The National Earth System Prediction Capability (ESPC) Project

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ESPC Overview

An interagency collaboration, initiated in 2010 between DoD (Navy, Air Force) and NOAA, and expanded to DoE, NASA, and NSF in 2012 for coordination of research to operations of a National earth system analysis and prediction capability.

It seeks to improve communication and synergy, for global prediction of weather, ocean, and ice conditions at weather to short-term climate variability timescales.

- Common prediction requirements and forecast model standards that enable agencies to improve leverage and collaboration.
- A national research agenda that will improve prediction across scales from days to decades.
- Cooperative demonstration projects to assess predictability of global scale high impact environmental conditions to inform S&T, R&D, and transition to operations.
- Towards an multi-model ensemble based air-sea-land coupled global prediction capability

http://espc.oar.noaa.gov/
ESPC Goals

Build the next generation operational national environmental prediction system:

• Advance computational and environmental numerical prediction science and technology through coupled model development
• Enhance our understanding of the complex interactions of the earth environmental system through process studies
• Identify and quantify uncertainty and risk through probabilistic prediction
• Improve operational predictive capability with better skill scores and longer lead times through technology transition
• Provide insight and guidance for informed decisions in an increasingly complex and changing global human enterprise

Implement an ESPC Suite across partner Operational Prediction Centers
Collaborative Programs Across Scales

Inter-agency *Atmospheric Weather and Coupled Climate* R2O Ensembles

- **Hurricane Forecast Improvement Program** (HFIP: 1-7 days)
  - Providing rapid improvement R2O capability for US (NOAA) and Global (Navy) Tropical Cyclone Track and Intensity
  - Distributed Production Centers leverage multi-agency resources

- **National Unified Operational Prediction Capability** (NUOPC: 5-16 days)
  - Improving medium-range forecasts and probabilities of specific events
  - Multi-model Ensembles are more accurate for longer lead times.
  - Distributed Production Centers leverage multi-agency missions and resources

- **National Multi-model Ensemble** (NMME: 3-9 months)
  - Multi-model Climate Ensembles are more accurate than any member
  - Distributed Production Centers leverage multi-agency and international computer infrastructure and investments.
  - Skill improves with spatial resolution - All are run at sub-optimal but best affordable resolution.
  - *Currently a Phase II research project through FY14 for higher resolution output suitable for sub-seasonal updates (Weeks 3-12)*
Collaborative Community Models

- The HYCOM ocean model and data assimilation system have been developed to provide daily, weekly and extended forecasts of the global ocean conditions at high (~3km) horizontal resolution.

- HYCOM and WaveWatch-3 have both been awarded the National Ocean Partnership Program (NOPP) Excellence in Partnering Award and engage with consortia consisting of Federal, university, and international partner institutions.

- Both the U.S. Navy’s and NOAA’s ocean forecast systems use HYCOM and WW-3 and they are used extensively in academia for continued research.

- Code repositories for HYCOM (NRL-Stennis), WaveWatch-3 (NOAA-NCEP), CICE (Los Alamos National Lab), the Land Information System (LIS) (NASA-GSFC), and Noah (NOAA-NCEP) allow universities and federal partners to openly access the latest improvements from community-based development while maintaining configuration management and documentation.
Why Coupled?

Short Range Prediction
• Tropical Cyclone intensity & track is dependent on ocean temperature and the depth of warm/cold water.
• Littoral/coastal prediction (Land-breeze/sea-breeze, sensor performance, abrupt wind/temperature changes at the north wall of the Gulf Stream, etc.)
• Sudden, gale force cold air surges (South China Sea, Ice shelf, etc.)

Medium Range Prediction
• Monsoon onset, breaks and intensity, Active tropical convection periods (Madden Julian Oscillations or MJO)
• Polar low pressure systems (resembling hurricanes), Blocking high pressure systems causing intense flooding and droughts
• Ocean fronts and eddies

Long Range Prediction
• Teleconnections or inter-global weather and climate links such as El Nino, Seasonal TC patterns, Ocean SST patterns, climatology shifts & anomalies)
• Arctic ice dynamics, droughts & floods, regional fires/smoke
NAVGEM/HYCOM Rainfall
“Daily Averaged Forcing Run R2”

**November Mean Rainfall**

R2 has improved representation of Indian Ocean rainfall compared with the fixed SST run R1.

