

# Developing and Supporting Global HWRF Ocean Coupling with Advanced Ocean Physics and Initialization Options and New Diagnostic Tools for Comprehensive Model Evaluation

PI: Richard M. Yablonsky  
Graduate School of Oceanography  
University of Rhode Island  
Narragansett, RI 02882\*

A final report submitted to the Developmental Testbed Center (DTC) Visitor Program

12 December 2014

\* Current affiliation: AIR Worldwide, 131 Dartmouth Street, Boston, MA 02116

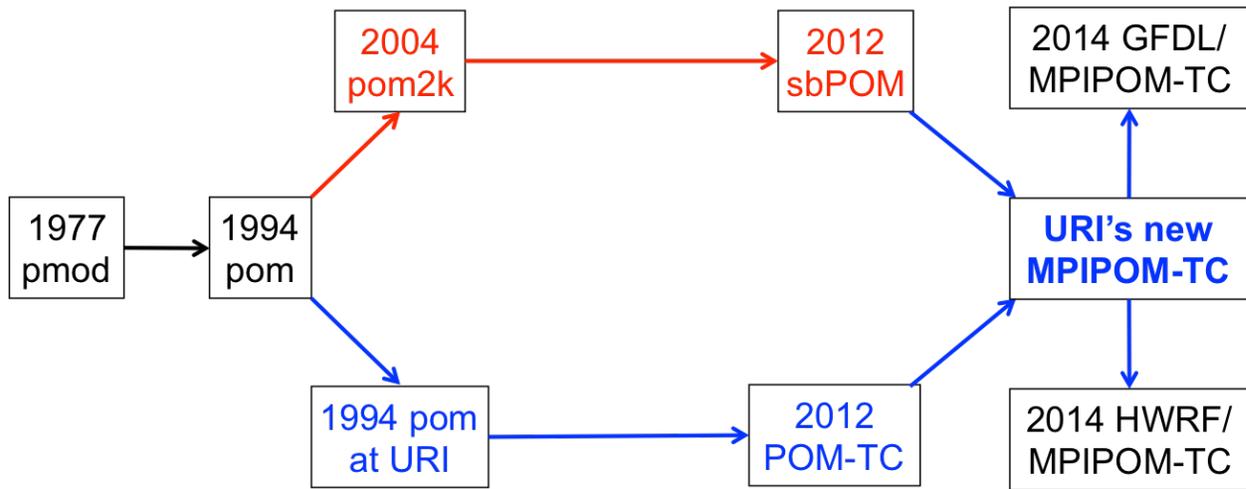
## Abstract

This project specifically addresses **Special Consideration Topic 4.2.d** by broadening the scope of the community-supported HWRF code to work in additional basins (beyond the North Atlantic and eastern North Pacific) via global HWRF coupling to the MPIPOM-TC ocean model, which has already undergone rigorous testing and evaluation in the North Atlantic and eastern North Pacific and was implemented into NOAA's operational HWRF and GFDL hurricane models at NCEP in 2014. This project also addresses **Special Consideration Topic 4.2.c** by developing new ocean diagnostic tools that can be used to provide much needed information about the strengths and weaknesses of the MPIPOM-TC ocean component of the currently operational HWRF and GFDL tropical cyclone prediction systems. This project also supports ongoing HWRF wave coupling efforts. Finally, this project involves incorporation of all newly developed HWRF code and diagnostic tools into the DTC's existing HWRF repository, and the details are documented in the latest version of the DTC's HWRF Scientific Documentation and Community HWRF Users' Guide.

## Background

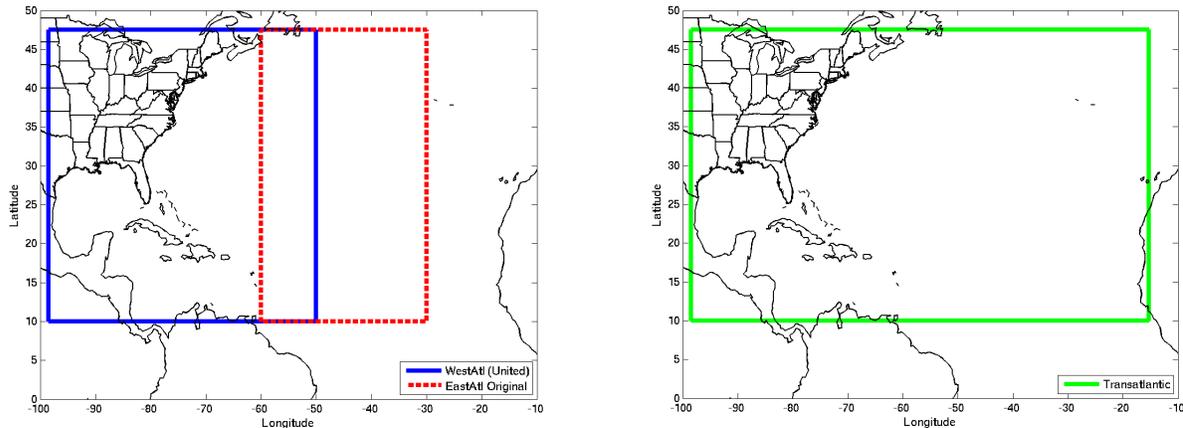
Under previous support from NOAA's Hurricane Forecast Improvement Project (HFIP) and Joint Hurricane Testbed (JHT), the PI developed a new ocean model component for the HWRF and GFDL tropical cyclone models, called the Message Passing Interface Princeton Ocean Model for Tropical Cyclones (MPIPOM-TC; Yablonsky et al. 2014b), which became operational at NCEP in 2014 (e.g. Tallapragada et al. 2014; Holt et al. 2014). MPIPOM-TC incorporates many of the community-based upgrades to the POM that have occurred between 1994 and 2012 by blending the community-based sbPOM (Jordi and Wang 2012) with POM-TC (Yablonsky and Ginis 2008, 2014a), the latter of which was coupled to HWRF through 2013 (e.g. Tallapragada et al. 2013; Bernardet et al. 2013, 2014) (Fig. 1). MPIPOM-TC's MPI capability allows for higher spatial resolution and a larger domain size than POM-TC. One of the key improvements is the replacement of the two overlapping POM-TC domains in the Atlantic Ocean, which have  $\sim 1/6^\circ$  grid spacing, with a single, transatlantic domain, which has  $\sim 1/12^\circ$  grid spacing (Fig. 2). MPIPOM-TC is computationally efficient, scalable, and has netCDF I/O, making it suitable for ocean coupling worldwide.

## POM community code development



## URI-based code development

**Figure 1.** Schematic detailing the history of POM from its initial development at Princeton in 1977 to the version transferred to URI in 1994, which ultimately led to the 2012/2013 version of POM-TC in HWRF and GFDL, and the subsequent merging of the 2012/2013 POM-TC with the community-based 2012 sbPOM to form URI's MPIPOM-TC, which itself became operational in HWRF and GFDL in 2014.



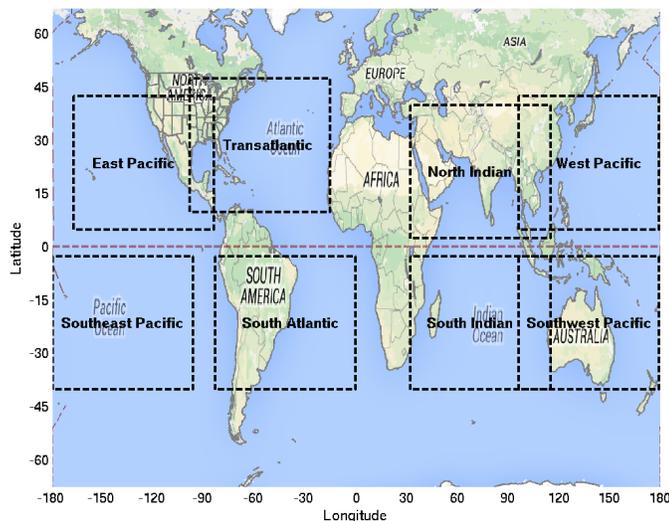
**Figure 2.** Overlapping United and East Atlantic POM-TC ocean domains (in the 2013 operational HWRF and GFDL), each of which have  $\sim 1/6^\circ$  horizontal grid spacing (left panel), and the new transatlantic MPIPOM-TC ocean domain (in the 2014 operational HWRF and GFDL), which has  $\sim 1/12^\circ$  horizontal grid spacing (right panel).

