Next-Generation Numerical Weather Prediction: Bridging parameterization, explicit clouds, and large eddies

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Data Box

TITLE: The Third International Workshop on Next-Generation NWP Models

WHAT: Scientists from Korea, Japan, France, England, Finland, and the United States discuss recent developments in the parameterizations of physical processes in next generation, high-resolution numerical weather prediction (NWP) models.

WHEN: 30 August-1 September 2010

WHERE: Seoguipo, Jeju, Korea

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After the second international workshop on the physical parameterizations in Numerical Weather Prediction (NWP) models in 2004 (Lee and Hong 2005), attendees at the third workshop on next generation NWP models met to discuss progress in high-resolution NWP modeling over the past six years, and to share ideas about future challenges. The main theme of the meeting was “the cloud-resolving modeling approach and beyond.” As of 2010, convection-permitting and cloud-resolving scale modeling have become practically feasible, along with the successful usage of Large-Eddy Simulation (LES) in developing sub-grid scale parameterizations for these models. Many national hydrometeorological centers are now running models in the 2-5 km grid-size range, and will be increasing resolution at a steady rate such that several centers may be at around 1 km in five years. The main topic of the workshop focused on future problems in physics as NWP models go to finer scales. The meeting provided a good opportunity for various scientists to describe recent modeling improvements and future challenges. Forty-five presentations were given, which covered the current status of high-resolution NWP and cloud-resolving models, progress with physical parameterization, and the application of LES to the development of sub-grid scale processes. Descriptions of the presentations are below. A plenary discussion on bridging parameterizations, cloud-resolving, and LES followed, and is also summarized.

Current status of high-resolution NWP models: Jongil Han of NCEP suggested that a cumulus parameterization scheme (CPS) should be included in NWP models to play a diminishing role as the resolution increases, and at 4-5 km grid-resolution the contribution of parameterized convection (such as mitigating excessive precipitation) may still be important. Eric Bazile of Météo-France introduced an operational 2.5-km non-hydrostatic model system, with a focus on the interaction between horizontal diffusion and other physics. Sang-Ok Han of the Korea Meteorological Administration (KMA) presented efforts to mitigate spurious grid-scale precipitation over East Asia in a highly unstable atmospheric environment by changing parameters in physics algorithms of the Met Office Unified Model (UM). Adrian Lock of the Met Office demonstrated the importance of turbulence mixing length in improving boundary layer clouds (stratocumulus, shallow cumulus, and fog) in the 1.5-km operational UM. Some evaluations of the UM at 100m resolution, UM-LES, were also given. Dong-Kyou Lee of the Seoul National University (SNU) showed efforts in alleviating excessive mountain rainfall in a 3-km real-time forecast framework over Korea using the Weather Research and Forecasting (WRF) model. At the Japan Meteorological Agency (JMA), an improved nonhydrostatic model has led to better prediction of heavy rainfall in Japan as concluded by Kazuo Saito of JMA's Meteorological Research Institute (MRI). He also outlined the model's recent improvements, including meso 4D-Var assimilation, and revisions in boundary processes. Sami Niemelä of the Finnish Meteorological Institute showed, using the HARMONIE (HIRLAM Aladin Regional/Meso-scale Operational NWP In Europe) model, the importance of horizontal diffusion as well as the representation of cloud microphysics on a 2.5-km grid. Jimy Dudhia of NCAR found a smaller sensitivity to PBL and land surface schemes than cloud microphysics in resolving storms on the Great Plains during the spring program simulations from April to June 2010.

