Next-Generation Global and Mesoscale Atmospheric Models

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LONG-TERM GOALS

The long-term goal of this research is to construct global and mesoscale nonhydrostatic numerical weather prediction (NWP) models for the U.S. Navy using new numerical methods specifically designed for modern computer architectures. To take full advantage of distributed-memory computers, the global domains of these new models are partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these sub-domains are local, high-order accurate, fully conservative, and highly efficient. Using these ideas we are developing global and mesoscale nonhydrostatic atmospheric models that will improve upon the operational models currently used by all U.S. agencies including the U.S. Navy.

OBJECTIVES

The objective of this project is to construct new high-order local methods for the Navy's next-generation global and mesoscale nonhydrostatic NWP models. The high-order accuracy of these methods will ensure that the new model yields better forecasts than the current global spherical harmonics model (NOGAPS) and better accuracy than the current mesoscale finite difference model (COAMPS). The objective is to achieve this accuracy while increasing the geometric flexibility to use any grid as well as to increase the efficiency of these models on large processor-count distributed-memory computers. Higher efficiency means that the new models will require less computing time which then allows for increasing the number of ensemble members and/or increasing the resolutions of the NWP models. The methods that we propose to use for these models are state-of-the-art and are not being used by either current or newly emerging NWP and climate models.

APPROACH

To meet our objectives we explore:

1. spectral element (SE) and discontinuous Galerkin (DG) spatial discretization methods;
2. high-order semi-implicit (SI) time-integrators with adaptive time-stepping for vastly improved efficiency;
3. high-order Lagrangian-like time-integrators that are fully conserving and scale well on modern computer architectures;

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14. ABSTRACT
The long-term goal of this research is to construct global and mesoscale nonhydrostatic numerical weather prediction (NWP) models for the U.S. Navy using new numerical methods specifically designed for modern computer architectures. To take full advantage of distributed-memory computers, the global domains of these new models are partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these subdomains are local, high-order accurate, fully conservative, and highly efficient. Using these ideas we are developing global and mesoscale nonhydrostatic atmospheric models that will improve upon the operational models currently used by all U.S. agencies including the U.S. Navy.

15. SUBJECT TERMS

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4. various forms of the governing equations in order to maximize accuracy, efficiency, stability, and conservation properties;
5. unified hydrostatic/nonhydrostatic formulations of the equations; and
6. fully unstructured (and possibly adaptive) grids.

The power of SE and DG methods is that they are high-order accurate yet are completely local in nature – meaning that the equations are solved independently within each individual element and processor. Furthermore, high-order methods have minimal dispersion error – this is an important property for capturing fine-scale atmospheric phenomena (e.g., tropical cyclones, Kelvin and Rossby waves). The theoretical development of SE and DG methods are now well-established and these methods are currently the two most successful methods found in the literature for fluid flow problems.

Semi-implicit (SI) and Lagrangian time-integrators offer vast improvements in efficiency due to the longer time steps that they permit; it should be mentioned that semi-implicit and Lagrangian-like methods can be classified together under the heading of implicit-explicit (IMEX) methods which has garnered much attention in the computational mathematics literature. Furthermore, in order to reap the full benefits of the high-order spatial discretization methods requires increasing the order of accuracy of the time-integration methods as well; this is a topic that too often has been ignored by most scientific computing communities, including the NWP community. Lagrangian methods have not been used successfully for mesoscale modeling because of their lack of conservation. Another problem that they pose is that they require vast amounts of inter-processor communication on a distributed-memory computer. We have worked on Lagrangian-like methods that are conserving and require no additional inter-processor communication (see [11]).

Before committing resources towards the development of new NWP models, it is important to identify the form of the governing equations that is most capable of conserving all quantities deemed important. We performed a study on this topic this year– that is, to identify the form of the governing equations capable of representing conservation of either mass, energy, or both. In addition, we have begun to analyze various forms of the governing equations with respect to robustness, flexibility, and efficiency in the context of implicit-explicit (IMEX) time-integration methods. Within this work we have also explored hybrid models that solve either the hydrostatic or nonhydrostatic equations. This feature allows the models to be used for research purposes by Navy scientists in order to test the importance of nonhydrostatic phenomena at specific resolutions.

One final area that needs to be explored is the concept of adaptive grids. In the past few years, adaptive grids have gained considerable momentum in the atmospheric modeling community – in fact, I have been invited to give a keynote lecture at the University of Reading in March 2009 to kick-off a year long program on adaptive modeling at the Newton Institute in Cambridge University, England.

