Short communication

Ocean modeling with flexible initialization for improved coupled tropical cyclone-ocean model prediction

Richard M. Yablonsky*, Isaac Ginis, Biju Thomas

Graduate School of Oceanography, University of Rhode Island, 215 South Ferry Road, Narragansett, RI 02882, USA

ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form 3 January 2015
Accepted 5 January 2015
Available online

Keywords:
Ocean circulation
Numerical model
Coupled model
Parallel computing
Tropical cyclone (hurricane) forecasting
Model initialization

ABSTRACT

This paper introduces the Message Passing Interface Princeton Ocean Model for Tropical Cyclones (MPIPOM-TC), created at the University of Rhode Island (URI). MPIPOM-TC is derived from a combination of the parallelized version of the Princeton Ocean Model (POM), called the Stony Brook Parallel Ocean Model (sbPOM), and URI's non-parallelized POM for Tropical Cyclones (POM-TC), which has been used for many years as the ocean component of NOAA's and the U.S. Navy's operational hurricane forecast models. In addition to parallelization, the flexible initialization capabilities of MPIPOM-TC and other elements of its architecture will facilitate further improvements to the ocean component of research-based and operational tropical cyclone (hurricane) forecast models worldwide.

© 2015 Elsevier Ltd. All rights reserved.

Software availability

Software name: MPIPOM-TC
Developers: Richard Yablonsky, Biju Thomas, and Isaac Ginis
Contact: wrfhelp@ucar.edu
Software requirements: Linux or Unix, Fortran compiler, mpich 2, parallel NetCDF, NetCDF
Programming language: Fortran 77/90
Availability and cost: Available for free since September 2014 as a component of the community HWRF hurricane model at http://www.dtcenter.org/HurrWRF/users/downloads/index.php

1. Overview

Tropical cyclones (hurricanes) are known to generate vigorous responses in the open ocean, which include upper-ocean currents of $1-2 \text{ m s}^{-1}$ and sea surface temperature (SST) cooling of several degrees. Ocean models that simulate these responses are an important component of coupled tropical cyclone-ocean prediction systems. The motivation to couple an ocean model to a hurricane model is to create accurate sea surface temperature (SST) and current fields for input into the hurricane model. An uncoupled hurricane model with a static SST field is restricted by its inability to account for SST changes during model integration, which often cause high intensity prediction bias (e.g. Bender and Ginis, 2000). Similarly, a hurricane model coupled to an ocean model that does not include fully three-dimensional ocean dynamics only accounts for some of the hurricane-induced SST changes during model integration (e.g. Price, 1981; Yablonsky and Ginis, 2009, 2013). Finally, two-way hurricane-ocean model coupling allows for real-time prediction of the ocean response under hurricane forcing.

The three dimensional, primitive equation, numerical ocean model that has become widely known as the Princeton Ocean Model (POM) was originally developed in the late 1970s and 1980s (Blumberg and Mellor, 1987). In 1994, a version of POM available at the time was transferred to the University of Rhode Island (URI) for the purpose of coupling to NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model to improve 3–5 day hurricane forecasts (Bender and Ginis, 2000). Since operational implementation of the coupled GFDL/POM model in 2001, additional changes to POM were made at URI and subsequently implemented in the operational GFDL model, including improved ocean initialization (Falkovich et al., 2005; Bender et al., 2007; Yablonsky and Ginis, 2008). This POM version (now known widely as POM-TC) was also coupled to NOAA’s Hurricane Weather Research and
Forecasting (HWRF) model (Yablonsky et al., 2015), which became operational in 2007.

Separate from the URI-based changes to POM for hurricane applications, both Princeton-based and community-based improvements to and applications for POM were made between 1994 and 2012, including development of pom2k (Mellor, 2004) and the addition of Message Passing Interface (MPI) routines to allow POM to run in parallel on multiple processors, as in the Stony Brook Parallel Ocean Model (sbPOM; Jordi and Wang, 2012) and the Advanced Taiwan Ocean Prediction (ATOP) system (Oey et al., 2013). With the availability of expanded computing resources at NOAA, URI has now merged the 2012 versions of the sbPOM and POM-TC and made additional improvements to allow for flexible initialization options and a relocatable grid, culminating in the

