An integrated hydrological modeling system for high-resolution coastal applications

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LONG-TERM GOALS

The long-term goal of this project is to develop, test, and transition a new prototype high-resolution coupled hydrological modeling capability within the Coupled Ocean/Atmosphere Mesoscale Prediction System®[1] (COAMPS). The proposed Navy capability will leverage ongoing and new hydrological community efforts to create an integrated, generalized Earth System Modeling Framework (ESMF)-based system compatible with current state-of-the-art land surface (LS) and hydrological systems, such as the NASA Land Information System (LIS) / Weather Research and Forecasting (WRF) Hydrological model (WRF-Hydro) and NASA LIS / North American Land Data Assimilation System (NLDAS). This initial capability will be obtained through the integration/development and testing at high-resolution of the linked LS hydrological system and the atmospheric moist physics scheme within the coupled air-land-ocean COAMPS framework. This linkage will provide a new capability for accurately quantifying the impact of coastal terrestrial hydrological events on the LS at high-resolution, such as flash flooding, beach erosion, and LS traffic-ability. The modular ESMF-based structure will facilitate inter-comparison with other LS, hydrological modules and moist physics/cloud schemes within LIS and WRF-Hydro. This new coupled system will serve as the baseline development and validation of important coupled atmospheric-LS hydrological processes and will establish the foundation necessary for a fully coupled land-ocean system that would include interactions with marine processes, such as fresh-water stream inflow affecting near-coast water density vertical structure and transport of riverine sediment impacting local bathymetry and water clarity.

OBJECTIVES

The objective of this project is to provide a new baseline capability for Naval LS-hydrological modeling by: i) quantifying the impact of the water cycle budget on LS dynamics, via the interactive feedback of LS hydrology within the COAMPS land-surface model (LSM) framework; ii) quantifying the impact of enhanced cloud-microphysical processes via linkage with COAMPS moist physics parameterizations; and iii) quantifying the feasibility of a "generalized" hydrological component within the COAMPS framework.

[1] COAMPS is a registered trademark of the Naval Research Laboratory.

APPROACH

The technical approach is to a) develop a generalized coupled hydrology and land surface analysis and forecast software infrastructure within COAMPS by leveraging the existing COAMPS ESMF coupling framework with the NUOPC implementation to couple LIS (at NASA-GSFC and NCEP EMC), WRF-Hydro (at NCAR), and NOAH (at NCEP EMC) into COAMPS. LIS would provide integrated and consistent land/atmosphere/hydrology initial conditions. For the forecast system, we will leverage existing infrastructure from WRF-Hydro to develop a similar "multi-grid" routing architecture in which the system runs on two grids. The routing runs on a "fine" grid (e.g., 500m-100m), with a "coarse" grid (4km-1km) used to update soil moisture states which are then used to initialize the NOAH LSM; and b) conduct extensive high-resolution (~1-3 km) validation of COAMPS precipitation forecast skill for one to two catchments of interest, focusing on validation of observations (precipitation; soil moisture) using WRF-Hydro. The specific catchments for validation will be case studies over the US (CONUS) and outside the US (OCONUS) near coastal areas. For the OCONUS test case, we will focus on the Luzon, Philippine area.

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WORK COMPLETED

To organize interdisciplinary parallel developments at various organizations, our group holds a monthly telecon meeting on the first Thursday of the month. Progress update and to-do lists are compiled and published in the meeting minutes at the HyCCAP wiki:
https://www.earthsystemcog.org/projects/hyccap/ .
Work completed on the technical tasks include:

a) NRL
  - Conducted monthly HyCCAP meeting to track team progress
  - Completed the COAMPS hourly forcing for the OCONUS Luzon case
  - Included the implementation and tests of the new generalized COAMPS cloud microphysics scheme into COAMPS-Hydro version 0.0 and the inclusion of a two-moment cloud aerosol scheme.

