

## **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 of 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 a Numerical Weather and Climate Prediction (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 develop, 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 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 NEPTUNE makes use of the NUMA dynamical core, which is based on the spectral element method. The discretization is performed on hexahedral elements (rectangular faces). 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 analytic nature of derivatives plays an important role in scalability because the communication stencil among neighbor computational cores is minimal. 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), semi-implicit, with the semi-implicit correction applied in all three dimensions or in vertical only, to split-explicit.

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## WORK COMPLETED

A major part of our effort in the past year has been to advance the Navy's next-generation non-hydrostatic modeling system NEPTUNE. We have focused on building the infrastructure to run real data cases. A local version control of the code has been maintained at NRL, which is accessible by other NEPTUNE/NUMA users including NPS. The major focus of work was getting NEPTUNE ready to run real data cases on massive parallel computers. We have implemented the following new features and improvements:

- A new time integrator based on the Runge-Kutta method using time-splitting, where the fast modes (related to sound waves) are resolved using a shorter (small) time step; the scheme is less diffusive and it allows a longer (large) time step which dictates when the physical parameterizations are computed.
- Input and output communications based on HDF5, needed for massive parallel computing. Previously all the data was gathered on a single compute node before the output, which represented an efficiency bottleneck. With HDF5, the I/O operations are fully parallel.
- New domain decomposition based on p4est needed for massive parallel computing.
- Digital filter to provide stable initial conditions and damping of fast modes.
- Semi-analytic metric terms to ensure stable hydrostatically balanced initial steady state on the sphere.

- A stabilization method to dampen noise at short wavelengths.
- A switch to use either shallow-atmosphere approximation, or full deep-atmosphere solution.

We have continued with our participation 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:

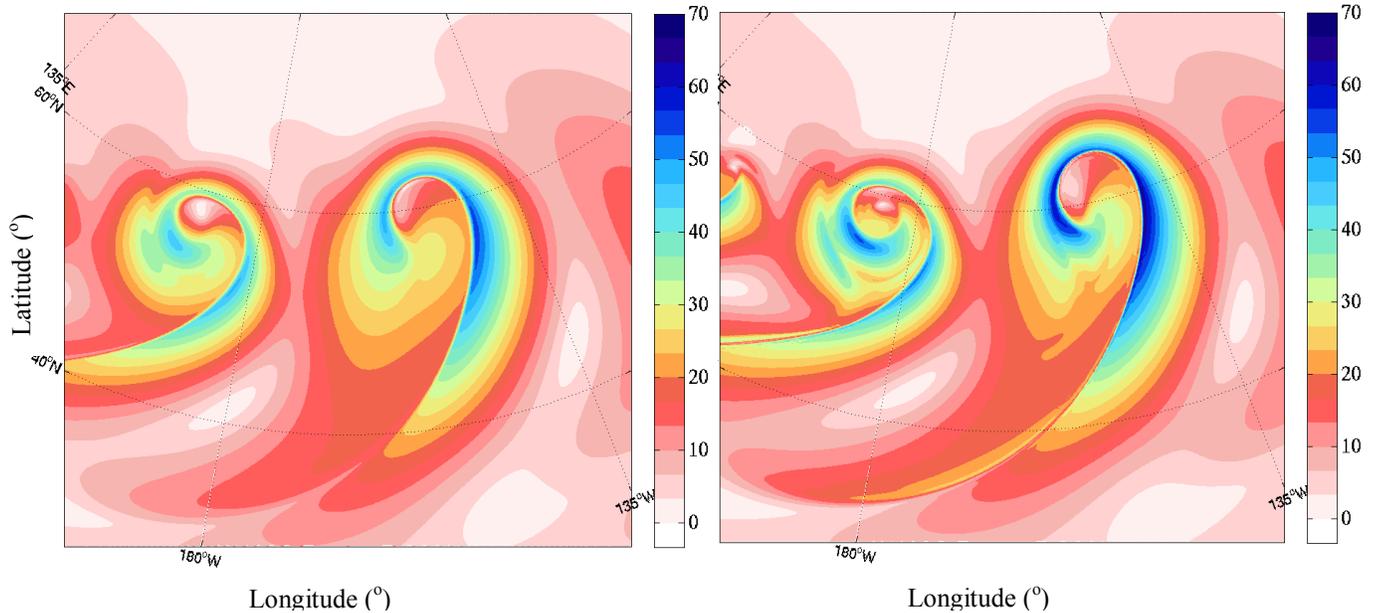
- An idealized baroclinic wave on the spherical earth.
- An orographic gravity wave test case on a scaled small planet.
- An idealized supercell test case on a scaled small planet.
- A real data tropical cyclone test case.