Multi-scale modeling: Jai-Ho Oh of Pukyong National University demonstrated small-scale local features such as typhoons in a 10-km grid global model, the Icosahedral-hexagonal Gridpoint Global Model (GME), which is the operational model of the German Weather Service. Masaki Satoh of the Atmosphere and Ocean Research Institute, University of Tokyo, demonstrated the capability of the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) to reproduce detailed cloud distributions over the globe without cumulus parameterization on a 7-km grid. Song-You Hong of the Yonsei University (YSU) introduced a multi-scale modeling system, the Global/Regional Integrated Model System (GRIMS), which has been used to develop the WSM/WDM microphysics schemes and YSU planetary boundary layer (PBL) scheme in the WRF model. Wei-Kuo Tao of NASA's Goddard Space Flight Center (GSFC) demonstrated the capability of the GSFC multi-scale modeling system with unified physics, focusing on aerosol effects on deep precipitation processes, and online tracer calculation related to the development and structure of hurricanes and mesoscale convective systems. Joon-Hee Jung of the Colorado State University demonstrated the advantages of a quasi-3D (Q3D) Multi-scale Modeling Framework, which combines a GCM with a Q3D cloud-resolving model (CRM), in resolving clouds explicitly at a reasonable computational cost. Wen-Yih Sun of Purdue University found that the simulation of vertical winds over mountains can be strongly affected by numerical schemes.

Precipitation and chemistry physics: Georg A. Grell of NOAA's Earth System Research Laboratory (ESRL) showed that a 3D convective ensemble parameterization approach, the Grell 3D scheme, is a promising tool for a smooth transition from convection-permitting to cloud resolving scales. Tae-Young Lee (YSU) examined the role of convective parameterization in simulations of heavy precipitation systems at grey-zone resolutions, and found that a modified trigger function in the Kain-Fritsch CPS scheme is found to behave smoothly, especially for simulations with 6 km and 9 km grids. Mary Barth (NCAR) found a higher reaction rate of formation of peroxy radicals in areas where the air has recently come from thunderstorms. She also revealed that the oxidation of carbon monoxide (CO) and organic peroxides influenced by convection in the upper troposphere are important reactions. Rokjin Park (SNU) demonstrated that, with the WRF WDM6 microphysics scheme, the high sensitivity of cloud microphysics to aerosol number and size distribution indicates the importance of dynamically varying aerosol characteristics to better simulate clouds and precipitation in NWP models. SNU's Ji-Young Han showed that higher levels of urban air pollution generally result in the development of stronger convective clouds, which produce more downwind precipitation under all moisture conditions considered.

Turbulence and subgrid-scale physics: Song-You Hong (YSU) stressed that while the validation of a scheme by a theoretical study and observations is important to accomplish improvements in numerical weather forecasts and climate prediction, the interaction between the boundary-layer and other physics algorithms is of equal importance. Eric Bazile (Météo-France) demonstrated that a better representation of the PBL structure with a TKE scheme associated with a new mass flux scheme significantly improves the low–cloud forecast and the quality of precipitation fields. Jongil Han (NCEP) showed overall improvement in the forecasts of 500 hPa height, precipitation, vector wind, and hurricane track in the NCEP Global Forecast System (GFS) by introducing an update to the deep and shallow convection and vertical diffusion package. Hye-Yeong Chun (YSU) examined the convective source and momentum flux spectra in a parameterization of convective gravity wave drag and found that the selection of two wave-propagation directions of 45° (northeast and southwest) and 135° (northwest and southeast) is best when a minimum number of wave-propagation directions is required for computational efficiency. So-Young Kim (YSU) examined typhoon-generated gravity waves, and found that significant momentum carried by TGWs is deposited into the upper troposphere and lower stratosphere, which consequently affects typhoon development.

Large-eddy modeling and its application: Chin-Hoh Moeng (NCAR) provided an overview of the LES technique in developing sub-grid scale physics algorithms in NWP models, and showed the feasibility of nesting a fine-grid LES inside a coarse-grid LES, which may imply the possibility of nesting LES inside NWP models. Lian-Ping Wang of the University of Delaware presented results from a hybrid direct numerical simulation approach designed to address the effects of air turbulence on geometric collision rate and collision efficiency of cloud droplets, finding that cloud turbulence can significantly reduce the time for warm rain initiation. Rachel Honnert (Météo France) demonstrated a new diagnostic based on the LES of convective boundary layers that clarifies which part of turbulence should be parameterized at kilometric scales. Boris Galperin of the University of South Florida demonstrated that a quasi-normal scale elimination (QNSE) theory of turbulence can be used to derive the Monin-Obukhov similarity functions in constant flux regions, which are important for applications in PBL as well as stably stratified boundary layer flows. Yign Noh (YSU) demonstrated that, using LES results of the ocean mixed layer, the presence of wave breaking and Langmuir circulation (LC) in oceans causes the formation of a diurnal thermocline, responding to the stabilizing buoyancy flux, instead of inducing strong stratification at the surface. Adrian Lock (Met Office) showed that LES models can be used to evaluate existing parameterization performance through comparison with single column versions of the full GCM, with a notion that LES results should be evaluated over the observations.