**Rainfall Hovmöller Diagrams**
(rainfall between 5S – 5N)

NAVGEM R2 run - hourly ingest of HYCOM Exp 24.1 SSTs

NAVGEM R1 run - Fixed NCODA SST (Control)

Reynolds, Hodyss, et al. 2013
COAMPS/NCOM Equatorial Variability
Precipitation (mm/day) for 5S-5N

- Remarkably good late-NOV MJO signature, esp. for C45O
- NAVGEM (not shown) does not capture late-NOV MJO  

Chen, Doyle, et al. 2013
Precipitation Time Series (mm/hr)

Tropical Indian Ocean

C45O (dashed blue) good at catching upswing in precip in late Nov.

C27O (dashed red) also shows increase in precip, but not as strong as C45O

Fixed SST runs (C45F, C27F, and N37F) show much weaker late-Nov. precip increase
Short/Medium Range Coupled Ensemble Prediction System

ECMWF Day 0 Coupled Model: equal skill in short range and better skill beyond Day 7  
*Miller & Vitart, 2013*

Exact approach to optimally evolving the SST in a forecast is still a research challenge.

**Current ECMWF Monthly Forecast System**

- **Atmosphere-only Integration at T639 (30 km)**
- **Initial condition**
- **Heat flux, Wind stress, P-E**
- **Day 9**
- **Coupled forecast at TL319 (60 km)**
- **Day 10**

**Ocean only integration**

**Figure:**

- **MJO Skills in Three Models (IOP)**
  - GFS
  - GFSv2
  - UH

- **Correlation (CORR)**
  - Forecast Day

- **RMSE**
  - Forecast Day

*Fu et al. 2013*
Earth System Prediction Suite (ESPS) Common Model Architecture

ESPS is a collection of Earth system component models and interfaces that are interoperable, documented, and available for community use. ESPS is intended to:

- formalize code preparation for cross-agency use
- simplify “toolkit” code selection for the broader research community
- focus on coupled modeling systems
- leverage legacy investments from NASA, NOAA, NSF, DOE, and Navy
- bridge climate (CESM) and weather (ESMF) scales
- establish “plug-and-play” implementation via the NUOPC interoperability layer.

ESPS codes:

- are NUOPC-compliant
- include model documentation
- have clear terms of use
- include compliance checking and tests for correct operation across the development community.

http://www.earthsystemcog.org/

Deluca2013
What Do We Gain from Multi-Model Ensemble Prediction?

Practical approach to estimating and understanding forecast uncertainty due to initial conditions/observation errors, model formulation and numerical uncertainties

- Multiple instances of single models can reduce initial condition error
- Single model ensembles are often over-confident (low spread) and have persistent error modes and biases
- Multiple model ensembles reduce model and numerical errors
- Each center can leverage distributed computing resources for a larger number of members

Result is a better prediction and an understanding of the uncertainty in the prediction and a natural focus for multi-institutional partnership
Ensemble of Intensity Forecast for Individual Hurricanes

Reliability - some storms/years are more difficult to predict than others.

Credibility – ensemble consensus skill is hard to beat.

Non-homogeneous sample of Atlantic 48-h intensity forecast errors (kt) for tropical storms and hurricanes provided by various techniques and during the 1989-2012 seasons. (DeMaria et al., 2013). Using the best-track positions as a hindcast for a 2002-2009 sample indicates that some intensity improvement may be achieved if track forecasts continue to improve, but further improvement in the intensity forecast itself is also needed.

