A Next Generation Atmospheric Prediction System for the Navy

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LONG-TERM GOALS

A long-term goal of this project is to develop a global cloud-permitting (~3-km resolution) forecast capability as part of the multi-agency next-generation Earth System Prediction Capability (ESPC) initiative. Within the next decade or less, computational platforms with more than 1,000,000 processors will be commonly available and high-fidelity global weather forecasts with variable resolution grids at the mesoscale or cloud permitting scales will be routinely feasible. Unfortunately, current generation weather models are incapable performing such forecasts because of their lack of variable resolution grid capabilities, inadequate numerical accuracy, and computational inefficiency. A paradigm shift in the numerical weather and climate prediction capabilities of the US Navy and the nation is needed in order to be at the leading edge in the future. The time is right and critical to embark on an accelerated development path of a modeling system with next-generation attributes since a decade of development is typically required to advance an NWCP system to the point where it is operationally viable. Global and regional models are currently applied as separate modeling systems at many operational centers such as the Navy, AFWA, NCEP, with the global models providing lateral boundary conditions for the local models with finer spatial resolution over areas of interest. Recently, the horizontal spatial resolution of global models used in the leading centers around the world is fast approaching the grid spacing traditionally used by the mesoscale models, which is on the order of 10 km. In the relatively near future, when the resolution becomes even finer approaching cloud permitting scales, the Nation's global model dynamical cores will need to account for non-hydrostatic effects. A new class of next-generation models is emerging. The long-term goal of this project is to develop, evaluate and eventually implement in operations a new atmospheric prediction system that is capable of scaling efficiently across a large number of processors (up to 1M processor counts and beyond), and has the capability to be applied on the globe at high resolution, as well as for limited area applications (e.g., urban scale, regional climate etc.).

OBJECTIVE

The objective is to evaluate, and demonstrate the capabilities of a new generation of atmospheric dynamical systems that allow for variable resolution on the sphere or for limited area domains, are highly scalable, and eliminate or mitigate spurious problems near the poles of the globe. These next-generation models are non-hydrostatic and valid for predictions ranging from nowcasting and weather

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time scales to seasonal and decadal climate scales. These new dynamical systems may comprise the atmospheric component of the multi-agency Earth System Prediction Capability.

APPROACH

A new class of next-generation weather prediction models is now emerging. These models include the GFDL High-Resolution Atmosphere Model (HiRAM), NCAR Model Prediction Across Scales (MPAS) and the Navy's NEPTUNE (*Navy Environmental Prediction sysTem Utilizing the NUMA corE*) using the Naval Postgraduate School's Nonhydrostatic Unified Model for the Atmosphere (NUMA) dynamical core. These models are nonhydrostatic, which is needed to fully address the Earth System Prediction Capability (ESPC) goals. These models all offer selective geodesic grid refinement, which allows for variable resolution on the sphere and avoids the pole problem.

The MPAS model makes use of a finite-volume numerical method discretized on irregular centroidal Voronoi mesh with each cell having a hexagonal horizontal footprint. Prognostic variables are C-staggered in both horizontal and vertical direction. The horizontal discretization conserves mass. The dynamical core is non-hydrostatic and fully compressible. The model includes the full physical parameterization suite from WRF. Limited area modeling can be achieved by either gradual refinement of global grid, or provision of lateral boundary conditions. In the former case, the feedback from resolved small scale features is seamlessly fed back to the coarser grid, avoiding problems with traditional nesting characteristic to the latter approach. The time integration scheme is explicit, the third-order Runge-Kutta scheme with fast modes being treated implicitly (vertically propagating) and explicitly with time-splitting (horizontally propagating).

The HiRAM system has been developed as a global model with a finite-volume dynamical core. Each volume is hexahedral (rectangular footprint). It is cloud-resolving with a non-hydrostatic core. It is designed for global simulations on a cubed-sphere. The physical parameterizations are the same as in the GFDL's global climate model, with some modifications and additions to reflect resolving phenomena on smaller spatial scales. The model uses a second order forward-backward time integration method HiRAM.