## Global HWRF Ocean Coupling with MPIPOM-TC

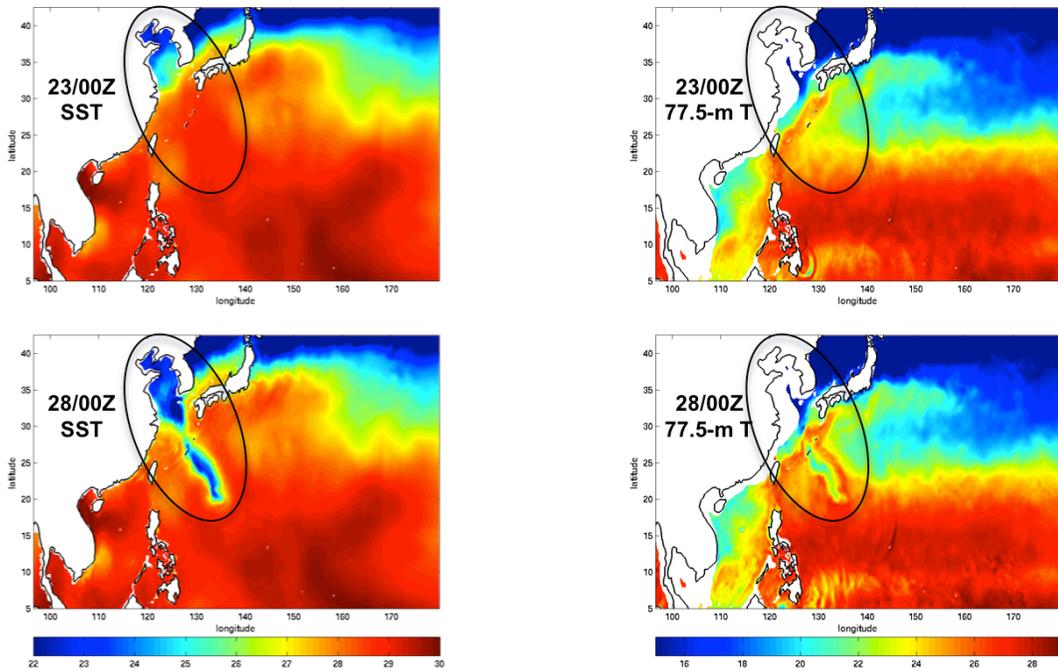
Under support from the DTC Visitor Program, HWRF ocean coupling with MPIPOM-TC has now been drastically expanded. Instead of coupling only being available in the Transatlantic and East Pacific region, as in the 2014 operational HWRF system, it is now available worldwide (with  $\sim 1/12^\circ$  grid spacing), including eight ocean regions: Transatlantic, East Pacific, West Pacific, North Indian, South Indian, Southwest Pacific, Southeast Pacific, and South Atlantic (Fig. 3). All worldwide ocean coupling development has taken place within the MPI\_POMTC\_WP and MPI\_POMTC\_20140930 branches of the HWRF repository, and as of the writing of this report, those developments were in the process of being transferred to the trunk of the HWRF repository (pending a consistency check by the DTC).

One key advantage of MPIPOM-TC system (compared to the old POM-TC system) is that the diagnostic portion of the ocean initialization procedure, including (but not limited to) the model grid specification, is separate from the prognostic MPIPOM-TC code. This architecture streamlines the process of expanding MPIPOM-TC ocean coupling globally. Originally, the proposed plan was to make the grid specification module a plug-and-play feature, with the same core prognostic ocean model code used in all ocean basins but with different grid specification modules for each region. Ultimately, this process was simplified even further by using a *single* grid specification module for *all* ocean regions. Region choice is selected simply by passing the basin identifier information from the ocean initialization script to the grid specification module, and an “if” statement within the grid specification module then selects the appropriate ocean region based on the basin identifier.

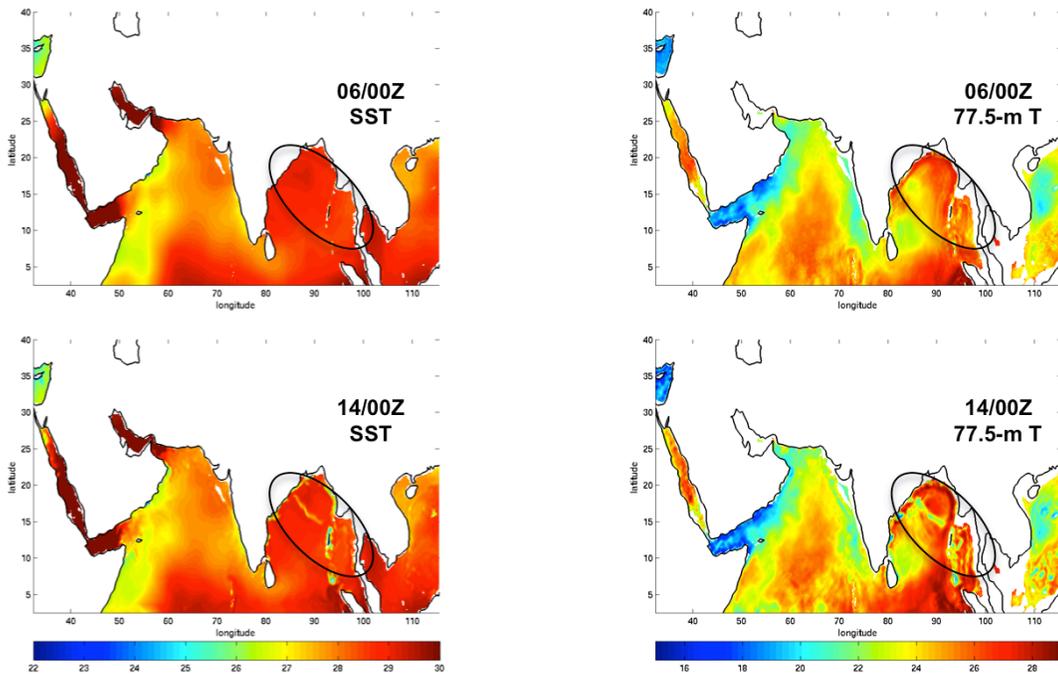
Like the grid specification, the choice of MPIPOM-TC ocean initialization product is separate from the core prognostic MPIPOM-TC code. By default, a module containing the feature-based ocean initialization (blended with the unmodified GDEM climatology east of  $50^\circ\text{W}$  longitude) is used in the Transatlantic domain, with the daily GFS SST assimilated into the upper ocean mixed layer (Yablonsky and Ginis 2008; Teague et al. 1990; Reynolds and Smith 1994), as in the 2014 operational HWRF system. Also by default, an initialization module containing the GDEMv3 climatology is used in all seven of the other ocean domains, with the daily GFS SST assimilated into the upper ocean mixed layer (Carnes 2009; Reynolds and Smith 1994). Figures 4-8 show the pre-storm and post-storm SST and 77.5-m ocean temperature simulated by MPIPOM-TC with observed wind forcing from Tropical Cyclones Bolaven (West Pacific), Phailin (North Indian), Bruce (South Indian), Sandra (Southwest Pacific), and Ian (Southeast Pacific), all using the default GDEMv3 + GFS SST product for ocean initialization.



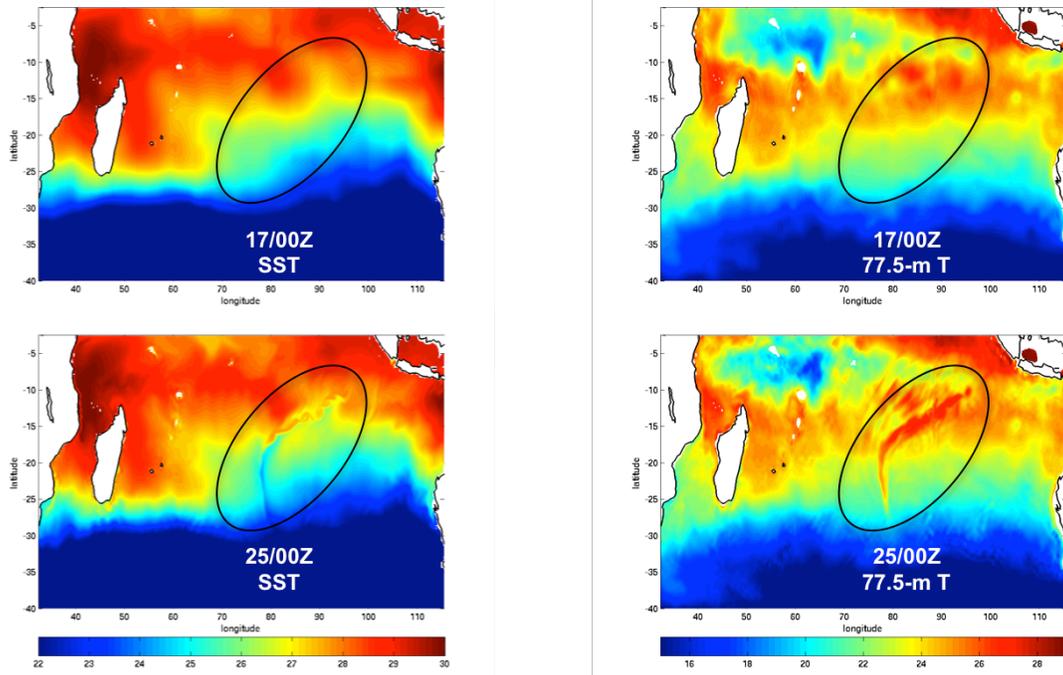
**Figure 3.** Global ocean domains for coupled HWRF/MPIPOM-TC.