Table 1

<table>
<thead>
<tr>
<th>File name</th>
<th>Changes from sbPOM to MPIPOM-TC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pom.f</td>
<td>Only used if uncoupled from hurricane model; if coupled, drive_ocean.f used.</td>
</tr>
<tr>
<td>initialize.f</td>
<td>Options added for f-plane, spatial smoothing and desmoothing (Bender et al., 1993), 1-D (vertical only) dynamics on an A-grid (vs. 3-D C-grid), wave-dependent turbulence, and non-zero initial currents (geostrophic or prescribed) and/or sea surface height; alternative values for input constants.</td>
</tr>
<tr>
<td>advance.f</td>
<td>Prescribed surface forcing only applied when uncoupled from the hurricane model; added missing MPI exchanges; omitted lateral viscosity, mode interaction, external mode, vertical velocity, horizontal advection, and horizontal diffusion for 1-D only dynamics; smoothing and desmoothing of temperature, salinity, and currents optionally applied; temperature growth eliminated; model fails if SST is unreasonably high.</td>
</tr>
<tr>
<td>bounds_forcing.f</td>
<td>Maximum depth and the number of vertical sigma levels are not specified here; new boundary conditions added for 1-D only dynamics on an A-grid.</td>
</tr>
<tr>
<td>solver.f</td>
<td>Missing MPI exchanges added; A-grid used for 1-D only dynamics; wave breaking energy disabled; wave-dependent turbulence optionally applied.</td>
</tr>
<tr>
<td>parallel_mpi.f</td>
<td>None, except for two minor changes when coupled to the hurricane model.</td>
</tr>
<tr>
<td>io_pnetcdf.F</td>
<td>I/O parameters added; print times and output directory changed; syntax fixed.</td>
</tr>
<tr>
<td>pom.h</td>
<td>Many new parameters added (see comments in code for details).</td>
</tr>
<tr>
<td>pom.nml</td>
<td>Ten name list parameters added to control new and enhanced capabilities.</td>
</tr>
</tbody>
</table>

Fig. 1. History of POM and MPIPOM-TC development from the late 1970’s to 2014.

Fig. 2. MPIPOM-TC worldwide ocean domains.
MPIPOM-TC for coupled hurricane-ocean models (Fig. 1), which became operational in the GFDL and HWRF hurricane forecast models in 2014.

2. Model description

MPIPOM-TC is an end-to-end ocean modeling system, with both research and operational applications, that includes generation of an initial ocean condition, a procedure for prescribed hurricane wind forcing, and/or two-way coupling between the ocean and a prognostic hurricane model (e.g., GFDL or HWRF). The MPIPOM-TC code is built on the parallelized sbPOM framework (Jordi and Wang, 2012), including the main driver (pom.f), problem setup (initialize.f), code advancement in time (advance.f), boundary conditions and forcing (bounds_forcing.f), basic dynamics (solver.f), parallel tasks for communications between processors.

Fig. 3. HWRF intensity error statistics (kt, upper left), track error statistics (nm, center left), and intensity bias statistics (kt, lower right) using 655 test cases from the 2010–2012 Atlantic hurricane seasons, run with either the 2013 baseline coupled with POM-TC (H131, red), as in Yablonsky et al. (2015), or the 2013 baseline coupled with MPIPOM-TC (H134, blue); courtesy of NOAA’s Environmental Modeling Center (EMC). HWRF coupled with MPIPOM-TC reduces the positive intensity bias compared to HWRF coupled with POM-TC; track differences are small. MPIPOM-TC SST (°C) cold wake (upper right), TRMM Microwave Imager 3-day averaged observed SST (center right), and MPIPOM-TC POM-TC SST cold wake difference (lower right), generated by Hurricane Katia’s forcing through 00 UTC 08 September 2011. MPIPOM-TC cooling compares well with observations and is generally greater than POM-TC, consistent with a reduced positive intensity bias. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
tests to ensure that the forecast completes within the operational time window, and (3) comparison of individual forecasts to both remotely-sensed and in situ ocean observations (e.g. Fig. 3; Yablonsky et al., 2015). Worldwide MPIPOM-TC operational implementation in GFDL, HWRF, and GFDN is planned after further testing and evaluation. The MPIPOM-TC framework described here will allow for more rapid improvements and transition of research to operations (R2O) in the future, including: development and evaluation of alternative initialization modules; physics improvements (especially to the turbulence closure model to properly account for wave-dependent turbulence); three-way coupling between MPIPOM-TC, a hurricane model, and a wave model (e.g. WAVEWATCH III, Tolman, 2014); and high-resolution nesting, especially at the coastline to forecast storm surge. While these new capabilities may improve forecasts of hurricanes and their impacts, R2O must consider a balance between the best model configuration and the computational efficiency required to produce timely forecasts with available resources. Nonetheless, advanced MPIPOM-TC configurations that cannot be immediately transitioned to operations may be used for research and further model development, including future R2O. In addition, simplified MPIPOM-TC configuration options (e.g. 1D only dynamics and idealized initial conditions) can isolate specific physical processes to guide future model improvements.