b) CIRES/UC
  - Developed NUOPC CAP and connector for WRF-Hydro
  - Completed the two-way COAMPS-LIS coupling
  - Developed and tested the two-way LIS-Hydro coupling
  - Modified the COAMPS time step interation driver for nest to nest coupling with LIS
  - Conducted weekly technical telecons to discussed coupling issues and results

c) NOAA/NCEP/EMC

d) NASA/GSFC
  - Released LIS public version 7.2
  - Reviewed the implementation of COAMPS-LIS and LIS-Hydro two-way coupling
  - Completed a second LIS spin-up run for the Hurricane Irene case using only the NLDAS forcing (7 years)

- Corrected the Noah LSM soil and vegetable tables
- Updated the remote sensing measurements from newer sensors such as SMAP, SMOS and AMSR2

e) NCAR

- Modified the WRF Preprocessing System (WPS) to accept the COAMPS coordinate system and domain configuration, resulting in a modified tool that can be used for future COAMPS domain file creation.
- Adapted WRF-Hydro code to accept multiple land-cover classification systems as opposed to the fixed USGS classes. This new feature permits the use of any land cover classification system supported by WPS (USGS, MODIS, modified MODIS) and adds capability to use a variety of land cover products natively without additional crosswalk tables.
- Completed the Hurricane Irene test case spin-up run (one year)
- Conducted experiments with reanalysis and COAMPS offline atmospheric forcings and evaluated results using the community Rwrfhydro model evaluation package.
- Test and revised the coupling between LIS and WRF-Hydro, including exchanges of soil moisture and ponded water statistics.
- Conducted uncoupled WRF-Hydro test runs to simulate flood response to the 2011 Hurricane on the east coast of the U.S to establish baseline comparison with the coupled COAMPS-LIS-Hydro system
- Completed the preliminary WRF-Hydro spin-up test for the Luzon test case using GFS and WRF forcing fields

The team regularly reviewed results from numerouns test runs of one-way and two-way coupling.

RESULTS

1. COAMPS-LIS-Hydro Coupling

The CIRES/UC ESMF team has made signigicant progress to deliver a series of milestones (COAMPS-LIS-Hydro v0.2 - v0.7), the final of which is a fully coupled, NUOPC-compliant system with all feedbacks enabled. The v0.7 system ran successfully with a telescoping nest configuration at 27-km, 9-km, and 3-km resolutions with domains over the US East Coast for a 2011 Hurricane Irene simulation. The COAMPS atmosphere, LIS/Noah 3.3, and WRF-Hydro are restarted from separate spin-up runs. The coupled system has been run out to a 72-hour forecast. This simulation produces physically realistic atmosphere-land interactions. Soil moistures from WRF-Hydro are physically realistic, but streamflows are not yet consistent with increased precipitation from the hurricane event. We have identified this is due to a needed surface head feedback from WRF-Hydro to LIS to ensure mass conservation. Full documentation for the v0.7 milestone release is available on the HyCCAP wiki: https://earthsystemcog.org/projects/hyccap/coamps_hydro_v07 .

In this configuration, an option was introduced into COAMPS to turn off the inline land surface model and instead receive land surface inputs via a NUOPC Connector. The COAMPS NUOPC CAP sends eight meteorological forcing fields to the external LIS/Noah 3.3 component. LIS/Noah 3.3 returns surface temperature, soil moistures, snow depth, snow area fraction, albedo, and effective mixing ratio back to the atmosphere. The land-hydro interaction includes sending soil moistures, surface runoff, and subsurface runoff to WRF-Hydro. After the WRF-Hydro routing executes, updated soil moistures are send back to LIS/Noah 3.3 (Fig. 1).