The NEPTUNE makes use of the NUMA dynamical core, which is based on the spectral element method. The discretization is performed on hexahedral elements (rectangular footprint). Since the spatial derivatives are computed analytically, there is no need for spatial staggering of prognostic variables and they all reside on the same nodal points. The conservation properties are accurate to the machine round off. The dynamical core is fully compressible and non-hydrostatic. The physical parameterizations using schemes from COAMPS, GFS, and NAVGEM are currently being implemented and tested (moist physics has already been included). The model simulations can be performed either on the globe while utilizing the cubed-sphere, or a limited area. Local mesh refinement has been implemented and tested. The model supports different time integration schemes, from fully explicit (leapfrog, Runge-Kutta), to semi-implicit. The semi-implicit correction can be applied in all three dimensions or in vertical only.

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WORK COMPLETED

In the past year, a major part of our effort has been to advance the Navy's next-generation non-hydrostatic modeling system that makes use of the Nonhydrostatic Unified Model of the Atmosphere (NUMA) dynamical core. We refer to the modeling system that makes use of NUMA as NEPTUNE (Navy Environmental Prediction sysTem Utilizing NUMA for Efficiency). We have focused on building the infrastructure to run real data cases with the NUMA dynamical core. We have established a local version control of the code at NRL, which is shared with other NUMA users including NPS. The basic input/output interface program has been developed in order to read in the many data bases for the model. New data bases have been added this past year. Additionally, an initialization module has been written to initialize the NEPTUNE model from a global model (e.g., NAVGEM).

One of our other major activities in the past year has been to participate in the NOAA High-Impact Weather Prediction Project (HIWPP) to test and evaluate various global non-hydrostatic dynamical cores under development at EMC, GFDL, ESRL, NRL/NPS and NCAR to assess their potential for achieving high-resolution global weather prediction at cloud resolving scales (~3 km horizontal resolution). The following tests have been carried out with NEPTUNE/NUMA in the past year:

- An idealized baroclinic wave on the spherical earth
- An orographic gravity wave test case on a scaled small planet.
- An idealized supercell test case on a scaled small planet.
- An optional tropical cyclone test case, which is still being set up at the time of this report.

These test cases are based on the multi-agency Dynamical Core Model Intercomparison Project (DCMIP) (https://www.earthsystemcog.org/projects/dcmip/).

RESULTS

a. *HIWPP Idealized Test Cases*

As part of the NOAA High-Impact Weather Prediction Project (HIWPP) non-hydrostatic next generation model inter-comparison tests, NRL has contributed idealized simulations computed with the NEPTUNE NWP system. NEPTUNE (Naval Environmental Prediction system Utilizing a Non-hydrostatic corE) is the Navy's next generation, highly scalable, non-hydrostatic global and mesoscale NWP system. NEPTUNE is based on the NUMA (Non-hydrostatic Unified Model of the Atmosphere) spectral element dynamical core and offers a flexible interface for predicting both mesoscale and global scale phenomenon within a unified modeling framework.

The current participation within the non-hydrostatic HIWPP project is to complete a series of idealized simulations and submit the results for comparison to the other participants. To date, two of the four idealized test cases have been completed and submitted, with a third nearing completion. The first is a series of 20-day global simulations of a developing baroclinic wave with horizontal resolutions varying from 120 km to 15 km. Figure 1 shows the 850 hPa vertical vorticity at day 9 of the 30-km horizontal resolution simulation. Day 9 is just after the initial wrapup and break-down of the leading baroclinic wave. As shown in Fig. 1, NEPTUNE is capable of generating the fine scale details of this wave, however, small scale instabilities are present in regions of sharp vorticity gradients which suggest additional work needs to be done to stabilize and smooth these features.

