LONG-TERM GOALS

In this project we diagnose and characterize model error as a function of resolution in extended-range (monthly) prediction using a linked global (NAVGEM) and regional coupled (COAMPS®) forecast system. Diagnosing and understanding the characteristics of model error as a function of horizontal resolution is a necessary step toward our long-term goal of producing useful extended-range predictions, and will set the groundwork for the development of the seamless weather-climate Earth System Prediction Capability (ESPC). Nesting a cloud-resolving model inside a hydrostatic global model serves as a bridge toward the next generation high-resolution global cloud-resolving modeling capability.

OBJECTIVES

There are several specific objectives proposed to accomplish our goal of understanding how resolution-dependent model error in our NAVGEM-COAMPS forecast system impacts the utility of extended-range forecasts and how this error may be mitigated.

1. Diagnose and examine in detail the characteristics of model error, including model biases, model energy spectra, variability and frequency of events of interest (e.g., gale-force winds), and specific phenomena such as tropical intraseasonal oscillations.

2. Determine how error in the large scale model influences the performance of the regional model nested within it.

3. Determine how model error and forecast performance change as a function of resolution (in both the large-scale and mesoscale simulations). This includes basic research to determine what scales of motion are fundamental to simulating and predicting large-scale phenomenon such as the Madden Julian Oscillation (MJO).

APPROACH

Our approach includes performing extended integrations for both the Navy global and mesoscale models using different configurations to evaluate and understand the potential for predictability on monthly to seasonal time scales.
1. Evaluate NAVGEM for monthly time scales at highest resolution possible, and at resolutions considered operationally feasible. Perform reforecasts with analyzed sea surface temperature (SST) and SST information available in real time.

2. Evaluate COAMPS simulations nested within NOGAPS/NAVGEM analyses to examine COAMPS biases that develop during extended integrations.

3. Run COAMPS nested within NAVGEM extended range forecasts in order to assess added value of an imbedded regional model for monthly forecasts.

4. Perform COAMPS simulations with and without the ocean component to assess importance of coupled modeling on the mesoscale model performance.

5. Use the COAMPS adjoint to understand the sensitivity of tropical phenomena, such as tropical cyclones and equatorial wave, to other phenomena and changes in the initial state.

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WORK COMPLETED

Experiments have been completed in which COAMPS extended-range forecasts have been run for a large domain over the Indian Ocean and western Pacific (see Fig. 1). The large domain is chosen such that the impact of the lateral boundary conditions is limited in the interior of the domain.

![Figure 1: Domain of the COAMPS grid with topography (m).](image)

Several 30-60 day extended integrations have been produced starting 31 October (see Table 1). This time period was chosen to coincide with the Dynamics of Madden Julian Oscillation (DYNAMO) field project in order to facilitate validation and simulation inter-comparisons. Here, “fixed” SST refers to the use of NCODA (Navy Coupled Ocean Data Assimilation) SST analysis valid at the start time of the simulation and held fixed through the integration. “Observed” SST simulations are performed with NCODA SST analyses that have been updated every 24 hours through the integration. This year, the investigation included higher-resolution COAMPS simulations (at 15 km) as well as COAMPS simulations using NAVGEM extended-range forecasts, rather than NOGAPS analyses, for lateral boundary conditions. Verification is based on NASA Tropical Rainfall Measuring Mission (TRMM) precipitation products and NOAA Outgoing Longwave Radiation (OLR) satellite observations, as well as ECMWF (European Center for Medium range Weather Forecasting) and NOGAPS analyses. Validation is extended to consider moist static energy diagnostics.
Table 1: Description of Model Simulations. COAMPS - Coupled Ocean/Atmosphere Mesoscale Prediction System; NOGAPS - Navy Operational Global Atmospheric Prediction System; NCOM - Navy Coastal Ocean Model; NAVGEM - Navy Global Environmental Model; and HYCOM - Hybrid Coordinate ocean Model.

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Model</th>
<th>Resolution</th>
<th>SST</th>
<th>Lateral Boundary Conditions</th>
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<tr>
<td>C45F</td>
<td>COAMPS</td>
<td>45km</td>
<td>Fixed</td>
<td>NOGAPS Analysis</td>
</tr>
<tr>
<td>C45O</td>
<td>COAMPS</td>
<td>45km</td>
<td>Observed</td>
<td>NOGAPS Analysis</td>
</tr>
<tr>
<td>C45C</td>
<td>COAMPS-NCOM</td>
<td>45km</td>
<td>Coupled</td>
<td>NOGAPS Analysis</td>
</tr>
<tr>
<td>C27F</td>
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<td>27km</td>
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<td>NOGAPS Analysis</td>
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<td>15km</td>
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<td>37km</td>
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<td></td>
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<tr>
<td>N37C</td>
<td>NAVGEM-HYCOM</td>
<td>37km</td>
<td>Coupled</td>
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</tbody>
</table>

We have also performed several COAMPS adjoint sensitivity studies. The adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state. The COAMPS adjoint is run at a 45-km resolution for 24-h and 36-h forecasts to explore the relationship between a tropical cyclone that formed in the Bay of Bengal in late November 2011, and equatorial Kelvin waves associated with a late-November MJO event. Previous results indicated that good simulations of one phenomenon were associated with good simulations of the other. Adjoint sensitivity is applied to the Kelvin waves to quantify their sensitivity to the tropical cyclone and vice versa throughout the late-November time period.

