Numerical Techniques and Cloud-Scale Processes for High-Resolution Models

James D. Doyle
Naval Research Laboratory
Monterey CA 93943-5502
phone: (831) 656-4716 fax: (831) 656-4769 e-mail: james.doyle@nrlmry.navy.mil

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LONG-TERM GOALS

The long-term goal of this project is to design and evaluate the components that will comprise a next generation mesoscale atmospheric model within the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]). It is anticipated that to meet future Navy requirements, next generation approaches to numerical techniques and physical parameterizations will be needed.

OBJECTIVES

The objectives of this project involve the development, testing, and validation of: i) new numerical techniques such as advection schemes and time differencing methods, and ii) new methods for representing cloud-scale physical processes. Both of these objectives are tailored to address high-resolution applications for horizontal grid increments at 1 km or less.

APPROACH

Our approach is to follow a methodical plan in the development and testing of a nonhydrostatic microscale modeling system that will leverage the existing COAMPS and new model prototypes. Our work on numerical methods will involve investigation of spatial and temporal discretization algorithms that are superior to the current generation leap-frog, second-order accurate numerical techniques presently employed in COAMPS and many other models; these new discretization methods will be developed and implemented. Our work on the physics for the next-generation COAMPS will feature the development of physical parameterizations specifically designed to represent cloud-scale processes operating on fine scales. A parameterization is proposed that properly represents the coupled nature between the turbulence and microphysics in droplet activation, evaporation, and auto-conversion processes for mesoscale and microscale models. Validation and evaluation of the modeling system will be performed using datasets of opportunity, particularly in regions of Navy significance.

The key participants of this project include the principal investigator Dr. James Doyle and Dr. Sasa Gabersek (UCAR), Dr. Jerome Schmidt (NRL) and Dr. Shouping Wang (NRL). The participants work

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[1] COAMPS® is a registered trademark of the Naval Research Laboratory.

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14. ABSTRACT
The long-term goal of this project is to design and evaluate the components that will comprise a next generation mesoscale atmospheric model within the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS?1). It is anticipated that to meet future Navy requirements, next generation ap-proaches to numerical techniques and physical parameterizations will be needed.

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closely with other members of the COAMPS team and scientists at the Naval Postgraduate School, including Prof. Frank Giraldo.

WORK COMPLETED

1. Spectral element model 2D prototypes.

The non-uniform spacing of nodal points inherent to spectral element models poses a severe constraint on the time step when using an explicit time integration scheme. A longer time step can be used only in conjunction with the semi-implicit time integration, which treats implicitly only terms responsible for fast modes (gravity and acoustic waves) in the governing equations. To facilitate the new scheme, the equation set was cast into a non-flux form. The inclusion of moist variables into the semi-implicit spectral elements model was revisited to prevent the squall line simulation from becoming unstable. Once stability was achieved, the model was used as a test-bed for warm microphysics parameterization with varying number of elements (h) and polynomial orders (p) to map out the h-p parameter space.

2. Weighted Essentially Non-Oscillatory (WENO) methods.

Atmospheric models require numerical methods that can accurately represent the transport of tracers with steep gradients, such as those that occur at cloud boundaries or the edges of chemical plumes. In atmospheric sciences, the most widely used numerical techniques for this type of problem are flux-corrected transport or closely related flux-limiter methods. The limiters are typically designed to prevent the development of new extrema in the concentration field. This limitation will preserve the non-negativity of initially non-negative fields, which is essential for the correct simulation of cloud microphysics or chemical reactions. One serious systematic weakness of flux limiter methods is that they also tend to damp the amplitude of extrema in smooth regions of the flow, such as the trough of a well-resolved sine wave. To avoid this problem, we have been investigating the application of WENO (Weighted Essentially Non-Oscillatory) methods to tracer transport in atmospheric models. WENO methods are widely used in many disciplines, but have scarcely been tested in atmospheric applications. WENO methods preserve steep gradients while simultaneously avoiding the dissipation of smooth extrema by estimating the value of the solution in a way that heavily weights the smoothest possible cubic polynomial fit to the local function values. Where the solution is well resolved, all possible cubic interpolants are weighted almost equally. Near a steep gradient, those interpolants are almost completely ignored. In FY09, we have concentrated on testing a semi-Lagrangian option and implementation and testing within the COAMPS system.