3. Model initialization and configuration

An innovative aspect of MPIPOM-TC is the development of flexible, plug-and-play, Fortran-based initial condition modules. In the 2014 operational GFDL and HWRF models, the initial condition module in the Atlantic Ocean (fbtr) involves feature-based modifications to the U.S. Navy’s Generalized Digital Environmental Model (GDEM) monthly temperature (T) and salinity (S) climatology (Yablonsky and Ginis, 2008; Tragou et al., 1990), followed by assimilation of a daily SST product (Reynolds and Smith, 1994); the initial condition module in the eastern North Pacific Ocean (gdm3) uses GDEMv3 (Carnes, 2009), assimilated with daily SST (Reynolds and Smith, 1994). Initial condition modules have also been developed using the stand-alone Navy Ocean Data Assimilation (NCODA) daily T and S fields (ncda; Cummings, 2005; Cummings and Smedstad, 2013) and versions of the HYbrid Coordinate Ocean Model (HYCOM) that use NCODA (e.g. Iyuc; Chassignet et al., 2009). All of these ocean products are available in the public domain for real time tropical cyclone forecasting. An idealized initial condition module (idel) with user-specified T and S, flat bathymetry, and no land is available too.

To simulate tropical cyclones worldwide, each MPIPOM-TC initial condition module is relocatable to regions around the world. Currently, these regions include the Transatlantic, East Pacific, West Pacific, North Indian, South Indian, Southwest Pacific, Southeast Pacific, and South Atlantic domains (Fig. 2), as well as the idealized domain. Domain overlap helps to prevent loss of ocean coupling. To avoid domain-specific code (pom.h), all worldwide domains are set to the same size: 869 (449) longitudinal (latitudinal) grid points, covering 83.2° (37.5°) of longitude (latitude) and yielding a horizontal grid spacing of ~9 km. Horizontal domain decomposition is 3 × 3, yielding 291 (151) local grid points on each of 9 processors. There are 23 full sigma levels from the sea surface to the sea floor, with higher vertical resolution in the mixed layer and upper thermocline.

4. Model evaluation and concluding remarks

The primary purpose of MPIPOM-TC development is to facilitate further improvements to both operational and research versions of hurricane forecast models (e.g. GFDL, HWRF, and the U.S. Navy’s version of the GFDL model [GFDN]). Initial operational MPIPOM-TC implementation in GFDL and HWRF was completed in 2014 for the Transatlantic and East Pacific basins after (1) rigorous evaluation of numerous hurricane track and intensity forecasts using either POM-TC or MPIPOM-TC (e.g. Fig. 3), (2) scaling and performance improvements to ensure that the forecast completes within the operational time window, and (3) comparison of individual forecasts to both remotely-sensed and in situ ocean observations (e.g. Fig. 3; Yablonsky et al., 2015). Worldwide MPIPOM-TC operational implementation in GFDL, HWRF, and GFDN is planned after further testing and evaluation. The MPIPOM-TC framework described here will allow for more rapid improvements and transition of research to operations (R2O) in the future, including: development and evaluation of alternative initialization modules; physics improvements (especially to the turbulence closure model to properly account for wave-dependent turbulence); three-way coupling between MPIPOM-TC, a hurricane model, and a wave model (e.g. WAVEWATCH III, Tolman, 2014); and high-resolution nesting, especially at the coastline to forecast storm surge. While these new capabilities may improve forecasts of hurricanes and their impacts, R2O must consider a balance between the best model configuration and the computational efficiency required to produce timely forecasts with available resources. Nonetheless, advanced MPIPOM-TC configurations that cannot be immediately transitioned to operations may be used for research and further model development, including future R2O. In addition, simplified MPIPOM-TC configuration options (e.g. 1D only dynamics and idealized initial conditions) can isolate specific physical processes to guide future model improvements.

Acknowledgments

We thank Ligia Bernardet’s HWRF team at the Developmental Testbed Center (DTC) for facilitating operations to research (O2R) by making MPIPOM-TC available as part of the 2014 community HWRF system. We thank Vijay Tallapragada’s NOAA/NWS/NECP/EMC/HWRF team and Morris Bender’s NOAA/OAR/GFDL team for facilitating 2014 operational MPIPOM-TC implementation. Finally, we thank Antoni Jordi for sbPOM assistance. This work was funded by two NOAA HFIP grants and one NOAA JHT grant awarded to URI (NA12NWS4680002, NA14NWS4680023, and NA13OAR4590192), as well as a DTC Visitor Program Award to Richard M. Yablonsky.

References