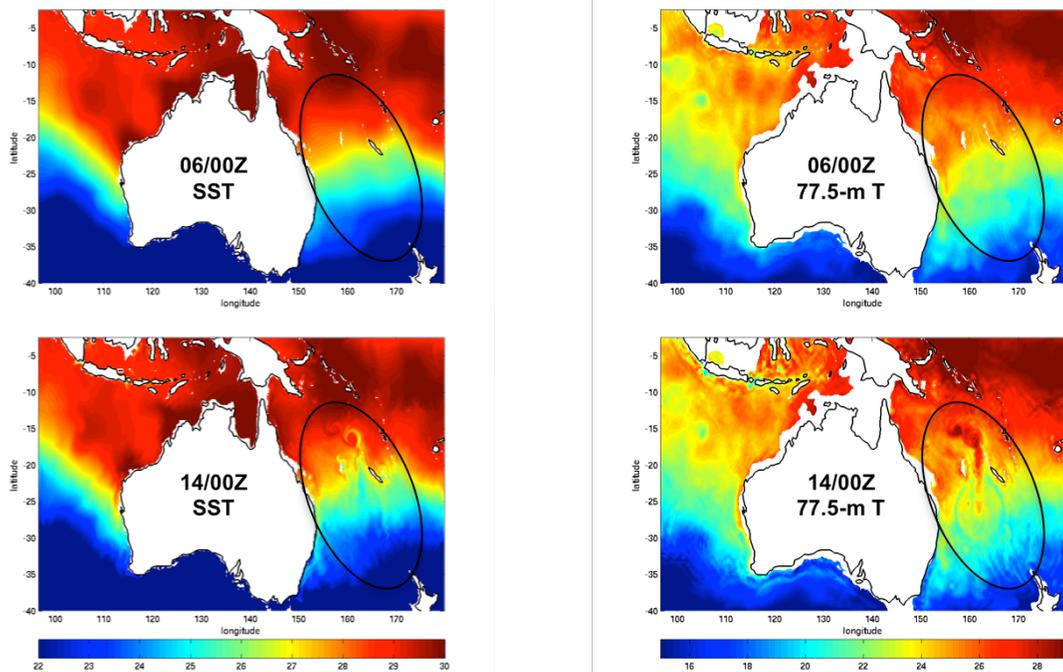
**Figure 4.** MPIPOM-TC's ocean response to West Pacific Supertyphoon Bolaven's observed wind forcing from 20120823 at 00Z to 20120828 at 00Z using the GDEMv3 + GFS SST initial condition: SST at 23/00Z (upper left); 77.5-m T at 23/00Z (upper right); SST at 28/00Z (lower left); 77.5-m T at 28/00Z (lower right).



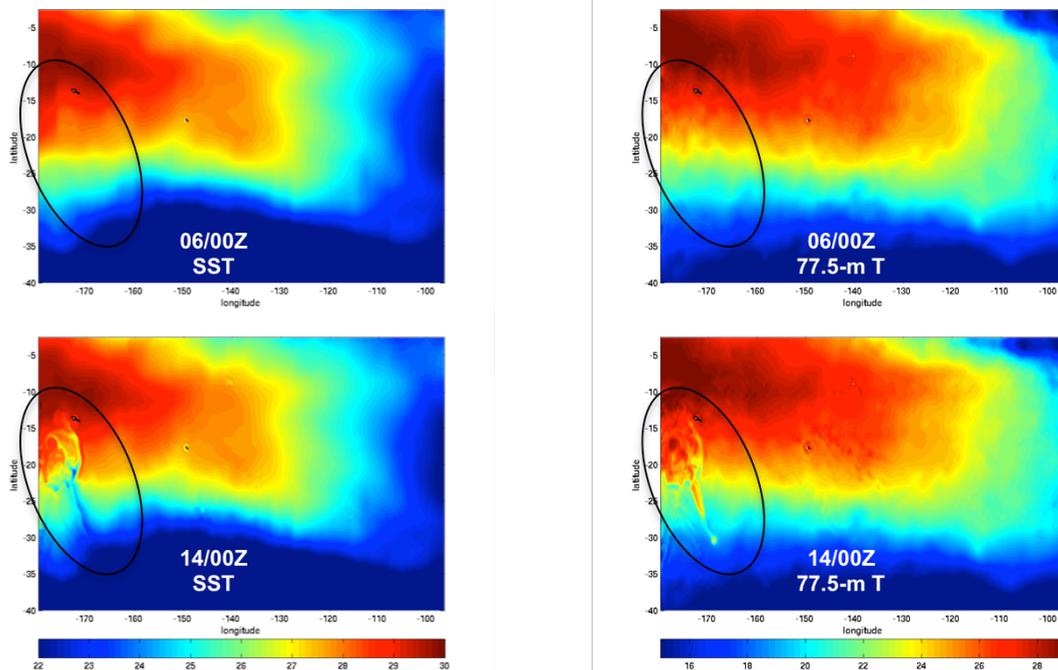
**Figure 5.** MPIPOM-TC's ocean response to North Indian Cyclone Phailin's observed wind forcing from 20131006 at 00Z to 20131014 at 00Z using the GDEMv3 + GFS SST initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).



**Figure 6.** MPIPOM-TC's ocean response to South Indian Cyclone Bruce's observed wind forcing from 20131217 at 00Z to 20131225 at 00Z using the GDEMv3 + GFS SST initial condition: SST at 17/00Z (upper left); 77.5-m T at 17/00Z (upper right); SST at 25/00Z (lower left); 77.5-m T at 25/00Z (lower right).



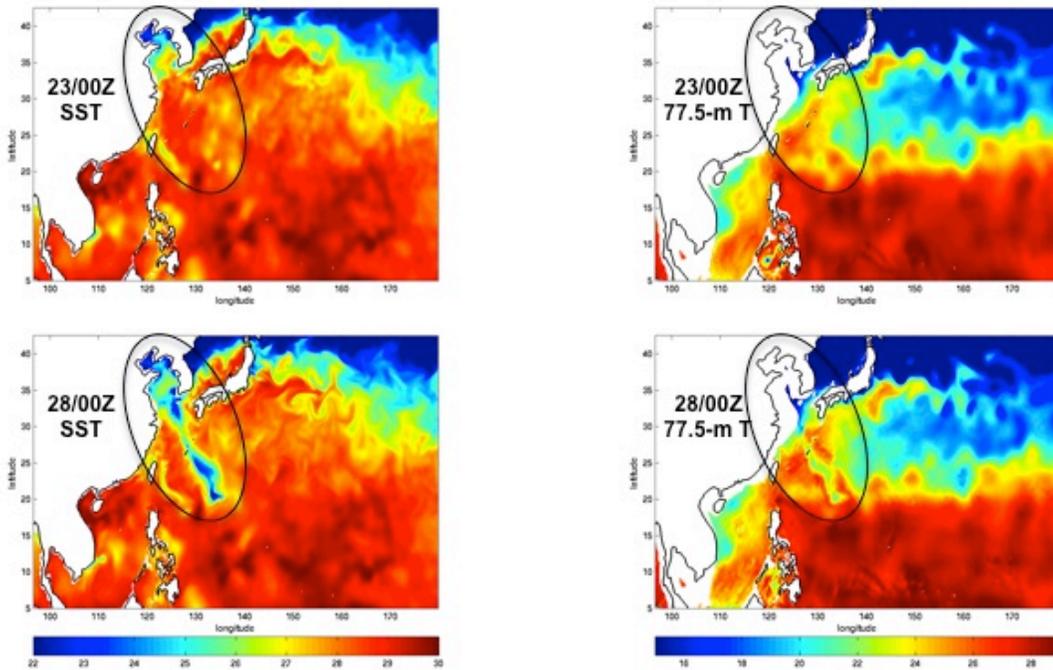
**Figure 7.** MPIPOM-TC's ocean response to Southwest Pacific Cyclone Sandra's observed wind forcing from 20130306 at 00Z to 20130314 at 00Z using the GDEMv3 + GFS SST initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).



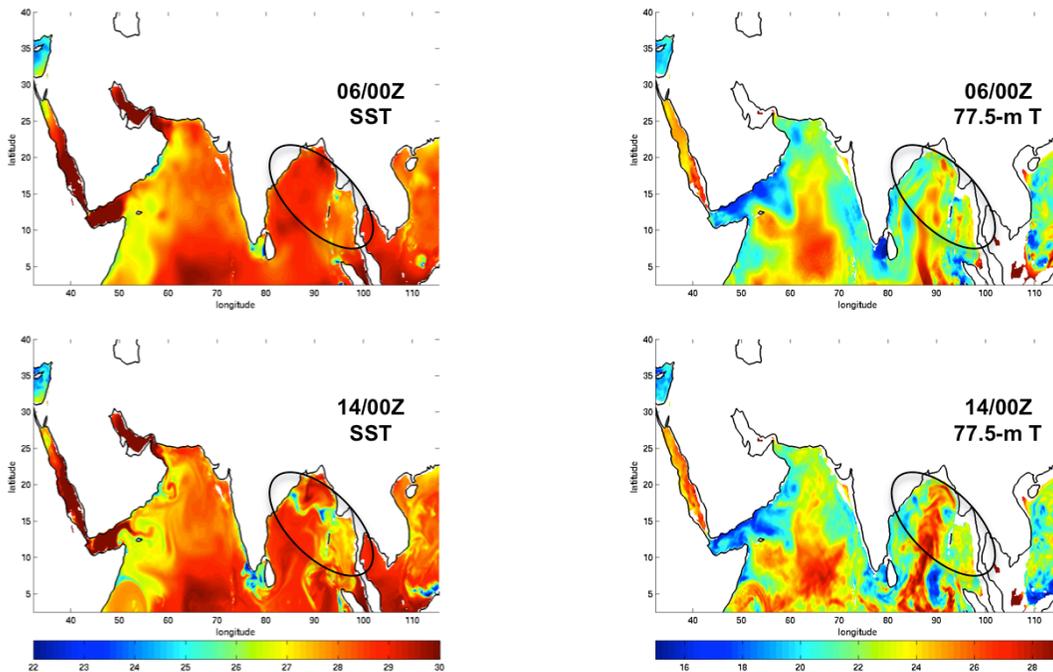
**Figure 8.** MPIPOM-TC's ocean response to Southeast Pacific Cyclone Ian's observed wind forcing from 20140106 at 00Z to 20140114 at 00Z using the GDEMv3 + GFS SST initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).