3. Accurate microphysical collection rates

Improvements in the numerical representation of the cloud microphysical processes have been implemented in COAMPS. The changes include the computation of accurate and efficient look-up tables for all nine liquid-liquid and ice-liquid collection processes currently handled in the model. Accuracy is improved by including the numerical bounding technique described by Gaudet and Schmidt (2007) and through the use of digitized variable drop-drop, drop-crystal, and drop-graupel collection efficiencies as computed numerically by Pinsky et al (2001), Wang and Ji (2000); and Khain et al. (2001). The numerical bounding technique will be particularly useful for the envisioned use of semi-Lagrangian techniques, as bounding helps preserve the accuracy of the discretized microphysical collection equations on larger time steps.

RESULTS

1. Spectral element 2D prototypes.

The explicit and semi-implicit time integration schemes were tested and compared for the 2D linear hydrostatic mountain wave case. The time step used in the semi-implicit method was up to eight times longer than the maximum time step allowed by the explicit method, with virtually the same error statistics. The overall computational cost was significantly reduced.

The squall line experiments suggest that the non-uniform nodal spacing affects the storm development. A combination of a high polynomial order with a low number of elements will result in convection to occur preferentially over the narrowest nodal spacing, close to the element boundaries (upper left portion of the h-p parameter space in Fig. 1). The 'single-column' storms will also result in higher vertical velocities and more intense precipitation (circle size and shade of blue, respectively in Fig. 1).

2. Weighted Essentially Non-Oscillatory (WENO) methods

We have developed a new method, in which WENO-like criteria for the presence of poorly resolved steep gradients are evaluated in a highly efficient manner and used to determine whether spurious new maxima and minima are likely to be created in the vicinity of a steep gradient. This new approach, which we call "selective limiting," can be applied to both flux-corrected transport (FCT) methodologies or to piecewise polynomial approximations for the fluxes in finite-volume methods, particularly the piecewise parabolic (PPM) or cubic methods (PCM). Over a wide range of tests, these schemes were found to give more accurate solutions than WENO methods for considerably less computational cost. A journal paper has been completed (Blossey and Durran, 2008) describing the selective limiting approach. We then turned our focus integrating our new method into the COAMPS model and testing it in a variety of situations. These tests are still underway, but one interesting example is shown in Fig. 6.

A squall line test case is shown in Fig. 2, based on a set of standard test problems for numerical weather prediction models by Bill Skamarock (www.mmm.ucar.edu/projects/srnwp_tests/index.html). The 2-dimensional squall line simulations are set up with an idealized sounding following Skamarock using a 1024x90 domain (x-z) with a horizontal grid increment of 500 m and a vertical grid increment of 75 m within the lower atmosphere that gradually stretches to a 250 m increment in the stratosphere. A radiation top boundary condition is used to mitigate the reflection of gravity waves. A warm-rain microphysics parameterization is used following the common Kessler type of approach. For semi-Lagrangian applications, the full microphysics are computed at the first dynamical step of the long time step, and during the other steps, saturation adjustment and the prorated evaporation and latent heating is incorporated. The long time steps are used only for rain water, while water vapor, cloud water and potential temperature are advanced on the dynamical time step, in this case 3 seconds.

Figure 2 shows the x-z cross section of rain with cloud contours, perturbation potential temperature, and velocity vectors at the final time integration, 6 h, for the squall-line simulation. The simulation in Fig. 2a shows a well developed squall line with a maximum in the rain and cloud concentration fields at the leading edge of the squall line. The control simulation used a time step of 3 seconds in this example. A significant advantage of our new method is that it can be used with much larger time steps in semi-Lagrangian simulations and could therefore be used to model tracer transport much more efficiently than the methods currently available. As an example, the simulation shown in Fig. 2b makes use of a much larger time step, in this case a factor of 8 times larger (24 s). Model stability is maintained because the selective advection has a semi-Lagrangian capability. The results with respect to the simulated squall line characteristics are similar in many respects to the control simulation. The simulation using the larger time step for the microphysics is approximately 15% faster than the control simulation for a single processor simulation.