The second idealized test is a series of mountain waves on a reduced radius sphere without rotation. The tests simulated a zonal equatorial jet, with and without vertical shear, over two types of terrain: a Schär mountain, and a quasi-2D ridge. The simulations were run at a resolution of 0.5 degrees in the horizontal and an average resolution of 500 meters in the vertical. Figure 2 shows a cross-section of vertical velocity at the equator for vertically sheared flow over a Schär mountain. NEPTUNE is able to simulate the strong non-hydrostatic response from the small scale terrain variations as well as the trapping by the sheared flow of the wave forced by the larger scale terrain profile.

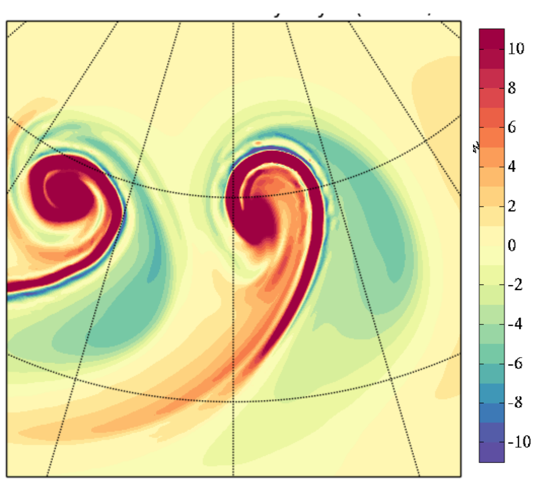

Figure 1: The day 9 snapshot of 850 hPa vorticity in a global simulation of a growing baroclinic wave simulated with NEPTUNE. The global horizontal resolution is approximately 30 km.

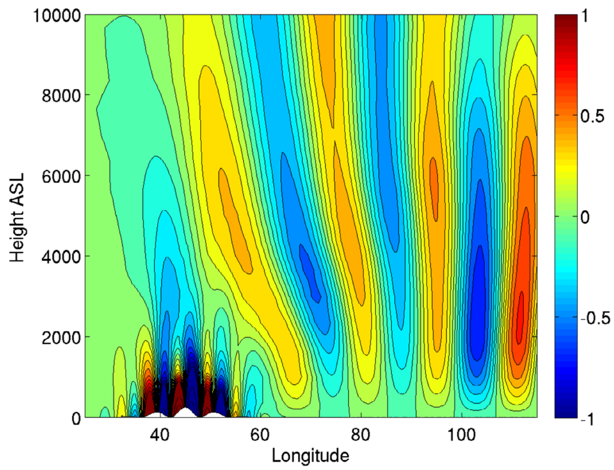

Figure 2: Cross section of vertical velocity at the equator for a global NEPTUNE simulation of a vertically sheared jet impinging upon a Schär mountain profile.

The third test case is a simulation of a supercell thunderstorm on a reduced radius sphere. A strongly unstable sounding is initialized along with a moderately sheared jet. The key to this problem is to solve for temperature and pressure fields with adequate discrete gradient wind balance and hydrostatic balance in the background state. A discretely balanced background will prevent spurious convection in the unstable atmosphere. A localized warm bubble is released to begin the primary updraft of the supercell. The shear profile is such that it supports a splitting supercell with an individual cell drifting poleward in each hemisphere. Preliminary results for a simulation using a relatively coarse average horizontal grid spacing (2 km) are shown in the following figures. Figures 2a and 2b show a snapshot of cloud water and rain water mixing ratio at t=45 minutes at a height of 5 km. The initiation of storm splitting can be seen in both figures, as well as in a matching cross section of the vertical velocity (Fig 3) at z=2 km. The final figure is a longitude-height cross section along the equator, combining vertical velocity with both cloud and rain water. It can be seen that the precipitation has already reached the ground, while there is a tilt in the updraft structure indicated by both vertical velocity and formation of new clouds ahead of the main updraft region.

b. NEPTUNE Real-Data Global Simulation Capability

We have conducted a number of tests to evaluate the performance of the NEPTUNE system on the sphere. The NUMA coordinate system matches other dynamical cores for applications in a three-dimensional "box" for idealized tests, but differs on the sphere where the origin is at Earth center. For static equilibrium on the sphere, and analytic horizontal pressure gradients are zero. However, the use of numerical derivatives creates substantial numerical instability such that the model blows. The issue is related to the inability to discretely represent the sphere's curvature using low order polynomials. The solution is to expand the chain rule used for derivatives to include an analytic description of the sphere's curvature. The polar singularities are bypassed using a rotation to the equator. Errors are reduced to machine precision, as shown in Figure 3.

