DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Development of the Navy's Next-Generation Nonhydrostatic Modeling System

Saša Gaberšek
Naval Research Laboratory
7 Grace Hopper Avenue, Stop 2
Monterey, CA 93943-5502
phone: (831) 656-4882 fax: (831) 656-4769 email: sasa.gabersek@nrlmry.navy.mil

Award Number: N0001414WX20041

LONG-TERM GOALS

The long-term goal of this project is to develop a Numerical Weather Prediction (NWP) model built around a next-generation dynamical core. Its advantages are that it is scalable over a large number of computational cores, highly accurate, and being unified in a sense that the same dynamical core is being used regardless of the temporal and spatial scales.

OBJECTIVES

The main objective is to finish implementing a complete set of basic physical parameterization packages in Navy Environmental Prediction SysTem Utilizing the NUMA corE (NEPTUNE), built on the Element Based Galerkin (EBG) method. The parameterizations will be tested individually and combined using idealized simulations in both two- (2D) and three dimensions (3D). The next step is to test NEPTUNE on a realistic weather forecast on the globe, using grid refinement.

The secondary objective is to explore possibilities to ensure positive definiteness for variables that do not posses physically viable negative values (e.g. tracers).

APPROACH

NEPTUNE has been developed in the past few years with a goal to become a candidate for the next generation, unified NWP model. While the physical parameterizations are being implemented and tested within this project, testing and evaluation is leveraged through participation in the Earth System Prediction Capability (ESPC) project. It has been extensively tested in both two and three dimensions, mostly using idealized simulations. NEPTUNE is the first fully three-dimensional spectral element model (SE) for the atmosphere, which is designed for high accuracy and scalability. The EBG models are built by subdividing the computational domain into elements, in which variables forming the governing equations are represented by high-order polynomial basis functions and expansion coefficients. If the points at the element boundaries are shared and continuity is ensured, the formulation is called a Continuous Galerkin (CG), or SE method. If the fluxes between the adjacent elements are shared, but the actual values at the element boundaries are allowed to differ, the formulation is called a Discontinuous Galerkin (DG) method.

The main effort of this project is aimed at completing physical parameterization packages and thorougly testing them using idealized and realistic framework. This will ultimately lead to a viable candidate for the next generation NWP model, positioning the US Navy at the leading edge of the existing NWP models used worldwide. NEPTUNE has advantageous and unique characteristics: an ability to efficiently scale over thousands of computational cores, the same dynamical core used over the globe and for local area predictions thus eliminating the need to run two separate models.
In order to ensure tracer mass conservation, positive definiteness needs to be implemented. Gibbs effect (ringing) is an ubiquitous side effect of EBG methods, made worse by steep gradients in the observed field. The ringing can yield physically implausible solutions, such as negative moisture.

Our approach is two pronged:

1. Physical Parameterization Packages

   We will complete the set of basic parameterization schemes describing physical processes. We will test each parameterization alone, as well as in combination with others, within a simplified idealized framework resembling realistic phenomena which allows intepretation and validation of results to be physically consistent and plausible.

2. Positive definitness

   We will explore options to ensure positive definiteness, focusing on the DG framework, which allows conservation laws to be enforced locally, within elements.

Key personnel: Saša Gaberšek (Naval Research Laboratory), P. Alex Reinecke (NRL), Kevin Viner (NRL), James D. Doyle (NRL), Dale R. Durran (University of Washington)

WORK COMPLETED

We have implemented a complete set of simple physical parameterizations: i) surface fluxes based on bulk Louis/TOGA-COARE scheme; ii) the convective parameterization based on the University of Washington shallow convection scheme (designed to be scale aware); iii) the radiation scheme based on the Rapid Radiative Transfer Model GCMs (RRTMG); iv) sub-gridscale mixing based on Smagorinsky isotropic turbulence, implemented to act in the vertical direction only; v) warm cloud (no ice species) microphysics, based on Kessler scheme.

A viable option to ensure positive defineteness has been tested and implemented within the EBG framework, although preliminary in two dimensions only.