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

## RESULTS

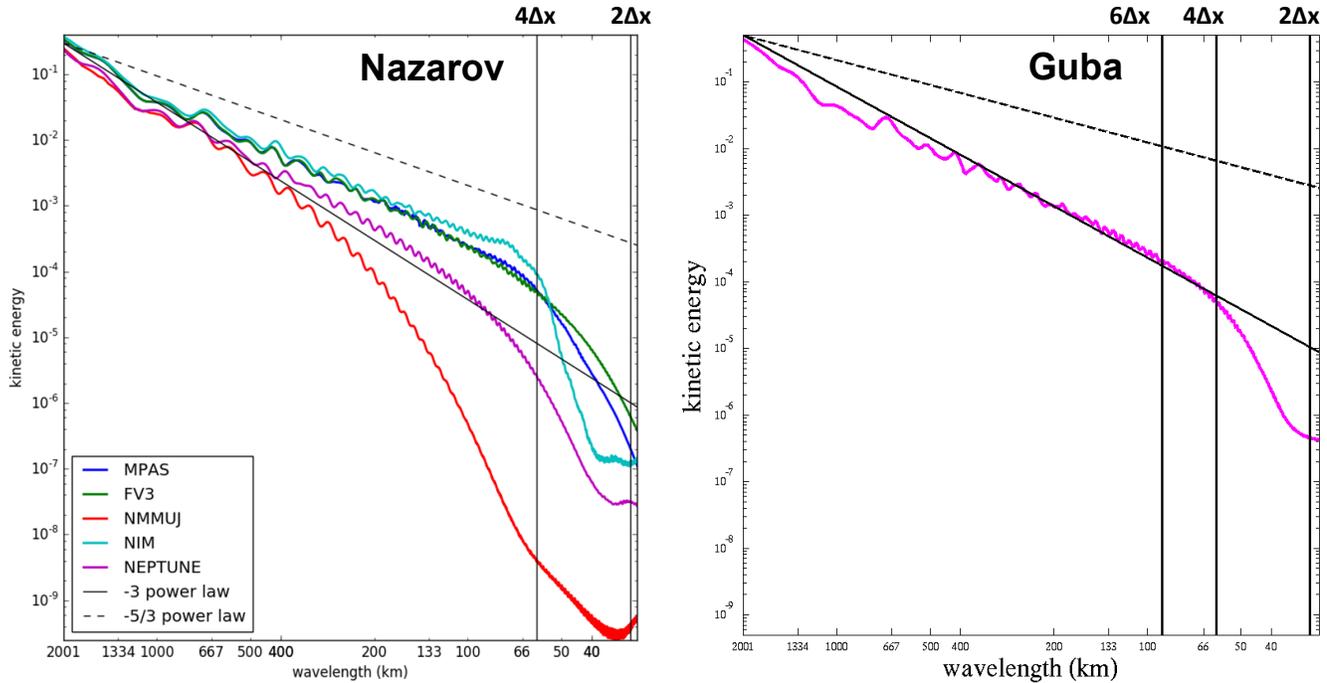
### *a. Idealized Test Cases*

A significant improvement in the baroclinic wave results with NEPTUNE was accomplished by implementing a more sophisticated stabilization method (Fig 1).