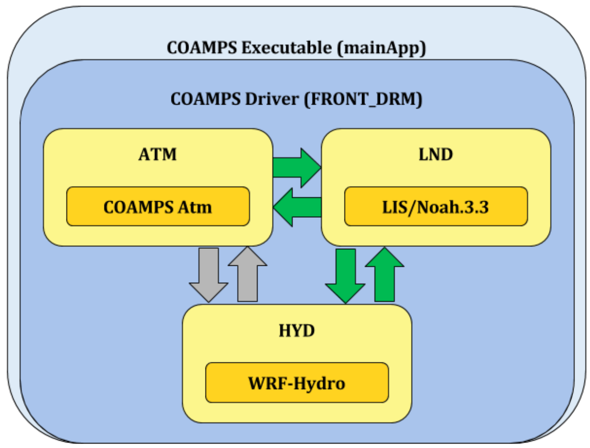

Figure 1: A diagram of the NUOPC coupling architecture of the COAMPS-Hydro v0.7 release. All components are active and two-way feedbacks are turned on between ATM-LND and LND-HYD.

All components are NUOPC-compliant. The LIS and WRF-Hydro NUOPC wrappers ("caps") are maintained in GitHub repositories[2] and are being used in the NOAA/NEMS system and will be used in a NASA coupled land-hydro data assimilation system. A custom NUOPC Connector was introduced to support nest-to-nest coupling between the atmosphere and land components: every atmospheric nest has a corresponding nest in the land model on the same grid. Nest-to-nest communication uses an ESMF parallel redistribution operation. A nearest neighbor option was added to extrapolate to any unmapped destination cells since land-sea masks are not always completely consistent between COAMPS, LIS, and WRF-Hydro. This custom connector also supports grid interpolation between atmosphere and land, if desired.

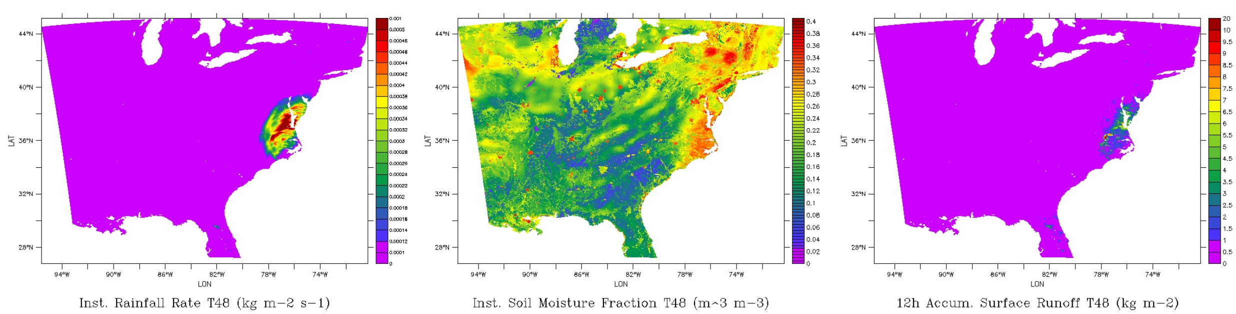

Figure 2: Hurricane Irene output from COAMPS-Hydro v0.7. Left - Rainfall Rate from COAMPS; Center - Soil Moisture Fraction from LIS/Noah 3.3; Right: Accumulated Surface Runoff from LIS/Noah 3.3

The next milestone, v0.8 currently in progress, will address two outstanding issues:

- The atmosphere-to-land coupling is currently exchanging data only at the time step of the outer nest (90 seconds). This will be updated so that nests couple at their individual time step, 90 seconds (outer), 30 seconds (intermediate), 10 seconds (inner).

[2] https://github.com/NESII/lis_cap
https://github.com/NESII/wrfhydro_cap

- The low streamflow values seen in the v0.7 release are attributed to a missing surface head feedback from WRF-Hydro to LIS. The feedback has been included on a development branch and is currently being evaluated. Figure 3 shows a preliminary COAMPS-LIS-Hydro 36h streamflow forecast with the surface head feedback from WRF-Hydro to LIS. However, the values are lower than the WRF-Hydro spin-up run using the NLDAS forcing. Efforts to identify and fixed the physics feedback between LIS and WRF-Hydro are ongoing.