RESULTS

The parameterizations were tested individually and combined using idealized cases to ensure physically plausible and correct results. For example, surface fluxes and subgrid-scale mixing were tested in an idealized test describing an evolution of a planetary boundary layer. Figure 1 shows a temporal evolution of the dry, stably stratified (isothermal) atmosphere, on a rotating mid-latitude f-plane, initialized with a constant wind speed profile and integrated for 48 hours. At the end of the simulation, a nicely developed, well mixed isentropic boundary layer has developed, capped by an inversion, with most of the mixing taking place at the lower boundary where the no-slip boundary

condition was imposed for the momentum. The change with height of the velocity vector reveals a super-geostrophic layer between the heights of 100 and 300 m, qualitatively consistent with the theoretical Ekman layer.

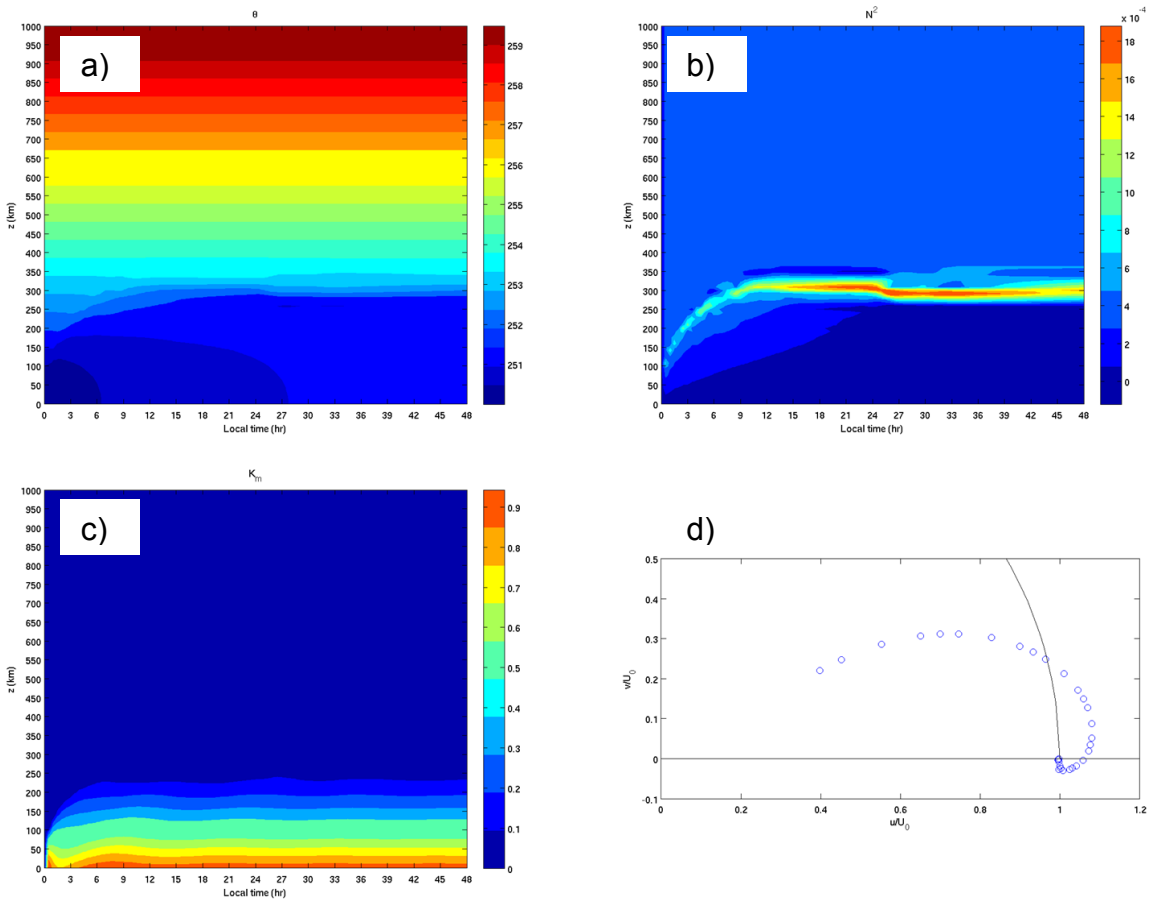

Figure 1: A vertical profile of potential temperature (a), atmospheric stability (b), subgrid-scale mixing (c) as a function of time, and a hodogram of normalized wind components at the final time (d).