RESULTS

To gauge the ability of the COAMPS simulations to capture interannual variability, particularly the MJO, time-longitude diagrams of precipitation along the equator are examined (Fig. 2). The top row shows coupled COAMPS simulations at 45, 27, and 15-km resolution using NOGAPS analyses for lateral boundary conditions, as compared with TRMM observations (top right panel). The bottom row shows coupled COAMPS simulations at 45, 27, and 15-km resolution using NAVGEM 30-day forecasts for lateral boundary condition. Comparison of the COAMPS simulations with the TRMM observations indicates that the 15-km runs better capture the fine-scale detail seen in the TRMM observations, particularly the westward-moving features embedded in the eastward-moving MJO precipitation cluster. Quantitative analysis indicates that biases in precipitation are reduced as resolution is increased, particularly the bias of excessive rainfall over the maritime continent, most apparent in the 45-km resolution simulations.

The good simulations of the MJO in the extended-range COAMPS runs were previously attributed to, in part, the use of analyses for later boundary conditions (which would obviously not be available in real time). The recent COAMPS simulations using the NAVGEM 30-day forecasts as later boundary conditions (bottom row of Fig. 2) also produce reasonable simulations of the late-November MJO,
despite the fact the NAVGEM forecast used here to provide the lateral boundary conditions did not itself capture the late-November MJO (not shown). This result points to intrinsic predictability in the tropics associated with this MJO. Further study is needed to understand what controls the predictability of this MJO.

Figure 2: Time-longitude diagrams of precipitation (mm day\(^{-1}\), scale given by color bar) from 40 E to 140 E, averaged between 5 S and 5 N, from 1 November through 30 November (time increases along the y axis) for C45C, C27C, C15C, and TRMM (upper row, from left to right), and C45N, C27N, and C15N (bottom row, from left to right). Top row simulations use NOGAPS analyses for lateral boundary conditions and bottom row simulations use NAVGEM forecasts.

Further evaluation of the performance of the different COAMPS simulations is accomplished through a moist-static energy (MSE) budget analysis. Time series of vertical profiles of quantities associated with the MSE budget, averaged from 0-5N and from 73-80E are shown in Fig. 3 for the ERA reanalysis (taken from Sobel et al. 2014, J. Atmos. Sci.), and for the C270, C27C, and C45C simulations. Sobel et al. (2014) show that the propagation of the MJO is associated with deep ascent during the active phase. Vertical advection of MSE provides moistening ahead of the active phase and drying behind it. Horizontal advection strongly dries the atmosphere in the wake of the active phase as westerlies associated with off-equatorial cyclonic gyres bring in subtropical air. MSE calculations for the C27O simulation show that all these processes are too week in the simulation, consistent with the weak bias in the C270 MJO simulation. The C45C simulation, on the other hand, has vertical
advection that is too persistent, and horizontal advection drying that is too weak. This is consistent with the C45C MJO simulation that is too persistent over the maritime continent and does not propagate into the western Pacific. In contrast, the MSE budget quantities calculated for the C27C calculation match the reanalysis well, and this is consistent with the good simulation of the MJO in that run.

Figure 3: Time series of vertical profiles of quantities associated with the moist static energy budget, including vertical velocity (top row), vertical advection (2nd row), horizontal advection (3rd row), and zonal wind (bottom row) averaged from 0-5N and 73-80E. The quantities are calculated from the ERA reanalysis (taken from Sobel et al., 2014, JAS), and from the C270, C27C, and C45C simulations. The black vertical lines indicate the passage of the active phase of the late November MJO.