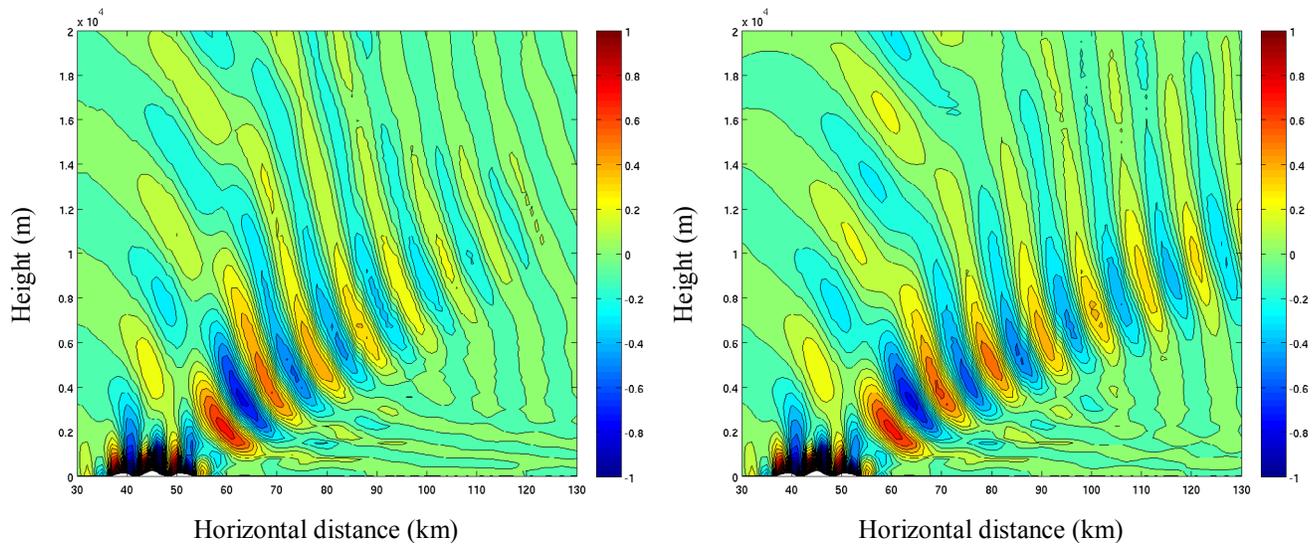
**Figure 1. Surface wind speed at day 9 of the idealized baroclinic wave test case using Nazarov based stabilization (left) and Guba-based stabilization (right). Horizontal resolution is approximately 120 km.**

A more quantitative measure of improvement is supported by the kinetic energy spectra at the surface (Fig. 2). With the initial results using Nazarov-based stabilization, the effective resolution of NEPTUNE was close to  $6\Delta x$ . The results obtained with Guba stabilization indicate the effective resolution at  $4\Delta x$ .



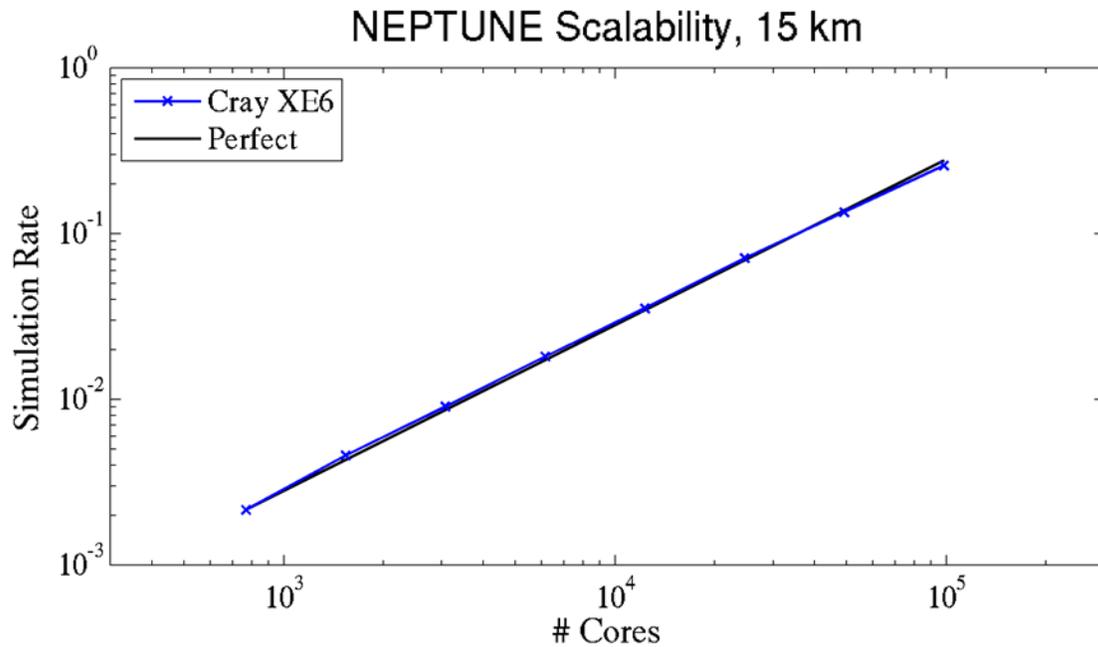
**Figure 2. Surface kinetic energy spectra day 9 of the idealized baroclinic wave test case using Nazarov based stabilization (left) and Guba-based stabilization (right). Average horizontal grid spacing is 15 km.**