In another idealized case, radiation and warm cloud microphysics parameterization packages were tested. The atmosphere was initialized with an elevated moist layer (95% relative humidity) between 1.5 and 4.5 km. For the radiation scheme, the latitude was set to 10° N, in an early summer, with the simulation starting at local noon, integrating for 24 hours (Figure 2). The main features are condensation due to radiational cooling at the top of the cloud, evaporative cooling below the cloud and associated moistening of the layer between the ground and the cloud base, and finally the initiation of rain, reaching the ground at around local midnight.

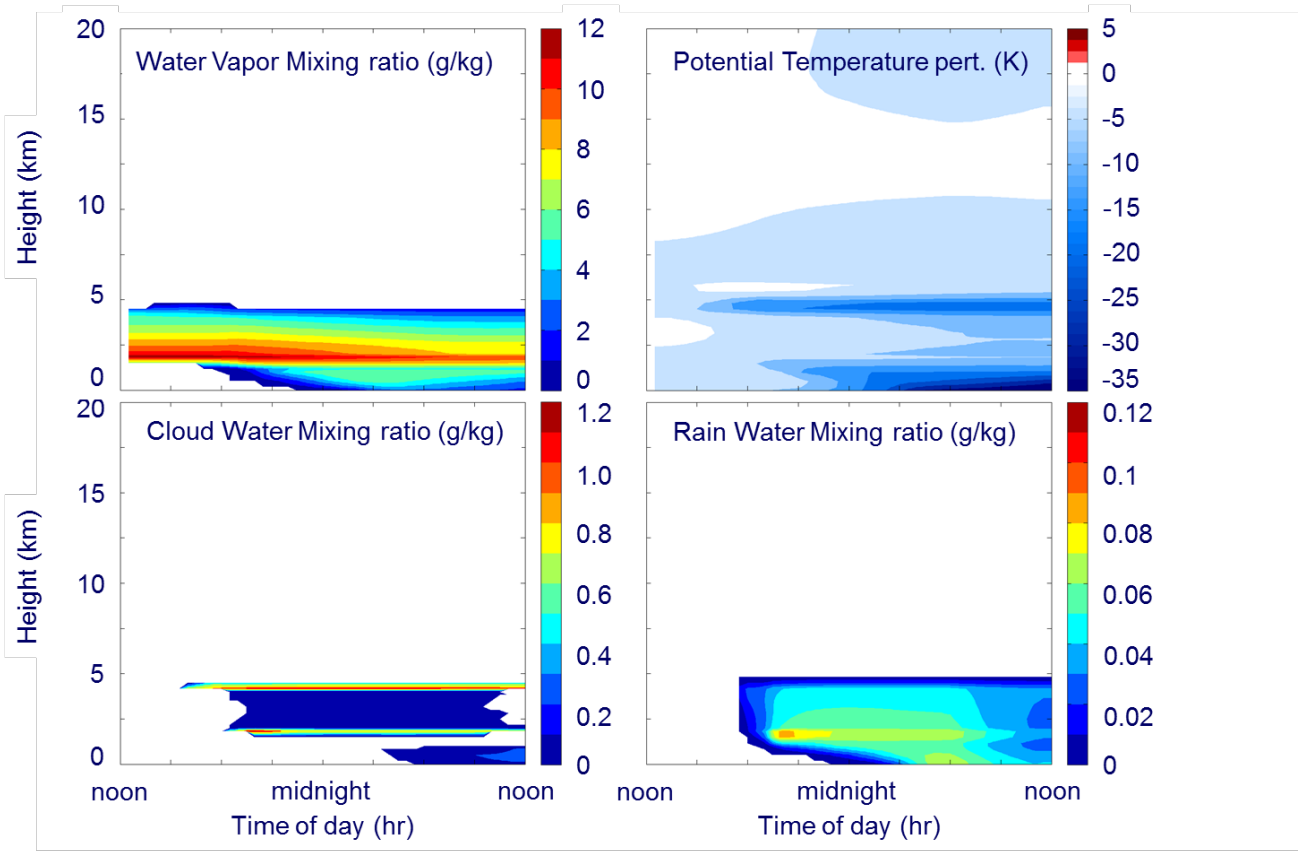

Figure 2: A vertical profile of water vapor mixing ratio (top left), potential temperature perturbation (top right), cloud water mixing ratio (bottom left), and rain water mixing ratio (bottom right) as a function of time.