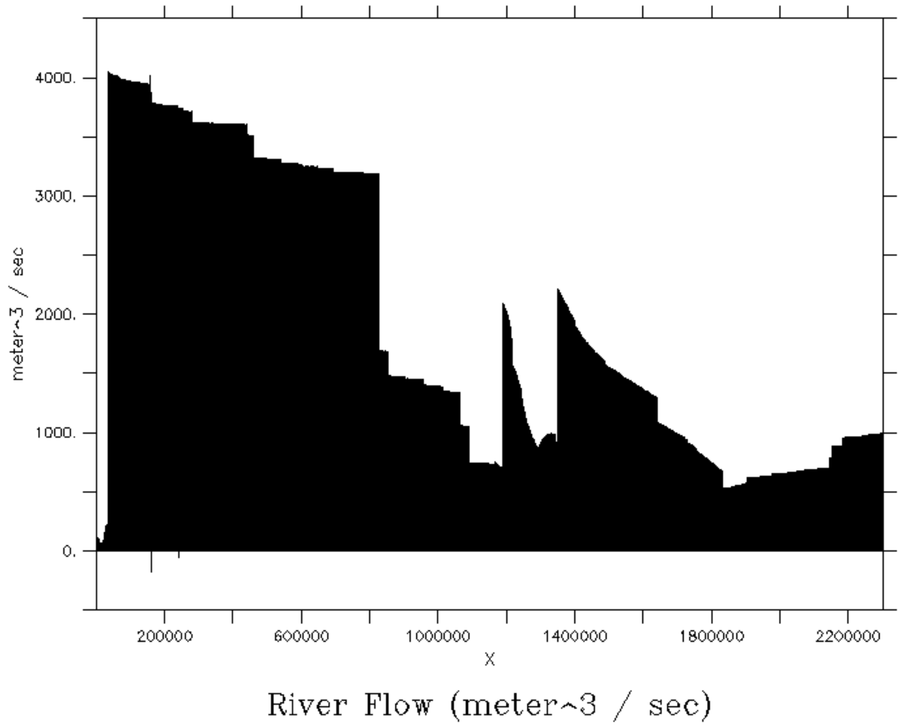

Figure 3: 36h COAMPS-LIS-Hydro forecast streamflow ($m^{3/s}$).

2. *Precipitation forecasts for COAMPS-LIS-Hydro System*

We evaluated the COAMPS precipitation forecasts for COAMPS-LIS-Hydro coupled system 0.2 to 0.8 releases. Mosaic boundaries were seen in the initial soil states due to the merge of NLDAS forcing with high resolution precipitation and the surface station network in the US, which results in unrealistic boundaries in many atmospheric lower boundary forecast fields. Thus, a new LIS spin-up run was performed to use only the GDAS forcing. Comparisons with the original LIS restart file that was spun-up using the high-resolution precipitation and surface station observations show some precipitation differences. With the two-way coupling (0.7 release) and using the new LIS restart, the maximum 72h accumulated precipitation is ~8 mm less than the uncoupled COAMPS using the inline Noah LSM; but the overall accumulated precipitation structure is similar between these two runs (Fig. 4).