Discussion

The workshop presentations were followed by parallel break-out discussions on the themes of (1) PBL/shallow convection, (2) deep convection/microphysics, and (3) aerosols/clouds/radiation. Additionally, this was followed by a plenary session with the break-out summaries, and general discussions on the themes of the break-outs. In particular several questions were posed for the break-out discussions:

- At what scales do the one-dimensional vertical-mixing planetary boundary layer schemes, usually separated from horizontal mixing, work?
- When do they need to be replaced with three-dimensional large-eddy simulating turbulence models?
- At what scales are models considered to be convection-permitting?
- When is a cumulus parameterization needed?
- When is a separate shallow convective scheme needed?

- What are the microphysics challenges at high resolution?
- How can we handle the grey-zone issues in convection and boundary-layer physics?

The following is a report that draws together conclusions from the break-out summaries and the subsequent plenary discussion.

While NWP centers are now very much in the grey zone for deep convection parameterization and cloud-permitting scales, it was recognized that one-dimensional (1-D) PBL schemes are adequate at grid sizes below 1 km, and probably 500 meters, which means that it may be a decade before the PBL grey-zone issues would need to be addressed in national forecast models. This time scale is governed by computing limitations that make 1 km real-time forecasts costly to do at reasonable speed with current computers. There was also discussion about the use of 3D sub-grid mixing schemes near 1 km grid-sizes (as used for many years in cloud-resolving research models), but they are not designed for cases of strong surface fluxes and boundary-layer development.

At grid scales nearer 100 meters, it is considered that vertical eddy mass fluxes will be resolved sufficiently by the dynamics so that the non-local or so-called counter-gradient sub-grid mixing effects of PBL schemes will no longer be needed, and all mixing can be considered local as with LES parameterizations. LES parameterizations work well in the inertial sub-range, but even their assumptions break down near the surface as more of the energy-containing eddies become sub-grid scale. The Honnert talk in the workshop highlighted the relative magnitudes of sub-grid and grid-resolved eddies as the grid size changes, pointing out the problems to be addressed by grey-zone PBL physics.

However, while dry vertical mixing may be adequately handled down to 1 km with current physics schemes, challenges include shallow convection, and the boundary-layer response to resolved deep-cloud downdrafts and subsidence around clouds, and conversely the impact of the boundary layer on resolved deep convection and moist processes in general. These also include how to handle fractional cloud coverage, both regarding their mass fluxes, and radiative effects. Also PBL schemes that have shallow convective components are still in need of further evaluation and development, which is achieved to some extent by the practice of using LES-scale models as "truth".

Many operational centers are now at convection-permitting scales where vertical motion in convective updrafts and downdrafts is explicitly resolved by the dynamics to the extent that sub-grid vertical deep transport (i.e. cumulus parameterization) is not needed. Several issues make it difficult to determine a clear grid size where convection-permitting can be assumed adequate. These issues include the dynamics and numerical techniques of the underlying model, e.g., Eulerian, Semi-Lagrangian, diffusiveness, and the type of convection to be simulated. For example, severe storms in the United States and tropical cyclones seem to be well captured with 3-4 km grid sizes, possibly due to their large mass fluxes and mesoscale self-organization, but it is not clear that isolated convection with narrower and weaker updrafts developing from weak forcing would be well resolved. The HARMONIE cloud-resolving model tests at 2.5 km show the sensitivity of convective behavior to numerical methods, such as diffusion schemes.