Challenges encountered while implementing the basic set of parameterizations in NEPTUNE were also related to the non-uniform spacing of grid points, associated with their spatial distribution within elements (Fig. 3a). We have developed a fast mapping transformation without any loss of accuracy between the NEPTUNE native grid on which the dynamical processes are calculated, and a vertically uniform grid on which the physical processes take place (Fig. 3b).

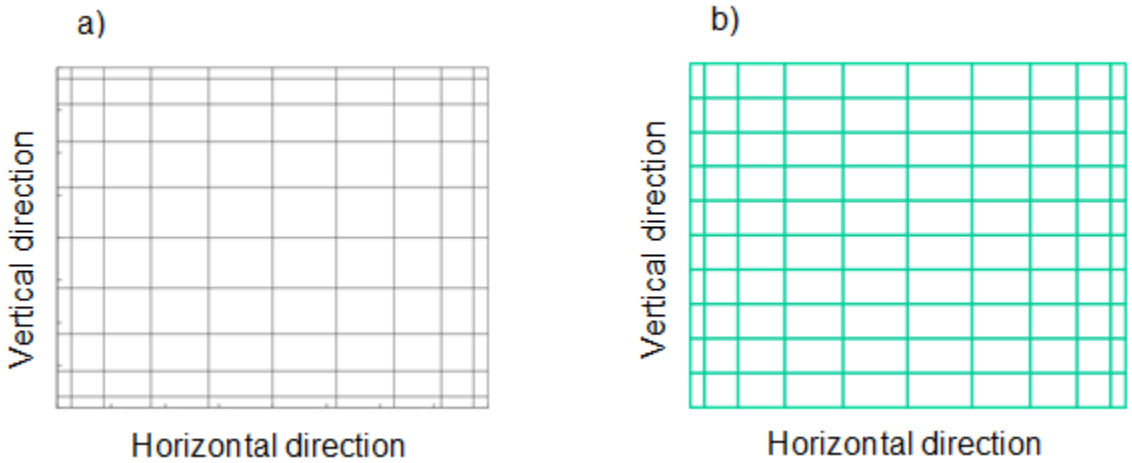

Figure 3: A distribution of nodal/grid points in a two-dimensional element: non-uniform grid spacing in the vertical used to calculate the dynamical processes (a); uniform grid spacing in the vertical used for the physical processes (b).

The key to solve the positive definiteness in the EBG methods is to conserve quantities locally. We propose a separate treatment of scalars that are not directly used within the dynamical core. In this approach, scalars would be essentially decoupled by treating them with the DG machinery. Values at the element boundaries do not need to be continuous across adjacent elements, thus element averages can be easily conserved. For each element, in which a solution is to be adjusted, we divide the element into equal cells and calculate cell averages (Fig. 4a). If there are negative values, they are reset to zero by 'borrowing' from the cells with positive averages, ensuring the element average remains constant (Fig. 4b). Next, the solution is recalculated through the adjusted cell averages (Fig. 4c).