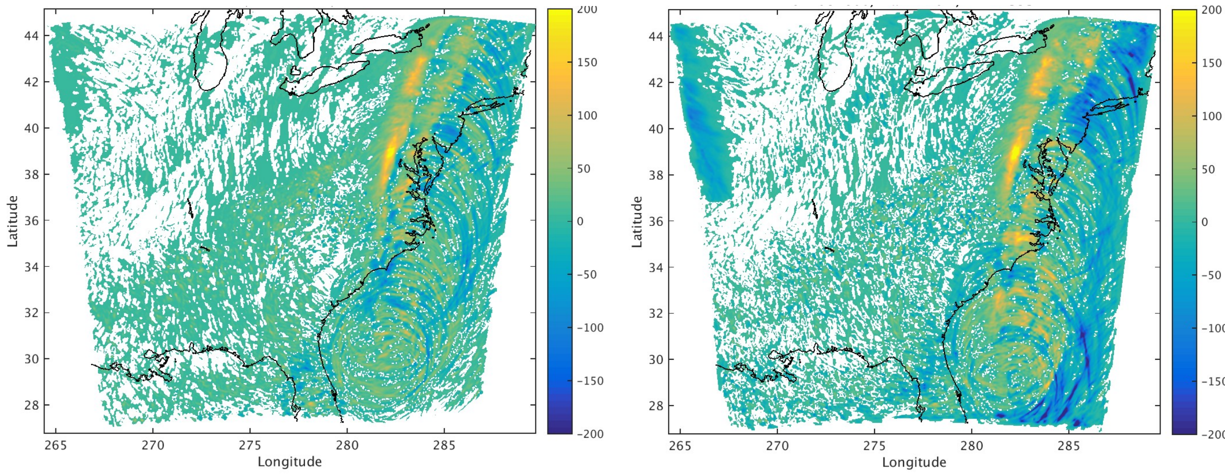

Figure 4:Comparison of 72 h accumulated total precipitation (mm) forecast using the two-way coupled COAMPS-LIS-Hydro 0.7 release (left panel) and uncoupled stand-along COAMPS (right panel). The maximum precipitation amounts are 232.5 mm and 240.1 mm, respectively.

The generalized ensemble-based cloud microphysics scheme was implemented and tested in COAMPS-Hydro release 0.0. The new generalized scheme provides the user with the flexibility to specify the size distributions for each condensate field at run time through namelist-provided switches. The user can run the scheme using either the analytically derived cloud microphysics conversions or more accurate numerically-based look-up tables. The numerical look-up tables can either be generated at run-time or predetermined and then read in as the model starts to improve computational efficiency. The look-up tables provide a more accurate representation of the cloud microphysical collection terms. This accuracy is garnered through inclusion of the diameter-dependent collection efficiencies and by accounting for the temporal truncation error in the collection equations themselves. This second factor often leads to the problematic condition that the computed inter-species collection-rates over-deplete a given species during a model time-step (Gaudet and Schmidt 2007). This creates a condition in which the collection rates have to be normalized to prevent the so-called “over collection” problem. The collection terms computed numerically avoid this issue by including a time-step dependent correction factor which ensures the computed rates never “over-collect” during a time step. The advantage of this approach is that the computed rates inherently account for time-step changes between model nests. The generalized code is highly simplified and only a few routines are needed to compute the collection terms. The use of look-up tables further improves the model efficiency as the expensive calculations are pre-computed prior to run-time and then accessed dependent on the ice or liquid water content of each species involved in the specific collection calculation. The inclusion of a two-moment cloud microphysics allows for the inclusion of aerosol impacts on the precipitation structure and evolution. This results from a change in the cloud water to rain water autoconversion terms which scale as the inverse of the drop concentration. This has been shown to impact landfalling hurricane precipitation structure, intensity, and timing in cases where the lower concentration marine aerosol layer pushes inland and encounters the local terrain.

3. *Upgrades of Operational NOAA NCEP Land Surface Models and Land Data Assimilation*

The Land-Hydrology Team at NCEP/EMC is responsible for all aspects of land-hydrology in the NCEP operational regional and global weather and seasonal climate models. The state-of-the-art Noah land model accounts for the evolution of land states (surface/soil temperature, soil moisture, soil ice, canopy water and snowpack) and, with a surface-layer turbulence scheme, then calculates the exchange of heat, moisture, and momentum with the atmosphere, the bottom boundary condition for the atmospheric model.