WORK COMPLETED

In this section, we describe the work completed this fiscal year. The work can be categorized into three sections: global modeling, mesoscale modeling, and development of new numerical machinery for solving mathematical issues related to both global and mesoscale modeling.

Global Modeling Work. Work on the global model consisted of incremental improvements to the model that has been under development for the past few years. This model, NSEAM, is hydrostatic and therefore would have a relatively short life-span as an operational model since we are developing nonhydrostatic models for both global and mesoscale applications. Nonetheless, NSEAM has been shown to be an effective tool for studying the strengths and weaknesses of the NOGAPS physical parameterization package. Using NSEAM, we have published a paper (see ref. [6]) showing the sensitivity of Kelvin waves and the Madden-Julian Oscillation on the NOGAPS physics; this paper exposed the strong sensitivity of the current physical parameterizations on the vertical discretization; this includes sensitivity to the resolution as well as to the placement of the grid points. This strong sensitivity to the vertical structure of global models is an issue that needs to be addressed by the atmospheric modeling community.

The path to building a nonhydrostatic global model can take one of two paths: the first is to extend the existing hydrostatic NSEAM model to be nonhydrostatic and the second approach is to build a state-of-the-art nonhydostatic mesoscale model that can then be modified to run as a global model. The first approach would constrain the equations to be written in a form that would not be able to conserve mass formally. This is the reason we have decided on the second approach. Let us now describe the work completed this year on the mesoscale models.

Mesoscale Modeling Work. The We have continued our analysis of the various forms of the Euler equations and their advantages/disadvantages for mesoscale modeling. We have included a few more forms to our study totaling 5 different forms of the equations which we now discuss. Specifically we

$$\frac{\partial \pi}{\partial t}+\mathbf{u}\bullet\nabla\pi+(\gamma-1)\pi(\nabla\bullet\mathbf{u})=0;\quad \frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\bullet\nabla\mathbf{u}+c_p\theta\nabla\pi=-f(\mathbf{k}\times\mathbf{u})-g\mathbf{k};\quad \frac{\partial \theta}{\partial t}+\mathbf{u}\bullet\nabla\theta=0$$

analyzed the following equations: Set 1 is defined as follows where the solution vector is Exner pressure, velocity, and potential temperature. Set 1 is the equation set used in the U.S. Navy's mesoscale model COAMPS. The main problem with this equation set is that it cannot conserver either mass or energy.

Set 2 in conservation form (denoted as Set 2C) is defined as follows where the solution vector is

$$\frac{\partial \rho}{\partial t}+\nabla\bullet\mathbf{U}=0;\quad \frac{\partial \mathbf{U}}{\partial t}+\nabla\bullet\left(\frac{\mathbf{U}\otimes\mathbf{U}}{\rho}+P\mathbf{I}_2\right)=-f(\mathbf{k}\times\mathbf{U})-\rho g\mathbf{k};\quad \frac{\partial \Theta}{\partial t}+\nabla\bullet\left(\frac{\Theta\mathbf{U}}{\rho}\right)=0;\quad P=P_A\left(\frac{R\Theta}{P_A}\right)^{\gamma}$$

density, momentum, and density potential temperature. Set 2 is the form used in WRF. This form is very attractive because it conserves mass although it does not conserve energy. It does, however, conserve density potential temperature which is related to entropy.

This set is of interest because it can also be written in non-conservation form while still conserving mass. We shall refer to it as Set 2NC (for non-conserving). and it is defined as follows:

$$\frac{\partial \rho}{\partial t}+\mathbf{u}\bullet\nabla\rho+\rho\nabla\bullet\mathbf{u}=0;\quad \frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\bullet\nabla\mathbf{u}+\frac{1}{\rho}\nabla P=-f(\mathbf{k}\times\mathbf{u})-g\mathbf{k};\quad \frac{\partial \theta}{\partial t}+\mathbf{u}\bullet\nabla\theta=0;\quad P=P_A\left(\frac{\rho R\theta}{P_A}\right)^{\gamma}$$

The interest in equation Set 2NC is that it conserves mass and offers much flexibility in the type of time-integrators that can be used with it. For example, note that the first two terms (in red font) of each of the components of mass, momentum, and potential temperature can be recast as a Lagrangian derivative. This then allows the use of Lagrangian-like time-integrators to be used such as those we describe in [11].