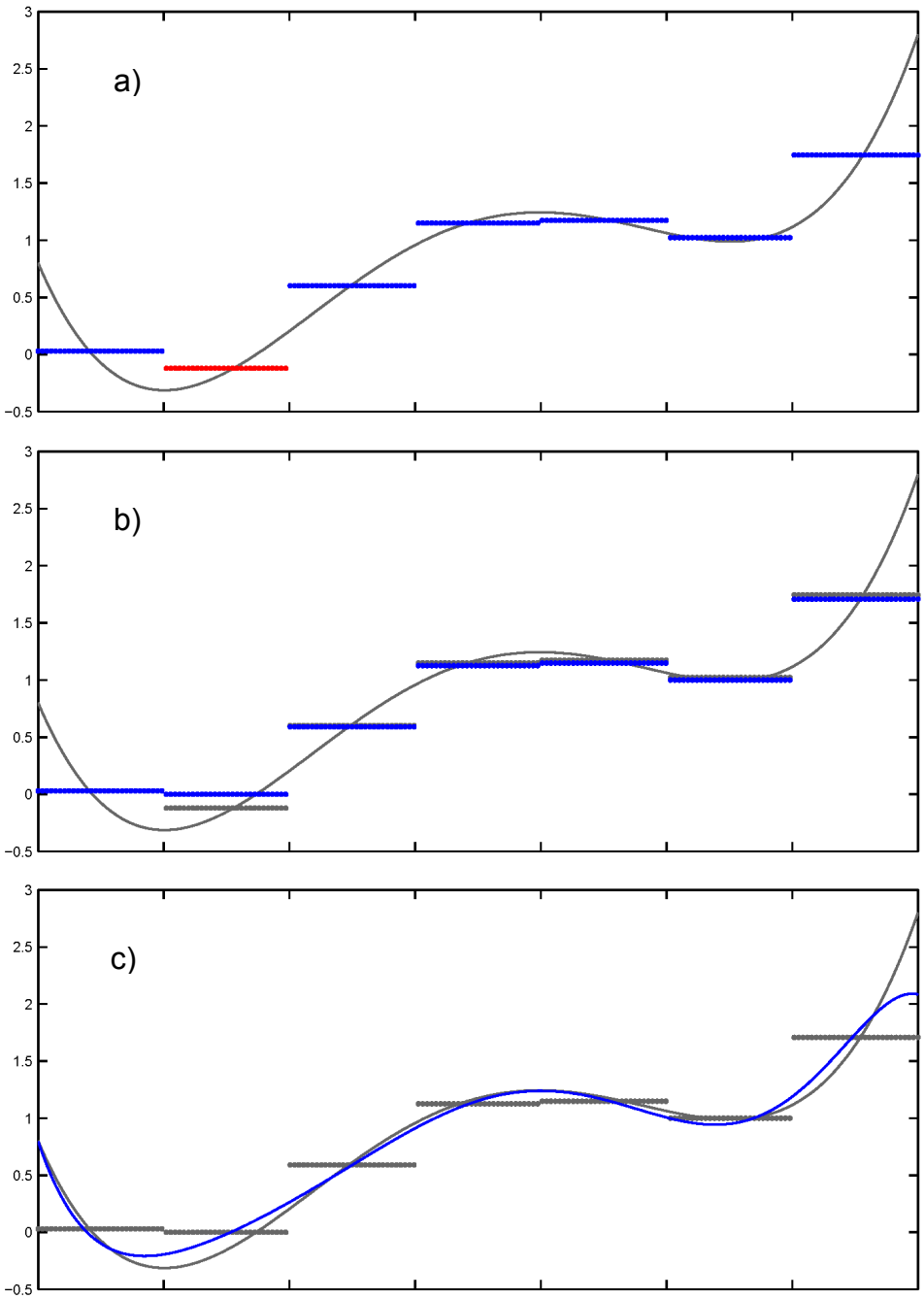

Figure 4: Stages of the positive definiteness adjustment: calculate cell averages (blue-positive, red-negative) for a solution within the element (gray line) (a); adjust the cell averages (blue cross bars), so that the element average is preserved and the negative values become zero (b); calculate the new fitting function (blue line) through the adjusted cell averages (gray cross bars) (c).

This approach has been successfully tested in a two-dimensional DG framework, as shown in Figure 5. In this test an initial tracer distribution is subjected to a cyclic swirling motion, in which the maximum deformation occurs at the half period (Figs 5a and 5c), after which the flow reverses and the tracer distribution returns to its initial position at the final time (Figs 5b and 5d).

To apply this method in NEPTUNE, which is CG based, the first approach will be to treat scalars and tracers separately with DG methodology. Ultimately, we will adopt DG framework for all variables.