The Noah land model is in the NAM (short-range) and GFS (medium-range) NWP models at NCEP, where Noah depends on land data sets, some rather static such as vegetation and soil types, and others more dynamic such as surface albedo and plant phenology, with land states updated via the proper representation of physical processes in the land. The current NASA LIS integrates NOAA operational land surface and hydrological models (NCEP's Noah, versions from 2.7.1 to 3.6 and the future Noah-MP). The newer versions of the Noah LSM used in operational models have a variety of enhancements compared to older versions, where the Noah-MP allows for different physics parameterization options and the choice could have large impact on physical processes underlying seasonal predictions. These impacts need to be reexamined before implemented into NCEP operational systems. A set of offline numerical experiments driven by the GFS forecast forcing have been conducted to evaluate the impact of snow modeling with daily Global Historical Climatology Network (GHCN).

Assimilation of land states, specifically snow and soil moisture for the project here, will help to improve model performance via better initial land conditions. The 557th Weather Wing SNODEP product and the NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) are used in current NCEP operational GLDAS to perform the daily snow analysis. However, the analysis method currently used is a simple approach that does not utilize advanced data assimilation techniques. The LIS-DA module provides an infrastructure to ingest various sources of remotely-sensed hydrologic observations to produce improved spatially- and temporally-consistent fields of land-surface states. LIS-DA includes advanced tools such as EnKF, which is widely accepted as an effective technique for sequential assimilation of hydrologic variables such as snow cover, snow depth, and soil moisture. A set of offline numerical experiments driven by the GFS forecast forcing have been conducted to evaluate the impact of assimilating snow with daily GHCN data. The statistics from LIS EnKF DA results with 20 members are better than all the other methods including AFWA SNODEP, operational GFS/GDAS product, LIS control run, and LIS DA with direct replacement (Fig. 5).

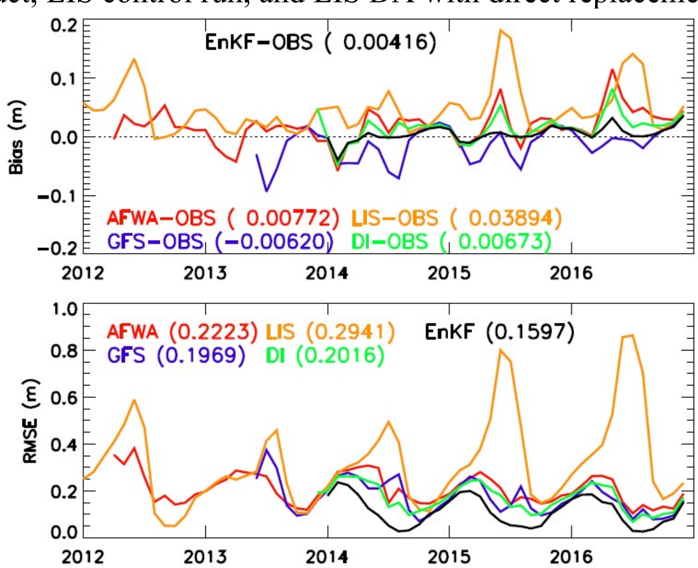

Figure 5: Bias and RMS errors of snow depth from AFWA SNODEP, GFS modeling, Noah control run, and data assimilation from direct insertion and EnKF comparing to the daily Global Historical Climatology Network (GHCN).

4. OCONUS Luzon Philippine flood case

The second flood case chosen to test the relocatability of the COAMPS-LIS-Hydro system outside CONUS is the Agno watershed flood case that occurred on 3 Sep 2013 in the Luzon, Philippines area. The COAMPS grid setup for this case consists of four nests (45-, 15-, 5-, and 1.33-km horizontal resolutions). The hydrographic stations in this region measured a maximum of 300-400 cms^{-1} discharge between 4-6 September. The uncoupled COAMPS precipitation during 3-6 Sep 2013 shows over 100 mm rain in the northern portion of the Agno watershed (Fig. 6c).