NEPTUNE results for the orographic gravity wave test and idealized supercell test (both on a reduced radius planet) were improved compared to results from the other participating models when the shallow-atmosphere approximation is used (the only option available for the rest of the models). When using the deep-atmosphere equations, the standing gravity wave train has a constant height-distance angle and is rapidly decreasing in amplitude. With the shallow-atmosphere equations, the wave train becomes more horizontal with distance from the orography and the magnitude of the perturbations is less evanescent (Fig. 3). The shallow-atmosphere switch was implemented solely for the model intercomparison purposes.



**Figure 3. Vertical cross-section of vertical velocity (m/s) for the Schaer mountain wave case when using the deep-atmosphere (left) and shallow-atmosphere approximation (right).**

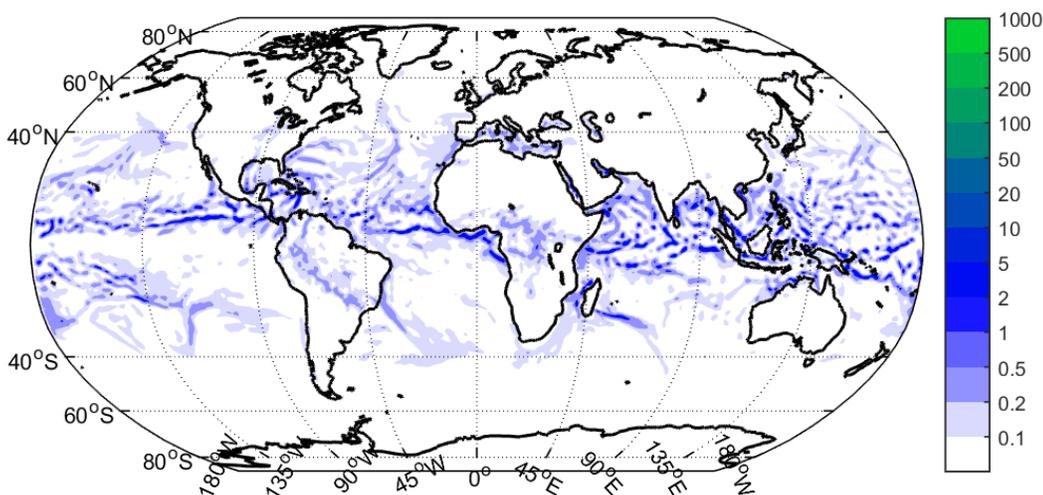
The baroclinic wave test was also used for scaling purposes. It has been shown that the NEPTUNE Spectral Element solver (dynamics only, no input/output) has nearly ideal scaling (Fig. 4) up to  $\sim 10^5$  computational cores (practical upper limit of the computational cores on the testing platform).



**Figure 4. Neptune scalability (blue line) with the increasing number of cores compared to a perfect simulation rate (black line).**

*b. NEPTUNE Real-Data Global Simulation Capability*

Hurricane Sandy was chosen for the real data capability. Initial conditions were based on GFS fields, interpolated onto the NEPTUNE grid. The simulation length was 72 hours, starting on October 24<sup>th</sup> at 18Z. We used the following physical parameterizations: microphysics, shallow and deep convection, surface fluxes, surface energy model, radiation, subgrid-scale mixing, cloud fraction, and planetary boundary layer. The successful simulation represent the first global weather prediction obtained with a fully three-dimensional spectral element model, using a whole suite of physical parameterizations.



**Figure 5. Total accumulated precipitation (mm) 18 hours into the simulation, using an average horizontal nodal spacing of 0.75°.**

## IMPACT/APPLICATIONS

This 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 will provide a characterization of the common operational picture as well as support 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, 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 to 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 are to develop a unified system that is capable of accurate coupled predictions on the globe 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 to test the new physics in NEPTUNE.

## **PUBLICATIONS**

### ***Refereed Publications: Submitted or appeared.***

Rabier, F., A.J. Thorpe, A.R. Brown, M. Charron, J.D. Doyle, T.M. Hamill, J. Ishida, B. Lapenta, C.A. Reynolds, M. Satoh, 2015: Global environmental prediction. Chapter in *Seamless Prediction of the Earth System*, edited by G. Brunet. WMO publisher.