### Advanced HWRP Ocean Initialization Options

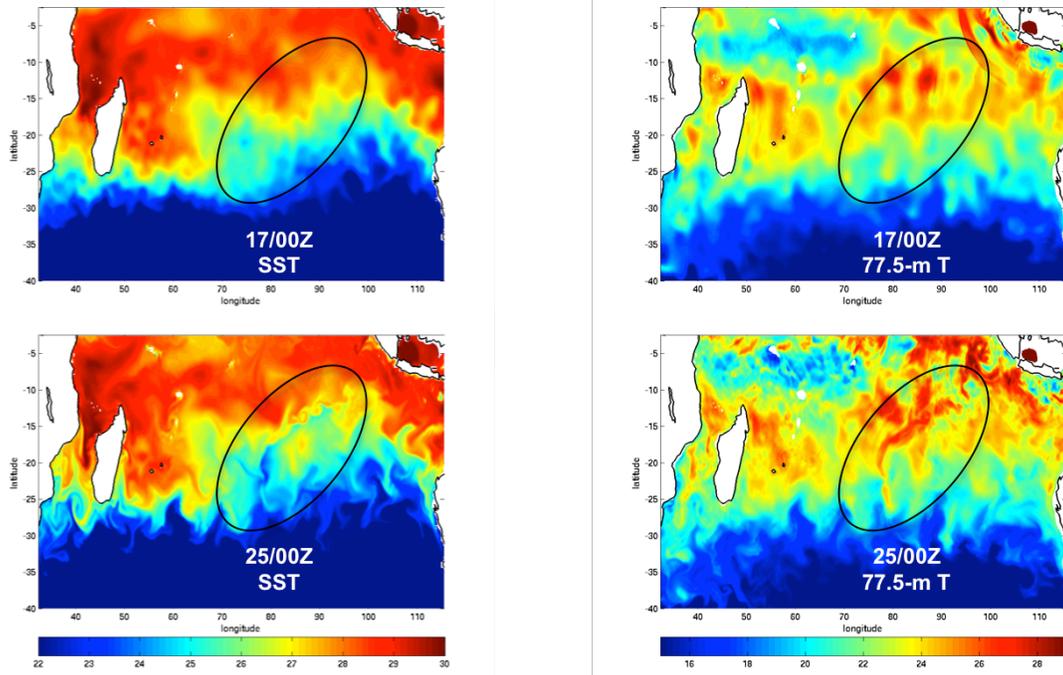
The DTC Visitor Program has helped to support ongoing development of alternative, advanced MPIPOM-TC ocean initialization options for the HWRP system. These products include the Navy Coupled Ocean Data Assimilation (NCODA; Cummings 2005; Cummings and Smedstad 2013), the Global HYCOM (Chassignet et al. 2009), and NCEP's Global HYCOM RTOFS (Mehra et al. 2011). While reading the ocean temperature, salinity, and (potentially) currents into the MPIPOM-TC initialization module is relatively straightforward, care must be taken to ensure that the bathymetry and land/sea mask used in each basin is created in such a way as to preserve the actual bathymetry as much as possible without generating instabilities during model integration. By building these initialization modules into the community HWRP repository and continuing to perform careful testing and evaluation of these ocean initialization products in all ocean basins, it will be possible to ensure that MPIPOM-TC is initialized with the best product(s) available for subsequent HWRP operational implementations and community releases. The ability to run the NCODA-based initialization module, which (like the other initialization modules) has the option to be assimilated with the GFS SST (Reynolds and Smith 1994), has now been incorporated into the MPI\_POMTC\_20140930 branch of the HWRP repository, and as of the writing of this report, this module is in the process of being transferred to the trunk of the HWRP repository (pending a consistency check by the DTC). Also, EMC has setup an archive and a real-time data stream for the NCODA files on Jet, so either historical or real-time storms can be run by any user on Jet using the NCODA-based MPIPOM-TC ocean initialization within the HWRP system. Figures 9-13 show the pre-storm and post-storm SST and 77.5-m ocean temperature simulated by MPIPOM-TC with observed wind forcing from Tropical Cyclones Bolaven (West Pacific), Phailin (North Indian), Bruce (South Indian), Sandra (Southwest Pacific), and Ian (Southeast Pacific), all using the NCODA product for ocean initialization. The Global HYCOM-based MPIPOM-TC ocean initialization module has also been incorporated into the HWRP repository, but further development is required.



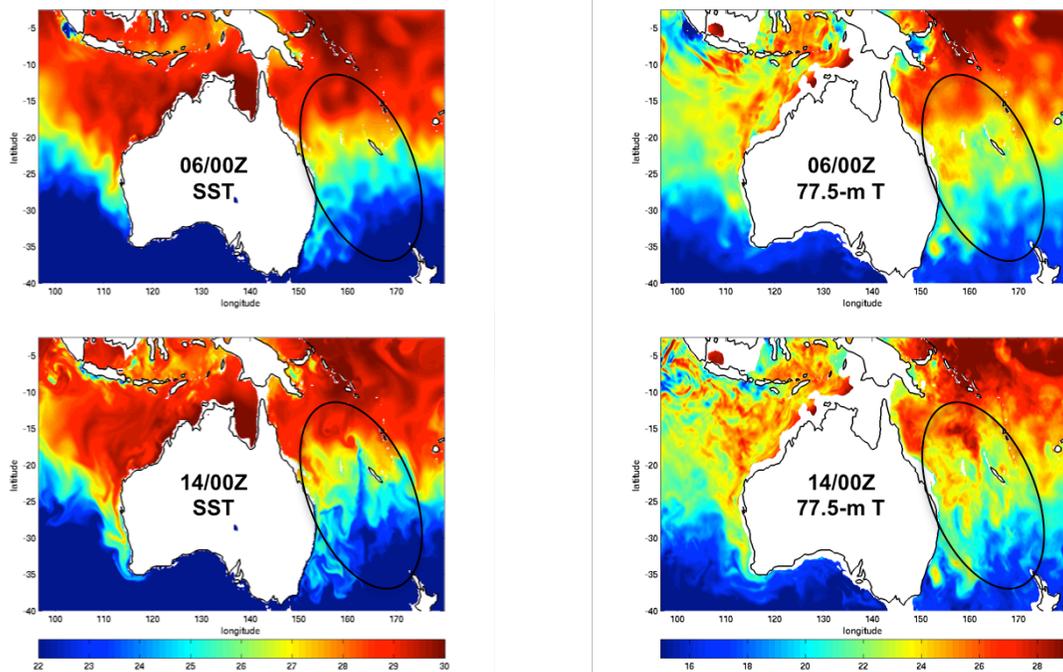
**Figure 9.** MPIPOM-TC's ocean response to West Pacific Supertyphoon Bolaven's observed wind forcing from 20120823 at 00Z to 20120828 at 00Z using the NCODA initial condition: SST at 23/00Z (upper left); 77.5-m T at 23/00Z (upper right); SST at 28/00Z (lower left); 77.5-m T at 28/00Z (lower right).