With a variety of cumulus schemes—from mass-flux type to adjustment type and moisture convergence type—some operational physics suites do better at 5 km without the cumulus scheme, while others do worse when using it, at the same resolution. There are situations where employing a convective scheme is better because it triggers deep clouds more quickly than the microphysics and dynamics can by themselves, which also mitigates a tendency toward a high-intensity bias that might occur without it (e.g., NCEP,'s global GFS, and JMA). On the other hand, an adjustment-type scheme produced unrealistically smooth structures at 4 km in the NCEP's regional NMM (Nonhydrostatic Mesoscale Model) system, and the model worked better without it. ALADIN's new cumulus scheme (Gerard et al., 2009) was designed to work reasonably at 3-8 km by allowing sub-grid prognostic updraft effects that closely interact with the microphysics. Cumulus schemes for these scales need to relax the scale-separation assumption that subsidence occurs in the same grid-column as the updraft, as with the newer Grell-3D scheme in WRF that spreads subsidence to neighboring columns, although traditional schemes still seem to work regardless of making the single-column assumption. Ideally grey-zone cumulus schemes should "turn themselves off" as the resolved scale takes over, and vice versa as the grid size gets coarser. It was generally agreed that no deep cumulus scheme is justified at 1-2.5 km, but a shallow convective parameterization is needed either independently of the deep cumulus scheme or as part of the PBL parameterization.

Several research efforts are using or planning to use large datasets from cloud-resolving models to continue development of cumulus parameterizations for global models and regional climate models. The sub-grid convection problems at GCM grid-box sizes (as discussed in Moeng's presentation) are different from those in NWP regional grids, as the former needs to include some organization effects, while the latter probably includes individual convective cloud effects. As NWP model resolution shrinks below 3 km, cumulus parameterization for NWP will become obsolete, Until this occurs in several years, however, the grey-zone parameterizations will still be needed, especially for outer nests that are often employed and used in data assimilation and ensembles. There was some discussion on using LES models to help evaluate and improve cumulus parameterizations for these scales.

Nesting LES models within NWP models for local high-resolution studies (e.g., urban areas and wind farms) was discussed, but it was agreed that for LES models to behave realistically, their upstream boundary needs to be far enough from the area of interest for eddies to develop.

For microphysics, the main question for forecast models is whether to go to double-moment schemes that predict number concentrations and have more flexibility to properly handle information about aerosols for cloud and ice nucleation. This would make sense in forecast systems that use chemical data assimilation, which are likely to be developed more in the future. It was also recognized that mixed-phase growth into hail or graupel is often treated too simply, and there are now several schemes that better handle riming as a gradual rather than discrete process.

Regarding atmospheric chemistry, it was recognized that mass-flux type cumulus schemes are capable of chemical transport, and models including this process can have their schemes evaluated with chemical tracer observations as well as meteorological ones. Boundary-layer and cumulus schemes should be developed, keeping in mind mixing multiple chemical tracers for generality. Aerosol-radiation interaction provides an important feedback to the meteorology, both directly and indirectly, through cloud microphysical effects. Levels of complexity of chemistry in models exist, from simpler aerosol or dust-only to gas-phase, aqueous-phase, and sectional (bin) models. For their initial application to real-time NWP, probably only the simpler ones are computationally feasible, although it was suggested that there are possible benefits to the meteorology from chemical data assimilation. Several NWP centers are considering aerosols initially for visibility and dust prediction, and it was recommended that aerosol radiative and microphysical effects, as well as air quality applications become more integral parts of NWP systems.

Data assimilation in relation to high-resolution models was briefly addressed. Current systems often do data assimilation at lower resolution than the cloud-resolving models, and there would be a spin-up delay for fine-scale structures unless the first-guess from the fine-scale model is cycled (as at the UKMO, for example). Data at cloud-resolving scales remains a challenge owing to a poor match between the data and the model resolutions that do not constrain the model well enough. It was recognized that at fine scales, deterministic forecasts are not likely to give as useful guidance as high-resolution ensembles, which give a measure of uncertainties, especially with convective systems.

A fourth workshop on this topic is expected to be held in 5 years. Abstracts and presentation materials presented in this workshop are available at http://nml.yonsei.ac.kr.

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