Set 3 is defined as

$$\frac{\partial\rho}{\partial t}+\nabla\bullet\mathbf{U}=0;\quad \frac{\partial\mathbf{U}}{\partial t}+\nabla\bullet\left(\frac{\mathbf{U}\otimes\mathbf{U}}{\rho}+P\mathbf{I}_2\right)=-f\left(\mathbf{k}\times\mathbf{U}\right)-\rho g\mathbf{k};\quad \frac{\partial E}{\partial t}+\nabla\bullet\left(\frac{E+P}{\rho}\mathbf{U}\right)=0;\quad P=\left(\gamma-1\right)\left(E-\frac{\mathbf{U}\bullet\mathbf{U}}{2\rho}-\rho\phi\right)$$

where the solution vector is density, momentum, and density total energy, where E=ρe with $e=c_vT+0.5\mathbf{u}\bullet\mathbf{u}+\phi$, in other words e represents internal energy, kinetic energy, and potential energy. This equation set is not used in atmospheric modeling but is the equation of choice in computational fluid dynamics (CFD). This set is very attractive because it conserves both mass and energy regardless of whether the flow is inviscid or viscous (with the proper viscous stressed included) (see [9]). One question we had about this set, however, is whether it could be coupled to existing physical parameterization packages which rely on potential temperature and not energy; this question has been answered in the past year with the recent results of the Japanese NICAM model which in fact uses this equation set.

The final equation set studied is Set 4 which is written as follows:

$$\frac{\partial\rho}{\partial t}+\mathbf{u}\bullet\nabla\rho+\rho\nabla\bullet\mathbf{u}=0;\quad \frac{\partial\mathbf{u}}{\partial t}+\mathbf{u}\bullet\nabla\mathbf{u}+\frac{1}{\rho}\nabla P=-f\left(\mathbf{k}\times\mathbf{u}\right)-g\mathbf{k};\quad \frac{\partial P}{\partial t}+\mathbf{u}\bullet\nabla P+\gamma P\nabla\bullet\mathbf{u}=0$$

Note that this equation is also amenable to various time-integration methods including Lagrangian methods since the first two terms of each of the components of the equations can be written as a Lagrangian derivative. Furthermore, as in Sets 2C and 2NC, Set 4 can formally conserve mass but not energy. Set 4 is a very good compromise between conservation and efficiency. Note that Sets 1 and 4 are the only fully closed systems requiring no equation of state, whereas Sets 2C, 2NC, and 3 all require an equation of state in order to couple the extra variable (pressure) to the prognostic variables. Set 4 is the equation set used by the LM model of the German Weather Service and has some good properties that we are analyzing.

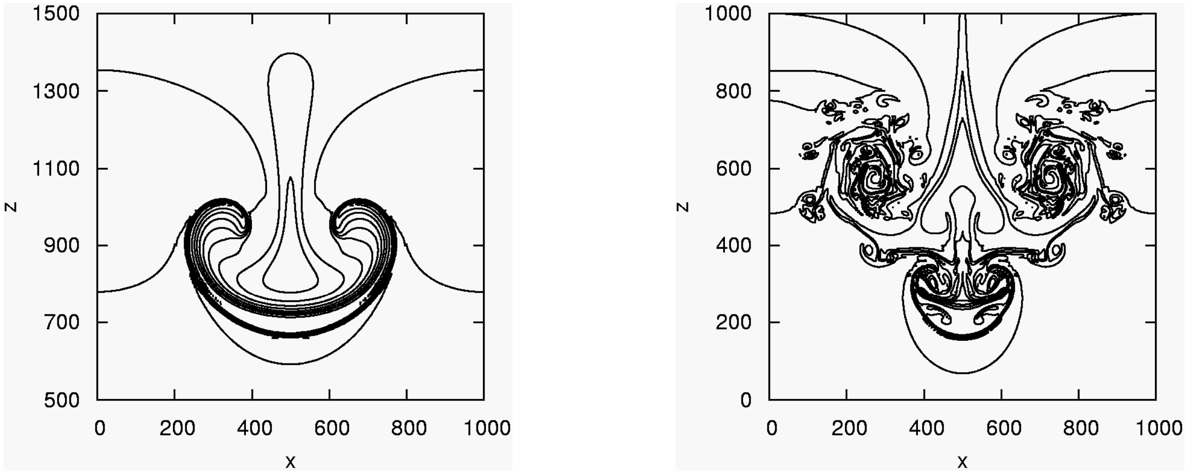
Using these 5 equation sets we developed x-z slice mesoscale models to: compare the spectral element and discontinuous Galerkin methods, analyze semi-implicit time-integrators, and to see how these models behaved under a series of test cases including sharp front simulations and nonhydrostatic flow over mountains. This work resulted in a peer-reviewed article that appeared this year (see ref. [9]) and another that is in preparation.