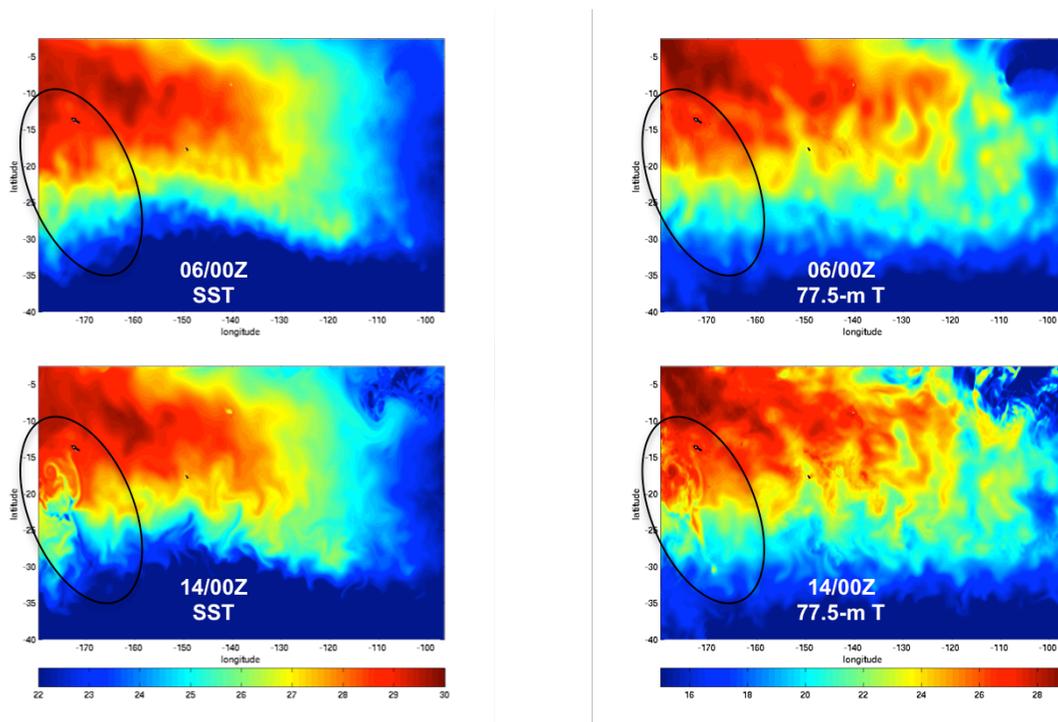
**Figure 10.** MPIPOM-TC's ocean response to North Indian Cyclone Phailin's observed wind forcing from 20131006 at 00Z to 20131014 at 00Z using the NCODA initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).



**Figure 11.** MIPOM-TC's ocean response to South Indian Cyclone Bruce's observed wind forcing from 20131217 at 00Z to 20131225 at 00Z using the NCODA initial condition: SST at 17/00Z (upper left); 77.5-m T at 17/00Z (upper right); SST at 25/00Z (lower left); 77.5-m T at 25/00Z (lower right).



**Figure 12.** MIPOM-TC's ocean response to Southwest Pacific Cyclone Sandra's observed wind forcing from 20130306 at 00Z to 20130314 at 00Z using the NCODA initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).



**Figure 13.** MIPOM-TC's ocean response to Southeast Pacific Cyclone Ian's observed wind forcing from 20140106 at 00Z to 20140114 at 00Z using the NCODA initial condition: SST at 06/00Z (upper left); 77.5-m T at 06/00Z (upper right); SST at 14/00Z (lower left); 77.5-m T at 14/00Z (lower right).

### Advanced HWRP Ocean Physics with Wave Coupling

Under HFIP support, the PI's URI team developed a three-way coupled framework to include wind-wave-current interaction (Fig. 14). The lower boundary condition of the HWRP atmosphere incorporates sea-state dependent air-sea fluxes of momentum, heat, and humidity (Reichl et al. 2013). The WAVEWATCH III model is forced by the HWRP wind stress and includes ocean current effects. The MIPOM-TC model is forced by the HWRP wind stress and includes ocean wave effects (i.e. Coriolis-Stokes effect, wave growth/decay effect, and Langmuir turbulence). Remaining travel support from the DTC Visitor Program is being transferred from the PI to professional research staff (e.g. Dr. Biju Thomas) and/or a graduate student (e.g. Brandon Reichl) at URI, under the direction of Professor Isaac Ginis, to work with EMC and/or DTC staff to finalize the implementation of the three-way coupled framework into the HWRP system.

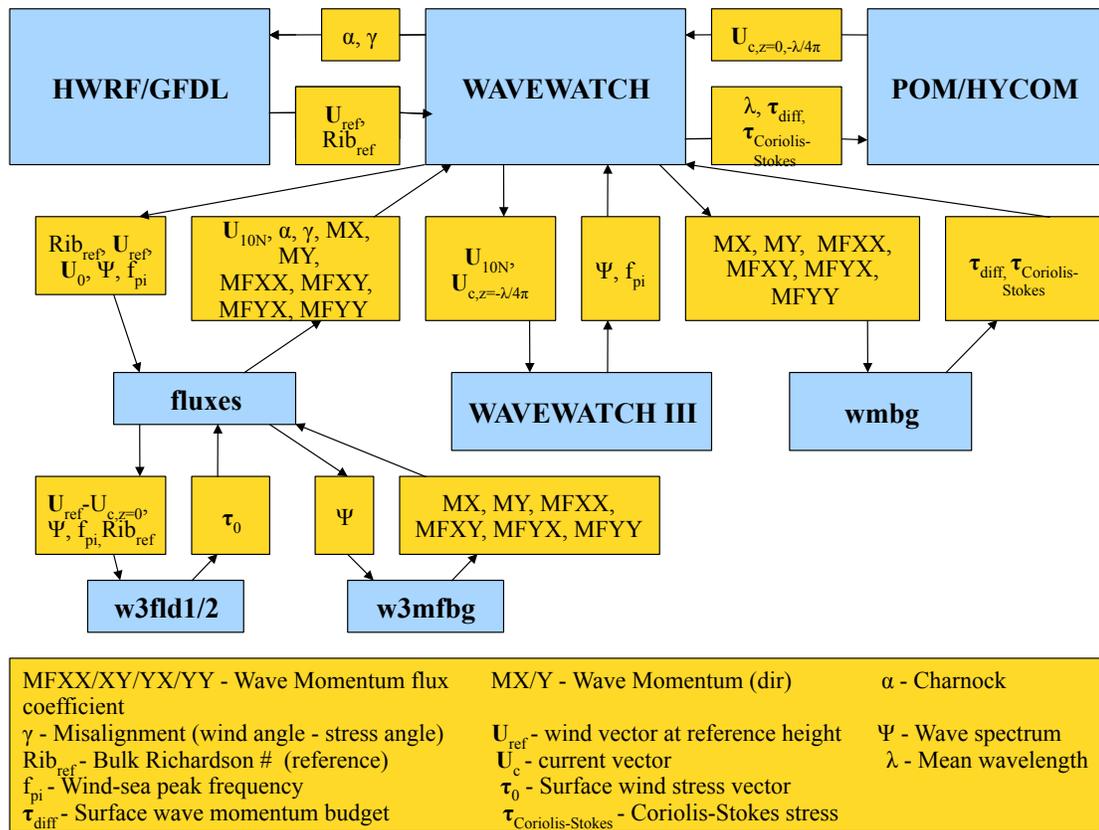


Figure 14. Three-way coupled atmosphere-wave-ocean framework for HWRG and GFDL hurricane models.

### New Diagnostic Tools for Comprehensive HWRG Ocean Evaluation

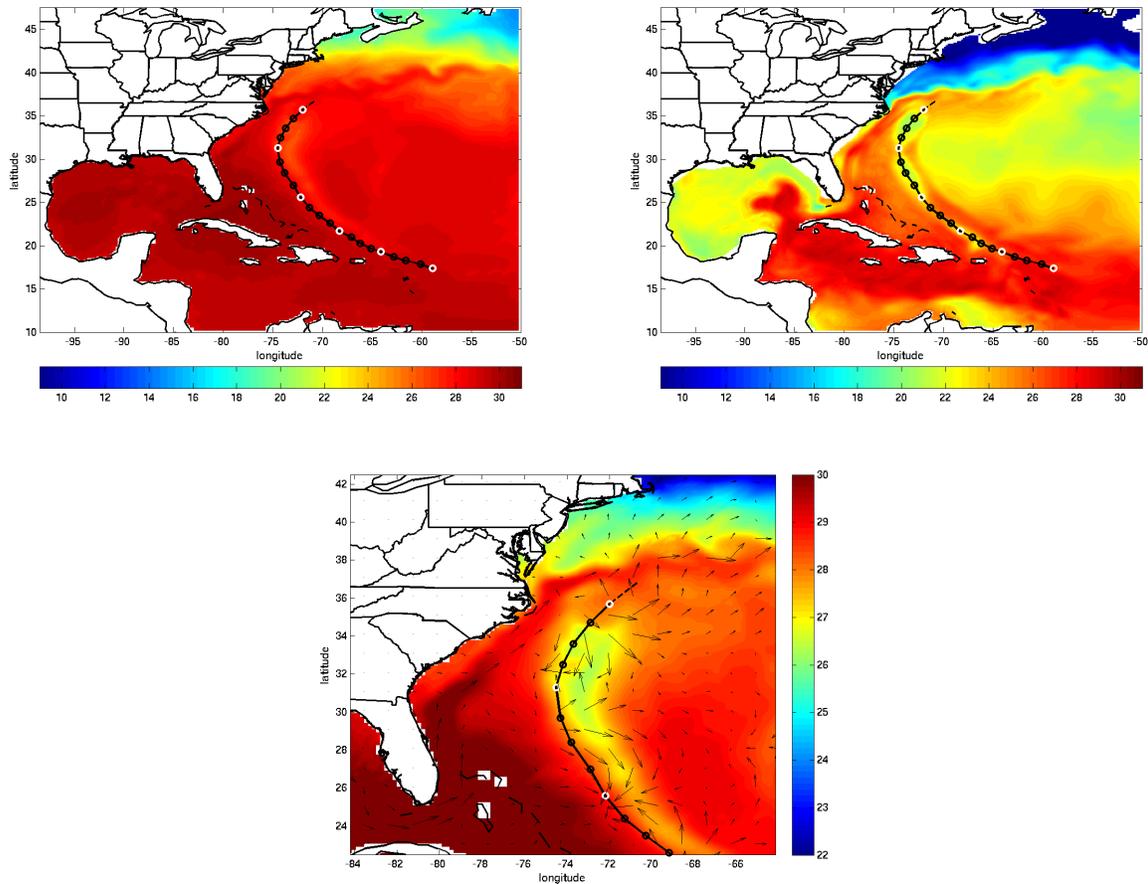
Under DTC Visiting Scientist support, a new set of diagnostic tools has now been developed for ocean evaluation of both real-time and retrospective HWRG/MPIPOM-TC simulations. To facilitate these diagnostics, a new set of NetCDF ocean output files have also been generated. These new NetCDF ocean output files are produced in 1.5-hourly increments and contain a subset of the information contained in the 24-hourly NetCDF ocean output files. Specifically, the 1.5-hourly files contain only the 2-D sea surface fields (i.e. sea surface temperature, currents, height, and air-sea fluxes), while the 24-hourly files contain the fully 3-D fields. This strategy uses minimal additional disk space while providing the most important ocean output at much higher temporal frequency.