The current COAMPS has an option for the Bott 3rd and 5th order accuracte advection schemes, which are positive definite. The relative timings for the Bott 3rd/Bott 5th/Selective methods are in the ratio 6/8/7, implying that our new method is faster than the 5th-order Bott scheme, but slower than the 3rd-order scheme. However, as discussed above a significant advantage of the new method is that it can be used with much larger time steps in semi-Lagrangian simulations and could therefore be used to model tracer transport much more efficiently than the methods currently available in COAMPS---provided COAMPS is modified to allow passive tracers to be integrated on longer times steps than those used for the dynamics. We are in process of implementing such a capability.

A preliminary test of the selective advection in COAMPS using a 45-km horizontal resolution is shown in Fig. 3. The 4 January 2008 severe extratropical cyclone was selected as a reasonable test case. The rainfall is compared between the conventional leapfrog advection (Fig. 3a) and the selective advection (Fig. 3b). In general, there are many similarities between the two advection methods with respect to the rainfall, however, there are some obvious differences between the two, as highlighted in Fig. 3c. At this point, we have not attempted to evaluate the superior scheme for each method, rather this initial test was primarily designed to test the stability of the system. As a result of these tests, we isolated several issues related to the implementation of the selective advection in COAMPS. These problems, including the implementation of the selective advection of the turbulence kinetic energy, are currently being addressed.

3. Microphysics Development

An important aspect of any cloud microphysical scheme is an accurate representation of the mass transfer rates between the various condensate categories of which the scheme is comprised. Within convective-scale updrafts, for example, a rapid transfer of liquid to the fast (graupel) or slower falling (snow and ice) categories will impact both the thermodynamics and loading terms affecting updraft maintenance or demise as well as the generation of long-lived convective-induced anvil clouds. One such conversion term that has an important role in the formation of faster falling graupel particles is the collection of rain drops by snow particles at temperatures below 273.0K. The accuracy of standard time discretization of this particular microphysical collection rate has been explored. We found that the snow-rain interaction acts as a complete sink of rain for nearly the entire spectrum of rain mixing ratio evaluated, even when the time step is as low as 5 seconds. Such an interaction would lead to rapid freezing of the rain at the first grid point just above the melting level. Taking larger time steps leads to a difference in the collection rate of nearly two orders of magnitude over that obtained through the numerical bounding technique. Further refinements to the rate calculations are incorporated through the use of variable collection efficiencies during the numerical integration of the collection rates.

IMPACT/APPLICATIONS

COAMPS is the Navy's operational mesoscale NWP system and is recognized as the key model component driving a variety of DoD tactical decision aids. Accurate mesoscale prediction is considered an indispensable capability for defense and civilian applications. Skillful COAMPS predictions at resolutions less than 1 km will establish new capabilities for the support of the warfighter. Operational difficulties with weapon systems such as the Joint Standoff Weapon (JSOW) have been documented in regions with fine-scale topography due to low-level wind shear and turbulence. Improved high-resolution predictive capabilities will help to mitigate these problems and introduce potentially significant cost saving measures for the operational application of JSOW. The capability to predict the atmosphere at very high resolution will further the Navy sea strike and sea shield operations, provide improved representation of aerosol transport, and will lead to tactical model improvements. Emergency response capabilities and Homeland Security issues within the DoD and elsewhere, such as LLNL, will be enhanced with the new modeling capability.

TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (managed by PMW-120) that focus on the transition of COAMPS to FNMOC. A number of improvements to the COAMPS dynamical core have been transitioned to the PMW-120 6.4 project and subsequently to operations.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling, boundary layer studies, and topographic flows and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components of COAMPS. .