Mathematical Issues for NWP Modeling. In collaboration with Marco Restelli (a previously funded ONR Global VSP visitor at NPS) the PI (Giraldo) was able to develop the first semi-implicit time-integrator for any DG model. This result is very important because, until this point, DG models were not competitive with other gridpoint models in terms of efficiency because it was not known how to construct semi-implicit time-integrators for DG. This work is currently under review (see ref. [5]). The high-order in time generalization of this method was submitted to a journal this year (see ref. [1]). In work in progress, we are extending this method to handle hydrostatic/nonhydrostatic hybrid equations (that allow the study to determine when nonhydrostatic effects are important) and adaptive time-stepping (that allow the model to automatically modify its time-step size in order to remain stable under any flow situation and yield efficient time-integrations). This work is in collaboration with another ONR Global VSP visitor, Matthias Läuter.

Another interesting mathematical issue for NWP modeling that we explored this year involved the development of high-order non-reflective boundary conditions for mesoscale models. This work was conducted by Air Force Maj. John Dea for his PhD dissertation which he successfully defended in September 2008 under my supervision. The results show that using a characteristic decomposition of the governing equations allows for a relatively straightforward implementation of Higdon-type non-reflecting boundary conditions (NRBCs) for the Euler equations; Higdon NRBCs are the high-order generalization of the classical Sommerfeld conditions. This work has been submitted to peer-reviewed journals (see refs. [2,3,8]). In his dissertation, Dr. Dea developed the theoretical framework for implementing this idea and implemented it to the linearized Euler equations (for stratified flow relevant to the atmosphere) using the finite difference method. A new PhD student will now extend Dr. Dea's ideas to high-order spatial discretization and time-integration methods in order to test them on our new x-z nonhydrostatic mesoscale models. In addition, a National Research Council (NRC) post-doc (Dr. Jim Kelly) will work on a number of mathematical topics related to the mesoscale models including: NRBCs, optimal time-integrators, parallelization of the models, and extending them to three dimensions.

RESULTS

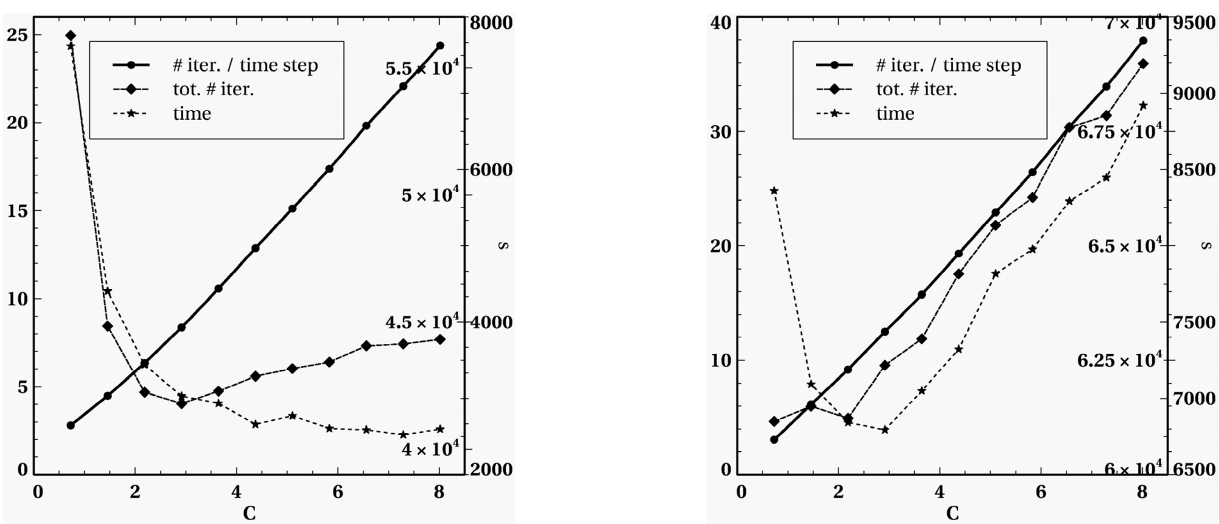
Mesoscale Nonhydrostatic Atmospheric Models. In Ref. [9] we present five mesoscale models using equation sets 1, 2, and 3, in conjunction with the SE and DG methods. For example, SE1 means that the SE method was used for set 1. Note that there is no DG1 because set 1 is not in conservation form and, therefore, cannot be used with the DG method. In Ref. [9] we show results for six test cases ranging from rising bubbles, density currents, to mountain wave problems. In Ref. [5] we show results for the DG3 with the semi-implicit method. We now show results from both of these papers. Figure 1 shows the results for a cold bubble dropping in an isothermal atmosphere. Figure 1a (left panel) shows the potential temperature perturbation contours for 4 meter resolution after 100 seconds and Figure 1b (right panel) shows the results after 200 seconds. The results show that the model resolves the fine scale features extremely well, even when using such large time-steps – moreover, the results are fully conservative meaning that both mass and energy are conserved up to machine precision.