The ocean diagnostic tools consist of FORTRAN-based diagnostic table-generating tools and MATLAB-based diagnostic plotting tools. The FORTRAN-based diagnostic table-generating tools are automatically compiled along with rest of the HWRG system, and a sample script has been provided to run the FORTRAN executable. This FORTRAN executable will then create four table files, each containing the average, minimum, and maximum SST and SST anomaly (from both ocean spinup phase 1 and ocean spinup phase 2) within a specific radius around the storm every 1.5 hours during the coupled model forecast; the four table output files correspond to four specific radii around the storm center: sst060km.dat (e.g. Table 1), sst100km.dat, sst150km.dat, and sst200km.dat.

MATLAB-based diagnostic tools are now available to plot the SST, subsurface temperature, and ocean current vectors at various times throughout the forecast and at various zoom levels (e.g. Fig. 15). Since MATLAB is available on Jet, these tools should be usable by any Jet user. A README file explains how to use the mature tools, and additional community-based plotting tools are also provided for users who wish to create my advanced plots (such as vertical cross sections).

**Table 1.** Sample FORTRAN-based diagnostic table output: sst060km.dat

FHOUR	LON	LAT	AVGSST	MINSST	MAXSST	AVGSSTD1	MINSSTD1	MAXSTD1	AVGSSTD2	MINSSTD2	MAXSTD2
0.0	-70.60	20.30	28.44	28.35	28.57	0.00	0.00	0.00	0.00	0.00	0.00
1.5	-70.85	20.30	28.49	28.35	28.64	0.00	-0.01	0.00	0.00	-0.01	0.00
3.0	-71.10	20.30	28.56	28.39	28.71	0.00	-0.01	0.00	0.00	-0.01	0.00
4.5	-71.15	20.35	28.58	28.39	28.76	-0.01	-0.01	0.00	-0.01	-0.01	0.00
6.0	-71.20	20.40	28.59	28.41	28.79	-0.01	-0.01	0.00	-0.01	-0.01	0.00
7.5	-71.35	20.55	28.66	28.47	28.94	-0.01	-0.02	0.00	-0.01	-0.02	0.00
9.0	-71.50	20.70	28.75	28.51	29.09	-0.01	-0.02	0.00	-0.01	-0.02	0.00
10.5	-71.65	20.80	28.83	28.57	29.21	-0.01	-0.03	0.00	-0.01	-0.03	0.00
12.0	-71.80	20.90	28.92	28.62	29.31	-0.02	-0.04	0.00	-0.02	-0.04	0.00
13.5	-72.00	21.00	29.03	28.71	29.38	-0.02	-0.04	0.00	-0.02	-0.04	0.00
15.0	-72.20	21.10	29.14	28.79	29.41	-0.01	-0.05	0.00	-0.01	-0.05	0.00
16.5	-72.35	21.20	29.23	28.87	29.42	-0.02	-0.05	0.00	-0.02	-0.05	0.00
18.0	-72.50	21.30	29.29	28.98	29.42	-0.02	-0.05	0.00	-0.02	-0.05	0.00
19.5	-72.65	21.40	29.34	29.08	29.42	-0.02	-0.04	0.00	-0.02	-0.04	0.00
21.0	-72.80	21.50	29.36	29.19	29.42	-0.02	-0.04	0.00	-0.02	-0.04	0.00
22.5	-72.95	21.60	29.37	29.26	29.42	-0.02	-0.03	0.00	-0.02	-0.03	0.00
24.0	-73.10	21.70	29.37	29.24	29.42	-0.02	-0.03	0.00	-0.02	-0.03	0.00
25.5	-73.30	21.85	29.37	29.22	29.46	-0.02	-0.04	0.00	-0.02	-0.04	0.00
27.0	-73.50	22.00	29.39	29.22	29.50	-0.02	-0.04	0.00	-0.02	-0.04	0.00
28.5	-73.70	22.15	29.42	29.25	29.51	-0.02	-0.04	0.00	-0.02	-0.04	0.00
30.0	-73.90	22.30	29.45	29.30	29.51	-0.02	-0.05	0.01	-0.02	-0.05	0.01
31.5	-74.10	22.50	29.46	29.36	29.51	-0.03	-0.05	0.01	-0.03	-0.05	0.01
33.0	-74.30	22.70	29.43	29.33	29.51	-0.03	-0.05	0.00	-0.03	-0.05	0.00
34.5	-74.50	22.85	29.40	29.32	29.49	-0.04	-0.05	0.00	-0.04	-0.05	0.00
36.0	-74.70	23.00	29.38	29.31	29.49	-0.04	-0.06	0.00	-0.04	-0.06	0.00
37.5	-74.90	23.15	29.35	29.24	29.47	-0.04	-0.10	0.00	-0.04	-0.10	0.00
39.0	-75.10	23.30	29.32	29.16	29.45	-0.05	-0.13	0.00	-0.05	-0.13	0.00
40.5	-75.25	23.50	29.27	29.13	29.40	-0.06	-0.14	0.00	-0.06	-0.14	0.00
42.0	-75.40	23.70	29.23	29.13	29.36	-0.07	-0.13	0.03	-0.07	-0.13	0.03
43.5	-75.55	23.95	29.24	29.13	29.39	-0.04	-0.13	0.11	-0.04	-0.13	0.11
45.0	-75.70	24.20	29.31	29.13	29.50	0.00	-0.13	0.13	0.00	-0.13	0.13
46.5	-75.95	24.35	29.39	29.15	29.60	0.05	-0.07	0.13	0.05	-0.07	0.13
48.0	-76.20	24.50	29.49	29.24	29.68	0.06	-0.03	0.13	0.06	-0.03	0.13
49.5	-76.30	24.70	29.53	29.32	29.71	0.05	-0.06	0.14	0.05	-0.06	0.14
51.0	-76.40	24.90	29.54	29.26	29.72	0.03	-0.08	0.14	0.03	-0.08	0.14
52.5	-76.50	25.15	29.51	29.09	29.71	-0.01	-0.14	0.10	-0.01	-0.14	0.10
54.0	-76.60	25.40	29.45	28.95	29.68	-0.04	-0.18	0.06	-0.04	-0.18	0.06
55.5	-76.65	25.65	29.38	28.88	29.62	-0.05	-0.21	0.07	-0.05	-0.21	0.07
57.0	-76.70	25.90	29.33	28.87	29.56	-0.03	-0.18	0.15	-0.03	-0.18	0.15
58.5	-76.75	26.15	29.32	28.86	29.51	0.00	-0.12	0.15	0.00	-0.12	0.15
60.0	-76.80	26.40	29.33	28.95	29.50	0.03	-0.11	0.16	0.03	-0.11	0.16
61.5	-76.90	26.65	29.37	29.06	29.50	0.03	-0.12	0.17	0.03	-0.12	0.17
63.0	-77.00	26.90	29.39	29.14	29.50	0.00	-0.12	0.19	0.00	-0.12	0.19
64.5	-77.10	27.15	29.40	29.18	29.50	-0.03	-0.14	0.14	-0.03	-0.14	0.14
66.0	-77.20	27.40	29.40	29.21	29.50	-0.06	-0.15	0.05	-0.06	-0.15	0.05
67.5	-77.20	27.55	29.40	29.21	29.50	-0.07	-0.16	0.03	-0.07	-0.16	0.03
69.0	-77.20	27.70	29.40	29.22	29.51	-0.08	-0.18	0.04	-0.08	-0.18	0.04
70.5	-77.15	27.90	29.39	29.23	29.51	-0.10	-0.21	0.04	-0.10	-0.21	0.04
72.0	-77.10	28.10	29.39	29.24	29.52	-0.12	-0.25	0.04	-0.12	-0.25	0.04
73.5	-77.05	28.30	29.39	29.24	29.52	-0.13	-0.27	0.02	-0.13	-0.27	0.02
75.0	-77.00	28.50	29.41	29.24	29.52	-0.14	-0.29	0.00	-0.14	-0.29	0.00
76.5	-76.95	28.70	29.42	29.22	29.52	-0.13	-0.31	0.02	-0.13	-0.31	0.02
78.0	-76.90	28.90	29.43	29.22	29.52	-0.11	-0.31	0.02	-0.11	-0.31	0.02
79.5	-76.80	29.10	29.41	29.20	29.51	-0.09	-0.32	0.02	-0.09	-0.32	0.02
81.0	-76.70	29.30	29.37	29.17	29.51	-0.07	-0.30	0.14	-0.07	-0.30	0.14
82.5	-76.60	29.50	29.37	29.15	29.69	-0.01	-0.24	0.51	-0.01	-0.24	0.51
84.0	-76.50	29.70	29.39	29.13	29.82	0.11	-0.13	0.67	0.11	-0.13	0.67
85.5	-76.45	29.95	29.40	28.87	29.83	0.25	-0.11	0.67	0.25	-0.11	0.67
87.0	-76.40	30.20	29.37	28.51	29.83	0.35	-0.19	0.67	0.35	-0.19	0.67
88.5	-76.35	30.35	29.32	28.34	29.83	0.34	-0.32	0.67	0.34	-0.32	0.67
90.0	-76.30	30.50	29.20	28.28	29.83	0.29	-0.41	0.67	0.29	-0.41	0.67
91.5	-76.20	30.70	28.99	28.26	29.80	0.15	-0.45	0.62	0.15	-0.45	0.62
93.0	-76.10	30.90	28.82	28.26	29.72	0.02	-0.45	0.47	0.02	-0.45	0.47
94.5	-76.00	31.05	28.71	28.25	29.68	-0.03	-0.45	0.42	-0.03	-0.45	0.42
96.0	-75.90	31.20	28.68	28.25	29.69	-0.03	-0.45	0.36	-0.03	-0.45	0.36
97.5	-75.85	31.45	28.75	28.25	29.70	0.02	-0.44	0.47	0.02	-0.44	0.47
99.0	-75.80	31.70	28.82	28.27	29.74	0.08	-0.40	0.50	0.08	-0.40	0.50
100.5	-75.75	31.90	28.86	28.22	29.74	0.09	-0.33	0.53	0.09	-0.33	0.53
102.0	-75.70	32.10	28.82	28.21	29.74	0.06	-0.50	0.55	0.06	-0.50	0.55
103.5	-75.55	32.30	28.66	28.18	29.74	0.01	-0.88	0.56	0.01	-0.88	0.56
105.0	-75.40	32.50	28.43	28.02	29.65	-0.10	-1.08	0.55	-0.10	-1.08	0.55
106.5	-75.30	32.80	28.20	27.84	28.76	-0.39	-1.25	0.53	-0.39	-1.25	0.53
108.0	-75.20	33.10	28.19	27.81	29.01	-0.54	-1.26	0.43	-0.54	-1.26	0.43
109.5	-75.15	33.35	28.38	27.86	29.56	-0.55	-1.26	0.12	-0.55	-1.26	0.12
111.0	-75.10	33.60	28.64	27.90	29.75	-0.50	-1.20	0.00	-0.50	-1.20	0.00
112.5	-75.05	33.95	28.90	27.71	29.76	-0.43	-1.24	0.10	-0.43	-1.24	0.10
114.0	-75.00	34.30	28.96	27.58	29.75	-0.42	-1.32	0.13	-0.42	-1.32	0.13
115.5	-74.90	34.60	28.87	27.53	29.73	-0.39	-1.32	0.32	-0.39	-1.32	0.32
117.0	-74.80	34.90	28.76	26.88	29.70	-0.24	-1.33	0.48	-0.24	-1.33	0.48
118.5	-74.70	35.25	28.08	24.23	29.59	-0.45	-3.10	0.69	-0.45	-3.10	0.69
120.0	-74.60	35.60	27.03	24.09	29.50	-0.97	-3.27	0.87	-0.97	-3.27	0.87
121.5	-74.45	35.95	26.51	24.07	29.49	-1.11	-3.31	1.03	-1.11	-3.31	1.03
123.0	-74.30	36.30	26.20	24.14	29.33	-1.19	-3.34	1.02	-1.19	-3.34	1.02
124.5	-74.20	36.70	25.35	23.35	27.33	-1.80	-3.46	0.64	-1.80	-3.46	0.64
126.0	-74.10	37.10	24.73	23.33	26.76	-2.15	-3.49	0.00	-2.15	-3.49	0.00



