timesteps.

A limiting case of using a detailed sub-column approach is the super-parameterization or multiscale modeling framework (MMF). We intend to implement this approach within the framework of CAM. The goal is to work with the CMMAP group to provide this functionality within 1-2 years as one of the research versions of the model.

Current Efforts: Unfunded plans for a sub-column generator. MMF integration though CMMAP and/or PNNL. Ghan is supporting someone at PNNL to (maybe) implement MMF in an up to date CAM version.

Cloud Closure

It is highly likely that the cloud fraction (macrophysics) will evolve further using some sort of PDFs and a sub-column generator as noted above. These efforts are parallel. Different closure approaches can be used in the same sub-column architecture, if it is flexible.

Current efforts: Park/Caldwell/Klein et al are working on this unified macrophysics scheme with Peter Caldwell/Steve Klein. One of the important issues on the treatment of sub-grid scale cloud processes is ‘consistency’ across the whole physical processes. For example, our future unified cloud macrophysics will assume a certain (Gaussian) PDF of qt: the same consistent assumption should be used in cloud microphysics, radiation, etc. The same assumption of vertical overlap of cloud (cumulus and stratus) should be used in all cloud macrophysics, microphysics, wet deposition of aerosol, and radiation. This cloud overlap issue is related with too much moisture in the tropics we have.

Morrison/Gettelman are working with Larson on implementing CLUBB into CAM, and developing the overall framework.

Microphysics

Requirements

- Improved representation of coupling between microphysics, aerosols, radiation, and sub-grid scale dynamics
- Accurate statistics of precipitation (precipitation rates, extremes, timing, distribution)
- A consistent treatment of clouds and precipitation at high resolution.

The basic physics direction will continue to include 2-moment microphysics. The option will exist to expand the treatment of microphysics with more detailed schemes typically developed for mesoscale models (e.g.: Thompson scheme). We expect to add prognostic precipitation to the current microphysics to meet some of the goals above. Prognostic precipitation will be necessary with smaller time steps and higher horizontal resolution because of advection of rain, and characterization of existing v. new precipitation when it does not fall to the ground in a timestep.

Additions to the ice nucleation scheme (and possibly droplet nucleation) will be explored, initially using codes from Nenes et al., or Morrison and Grabowski.

In order to achieve the goals of better understanding aerosol effects, we will complete the budget of aerosols and cloud drops at least in the stratiform microphysics so an improved scavenging formulation can be built (this will require community support).

Current efforts: Plans by Gettelman/Morrison to extend current Morrison microphysics and test Thompson microphysics. Also Gettelman/Chen/Liu/Nenes effort to put Nenes ice nucleation into CAM

Atmospheric Boundary Layer

Requirements

- Simulation of a wide range of near surface atmospheric structures (stable, unstable, cloud-toppped)
- Accurate coupling between the surface and atmosphere, particularly on diurnal timescale over land
- Accurate transport and distributions of surface emission species and of water species

We will continue to use a moist boundary layer (Bretherton and Park). Continuously improve the UW moist turbulence scheme and enhance feedback and consistency with the other physics schemes. Some additional improvements we being considered are: (1) refined treatment of TKE transport, (2) exploration of prognostic TKE scheme instead of diagnostic TKE, (3) TKE-based entrainment closure instead of wstar-based entrainment closure, (4) refinement of merging process, (5) more refined treatment of turbulent transport of cloud droplet number concentration. , and (6) computation of variance and/or covariance statistics for application to the future cloud macrophysics.

Represent the direct interaction of deep convective downdrafts on the TKE of the PBL, such that it may work as a positive feedback to convection at least dynamically.

In addition, planned work includes (1) allowing some turbulences in a very stable regime ($Ri > 0.19$), (2) improving the formulation of turbulent mountain stress.

In parallel, we will also further develop the KPP PBL to be consistent with moist physics and thus work effectively across the range of atmospheric stability regimes, i.e. Richardson Numbers.

Convective motions/Parameterization

Requirements

- Representat moist convection at various scales to correctly simulate key modes of variability (e.g., Organization on the mesoscale, MJO scales)
- Improved statistics for timing and intensity of precipitation
- Consistency with stratiform microphysics, aerosol cloud interacations.

- Continuous treatment of shallow and deep convective motions.

A unified scheme should address the following issues: (1) we should use one single convection scheme, not the separate 'shallow' and 'deep' and should be compatible with the small-scale turbulent scheme (PBL) (2) should address other relevant issues in the current convection schemes (e.g., unified treatment of dry and moist convection, free and forced convection, convective updraft an downdraft), (3) should have more elegant cumulus microphysics that can handle aerosol indirect effect, (4) ideally, should be applicable in all the resolutions and (5) also be should be prognostic. Convection scheme is related to the MJO, diurnal cycle of precipitation, and many other issues. Including meso-scale organization is likely to be a key component for developing a unified convection scheme. Some effort has started but further work is required in closing the scheme (e.g., estimation of plume radius and parameterization of meso-scale organization).

We should develop in-model modularity for calculating organization, statistical perturbations, microphysics and sub-grid scale states (sub-columns) independently of the 1-D calculations of convective instability and closures. Ultimately, there won't really be a self- contained convection scheme, but instead a collection of convection relevant processes and calculations.