a) *b)*

Figure 1: Potential Temperature contours for a cold bubble test after a) 100 seconds and b) 200 seconds for the semi-implicit DG3 model with a Courant number of 100.

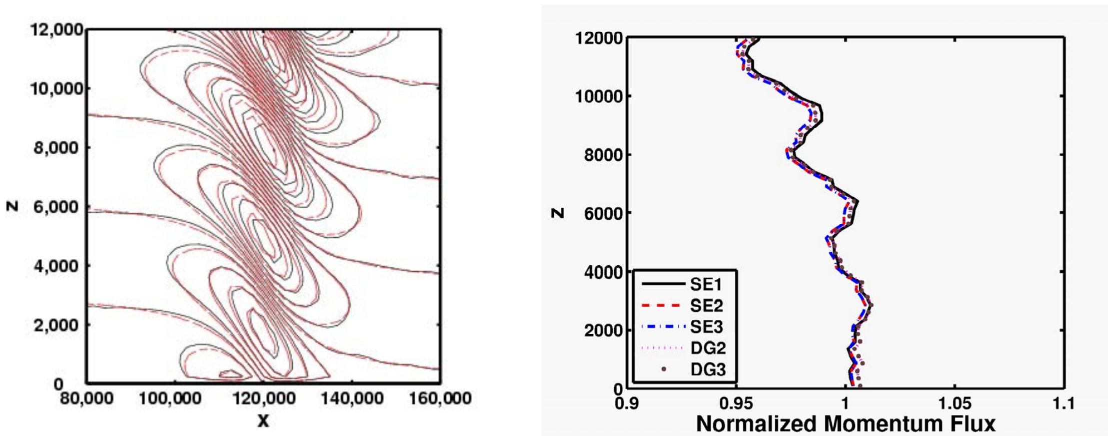
In Fig. 2 we show the performance study of the semi-implicit discontinuous Galerkin method for the cold bubble test. In order to construct an efficient semi-implicit formulation, after the system of equations are discretized in time, they must be reduced to a block LU decomposition for one of the variables only. The resulting equation takes the form of a Helmholtz operator and for this reason, this reduction is called the pseudo-Helmholtz form of the equations. Figure shows the number of GMRES iterations per time-step (• on left-axis), the total number of GMRES iterations (♦on first right-axis), and total CPU time (∗ on second right-axis) as functions of Courant number. Figure 2a (left panel) shows the results using the pseudo-Helmholtz form while Figure 2b (right panel) shows the results without the pseudo-Helmholtz form. The main point of these results is that the total CPU time does not grow linearly with Courant number if one uses the pseudo-Helmholtz form, without the pseudo-Helmholtz form, the cost clearly increases linearly with increasing Courant number (i.e., time-step size).



a) *b)*

Figure 2: Performance study of the semi-implicit DG3 model for the cold bubble test for various Courant numbers a) with and b) without the pseudo-Helmholtz form.