**Figure 15.** Sampling of MATLAB-based MPIPOM-TC ocean diagnostic plots generated by the plotting tools: SST over the entire ocean domain at a specified time (upper left), 77.5-m ocean temperature over the entire domain at a specified time (upper right), and SST and surface current vectors zoomed in on a 20-degree by 20-degree box around the storm center at specified time (lower).

## References

- Bernardet, L., S. Bao, R. Yablonsky, D. Stark, and T. Brown, 2013: Community HWRP Users' Guide V3.5a, August 2013. Developmental Testbed Center, 139 pp. NOAA Technical Memorandum OAR GSD-43. Available from [http://docs.lib.noaa.gov/noaa\\_documents/OAR/GSD/NOAA\\_TM\\_GSD-43.pdf](http://docs.lib.noaa.gov/noaa_documents/OAR/GSD/NOAA_TM_GSD-43.pdf).
- Bernardet, L., V. Tallapragada, S. Bao, S. Trahan, Y. Kwon, Q. Liu, M. Tong, M. Biswas, T. Brown, D. Stark, L. Carson, R. Yablonsky, E. Uhlhorn, S. Gopalakrishnan, X. Zhang, T. Marchok, B. Kuo, and R. Gall, 2014: Community support and transition of research to operations for the Hurricane Weather Research and Forecasting (HWRP) Model. *Bull. Amer. Meteor. Soc.*, in press.
- Carnes, M. R., 2009: Description and evaluation of GDEM-V 3.0. Naval Research Laboratory, Stennis Space Center, MS 39529, 21 pp. [NRL/MR/7330--09-9165].
- Chassignet, E. P., H. E. Hurlburt, E. J. Metzger, O. M. Smedstad, J. A. Cummings, G. R. Halliwell, R. Bleck, R. Baraille, A. J. Wallcraft, C. Lozano, H. L. Tolman, A. Srinivasan, S. Hankin, P. Cornillon, R. Weisberg, A. Barth, R. He, F. Werner, and J. Wilkin, 2009: US GODAE: Global ocean prediction with the HYbrid Coordinate Ocean Model (HYCOM). *Oceanogr.*, **22**, 64-75.

- Cummings, J. A., 2005: Operational multivariate ocean data assimilation. *Q. J. R. Meteor. Soc.*, **131**, 3583-3604.
- Cummings, J. A., and O. M. Smedstad, 2013: Variational data assimilation for the global ocean. *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, Vol. II, S. Park and L. Xu, Eds., Springer, 303–343.
- Holt, C., L. Bernardet, T. Brown, and R. Yablonsky, 2014: Community HWRF Users' Guide V3.6a, September 2014. Developmental Testbed Center, 161 pp.
- Jordi, A., and D.-P. Wang, 2012: sbPOM: A parallel implementation of Princeton Ocean Model. *Environ. Modelling & Software*, **38**, 59-61.
- Mehra, A., I. Rivin, H. Tolman, T. Spindler, and B. Balasubramanyian, 2011: A real-time operational global ocean forecast system. Poster, *GODAE OceanView – GSOP – CLIVAR Workshop on Observing System Evaluation and Intercomparisons*, Univ. of California, Santa Cruz, CA, OS21B-1502.
- Reichl, B. G., T. Hara, and I. Ginis, 2013: Sea state dependence of the wind stress over the ocean under hurricane winds. *J. Geophys. Res.*, **118**, DOI: 101002/2013JC009289.
- Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J. Climate*, **7**, 929-948.
- Tallapragada, V., L. Bernardet, S. Gopalakrishnan, Y. Kwon, Q. Liu, T. Marchok, D. Sheinin, M. Tong, S. Trahan, R. Tuleya, R. Yablonsky, and X. Zhang, 2013: Hurricane Weather Research and Forecasting (HWRF) Model: 2013 scientific documentation. Developmental Testbed Center, 99 pp. Available from <http://www.dtcenter.org/HurrWRF/users/docs/>.
- Tallapragada, V., L. Bernardet, M. K. Biswas, S. Gopalakrishnan, Y. Kwon, Q. Liu, T. Marchok, D. Sheinin, M. Tong, S. Trahan, R. Tuleya, R. Yablonsky, and X. Zhang, 2014: Hurricane Weather Research and Forecasting (HWRF) Model: 2014 scientific documentation. Developmental Testbed Center, 105 pp.
- Teague, W. J, M. J. Carron, and P. J. Hogan, 1990: A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *J. Geophys. Res.*, **95**, 7167-7183.
- Yablonsky, R. M., and I. Ginis, 2008: Improving the ocean initialization of coupled hurricane-ocean models using feature-based data assimilation. *Mon. Wea. Rev.*, **136**, 2592-2607.
- Yablonsky, R. M., I. Ginis, B. Thomas, V. Tallapragada, D. Sheinin, and L. Bernardet, 2014a: Description and analysis of the ocean component of NOAA's operational Hurricane Weather Research and Forecasting Model (HWRF). *J. Atmos. Oceanic Technol.*, in press.
- Yablonsky, R. M., I. Ginis, and B. Thomas, 2014b: MPIPOM-TC: A new ocean modeling system with flexible initialization for improved coupled tropical cyclone-ocean model forecasts. *J. Atmos. Oceanic Technol.*, in review.