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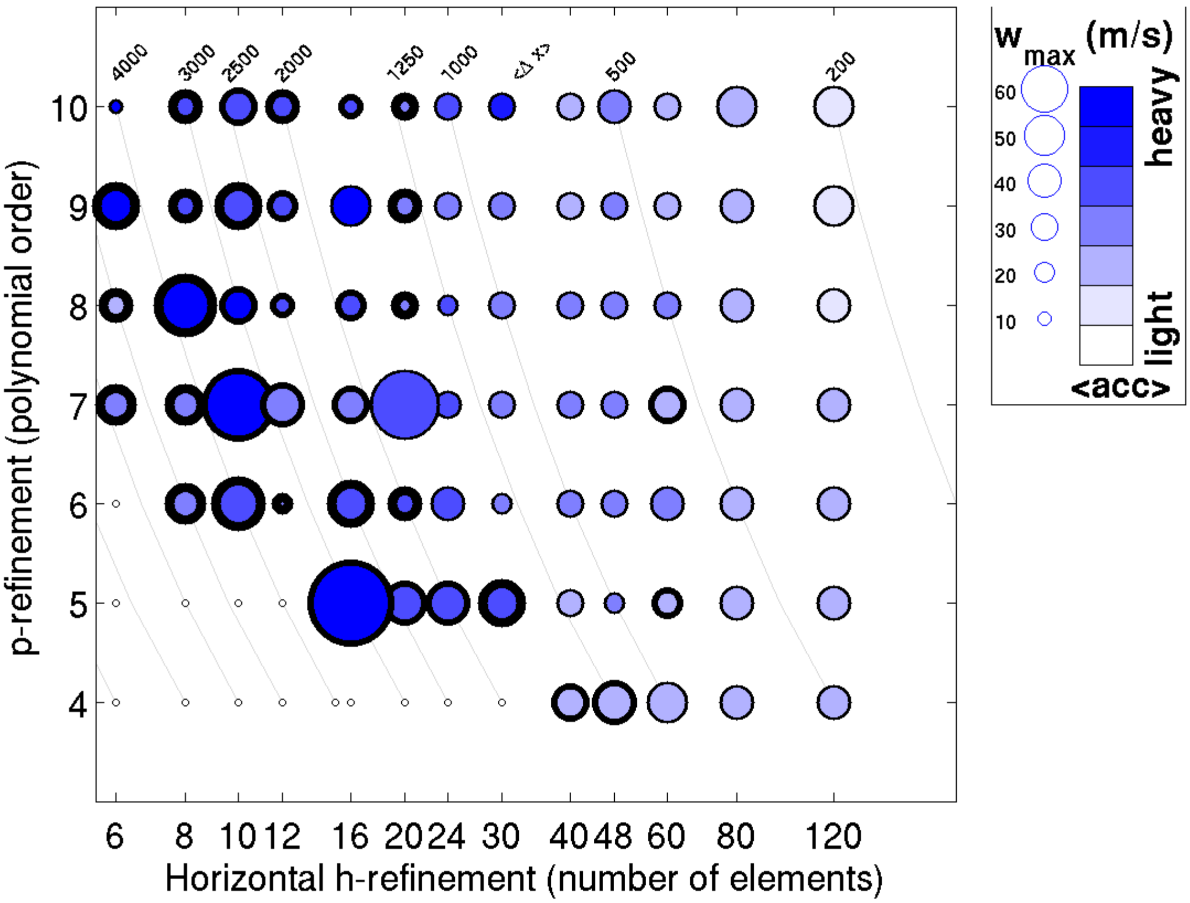

Figure 1. A summary of squall line tests, where each point represents a simulation. The size of the symbol is proportional to the maximum vertical velocity, the shading is proportional to the accumulated precipitation and the border width is proportional to the anisotropy of the vertical velocity distribution across the nodal points (thinner is better). Simulations with no storms (lower left corner) are represented with small white circles. Curved lines connect simulations with the same average horizontal grid spacing.