Adapted from Elsberry 2013, DeMaria et al. 2013
**ESPC Demonstration Projects**
Assessing link from Predictability to Prediction at S2S and ISI Timescales

- Extreme Weather Events: Predictability of Blocking Events and Related High Impact Weather at Lead Times of 1-6 Weeks *(Stan Benjamin)*
- Seasonal Tropical Cyclone Threat: Predictability of Tropical Cyclone Likelihood, Mean Track, and Intensity from Weekly to Seasonal Timescales *(Melinda Peng)*
- Arctic Sea Ice Extent and Seasonal Ice Free Dates: Predictability from Weekly to Seasonal Timescales *(Phil Jones)*
- Coastal Seas: Predictability of Circulation, Hypoxia, and Harmful Algal Blooms at Lead Times of 1-6 Weeks *(Gregg Jacobs)*
- Open Ocean: Predictability of the Atlantic Meridional Overturning Circulation (AMOC) for Improved Weather and Climate Forecasts *(Jim Richman)*
Extending the Forecast
Global Impacts of MJO

Maloney and Hartmann (2000)


McPhaden (1999)
Example: Typhoon Probability/Track

5-7-day HFIP/NRL Ensemble

Decreasing but “statistically significant” skill

30-day NPS Research Forecasts to JTWC Ensemble Probabilities

Seasonal Track Frequency/Probability based on ISI Predicted state

Maloney and Hartmann (2000)

Model Improvement through process studies

Operations:
- Numerical Environmental Prediction Code
- Application Specific Modeling System (DA, Resolution, Forecast Length, Ensemble Design, Post-processing, Product Selection etc.)
- Skill Assessment & Metrics (Objective Multi-variable Scorecard, Probabilistic Measures, Case Studies, User Surveys)
- Identify error modes suitable for improving general model performance

Research:
- Implement, test, decide on transition of new model formulations or parameterizations
- Develop improved parameterizations for specific process (synthesis of model and observational results)
- Perform numerical or field experiments focused on specific phenomena or processes
- Select suitable process studies for phenomena of high impact and/or low skill

Model tuning (limited insight – must be redone for every upgrade, resolution change, etc.)

Improved resolution, initialization, implementation of currently available parameterizations (limited insight – often results in new/different error structures)

Great insight – potentially limited impact on performance

After Jakob, BAMS2009
### Overarching DYNAMO Goal:
To expedite the progress of advancing our understanding of MJO initiation processes and improved simulation and prediction of the MJO.

### LASP Goals:
- A better understanding of physical processes and numerical representation of coupled modes.
- Better operational prediction in the maritime tropics and subtropics.
Process-oriented Field Studies

What’s after DYNAMO?

- Monsoon Mission?
- Year of Maritime Continent?
- BSISO/ MISO, MC Prediction Barrier, etc.?
- Link to Tropical Cyclone sub-seasonal variability?
- Link to mid latitudes or arctic?

Ridout and Flatau, JGR 2011

Sharmilla et al. 2013
Change in blocking frequency in the east Pacific and Atlantic observed with a lagged phase after a strong Indian Ocean MJO. Day +6 GEFS replicates this to some degree; however, there is still a 3-4 day lag in realized skill.

Tropical cyclone outflow characteristics impact the type of midlatitude response:
1) Circular outflow pattern and ridge amplification
2) Linear outflow pattern and jet elongation

The midlatitude response impacts the potential for blocking, the longitude of blocking, and the intensity of the block.
Objective: To develop a significantly improved capability to simulate and predict the coupled global air-ocean-land-ice ocean system at eddy-resolving spatial scales and ISI timescales in a computationally efficient and operationally affordable architecture towards real-time forecast capability.

Technical Approach: An interdisciplinary team of computer scientists, oceanographic and meteorological scientists, numerical methods experts, and software engineers will develop approaches to massive fine-grain parallelism suitable for data-assimilating coupled forecasts of environmental conditions. Automated code refactoring and emerging technologies for many core accelerators will be assessed and portability to multiple platforms is desired.

Expected Outcome: Demonstrated improved scalability to thousands of nodes, with computational accuracy and run-time efficiency relative to legacy architectures within the Navy, NOAA, and DoE’s coupled global weather and climate models.