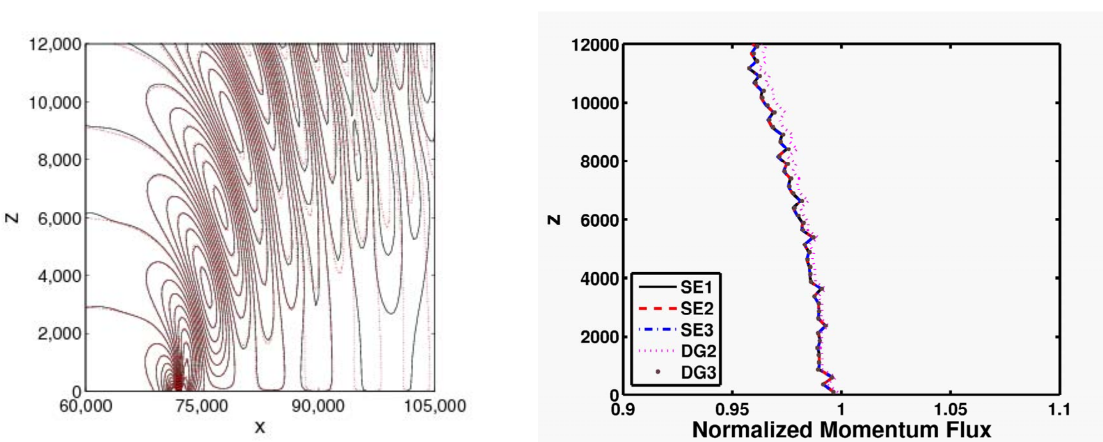
Figure 3 shows the vertical velocity contours and normalized momentum flux for the linear hydrostatic mountain test. In Fig. 3a (left panel) the dashed red lines denote the analytic solutions while the solid black lines are the numerical solutions. Note how accurately the numerical results agree with the analytic solutions. In Fig. 3b (right panel) we show the normalized momentum flux which is a good measure of the accuracy of the model. A perfect model would yield values of 1 and we can see that we are near 1 for all five models developed and for the entire vertical column of the atmosphere. The values near 12 kilometers differ from the value 1 due to the effects of the non-reflecting boundary conditions.



a) *b)*

Figure 3: Results for the linear hydrostatic mountain test. We show a) vertical velocity contours showing the analytic solution (dashed red lines) and the numerical solution (solid black lines) and b) the normalized momentum flux for 5 different models we have developed.

Figure 4 shows the vertical velocity contours and normalized momentum flux for the linear nonhydrostatic mountain test. In Fig. 4a (left panel) the dashed red lines denote the analytic solutions while the solid black lines are the numerical solutions. Note how accurately the numerical results once again agree with the analytic solutions. In Fig. 4b (right panel) we show the normalized momentum flux for all five models developed and we see that we do indeed get values near 1.



a) *b)*

Figure 4: Results for the linear nonhydrostatic mountain test. We show a) vertical velocity contours showing the analytic solution (dashed red lines) and the numerical solution (solid black lines) and b) the normalized momentum flux for 5 different models we have developed.

From the preliminary results of the previous year, we concluded that Sets 2 and 3 are clearly superior to Set 1. However, this year we have included two additional sets (Set 2NC and Set 4). The reason for considering these two sets is to consider not only the accuracy of the equation sets with respect to the SE and DG spatial discretization but also to consider the effects of the time-integrators. While the preliminary results of this year show that all equation sets yield similar results (in terms of accuracy, efficiency, and robustness) set 2NC and set 4 offer the most flexibility in the choices of time-integrators that can be used with them; we plan to demonstrate this in the next year. Furthermore, we propose to develop Eulerian and Lagrangian semi-implicit time-integrators for these equation sets.

IMPACT/APPLICATIONS

NOGAPS and COAMPS are run operationally by FNMOC and is the heart of the Navy's operational support to nearly all DOD users worldwide. This work targets the next-generation of these systems for massively parallel computer architectures. NSEAM and its mesoscale cousins have been designed specifically for these types of computer architectures while offering more flexibility, robustness, and accuracy than the current operational systems. Additionally, the new models are expected to conserve all quantities such as mass and energy and use state-of-the-art time-integration methods that will greatly improve the capabilities of the Navy's forecast systems.

TRANSITIONS

Improved algorithms for model processes will be transitioned to 6.4 (PE 0603207N) as they are ready, and will ultimately be transitioned to FNMOC with future NOGAPS upgrades.

RELATED PROJECTS

Some of the technology developed for this project could be used to improve NOGAPS in other NRL projects. The work performed in this work unit on coupling NSEAM with NOGAPS physics has already revealed some sensitivities of the physical parameterization to the vertical coordinate; this information can now be used to improve the forecasts of NOGAPS. In addition, the work on the mesoscale models will help improve COAMPS. An example is the time-integration methods that we are exploring for the new models may well be incorporated into the current operational version of COAMPS.

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2. Dea, J., Giraldo F.X., and Neta B., 2008: Hagstrom-Warburton Non-Reflecting Boundary Conditions for the Linearized 2D Euler Equations. *International Journal of Computational Fluid Dynamics*, [submitted].
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HONORS/AWARDS

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