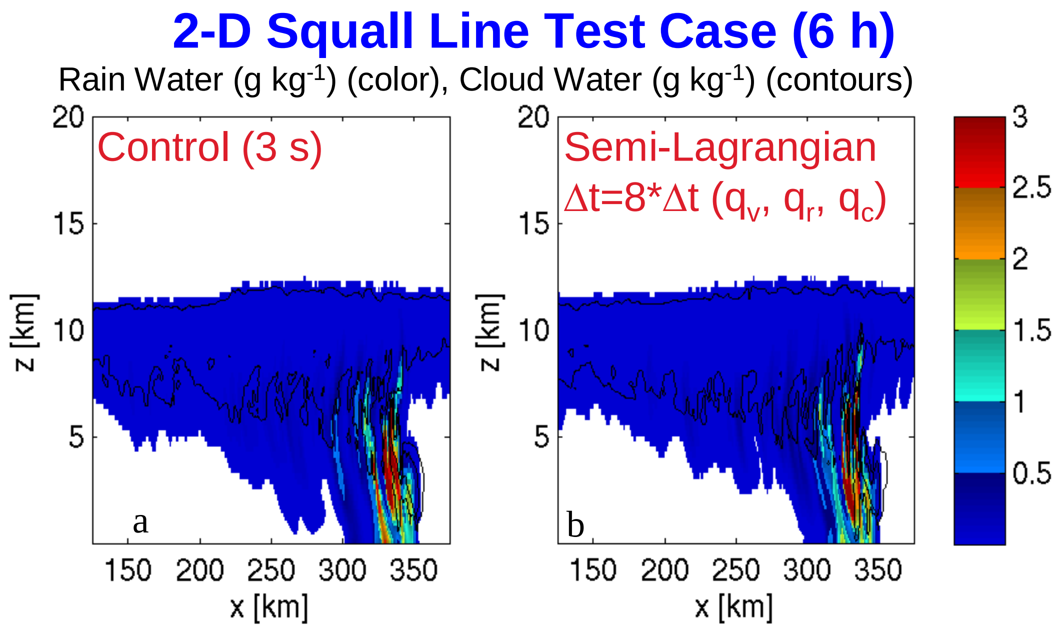

Figure 2. Simulated rain water (g kg^{-1}) shown in color, cloud water (g kg^{-1}) in contours for the control time step of 3 seconds (left) and semi-Lagrangian using a time step of 24 seconds (right).

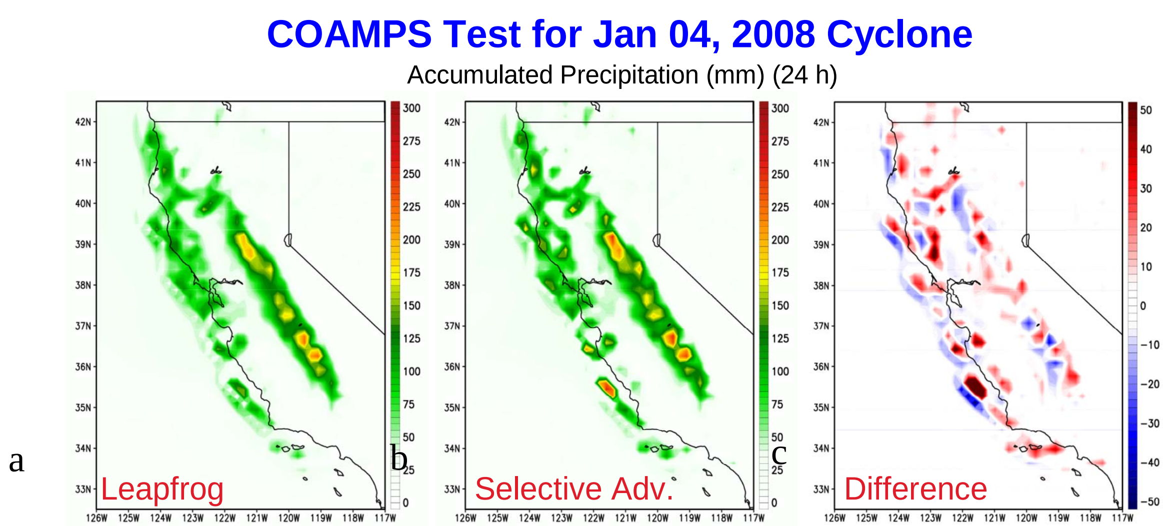

Figure 3. Accumulated precipitation (mm) using COAMPS for the 4 January 2008 California severe extratropical cyclone after 24-h of integration for the (a) standard leapfrog formulation, (b) selective advection formulation, and (c) difference field.