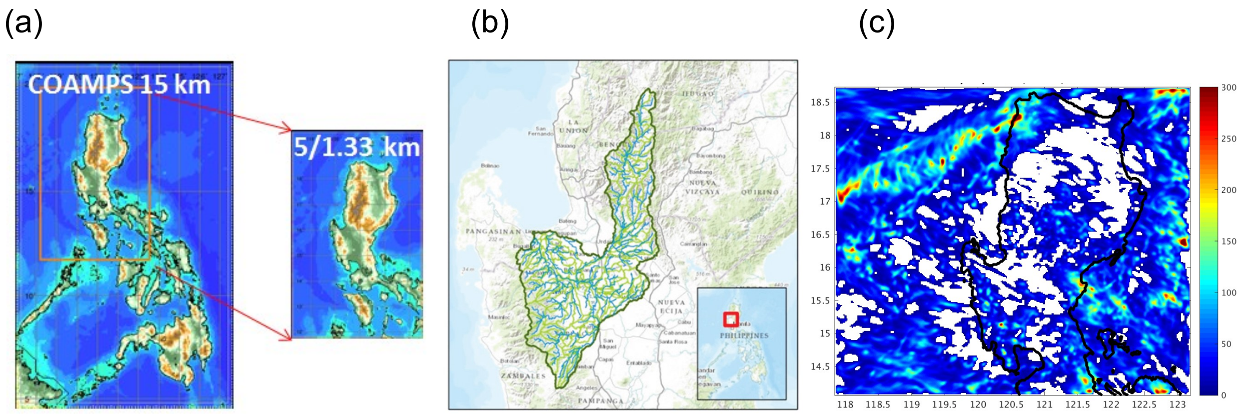

Figure 6: (a) COAMPS grid 2-4 domains. (b) Map of the Agno watershed, Luzon, Philippines. (c) COAMPS 6h forecast of 3-day total rain (mm) during 0000 UTC 3-6 Sep. (c) COAMPS accumulated precipitation between 3-6 Sep 2013.

IMPACT/APPLICATIONS

This new high-resolution coupled hydrological modeling capability within COAMPS will have a tremendous impact of the near-shore coupled modeling and simulation capability available for Naval operations. A basic weakness of many LSMs is that runoff and streamflow typically does not recycle back into the water cycle, but is simply treated as a sink in the system. Thus, a key feedback mechanism is not properly accounted for in the budget. With this new development and its potential for future linkage with near-shore ocean models, a more accurate representation of near-shore processes will be available. In addition, with the development of an improved hydrological modeling capability within COAMPS, the importance of accurate quantitative precipitation forecasting (QPF), particularly at high-resolution will be magnified. A new generalized two-moment ensemble-based microphysics scheme has recently been developed for use in COAMPS. The scheme is expressed in terms of a few coefficients which govern all mass-diameter, velocity-diameter, and particle size distributions relationships so that uncertainty in the model microphysics can be readily incorporated within an ensemble framework. The scheme allows the user to specify the moments of the particle size distribution at run time and uses highly accurate numerical-based lookup tables to compute all interspecies collections terms. This allows one to incorporate diameter-dependent collection efficiencies and numerical bounding techniques that reduce the temporal truncation error associated with the usage of larger time-steps across various model nests. The goal is to provide a linkage between this new microphysics scheme and the new terrestrial hydrology model to improve forecast capability through improved atmospheric-LS hydrological feedback.

TRANSITIONS

The transition path for this project is to FNMOC via ONR 6.4 Small-scale atmospheric models.

RELATED PROJECTS

This project is related to NRL 6.2 projects within PE 0602435N that focus on the development of the atmospheric and air/ocean coupled components (QC, analysis, initialization, and forecast model) of COAMPS and “River influence at Multi-Scales”. Developments in model post-processing software concerning the diagnosis and analysis of fields relevant to coupled prediction generated for this work would be transtioned via the ONR-funded “Small-scale atmospheric models (COAMPS)” and “COAMPS-On Scene” projects.