Previous results have shown that good simulations of the late November MJO also tend to have good representation of a tropical cyclone, TC05, which occurred during that period. TC05 developed in late November, moving from the Bay of Bengal into the Arabian Sea at the same time that two Kelvin waves associated with the MJO were propagating along the equator in the central and eastern Indian Ocean. We explore the potential interdependence of these two phenomena using COAMPS adjoint sensitivity diagnostics. Results from the COAMPS sensitivity calculation for the 45-km 36-h forecast started on 00Z 23 NOV 2011 are shown in Figure 4. The sensitivity of the lower-tropospheric kinetic energy in the equatorial western Indian Ocean (box in upper right panel) in the COAMPS forecasts to
changes in the 850-hPa temperature and 850-hPa zonal wind at analysis time are shown in the right panels. Warm (cold) colors indicate regions where increased (decreased) temperature or zonal wind at initial time will increase the kinetic energy in the box 36 h later. The wind vectors and wind speed (shaded) of the 36-h forecast are shown in the upper right panel. The tropical cyclone that develops in the Bay of Bengal and moves into the Arabian Sea (TC05) is off the southern coast of Indian at this time. The sensitivity patterns exhibit strong similarities with the classic Rossby/Kelvin wave response to equatorial heating in the simple two-layer model from Gill (1980), as shown in the lower right panel. In addition, the equatorial westerly also show sensitivity to the circulation that evolves into TC05 (green circle, upper left panel), indicating that the Kelvin wave associated with the westerlies is indeed sensitive to TC05, despite the fact that TC05 is well to the north-east of the Kelvin wave at this time.

Figure 4: 850-hPa temperature sensitivity (upper left, shaded) and zonal wind sensitivity (lower left, shaded) of the low-level kinetic energy associated with the 36-h COAMPS forecast from 00Z 23 NOV 2011 in the western Indian Ocean (black square in upper right panel). Sensitivities in the left panels are shown with the 850-hPa analyzed wind vectors. 36-h forecast 850-hPa wind vectors and wind speed (shaded) are shown in the upper right panel. The response to symmetric equatorial heating in a simple two-layer model from Gill (1980) is shown in the lower right.

During the time when the Kelvin wave is just south of TC05, sensitivity experiments indicate that the forecast of TC05 is sensitive to the Kelvin wave and that the forecast of the Kelvin wave is sensitive to TC05 (not shown). For forecasts started on 12 Z 25 NOV, when TC05 is moving into the Bay of Bengal, the picture changes (Figure 5). At this point, the sensitivity of the forecast of TC05 to changes in the analysis is local to the TC circulation itself, while the sensitivity of the Kelvin wave forecast to changes in the analysis includes both the Kelvin wave itself, as well as sensitivity to TC05. These results confirm the interdependence between TC05 and the Kelvin wave forecasts, and are consistent with results that find the simulation of one is sensitivity to the fidelity of the simulation of the other. It is encouraging that the COAMPS sensitivity exhibits similarities with the idealized Rossby/Kelvin wave response to equatorial heating, as adjoint sensitivity diagnostics in the tropics have thus far been primarily limited to tropical cyclones.
Figure 5: 850-hPa zonal wind sensitivity of the low-level kinetic energy associated with the 24-h COAMPS forecast of TC05 (upper left) and the Kelvin wave (lower left) from 12Z 25 NOV 2011. Sensitivities in the left panels are shown with the 850-hPa analyzed wind vectors. 24-h forecast 850-hPa wind vectors and wind speed (shaded) are shown in the upper right panel. Black and blue boxes in the upper right panels show the response function regions associated with TC05 and the Kelvin wave respectively.

IMPACT/APPLICATIONS

These experiments allow for an assessment of potential extended range forecast utility (both global and regional) for Navy-relevant metrics such as potential for high winds, extreme events, or tropical cyclones that are influenced by the MJO. The results so far are extremely encouraging, as the coupled 27-km COAMPS simulations (with analyzed boundary conditions) produce realistic simulations of MJO events out to two months. The extension of the simulations to 15-km resolution results in more realistic precipitation organization and reduces biases even further. The COAMPS simulations using NAVGEM forecasts as later boundary conditions rather than NOGAPS analyses show that reasonable MJO simulations are possible even without analysis-quality information coming through the later boundaries. Adjoint sensitivity studies support the utility of COAMPS adjoint simulations in the tropics through similarities to expected Rossby and Kelvin wave responses to equatorial heating, and confirm the interdependence of TC05 and Kelvin waves associated with the MJO. The assessment of model errors as a function of resolution also allows for feedback to model developers. Experience gained under this project will also have relevance for the potential development of a global model with adaptive mesh refinement capabilities. Understanding what resolution is needed for skillful extended range forecasts will also pave the way for the next generation fully coupled earth system prediction capability. For example, these experiments indicate that coupled models provide more skillful forecasts of tropical precipitation and the MJO than uncoupled models on monthly time scales.
TRANSITIONS

The potential for extended-range forecasting demonstrated in this program will be transitioned to operations through existing and future 6.2 and 6.4 programs.

RELATED PROJECTS

COAMPS is being used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling and the simulation of the Madden-Julian Oscillation, and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components of COAMPS. Improvements to NOGAPS/NAVGEM developed under an ONR Unified Physics DRI and 6.4 NAVGEM projects, are being leveraged for this project.

PUBLICATIONS