Partnerships: ONR, NOAA, NRL, DOE

http://coaps.fsu.edu/aoli/projects
Successful Proposals

**Accelerated Prediction of the Polar Ice and Global Ocean (APPIGO)**
Chassignet, Eric and Bozec, Alexandra - Florida State University
Campbell, Tim and Wallcraft, Alan - NRL, Stennis Space Center
- U Miami
Hunke, Aulwes, and Jones - LANL
Kirtman, Ben and Iskandarani, Mohamed

**An Integration and Evaluation Framework for ESPC Coupled Models**
DeLuca, Cecelia - University of Colorado
Kirtman, Ben - University of Miami
Jacob, Robert - University of Chicago
Chassignet, Eric and Bozec, Alexandra - Florida State
Kinter, Jim - George Mason University/ COLA
Campbell, Tim – NRL Stennis Space Center
Wilson, Paul - University of Wisconsin
Vertenstein, Mariana – NCAR

**RRTMGP: A High-Performance Broadband Radiation Code for the Next Decade**
Mlawer, Eli – Atmospheric & Environmental Research, Inc.
Eaton, Brian – NCAR
Monterey
Pincus, Robert – University of Colorado
Reynolds, Carolyn and Liu, Ming – NRL

**NPS-NRL-Rice-UIUC Collaboration on Nonhydrostatic Unified Model of the Atmosphere (NUMA) Coupled Models on Many-Core Computer Architectures**
Wilcox, Lucas and Giraldo, Frank – Naval Postgraduate
Campbell, Tim – NRL Stennis Space Center
Warburton, Tim – Rice University
Klöckner, Andreas - University of Illinois, UC

http://coaps.fsu.edu/aoli/projects
International Sea Ice Prediction Research Network

Julienne Stroeve, Cecilia Bitz, Hajo Eicken, Larry Hamilton, Helen Wiggins, Elizabeth Hunke, Phil Jones, Adrienne Tivy, Jim Overland, Muyin Wang, Jenny Hutchings, Walt Meier

and dozens of international collaborators
Prediction Network

• Evolve the SEARCH Arctic Sea Ice Outlook to an International Sea Ice Prediction Network
• Prediction at seasonal to interannual timescale, synergy with climate projections
• Collaboration of observers, modelers, physicists, and social scientists
• Focus on public engagement and advancing the science of sea ice prediction
Prediction Network Goals for Modeling

- To determine the predictability of Arctic sea-ice at regional and local level
- To advance sea ice prediction methods
- To improve sea ice models for prediction
- To determine how we can best observe the Arctic system to inform sea ice prediction
- To make sea ice forecasts with uncertainty estimates
- Link research and operation efforts
Action Team Mechanism

- Kick-off meeting in late-winter 2013/spring 2014
- Monthly virtual meetings
- Web resources
- Email lists
- Meet in Breckenridge next year in evening/extra day?
- suggestions?

We want your input!
Prediction experiments and methods, observations, metrics, communication styles, etc
The High Impact Weather Prediction Project (HIWPP)

HIWPP Goals

To improve the United States' operational global numerical weather prediction systems. In the next two years we seek to improve our hydrostatic-scale global modeling systems and demonstrate their skill. In parallel, we will accelerate the development and evaluation of higher-resolution, cloud-resolving (non-hydrostatic) global modeling systems that could make a quantum leap forward in our nation’s forecast skill, targeting 2020 and beyond.

- A 2-Year $12.905M Project, which begins Fall, 2013
- Five Thrusts:
  - Global hydrostatic ensembles for medium-range (0-32 day) forecasts (with enhanced resolution, physics & assimilation)
  - Accelerated development of a global non-hydrostatic (0-14 day) prediction system
  - A services framework focused on the timely and accurate delivery of global weather data and related earth system information
  - Incorporating nested regional Hurricane WRF models into the NCEP NMM-B (and other) modeling system
  - Augmenting the National Multi-Model Ensemble (NMME) capability for seasonal (long-range weather) prediction
Towards a National ESPC

Federal partnering to improve adoption of research breakthroughs from a wider community into operations.
HFIP, NUOPC, and NMME have shown great benefit to operational National forecast skill for short/medium/seasonal range weather, and should be continued and expanded.

The goals of the ESPC Inter-Agency Project indicate that R2O should:

• be extended to transition of regional and global air-sea-wave-ice coupled models leveraging community models
• improve adoption of ESMF standards through the ESPS initiative and CMA committee
• Extend/continue the multi-model ensemble approach at sub-sesonal and seasonal scales through an NMME follow-on for operationalizing this research.