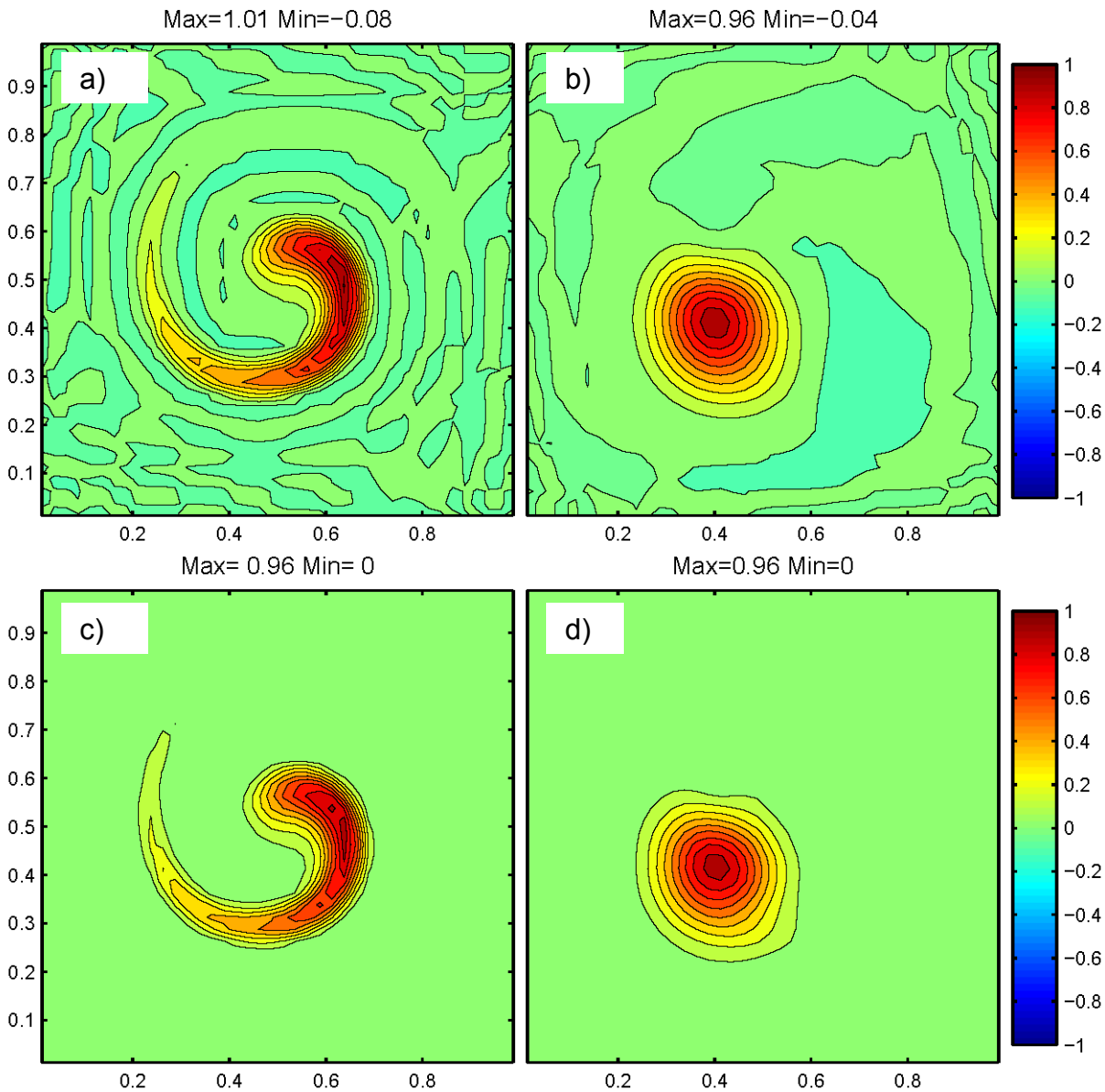

Figure 5: A comparison of the reversible advective swirling flow of a passive tracer with no positive definiteness (top row) and with positive definiteness (bottom row), at the half time (a,c) and final time (b,d), at which the tracer returns to its initial position. Note that a smoother and more accurate solution can be obtained with finer grid/nodal spacing.

IMPACT/APPLICATIONS

NEPTUNE could become the unified dynamical core for both global and mesoscale weather forecasts for the US Navy. The design of the model and its structure yield excellent scalability that can take a full advantage of available computational cores as they become readily accessible in large numbers (~100000) in the near future. The advantage of using a unified model can be exploited to study phenomena spanning various spatial and temporal scales, e.g. Madden-Julian Oscillation and extra-tropical cyclones.

TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-120, ESPC Dynamical Core project).

RELATED PROJECTS

NEPTUNE will be used in a related 6.2 project within PE 0602435 for an intercomparison of dynamical cores aimed at prediction across scales.