Chemistry/Aerosols

Requirements:

- Represent chemistry-climate interactions with consistent chemistry, radiation and scavenging
- Represent aerosol-cloud interactions and the complete aerosol lifecycle (production through scavenging).
- Consistent and conservative treatment of advected constituents
- Flexible and tracible chemistry code
- Consistent chemistry code across scales (mesoscale, global scale)

CAM5 will use the RRTMG package from AER. The interface for modal aerosols needs to be reworked in order to recover the functionality of on-line direct radiative forcing. When the interface standards have been restored, support for offline computation of radiative forcing and feedback will be possible.

The current code can represent aerosol-cloud interactions. They are clear for microphysics and particle sizes (and effects on radiation). Effects on precipitation are not clear: because these interactions are not part of the convection code. We need microphysics and droplet activation within convection.

CAM will also continue to use the PNNL modal aerosol code. We need to build more diagnostics for aerosols into the standard diagnostic package. We may also want the ability to use a bin aerosol scheme. We may be able to use CAM/CARMA for that.

CAM can be run with MOZART+ chemistry.

We clearly need a prescribed aerosol mode for CAM not only for efficiency, but also because of the large science uncertainties in processes like scavenging. We need to be able to easily cut the chain of feedbacks at some point (or several). This is in progress.

Tactically we also need to merge the volcanic aerosol treatment with the PNNL modal aerosols.

Radiation

CAM currently maintains two completely separate radiative transfer models. We will converge on one model for future development.

Requirements:

- State of the art representation of atmospheric radiative transfer for gas phase and condensed species
- Fully consistent representation of radiatively active species
- A flexible and reproducible framework for radiative transfer
- Ability to identify all constituents affecting radiative transfer through the rad_constituents namelist
- Ability to recreate (bit for bit) online radiative transfer computations with an offline computation.
- Diagnose instantaneous radiative forcing of alternative compositions as part of the online radiative transfer computation.

The interface between the specification of atmospheric composition and computation of radiative transfer needs to be extended to include modal aerosols, solar specification, thermodynamic state, top-of-model to top-of-atmosphere specifications, and surface specifications. In particular, the optics of constituents should be inside the radiation interface. The specification of composition, thermodynamic state, microphysical state, and surface characteristics should be external to the radiation code. Much of this was accomplished for CAM4, however, CAM5 has backtracked on several of these aspects.

In particular we plan to:

1) Separate of the specification of atmospheric state from the radiation.
A.) Separate sub-grid variability from radiation
i) clouds (ice, water, other)
ii) hydrometeors (rain, snow, graupel?)
iii) water vapor sub-grid variability?
iv) aerosols sub-grid?
v) clarification of various cloud fractions (See subcolumn generator discussion elsewhere)

B.) Separate microphysical composition separated from optical characterization

2) Develop code to output composition, thermodynamic, surface, and microphysical states along with subgrid variability specifications for offline radiative transfer computations.

3) Development of an offline radiative transfer scheme for
   A) Cam-style radiative forcing computation
   B) IPCC -style radiative forcing
   C) Single column, multicolumn, or global data sets
   D) 1 timestep or multi-timestep or multiple file data sets
   E) comparison with line-by-line reference computation
      (Note: not possible until composition is separate from radiation)

4) Improve the specification of the atmosphere through the portion of the atmosphere between model top and space.

5) Maintain state of the art radiation code by using current versions of RRTMG from AER.

6) Provide a single subcolumn specification that can be queried by radiation, transport, cloud/aerosol, and diagnostic models. Inclusion of a sub-column generator will simplify the radiation interface and allow for better reproducibility.

7) Remove any physical characterization of aerosols from the radiation interface. (Radiation does not care about the hygroscopicity of sulfate, but it does care about mass, size distribution, and mixtures of the aerosols.) Even more importantly, radiation should not be responsible for providing data (such as "dry number mode radius of aerosol") to other portions of the code.

8) Provide a comparison of heating rates from an offline reference radiative transfer model with heating rates from the CAM radiative transfer models.

9) We will identify process for migrating changes from both AER and CCSM so that the code bases do not diverge. At the moment, these code bases are quite distinct and very difficult to compare.

Other Components

A suite of easy to use tools for model evaluation and development is a great facilitator of model development for the entire CAM community. We will attempt to extend our current suite of tools beyond just a single column model framework.

The Single Column Atmosphere Model (SCAM) should be maintained on a sound footing, and we should attempt to have available a standard suite of test cases using field program data (e.g.: from the ARM sites). The system should include observations in the forcing data files, and we should make these outputs and scripts to run SCAM available to the community. There are currently DOE supported efforts at BNL with this type of activities (the FASTER project). AMWG will work with BNL to find a best way for in-house model development and research by the community.

We will continue to advance both CAPT and DART assimilation methodologies forward. We will attempt to use these systems for testing and evaluation of model components.

We develop a "replay" (i.e. nudging to analysis) configuration for CAM. This should be flexible and easy to implement – complements CAPT framework, but can also applied to extended coupled atmosphere-ocean runs for example. This mode (called 'specified dynamics' or SD) has already been developed for WACCM use.

We will develop simple, limited-area, or idealized e.g. doubly periodic geometries for CAM. This is an extension of a single column framework forcing that starts to approach the functionality of a LES or cloud resolving model forcing. These could be used for testing purposes- e.g. how do convection statistics change with parameterization changes in a warm pool-like regime, or more broadly how scale dependent are the parameterizations as we move to sub-column architectures and very high (below 20km) horizontal resolutions.