A National ESPC will provide the next generation of operational environmental prediction services for 0-16 days and 3-9 Months, a major challenge is still to address the sub-seasonal (weeks 2-12) where skill is lowest, and extend skill globally to Mid-Latitudes and Arctic.
Discussion
Back-up slides
Where We Are Today

• Updated MOA signed by all partners (Navy, NOAA, Air Force, NASA, DoE, NSF) in April 2013

• Implementation Plan in draft modeled after the Initial Operational Capability of the NUOPC North America 0-16 Day Unified Ensemble in January 2011 (Navy, Air Force, NOAA, Canada)

• Software architecture and interoperability standards part of latest release of the Earth System Modeling Framework

• Demonstration Projects established

• Initial discussions with ongoing related inter-agency collaborations (HFIP, NUOPC, NMME)

• ONR/NOAA NOPP project on massively parallel fine grain computing for ESPC models and NOAA/ONR project on High Impact Weather Prediction (HIWPP) initiated for 2014 starts
FY14 Plans

- **Continue Navy-ESPC System Implementation**
  - Test Coupled NAVGEM-HYCOM-CICE

- **Assess suitability of NMME to shorter timescales, higher resolution, additional output fields, and (global) areas of interest**

- **Develop community collaborations among Federal Sponsors and Numerical Prediction Developers**
  - ESPC Demonstration projects
  - NOPP Topic on Global Coupled Models on Massively Parallel Computers
  - Component Air-Sea-Wave-Ice models and Data Assimilation
  - Improve Coupled Ensemble construction and validation metrics

- **Continue/extend NUOPC/ESPC CMA and Interoperability**
  - Expand ESPS for Global Coupled Models, new grids, fault-tolerant Ensembles
  - Integrate capabilities in ESMF, NUOPC and CESM Drivers towards ESPS goals
  - Working Groups on ESPC Demonstrations, Managed Ensembles, Improved Computational Efficiency, Physics Interoperability, Common Modeling Architecture, and the High Impact Weather Improved Prediction Project (HIWIPP)
Earth System Prediction Capability

ESPC Schedule

FY12 FY13 FY14 FY15 FY16 FY17 FY18 FY19 FY25

Major Milestone or Transition of capability

Decision Brief to ESG
Update Brief to ESG

Minor Milestone Schedule/Status Assessment

Management

Outreach, Communication, & Public Comment

ESPC CMA and Coupled/ Component Model Development Common Scorecard

Internal Communication & Coordination

Milestones

Prelim Phase 0

Demonstrations Phase 1 (S2S)

Transition Planning

Phase 2 (ISI) Phase I IOC

Beta Test Phase 3 (Decadal) FOC

Adopt Interoperability Standards

Develop Future Model Architecture

Build Common Test Framework & Adopt Common Skill Diagnostics

Earth System Development & Coupled DA

Beta Testing of ESPC ver. 1 & Spiral 1 Upgrade Planning from Demo Results

PM, DPM Project Office Est.

MOA Signed, Implementation Plan Drafted

Develop S2S Demo Transition Plans

Develop ISI & Decadal Transition Plans

Develop ESPC Transition Plans for ver. 1

Annual AMS, AGU, GOV/WGNE Conferences

Annual NWS, USAF, USN User Surveys

Ops Infrastructure Upgrades & Advocacy based on R&D Infrastructure Results

User/Product Plans, Training & Advocacy

Decision Brief to ESG

Update Brief to ESG

Minor Milestone Schedule/Status Assessment

Major Milestone or Transition of capability
Community and Agency Calls to Action

- An Earth-System Prediction Initiative for the Twenty-First Century (Shapiro et al. 2010)
- Collaboration of the Weather and Climate Communities to Advance Subseasonal-to-Seasonal Prediction (Brunet et al. 2010)
- Assessment of Intraseasonal to Interannual Climate Prediction and Predictability (Weller, 2010)
- Arctic Security Considerations and the U.S. Navy’s Roadmap for the Arctic (Titley and St. John, 2009)
- The Uncoordinated Giant: Why U.S. Weather Research and Prediction are not Achieving their Potential (Mass, 2006)
Sources of Extended Range Predictability: Subseasonal, Intraseasonal and Interannual (ISI) Timescales

Assessment of Intraseasonal to Interannual Climate Prediction and Predictability, 2010, THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001
What Do We Gain from Multi-Model Ensemble Prediction?