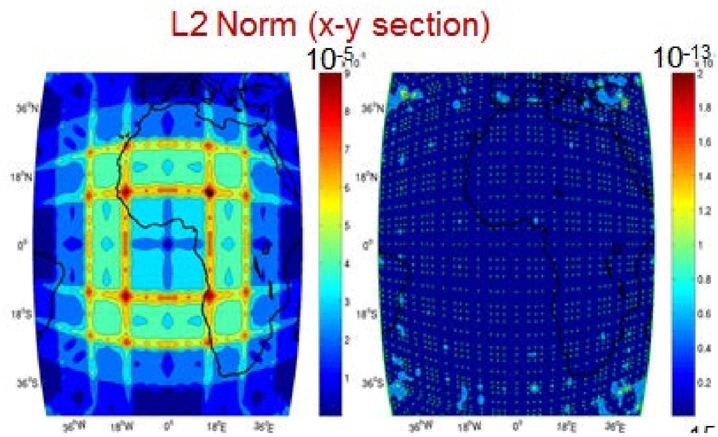

Figure 3. Errors for an idealized test on the sphere, specifically the L2 norm. The left panel shows the growth of errors due to the inability to discretely represent the sphere's curvature using low order polynomials. The right panel shows the new version in which errors are reduced to machine precision.

We have built the infrastructure to run real data cases with the NEPTUNE NWP system using the NUMA dynamical core. We have established a local version control of the code at NRL, which is shared with other NUMA users including NPS. The basic input/output interface program has been developed in order to read in the many data bases for the model. New data bases have been added this past month. Terrain and surface fields have been interpolated to the cubed sphere grid, which is used for the initial test for the model.

Physical parameterizations have been incorporated into NEPTUNE. These include representations of surface flux, boundary layer, shallow convection, warm-rain microphysics, and radiation processes. An example of a short term (6 h) forecast of the 200-hPa winds using NEPTUNE on the cubed sphere is shown in Fig. 4. This real data simulation has been integrated to 24 h as a test case. This real-data simulation is the first NWP type of simulation ever performed using the spectral element method in three dimensions.