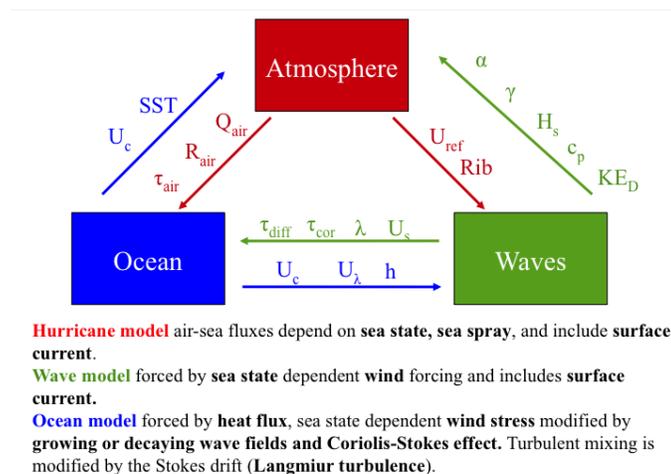
# Advancing Air-Sea-Wave Coupling in HWRF

PI: Isaac Ginis and Biju Thomas  
March 18, 2016

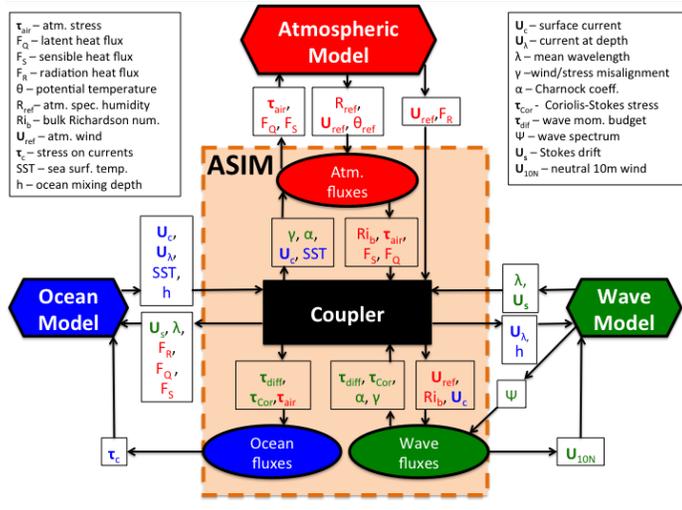
A report submitted to the Developmental Testbed Center (DTC) Visitor Program

This report describes the work accomplished by URI under the DTC Visitor Program focusing on improving the operational HWRF prediction system through new advancements in the air-sea coupling. The DTC Visitor Program provided travel support for Dr. Biju Thomas to visit NCEP/EMC in December 2015 to finalize the new three-way coupled system implemented into the operational HWRF forecast system. Below we briefly describe the key elements of the new HWRF coupled framework and the Fortran modules implemented into HWRF.

The HWRF three-way air-sea-wave coupled framework is based on a comprehensive, physics-based treatment of the wind-wave-current interaction. The basic structure of the coupled system and the parameters passed between the atmospheric, wave and ocean model components are shown in Fig 1. At the heart of the new HWRF coupled framework is a computationally efficient, unified Air-Sea Interface Module (ASIM) that establishes a physically based representation of the air-sea interface (Fig. 2). A key requirement for the ASIM is that it supports both technical and scientific interoperability over a range of parameterizations and data resources. In the coupled framework, the bottom boundary condition of the atmospheric model incorporates sea-state dependent air-sea fluxes of momentum, heat, and humidity, and it includes the effect of sea-spray. The wave model is forced by the sea-state dependent wind stress and includes the ocean surface current effect. The ocean model is forced by the sea-state dependent wind stress and includes the ocean surface wave effects (i.e. Coriolis-Stokes effect, wave growth/decay effect, and Langmuir turbulence effect).

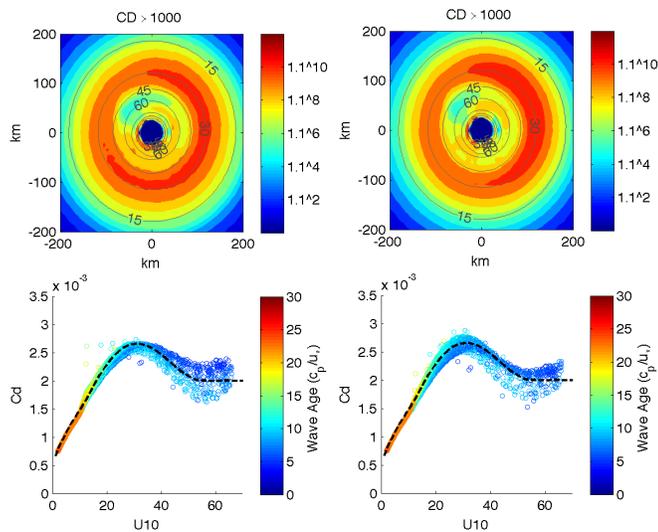


**Figure 1.** The basic structure of the coupled system and the parameters passed between the atmospheric, wave and ocean model components.



**Figure 2.** The Air Sea Interface Module (ASIM) implemented into the HWRF- WW3-MPIPOM coupled hurricane model.

In the HWRF wave coupled system two different wind stress parameterization schemes are implemented, one based on Donelan et al. (2012) and the other based on Reichl et al. (2014). In addition, the behavior of the drag as a function of wind speed is made to be consistent, on average, with the  $C_d$  formulation implemented in the 2015 operational HWRF model. Examples of the spatial distribution of the drag coefficient under a typical (idealized) TC are shown in Fig. 3 (top panels). Although the wind speed is nearly axisymmetric, the drag coefficient significantly varies depending on the location relative to the hurricane center. In particular, the drag coefficient is significantly reduced in the front right quadrant in both parameterizations. The sea state dependence of the drag coefficient at different wind speeds is shown in Fig. 3 (bottom panels). The sea state dependence is enhanced most significantly at higher wind speeds.



**Figure 3.** 10-meter neutral drag coefficient for an idealized tropical cyclone with a radius of maximum wind of 50 km and a maximum wind speed of 65 m/s. The top panel shows spatial distributions. The tropical cyclone is moving from right to left at 5 m/s. The bottom panels show sea

*state dependence of the drag coefficient at different wind speeds. Left panels: Donelan et al. (2012) drag coefficient; Right panels: Reichl et al. (2014) drag coefficient.*

The following new Fortran modules are implemented into the HWRF prediction system:

**w3asim**

Purpose: Called at beginning of WAVEWATCH-III routine. Calculates wind stress according to selected wind stress method based on wind speed and stability passed from atmosphere at reference height. Calculates 10 meter neutral wind speed for driving wave model. Calculates Coriolis-Stokes stress, wave momentum flux budget, and mean wave length for passing to ocean model. Calculates  $\alpha^*$  and  $\gamma$  for passing to atmospheric model.

**w3fld1**

Purpose: Calculates wind stress ( $u^*$ ) and surface roughness ( $z_0$ ) from wave spectrum ( $\Psi$ ), reference relative wind ( $U_{ref}$ ), and atmospheric bulk Richardson number ( $Rib$ ) based on methods of Reichl et al. (2014.)

**appendtail**

Purpose: Adjusts high frequency wave spectrum based on desired saturation level.

**w3fld2**

Purpose: Calculates wind stress ( $u^*$ ) and surface roughness ( $z_0$ ) from wave spectrum ( $\Psi$ ), reference relative wind ( $U_{ref}$ ), and atmospheric bulk Richardson number ( $Rib$ ) based on methods of Donelan et al. (2012).

**w3mfbg**

Purpose: Computes wave momentum and momentum flux components. Calculates significant wave height at each time step for filtering sea-state dependent stress call. Calculates mean wavelength at each time step.

**wmbg**

Purpose: Computes wave momentum flux budget. Computes Coriolis-Stokes stress. Computes surface volume flux boundary condition.

**ASIM.inp**

Purpose: Contains switches for various ASIM components of the new HWRF system.

All these sea-state dependent modules will be tested and the impacts on the HWRF hurricane predictions will be evaluated during the 2016 hurricane season.

References

- Donelan, M. A., M. Curcic, S. S. Chen, and A. K. Magnusson, 2012: Modeling waves and wind stress. *J. Geophys. Res.*, **117**, C00J23.
- Reichl, B. G., T. Hara, and I. Ginis, 2014: Sea state dependence of the wind stress over the ocean under hurricane winds. *J. Geophys. Res.*, **119**, 30-51.