**Uncertainty in initial state**: members with different initial conditions

- Methods to perturb initial conditions: Parallel data assimilation cycles, rapidly growing linear perturbations, Kalman filter methods
  - Ensemble Transform (ET, McLay et al. 2008; banded ET, McLay et al. 2010): Transform 6-h ensemble perturbations to be consistent with analysis error estimates. Because it is a cycling scheme, model perturbations impact initial perturbations.

**Uncertainty in model formulation**: utilize varying models

- Methods to include model uncertainty: Different forecast models, different sub-grid-scale parameterizations, stochastic forcing, boundary forcing (SST, land)
  - **Multi-model ensembles**
  - Parameter variations
  - Stochastic convection, stochastic kinetic energy backscatter, diurnal SST
Strategy

Seamless Prediction System

- Weather Model (currently 7-10 days)
- Climate Model (currently decadal to centennial)
- New prediction systems
- Adaptive Grids
- Seasonal Prediction (1-3 months)
- Seamless Prediction
- Increase resolution
- Coupled with ocean

Earth System Prediction Capability
Navy Global Environmental Model
NAV GEM (Operational March 2013)

- A new Navy global prediction system developed by NRL and tested on NRL, FNMOC, and DSRC computer systems
- Improved dynamics (SI/SL), physics, and data assimilation (Hybrid ENKF/4DVAR) under development
- Chosen as the Bridging Strategy for the Navy global forecast system toward ESPC

NAV GEM is the first operational global model with SL/SI dynamic core in the nation
Recent Model Performance Comparisons

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<th>System</th>
<th>Resolution</th>
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<td>ECMWF</td>
<td>16kmL91</td>
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<td>UKMO</td>
<td>25kmL70</td>
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<td>CMC</td>
<td>25kmL79</td>
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<td>NCEP</td>
<td>27kmL64</td>
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<td>Navy</td>
<td>37kmL50</td>
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### Coupling infrastructure and interoperability layer extension across all ESPC components

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<td>coupling infrastructure that</td>
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<td>integrates ATM, OCN, WAV,</td>
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- **S** – Start, **D** - Demonstration/Evaluation, **C** - Complete
- **Infrastructure Implementation**: 60% complete; currently testing (w/o flux-exchange layer) in COAMPS;
- **Model Integration**: 30% complete; functional ESMF/NUOPC interface implemented in NAVGEM, HYCOM, CICE; current testing with NUOPC generic driver; integration into ESPC system next step;
- **Flux Exchange**: 10% complete; “pass-through” version; flux calculations in progress; fractional cell approach next step;
Objective – Investigate interaction of NAVGEM / HYCOM in a controlled manner that limits the feedback process, and thus facilitates identification of system biases and physical deficiencies.

Methodology – Alternating sequences of NAVGEM and HYCOM hindcasts are carried out in which NAVGEM (HYCOM) is run using boundary data from the preceding HYCOM (NAVGEM) run.

Initial Case – 30-day runs beginning on 1 November, 2011 (chosen for the availability of oceanic and atmospheric data for validation from the DYNAMO Experiment).
**Coupled Regional Mesoscale Model Experimental Design**

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<th>Model</th>
<th>Resolution</th>
<th>SST</th>
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<td>C45F</td>
<td>COAMPS</td>
<td>45km</td>
<td>Fixed</td>
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<td>C45O</td>
<td>COAMPS</td>
<td>45km</td>
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<td>C27F</td>
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<tr>
<td>N37F</td>
<td>NAVGEM</td>
<td>37km</td>
<td>Fixed</td>
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**Fixed SST:** NCODA SST analysis on 31 October held fixed through integration

**Observed SST:** NCODA SST analyses updated every 24 hours.

**Verification**
- NOGAPS analysis (42 km)
- NASA Tropical Rainfall Measuring Mission (TRMM)
- NOAA OLR
Blocking pattern and uncertainty in the observed initial conditions resulted in a bifurcated track scenario in the GFS ensemble with one cluster of GEFS members moving the storm eastward and another cluster westward towards the US East Coast. Several other models locked onto the westward track earlier and all forecast models indicated probable landfall by about a 5-day lead time. Communicating variance about the mean and collapsing a 30-50 member ensemble down into meaningful guidance continues to be a challenge.