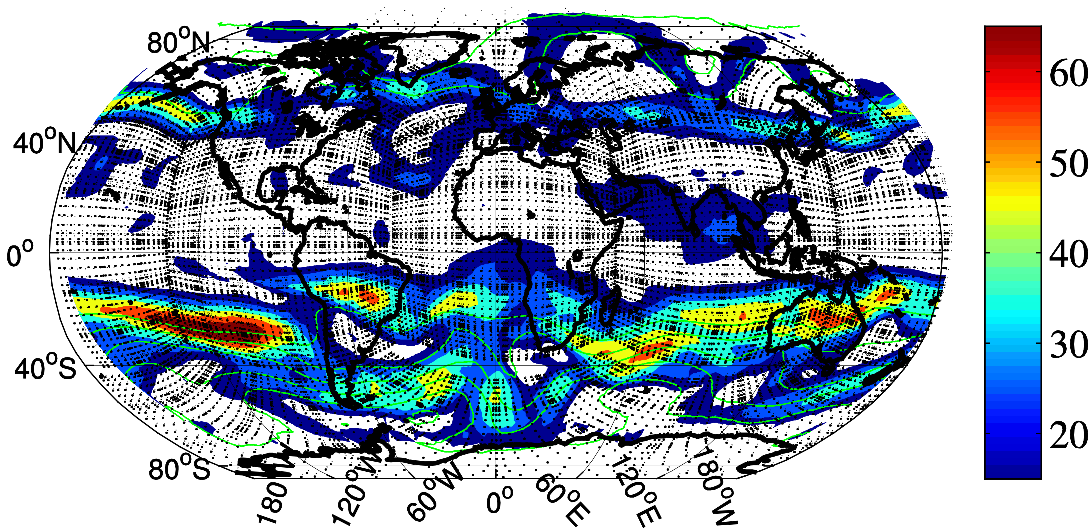

Figure 4. A real-data six-hour forecast using NEPTUNE (grid increment of 100 km). The 200-hPa wind Speed (m s^{-1}) forecast is valid at 06 UTC 25 June 2013.

IMPACT/APPLICATIONS

The project will provide a new generation weather and climate prediction model, which will accelerate the US Navy capabilities to the forefront. A new generation of models will allow us to simulate phenomena across both spatial and temporal scales. On fine scales, such as applications over coastal regions or complex terrain, the off-line forcing from the lateral boundary conditions will no longer be required. On large scales, feedback from smaller scales will be handled in a natural and explicit manner instead of being represented through crude parameterizations.

Information superiority is a key element of the DoD's strategic plan to ensure battlespace dominance in the 21st century, as outlined in Joint Vision 2020. Situational awareness is a critical aspect of information superiority. A high fidelity four-dimensional (4D) depiction of the battlespace environment using a variable resolution model capturing scales ranging from planetary to clouds can be exploited for a number of warfare areas, including Intelligence, Surveillance and Reconnaissance (ISR); Strike Warfare (STW); Anti-Surface Warfare (ASuW); Anti-Submarine Warfare (ASW); as well as to prevent damage by winds and seas during routine Maritime and Aviation Operations. High-fidelity forecasts from a unified modeling system of the characterization of the common operational picture as well as tactical decision making required by the warfighter. Great strides have been made towards the development and testing of a new generation of models such as NEPTUNE (*Navy Environmental Prediction sysTem Utilizing NUMA for Efficiency*), MPAS, and HiRAM, but much of this technology has yet to be validated in real-time environment and impact operational forecasts within the Navy or any other operational center. These emerging technologies can be exploited over the next several years that will enable for the first time a high-fidelity global depiction of the battlespace environment to serve the U.S. Navy and DoD needs.

TRANSITIONS

The research performed under this project will be transitioned as part of the Earth System Prediction Capability (ESPC) program. We anticipate the new atmospheric model will be transitioned into operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC) in the next 7-10 years. Transitions of advanced physical parameterizations will be made to the NAVGEM and COAMPS 6.4 programs during the next several years. The ultimate goals is to develop a unified system that is capable of accurate coupled predictions on the global and for limited area high-resolution applications.

RELATED PROJECTS

The basic NEPTUNE development is advancing under various programs and sponsorship. Development in 6.2 is taking place in the ONR funded program “COAMPS-NG” as well as ONR sponsorship at the Naval Postgraduate School. The MPAS system has been supported by DOE and NSF, while the HiRAM system has primarily been supported by NOAA, although both models have leveraged considerably from indirect and direct sponsorship outside their own organizations. We expect close coordination with the ONR DRIs Physical Parameterization and Seasonal Prediction, to draw on the community expertise with both MPAS and HIRAM. NRL is a no-cost collaborator with a number of proposals for the ONR Seasonal Prediction and Physical Parameterization DRIs. Additionally, this work will benefit from ongoing ONR and NRL base supported 6.2 COAMPS and NAVGEM efforts. This work is closely coordinated with the ongoing 6.4 Small Scale and 6.4 Global modeling efforts. In particular, we are leveraging mature physical parameterization research that is in the transition process in these projects and test the new physics in NEPTUNE.

PUBLICATIONS

Refereed Publications: Submitted or appeared.

Viner, K.C., C.C. Epifanio, J.D. Doyle, 2013: A steady-state solver and stability calculator for nonlinear internal wave flows. *J. Comput. Phys*., **251**, 432 – 444.